Quaternary Marine Terraces on Cyprus: Constraints on Uplift and Pedogenesis, and the Geoarchaeology of Palaipafos

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Jay S. Noller

Numerous flights of Quaternary marine terraces are present around the island of Cyprus, in the Eastern Mediterranean. These terraces are a result of the global eustatic sea-level curve and local tectonism. Marine Isotope Stage (MIS) 5 through MIS 13 terraces are identified, mapped and dated. Palaeoshoreline elevation, an excellent indicator for a past sea–level, and new numerical geochronology are used to calculate an Upper Pleistocene uplift rate for various coastal sectors. Southwestern Cyprus presents the highest uplift rates of 0.35-0.65 mm/year with other sections suggesting uplift of 0.07-0.15 mm/year. This Upper Pleistocene tectonic signal is attributed to an active offshore subduction/collision system to the southwest of Cyprus, evidenced from the seismic activity offshore and the surface expression of a blind thrust fault in the Pafos region.

Soil chronosequences and geology in southwestern Cyprus are studied in order to understand the Quaternary development on this uplifting landscape. Soil profile properties are used to calculate a profile development index (PDI), a method often applied to geomorphic surfaces as a relative dating method. Well-developed red and clayey soils occur in the coastal sector, on broad and low-angle surfaces, specifically on marine terraces and alluvial fans. Higher elevations of steep slopes consisting of carbonate and ophiolite lithologies host poorly developed soils. Results show variable PDI's on uplifted terraces, obscured by transported materials, active alluvial fan buildup and hillslope erosion. Calcium carbonate build-up in soil profiles in the form of nodular and laminar accumulations are used as another relative dating method. Geochronology of marine terraces is used as an age range approximation for carbonate stages.

Geomorphologic mapping focuses on the southeastern part of the Pafos thrust fault, the only point on the landscape where this otherwise blind fault is exposed on the surface. This is the location of Palaipafos, an important Ancient polity, today the site of the village of Kouklia. Geoarchaeological study suggests little landscape change over the last 4000 years in the vicinity of the urban core of Palaipafos, this being attributed to bedrock and landscape resistance of its location, a plateau at 80 m amsl. Copper deposits in the Palaipafos hinterland had provided a valuable resource at one time. Soil and water resources continue to sustain agriculture.Tectonic uplift in this part of the Pafos thrust fault is estimated to be 2.1mm/year, considered, together with Late Holocene sea-level change responsible for the shifting locations and eventual abandonment of the Palaipafos harbor in the coastal lowlands.

Quaternary Marine Terraces on Cyprus: Constraints on Uplift and Pedogenesis, and the Geoarchaeology of Palaipafos

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Zomenia Zomeni, Author

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1 Introduction to the Quaternary geology of Cyprus

The Mediterranean is a unique semi – closed sea basin with distinct climate, geomorphology, and soils. It has steep mountains and infilled valleys, extensive coastal zones with significant additions of Saharan dust (Yaalon, 1997) and a rich Quaternary seismic and human history. All these attributes contribute to the Mediterranean being a significant field laboratory for studying Quaternary environments. It has rightly been referred to as “a sea behaving as an amplifier of the palaeoclimatic and palaeoceanographic signal” (Cita and McKenzie, 1999, 2000).

Cyprus, the third largest Mediterranean island (9,250 km^2), is notable for its geodiversity and tectonics, both of which have created a unique landscape and natural environment. Robertson et al. (1995) could not have made a more representative statement about the geology of Cyprus when stating that “one of the most fascinating aspects of eastern Mediterranean geology is the very rapid Plio – Quaternary uplift of the Troodos ophiolite, Cyprus”. In light of this very strong but also very true statement, this study attempts to contribute further to our understanding of this unique place.

1.1 Main Objectives

This study documents and evaluates Quaternary uplift which has contributed to the formation of its coastal morphological features, coastal soils on uplifted marine terraces and thriving ancient Polities. The area under study includes the whole coastal zone of Cyprus which is known to constitute much of the Quaternary geomorphic landforms and deposits of the island. The main objectives of this study are:

- To create an updated report on the Pliocene-Quaternary geological setting of the island based on the latest research and publications available (Chapter 1),
- To evaluate coastal uplift in the Quaternary period by mapping and dating uplifted marine terraces (Chapter 2),
- To suggest constraints on soil chronosequences on Quaternary terraces (Chapter 3),

- To understand the geomorphology and geoarchaeology of Palaipafos (Chapter 4),
- To draw conclusions on the Quaternary history of Cyprus and the sustainability of its coastal environments based on the above conclusions (Chapter 5).

1.2 East Mediterranean tectonic setting

The present tectonic framework of the Eastern Mediterranean and Middle East region is dominated by the collision of the Arabian and African plates with the Eurasian plate (McKenzie, 1970). The Mediterranean Ridge System (Figure 1-1), a long feature extending from Anaximander Mountains to the Bay of Iskenderun developed by the compression between Eurasia and Africa. The Levantine Basin, the easternmost basin of the Mediterranean has a complex structure and topography, with islands, seamounts and narrow continental shelves reflecting the continuing tectonic activity in the region (Robertson, 2000).

Plate boundaries in the eastern region of the Mediterranean express strain accumulated from the northward subduction of the African plate along the Hellenic (Aegean) and Cyprus trenches beneath the Anatolian plate. This plate collision process has been the result of the NNW displacement of the Arabian plate relative to the Eurasian. East of the Mediterranean Sea, the Dead Sea Transform fault separates the Arabian plate from the African plate (Figure 1-1). This transform fault has accommodated the difference in the rate motion between these two plates that results from the opening of the Red Sea.

Geological evidence including the overall seismotectonic model of the island suggests that uplift has continued through the Pleistocene. One of the possible explanations for the present uplifting process is that the African plate is being subducted under the Eurasian plate, giving Cyprus a significant vertical push and intense seismicity on the Cyprean arc, the collision zone between the two plates passing south of the island and extending northwest to Crete and the Ionian sea. In the vicinity of the Cyprus arc, the African plate penetrates below the locally oceanic Mediterranean crust (Makris, 1983) in the western part of the arc, in the proximity of Anaximander and Florence continental crust Seamounts and this is evident from the deep earthquakes in this region (Ambraseys, 1992a, 1992b, 1992c, 1992d).

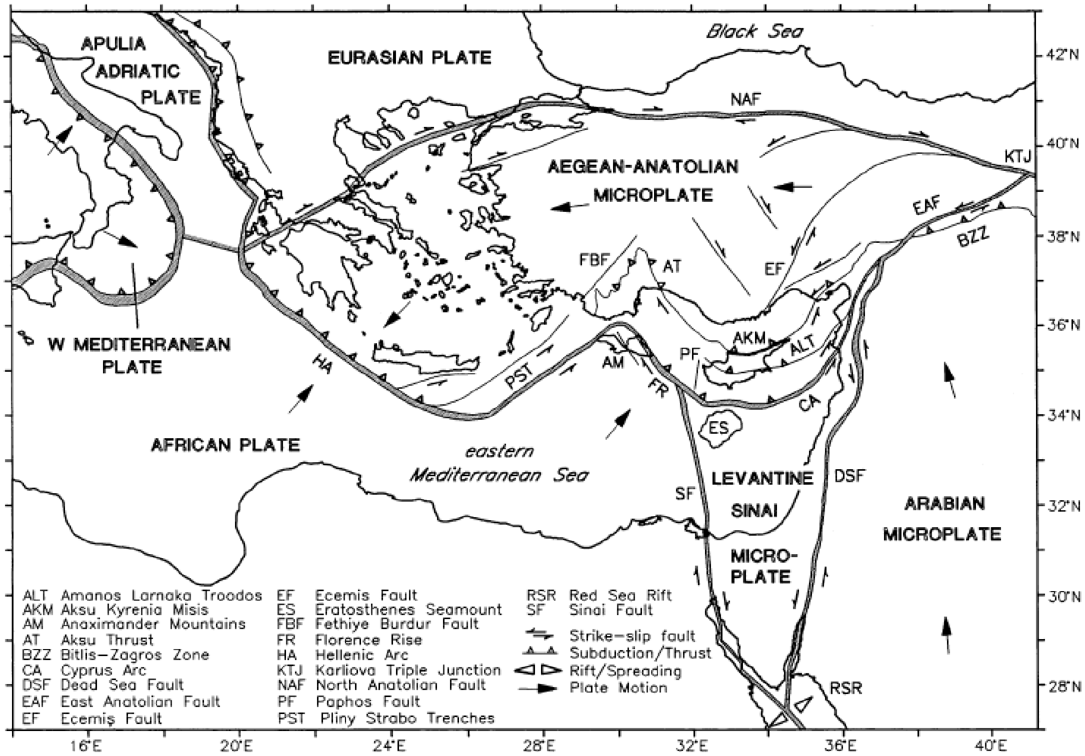


Figure 1-1 Tectonic setting of the Eastern Mediterranean showing the inferred location of the present-day Cyprus Arc (from Aksu, 2005).

The Cyprus arc is more of a collisional boundary in its central part where the Eratosthenis seamount, a continental crust microplate, and the Cyprus island, are undergoing intensive shallow deformation. In the eastern part, there is a wide zone of left-lateral strike- slip faulting (Ben-Avraham, 1995) in the vicinity of the Latakia ridge which extends all the way to the Syrian coast. The most intense seismic activity occurs in this central part of the Cyprus Arc and more specifically the Pafos fault (Figure 1-1) in the offshore southwest of the island. This comes evident in the deep borehole in Palaichori (in the northeastern part of the Troodos mountains) which displays maximum horizontal stress in a direction N70^{o}E ±10^{o} and minimum horizontal stress at N20^{o}W ±15^{o} (Haimson *et al.*, 1990).

1.3 Geological structure of Cyprus

The tectonic structure and topography of the island is controlled by its four geological terranes: 1) and 2), the Troodos and Arakapas Terrane, an autochthonous bedrock terrane which consists of a Turonian ophiolite sequence, and an off-axis ophiolite sequence, respectively; 3) the Mamonia Terrane consisting of Upper Triassic – Cretaceous sedimentary rocks and basalts; and 4) the Keryneia Terrane, consisting of Carboniferous – Cretaceous limestones and Cretaceous – Miocene carbonate sediments and greywackes. All four terranes are covered by autochthonous sediments, usually referred to as the Circum-Troodos sedimentary succession. Hundreds of publications have been written about the Troodos ophiolite, its formation, its emplacement, its significance and especially its Cyprus-type massive sulphide deposits (Zomeni, 2006).

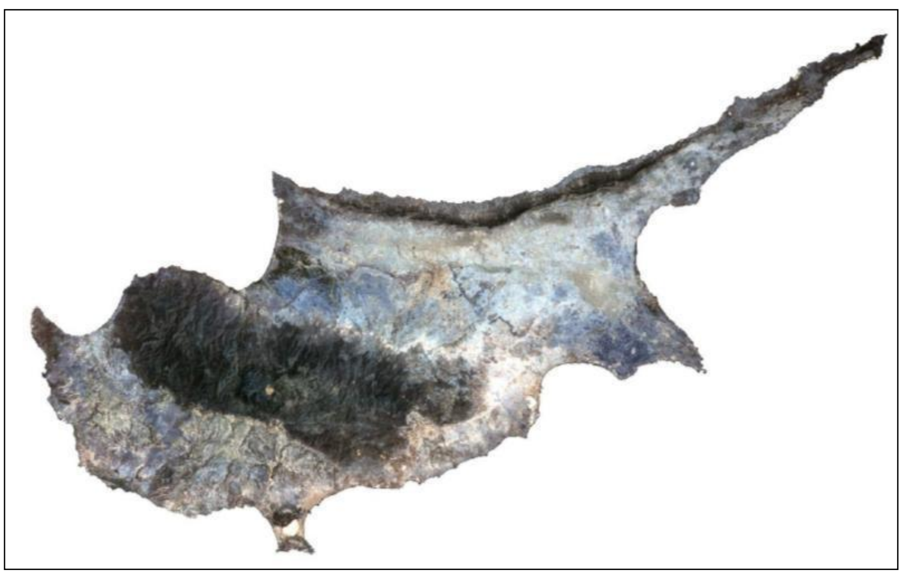


Figure 1-2 Landsat Satellite Image of Cyprus with a 30 m resolution. Note the dark ophiolite rocks making up the Troodos mountains, the pale central dot of the asbestos mine, the dark limestone rocks in the Keryneia range and the United Nations buffer zone along the Mesaoria plane across the center of the island showing up as a dark uncultivated uninhabited zone.

The Troodos Mountain Range is the main geomorphologic feature of the island of Cyprus. It covers an area of about 3200 km^2 and its highest peak, Olympus, has an elevation of 1951 m. Ophiolite terranes almost always present complex geology and structure due to their complex tectonic history, during intraoceanic formation, detachment emplacement and post-emplacement tectonic events. Formed in a Neotethyan supra-subduction zone by seafloor spreading at a constructive plate margin during the Turonian, the Troodos ophiolite terrane forms the central geologic zone and terrane on the island of Cyprus with a relatively intact and complete ophiolitic rock sequence.

Its well-preserved structure and stratigraphy makes the Troodos ophiolite unique in relation to the other Tethyan ophiolites. It includes all components of an ophiolitic sequence, an ultramafic core consisting mainly of serpentinized hartzburgite, plutonic ultramafic and mafic rocks, a sheeted-dyke complex, a volcanic sequence of mostly pillowed lava flows and topped with iron- and manganese-rich hydrothermal sediments.

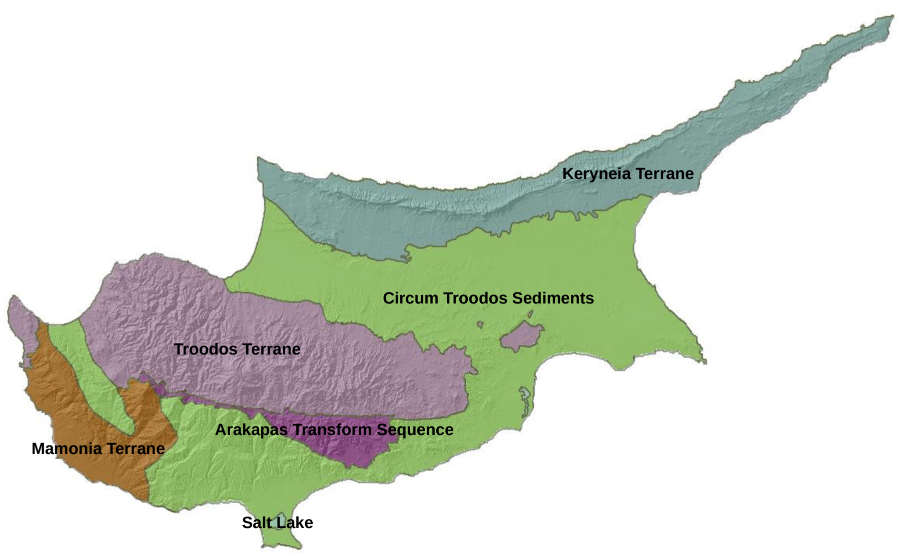


Figure 1-3 Major geological and tectonic zones of Cyprus.

The allochthonous Mamonia Terrane (also known as the Mamonia Complex) was juxtaposed during the Upper Cretaceous in the southern part of the island (Figure 1-4). The complex includes groups of formations which range in age from Upper Triassic to Mid-Cretaceous and consist of igneous, sedimentary and minor occurrences of metamorphic rocks. Deformation within the complex is quite intense as they have been severely broken and folded during their juxtaposition. Their juxtaposition formed thick and extensive mélanges referred to as the Mamonia Mélange in the west and the Moni Mélange in the south. Small exposures of the Mamonia Terrane appear in Akrotiri peninsula in the south and the Sotira Paralimni area in the east. A 5-km wide and well-exposed mélange zone in the southwestern part of the island presents an erosional window into this suture zone.

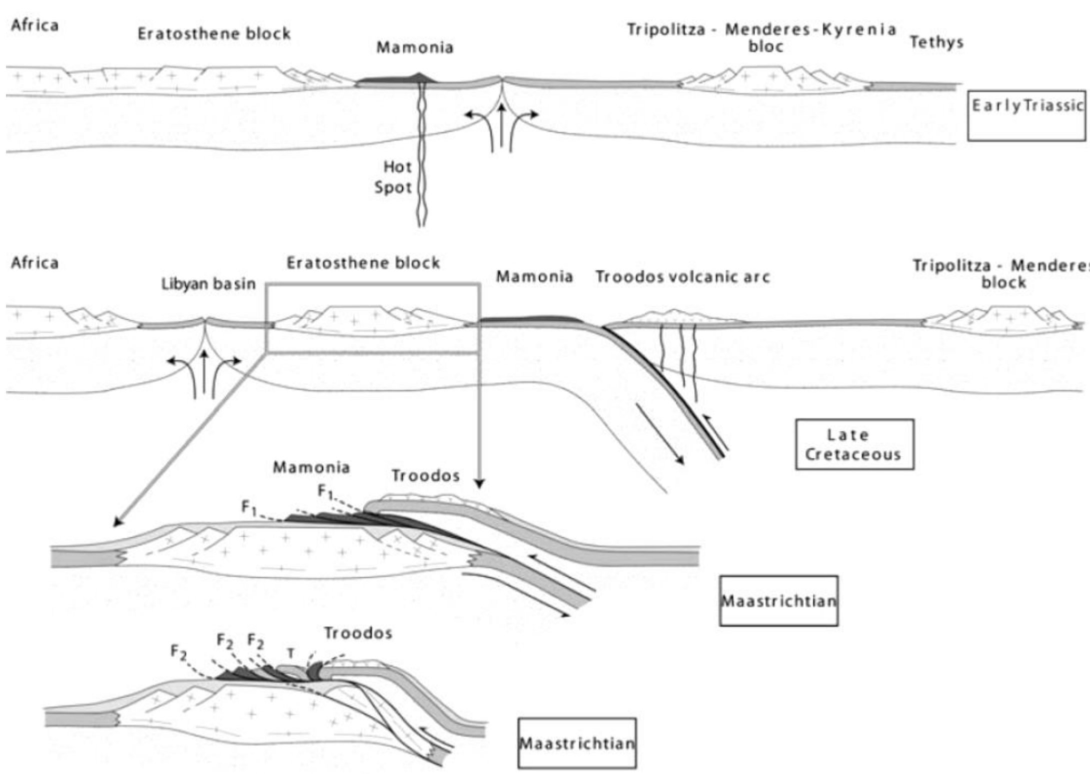


Figure 1-4 Schematic reconstruction of the structural pattern of the Troodos and Mamonia complexes involving tectonic events in the Upper Cretaceous (from Lapierre *et al.*, 2007).

Figure 1-5 Characteristic view of the Mamonia Terrane landscape.

The base of the Circum - Troodos sedimentary succession is marked by the 750 m thick Campanian to early-Maastrichtian Kannaviou Formation consisting of bentonitic clays and volcaniclastic sandstones indicating volcanism. This formation is extensively exposed in western Cyprus. The overlying Kathikas Formation in the western part of the island consists of debrites with a distinct clayey matrix. Whereas at the bottom of the Cretaceous Tethyan Sea the Troodos and juxtaposed Mamonia terrane were topped with pelagic chalks and cherts of the Lefkara Formation, the earliest carbonate sediments. Equivalent to the Lefkara Formation (southern Cyprus) is the Lapithos Formation (northern Cyprus) which is the oldest autochthonous unit in the Kyrenia Terrain. Lapithos Formation is of Maastrichtian to Eocene age and consists mainly of pelagic marls and chalks with cherts. The Lefkara Formation was deposited in a quiet marine setting and is devoid of volcanic rocks; the Lapithos Formation is a unit deposited in front of an advancing nappe and contains blocks of pillow lavas.

The Pachna Formation rests on the Lefkara or Lapithos Formations and is comprised of two Members of reef limestone, the Tera Member at the base and the Koronia Member at the top with the typical Pachna sediments being cream-colored chalks and marls, in sharp contrast with the white chalks of the underlying Lefkara Formation. Limestones in the lower and again the upper Miocene suggest periods of shallower marine conditions due to a falling sea-level and a now well established subduction of the African plate beneath Cyprus (Robertson *et al.*, 1991, 1995). Another characteristic feature of this sequence is the occurrence of variable thicknesses of sandstone beds. The upper formation contains rock fragments derived from the Troodos ophiolite as well as shallow water carbonate material, indicating the onset of partial subaerial exposure and erosion on an emerging island.

Miocene juxtaposition of more continental crust in the north gives rise to the intricate and precipitous mountain peaks of the Keryneia terrane consisting of a complex assemblage of limestone blocks, thick sandy flysch (Kythrea Formation) and limited metamorphic and igneous rocks. It forms a narrow, steep-sided mountain that rises abruptly from the surrounding lowlands. The oldest rocks are Permian limestones, flanked to the south by the broad lowlands of the Mesaoria Plain. The limestones are allochthonous and form a series of thick beds thrusted southwards or partly imbricated with younger sediments, mainly those of the Lapithos, Kalogrea, Ardana and Kythrea Formations.

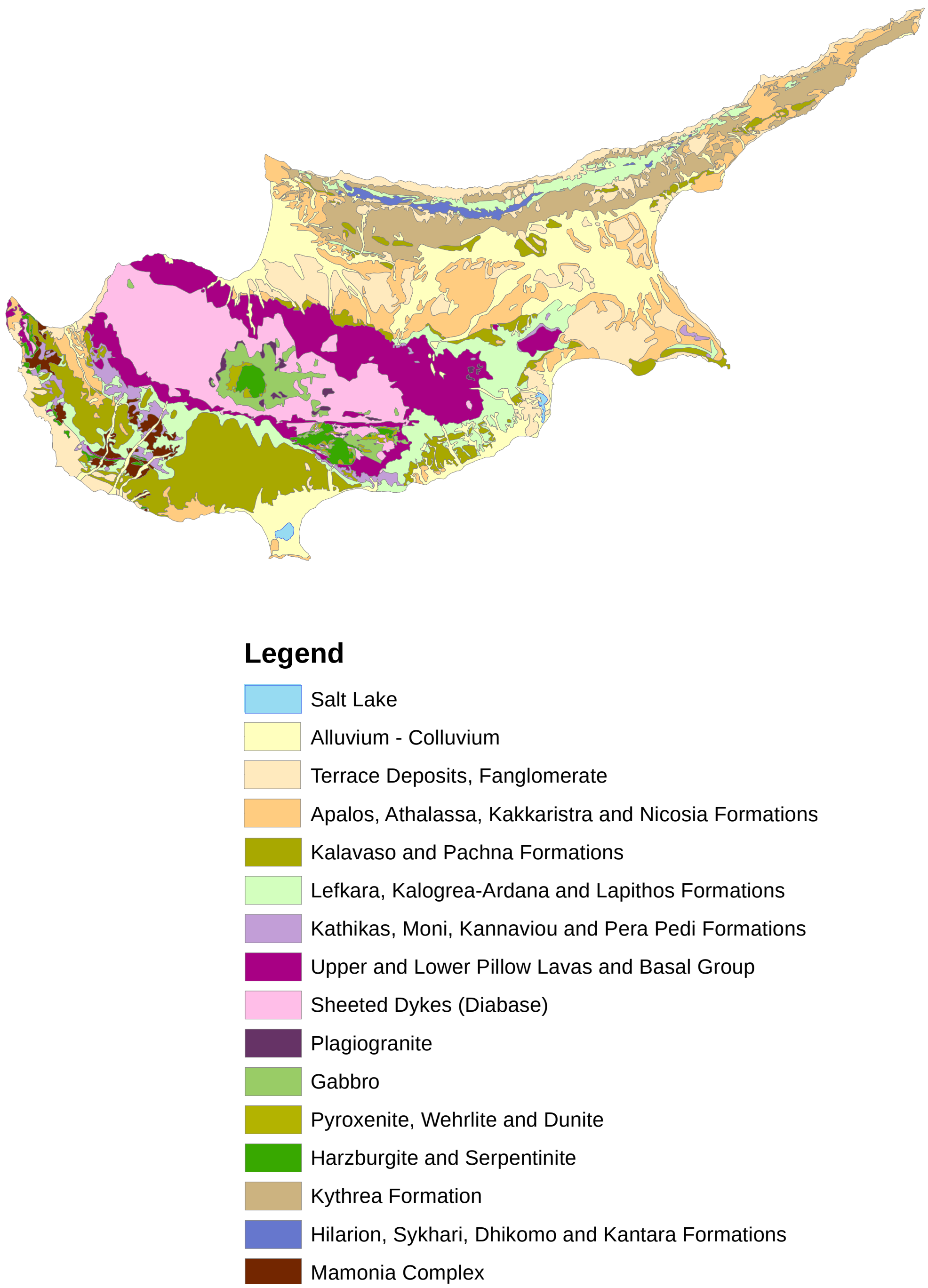


Figure 1-6 General Geology of the island of Cyprus derived from the 1:250,000 Geological map of Cyprus (Cyprus Geological Survey, 1995).

The Kythrea Flysch is conformably overlain by up to 120 m of chalks and marls with gypsum layers towards the top of the succession. In the south part of the island, similar sequences of Messinian evaporites are known as the Kalavasos Formation and consist of gypsum and gypsiferous marls. In the Keryneia Range, the Lapatza Formation would be in part equivalent to the Kalavasos. The evaporites mark the top of a mega-regressive sedimentary sequence found in most coastal Mediterranean regions, caused by the Messinian Salinity Crisis due to a large drop in the Mediterranean sea-level (2,000 m).

Reestablishment of the Mediterranean sea-level in the Late Miocene – early Pliocene formed marly deposits across the whole Mediterranean basin. Locally, the Marl Member of the Nicosia Formation was deposited in the shallow seas which today form the central and coastal lowlands. The Nicosia Formation has a maximum thickness of up to 900 m and spans almost the whole of the Pliocene and the Gelasian. Its thickest members, marine calcareous marls and lithic sandstones, are of Pliocene age.

1.4 Seismicity and tectonics

Ambraseys (1962) established the first earthquake and tsunami catalogue for the Eastern Mediterranean. Historical earthquake events had first been suggested by archaeologists in the beginning of the 19th century. Numerous archaeological excavations have revealed destroyed cities marking the end of flourishing island polities. One such detailed excavation at Kourion (west of Lemesos) revealed a whole city destroyed by an earthquake on July 21, 365 A.D. (Soren and Lane, 1981; Soren, 1988) and whole families buried in the ruins (Figure 1-7). Evidence for past earthquakes has come from historical references and archaeological excavations.

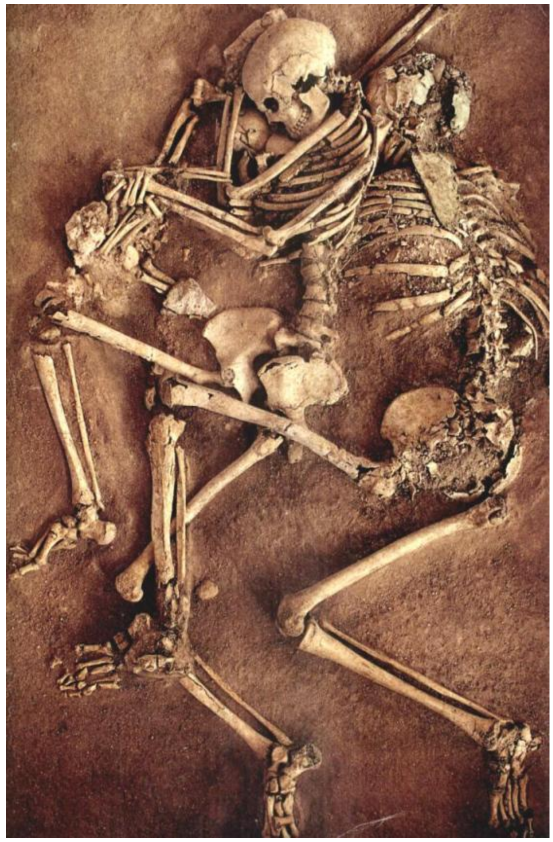


Figure 1-7 A family in arms, revealed during the excavation of the ancient polity of Kourion by the University of Arizona archaeological expedition (photo from Soren, 1988).

Many active faults have been identified on Cyprus, deforming Quaternary sediments and playing a significant role in the geomorphological and landscape evolution of the island, both inland but mostly on the coast (Figure 1-8). The faults of Arakapas/Gerasa and Mesaoria are mostly a result of the older in age, more megatectonic regimes of the Cyprus microplates. The coastal faults, at least in southern and western Cyprus, like the Pafos Thrust System seem to be more of a response to the proximal subduction zone which causes both a compressional regime in the upper crust and a relatively steady uplift rate, at least during the Quaternary. These shallow earthquakes off the coast of Cyprus are accompanied occasionally by seismogenic sea waves, more widely known as tsunamis.

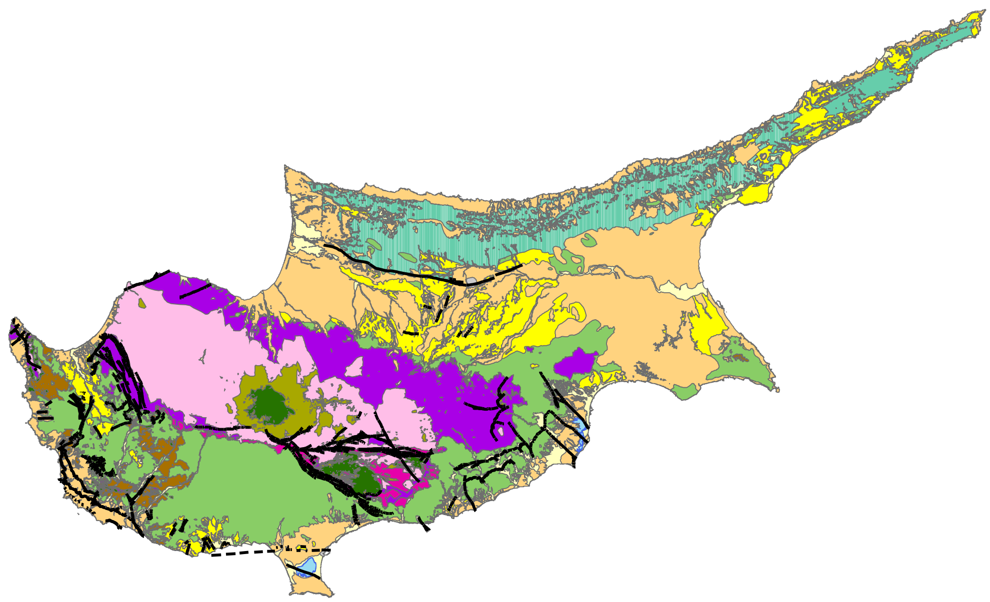


Figure 1-8 Quaternary faults (black lines) on Cyprus geological map (data from Cyprus Geological Survey).

During antiquity, the most significant and destructive earthquakes used to be recorded in historical manuscripts with smaller earthquake events remaining unrecorded. The assessment of such records requires for the historical documents to be evaluated with respect to the environmental conditions and historical factors that may have biased the way the event was documented. In evaluating the evidence for individual historical earthquakes, attention must be given to exaggeration, the role of population distribution, availability of documents, but most importantly the effect of building practices on damage scales.

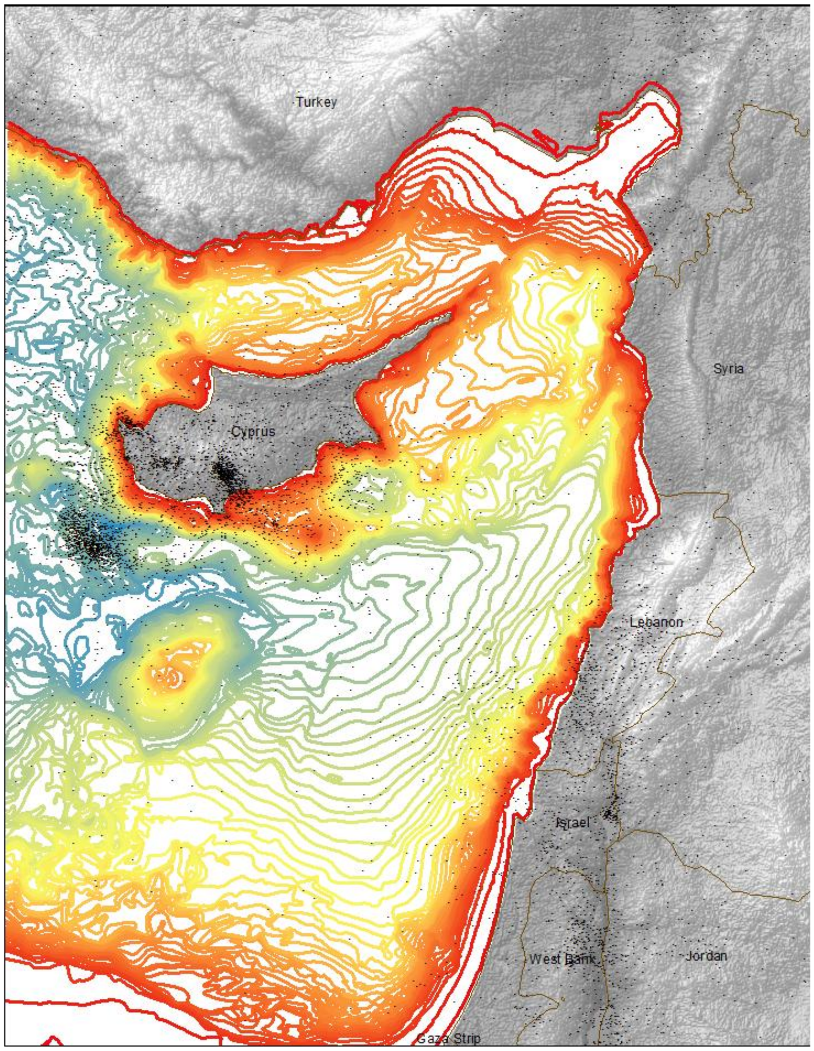


Figure 1-9 An earthquake catalogue compiled from recent Cyprus Geological Survey Department data and data from DeCoster *et al.* (2004). It includes more than 23,000 earthquake events in the eastern Mediterranean for the period of the last 3,500 years. Bathymetric contours are shown in reds for depths up to 1000m, greens up to a depth of 2000m and blues for a depth up to 2900m.

In the last 50 years, a more complete record is available with the use of seismic networks. Most of what is known about the seismicity of Cyprus since about 1900 is found in the records of regional seismic networks in the central and eastern Mediterranean area and from international earthquake data centers, notably the International Seismological Centre in

Newbury, UK (DeCoster *et al*., 2004). The most recent but also most complete earthquake catalogue for the Eastern Mediterranean has been compiled by Ted Algermissen during a 3 year seismic hazard assessment study on the island of Cyprus (DeCoster *et al*., 2004). The earthquake catalogue (Figure 1-9) was based on all available regional, worldwide, and historical data, was processed to remove duplicates, foreshocks, and aftershocks and supplemented with a consistent magnitude estimate for all events.

Table 1-1 List of most important earthquakes since antiquity (data from Cyprus Geological Survey)

BC	**Year**
Destructive earthquake in Pafos and Egypt	26
Destructive earthquake in Pafos and Kourion	15
AD	
Destructive earthquake in Pafos and Amathous	6
Most destructive earthquake and tsunami in Pafos, Salamina, Kition	76-77
Destructive earthquake in Salamina	332
Destructive earthquake and tsunami in Pafos	342
Destructive earthquake and tsunami in Crete	21 July 365
Destructive earthquake in Kourion and Akrotiri	367
Earthquake in Pafos and Salamis	394
Earthquake in Pafos area	19 May 1144
Earthquake in Pafos and NNE of Nea Pafos	1183
Earthquake in Cyprus and tsunami in Eastern Mediterranean	1202-3
Earthquake in Pafos and Lefkosia	3 May 1481
Earthquake in Pafos	18 December 1481
Earthquake felt on the whole island	25 May 1491
Earthquake in Pafos district	Dec 1567
Destructive earthquake (6.3 Ms) in Pafos district with 63 dead, 200 wounded and 4000 homeless	1953

1.5 Quaternary stratigraphy

Across this dissertation, the latest stratigraphic chart issued in August 2009 by the International Commission on Stratigraphy of the International Union of Geological Sciences is used as a guide. The major changes appearing in the new stratigraphic chart which are relevant to this study are those which relate to the Quaternary (Table 1-2) and its redefinition.

Table 1-2 Changes in the International Stratigraphic chart published in August 2009 (International Commission on Stratigraphy, 2009).

System Period	**Series Epoch**	**Stage Age**	**Lower Age Limit (Ma)**
Quaternary	Holocene		0.0117
	Pleistocene	Upper	0.126
		“Ionian”	0.781
		Calabrian	1.806
		Gelasian	2.588
Neogene	Pliocene	Piacenzian	3.600
		Zanclean	5.332

In general, these changes are:

1) the base of the Pleistocene Series/Epoch is lowered such that the Pleistocene includes the Gelasian Stage/Age and its base is defined by the Monte San Nicola GSSP, which also defines the base of the Gelasian;

2) the base of the Quaternary System/Period, and thus the Neogene-Quaternary boundary, is formally defined by the Monte San Nicola GSSP and thus be coincident with the bases of the Pleistocene and Gelasian, and

3) with these definitions, the Gelasian Stage/Age is transferred from the Pliocene Series/Epoch to the Pleistocene.

Table 1-3 Pliocene - Quaternary deposits on the island of Cyprus.

Formation		Age	Maximum Thickness (m)	Description
Alluvium, colluvium, beach deposits		Holocene	10	River alluvium and beach sands and gravels
Marine and fluvial Terraces		Gelasian - Upper Pleistocene	10	Marine terraces on elevated coastlines and fluvial terraces and fans in downcut / uplifted valleys
Fanglomerate		Early – Middle Pleistocene	90	High energy, coarse clastic alluvial fan conglomerates
Apalos Formation		Gelasian - Calabrian	45	Fluvial silts and clays, flood plain deposits and channel gravels
Nicosia Formation	Marine Littoral Member	Pliocene - Gelasian	10	Gravel, sand and silt of intertidal zone
	Aspropamboulos Member		7	Fine grained cross-bedded oolite
	Lithic Sand Member		50	Sandstones of a lithic origin
	Athalassa Member		20	Shallow marine calcarenites, biocalcarenites and conglomerates
	Kefales Member		20	High energy, coarse clastic imbricated fan delta conglomerates
	Marl Member	Pliocene	600	Marl and silty or sandy marl

These recommendations were approved by a majority vote of the IUGS Executive Committee on 29 June 2009. Formation and member names of local geology as well as geographical names used in this dissertation are adopted by terminology officially used and adapted by the Cyprus Geological Survey Department being the local legal authority on local geology.

Quaternary stratigraphy is of special importance in this dissertation since this study addresses Quaternary coastal environments, marine deposits, soils and geomorphology. Table 1-3 summarizes Pliocene - Quaternary stratigraphy in a generalized way. The following sections address the different units giving information on their depositional environment.

1.5.1 Plio-Pleistocene Nicosia Formation

After the deposition of the Marl Member of the Nicosia formation, and during the shallowing up of the seas around the Troodos and Keryneia Mountains, the depositional environments are predominantly shallow marine, coastal and fan-delta. Figure 1-10 shows an approximation of this Pliocene coastline. This Pliocene transgression marked by the deposition of the Nicosia Formation Marl Member is followed in places by the deposition of five other members, the Lithic Sand, Athalassa (Figure 1-11), Kefales, the Marine Littoral and the Aspropamboulos Aeolianite member (Figure 1-12). Palaeontological analyses of this formation indicate that the base of the Marl Member is Late Miocene; the exact age of the top is unknown and is Early Pleistocene (Panayides, 2004). Calcarenites, sands and thin conglomerates at the top of the formation are indicative of the final shallowing of the depositional basin.

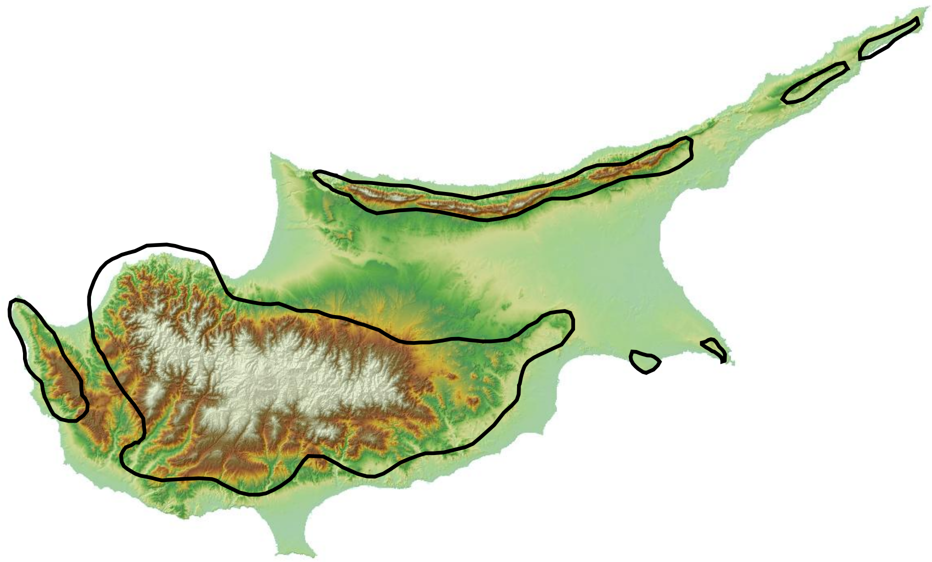


Figure 1-10 Approximate Pliocene sea level (5 million years ago) deduced from the extent of Pliocene marl deposits below the inferred coastline.

The Kefales Member and the Athalassa Member were previously termed Kakkaristra and Athalassa Formations respectively and both were correctly considered Pleistocene in the past. The Kefales Member is a sequence of fan-delta deposits which include “Gilbert-type” marine delta, bay and lagoonal facies, occurring on the southern side of the Mesaoria basin and consisting of a series of siltstones, cross-bedded conglomerates and fine-grained sands with conglomeratic intercalations. The Athalassa Member (Figure 1-11) is made up of a series of fossiliferous medium to coarse-grained, cross-bedded shallow marine calcarenites (McCallum and Robertson, 1995a, b). The Marine Littoral and the Aspropamboulos Oolite member mark the final regression of the Plio-Pleistocene seas and the establishment of subaerial environments in the Mesaoria plains.

This Marine Littoral Member literally represents the Plio-Pleistocene coastline and is now located at an elevation of 260 m amsl. This unit, believed to chronologically represent the beginning of the Gelasian period can help provide a rough estimate for the overall uplift of the island of Cyprus over the last 2.6 million years to be 0.1 mm/year or 10 cm/1000 years.

Figure 1-11 The Athalassa Member of the Nicosia Formation, also known by the local geologists as the Nicosia calcarenite.

Figure 1-12 Aspropamboulos Member, predominantly an oolitic sandstone

1.5.2 Apalos Formation

It is widely known that fluvial deposition may respond directly to climatic fluctuation and or tectonic activity (Bull, 1991). Unfortunately, current geochronological dating methods don't readily facilitate numerical dating of Early and Middle Pleistocene sediments. At the top of the Athalassa and Kefales Members of the Nicosia Formation is a series of near-horizontal reddish fluvial muds, silts and gravels, known as the Apalos Formation (Figure 1-13). These deposits reach a maximum thickness of 45 m at the type locality and elsewhere the thickness ranges from 10 to 30 m.

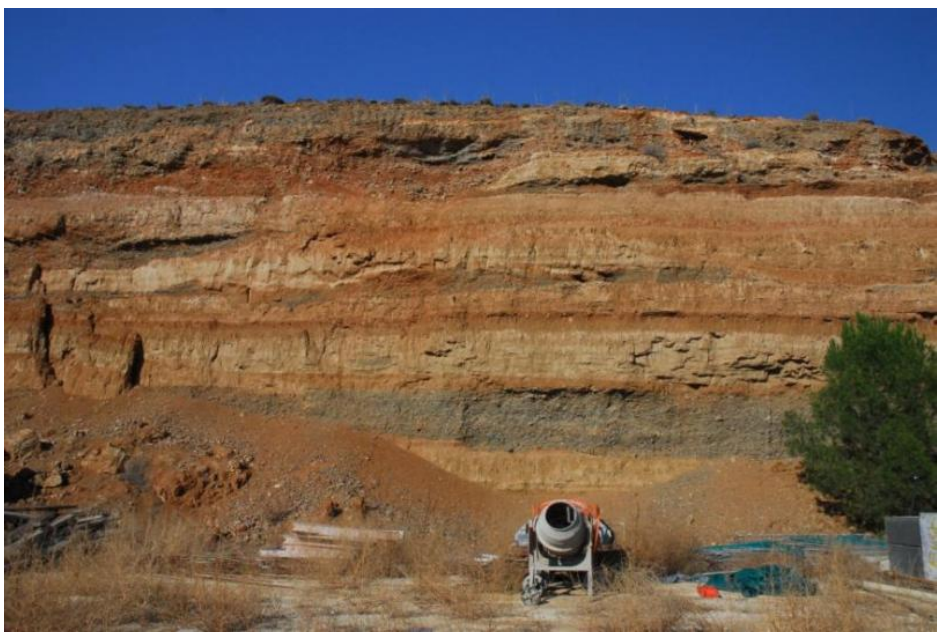


Figure 1-13 Apalos Formation at the Vlokarka type section showing alternating bands of fluvial silts, sands and gravels with at least 5 buried palaeosols.

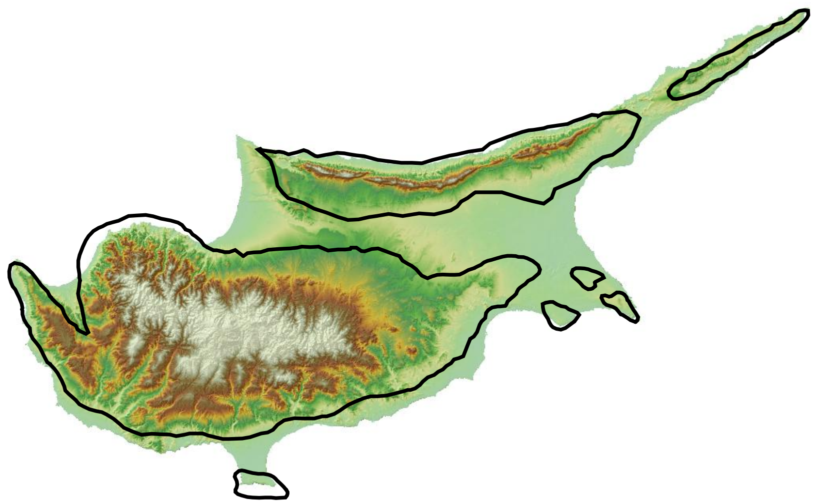


Figure 1-14 An approximation of the Gelasian – Calabrian coastline (app. 1.8 million years ago) based on Pleistocene terraces and not accounting for subsequent uplift.

The Apalos Formation consists primarily of fluvial deposits whose pattern shows alluvial-fan surfaces underlain by palaeosols, sand and gravel, gravel, sand, silt, and clay. The unit is described as repeating sequences of braided channel deposits, inter-bedded with flood plain deposits, sequences of laminated, fining upward sand, silt, and clay (Panayides *et al.*, 2004). Carbonate palaeosols and caliche, (locally known as havara) commonly occur at the top of each sequence. Gravel clasts are chiefly rounded and derived from the Troodos ophiolite lithologies, mostly consisting of durable gabbro and diabase. The remnant plains at the uppermost gravelly surface beds of the formation are capped by a palaeosol with thick calcium carbonate horizon (locally known as kafkalla). Schirmer *et al.* (2010) and Weber *et al.* (2011) recognized and analyzed 24 fluviatile units with 445 samples. The Apalos Formation marks the boundary between subaerial and marine processes in the Mesaoria plain. Their magnetostratigraphic correlation fixed the age of the Apalos Formation to the Gelasian – Calabrian (Figure 1-15). Kinnaird *et al*. (2011) repeated the palaeomagnetic sampling and found similar results.

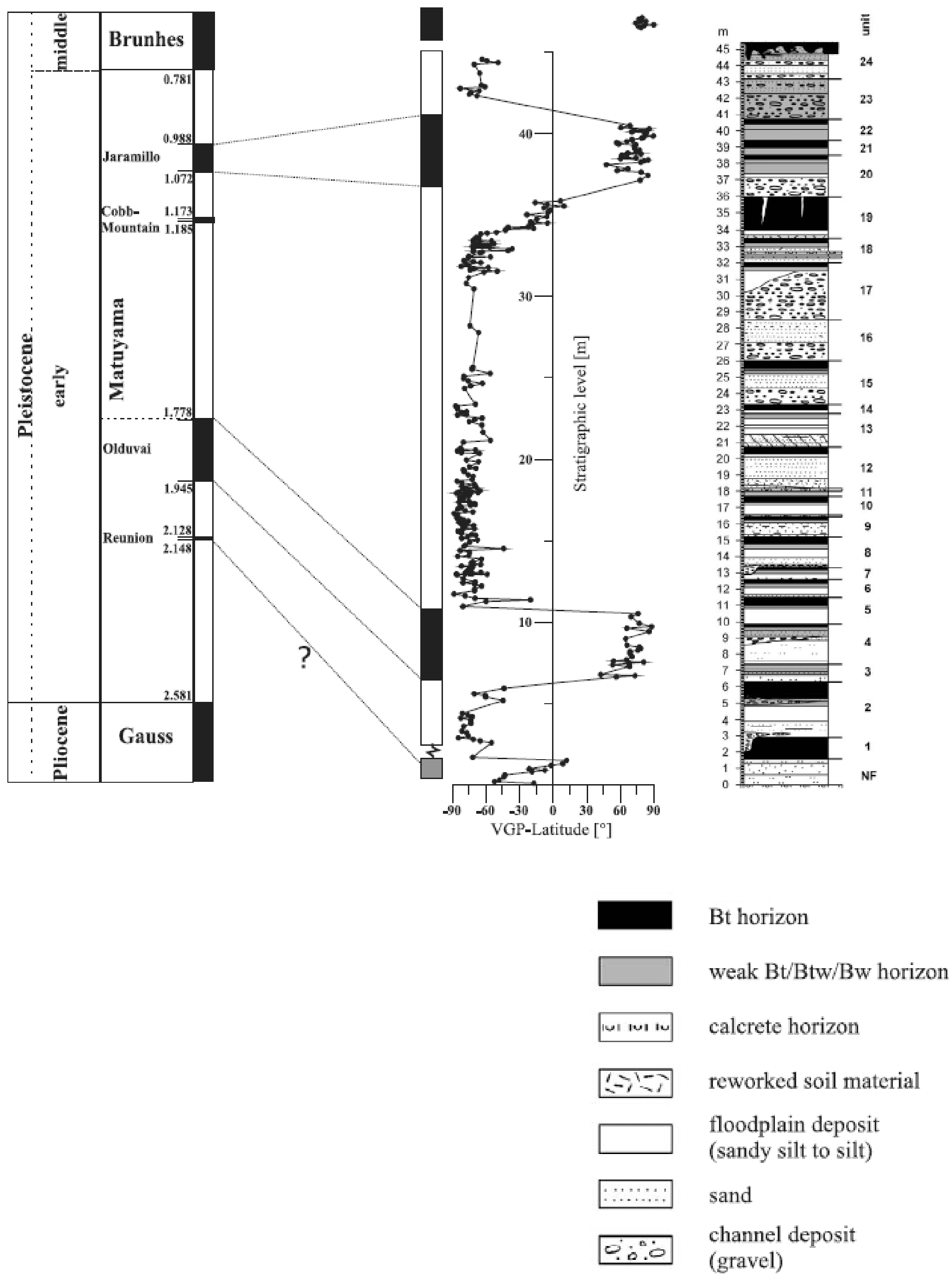


Figure 1-15 Magnetostratigraphic correlation and detailed stratigraphic column of the Apalos Formation showing age constraints (adapted from Schirmer *et al.*, 2010 and Weber *et al.*, 2011).

1.5.3 Fanglomerate

The almost linear northern boundary of the Troodos Terrane (Figure 1-16) also forms a line of apexes for sequences of extensive Pleistocene alluvial fans known in Cypriot stratigraphy as the Fanglomerate. Along the northern boundary of the Troodos mountains, the Fanglomerate formation is most well developed and best exposed. It unconformably overlies all other Circum-Troodos sediments and can be traced southwards to even lap onto the Troodos ophiolite itself, where it reaches a maximum thickness of 90 m (Zomenis, 1978).

Figure 1-16 Landsat Satellite image of the Fanglomerate units in the northern foothills of the Troodos mountains where they are thickest and more extensive.

These alluvial fans are composed of smaller coalescing fans consisting of semi-angular to semi-rounded clasts from gravel to cobble size. The clasts are almost entirely derived from the ophiolitic lithologies of the Troodos mountains. The matrix is silty clay, rich in oxidized metallic minerals. Often, it is interlayered with fluvial sands, clays and silts. The degree of cementation decreases with depth where clasts and matrix are well packed but mostly poorly cemented. On exposed surfaces, soils have developed well cemented petrocalcic soil horizons. The petrocalcic horizons form resistant top layers of buttes and mesas. The Fanglomerate usually constitutes the parent material on which luvisols and chromic luvisols (locally known as red terra-rosa soils) form and are intensely cultivated today.

These alluvial fans are the result of intense hillslope erosion and subsequent fan deposition on the Troodos mountain fronts of the uplifting island probably during the presumably wetter phases of the Pleistocene. Often, there will be layers of flows showing features of oversaturated debris transport. Three depositional cycles can be found on some outcrops identified by the presence of palaeosols possibly marking climatic periods facilitating soil development (Xenophontos, 2002). Deposition of the Fanglomerate formation was controlled by tectonic uplift, sea-level change affecting the channel gradients and incision rates, and climate change influencing erosion and supply of sediment.

De Vaumas (1963b) reports of alluvial fan units (piedmont formation) in Kambos tis Tsakistras and correlates it with sandstones of the Pomos coast with the assumption that they formed during cold periods. The term Fanglomerate formation has since being used to describe any alluvial fan deposit that is believed to be younger than the Pliocene. Their age and relation to palaeoclimate and the Quaternary marine isotope stages have never been investigated in depth.

Noller (2009) demonstrates that fluvial deposition is concurrent with uplift for the whole Pleistocene. Kinnaird (2008) assigns an early Pleistocene age to the alluvial fans in southern Cyprus and Waters *et al.* (2009) assign an age of late Pleistocene (MIS 5e to MIS 1) to the fans in the Vasiliko valley. Such conglomeritic fan deposits in semi-arid environments in Israel are found to be coincident with high water levels in Lake Lisan (the precursor of the Dead Sea) during wet periods (Bartov *et al*., 2002). U/Th dates on calcium carbonate nodules have yielded ages of 59,000 years BP for Vasiliko and 52,000 years BP for Pissouri (Waters *et al*., 2009) for fanglomerates on the MIS 5 marine terrace.

1.5.4 Marine terraces and aeolianites

Marine terraces provide a documented history of upper plate deformation and studying them can yield valuable data for tectonic models. These studies usually involve mapping and dating of the uplifted marine terraces in an attempt to better evaluate the uplift rate of coastal regions during the Quaternary and its differential uplift due to active faulting. The recognition of transgressions and regressions is based greatly on faunal assemblages. These marine deposits are usually dated with corals e.g. *Cladocora caespitosa* on Cyprus (Poole *et al*., 1990).

Figure 1-17 Elevated wave – cut platforms (at least five) in Miocene reef limestone bedrock of Cape Greco.

Found at elevations as high as 610 m amsl on Cyprus (Turner, 1971b), these marine terraces are relics of past coastlines (Figure 1-17). They are mostly marine calcarenites, biocalcarenites (packstones) and grainstones with basal conglomerates at the bottom and aeolianites at the top. The calcarenites are very rich in biogenic material and marine shells, making them prone to solution. This very porous rock is locally known as pouropetra (literally meaning porous rock) and has been widely used as building material from antiquity until today. This is mostly because of the ease with which it is quarried, the fact that it is widely found exposed at the surface and that it occurs in the coastal zone, the most densily populated areas.

Terraces at the highest elevations are probably of Pliocene age (Poole et al., 1990; Tsiolakis and Zomeni, 2008; Kinnaird, 2008). Terraces at lower elevations, e.g. those at 400 m amsl in Pafos, are attributed by Poole et al. (1990) as MIS 11 - 13, if one counts backup the exposed terraces from the coast. Fauna suitable for uranium-series dating *Cladocora caespitosa* revealed ages of 185-192 ka (MIS 7) for the terraces at the 8-11 m elevation and ages of 116-130 ka for the terraces at the 3m elevation. An approximation of the MIS 5e Calabrian coastline is shown in Figure 1-18. Detailed account of the marine terraces in Cyprus, their extend, elevation and age will be provided in Chapter 2.

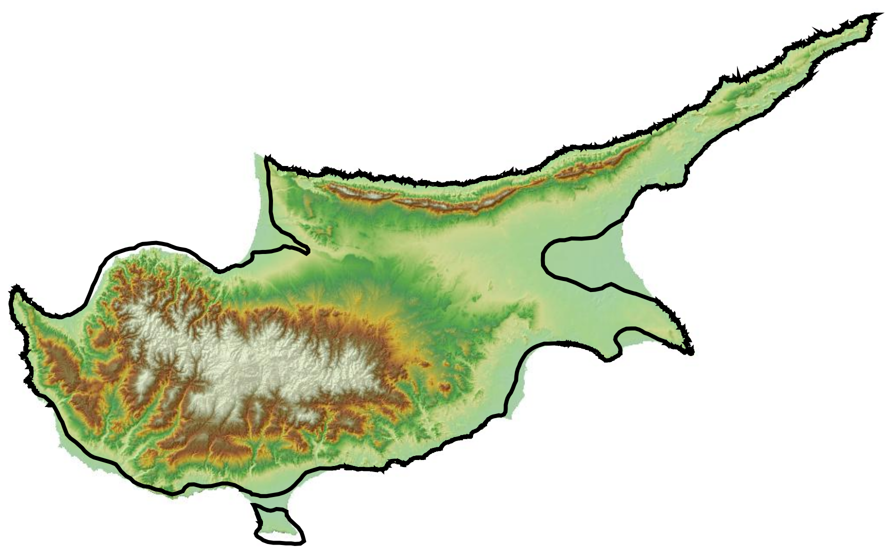


Figure 1-18 An approximation of the Ionian coastline (200,000 years ago) not considering subsequent uplift.

Aeolianites are very distinct coastal Quaternary deposits, in that most aeolianites preserved today are of Pleistocene age. This is either because they are characteristic of the Pleistocene glacials and interglacials, or simply because older aeolianites are poorly preserved (Brooke, 2001). Aeolianites are a major feature of the coastal geomorphology of the island. It is not absolutely clear if these aeolianites are forming mostly during wet or dry periods. It depends primarily on the availability of the source material, the sand. In the coastal European environments, especially the Mediterranean environments, it is believed that they are probably deposited during glacial maxima when the climate was dryer and colder, mobilising sand from exposed littoral zones and other proximal dry and poorly vegetated environments.

1.5.5 Alluvium and colluvium

Vita-Finzi's 1969 classic publication on Quaternary river development in the Mediterranean (Vita-Finzi, 1969) had served as a great synopsis for the geological observations that had been made for centuries about river valleys and terraces. Mediterranean fluvial sequences are characterized by extensive flights of terraces and deeply incised valleys (Figure 1-19), a response to uplift and/or reduced sediment supply. The difficulty of dating fluvial sequences older than the ^{14}C method limit has been a factor for the limited knowledge on Mediterranean Pleistocene sediments until recently (Macklin *et al.*, 2002). Other techniques like geomorphology, pedostratigraphy, palaeomagnetism and especially luminescence geochronological techniques have provided Mediterranean fluvial studies with new tools in the last 10 years.

In a Mediterranean regional study, Macklin and others (1995; 2002) have been able to correlate 13 alluviation episodes in various river basins. At least for the late Pleistocene, they have determined that river alluviation phases occur during cool stadials (especially MIS 5d) and that, phases of river incision occur during warm interstadials. The sensitivity and response of river systems to Pleistocene climate may be controlled by the proximity of the Mediterranean coasts to the forest/steppe ecoboundary and thus the changing sediment runoff amount, the high relief in the areas providing sufficient slope channel coupling (Macklin et al., 2002) and lastly, the high rates of crustal uplift facilitating incision and river terrace preservation.

Figure 1-19 Fluvial terraces in the Petra tou Romiou area

The Holocene alluvial deposits on Cyprus consist mostly of gravel, sand, silt and clay, and some organic material, deposited by modern ephemeral streams in channels eroded into older alluvial deposits. Alluvium commonly consists of poorly sorted pebble to cobble gravel and sand in channel and point-bar deposits, locally overlain by laminated and thinly bedded sand, silt, and clay; the fine-grained over - bank deposits occur on flood plain terraces that probably correlate with the 2-5 year flood frequency. Along smaller streams, modern alluvium is composed chiefly of sand and gravel derived from adjacent fluvial, colluvial, or weathered rock materials. The alluvial sequences and raised alluvial terraces are extensively terraced, dammed and farmed.

Figure 1-20 Colluvium in the area of Ergates village, well – cemented and covered with well developed soils, sometimes forming inverse topography.

Colluvial and talus slopes are characteristic of all geomorphic regions and landscapes on the island. Talus slopes are more common in the Troodos terrane where topography is more complex and steep. These talus slopes can be extensive and form little golden oak biotopes. Down on the planes, old colluvial slopes (possibly Pleistocene) are capped with calcium carbonate and soils, sometimes forming surfaces more resistant than the original rocks they are formed from, creating what is known as inverse topography (Figure 1-20). The higher tips of these features represent the old apex of the fossil fans.

1.5.6 Coastal deposits

Coastal deposits such as beach sands, gravels, beachrock, salt lakes, sand dunes and pumice are found on many beaches all around the island. Classically known for its sandy beaches, the island now has predominately sand – starved beaches due to the construction of dams and river flow works and diversions on all the major rivers. A recent study by Garzanti *et al*. (2000) was the first to investigate the provenance of the sand materials and establish a first approximation of the longshore transport directions around the island (Figure 1-21).

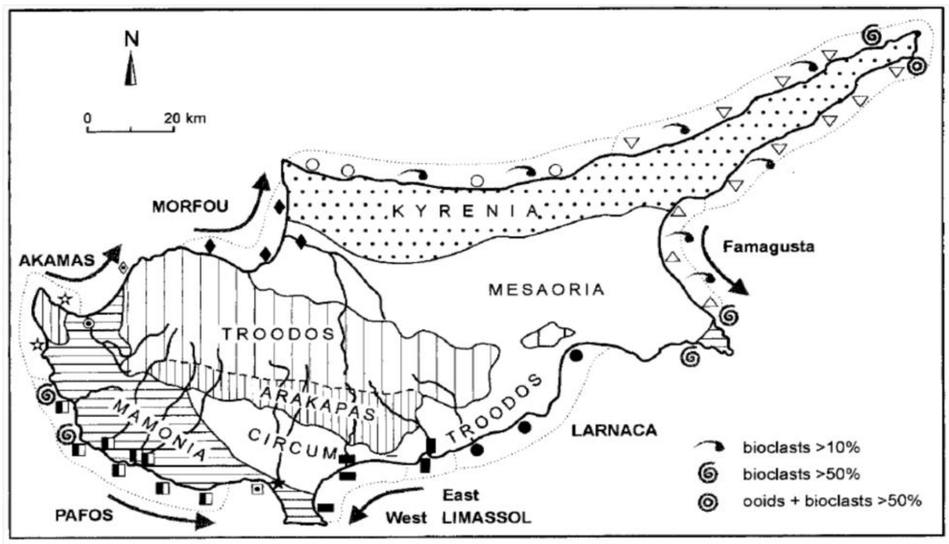


Figure 1-21 Main directions of longshore transport assessed by petrographic analysis (from Garzanti *et al*., 2000). Geometric symbols depict similar lithologies in unique littoral cells.

Pumice has been collected for centuries around Agia Irini, Vavilas and Davlos villages on the western and north eastern coasts of Cyprus (Bear, 1963). In the years between 1933 and 1935 a total of 330 tons of pumice were collected and exported from the beach of Agia Irini alone (Bear, 1963). It is believed to have travelled on the sea surface from the Aegean or the Italian volcanoes. Its significance actually as a surficial deposit is two-fold. Large quantities of pumice is found on elevated terraces, the question is whether they have been deposited on land during storms when the terraces where at sea level or whether they have been deposited on already elevated terraces by tsunamis.

Figure 1-22 Coastal engineering works in northeast Lemesos for the purpose of sand capture.

The construction of coastal sand-capturing walls (Figure 1-22) serve as decent local solutions but transfer the problem down the longshore transport direction. Sand starvation of rivers, uncontrolled sand and gravel quarrying in river beds and beaches until the late 70's and long lasting human occupation of the coastal zone have made beaches sand starved and sand dunes rare. The few sand dunes that are still somewhat active are mostly stabilized by vegetation (Figure 1-23) or destroyed by human activities. By far the most important geotechnical problem on the coast is coastal erosion.

Figure 1-23 One of the biggest active sand dunes in Cyprus located in the northern - most tip of Karpasia peninsula, just southeast of the Apostolos Andreas Monastery along Pachyammos beach.

1.5.7 Tsunami deposits

Kelletat and Schellmann (2001) were the first to identify the tsunamogenic depositional nature of large blocks and foraminifera rich gravel deposits on the coasts of Cyprus. More recent studies by Noller *et al.*, (2005, 2011) have revealed numerous pieces of evidence that seismic waves have reached almost all of the coasts on Cyprus. Cyprus has a long history of tsunami activity, as noted in written, archaeological and geological records. Because of the work of Ambraseys (1962) and others, there exists a rich bibliography of a literary historical record relating to tsunamis in the Eastern Mediterranean. As only destructive tsunamis were taken note of in the past, one must consider the number of events to be greater than this and hence their recurrence to be less than 30 years (Noller *et al*., 2011).

Figure 1-24 Tsunami boulders on the coast of Pegeia in the Akamas nature reserve.

With respect to geological evidence of tsunamis on Cyprus, such as boulder deposits and bimodal deposits, the dates of Whelan and Kelletat (2002) cluster into four periods. The latest of these events, evident from bi-modal tsunami deposits in western Cyprus have been dated to 1650 -1700 AD and are located at 1.5 – 4.5 m above sea level (Scheffers and Kelletat, 2004). There is an apparent coincidence in several of the historical tsunamis with that of the geologically determined events. Nearly all of the coastal sites display one or more of the geomorphological indicators of past tsunami activity. Ogerius Panis and Marchisius Scriba (ca 1294 AD), wrote about a tsunami event in Lemesos and Pafos which is believed to have taken place in May 1222 AD:

> "... at Cyprus, the sea was lifted up by the shock and rushed inland; the sea in places opened up in huge masses of water big as mountains and surged inland, razing buildings to the ground and filling villages with fish ... Baffa (Pafos), they say, suffered most ... the harbor dried up and then the town was submerged by the sea ... the town and its castle were completely ruined and its inhabitants wiped out …"

This account leaves no doubt about the occurrence of a tsunami for the May AD 1222 earthquake event. Archaeologists, historians, but mainly seismologists and geomorphologists, have often tried to collect and evaluate these past events. The tsunami record on Cyprus comes from several sources, involving the disciplines of history, archaeology, geomorphology, soil science and geology. A lot of recent geological research has focused on the nature and timing of ancient tsunamis in the Eastern Mediterranean. Some past strong earthquakes were associated with tsunami waves. More recently, the earthquakes of 18 June 1949 and 10 September 1953, were reported to have caused small local tsunamis.

A recent computer simulation of the 1222 AD event (Yolsal *et al.*, 2007), models a 7.0-7.5 magnitude earthquake with an epicenter off the southwest coast of the island, a focal depth of 15 km, a 3m coseismic displacement along a 50 km long fault. The propagation of the wave was generated using non-linear shallow water theory and produced results of wave height and arrival times for the whole eastern Mediterranean coast including the coasts of Cyprus. With an initial wave of about 1 meter at sea, tsunami waves reach the Cyprus coast in less than a minute and vary from 30 cm high at Cape Akamas to 190 cm high at the Pafos Airport. It also becomes evident from Yolsal's results that maximum wave heights occur at the capes, a phenomenon verified by field work. An impressive 82 cm high wave reaches Alexandria in Egypt in approximately 71 minutes. Historical accounts do mention the castle at Pafos collapsing and the earthquake causing damage in Alexandria. Similarly, an 8.0 magnitude earthquake off the southeast coast of Crete will result in a 90 cm high tsunami on the western Pafos coast and smaller waves elsewhere on the Cyprus coast.

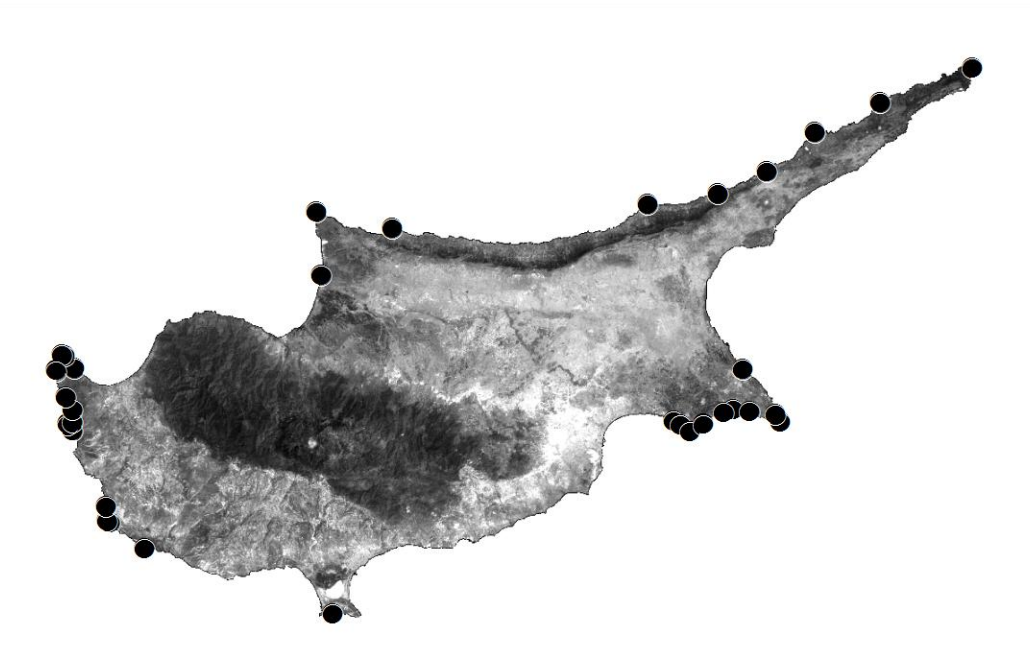


Figure 1-25 Shaded relief map showing distribution of geomorphological features indicating or suggesting origin by tsunami process (Noller *et al*., 2011).

Large rock blocks (20 to 50 ton) lifted up by tsunamis and deposited on higher ground have been recorded on Cape Kormakitis, the coast of Gialousa, Cape Greco, Agia Napa, Pafos Airport, Kissonerga coast, Lara Bay and the Akamas peninsula. Nearly all of the coastal sites visited displayed one or more of the indicators of tsunami activity. The presence of these large rock blocks is almost always out of geological context, located inland at a distance much further than any possible storm deposits and many times displaying inverse stratigraphy. Records of these “tsunami blocks” have been used worldwide as indicators of tsunami activity in Italy (Scicchitano et al., 2007). Located 2–5 m amsl, they reach 182 t in weight, isolated or stacked and having a variety of features suggesting that they were dragged from the mid-sublittoral or mid-supralittoral zones (Figure 1-24, Figure 1-26). Similar finding are recorded on most of the coasts of Cyprus (Figure 1-25).

Figure 1-26 At Cape Greco a long line of imbricate boulders of Pleistocene calcarenite sandstone lies at an elevation of 4 m amsl. J. Noller on the left, is standing next to an approximately 16-18 ton boulder.

1.6 Palaeoclimate

Continental and marine proxy climatic records indicate a closely coupled system in which the North Atlantic atmospheric and climatic history extended its influence into the Mediterranean Basin (Macklin *et al.*, 2002). Climate during the Pleistocene must have been greatly affected not only by the ice ages but also by the changing topography of the island due to tectonic movements.

Small semi-closed oceans like the Mediterranean Sea are often more responsive to palaeoceanographic and palaeoclimatic changes than global oceans like the Atlantic or the Pacific because of their smaller size and partial isolation. This sensitivity to climatic change seems to be especially true for the Mediterranean Sea, where the connection to the world ocean has been the narrow and shallow Gibraltar Strait since the end of the Messinian 5.3 million years ago.

The central Troodos terrain must have acted as the key factor in the microclimate of the island, just as it does today. As an orographic high, it captures moisture from the west and precipitates it on its mountain peaks and the rest of the island. Some parts of the Troodos had emerged during the Miocene, which is made evident from the shallow reefs and the calcarenites of the upper part of the Pahkna Formation both of which contain clasts of the Troodos lithologies. A much more intense uplift pulse followed in the Pliocene, caused by the coupled effect of diapirism due to serpentinization of the ultramafic core and the vertical tectonic component of the Cyprus arc collision / subduction zone. A critical height had to be reached before the newly formed orography could contribute to a new climatic regime.

Throughout most of the Pliocene and the Quaternary, deposition of marine dark colored organic, carbon-rich sediments in the eastern Mediterranean is strongly connected to palaeoclimate (Giunta et al., 2006). More than 90 such sapropel layers exist at ODP Site 967 in the Levantine Basin of the eastern Mediterranean (Kroon et al., 1998), and over 60 are present at ODP Site 979 in the Alboran Basin of the western Mediterranean (Murat, 1999). These deposits are always related to precession minima indicating warm and wet climatic conditions on land.

Table 1-4 Palaeoclimate data for the last 25,000 years in the eastern Mediterranean, definite cold and warm climatic events shown in blue and red respectively.

Time BP	Climatic conditions	reference
25000-17000	**Extensive ice sheets over northern Europe** ocean temperatures 2-3^{o}C cooler Temperatures in Middle east about 6^{o}C lower based on pollen data 23,800 BP Heinrich event 2 (cold) C3 and C4 vegetation	(Rossignol-Strick *et al.*, 1989;1993), Bar-Matthews *et al*. (1997; 1999)
17000-15000	Warming (2-3^{o}C), increase in precipitation, C3 type vegetation in Soreq cave Israel	Bar-Matthews *et al*. (1997; 1999)
15000-13000	**The Bølling-Allerød warm interval**	Robinson et al., 2006

Table 1-4 (Continued)

Time BP	Climatic conditions	reference
12000-10000	High lake levels in north Africa	Lezine and Casanova, 1991
12700-11500	**The Younger Dryas** global colder conditions, aridity in Israel, sand dune migrations Interruption of sapropel formation Most arid conditions in the last 2 million years	Robinson et al., 2006 Magaritz and Goodfriend, 1987, Bottema, 1995 Rossignol-Strick et al., 1989 Horowitz, 1989
9450	Palestine and Jordan valley population deserting and moving north into Jordanian plateau	
8200	**"The 8.2 Cold Event" (6200 BC)** Cold (>4^{o}C) and dry in northern Greece (Tenaghi Philippon in Drama basin), triggered by collapse of an ice dam into the Labrador sea, disruption in neolithic cultures in the East Mediterranean Khoirokitia deserted and Kalavasos Tenta occupied	Robinson et al., 2006 Weninger *et al.* (2006), Pross *et al*. (2009)
8000	Interruption in sapropel 1 deposition (cold spell)	Rohling *et al*., 2002
8400-6900	Interruption of flash-floods in Soreq cave Israel	Bar-Matthews *et al*., 2003
7850	Kalavasos Tenta deserted (5850 BC)	Weninger *et al.* (2006),
7500-5500	African Humid Period Increased precipitation, greater Nile river flow	Stanley and Bernhardt, 2010
7000	East Mediterranean aridification	Schilman *et al*. (2001)
4200	**The Mid-Holocene wet event (2200 BC)** Favorable agricultural conditions	Robinson *et al*., 2006
4000-3500	Arid conditions in the eastern Mediterranean Dead Sea water level lowered by 100 m Collapse of Akkadian agriculture in N. Syria Urban collapse in the Aegean around 3,800 BP Nile discharge reduced Santorini eruption in 1628 BC	Weiss *et al*., 1993 Staubwasser *et al*., 2003 Petit-Maire, 2003

Table 1-4 (Continued)

Time BP	Climatic conditions	reference
3500-3000	Humid phase in southeast Mediterranean (especially 3200 BP) World – wide glacial advance	Schilman *et al*. (2001)
3150-2800	**"The Dark Ages Drought Event"** in ancient Ugarit, Syria (1200-825 BC), social instability in E Mediterranean Arid conditions in southeast Mediterranean (especially 3000 and 2800 BP)	Kaniewski *et al*. (2010) Schilman *et al*. (2001)
1700-1000	Humid phase in southeast Mediterranean (especially 1400)	Schilman *et al*. (2001)
1100-800	Medieval Warm Period (900 – 1200 AD) Peak of Medieval Warm Period (950-1100AD) Byzantine period on Cyprus	(Lanb, 1965)
450 – 100 310-240	Little Ice Age (1550 -1900 AD) Ottoman period on Cyprus Peak of Little Ice Age in Europe (1690 – 1760 AD) Decrease in flash flood frequency and increase in temperate floods in the Gialias watershed, eastern Cyprus	Mann, 2002; Lamb, 1965 Devillers, 2003, 2005a, 2005b

Deep sea cores near Sicily indicate millennial scale variations in both climate and vegetation cover for southern Europe between 55,000-33,000 BP were closely associated to global climatic change (Rossignol and Planchais, 1989). In coastal Mediterranean countries onland preserved organic matter like pollen and charcoal due to the strongly oxidizing geochemical environment.

Isotopic analysis by Bar-Matthews (1999) in the Soreq cave of Israel, have identified six cold peaks to have occurred during the last 60,000 years. The nature of the peaks suggest that climatic events of the Atlantic are making their mark even in the far eastern Mediterranean regions, but not entirely. Heinrich events 3 and 4 are missing from the Soreq cave speleothems. No cave or rock shelter in the eastern Mediterranean has been found to contain a complete sequence of the Pleistocene Atlantic record (Woodward, 2001).

Coming closer to the Holocene, a general aridification trend seems to have begun about 7,000 years ago in the eastern Mediterranean region (Schilman et al., 2001). Interpreted cores off the coast of Israel were found to be reliable recorders of climate for the Holocene, in particular the last 3,600 years. Two wet periods occurred at about 3,200 and 1,400 years ago and arid conditions prevailed between 3,000 and 2,000 years ago. Alkenone, foraminifera and pollen records show that the Mediterranean climate was cool and dry at times of Heinrich events (Shackleton *et al*., 2000). Schilman *et al*. (2001) saw evidence for the Medieval Warm Period (around 800 years ago) and the Little Ice Age (around 270 years ago).

1.7 Oceanography

The surface flow progresses anti-clockwise along the Egyptian and Middle Eastern coasts. In this region there is intense mesoscale activity. Clockwise eddies induce a southwards current along the coasts of Israel and Lebanon, opposing the average northward flow. In the southern Turkish coast there is a warm coastal current called the Asia Minor current (Figure 1-27).

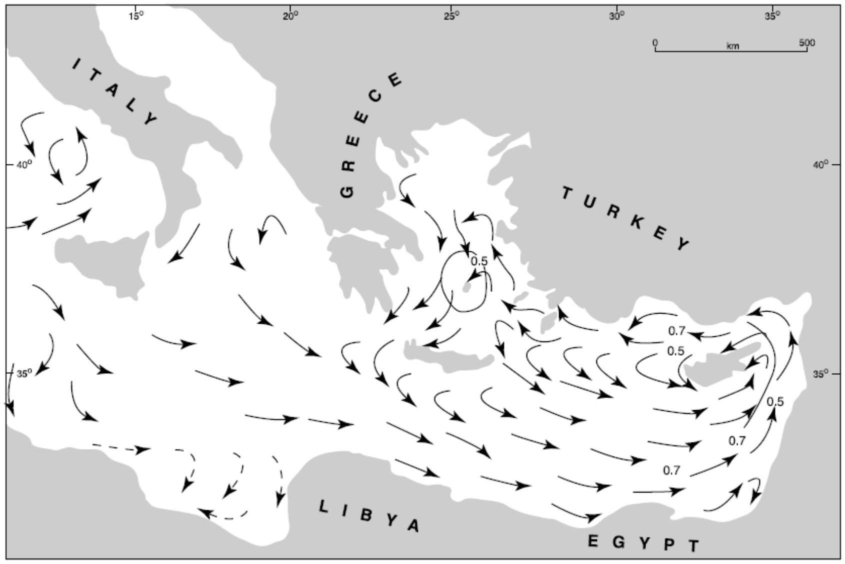


Figure 1-27 Sea surface flow directions in the Eastern Mediterranean, numbers representing surface current velocity in knots (from Dominey-Howes, 2004).

The tidal range, mainly semi-diurnal, is very small, in most places 0.3 m or less and nowhere exceeding 0.5 m. Consequently, meteorological conditions (e.g. strong winds) may often have more effect on sea level than the tide. Winds from the south-west with a long fetch produce the greatest swell around Cyprus and off the coasts of Turkey and Syria.

Salinity values of the Mediterranean Sea are on average 2.5 psu to 3.0 psu higher than the Atlantic Ocean. Ocean water globally has an average salinity value of approximately 35 psu. In the top 200 m of the Mediterranean, the salinity ranges from 37.5 psu in the west to 39.4 psu in the east. At greater depths, the salinity becomes more uniform through the basin, with values of 38.4 psu in the west and 38.8 psu in the east.

A difference of about 5°C in sea surface temperatures (a range of 10 °C -15 °C) exists between the north-west and south-east Mediterranean in the winter. In the summer months, the Eastern Mediterranean has a temperature of 30 °C, twice its winter temperature. The sea surface temperature range in August is much greater between east and west, at about 10 °C (a range of 20 °C -30 °C).

1.8 Geomorphology and Quaternary evolution

The island is divided into eight physiographic/geomorphologic regions for which relief, bedrock and climate/vegetation have been important factors for their formation (Noller, 2009). These physiographic regions (Figure 1-28) owe their formation to the tectonic evolution of the island which has helped create an island of intense topography very unlike the topography in nearby Egypt or Israel.

The Troodos physiographic region is by far the most impressive region both geologically and geomorphologically. Its serpentinized core (Olym) is a classic moon–like landscape of highly fractured rock blocks of hurtzburgite and serpentinized hurtzburgite. High peaks and ridges of young v–shaped valleys in diabase bedrock is the predominant feature in the Kykkos mountains of western Cyprus (Kyk), topography being strongly controlled by the differential weathering of the diabase sheeted dykes. Similarly, diabase, gabbro, pillow lava and plagiogranite country in the Kyperounta region (Kyp) create a more topographically complex terrain populated with small villages on rocky slopes or hidden in small valleys. The Arakapas region (Ar) is predominately controlled by its northern and western Arakapas and Gerasa faults respectively and the very rugged terrain, poor soils and infertile land making it a very sparsely populated area. It is worth mentioning that as an exception, the mild winter microclimate of the Arakapas tectonic zone has thick colluvial Cambisol soils ideal for citrus cultivation. Highly fractured lava rocks with exposed massive sulphide deposits are characteristic of the hummocky terrain in Stavrovouni region (St), which are dotted by abandoned copper mines and invaluable mining heritage locations.

Bedrock geology of the Mamonia Terrane is the major parameter for the characteristics of the Pafos physiographic region. The PHL region (Pafos highlands) is rugged due to complex geological structure and lithology. Marked as a collision and uplift zone in southwest Cyprus, this uplift is a highly erodible landscape; the clay–rich formations create a smooth and complex terrain with allochthonous blocks on land and exotic sea stacks on the coastline. The Ktima region (Kt) is early Pleistocene uplifted marine terrace terrain. The Coastal lowlands (CL) are late Pleistocene marine terrace calcarenites terrain. In the Akamas region (Ar), a piece of ophiolite crust and Mamonia complex rocks create a complex landscape with steep valleys fed by underfit ephemeral streams.

White chalk and marl repeating bed morphology dominates the major deposition basin of the Pachna Formation in the Lemesos region. Highly terraced agricultural land known as Omodos viticulture country (Om) and the Pachna region (Pac) are classic chalk and marl topography with radial and trellis drainage on south facing beds, their dip attributed to the uplift of the Troodos terrane. The coastal lowlands (CL) and the uplifted block of Akrotiri (Akr) are surrounding the salt plains of the Lemesos Salt lake (SLL). The coastal lowlands are the most populated areas in this physiographic region.

The Larnaca region is distinct for its low hills of white Lefkara Formation chalks and gypsum dissolution features over the gypsum lowlands (La HL). Just like in Lemesos and Pafos, the coastal lowlands (CL) and again the Salt lakes (SLL) are the most populated areas in this region and own their formation to Quaternary processes, especially tectonics. The Troulli inlier (Tr), as it is locally known in geological terms, is another outcrop of the Troodos terrane but in this case much smaller than the Akamas region.

In Karpasia physiographic region (Kar), structural complexity with many north- south-trending faults, together with the erodibility of the highly sandy Kythrea flysch are responsible for the rough topography and geomorphological uniqueness of this peninsula.

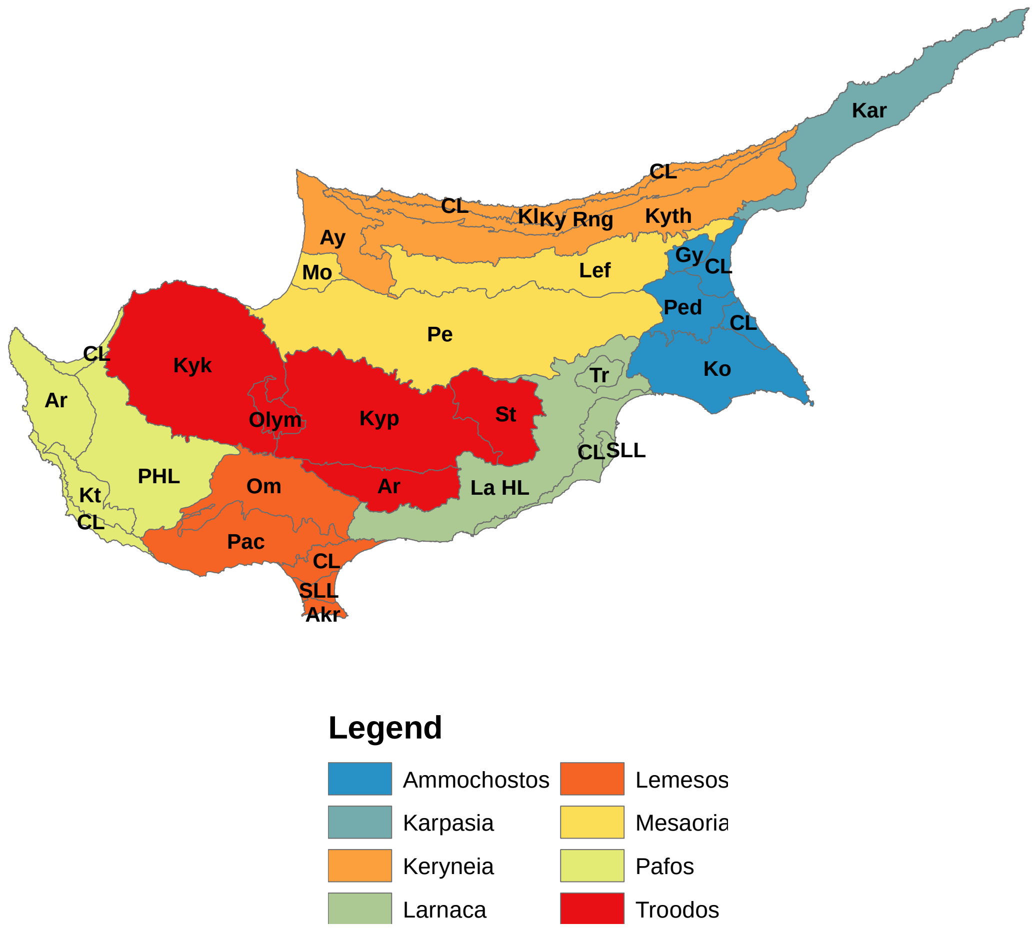


Figure 1-28 Physiographic regions of the island (Noller, 2009).

The Keryneia region has very precipitous crystalline limestone mountain peaks in the central range (Rng), hummocky and mainly bedding-dip controlled, north- and south-facing slopes of Kythrea flysch beds (Kyth) and an extensive coastal marine terrace range (CL).

The east-draining river system of Pediaios is responsible for the extensive flat lowlands and marshlands of the northern part of the Ammochostos region (Ped). In the southern Ammochostos region, a high-lying platform (Ko) with red, well-developed terra rosa soils constitutes a unique part of this region known as the Kokkinochoria area, literally meaning “red villages". The gypsum bedrock in the north (Gy) near the village of Gypsou is controlled by dissolution and karstic topography, leading to "disappearing" streams.

Lastly, the Mesaoria region forming the Plio-Pleistocene central plain (Pe) between the Troodos mountains in the south and the Keryneia range in the north consists of broad and gentle foothills, eroded into mesas and valleys which develop into two major river systems, one draining west and one draining east. The Morfou coastlands (Mo) and marshlands mark the Serrachis and Ovgos deltaic deposits.

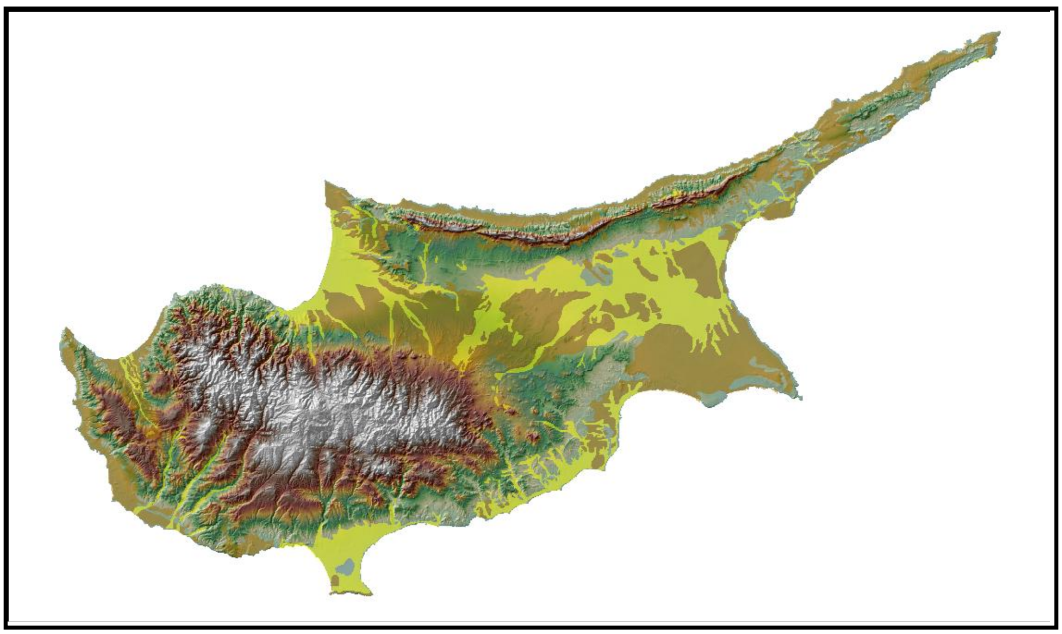


Figure 1-29 Quaternary units on Cyprus develop mostly on the central and coastal lowlands. Pleistocene deposits are shown in brown polygons and, Holocene alluvium and colluvium deposits in yellow polygons over a digital elevation model. Map is adapted from the 1:250,000 geological map of Cyprus (Cyprus Geological Survey, 1995).

Pliocene and Quaternary surficial processes have also contributed to the formation of this very diverse present landscape. Uplifting and active faulting have made significant imprints on the evolution of the landscape. Rapid uplift increases the hydraulic gradient and erosional capacity of rivers. This uplift increased markedly 2 million years ago (Poole et al., 1990). Uplift on Cyprus can be attributed to two geological processes. Firstly the serpentinization of the ophiolite core created a dome feature centered about the highest peaks of the Troodos mountains. This hydration process, following and as a result of dehydration of underlying lithologies (Moores and Vine, 1971; Shelton, 1993) serpentinized the hartzburgite increasing its volume and decreasing its density (Magaritz and Taylor, 1974). Bouyant rise of the serpentinite led to the domal uplift. Secondly, the tectonic regime of the eastern Mediterranean has added a significant vertical component to the resultant vector of the Cyprus plate.

Thick coarse alluvial fans formed predominately along the north and south Mesaoria Plain feeding material into the Pediaios, Serrachis and Ovgos rivers. Wide flood plains are the main characteristics of the present landscape in the Mesaoria. At the two coastal margins of this central plain, thick deltaic, aeolian and beach deposits of prograding coastlines form what are today the lowlands of Morfou Bay in the west and Ammochostos Bay in the east. Steeper terrain predominated on the rocky complicated coastline of the Troodos, Arakapas and Mamonia terranes in the south and the Keryneia terrane in the north. Pleistocene uplift and repeated sea level rise and fall, laced the coastal landscape with flights of uplifted marine terraces and the valleys with fluvial terraces.

The erosion of the mudstones around Lefkosia and the formation of stand-alone mesas are strong indications of the uplift and induced alluvial erosion of the island. Another strong indicator is the intense river erosion of the Troodos Mountains and the deposition of thick alluvial fans on the plains. The large boulders derived from Troodos ophiolitic lithologies, contained in these gravel deposits are indicators of the erosional and transportational capacity of the Pleistocene rivers.

In the coastal region the predominance of marine sediments over terrestrial sediments suggests the character of an emerging coastal landscape. Numerous preserved sea level indicators offer great opportunity for studying coastline evolution as a function of time.

1.9 The first humans and land use

A big part of palaeontological research for the Quaternary period in the Mediterranean concerns pygmy hippopotamuses and pygmy elephants. Their remains are usually found on coastal sites, mostly caves and rock shelters. These Pleistocene mammals were common on Mediterranean islands and coasts (Marra, 2005), where they are believed to have made their way either by swimming or with the help of floating trees. One can assume that during the glacial maxima, especially MIS 8, 6 and 2, the distance between Cyprus and neighboring main lands was as short as 30km, like in the case of the distance between Cape Apostolos Andreas and the Bay of Iskenderun.

The main islands of the Mediterranean, including Sicily, Crete, Cyprus, Rhodes, and many others, were all settled in Neolithic times, if not before. By the Bronze Age, several of these islands hosted advanced civilizations, mostly based on trade and shipping. Cyprus seems to have first been visited by humans about 12,000 years ago, probably in small groups from neighboring main lands which lived by hunting and gathering food (Ammerman and Noller, 2005). Aeolianites on almost all the coasts of the island contain scattered flint tools and flint tool waste pieces from those ancient hunters and gatherers (Figure 1-30) (Ammerman and Noller, 2005). These flint tools were probably preserved because aeolianites never hosted thick soils suitable for cultivation. Any agricultural activity would have destroyed the archaeological strata.

Figure 1-30 Flint tools are found in the hundreds, scattered mostly near the coast, this one in Kissonerga, western Cyprus.

One important rock shelter, Aetokremnos, is located on Cape Aspro, the western tip of Akrotiri peninsula on the cliff about 10 meters above sea level. Mandel and Simmons (1992, 1996, 1997) have identified animal bones (200 hippopotami and 3 elephants), flint tools, shells and aeolian sand deposits in a human and/or animal shelter. They have since been attempting to decouple the geologic and human signals on it. Radiocarbon dating has revealed that human presence at the shelter goes back to 10,000 BP calibrated (30 samples), maybe the first human hunter presence on the island, made evident from chip stone tools and picrolite artifacts (Simmons and Reese, 1993; Ammerman and Noller, 2005). Other coastal sites are in Agia Napa and Aspros in Akamas. A few other sites, Agia Varvara Asprokremnos, Ais Giorkis, Pafos and the Roudias Bridge site in the Xeros river basin in Pafos, are all interior sites dating also to the PPNA (Pre – pottery Neolithic, 10,500 – 8,800 BC). These interior sites are associated with fire hearths, chip stone dumping, pieces of picrolite and stone vessels and tools.

Figure 1-31 General view(looking west) of Aetokremnos area on the southern shores of Akrotiri peninsula, the site of the first human presence on the island.

One of the major evolutionary changes of these Pleistocene island mammals was dwarfing, which allowed them more ease of movement. *Hippopotamus minutus (Phanourios minutus)* was about 1.5 m long and 0.75 m high. *Elephas cypriotes* was only 1 m high. *Hippopotamus minutus* greatly outnumbers *Elephas cypriotes* in population numbers by a ratio of about 9:1. Their fossils have been found in many locations, first by Dorothea Bates between 1902 and 1904, and later studied by Boekshofen and Sondaar (1972a, 1972b), Simmons and Reese (1993).

Since Neolithic times, humans have been altering the land they lived on and cultivated. With the establishment of the first communities in the Ceramic Neolithic we expect the introduction of agriculture (Table 1-5), systematic fishing, hunting, domestication of animals, grazing, logging for fuel and for the purposes of land clearing. By this time sea-level rise after the Last Glacial Maximum has slowed down and coastal communities are becoming more established. These activities are considered to be the first human impact on the landscape.

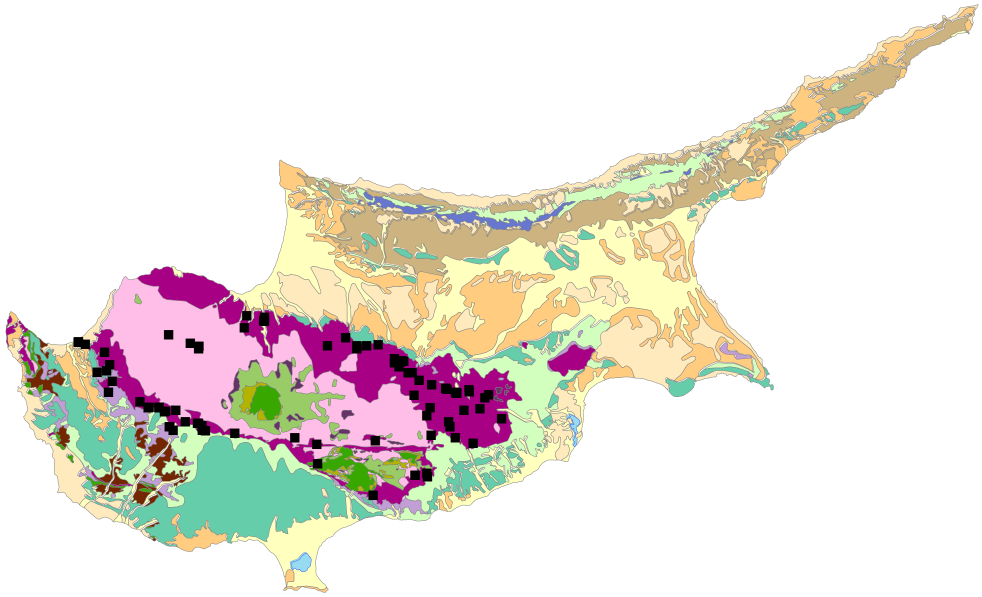
The second significant human impact on the landscape occurred with the introduction of copper mining in the Chalcolithic period (Table 1-5). Cyprus had extraordinary copper deposits exposed at the surface, made attractive to the ancient Cypriots by their bright colors of iron and copper oxides. They were intensely mined in ancient and classical times. The name for copper, from the Latin *aes cyprium* which means "cypriot copper" originated here. According to Pliny, the principal mines were in the southern mountain range but soon they spread around the Troodos ophiolite in the pillow lava basalt belt. This is supported by the ^{14}C chronology on charcoal sampled from ancient copper slag deposits (Gale et al., 1998) that amount to about 4 million tons in many heaps. Unearthed furnaces at Agia Varvara Almyras and Politico Phorades attest to the localized metallurgical processing in relation to the location of the ore. Evidence for ancient metallurgy suggests that it ends at about 700 AD and resumes again in the beginning of the 19th century with the introduction of modern technology.

Table 1-5 Simple chronological account of human occupation on Cyprus.

PERIOD	DATE	HISTORY
Akrotiri-Aetokremmos	11th millenium BC	Hunter-gatherer communities, ephemeral occupation. Oldest dated human existence at 10,000 BC
Pre-Pottery Neolithic	8800 - 7000 BC	Agropastoral settlement, introduction of pig, goat/sheep, cattle, fallow deer
	7000 BC	Apparent settlement discontinuity
Aceramic Neolithic	7000 - 5500 BC	First farming, domestication of animals, agricultural settlements
	5500 – 5000 BC	Settlement discontinuity
Ceramic Neolithic	5000 - 3900 BC	First farming communities and the first pottery made, deer hunting important.
	4000 BC	Apparent settlement discontinuity
Chalcolithic	3900 - 2500 BC	Production of copper objects and population expansion. First copper objects in tombs of Souskiou, Erimi and Kissonerga in Pafos area. Independent houses and house—based societies. Olive tree and vine cultivation. Move from hunting sustenance to animal husbandry. The same period as the Minoan civilization on Crete.
Philia Culture	2500 – 2350 BC	
Early Bronze Age	2500 - 1900 BC	Bronze, was first used to make tools and ornaments. Establishment of town and social life.
Middle Bronze Age	1900 - 1700 BC	A short and relatively peaceful period when many villages were settled.
Late Bronze Age	1700 - 1050 BC	Trade links with Egypt and Near East well established, the time of the Mycenaean period in Greece.
Geometric	1050 - 750 BC	(a.k.a. Iron Age) Cypriot culture shows much influence from Greece. New settlement patterns. Contact with the Phoenicians from the 9th century.
Archaic	750 - 480 BC	Period of the city-polities, Assyrians, from 709 BC; Egyptians, from 570 BC; and Persians, from 545 BC. Nevertheless, urban growth and prosperity from copper production and export.

Table 1-5 (Continued)

PERIOD	DATE	HISTORY
Classical	480 - 310 BC	Ruled by the Persians until their defeat by Alexander the Great of Greece in 333BC. Cypriot polities then come under Greek rule.
Hellenistic	310 BC - 30 BC	Freed by Alexander the Great for their help in defeating Persians. Annexed by Egypt from 294BC-30BC, the death of Cleopatra VII
Roman	30 BC - 330 AD	A senatorial province of Imperial Rome in 30BC, until the division of the Roman Empire by Constantine the Great in AD395. Salamina and Kourion flourish. Hadrian’s plague in 167 – 172 AD.
Early Christian	330 - mid 7th century AD	(a.k.a. Late Roman – Early Byzantine) Spread of Christianity, Justinian’s plague around 542 AD.
Byzantine - Arab raids	mid 7th century - 965 AD	Arab – Byzantine conflicts. Arab raids 849 – 911 AD destroying many coastal towns.
Byzantine	965 - 1191 AD	Part of the Eastern Roman Empire, Byzantium, ruled from Constantinople, building of many churches and monasteries.
Frankish	1191 - 1489 AD	Captured by the crusader Richard I of England in 1191 and then purchased by the Frankish "King of Jerusalem", a feudal system by French nobility with rural oppression. Black Death 1348 – 1438.
Venetian	1489 - 1571 AD	The Italian state of Venice ruled Cyprus. Population expansion maybe up to 200,000. Cereal production double local demand (Lusignano, 1573)
Ottoman	1571 - 1878 AD	Ruled by the Ottoman Empire with collaboration from the local Orthodox church. Severe poverty, emigration and depopulation.
British	1878 - 1960 AD	Ceded to Britain in 1878 in return for assistance in the Russo-Turkish war. Britain annexed the island in 1914 after Turkey entered World War I. Population in 1881 is 186,000. Officially a British Colony in 1925, but independent in 1960 (population 578,000).



1-32 Ancient copper slag locations (data from Cyprus Geological Survey).

The account which Strabo gives of the mines of Tamasos shows that the ore was smelted in furnaces which were heated by wood fires. Forested areas of the island were under pressure from timbering at least 6000 years ago. Only in Skouriotissa, an ancient heap, 135 m long is estimated to amount to 2 million tons of slag. Strabo of Amasia, Greek historian and geographer, paragraph 14.6.5 wrote in 19 AD:

> "As a fertile island, Cyprus is unsurpassed, for it produces good wine, good oil and also enough corn for its own use. In Tamasos there are, moreover, a large number of copper mines, containing copper sulphates as well as copper oxide, which is suitable for medical purposes. Eratosthenes [3rd century BC] tells us that in ancient times the plains used to be covered with dense forest and, as a result, could not be cultivated, but the mines remedied the situation, for the inhabitants chopped down the trees in order to smelt copper and silver. Eratosthenes also says that shipbuilding was a further reason for deforestation, for the sea was a traffic route, sometimes for whole merchant fleets. Since the islanders were unable, in spite of this, to master the sheer extent of the forest on the island, they allowed anyone who was willing and able to fell trees, to adopt the land thus won as their own property, without having to pay any taxes"

Chrysotile asbestos was discovered and utilized in Cyprus during classical times, perhaps as early as 5,000 years ago, for manufacture of cremation cloths, lamp wicks, hats, and shoes (Dioscorides). Bowles (1955) suggests a location for the ancient asbestos deposits, and states that Cyprus was a well known source of asbestos in ancient times and that:

> "although it is difficult to determine, from early references the exact location of the ancient deposit, probably it was southeast of Mount Troodos in a village known as Amianto, the identity of which is lost."

Figure 1-33 Amiandos open pit mine (chrysotile asbestos), abandoned and now under restoration in the serpentinized hartzburgite area of the Troodos mountains.

Intensive mining for thousands of years had a twofold impact on the environment. Firstly, it initiated land clearing from timbering activity, where the timber was used for the smelting of the ore and for ship building to serve the blooming exporting industry. Secondly, it initiated the clearing of the rich mining areas to make open areas for mining exploration. Both of these activities are believed to have contributed to uncontrolled soil erosion, the first intense environmental impact of humans on the island.

Figure 1 20 Terracing for reforestation purposes is a century old method by the Forestry Department in an attempt to stop hillslope erosion and to reinstate the environment to its original forested state.

Agricultural manipulation of the Cypriot landscape, which began at least as early as 9000 years ago, has had mixed effects on the nature and location of erosion (Noller, 2005a). Despite the fact that some of the forests were regrown and timbered numerous times mostly for mining purposes, they soon begun to be threatened by expanding agricultural activities. The apparent loss of significant portions of the forests, certainly by the end of the 19th century, has long been thought to have contributed to soil loss and severe disruption of Cypriot society. These sediments reached the coasts and slowly filled in ports and harbors of those times (Noller, 2005a, 2005b).

Figure 1-34 Helicopter view of intensively cultivated terraced slopes in the vicinity of Omodos village.

Living on a landscape with complicated topography and a semi – arid climate and becoming aware of the importance of soil resources at an early stage, the ancient Cypriots practiced soil erosion prevention as early as the Bronze Age. The method involved mainly the building of dry stone terraces along contoured elevations. Soil and water would slowly move downslope and be retained behind the terrace creating soft, fertile and flat agricultural land. These terraces are preserved until today in many mountain landscapes and still contribute to soil erosion prevention. Another method of agriculture was the conservation of water runoff in small check dams built in many elevations up the hills and across the flow path of small ephemeral creeks.

Figure 1-35 Close – up view of small rock terraces in small ravine in Pissouri.

1.10 Study problems to be answered

This dissertation focuses on the coastal environment of the island of Cyprus and investigates the Quaternary environments of coastal uplift, geomorphology, pedology and landscape change. The following three chapters arranged from general, wide area to specific, site area, will address the island–wide issue of Quaternary uplift, the rates of pedogenesis in southwestern Cyprus and the landscape response to human occupation for the last 4000 years in the area of Kouklia–Palaipafos.

1.10.1 Eustacy vs uplift in differentiating marine terraces, hypothesis for Chapter 2

Taking into account the global eustatic sea-level curve with its unequal distribution of unique high and lows elevations, one can assume that a coastal zone will host flights of marine terraces and associated deposits correlable to marine isotope stages (MIS). These marine landforms and deposits will appear at elevations depending on the relative sea level at the time of their formation. Their ages are determined by geochronological methods. Where marine terraces appear at elevations outside the range of eustatic sea-level, it can be assumed that land level change has occurred – typically it can be assumed that the coastal terrain is being uplifted. Such uplifted flights of terraces appear all around the island of Cyprus and are the subject of Chapter 2. The hypothesis in this chapter is that uplift of Cyprus during the Quaternary can be estimated with dated marine terraces and that this uplift rate varies along the coast in response to deformation on different geological structures.

1.10.2 Rates of pedogenesis, hypothesis for Chapter 3

Rates of pedogenesis on an island like Cyprus can be studied and estimated using soils on dated surfaces. Uplifted marine terraces present the opportunity to get a good estimate for the time factor in the soil-forming function because the time of subaerial exposure for these surfaces is known from the results of Chapter 2. Chapter 3 will focus on the coastal environment of southwestern Cyprus and be based on the hypothesis that a soil-development index (PDI) can serve as a proxy for age and spatial variations in soil chronosequences. Prior soil surveys note rubification and calcium carbonate accumulation as two distinct characteristics of the area’s soils and thus shoul be strong PDI indicators The southwestern part of Cyprus was chosen for this study due to the availability of soil and new geological data and, most importantly, because the uplift evident in this area suggests numerous marine terraces well-separated in time for developing a reliable soil-age relationship (chronofunction).

1.10.3 Landscape response, hypothesis for Chapter 4

With landscape change and landscape adaptation being a very contemporary issue for geomorphological studies, Chapter 4 will focus on a small part of southwestern Cyprus, the ancient polity of Palaipafos in the present village of Kouklia. The polity of Palaipafos, established in the second millennium BC, at the beginning of the of the Late Bronze Age, most probably prospered from the production and trade of copper and later became known for its temple to the goddess of Aphrodite. This study area was chosen because the site of Palaipafos presents interesting geomorphology because of tectonics, coastline evolution, local archaeometallurgy and long human occupation and land use. The diversity of the geomorphological units on the landscape of Palaipafos is evidence for the tectonic and climatic dynamics of its environment.

2 Quaternary Uplift of Marine Terraces in Cyprus

A large island with such a laced coastline and diverse geology is attractive for the study of Quaternary coastal deposits. For marine terraces, their elevation and age becomes important to tectonic studies. For the last 50 years, very little attention has been paid to Quaternary geological units on the island of Cyprus. The scientific significance and attraction of the Troodos ophiolite as a unique and well preserved piece of oceanic crust and the importance of Cyprus in the tectonic setting of the eastern Mediterranean left little room for Quaternary research on the island. In addition, the illegal military occupation of the northern part of the island by Turkish troops for the last 38 years hampered island-wide geological studies. This chapter attempts to make an island–wide assessment of what the marine terraces reveal about Quaternary uplift of the island.

2.1 Main Objectives

The main objectives of the work described in this chapter are:

- To collect and evaluate all data from previous works,
- To extrapolate past sea levels using palaeoshoreline elevations and age of fossil corals in marine terraces ,
- To estimate the Pleistocene uplift history for the island of Cyprus with emphasis on the Upper Pleistocene,
- To comment on a Holocene sea level curve.

2.2 Marine terraces in the Eastern Mediterranean

The Pliocene transgression following the Mediterranean-wide Messinian Salinity crisis (Blanc, 2000, Butler *et al*., 1999) set the depositional environment for marly deposits along the entire Mediterranean coastline. The onset of the Pleistocene Ice Ages from the beginning of the Gelasian (ca. 2.58 MA) in the tectonically active environment of the Mediterranean Sea, which is literally a wide zone with predominantly compressive stress regime due to the collision of the Eurasian plate with the African plate in the south and the Anatolian plate in the east, constituted an excellent setup for the formation of uplifted marine terraces along the whole Mediterranean coast.

Intensive field research on Pleistocene marine terraces in the central Mediterranean region serves as guide to this study. Italy has a complicated and long coastline due to Quaternary tectonic and volcanic activity. Research in Pleistocene coastal geology along the Adriatic, Ionian and Tyrrhenian seas contributed immensely to the study of the Mediterranean Quaternary and helped coin the terms Calabrian, Tyrrhenian, and Ionian. Prior to this work, studies in the Mediterranean assumed the existence of four climatic periods, which impacted shorelines unique to each and named differently in northern Europe, in the British Isles, and the Italian coast. In the eastern Mediterranean (Syria, Cyprus, the Lebanon). De Vaumas, a Quaternary geologist, attempted to map Quaternary fluvial and marine sediments with the trained eye of a northern European (De Vaumas, 1965a and 1965b).

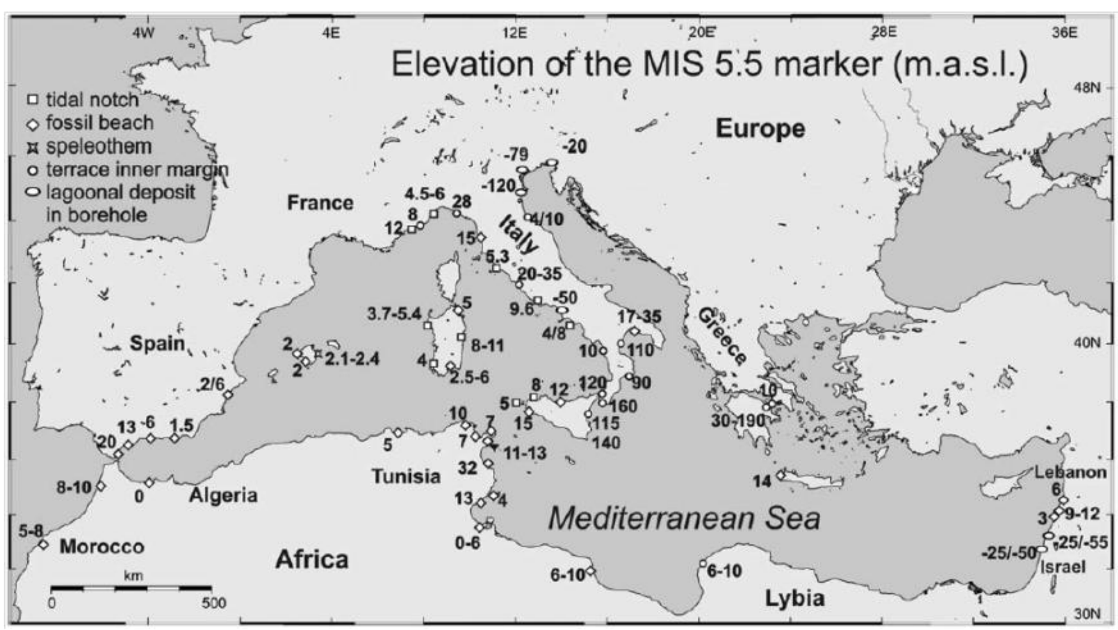


Figure 2-1 Generalized elevation distribution of the MIS 5.5 marker in the Mediterranean Sea (from Ferranti et al., 2006).

By far the most distinct and extensive marine terraces in the Mediterranean coast are those formed during the Marien Isotope Stage (MIS 5), also referred to as the Last Interglacial for this reason. The invasion of thermophilous Senegalese warm fauna into the Mediterranean Sea during Marine Isotope Substage 5e (125 ka), which is also the substage with the highest sea level relative to the present, has helped correlate uplifted marine terraces along the whole Mediterranean coast. The *Strombus Bubonius Lamark* (Lmk) gastropod being the biggest and most easily recognizable fossil of the Senegalese warm fauna, has been established as an excellent index fossil for identifying the 5e marine terraces across the Mediterranean (Figure 2-1) (Ferranti *et al*., 2006). It has helped make the term Tyrrhenian synonymous with "Senegalese fauna" (Issel, 1914). In tectonically stable regions away from ice sheets (where isostacy is minimal) this index fossil is expected to be found in marine terraces 6 ± 3 m above present sea level (Lambeck *et al.,* 2004a, Ferranti *et al*., 2006).

Some occurrence of warm fauna in the western Mediterranean basin (Mallorca, Spain, Atlantic coast of Spain) during MIS 7, has been suggested (Hillaire-Marcel *et al*., 1986; Zazo and Goy, 1989, 7c in the Canary islands, 7a in Spain (Zazo, 1999) and 5e in Italy (Ferranti *et al*., 2006). Ferranti *et al*. (2006) report on 246 sites of the 5e terrace in Italy and interpret coastal tectonic deformation for the whole Italian coast for the last 130 ka based on their elevation which ranges from +175 m to -125 m. It is questionable whether warm Senegalese fauna did occur earlier than MIS 5e, that is MIS 7, since dates that place the fauna back to MIS 7 are based on U-series mollusk chronologies and not corals (Hearty and Dai Pra, 2003).

In Tunisia, dating of fossil Ostraea shells using $^{234}U/^{238}U$ ratios found their ages to cluster between 147-100 ka (ca. MIS 5e). They occur at about 5m amsl and coexist in a Strombus-rich boulder bed (Jedoui et al.., 2003). Ostraea shells are found to act as closed geochemical systems with respect to $^{234}U/^{238}U$ ratios in relation to other aragonitic mollusc species such as *Cardium, Glycymeris, Chlamys, Arca, Strombus, Spondylus, Conus, Cerithium, Thais, Murex,* and *Trochus*.

In the central Mediterranean, Antonioli *et al.* (2006a) have mapped and dated the *Strombus bubonius* rich MIS 5e marine terrace all along the Sicilian coast. They have dated terraces using amino acid racemization, electron spin resonance, U-series and luminescence methods. The MIS 5e terrace has been found on elevations of 7-12 m in western Sicily and on elevations of 100-175 m in the northeastern part of Sicily in the vicinity of Etna volcano (Monaco et al., 2000). The *Strombus Bubonius* samples in Sicily correlate well with the MIS 5e dated marine terraces and indicate a sea – level of approximately +7m for the Italian coast (Lambeck et al., 2004a).

In the eastern Mediterranean, *Strombus* – bearing units are recognized in Israel (Issar and Kafri, 1972; Sivan et al., 1994; Sivan, 1996; Sivan et al., 1999) and some sites in Lebanon (Sanlaville, 1980). By far the most reliable geochronology data for Quaternary marine terraces is the U-series dating method on corals such as *Cladocora caespitosa* where not recrystallised. The following sections present results for some coral dates and *Strombus Bubonius* sites from Cyprus. The relative sea level of MIS 5e in Cyprus is discussed in section 2.6.1.

2.3 Cyprus Marine Terraces

Found at elevations as high as 610 m amsl in northwest Cyprus (Turner, 1971a), these marine terraces are excellent markers of past coastlines. Remnant terraces are typically recognized in the field as marine calcarenites, biocalcarenites (packstones) and grainstones with basal conglomerates at the bottom and aeolianites at the top of the sequence. The terraces show similar depositional environments, where, basal conglomerates characteristic of marine transgressions are topped with corals and algae. Younger units on top may show a gradual regression and finally aeolianite deposition behind a withdrawing coastline.

In lack of a global marine curve and of geochronology methods during the 60’s and 70’s, authors like De Vaumas (1962); Ducloz (1964, 1968); Baroz (1979); Pantazis (1967a, 1967b, 1967c); Dreghorn (1971, 1978); and Turner (1971a, 1971b, 1971c) attempted to assign relative ages to the marine terraces of Cyprus based on relative elevation and correlations with other Mediterranean terraces at similar elevations. Research on the Quaternary marine terraces of

Cyprus can be divided in two parts, the first and earlier part incorporating publications before the wide use of geochronology methods and the second part incorporating publications which make use of recent geochronology techniques like the U-series method on corals and ESR method on mollusca. It is important to note here that all of these data are taken into consideration in the present analysis and that an attempt was made to visit and re-evaluate all of these sites.

The very first reference for a *Strombus Bubonius* fossil was made by Gaudry (1862) in the first comprehensive account for the geology of Cyprus. He reports the index fossil in Larnaca Salt Lake. De Vaumas (1963a, 1963b) much later published some of the first references on three uplifted marine terraces of northwest Cyprus in the vicinity of the village of Pomos. He also reported a *Strombus Bubonius* fossil on the coast of Gastria (north of Famagusta) but with no reference to elevation (De Vaumas, 1962).

Quaternary uplift was evident to these first Quaternary geologists and marine and fluvial terraces often correlated to central European Pleistocene stages. Moshkovitz (1963, 1966) published the first paper on the Quaternary marine terraces of Cyprus based on work done for a PhD dissertation later published in 1968, (Moshkovitz, 1968). He also makes mention of *Strombus Bubonius* fossils found by Horowitz (year unknown) in Panagia Afentrika in Gialousa based on personal communication. The same reference to personal communication (to Supkow and Horowitz) is made by Ducloz (1964, 1968) for the same fossil found on the "north shore of Karpasia, in Plakoti" which is again in Gialousa.

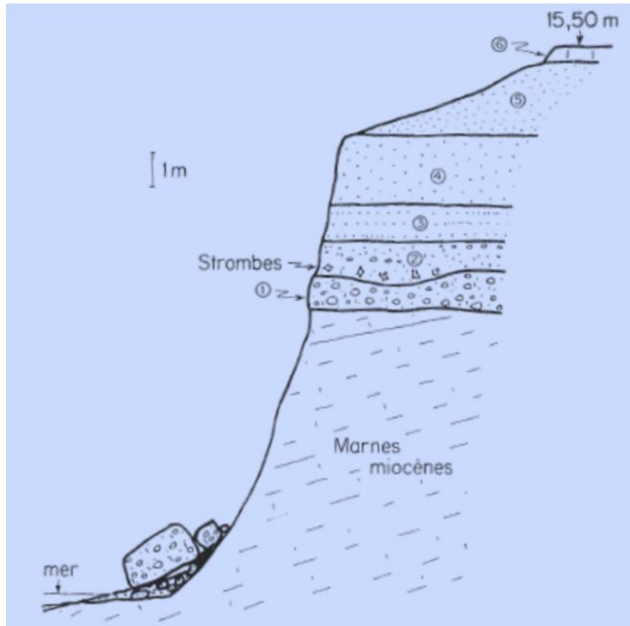


Figure 2-2 Marine terrace bearing *Strombus Bubonius* LMK in Mavra Litharga in Mari, southern Cyprus (Ducloz, 1968).

Pantazis (1967a) introduced systematic Quaternary geological mapping to Cyprus. He incorporated Pleistocene marine terraces and soils in geological maps and reports and used them to interpret the landscape (Pantazis, 1966a, b, c, 1967a, b, c). His experience as a soil scientist first at the Soils Department and then as a geologist at the Cyprus Geological Survey did a great service to Cyprus Quaternary studies. Later Ducloz (1968, 1972) revisits and verifies locations reported by Pantazis (Figure 2-2). His work in the north coast remains until today as the only basic and substantial data available in that part of the island (Table 2-1).

Turner (1971c) describes marine terraces in the Polis graben as the Akamandis Formation. Unfortunately for Turner, the Polis Bay is not the best location for extensive studies on marine terraces. In contrast, his work in the western Akamas peninsula (Turner, 1971a) is remarkable if one considers the vastness of the area that was mapped, the lack of a road network or any topographic maps during the period he worked in. Further itt was a British naval firing range at the time.

Table 2-1 Marine terraces in the north coast (adapted from Ducloz, 1972).

Marine terrace name	**Elevation (m amsl)**	**MIS**
Koupia	5	
Keryneia	15-20	*5e (Strombus bubonius)*
Agios Epiktitos	50	7
Toumba	140	9
Trapeza	185	11?
Klepini	230	13?
Talus and lake deposits	300-360	

Poole and Robertson (1990, 1991, 1998) have mapped and dated marine terraces in southwest, south and southeast Cyprus and have identified numerous offsets in the marine terraces due to neotectonic activity. The fractures they note are oriented at right angles to the direction of the average orientation of the subduction off the southern coast of Cyprus. In the southeastern part of coastal Cyprus, the fractures are indicating left – lateral movement in the west and collisional deformation to the east. Fauna suitable for U-series dating *Cladocora caespitosa* revealed ages of 185-192 ka (MIS 7) for the terraces at the 8-11 m elevation and ages of 116-130 ka for the terraces at the 3m elevation.

Galili *et al*. (2009, 2011) identify of S*trombus Bubonius* fossil in north Cyprus during on a geoarchaeological expedition in 2008-9. Their 2 short abstracts plots three Strombus Bubonius fossils on 15.5-17 m elevated marine terraces in Keryneia. Amongst the above authors is Moshkovitz, who revisits the Keryneia coast in 2009 after his 1966 and 1968 publications.

2.4 Methodology

What is attempted here is to derive an uplift model for the island and identify coastal sectors with different uplift histories. Areas with distinct marine features were given emphasis as more promising locations for valuable data. Areas with poor distribution of marine deposits and marine features as well as built – up areas were given less attention. Topographical and satellite data were used to facilitate mapping of palaeoshorelines. Corals were sampled in areas with gaps in geochronological data. Uplift rates were calculated based on dated surfaces in relation to corresponding palaeoshoreline elevation.

2.4.1 Use of existing geological and topographical data

Reconnaissance mapping of marine terraces was performed with the use of recent georeferenced high-resolution satellite imagery (0.6m grid cell), stereo pairs of panchromatic aerial photographs from the 1960's and the 1990's, topographical maps with scales 1:5,000 and 1:25,000, and digital elevation models. Geological data from both published and unpublished maps in digital and analog format were aggregated in a new GIS vector file and named OneGeology Cyprus resulting in a seamless, digital vector map with over 13000 geological polygons having island-wide coverage.

This OneGeology GIS layer provides the best geological information at any location and was derived comprehensively from published and unpublished geological maps with field checking where appropriate. It attempts to improve interoperability on four levels, semantic, schematic, syntax and system-wise. It involved collecting data and making it topologically correct, sustaining updates and changes by various contributions and making it interoperable with other geospatial data. The GIS was designed to provide access harmonization, semantic harmonization with vocabulary and lithologic and/or rock formation harmonization, eliminating obsolete names.

Issues that come up when there is a big difference in source scales, author mapping methods and level of geological complexity involved in the initial mapping process were overcome for each region separately. Extensive use of the 1:50,000 scale Quaternary Geology and Geomorphology maps by Noller (2009) provided the additional information that was always missing from previous publications due to the emphasis given to bedrock and especially ophiolite geology in the past.

The Lands and Surveys Department of Cyprus has provided elevation point data derived from recent photogrammetry. The points are anywhere from 5 to 50 meters apart, for steep and flat areas respectively. The elevation is recorded in meters with 2 decimal places, which provides resolution to the closest centimeter. A digital elevation model (DEM) was created using the Topogrid command in ArcGIS. The DEM is in raster format and has a 20 meter cell size. No photogrammetry elevation data are available for the non-government controlled areas i.e. the United Nations buffer zone or the north part of the island. For those areas, older data were used, specifically, a 25 meter cell size digital elevation model derived from contours which were digitized from recent topographic maps with scale 1:50,000. The two DEMs where merged and a new DEM was created with resampled 20 meter cells. The seam line presents a satisfactory match in elevation data.

Published geochronology data were evaluated on a sample by sample basis. Sample ages were used in the analysis avoiding the use of interpreted analysis by other authors. Older authors often assigned sample elevation to a sea-level highstand neglecting to take into consideration water depth at time of deposition for corals in life position or marine terrace notch as the representation of sea level at time of sea-level highstand for corals not in life position. No corals in life position have been found by the author during the five years of field work.

2.4.2 Field Mapping

This study presents recent and extensive island-wide investigations that have led to the discovery of additional Pleistocene raised shorelines, and new data in many previously completely unmapped areas. An island–wide geological survey was performed in the coastal belt between the years of 2005-2010. Mapping of marine terraces involved field reconnaissance trips, followed by remote-mapping methods, and, finally, with detailed field checking. Shore-normal narrow and wide river valleys have produced numerous inlets in which one finds cross-cut marine terraces or flights of alluvial terraces with marine sand facies closer to river mouths. Other artificial cuts such as road cuts, quarries and private housing excavations offered excellent opportunities for field mapping and sampling. No underwater survey was performed for mapping submerged marine terraces.

The survey focused on uplifted terraces, looking for evidence of terraces older than MIS 5c, even if underwater mapping of marine notches is both possible and promising. The occurrence of submerged marine notches in 150 underwater profiles in the western Mediterranean have hinted relative sea–levels at -11, -17, -25, -35, -45, -55, and -100m depth (Collina-Girard, 2002).

The coastline survey was in search of spatial relationships and datable materials. Lithofacies and depositional environment were recorded at sampling sites. Selected marine deposits were logged, described and photographed. Some coastal features are much more difficult to map remotely from maps or satellites. These are tidal notches or the numerous marine terrace inner edges revealed by cross sections of road cuts. Difficult also to identify and map remotely, are terraces with small widths which do not project well on a 25 or 30 m cell-sized digital elevation model. Ferranti and others (2006) classified these coastal markers according to their nature and level of uncertainty (Table 2-2). The marine terrace inner margin and tidal notch erosional markers were used in this study for estimating sea-level.

Table 2-2 Type of markers for sea-level estimation and related uncertainty (adapted from Ferranti *et al.*, 2006).

Type of marker	**Feature**	**Uncertainty**	**Quality**
Depositional marker	Beach / lagoon deposits	- 2 m	1
	Backshore / foreshore deposits	± 5 m	2/3
Erosional marker	Marine terrace inner margin	+ 3 m	1
	Marine terrace with inner margin concealed	- 20 m	3
	Marine terrace	+ 20 m	3
	Tidal notch	± 0.1 m	1
Biological marker	Lithofaga hole band	+ 2 m	1
	Dendropoma reef	± 0.2 m	1

The elevation of samples was determined with the use of photogrametrically-derived elevation point data supplied by the Lands and Surveys Department of the Ministry of the Interior of the Republic of Cyprus. Point data had an average spacing of 20m and record elevations to the nearest centimeter. Elevation of sample sites was estimated by triangular interpolation on the four nearest points. Elevation of the terraces and sea level highstands are reported according to the closest approximation of the palaeoshoreline. A scarp separating flat terrace surfaces is interpreted as a past sea cliff and its base, the shoreline angle, as a past sea level. Surficial deposits from slope processes in the vicinity of these cliff bases cover past sea level indicators. Their uncertainty can reach ± 20 m in the vertical direction (Table 2-2). The shoreline angle elevation is then used for calculating tectonic uplift rates.

2.4.3 Digital maps

Remote mapping of marine terraces was digitally performed with ArcGIS™ geographical information system software. Raster data such as topographical maps, aerial photographs, geological and soil maps as well as satellite images (Table 2-3), were used to create an initial location map for marine terrace risers which can then be verified with field visits. All the maps are available in georeferenced raster format; some of them also exist in vector format.

Aerial photographs, satellite images and topographical maps are primary sources for this type of geomorphological feature identification. Satellite images, having a high resolution and, true-color image capture are invaluable for remote reconnaissance mapping. Aerial photographs, although some are older series (circa. 1963 -1994) provide another invaluable tool exactly for that reason. Geomorphological features are more evident in photographs taken before any urban, agricultural and coastal development that took place in the late 70's masking the landscape with man-made features.

Table 2-3 Sources of geographical data that were used for remote mapping of marine terraces and other coastal features.

Data	**Scale**	**Vertical uncertainty (m)**	**Source**	**Format**	**Island coverage**
Soil maps	1:25,000	10	Soils Department	vector	25%
Topographical maps	1:5,000	2	Lands and Surveys Department	raster	70%
Topographical maps	1:25,000	10		raster	complete
Topographical maps	1:50,000	10		vector	complete
Aerial photographs	1:8,000	na		analog	complete
Geological maps OneGeology	varies	na	Cyprus Geological Survey	vector	complete
Quickbird Satellite images	60 cm cell size	na		raster	complete
Digital Elevation Model and derivatives	25 m cell size	5	Derived from recent photo-grammetry	raster	65%
5m interval contours		2-3	from recent digital photo-grammetry	vector	65%
Digital Elevation Model and derivatives	50 m cell size	10	Derived from 1:50,000 maps	raster	complete

The digitized vector format of the topographical information, as well as new data from recent photogrammetry, was converted to 25m cell-sized digital elevation models which were used to construct topographical profiles of the coast. These profiles provide an additional tool for identifying position and elevation of marine terraces and other coastal geomorphological features. Other digitized data are soil and geology maps of various series, editions and year of publication. Marine terraces, usually mapped as calcarenite outcrops have populated quite a few geological map publications of the Cyprus Geological Survey in the last 20 years. Soil maps, even if they mostly exist in a 1:25,000 scale, provide valuable preliminary data on soil types and their spatial extension, many times coinciding with marine terrace topography.

2.4.4 Relative sea level

This study adopts the global oxygen isotope curve by Liciecki and Raymo (2005) for matching Marine Isotope Stages to local marine terraces. The curve that has come to be known as the LR04 stack contains benthic d^{18}O data from 57 globally distributed sites and has an average standard error of only 0.06‰. The LR04 stack agrees well with previously published data and is also the first stack to include data before 2.5 Ma.

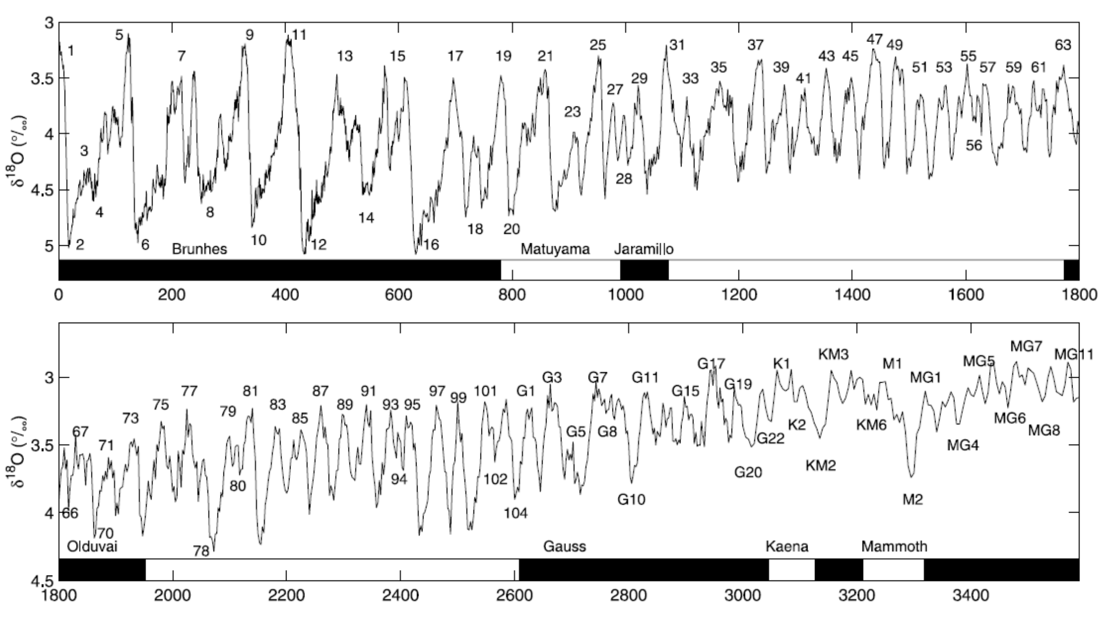


Figure 2-3 The LR04 benthic δ^{18}O stack constructed by the graphic correlation of 57 globally distributed benthic δ^{18}O records. Note that the scale of the vertical axis changes across panels. (Liciecki and Raymo, 2005). Labels refer to marine isotope stages.

Global ice volume and consequently sea level during the last 5 million years were dependent on variations in the obliquity, precession and eccentricity of the earth (Milankovitch, 1941). Between 2.6 and 0.8 Ma there is a periodicity of 40-42 ka (correlating well with obliquity variations) whereas after 0.8 Ma there is a 100 ka cycle (correlating well with the eccentricity cycle) (Pillans *et al.*, 1998). Sea level in a semi-closed, almost tide-free sea such as the Mediterranean is a function of the eustatic change, the glacio-hydro-isostatic response of land and any tectonic movements on the coast (Lambeck and Purcell, 2005). Lambeck expresses relative sea-level change $\Delta z\ rsl\ (x,t)$ schematically as:

$$\Delta z\ rsl\ (x,t) = \Delta z\ esl\ (t) + \Delta z\ I\ (x,t) + \Delta z\ T\ (x,t) \qquad \text{eq. (a)}$$

with

$$\Delta z\ I\ (x,t) = \Delta z\ I\text{-}g\ (x,t) + \Delta z\ I\text{-}h\ (x,t) \qquad \text{eq. (b)}$$

where,

$\Delta z\ rsl\ (x,t)$ represents the change at location x of the sea surface relative to land at time t, compared to its present position.

$\Delta z\ esl\ (t)$ represents the ice-volume equivalent sea-level contribution (esl), meaning the change in sea level

$\Delta zT\ (x,t)$, is a tectonic contribution for tectonically active areas, meaning any tectonic subsidence or uplift,

$\Delta zI\ (x,t)$ is the isostatic contribution, meaning the rebound of land after the melting of ice, and is divided into two contributions:

$\Delta zI\text{-}g\ (x,t)$, the glacio-isostatic part, the vertical adjustment caused by the release of the weight of accumulated ice

and

$\Delta zI\text{-}h\ (x,t)$, the hydro-isostatic part, the vertical adjustment caused by coastal sea water on flooded coastlines after sea level rise.

Table 2-4 Time-elevation model used in this study (after Martinson *et al*., 1987; Waelbroeck *et al.,* 2002). MIS stands for marine isotope stages.

MIS	Peak of MIS (years BP)	Sea level relative to present m.s.l. (m)
1	0 (?)	0
2	18,000	-120
3	40,000	-62
4	65,000	-84
5a	81,000	-19 ± 5
5b	87,500	-48
5c	100,000	-20 ± 3
5d	110,000	-44
5e	124,000	+6 ± 3
6	134,000	-129
7	216,000	-3.5
8	250,000	-108
9	330,500	+5
10	344,000	-126
11	402,000	+6

It should be clarified that Quaternary absolute local sea – level curves can only be accurate if the coast is tectonically stable. In the coastal areas of Cyprus relative sea level curves can help make the distinction between tectonic movements and eustatic sea – level changes. The uplift rate of a terrace will be determined by taking into consideration the relative sea level during the stage it represents and dividing by its age. A good approximation of relative sea level is by Waelbroeck et al., (2002) shown in Figure 2-4 and Table 2-4. Uplift rates may and will differ over the span of the Quaternary period depending mainly on the variability of aseismic and coseismic vertical displacement over time. Along the coastline, differential uplift between terraces of the same age is attributed to tectonic activity along coastal faults which will explain the existence of distinct rigid blocks.

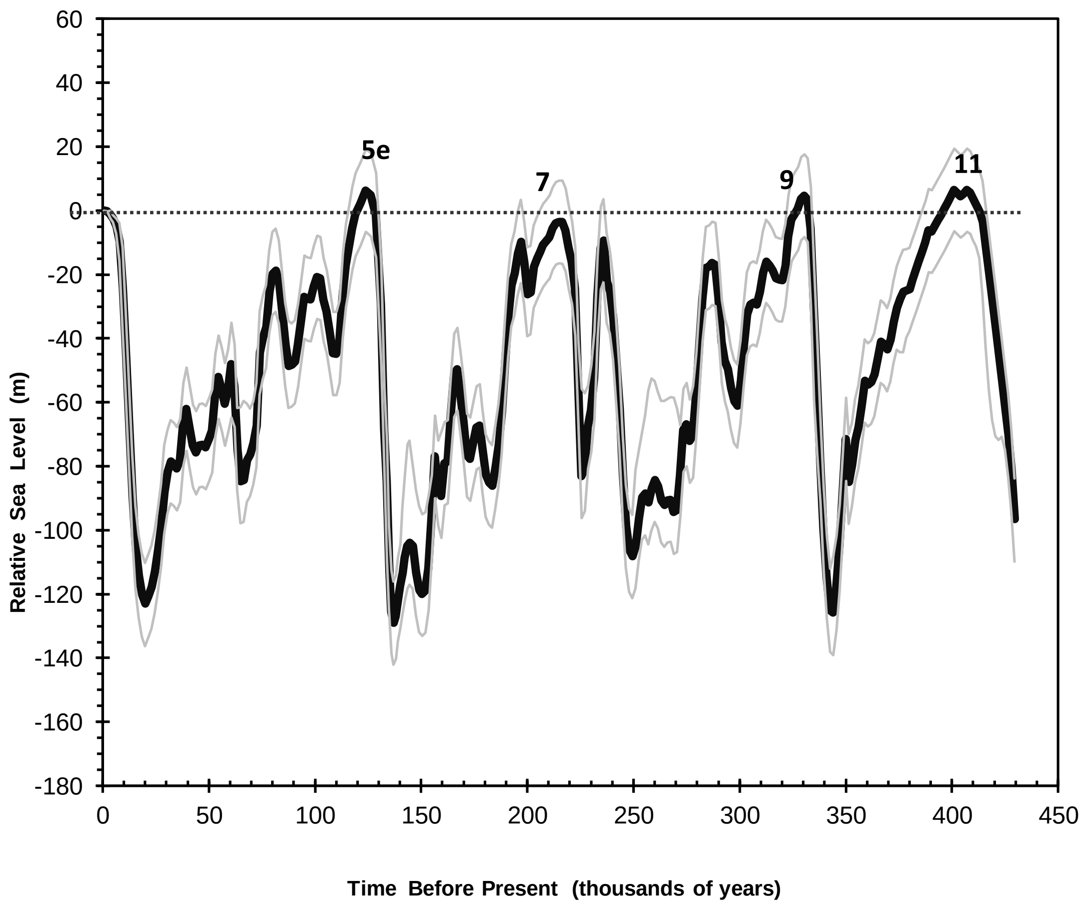


Figure 2-4 Relative sea level adapted from Waelbroeck et al., (2002).

Assuming the formation of a tidal notch or a shoreline can be directly correlated to a sea – level highstand, then its present elevation can be correlated to its past relative sea – level in order to extract conclusions on its tectonic movement. In a few words, a marine terrace located 20m above sea level today and dated as belonging to MIS 5e, must have undergone a 14 m uplift in 124,000 years considering MIS 5e sea–level was 6m higher than the present. With the assumption of a constant uplift rate, one can conclude that in the above example uplift rate was 0.113 mm/year. Any younger marine terraces at the same location can be used to test the assumption made for a constant uplift rate and/or plot the change of uplift rate as a function of time in a given area.

In summary, all of the above make the following assumptions:

- Sea - level change is global
- Effects from flow mechanics at the Straits of Gibraltar are minimal
- The 30 cm tidal range effect in the eastern Mediterranean is minimal
- Local salinity affects are minimal
- Local sea water temperature effects are minimal
- Gravitational equilibrium effects in the Mediterranean are minimal
- Isostatic effects in Cyprus are minimal
- Tectonic uplift is neither too rapid or oscillating so as to obscure the eustatic signal
- Based on point no. 8, most marine terrace platforms are considered to represent sea – level highstands.

The isostatic factor relating to ice-sheet loading and unloading in territories of continental Europe are, of course, different from those of the island of Cyprus considering there is no evidence for ice – sheet accumulation on Cyprus, nor within the distance considered to effect such influence.

2.4.5 Geochronology methods with corals

Many authors have successfully used corals for dating Quaternary marine terrace deposits across the planet, especially the coral *Cladocora caespitosa* which is a colonial, bioherm - building zooxanthellate scleractinian coral belonging to the family Faviidae. It occurs throughout the Mediterranean Sea (Peirano *et al*., 1988) and can be locally abundant (Zibrowius, 1980). In Cyprus, intact and *in situ* colonies of the coral are scarce and most samples collected for this study were pieces of coral incorporated in the clastic transgressive and regressive facies of the marine terrace deposits. It is questionable if previous researchers have sampled in-situ corals as they claim (Poole, 1998). Field surveys for the last 5 years have not been able to support this. It is quite easy to confuse an in situ coral with a piece of coral in the sediment facies because large coral pieces will tend to position themselves in an upright position during deposition.

Small colonies have been found in Geroskipou and Larnaka, the biggest one being on the Dhekelia coast which included one meter diameter colonies over a 10 meter stretch. *Cladocora caespitosa* fossils found in the Pliocene Marl Member of the Nicosia Formation mark the onset of marine conditions in the central E-W Mesaoria plain (Dornbos *et al*., 1999). The coral is common in terraced deposits of Middle to Late Pleistocene age, and was more abundant during warmer climatic phases (Morri et al., 2001). Sedimentological evidence in Cyprus suggests that it grows in depths not exceeding 10m (Poole, 1992).

Corals were analyzed in the Berkeley Geochronology Center in California using the U-series disequilibrium method that measures the ^{234}U, ^{238}U isotopes and their related daughter products including ^{230}T. Living corals are considered to have a closed system incorporating uranium from the shallow marine water into their exoskeleton. Upon their death, ^{234}U radioactively decays into ^{230}T. The ratio of ^{230}T to ^{234}U is considered to be an excellent proxy for the time period since the death of the coral. Coral samples had a minimum weight of 4-5 grams. Corals containing less than 90% aragonite, and showing calcite replacement, are considered too far re-crystallized to be able to provide reliable ages. Reliable ages with this method are also possible for corals as old as 350 ka (Broecker, 1963).

2.4.6 Geochronology methods with Senegalese fauna

Previous sections have pointed to the significance of MIS 5 on the landscape because of its long duration and the fact that sea level had reached higher elevations than the present making the marine terraces of MIS 5 easily recognizable on higher coastal elevations across the Mediterranean. The 5e marine terrace is also easily recognizable by some of its fossils (see section 2.2). Senegalese fauna is mainly represented by the mollusks *Strombus bubonius, Conus testudinarius, Cardyta calyculata senegalensis, Hyotissa hyotis* (Gignoux, 1913). Gignoux had introduced the “couches a Strombe” term and proposed a beach deposit at Cala Mosca in Sardinia as a stratotype of the so –called Eytyrrhenian subunit which is now known as the 5e marine terrace.

2.5 Results

2.5.1 Stratigraphy and geomorphology of the marine terraces

Marine terraces in Cyprus are formed and preserved better on rocky coasts. Bedrock lithology seems to be a strong control on the ability of the landform to form and later preserve a marine terrace (Ferranti *et al.*, 2006). Weakly cemented rocks, Pliocene marls and Messinian gypsiferous deposits are prone to great erodability or dissolution and have little ability to preserve terrace markers once the markers become exposed to subaerial erosional and weathering processes. The typical terraces in Cyprus are calcarenite deposits (5-30 m thick calcareous sandstone deposits) and wave – cut platforms on platform features on hard bedrock (usually Miocene reef limestone).

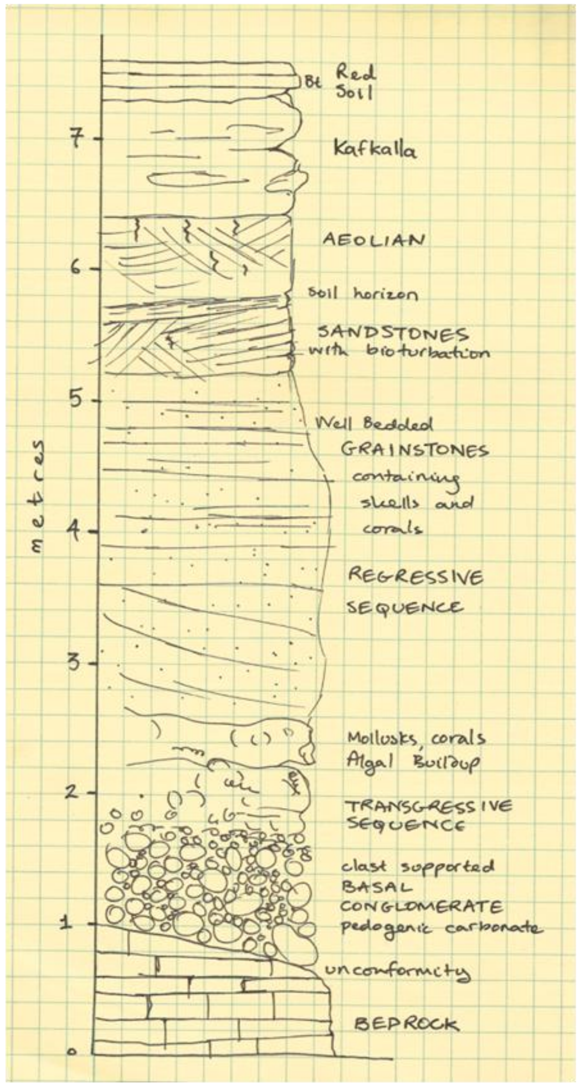


Figure 2-5 Stratigraphic column for a typical marine terrace on Cyprus.

Basal conglomerate is very common and usually consists of well rounded gravels and boulders with sand and sometimes marine shells. The transgressive sequence consists of 0.5 -1.0 m thick algal build-up topped by well cemented calcareous sandstone or packstone deposits. The regressive sequence is usually better stratified and graded with coarsening upward trends and aeolian deposits on top. Sometimes palaeosol deposits between aeolian facies indicate periods of pedogenesis. The aeolian deposits are capped with thick calcium carbonate accumulation and topped with red soils. This last feature is the subject of the following chapter.

2.5.2 Geochronology results

Geochronology results were collected from bibliography and added to a new database created for this study. Table 2-5shows the listing of these results and Table 2-5 shows their spatial distribution. Data were evaluated and correlated with results based on observations, mapping and dating of terraces executed during this study. Older data from Gaudry (1862), De Vaumas (1962), Horowitz (1965), Pantazis (1966a, b, c, 1967a, b, c), Ducloz (1968) and Turner (1971a, 1971b) are always questionable but all of the sites mentioned by these authors were revisited and re-evaluated.

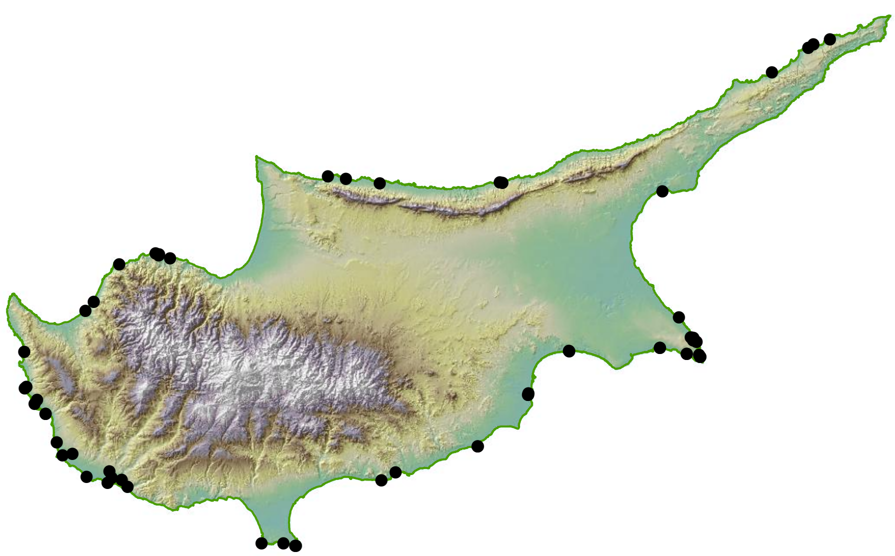


Figure 2-6 Distribution of geochronology samples from Table 2-5.

The maps of these authors were mainly accompanied by palaeontological analyses and reference to the *Strombus bubonius* LMK index fossil becomes common after Italian bibliography especially in the sixties makes the definite link between this index fossil and MIS 5e. Data from the northern shores of Keryneia were especially valuable considering the difficulty in conducting field work in this part of the island. Reference to *Strombus bubonius* LMK locations were thus used as a first approximation.

Table 2-5 Table of samples **1**= Gaudry, 1862, **2**= Birot and De Vaumas, 1962, **3**= Horowitz, 1965, **4**= Pantazis, 1966a, b, c, **5**= Moskhowitz, 1963 and Pantazis, 1967, **6**= Ducloz, 1964, 1968, **7**= Turner, 1971a, b, **8**=Poole, 1992, **9**= Shellmann and Kelletat, 2001, 2008 **10**= Theodorou, 2005, **11**=Noller, 2009, **12**=Galili et al., 2009, 2011. Samples in bold letters are data taken into consideration in this study.

no	**Locality**	**Dating method**	**material**	**Age (y BP)**	**Error**	**M.I.S.**	**Sample Elevation (m)**	**ref**
	Larnaca	Palaeontology	*Strombus bubonius LMK*	125000		5e	4-6	1
	Gastria	Palaeontology	*Strombus bubonius LMK*	125000		5e	Not reported	2
	Aigialousa	Palaeontology	*Strombus bubonius LMK*	125000		5e	Not reported	3
	Krotiri Mavro	Palaeontology	*Strombus bubonius LMK*	125000		5e	Not reported	3
	Agios Therissos	Palaeontology	*Strombus bubonius LMK*	125000		5e	Not reported	4
	Larnaca Salt Lake	Palaeontology	*Strombus bubonius LMK*	125000		5e	9-12	5
	Mavra Litharga, Mari	Palaeontology	***Strombus bubonius LMK***	**125000**		**5e**	**9-12**	**5**
	Keryneia	Palaeontology	*Strombus bubonius LMK*	125000		5e		6

Table 2-5 (Continued)

no	Locality	Dating method	material	Age (y BP)	Error	M.I.S.	Sample Elevation (m)	ref
	East of Cape Plakoti, Karpasia	Palaeontology	*Strombus bubonius LMK*	125000		5e		6
	Akamas	Palaeontology	*Strombus bubonius LMK*	125000		5e	12-21	7
	Petounda Point	**U/Th**	***cladocora caespitosa***	**204000**	**6000**	**7**	**8-11**	**8**
	Coral Bay	**U/Th**	***cladocora caespitosa***	**192000**	**6000**	**7**	**8**	**8**
	Larnaca	**U/Th**	***cladocora caespitosa***	**185000**	**2000**	**7**	**8**	**8**
	Cape Greco	**U/Th**	***cladocora caespitosa***	**141000**	**4000**	**6**	**8**	**8**
	Cape Greco	**U/Th**	***cladocora caespitosa***	**219000**	**16000**	**7**	**8**	**8**
	Paralimni	**U/Th**	***cladocora caespitosa***	**134000**	**4000**	**5**	**<3**	**8**
	Pafos	**U/Th**	***cladocora caespitosa***	**130000**	**4000**	**5**	**<3**	**8**
	Dhekelia	**U/Th**	***cladocora caespitosa***	**116000**	**2000**	**5**	**<3**	**8**
	Ag. Anargiroi	**ESR**	***Spondylus sp.***	**139000**	**10000**	**5e**	**9.5**	**9**
	Ag. Anargiroi	**ESR**	***Glycymeris sp.***	**105000**	**9000**	**5c**	**10**	**9**
	Ag. Anargiroi	**ESR**	***Spondylus sp.***	**69000**	**5000**	**5a**	**7.5**	**9**
	Cape Greco	**ESR**	***Glycymeris sp.***	**134000**	**10000**	**5e**	**9.5**	**9**
	Cape Greco	**ESR**	***Glycymeris sp.***	**137000**	**24000**	**5e**	**9**	**9**
	Cape Greco	**ESR**	***Glycymeris sp.***	**153000**	**15000**	**5e**	**3.5**	**9**
	Cape Greco	**ESR**	***Glycymeris sp.***	**130000**	**14000**	**5e**	**3**	**9**
	Cape Greco	**ESR**	***Glycymeris sp.***	**157000**	**19000**	**5e/7**	**3**	**9**
	Cape Greco	**ESR**	***Glycymeris sp.***	**204000**	**22000**	**7**	**3**	**9**

Table 2-5 (Continued)

no	Locality	Dating method	material	Age (y BP)	Error	M.I.S.	Sample Elevation (m)	ref
	Cape Greco	**ESR**	***Helix sp. in aeolianite***	**72000**	**5000**	**5a**	**14.5**	**9**
	Cape Greco	**ESR**	***Helix sp. in aeolianite***	**67000**	**6000**	**5a**	**14.5**	**9**
	Cape Greco	**ESR**	***Helix sp. in aeolianite***	**88000**	**10000**	**5b**	**11.5**	**9**
	Cape Greco	**ESR**	***Helix sp. in aeolianite***	**66000**	**4000**	**5a**	**11.5**	**9**
	Cape Greco	**ESR**	***Helix sp. in aeolianite***	**70000**	**7000**	**5a**	**11**	**9**
	Cape Greco	**ESR**	***Helix sp. in aeolianite***	**71000**	**6000**	**5a**	**11**	**9**
	Cape Greco	**ESR**	***Helix sp. in aeolianite***	**6800**		**1**	**12**	**9**
	Agia Napa	**ESR**	***Helix sp. in aeolianite***	**84000**	**6000**	**5a**	**12**	**9**
	Agia Napa	**ESR**	***Helix sp. in aeolianite***	**95000**	**7000**	**5c**	**12**	**9**
	Cape Geronisos	**ESR**	***Glycymeris sp.***	**178000**	**18000**	**7**	**7**	**9**
	Lara	**ESR**	***Spondylus sp.***	**161000**	**14000**	**5e/7**	**7**	**9**
	Lara	**ESR**	***Spondylus sp.***	**146000**	**14000**	**5e**	**7**	**9**
	Cape Drepanon	**ESR**	***Glycymeris sp.***	**83000**	**7000**	**5a**	**4**	**9**
	Cape Drepanon	**ESR**	***Glycymeris sp.***	**73000**	**5000**	**5a**	**3.5**	**9**
	Cape Drepanon	**ESR**	***Glycymeris sp.***	**116000**	**8000**	**5e**	**2.5**	**9**
	Cape Drepanon	**ESR**	***Glycymeris sp.***	**189000**	**14000**	**7**	**1.8**	**9**
	Cape Drepanon	**ESR**	***Glycymeris sp.***	**191000**	**16000**	**7**	**Not reported**	**9**

Table 2-5 (Continued)

no	Locality	Dating method	material	Age (y BP)	Error	M.I.S.	Sample Elevation (m)	ref
	Cape Drepanon	**ESR**	***Glycymeris sp.***	**167000**	**15000**	**5e/7**	**32**	**9**
	Cape Drepanon	**ESR**	***Glycymeris sp.***	**155000**	**17000**	**5e/7**	**32**	**9**
	Cape Drepanon	**ESR**	***Glycymeris sp.***	**183000**	**12000**	**5e**	**32**	**9**
	Cape Drepanon	**ESR**	***Glycymeris sp.***	**128000**	**9000**	**5e**	**15.5**	**9**
	Maa	**ESR**	***Spondylus sp.***	**110000**	**17000**	**5c/e**	**7**	**9**
	Maa	**ESR**	***Spondylus sp.***	**84000**	**6000**	**5a**	**7**	**9**
	Coral Bay	**ESR**	***Glycymeris sp.***	**125000**	**6000**	**5e**	**11**	**9**
	Coral Bay	**ESR**	***Spondylus sp.***	**112000**	**9000**	**5c/e**	**5.2**	**9**
	Coral Bay	**ESR**	***Spondylus sp.***	**108000**	**8000**	**5c/e**	**14**	**9**
	Kissonerga	**ESR**	***Glycymeris sp.***	**81000**	**6000**	**5a**	**1.5**	**9**
	Pafos	**ESR**	***Glycymeris sp.***	**94000**	**8000**	**5c**	**3**	**9**
	Pafos	**ESR**	***Glycymeris sp.***	**99000**	**10000**	**5c**	**3**	**9**
	Cape Greco 596906mE, 3869530mN	Palaeontology	***Strombus bubonius LMK*** **includes *cladocora caespitosa***	**125000**		**5e**	**Not reported**	**10**
	Protaras 598098mE, 3871959mN	Palaeontology	***Strombus bubonius LMK***	**125000**		**5e**	**Not reported**	**10**

Table 2-5 (Continued)

no	Locality	Dating method	material	Age (y BP)	Error	M.I.S.	Sample Elevation (m)	ref
	Cape Greco 596919mE, 3869532mN	Palaeontology	***Strombus bubonius LMK***	**125000**		**5e**	**Not reported**	**10**
	Akamas, 436374mE, 3883478	Palaeontology	***Strombus bubonius LMK***	**125000**		**5e**	**Not reported**	**10**
	Akamas, 435954mE, 3883776	Palaeontology	***Strombus bubonius LMK***	**125000**		**5e**	**Not reported**	**10**
	Pegeia	Palaeontology	*Strombus bubonius LMK*	125000		5e	Not reported	**10**
	Cape Greco, 598270mE, 3870819mN	Palaeontology	***Strombus bubonius LMK***	**125000**		**5e**	**Not reported**	**10**
	Paralimni , 592242mE, 3879957mN	Palaeontology	***Strombus bubonius LMK includes cladocora caespitosa***	**125000**		**5e**	**Not reported**	**10**
	Mandria, Pafou	**U/Th**	***cladocora caespitosa***	**133400**	**3100**	**5**		**11**
	Mandria, Pafou	U/Th	Pedogenic carbonate on fluvial gravels	38300	5000			**11**
	Anarita	U/Th	Pedogenic carbonate	5300	4000			**11**
	Kato Pyrgos	U/Th	Pedogenic carbonate	6600	3000			**11**
	Pigenia	U/Th	Pedogenic carbonate	79600	3700			**11**
	Mandria, Pafou	U/Th	Pedogenic carbonate	Excess ^{230}Th				**11**

Table 2-5 (Continued)

no	Locality	Dating method	material	Age (y BP)	Error	M.I.S.	Sample Elevation (m)	ref
	Agia Napa	OSL	aeolianite	53850	4400	3		**11**
	Agia Napa	OSL	aeolianite	55450	5200	3		**11**
	Keryneia	Palaeontology	***Strombus bubonius LMK***	**125000**		**5e**	**15.5-17**	**12**
This study								
4	Agia Napa	U/Th	*cladocora caespitosa*	143400	9300	6		
6	**Agia Napa**	**U/Th**	***cladocora caespitosa***	**152000**	**7600**	**6**		
7	**Paralimni**	**U/Th**	***cladocora caespitosa***	**157000**	**13700**	**6**		
10	**Mazotos**	**U/Th**	***cladocora caespitosa***	**159300**	**8300**			
16	**Pegia**	Palaeontology and U/Th	***Strombus bubonius LMK* includes *cladocora caespitosa***	**125000**		**5e**	**36**	
38	Mari	Palaeontology	***Strombus bubonius LMK***	125000		5e	14	
40	Paralimni	Palaeontology	***Strombus bubonius LMK***	125000		5e	2	

2.5.3 Elevation of marine terraces

Figure 2-7 shows the vertical distribution of marine terraces in 16 different coastal sectors around the island. Both marine terrace deposits and marine platforms are represented with a short horizontal line symbol. In the following sections of this text, the coastal zone of Cyprus is considered by geographic sector. Each sector differs from the next one in that it presents a unique picture of marine-terrace flights. At first glance it becomes evident that lithology controls the formation and preservation of terraces and marine platforms. Deposits and features in hard bedrock such as the Akamas and the reef limestone of Pegeia, western Polis, Cape Pyla and Cape Greco are more pronounced and better preserved. Palaeoshorelines in reef limestone are very well preserved and easily recognizable both in the field and in the digital elevation models.

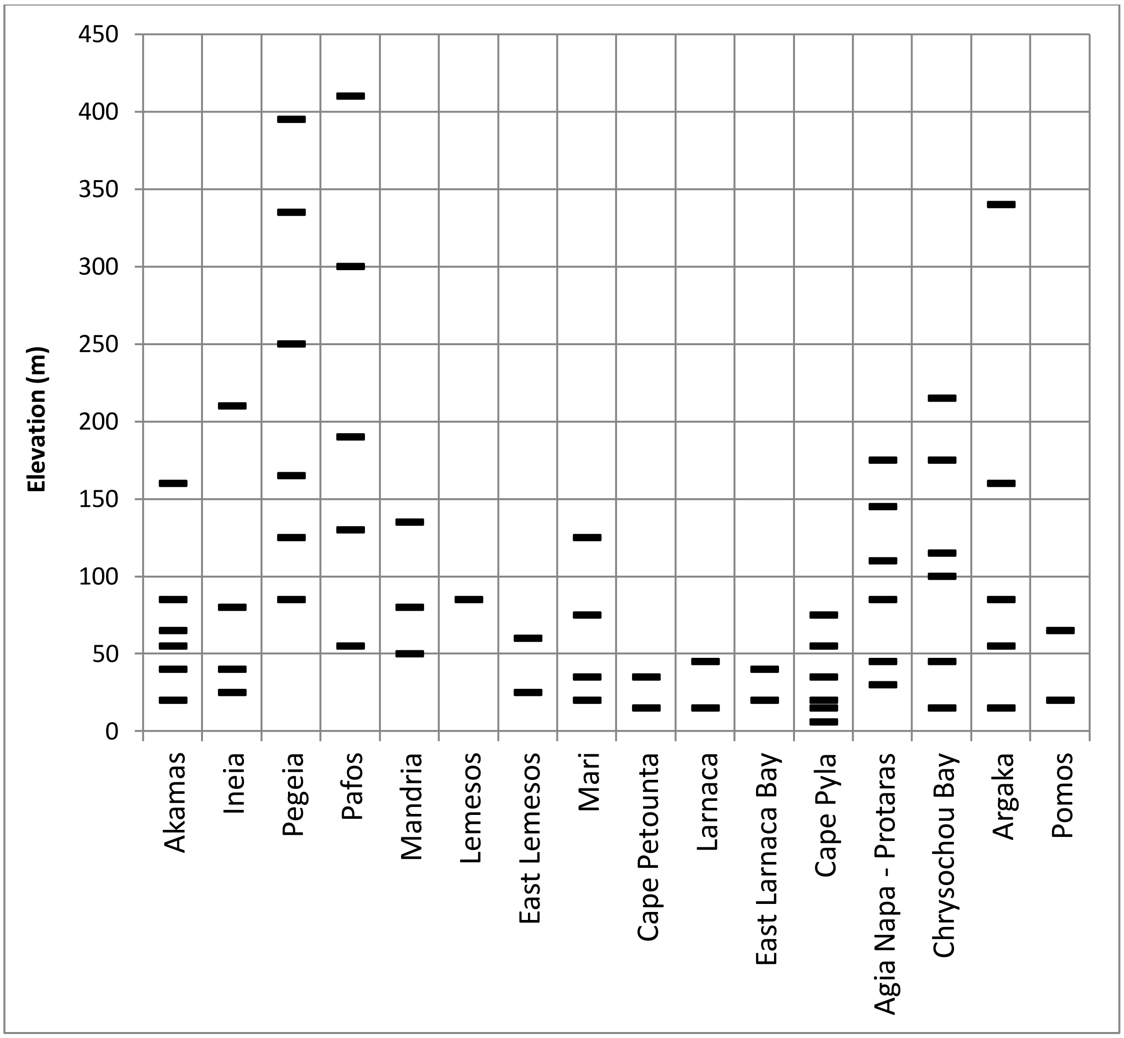


Figure 2-7 Vertical distribution of marine terraces in 16 different coastal sectors around the island.

The following sections present the geographic distribution of marine terraces with their assignment to marine isotope stages based on geomorphology and geochronology.

2.5.4 Distribution of marine terraces in western Cyprus

Terraces in Akamas peninsula are well preserved due to the resistance of bedrock lithology but also the total absence of man and infrastructure. Miocene Pachna formation chalks and Tera and Koronia Member reef limestone are the bedrock lithologies in this area.

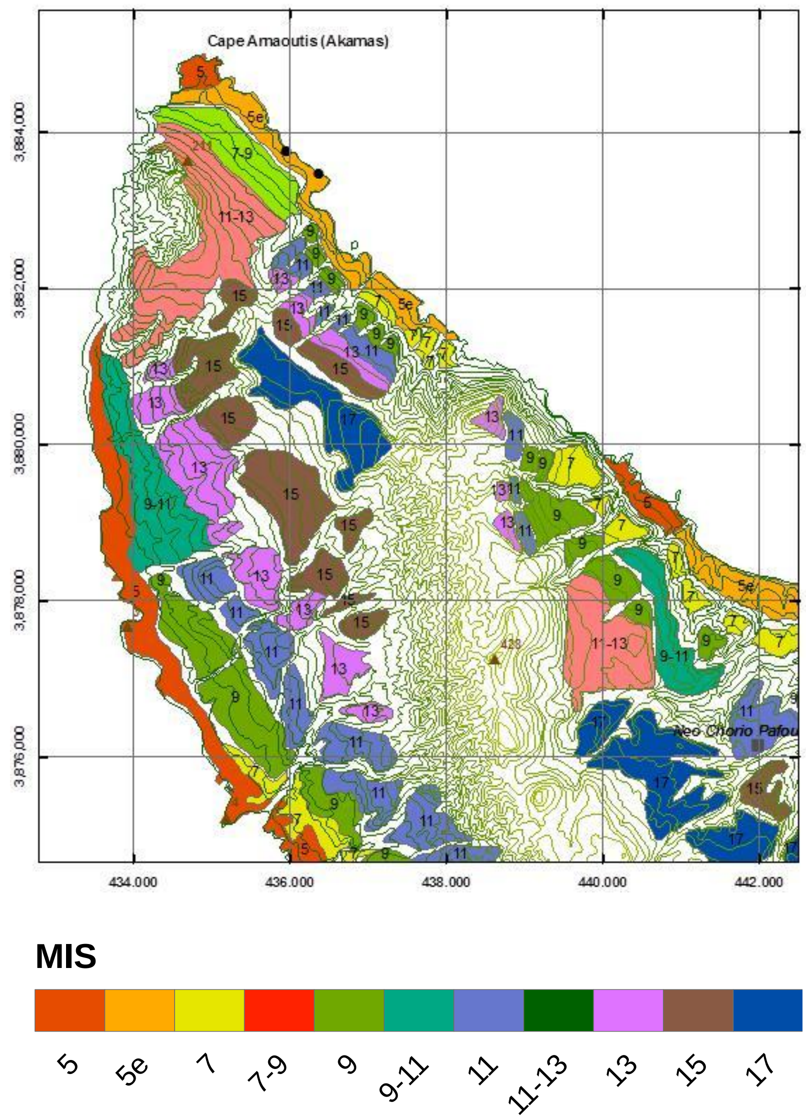


Figure 2-8 Map of terraces in Akamas Peninsula with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

Figure 2-9 MIS 5 terrace in northeastern Akamas at 3,881,500 m north.

Palaeoshorelines in Akamas are distinct features on the landscape and easily recognizable on a topographic map and on a satellite picture. Due to the fact that the Akamas peninsula is a national park with no main roads but only all – weather coastal roads, field work was conducted for the western slopes of the peninsula where roads transect the marine terraces. Marine terrace palaeoshorelines show continuity along the shoreline and are not being transected by any evident faults across the coastline.

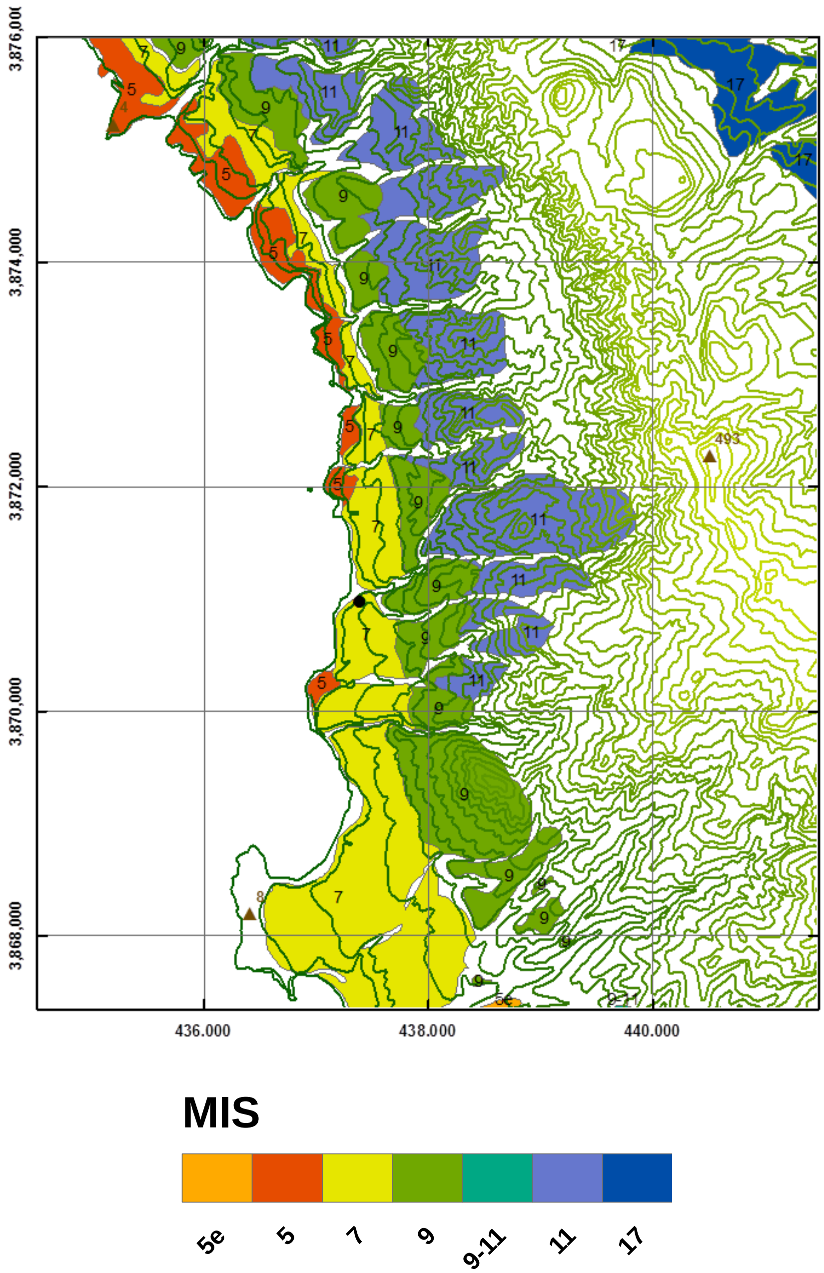


Figure 2-10 Map of terraces in Ineia area, from Cape Geronisos in the north to Lara Bay in the south with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

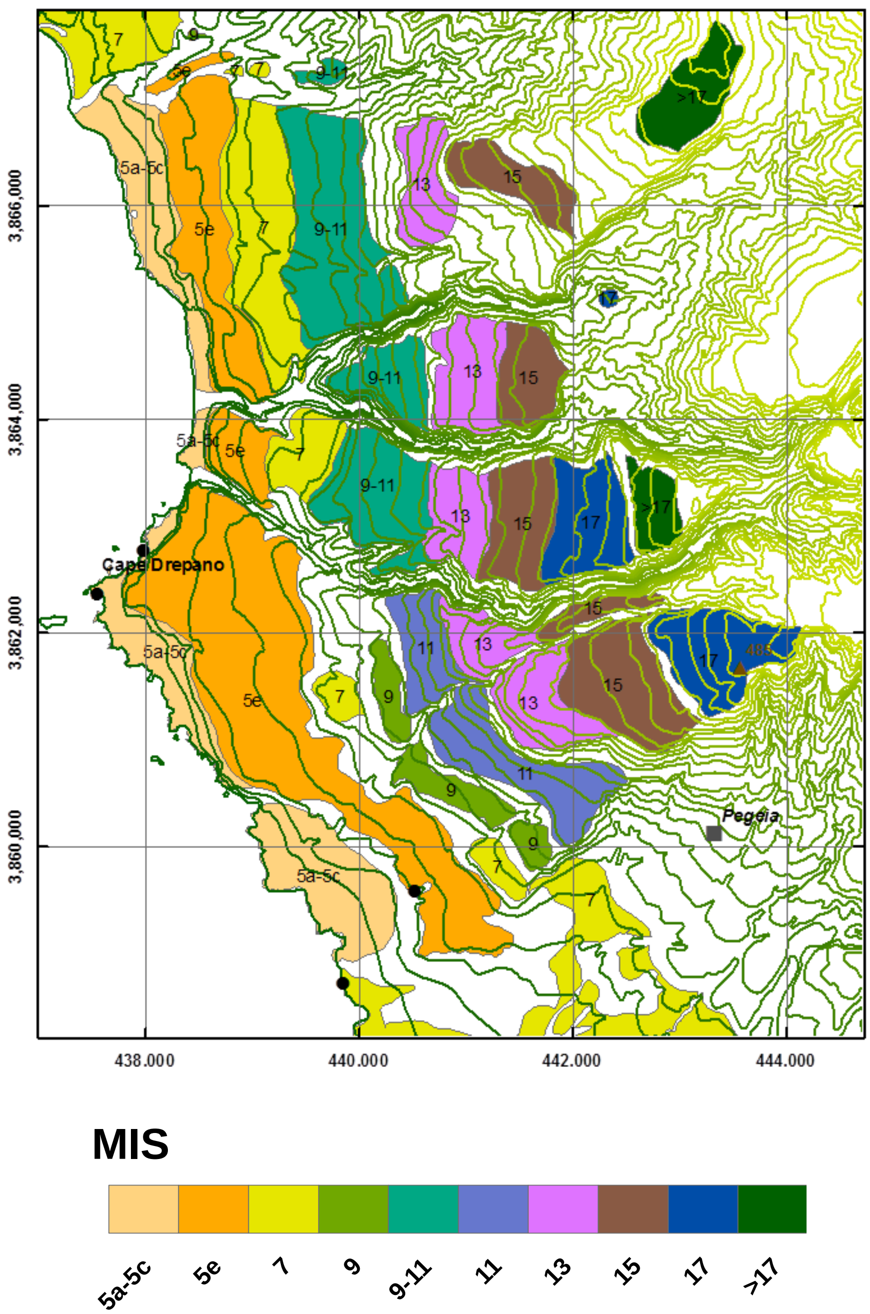


Figure 2-11 Map of terraces in Pegia with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

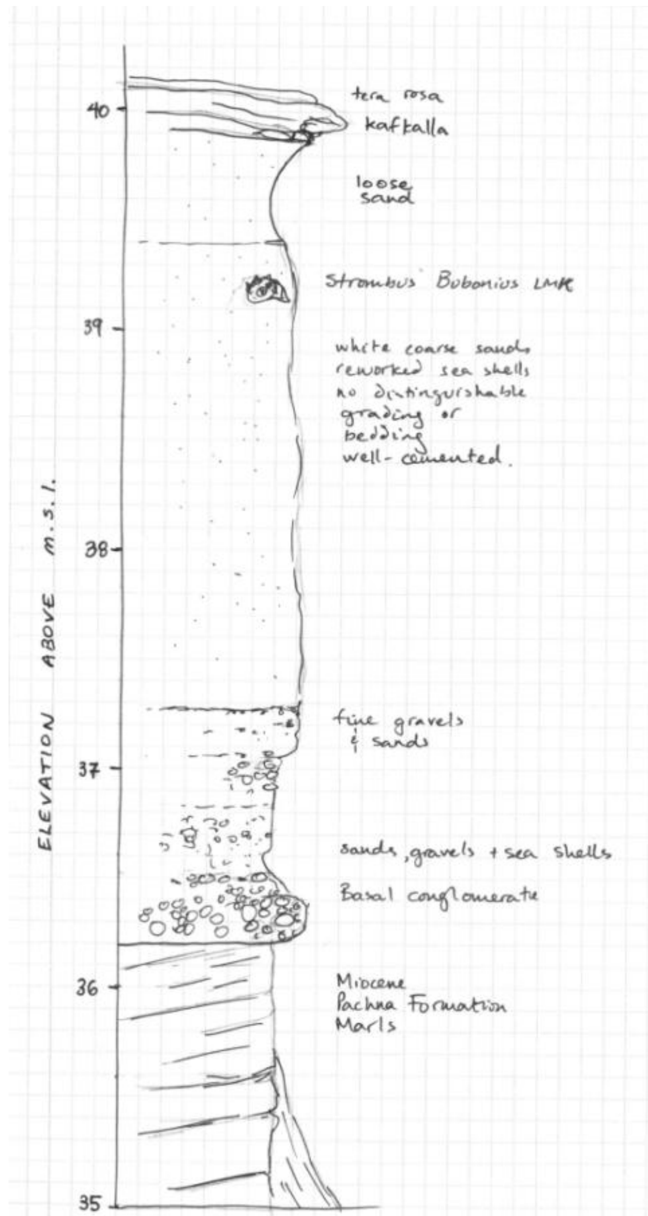


Figure 2-12 Stratigraphic column of the MIS 5e terrace in Pegia.

The higher terraces occur in Pegeia and Pafos where they reach a height of 400-410 m a.m.s.l. Pegeia becomes an important point on the map because of the location of a *Strombus*

Bubonius LKM fossil at an elevation of 39m (Figure 2-13). The palaeoshoreline elevation of this marine terrace is at 85 meters. Theodorou (2005) reports on *Strombus Bubonius LKM* fossil found in Pegeia but does not report on an elevation. His reference to the gas station location on the main road (Theodorou, per. com., 2012) places the fossil even higher than what is shown in Figure 2-12 and verifies the 85 m elevation of the palaeoshoreline. This is the highest elevation at which MIS 5e terrace is found in Cyprus.

Figure 2-13 *Strombus Bubonius* LMK from Pegia 5e terrace.

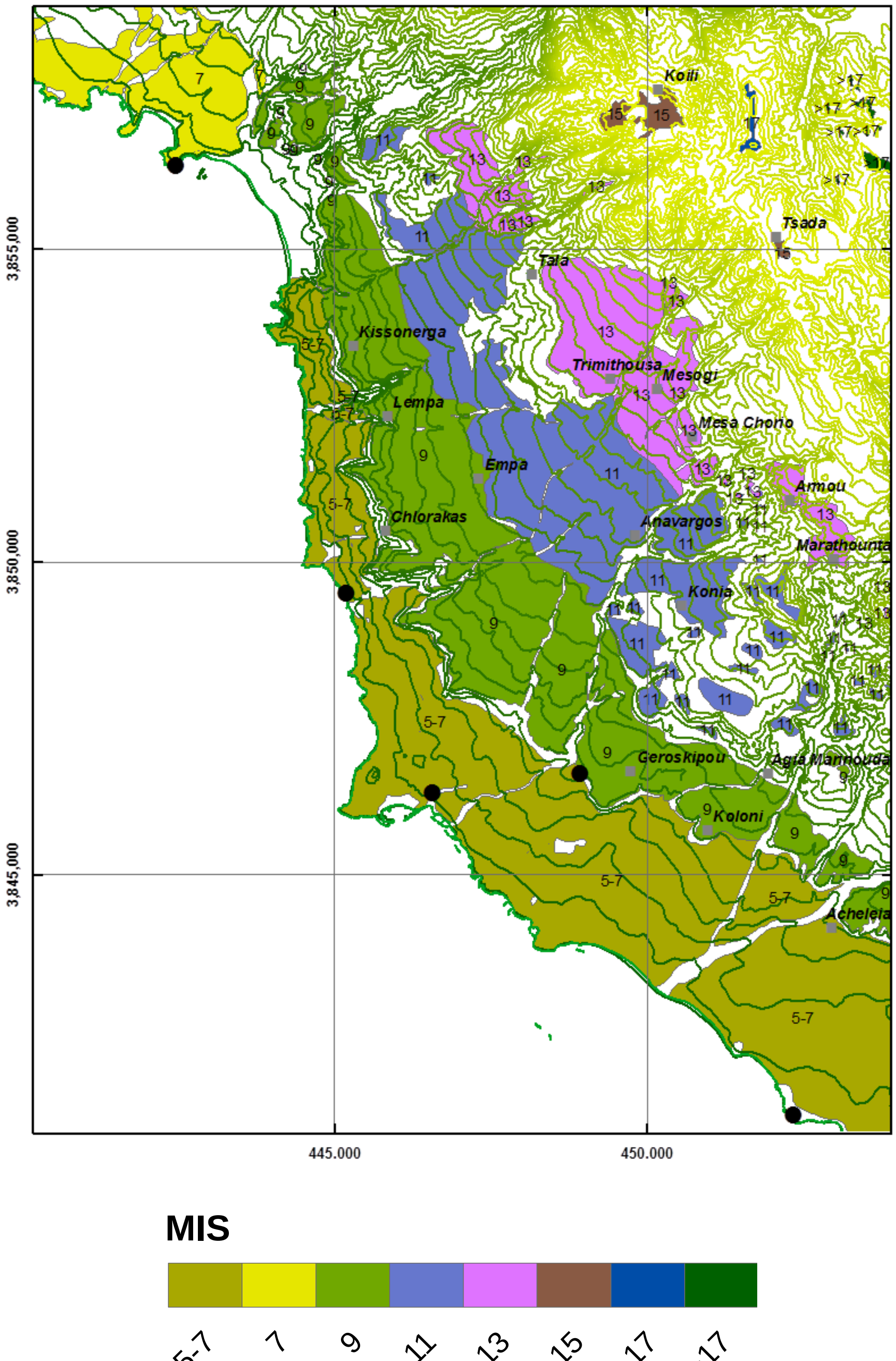


Figure 2-14 Map of terraces in Pafos with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

Figure 2-15 MIS 5 in Kato Pafos in a large excavation.

From Kissonerga to Pafos airport a prominent marine platform has a width reaching as much as 3km. This broad marine terrace is mapped with a palaeoshoreline elevation at 50-55 m. Poole (1992) reports a coral date from an elevation of approximately 3 m of 130,000 years ± 4,000 in downtown Pafos (at 446,000 m E, Figure 2-14) and Noller (2009) on a coral dated 133,400 years ± 3,100 on the coast of Mandria (at 457,000 m E, Figure 2-16). MIS 5 terrace follows the probable location of the surficial expression of the Pafos Thrust fault which is exposed on the surface in a small window between 452,000- 464,000 m E (will be discussed in Chapter 4), just below MIS 7. MIS 5 follows this blind thrust line and ends in Kouklia where a fold marks the only visible point of this surficial expression.

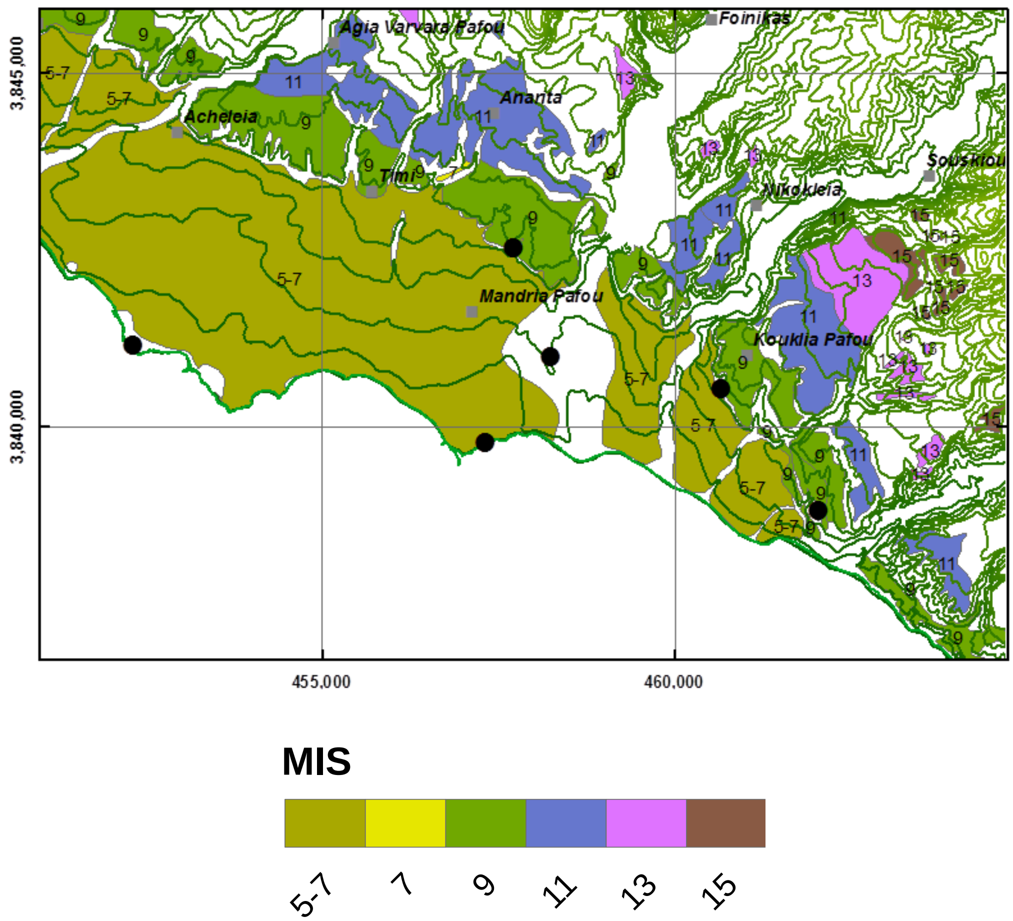


Figure 2-16 Map of terraces in Mandria area, from Koloni to Kouklia with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

2.5.5 Distribution of marine terraces in southern Cyprus

Exposed gypsum deposits in the coastal area from Pissouri to Aradippou made this part of the southern coast of Cyprus less likely to have deposited and later preserved clastic marine deposits. In this southern section of the island marine terraces are nonexistent or eroded, their remnants are thin, calcified and sometimes colluvial slopes can be easily mistaken for marine terrace deposits. Akrotiri and Cape Petounta are the only two locations with well – formed and preserved marine deposits.

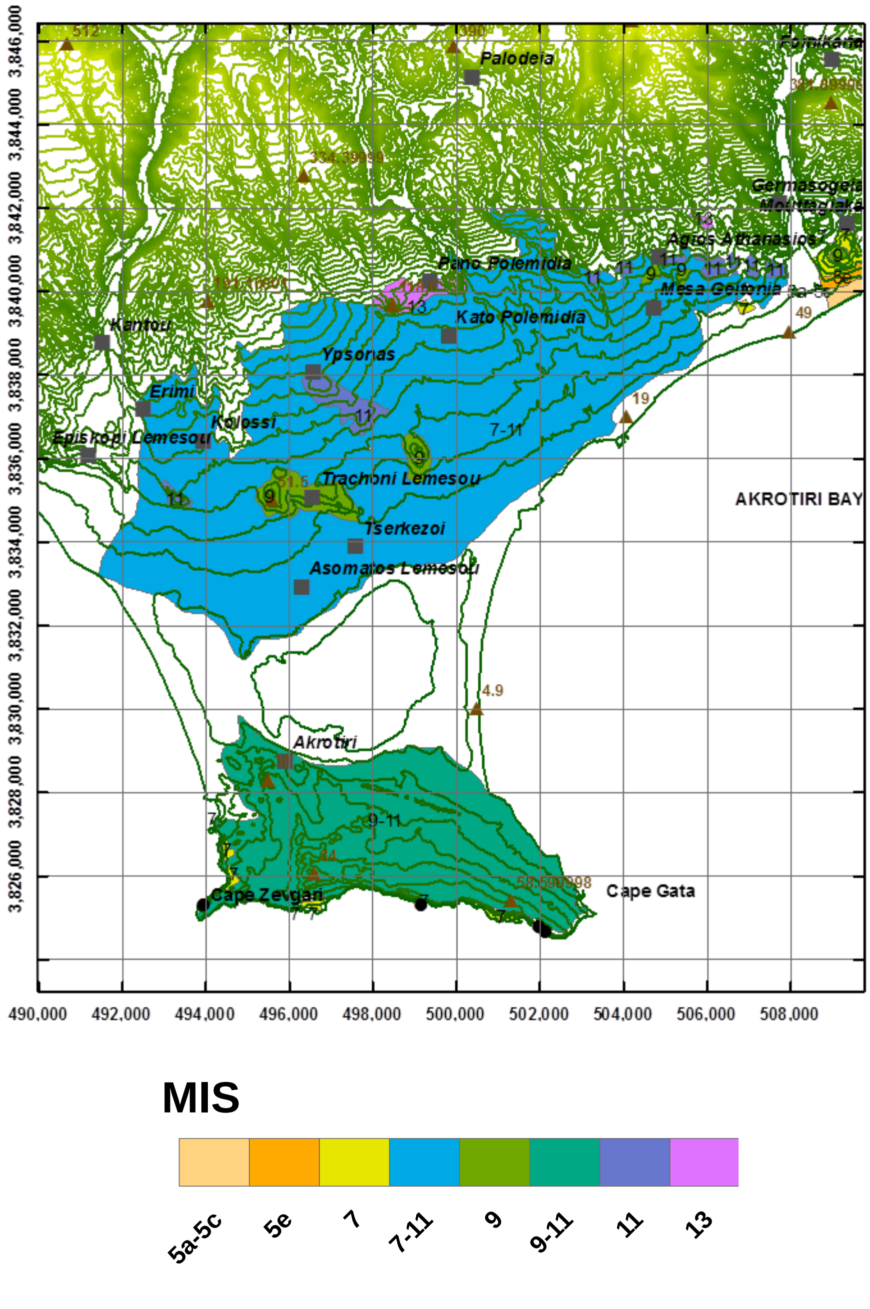


Figure 2-17 Map of terraces in Lemesos with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

There are very few opportunities for mapping marine terraces and palaeoshorelines in Lemesos town. Extensive construction in the built – up area and the smooth topography of the coastal zone offer no evidence for any topographic anomalies that can be attributed to palaeoshorelines. Mapping in the British Sovereign Base on Akrotiri peninsula (Figure 2-17) revealed a broad marine terrace topping Lefkosia and Pachna formation rocks in the central and east sections and Mamonia mudstones in the western tip of the peninsula. Three samples of corals have failed to determine an age for this broad terrace. A lower terrace is found at 2-3 meters above sea level at the bottom of the crest, right below the Aetokremnos Neolithic site, but no datable materials were found.

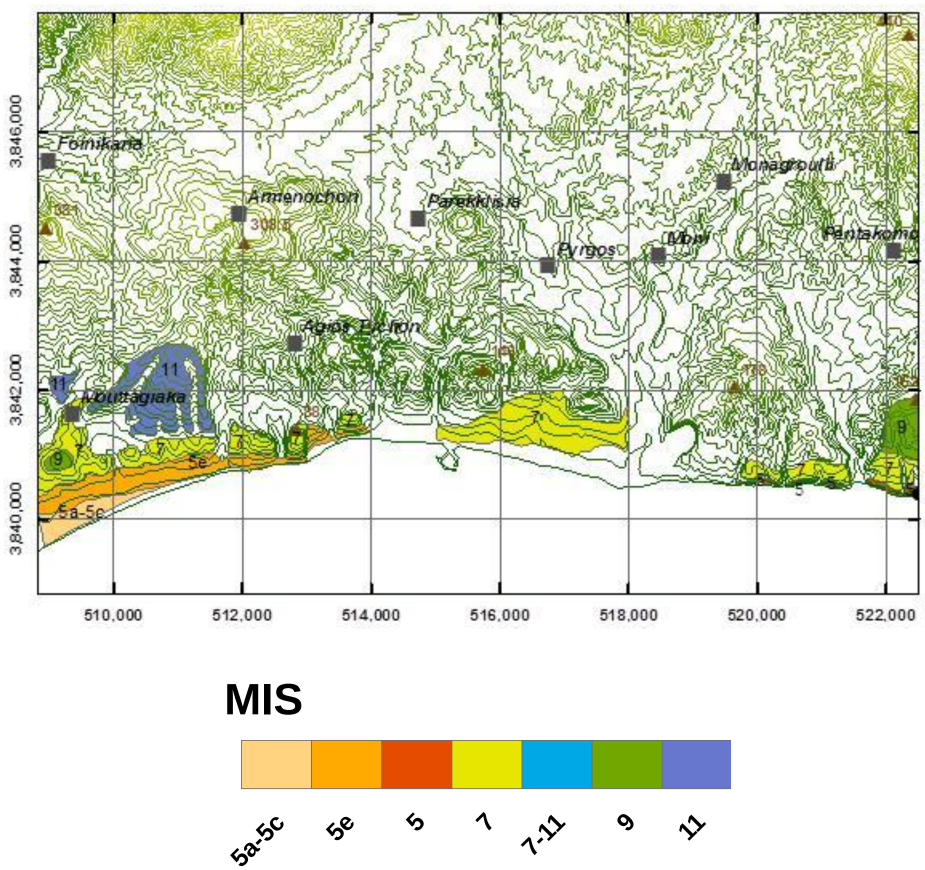


Figure 2-18 Map of terraces east of Lemesos with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

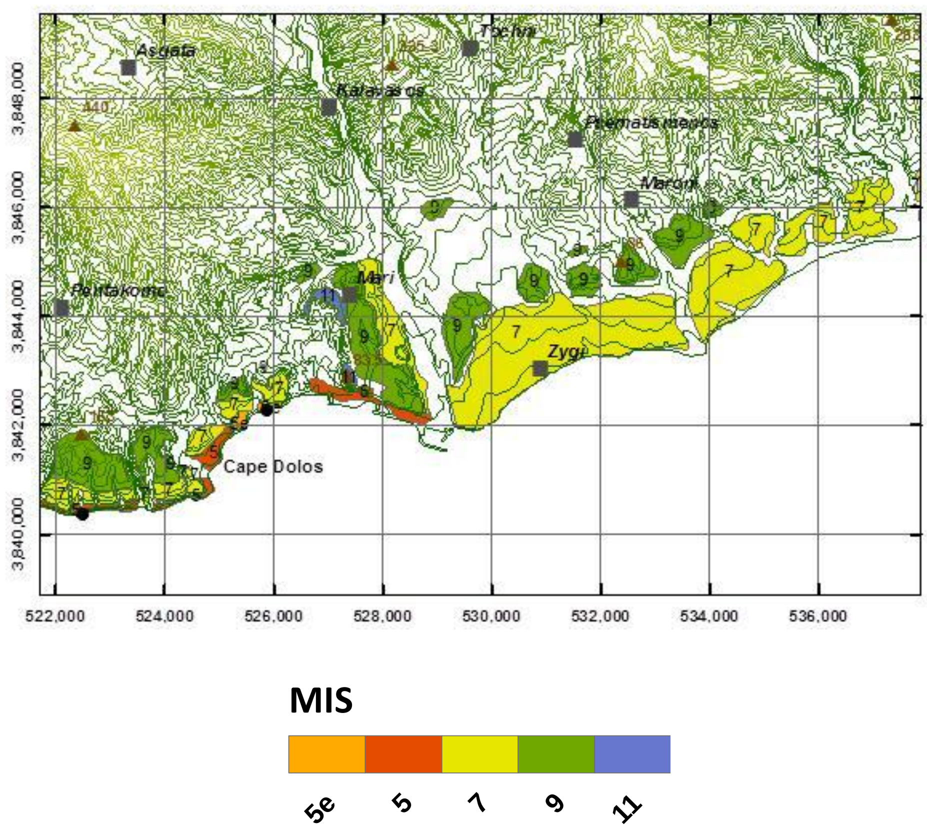


Figure 2-19 Map of terraces in Zygi area with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

Figure 2-20 Strombus Bubonius LMK from Mavra Litharga in Mari (just east of Cape Dolos).

Figure 2-21 MIS 5 terrace on the coast of Pentakomo (west of Governor’s Beach).

A 7 – km stretch of coast from Moni to Mari consists of almost uncemented marine gravels and red sands deposited on top of Lefkara formation chalks (Figure 2-21) which make up the popular coastal landscape of what is known as Governor's beach. The texture and cementation of this terrace deposits and the colluvial slopes that top them make exact palaeoshoreline assignment difficult. Mapping in the Mari Military Naval Base revealed a very well cemented deposit with a Strombus Bubonius LMK fossil (Figure 2-20). Pantazis has mapped the same area for the publication of Kalavasos – Pharmakas Geological map (Pantazis, 1967a) and reports on the same fauna. East of the Mari MIS 5e terrace there is no field evidence for a prominent MIS 5 terrace.

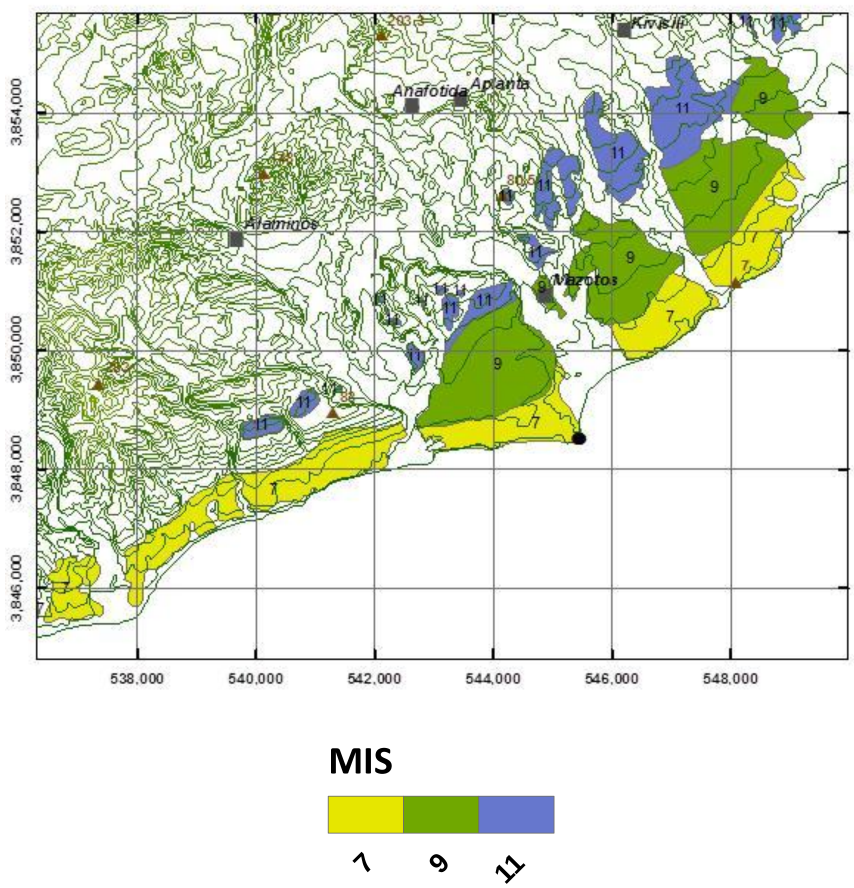


Figure 2-22 Map of marine terraces at Cape Petounta with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

2.5.6 Distribution of marine terraces in eastern Cyprus

Larnaca presents one of the biggest puzzles for marine terrace mapping. The presence of the lake and the active faults of the Larnaca airport area obscure the sea level signal. It is anticipated that Cape Kiti hosts Holocene marine deposits onshore due to a SSW – NNE active fault (Tsiolakis, per. comm., 2012). Gaudry (1862), Pantazis (1966, 1963) and Moskhowitz, 1963, all report on *Strombus Bubonius LMK* fossils in the Larnaca Salt Lake, they report on an elevation height of 9-12 m but none of them report on a specific location.

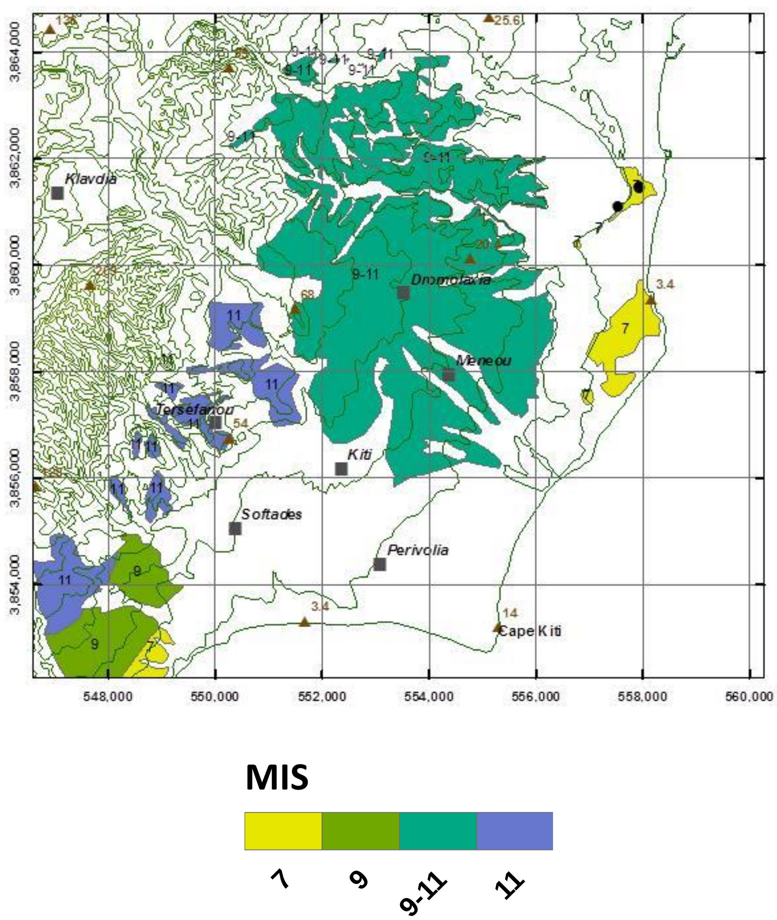


Figure 2-23 Map of terraces in the Larnaca lowlands with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

Figure 2-24 *Cladocora caespitosa* coral in the Dhekelia area at 567,000 m East

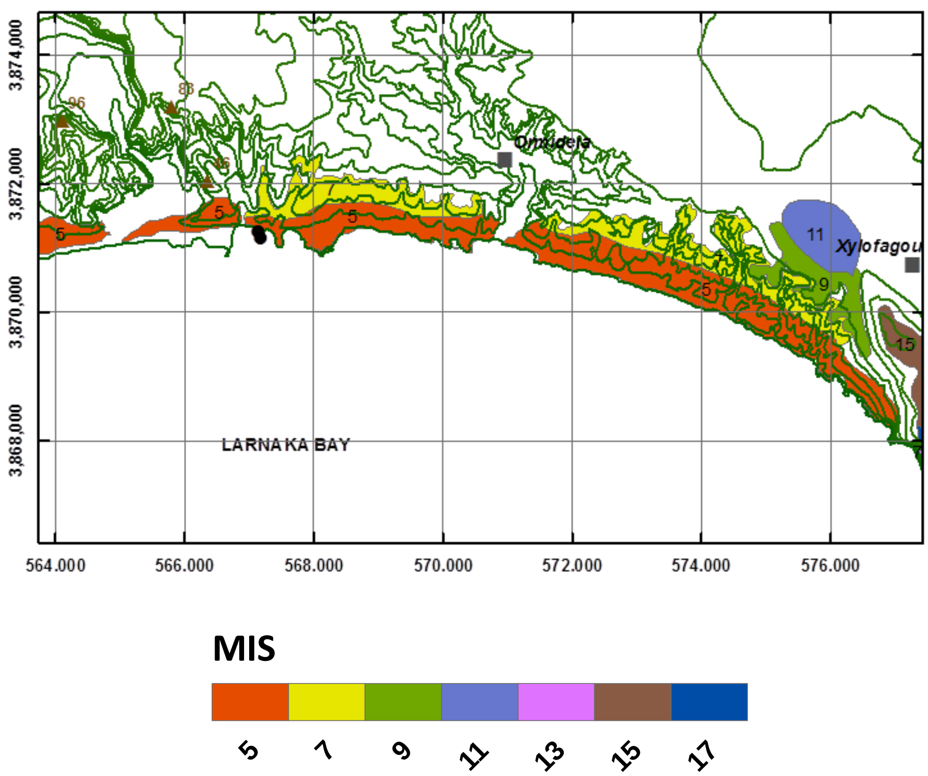


Figure 2-25 Map of terraces in east Larnaca Bay with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

Marine terraces in the Bay of Larnaca (Figure 2-25), east of Larnaca, what is known as the Dhekelia British Sovereign Base, presented a unique opportunity to sample an in situ coral (Figure 2-24) at easting 567,000 m. Poole (1992) gives an age of 116,000 ± 2,000 years for this coral and thus the marine terrace stretch from Dhekelia to Xylofagou, with a palaeoshoreline at 20m is assigned to MIS 5. The sediments of the higher terrace are poorly – cemented gravels and the shoreline angle is roughly seen at 40 m.

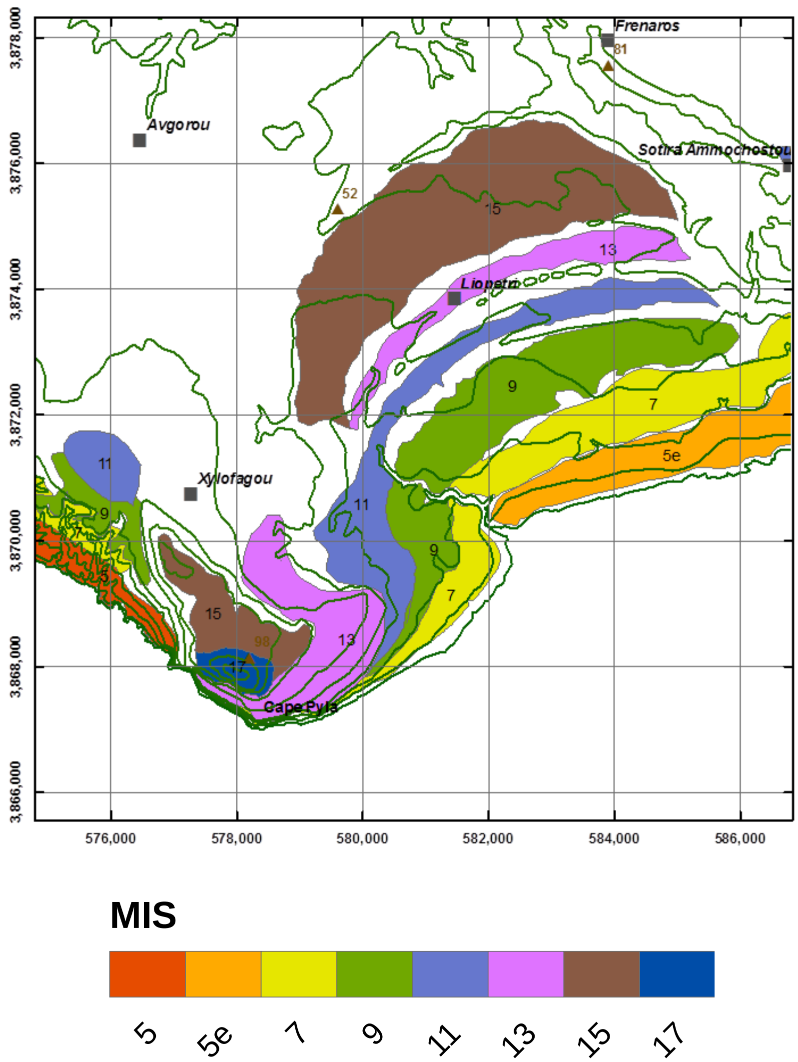


Figure 2-26 Map of terraces at Cape Pyla with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m. Terraces here largely based on Noller (2009).

Cape Pyla is a prominent Cape east of Larnaca and consists of very thick deposits of Koronia Member reef limestone. Bedrock hardness reproduces here the topography of Pegia where marine platforms are also formed on hard reef limestone bedrock. Terrace deposits are non – existent on the Cape and palaeoshorelines are evident from the topographic map. It is important to repeat here that the topography used in the analysis has a 5 m contour interval resolution while the contours shown on the figures have a contour interval of 10m up to the 100m elevation and 20m for elevations higher than 100m. Six palaeoshorelines are preserved representing seven terraces (Figure 2-26). These shorelines extent into the Kokkinochoria area to the east, where they create a broad platform with distinct terraces and beach ridges in front of them. They host some of the most fertile soils on the island. MIS 5 terrace has carved a distinct tidal notch with small terrace just below the MIS 7 terrace shown in Figure 2-27.

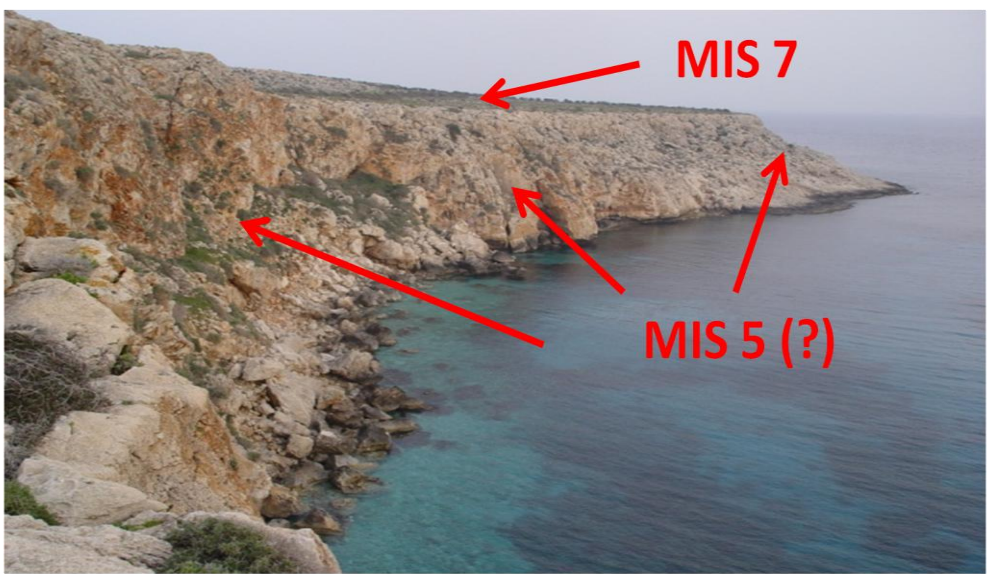


Figure 2-27 MIS 7 terrace on the eastern side of Cape Pyla and a possible notch of MIS 5.

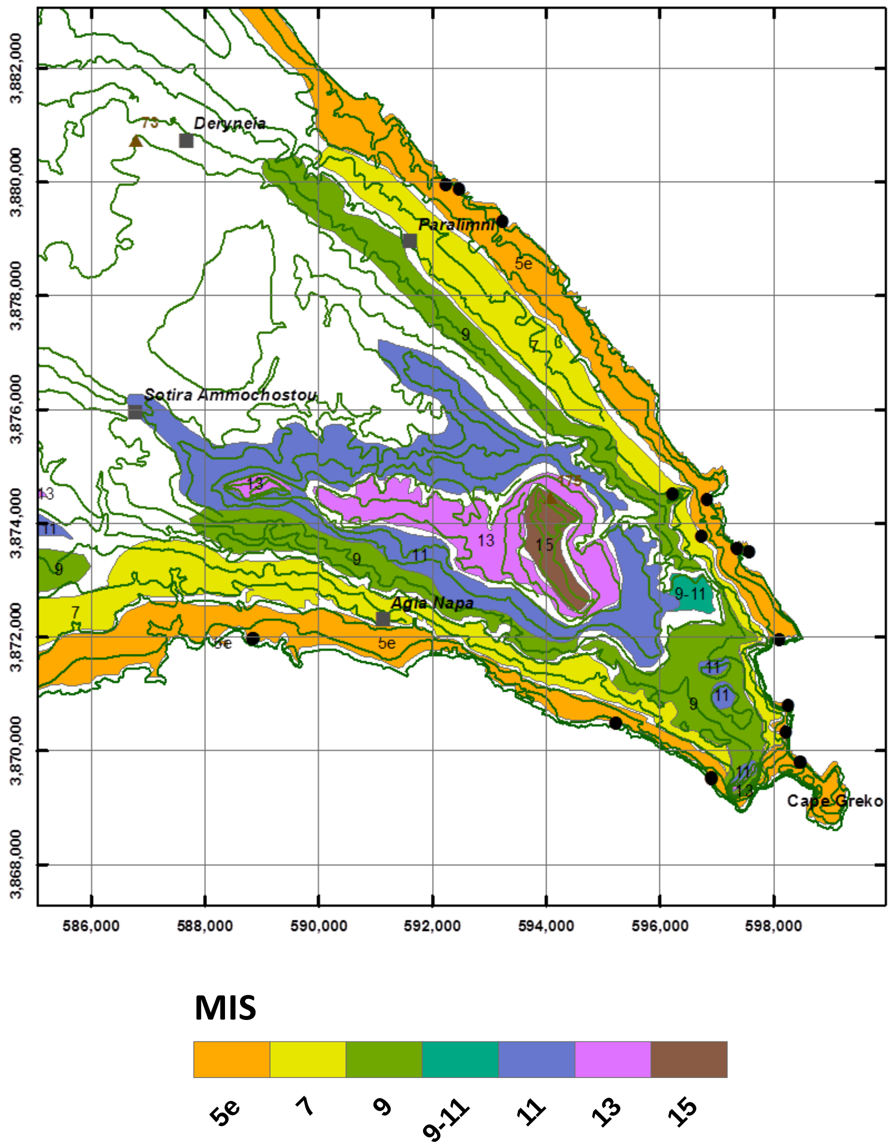


Figure 2-28 Map of terraces from Agia Napa to Protaras with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

Figure 2-29 Marine Isotope Stage 5e tidal notch at Cape Greco at an elevation of 30 m.

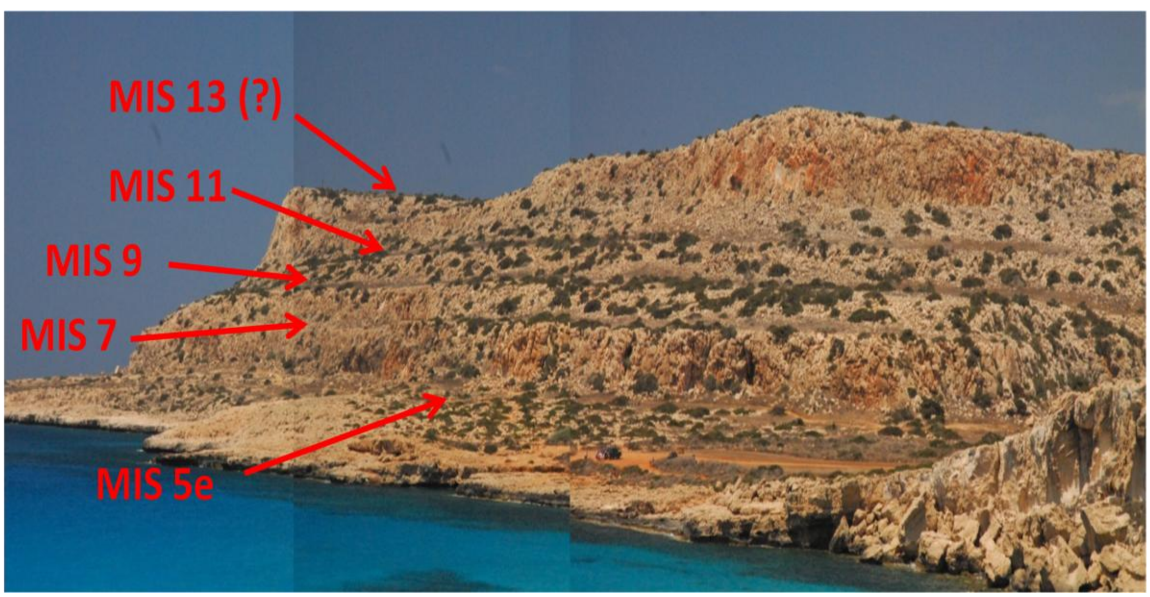


Figure 2-30 Uplifted flight of marine terrace at Cape Greco, just a few hundred meters west of the location shown in Figure 2-29. Table 2-4 lists ages of these marine isotope stages.

East of Agia Napa to Cape Greco the terraces of coarse calcarenites carved into reef limestone and carbonate rocks of Pachna Formation. The town of Agia Napa located on MIS 5 and MIS 7 has a characteristic break in terrain across town when driving from the MIS 5 lowlands to the higher ground of MIS 7. *Strombus bubonius LMK* locations by Theodorou (2005) just west of Cape Greco and east of Paralimni town have been verified in the field together with the shoreline angle they correspond to. *Cladocora caespitosa* corals in two locations in the same terrace, 2 km west of the *Strombus bubonius LMK* site in eastern Agia Napa gave dates 143400 and 152000 years (this study). Thermoluminescence dating on aeolianites topping the MIS 5 terrace in downtown Agia Napa (588,000 m E in Figure 2-28) gave ages of 53850 ± 4400 and 55450 ± 5200 (Noller, 2005). At the Cape Greco location there is a very prominent tidal notch belonging to MIS 5e (Figure 2-29). This MIS 5e tidal notch can be traced to the east but more easily to the west where as flight of marine terraces (Figure 2-30) can be used to trace terraces as far back as MIS 13.

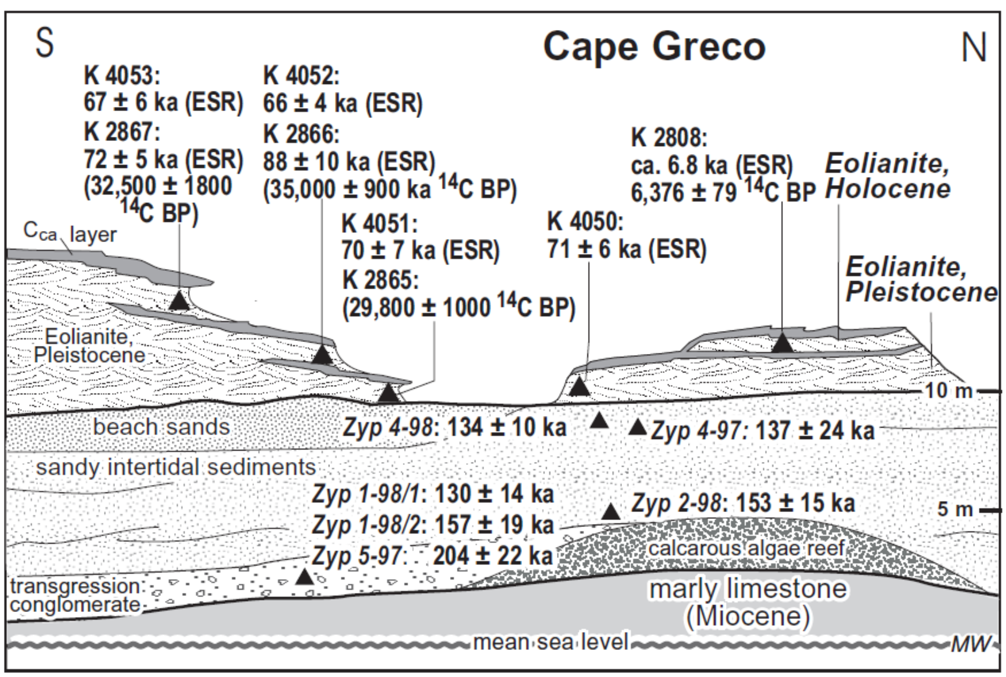


Figure 2-31 Geochronology results from ESR dating of marine shells from the marine deposits and Helix sp. Land snails from the aeolianite cover sediments (from Schellmann and Kelletat, 2001).

2.5.7 Distribution of marine terraces in northern Cyprus

Data on the northern coasts of Cyprus is limited because of the few terraces forming on precipitous slopes. Beyond Pyrgos (not shown on a map here) travel is difficult for field geologists. In addition, topographic data are only available from 1 :50,000 scale maps and air photography and satellites offer the only solution. Nevertheless, these data are not presented here. Palaeoshorelines and some marine sediments are well - preserved down the slope from Androlykou village on the very resistant reef limestone bedrock (Figure 2-32). MIS 5 and MIS 7 terraces in the vicinity of Lakki are in horizontal agreement with thick deltaic gravel deposits at the mouth of Chrysochou river that drains to the north into Chrysochou Bay.

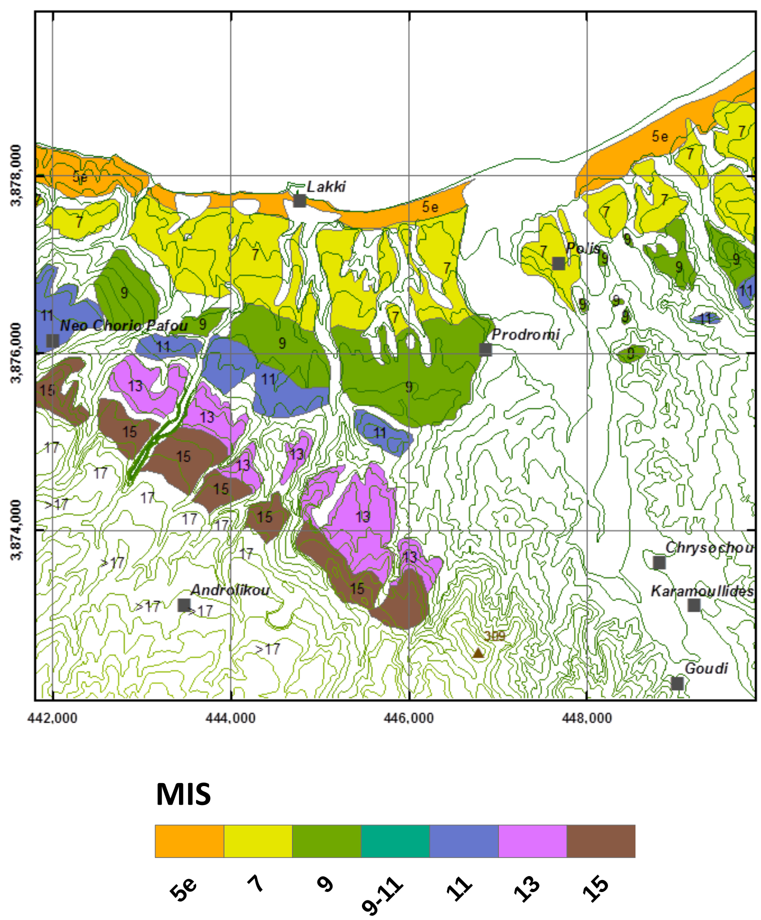


Figure 2-32 Map of terraces in Chrysochou Bay with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

East of the town of Polis tis Chrysochou, diabase and pillow lava bedrock help form a long and easily recognizable outcrop of MIS 7 marine terrace (Figure 2-34) and the palaeoshoreline of MIS 5e (Figure 2-33) along the long coastal road leading to Pomos. Numerous long rivers have supplied enough sediment on the coast to create 3-4 m thick marine terraces that persist in length along the road. The characteristic long fine gravel beaches on this stretch of Chrysochou Bay is probably the landscape that persisted during MIS 7 and MIS 5.

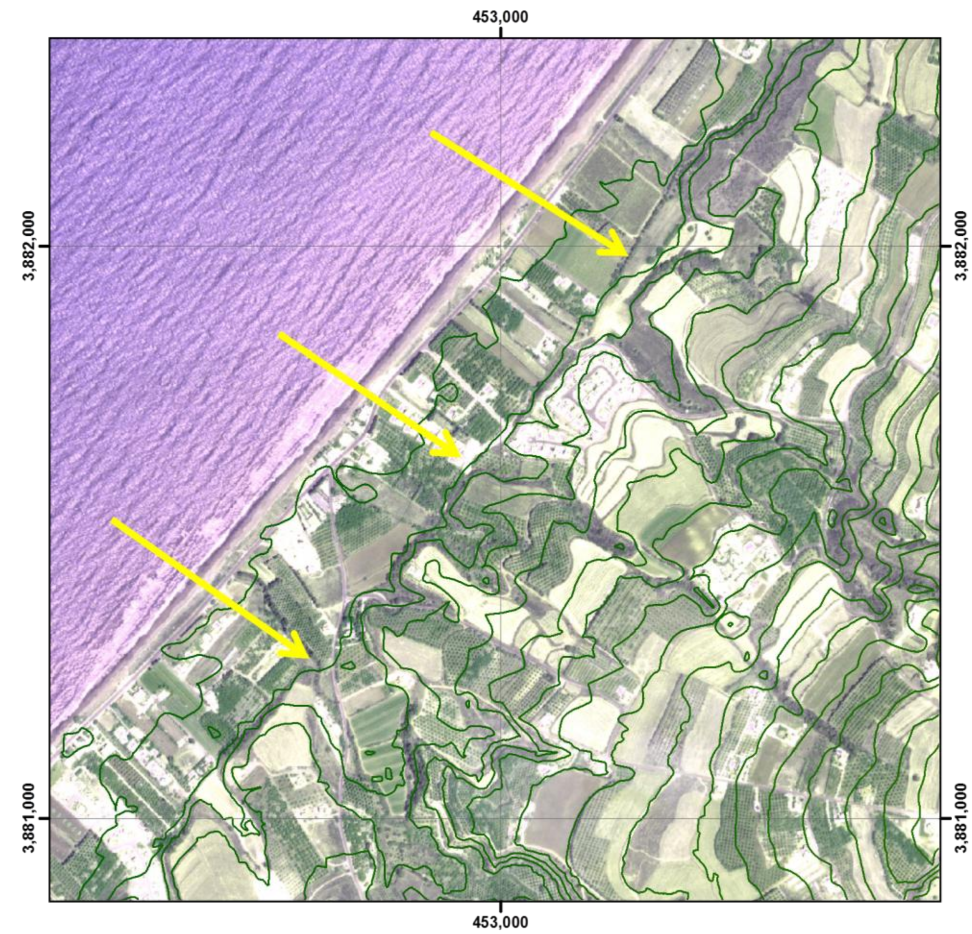


Figure 2-33 Prominent shoreline angle of MIS 5e along the road from Polis to Argaka.

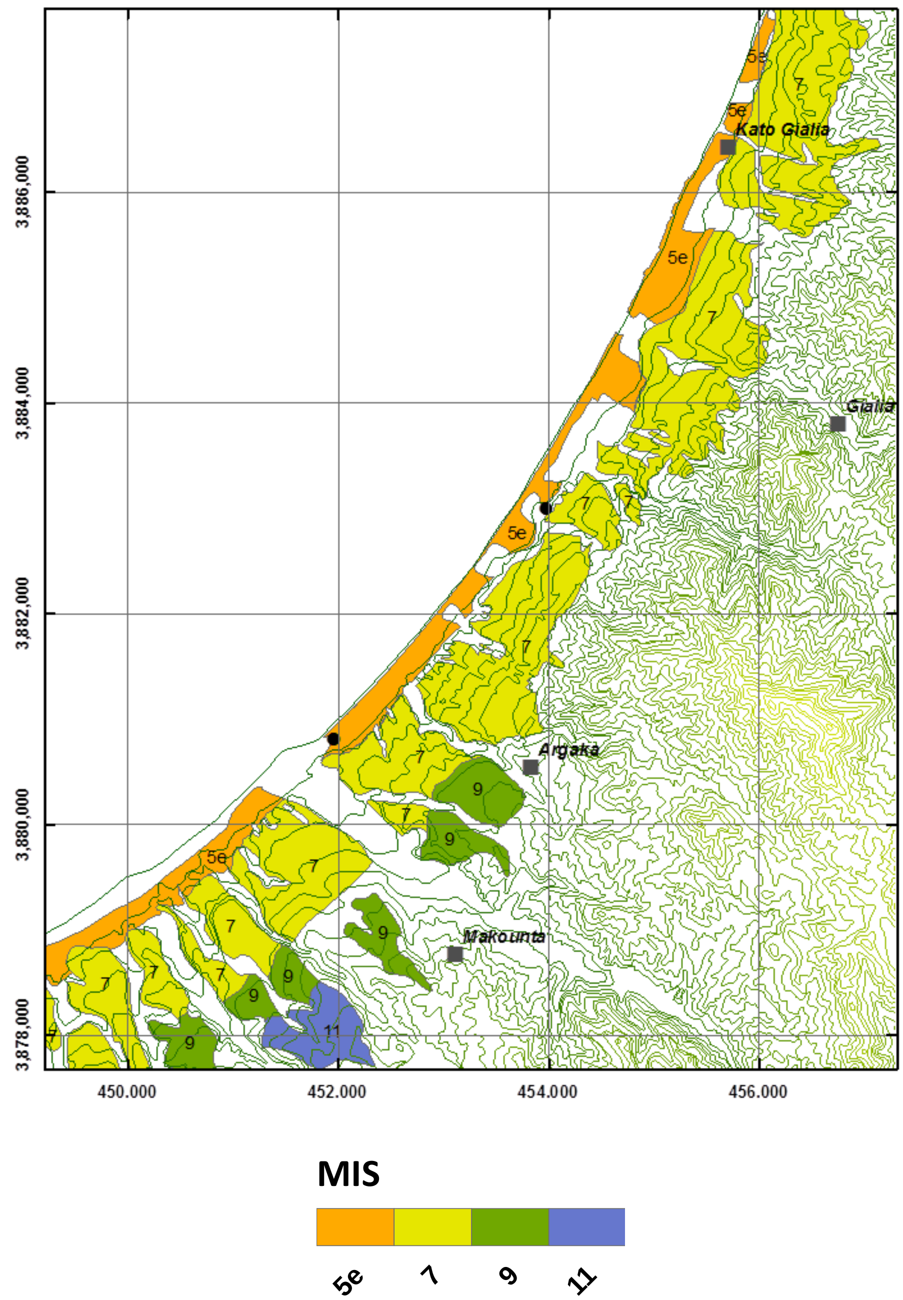


Figure 2-34 Map of terraces in Argaka (along Polis – Pomos road) with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

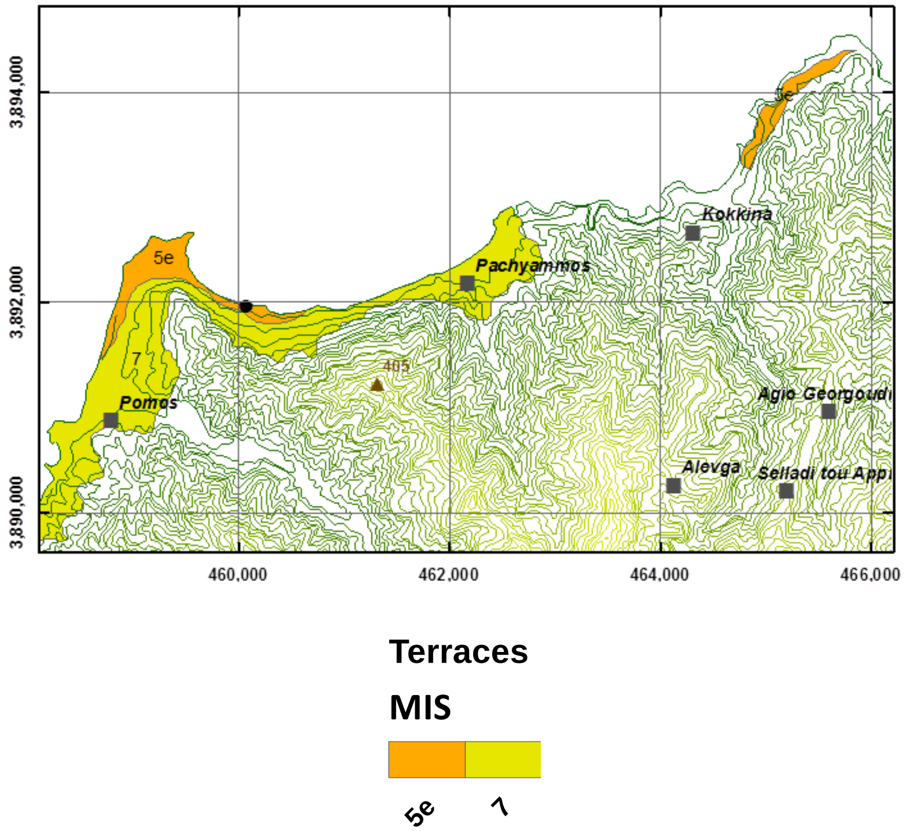


Figure 2-35 Map of terraces in Pomos with contour intervals at 10m up to 100m elevation and 20m for elevations higher than 100m.

Coastal landscape on the coastal road from Nea Dhimmata to Pyrgos is characterized by a precipitous coastal cliff into hard pillow lavas and diabase. The few and small rivers that flow to the sea are steep, narrow and sometimes form 10-20 m thick fluvial fans that are truncated by the coastline. Marine terraces are mapped in correlation to the Pomos terrace including interpretation of a higher palaeocoastline (Figure 2-35). Eroded marine platform features are seen at higher elevations but their age is uncertain at this time. The marine terrace overlooking the small port of Pomos is the only reasonably well–formed marine terrace (Figure 2-36).

Figure 2-36 MIS 5e terrace in Pomos. Red arrows show terrace outcrop and white arrows show the palaeoshoreline.

2.6 Discussion

2.6.1 Island – wide marine terrace distribution and uplift rates

Assignment of marine isotope stages on marine terraces shown on figures of the previous 4 sections are summarized in Table 2-6. MIS elevation assignments shown in bold numbers were assignments based on geochronology results previously shown in section 2.5.2. The preservation of uncrystallized corals yielding good geochronology results for the lower elevations together with the occurrence of the Strombus *Bubonius* LMK index fossil in the 5e terrace, the Last Glacial Minimum gives more accuracy to the lower terraces, namely MIS 5 and MIS 7. It is quite possible that higher marine terraces represent 2 or 3 marine isotope stages. It is possible for example that MIS 9 terrace builds on the smooth regressive surface of MIS 11. This may be the case for Pafos, Larnaca and Akrotiri.

Table 2-6 Elevation of terrace palaeoshorelines, elevation shown in bold numbers have absolute dates from geochronology methods.

	Marine Isotope Stage (MIS) Elevation of palaeoshoreline (m)					
Sector	**5e**	**7**	**9**	**11 (?)**	**13 (?)**	**15 (?)**
The southern coast						
Akamas (Figure 2-8)	**20**	40	55	65	85	160
Ineia (Figure 2-10)	25	40	80	210		
Pegeia (Figure 2-11)	**85**	125	165	250	335	395
Pafos (Figure 2-14)	<55 (?)	**55**	130	190	300	410
Mandria (Figure 2-16)	<50 (?)	**50**	80	135		
Lemesos (Figure 2-17)				85		
East Lemesos (Figure 2-18)	25	60				
Mari (Figure 2-19)	**20**	35	75	125		
Cape Petounta (Figure 2-22)		**15**	35			
Larnaca (Figure 2-23)		**15**	45			
East Larnaca Bay (Figure 2-25)	**20**	40				
Cape Pyla (Figure 2-26)	6	15	20	35	55	75
Agia Napa – Protaras (Figure 2-28)	**30**	45	85	110	145	175
The northern coast						
Chrysochou Bay (Figure 2-32)	15	45	100	115	175	215
Argaka (Figure 2-34)	15	55	85	160	340	
Pomos (Figure 2-35)	20	65(?)				

It is worth mentioning that even if good topographical data does not exist for the northern coast of Keryneia, the *Stombus Bubonius* fossil of Ducloz (1964, 1968) and recently Galili *et al.* (2009, 2011) can be used for a conservative approximation of an uplift rate of 0.12 mm/year for this part of the island.

A graphical representation of Table 2-6 is shown in Figure 2-37. Pegeia, Pafos and Mandria show the highest elevation for MIS 5e suggesting a tectonic regime that creates increased uplift in a westward direction, from Mandria to Pafos and finally to Pegeia. Some representative profiles are shown in the following figures. To derive the most recent uplift history it is attempted to use the lower terrace, which is either MIS 5, MIS 5e or MIS 7.

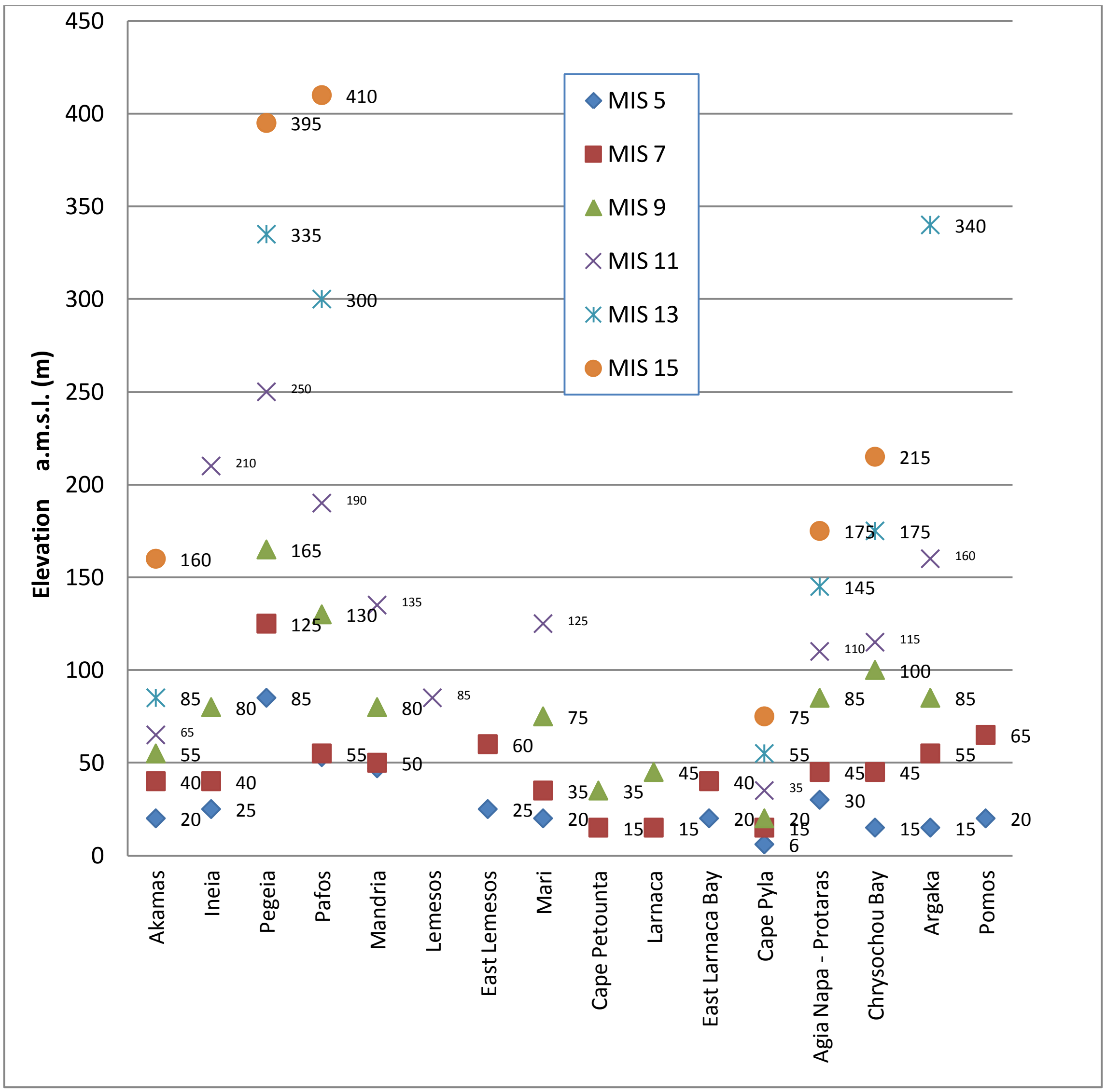


Figure 2-37 Vertical distribution of marine terraces in 16 different coastal sectors around the island with assigned marine isotope stages.

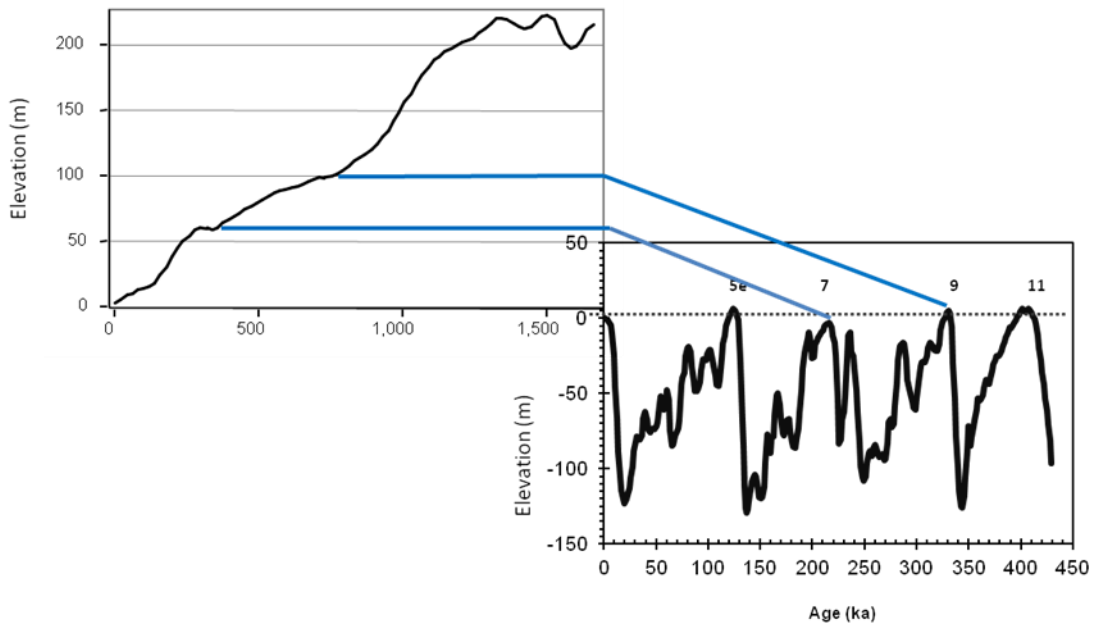


Figure 2-38 Graphical correlation of marine terraces on the coast of Ineia.

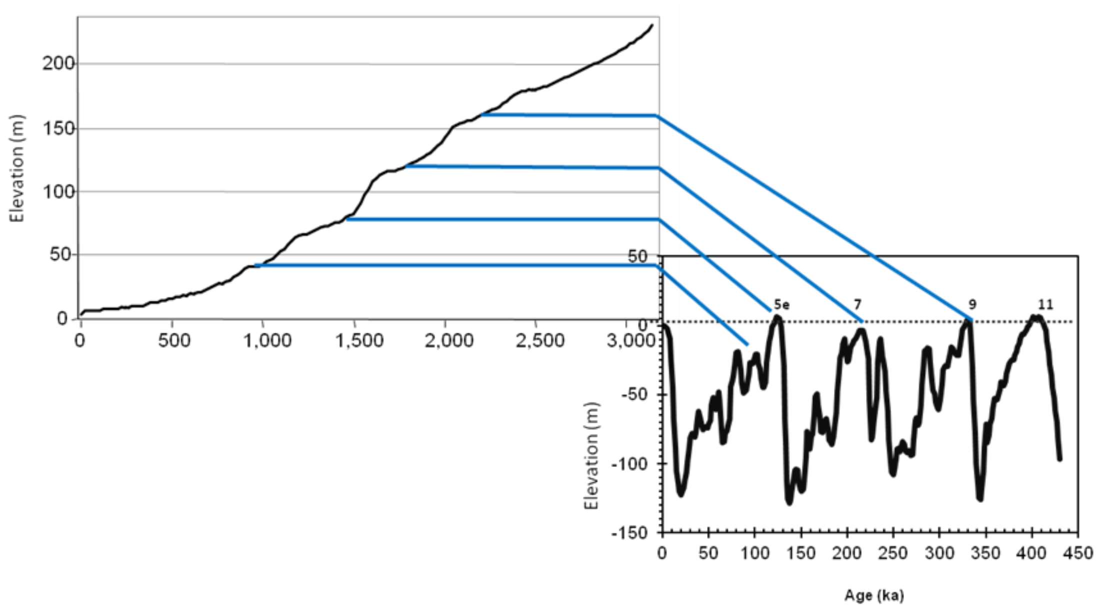


Figure 2-39 Graphical correlation of marine terraces in Pegia.

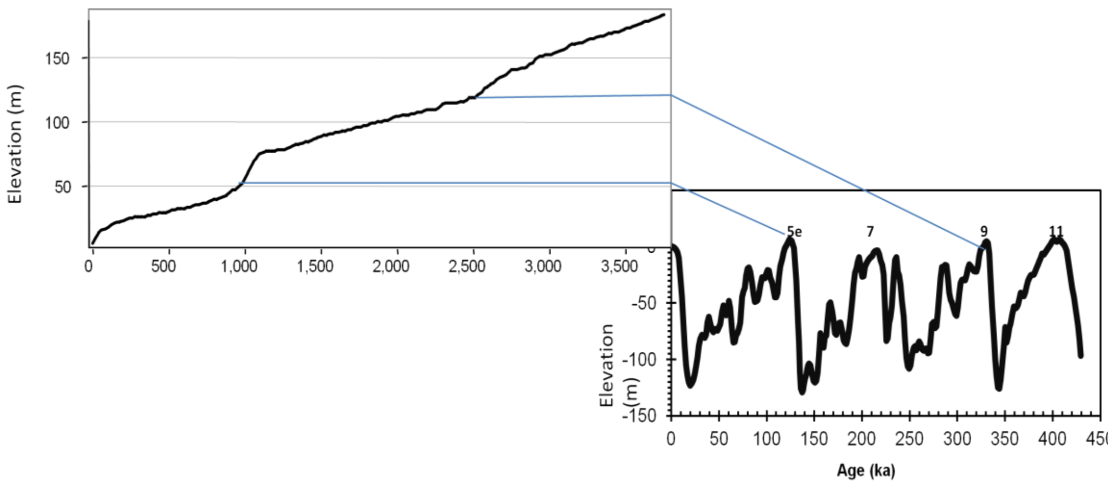


Figure 2-40 Graphical correlation of marine terraces in Pafos (can be correlated to Figure 2-42).

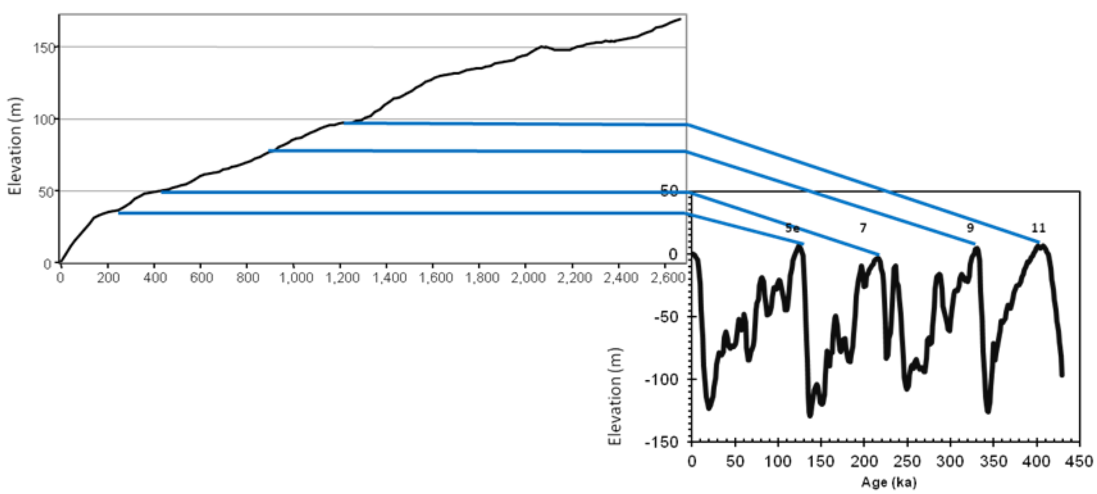


Figure 2-41 Graphical correlation of marine terraces in Agia Napa (can be correlated to Figure 2-43).

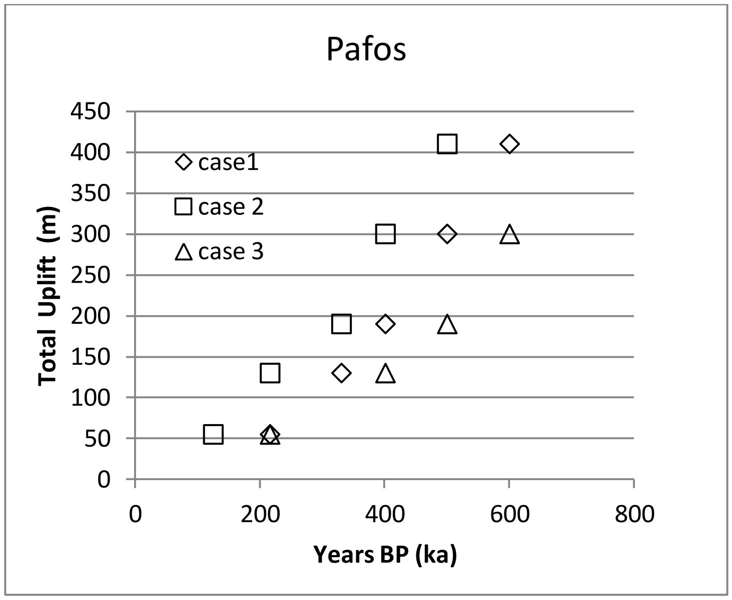


Figure 2-42 Graphical comparison of different scenarios for the Pafos area showing the case 1 scenario used in this study as the most reliable (total uplift takes sea-level differences between MIS into consideration).

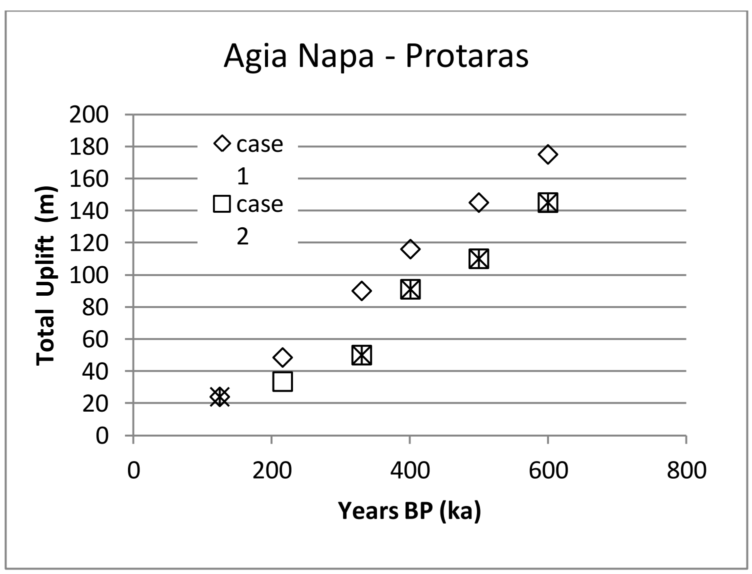


Figure 2-43 Graphical comparison of different scenarios for the Agia Napa – Protaras area showing the case 1 scenario used in this study as the most reliable (total uplift takes sea-level differences between MIS into consideration).

Table 2-7 Uplift rates for different coastal sectors on Cyprus.

Sector	Uplift rate (mm/year)	
	With MIS 5e data	With MIS 7 data
Akamas	0.11	0.20
Ineia	0.15	0.20
Pegeia	0.63	0.59
Pafos	0.39 (?)	0.27
Mandria	0.35 (?)	0.25
Lemesos		0.02
East Lemesos	0.15	0.29
Mari	0.11	0.18
Cape Petounta		0.09
Larnaca		0.09
East Larnaca Bay	0.11	0.20
Cape Pyla	0	0.09
Agia Napa - Protaras	0.19	0.22
Chrysochou Bay	0.07	0.22
Argaka	0.07	0.27
Pomos	0.11	0.32

Western Cyprus presents the highest uplift rates. Similar studies by Kinnaird et al (2011) had proposed an uplift rate of 0.08 mm/year based on magnetostratigraphic testing on terrace samples as high as 400 m in Pafos. The samples were found to be normally magnetized, suggesting they were all deposited during the Brunhes chron (0.78 Ma). With these data Kinnaird had concluded that uplift rate in southwestern Cyprus is approximately 0.08 mm/year. The conclusion that these terraces are younger than 780,000 years is not in disagreement with this study but provides a very conservative result in modeling uplift in southwestern Cyprus. Considering that the Brunhes chron goes as far back in time as MIS 19, it would be very useful to conduct palaeomagnetic dating in Akamas or Pegeia where the marine sequence has 7-8 or maybe more marine terraces (probably going back to MIS 17 or 19), maybe crossing the Brunhes – Matuyama chron boundary.

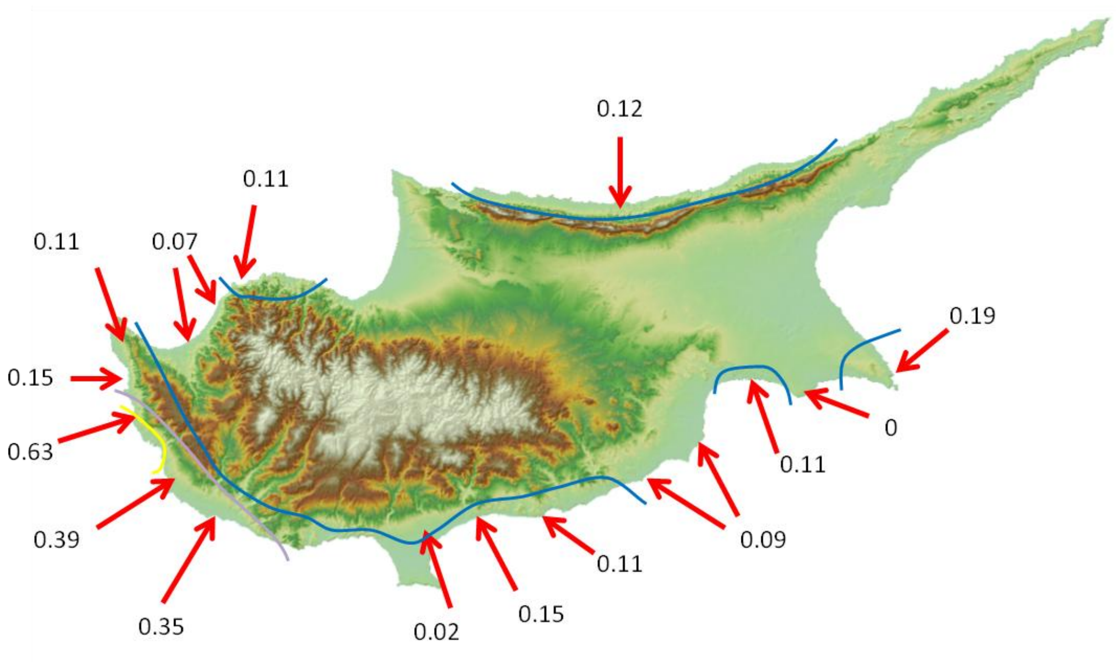


Figure 2-44 Upper Pleistocene uplift rates in mm/year using only the data from MIS 5 and MIS 7 terraces. Blue line is the 0.1mm/y uplift line, purple line is the line is the 0.2mm/y uplift line and yellow line is the 0.4mm/y uplift line.

2.6.2 Suggestions for a Holocene sea level curve

Glacio – eustatic sea – level changes are global but not uniform around the globe due to the effects of local isostacy and ocean surface gravitational disequilibriums. Eastern Mediterranean relative sea level needs to be resolved and established for a tectonically stable area first and then applied to tectonically active areas. Pirazolli *et al*. (1996) have geochronological evidence for an Early Byzantine tectonic Paroxysm (between the middle of the 4th and middle of the 6th century A.D.) in the Eastern Mediterranean. Islands in the Ionian Sea, locations in the Gulf of Corinth, the coast of Thessaly, Crete, southern Turkey, Syria and the Lebanon have experienced 0.5 – 1.0 m of coastal uplift. Western Crete has experienced as much as 9 m of co-seismic uplift in the 365 A.D. earthquake which triggered a tsunami in the eastern Mediterranean (Stiros, 2001) and uplifted the Phalasarna harbor by 9m (Pirazolli *et al*. 1992, 1996).

Uplifted and submerged harbors have always received a lot of attention firstly because of their archaeological significance but more recently due to their value in studying Holocene environments and coastal tectonics. A very comprehensive review of the contribution of harbor archaeology to Holocene coastal geomorphology and vise versa has been published by Marriner and Morhange (2007), specifically for the Mediterranean Sea. Abandoned harbors are excellent sea level markers but also offer accurate dating possibilities for their time of abandonment, making them useful in estimating vertical movements, sea-level changes and sediment fluxes (Marriner and Morhange, 2007).

In Cyprus, such ancient sites have also received great attention, like for example the uplifted and/or silted harbor of Kition Bamboula (Morhange *et al*., 2000) in the south of the island and the submerged harbor of Amathus, again in the south. Ammianus Marcellinus in 390 A.D. describes the island of Cyprus as insula portuosa, meaning an island with many harbors. Extensive geomorphological and geochronological studies have been done for the Bay of Ammochostos on the eastern part of the island which hosted the Early/Middle Bronze Age harbor for the town of Kalopsida, located in ancient Enkomi (Figure 2-45). The harbor site was moved east from the Enkomi site to the Greco-Roman ancient polity of Salamina and, finally to the Medieval site of the city of Ammochostos (Devillers, 2005).

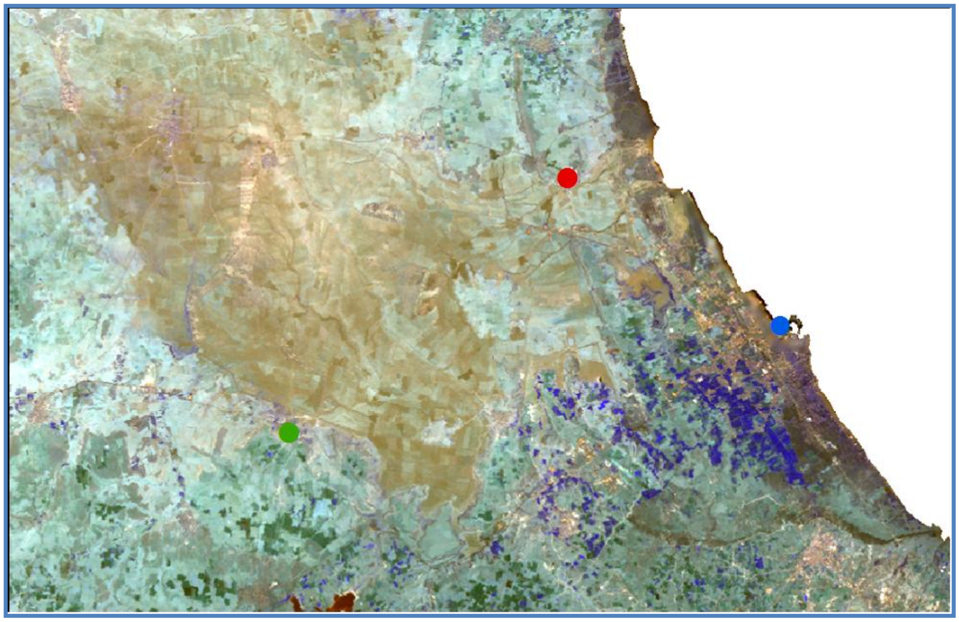


Figure 2-45 The early/Middle Bronze Age town of Kalopsida (green dot) is located about 13 km from the present coast. Its port, Enkomi (red dot) originally a port for Kalopsida later flourished as a polity in the Greco-Roman period. The port later moved to Salamis and finally to its present location of Medieval Ammochostos (blue dot).

In a paper by Pirazolli (2005) the possible eustatic, isostatic and tectonic contributions are investigated in eight late - Holocene sites in the Mediterranean. He concludes that the eustasy in the Mediterranean sea - level curve is consistent with the global eustasy which predicts an almost stable sea level since 6000 years BP. The complex coast of the Mediterranean with both volcanic and intense tectonic activity and in the Holocene, presents a great laboratory for studying the Holocene sea – level curve. Human occupation and archaeological structures on the coast provide the opportunity for recording these small changes in the sea – level curve of the last 5000 years.

In the southern tip of Italy, Dini *et al*. (2000) have mapped and dated pulmonate gastropods in aeolian dune and red palaeosol sequences, travertine samples, vermetidae and charcoal to reveal a steadily high relative sea level curve between 6500 and 5000 years BP. Between 5000 and 2500 years BP sea level was 2 m below the present sea level. Subsequently, sea level had risen to its present position drowning numerous Hellenistic, Roman and Medieval coastal artifacts.

Antonioli *et al.,* (2002) obtained data from Vermetid reefs and Lithophaga from Marettimo island in NW Sicily. The data concentrated in 2 groups, a sea level low of 30 cm below m.s.l. and a sea level low of 40 cm below m.s.l. for 200 years BP and 400 BP respectively. Lithophaga are very common on the Cyprus coasts and offer promising possibilities for dating.

Toker *et al.* (2011) used data from 100 locations including coastal water wells and coastal buildings in Akko, Atlit, Ashkelon, Caesarea and other places in Israel and have estimated a 50 ± 20 cm drop in sea-level during the period 900-1300 AD (Byzantine Period in Cyprus). Sivan *et al*., (2001), Toker *et al*., (2011), Nir (1997) and Nir and Eldar, (1986, 1987) are suggesting an even bigger drop in sea-level, during the Hellenistic period, again in Israel, estimated to be as much as 1.6m below present sea-level. Israel has been tectonically stable for the last 3000 years (Toker *et al.,* 2011) so its Late Holocene sea-level curve is free of any tectonic contributions (Figure 2-46). This sea level curve can be applied to Cyprus in order to identify areas of Holocene tectonic instability.

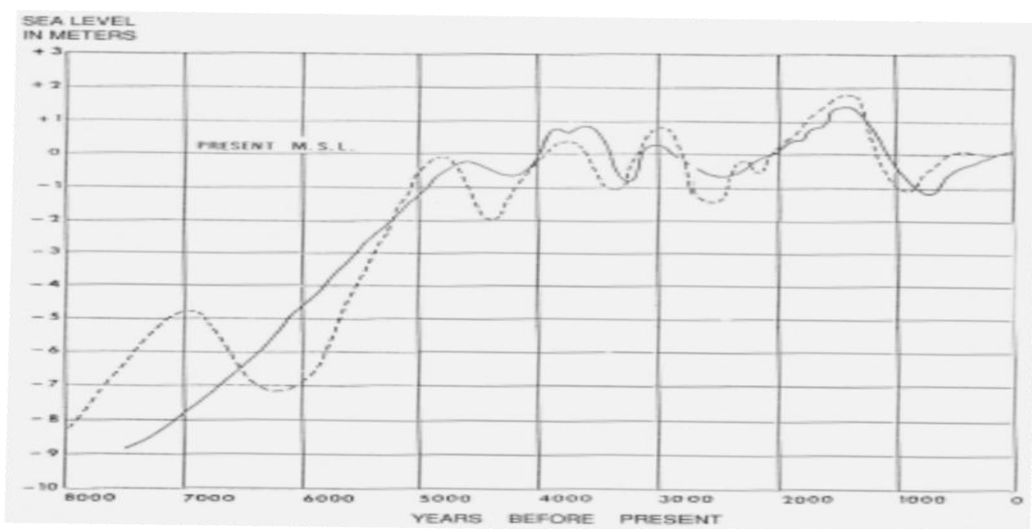


Figure 2-46 Sea level at Dor in Israel (shown with solid line) and sea level in the Mediterranean (shown with dashed line), after Raban, 1995.

Extensive *Dendropoma petraeum* reefs exist in Rizokarpaso (Figure 2-47) and Cape Greco. They are 30-40 cm thick with the upper 10 cm consisting of living organisms. This upper part is exposed during low tide and under water during high tide. With the tidal range being 30 cm in Cyprus, these thin dendropoma reefs are excellent past sea level indicators when found as fossils and can be easily dating using the ^{14}C method. These *Dendropoma petraeum* reefs are typical of warm-temperate areas like the Mediterranean Sea, their growth is restricted in the tidal zone which is very small (0.30 cm) in the Mediterranean, and they are very easily accessible (Antonioli et al., 2002)

Figure 2-47 Extensive *Dendropoma petreum* reef in Rizokarpaso.

A field reconnaissance study in the winter of 2012 with Prof. Dorit Sivan from the University of Haifa and Prof. Stella Demestica from the University of Cyprus had attempted to locate coastal archaeological sites with the potential to study the relative Holocene curve of the eastern Mediterranean. Sites such as the Kissonerga wells, the Tombs of the Kings in Pafos, the Pafos port and medieval castle, Palaipafos, Amathus polity and two ports, Larnaca salt lake and Hala Sultan Tekke, Kition Bamboula (Figure 2-48), and a few sites in Agia Napa were visited. Fish piscines in Lambousa, cut in calcarenite (Figure 2-49), are now located 1 m above the height in which it is believed they were initially functional (Dreghorn, 1981). The period during which they were functional was 400-700 A.D.

Figure 2-48 Archaeological sites like the ancient port of Kition – Bamboula presently located 4m above sea – level has potential for the study of the Holocene relative sea level curve of Cyprus.

Figure 2-49 Fish piscines in Lapithos (ancient Lambousa).

2.7 Conclusions

Previous suggestions were made that the marine terraces higher and including the 60m high terrace in SW Cyprus were Calabrian (1.81-0.78 Ma) (Xenophontos et al., 1994). What in this study is assigned to MIS 5 in Pafos, was previously believed to be Calabrian – Sicilian. Later, numerous studies had been done about marine terraces on Cyprus which mostly involved dated materials (Poole, 1992). The dated material was considered as significant for the elevation and the context in the stratigraphic column in which it was exposed. Coral heights were estimated by taking the sample height and considering some depth of water during life or deposition. Unfortunately, Cyprus does offer much opportunity for sampling in situ corals. The assumption for a sample depth and the use of the absolute height and age of the sample in determining uplift rates can carry a large error.

This study differs from previous work in that it builds an island – wide geomorphological analysis of terraces and marine deposits and looks at their horizontal extent, and most importantly, the position of palaeoshorelines. Palaeoshorelines, although difficult to find in the field, offer the best accuracy in sea level estimations because it is sea – level itself (Table 2-2, Ferranti *et al.*, 2006). In this study, palaeoshorelines were considered as the most concrete evidence for the existence of a sea – level highstand at a specific or uplifted elevation.

In this way the exact date of the sample was not used to date the exact elevation of its location. Instead, the terrace palaeoshoreline was assigned a date by correlating the duration of the MIS with the date of the sample. For example, a sample dated as 122,000 years old did not give an uplift rate of 0.20 mm/year for its 25 m elevation but a 125,000 age on the 27 m high palaeoshoreline resulting in an uplift rate of 0.22 mm/year. This example is not considering the +6 relative sea level for MIS 5e for simplicity in this argument. This method helps avoid errors based on estimations of sample depth, marine terrace thickness or water depth.

Upon establishing a map of terraces, features of marine platforms or marine deposits were assigned dates based on geochronology of any terrace along a profile that run perpendicular to the coast. In the absence of a geochronology sample, horizontal continuity of a MIS was attempted with adjacent terraces of similar elevation. In the absence of nearby data, terraces were assigned stages by first assigning MIS 5 to the lowest one. This last method was only applied in the far distant terraces of Akamas peninsula. Every sector of the coast shown in Table 2-6 has a geochronology date associated with it except Lemesos and the northern coast.

This method gave uplift rates ranging from zero to 0.65 mm/year. Pegeia and Pafos terraces predict the highest uplift rates in Cyprus for the Upper Pleistocene. The Pafos thrust fault mapped in detail (NEOCYP Consortium, 2005, Tsiolakis and Zomeni, 2008) is the driving force behind this documented uplift in southwestern Cyprus. Calculated uplift of 0.65 mm/year is indicative of the collision/subduction zone evident in the southwest of Cyprus.

3 Soil chronosequences on Quaternary surfaces of SW Cyprus

Quaternary uplift rates in southwestern Cyprus are the highest on the island. Numerous marine terraces have been exposed to subaerial processes and soil formation at least since the Ionian. Based on the above and the availability of published soil maps and soil memoirs, the experience with geological mapping in southwestern Cyprus and the excellent opportunity that southwestern Cyprus presents for Quaternary studies, it was decided to focus on this area for looking at age relationships between Pleistocene surfaces and the soils they host. As an alternative to expensive geochronology methods this section seeks to identify characteristics in the soil profile, to develop chronofunctions, which can then be attributed to the time factor of the soil-forming equation as proxy for soil age in future soil survey of Cyprus.

The study area (Figure 3-1) presents the most complicated coastal geology, both lithologically and structurally, in relation to other coastal areas in Cyprus. It extends from the town of Pegeia on the northewest to the town of Kouklia on the southeast and covers an area of 377 km^2. The work included field work, geological mapping, soil descriptions, soil development index calculations and finally, soil-age correlations.

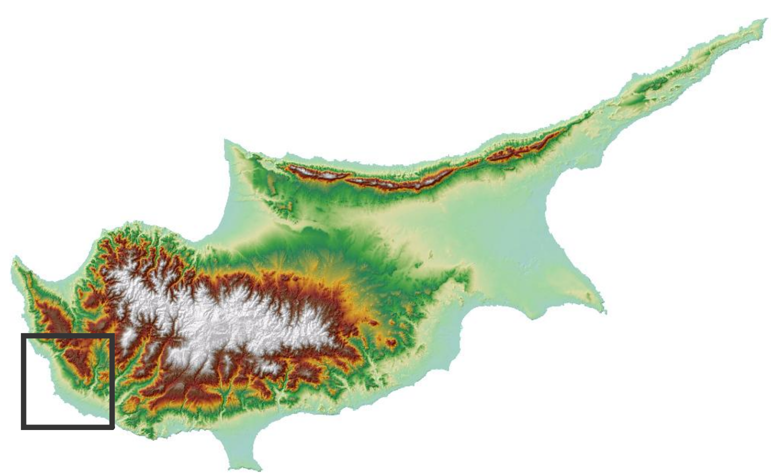


Figure 3-1 Study area for this chapter (377 km^2).

3.1 Main objectives

The reasons behind this study are that soil development is usually used as a relative method for dating Quaternary stratigraphy e.g. marine terraces. Here the opposite is attempted. Soil characteristics on dated marine terraces (Chapter 2) are used as a tool for understanding soil development in southwestern Cyprus. Southwestern Cyprus is the most seismically active area in Cyprus and the one that shows the greatest uplift (Chapter 2). Fast uplift has helped preserve numerous marine terraces that present a statistically meaningful set of data and observation points across the soil toposequence. The coast has been intensively mapped by the author (Tsiolakis and Zomeni, 2008) and presents a familiar place, which presents a coastal zone of uniform bedrock and surficial geology, thus minimizing parent material variability in soil formation.

The main objectives in this chapter are to:

- To present a thorough review of soils on the island of Cyprus,
- To collect and evaluate soil profile descriptions from uplifted marine terraces in southwestern Cyprus,
- To use soil properties in the development of soil chronofunctions and to explore the correlations of soil development over time on the dated marine terraces.

3.2 Main soil types on Cyprus

Soil survey mapping on the island has focused on the needs of agriculture - irrigation, land consolidation projects, land suitability, pasture and range, and watershed soil conservation. Most of the soil series maps are mapped on the 1:25,000 scale. Ten out of forty possible sheets have been mapped to date and are described in the following sections (Figure 3-2). The uniqueness of Cyprus soils is due to geological complexity, morphotectonics, its unique flavour of Mediterranean climate and the long presence of man, all of which lead to a diverse soilscape and geoecology.

Distributed on the landscape with close association to bedrock lithology, the soils of Cyprus vary between lithosols, leptosols, regosols, gypsisols, solonchaks, solonetz, vertisols, and cambisols based on the WRB (World Reference Base) of FAO (Food and Agriculture Organization of the United Nations) soil classification system (FAO, 1989). Detailed mapping has only been conducted for about 25% of the island, though a general soil map at 1:250,000 scale has been maintained for decades. Soils on the island of Cyprus are generally poor in organic matter (Koudounas, and Makin, 1981; Grivas, 1988) and closely associated to parent material and landscape position. The units shown in Figure 3-2 are only a generalized approximation of the soil diversity on the landscape.

Soil forming factors are all those environmental factors that contribute to the development of a soil. Jenny (1941) coined the equation:

$$\text{Soil} = \int clorpt,$$

Where cl=climate, o=organic matter, r=relief, p=parent material and t=time.

This section attempts to address the local soil-forming factors and present data, sometimes evidently insufficient for the understanding of local conditions pertaining to soil formation. It is here attempted to give a general view of what these soils are and what their formation is attributed.

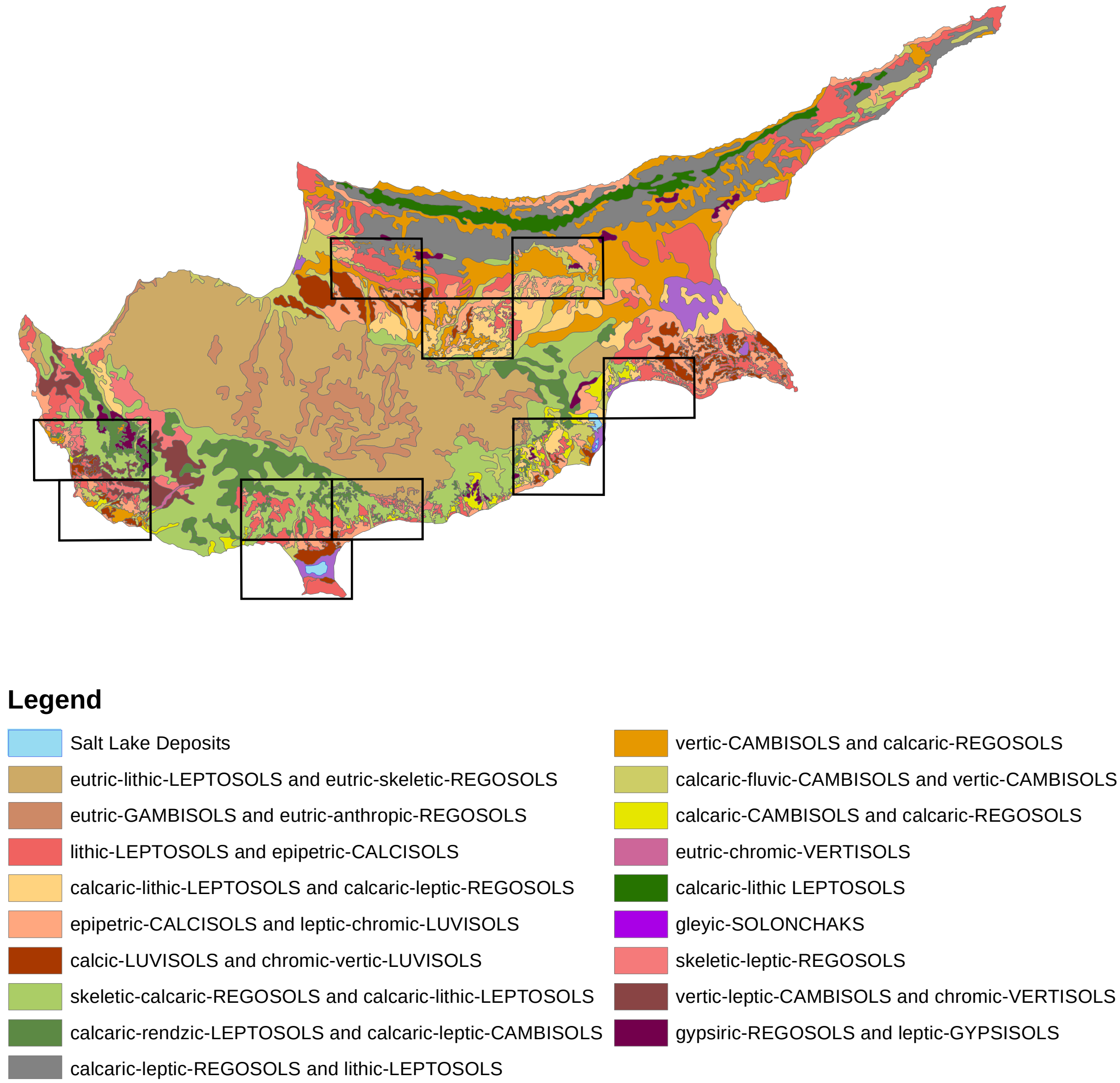


Figure 3-2 Soil map of Cyprus and availability of soil maps at the 1:25,000 scale (from the Soil Map of Cyprus (1999), by the Soil and Water Use Section, Cyprus Department of Agriculture).

Parent material varies between areas were soils form as residuum, that is they are formed in place from bedrock parent material, or were soils form on transported materials such as alluvial deposits (alluvial fans & deltas), colluvial deposits (slope deposits), aeolian deposits (sand dunes and desert dust), marine deposits (sands and gravels) and lake and estuarine deposits (silts and clays). Soil formation on the island is controlled primarily by parent material and landscape position and vegetation type. Table 3-1 shows the main soil associations on Cyprus and Figure 3-4 shows a simplified model of these associations.

Table 3-1 Main soil associations on Cyprus from the Soil Map of Cyprus, Soil and Water Use Section, Department of Agriculture (1999).

SoilType	Major characteristics and associations
calcaric-CAMBISOLS and calcaric-REGOSOLS	Forming in coastal river valleys which have numerous fluvial terraces with continous additions of alluvial and aeolian inputs
calcaric-leptic-REGOSOLS and lithic-LEPTOSOLS	Thin and calcareous soils on colluvium forming on the Kythrea Flysch of the Keryneia Terrane
calcaric-lithic-LEPTOSOLS and calcaric-leptic-REGOSOLS	Sandy soils on Gelasian sandstones of the Athalassa Member of the Nicosia Formation, gravelly and cemented sands, but may contain some associations of Pleistocene red soils
calcaric-lithic LEPTOSOLS	Forms in karst topography on Keryneia Terrane crystalline limestone outcrops
epipetric-CALCISOLS and leptic-chromic-LUVISOLS	Broad Pleistocene surfaces of marine terraces or fluvial fans with thick accumulations of calcium carbonate
calcic-LUVISOLS and chromic-vertic-LUVISOLS	Same as above but topped by thick and red soils (terra rosas) forming premium agricultural land
eutric-chromic-VERTISOLS	Clay-rich deep colored fertile soils forming on fluvial terraces and alluvial plains consisting of materials derived from clayey Mamonia Terrane lithologies
eutric-GAMBISOLS and eutric-anthropic-REGOSOLS	Formed on gravelly fluvial terraces and talus slopes on the Troodos mountains; terrace- produced anthropic soils on slopes
eutric-lithic-LEPTOSOLS and eutric-skeletic-REGOSOLS	Thin gravelly soils on Troodos Terrane diabase and gabbro lithologies and extrusive sequence, silty clay loams of 1.5-4.6% organic matter (Robins, 2004)
gleyic-SOLONCHALKS	Soils in Holocene marshes and estuaries, (“lichines country”), saline soils with a high water table, saturated most of the year, salt pan topography with salt-tolerant shrubs and grasses
gypsiric-REGOSOLS and leptic-GYPSISOLS	Formed on gypsum outcrops of the Messinian Kalavaso Formation, thin and poor for cultivation; mostly used for viticulture in Pafos region; regosols form on the slopes

Table 3-1 (Continued)

SoilType	Major characteristics and associations
lithic-LEPTOSOLS and epipetric-CALCISOLS	Infertile, stoney thin soils on steep and extensive slopes of the Circum – Troodos carbonate mountains; poor in organic matter
calcaric-rendzic-LEPTOSOLS and calcaric-leptic-CAMBISOLS	Forming on flat south-facing slopes in Pachna formation carbonate rocks (used to be referred to as rendzina soils)
skeletic-calcaric-REGOSOLS and calcaric-lithic-LEPTOSOLS	In association with the above but forming on slopes mostly on loam colluvium
vertic-CAMBISOLS and calcaric-REGOSOLS	Soils forming on young alluvium of the broad and flat Mesaoria plains; mostly used for growing cereals
calcaric-fluvic-CAMBISOLS and vertic-CAMBISOLS	Same as above but forming on older alluvial terraces; better developed horizonation, clay content and structure
vertic-leptic-CAMBISOLS and chromic-VERTISOLS	Soil catenas in Mamonia Terrane; deep colored soils on clay-rich formations; prone to landslides, poor agricultural value
skeletic-leptic-REGOSOLS	Same as above but thinner and undeveloped soils on slopes

Late Pleistocene and Holocene sediments on the Mediterranean island of Lampedusa are wholly sourced from carbonate rocks leading Giraudi (2004) to conclude that the considerable amounts of quartz in those sediments must derive from southerly winds blowing in from the African continent. Estimates of Saharan dust emissions vary between 500 and 1000 Tg / year, which is about half of the global total (Engelstaedter *et al*., 2006). Guerzoni *et al.* (1997) claim that at least during the Holocene, quartz is the main component of the Saharan dust that reaches the islands and deep waters of the Mediterranean Sea. Giraudi (2004) has laboratory data that show these quartz grains to be well-sorted, rounded to sub-rounded, translucent or with coatings of iron oxides.

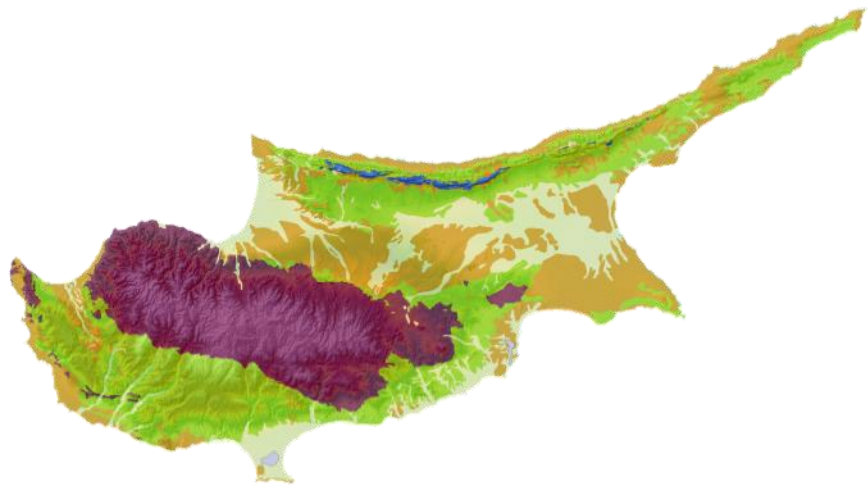


Figure 3-3 Soil parent material on Cyprus, includes ophiolitic rocks (purple), carbonate rocks (green), crystalline limestone (blue), Pleistocene fluviomarine terraces (brown) and Holocene fluviomarine sediments (yellow).

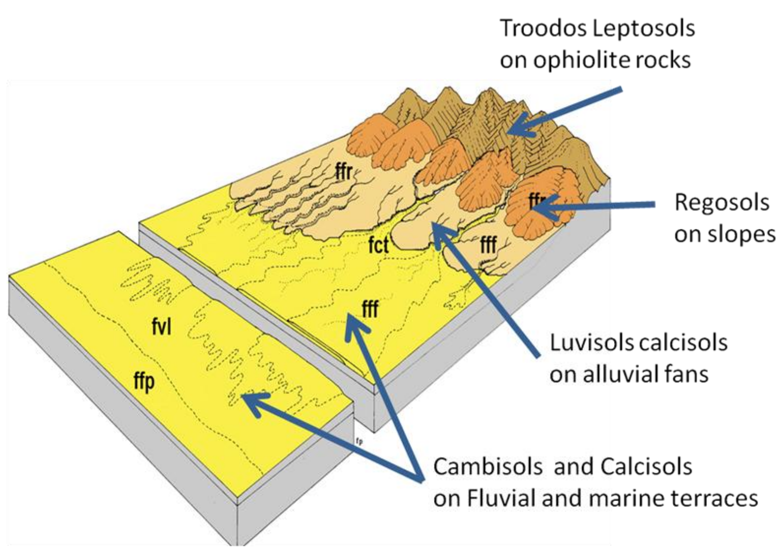


Figure 3-4 Simplified landscape – soil model for Cyprus with figure adapted from Peterson (1981). Map facies initials (e.g. ffp) refer to map units of Noller (2009).

The flux of Saharan dust to the north to Europe and to the East Mediterranean is estimated by Kubilay *et al.* (1997) to be about 100,000,000 tons a year, with an average surficial coverage (layer) of 20 µm per year (Yaalon, 1997). The most common modern dust storms arriving in Cyprus originate from the Saharan and Libyan sedimentary desert basins. Arid Saharan climate, supporting a desert barren environment, promotes surface dust to become airborne by turbulent winds. These winds are associated with shallow, warm, low pressure systems that occur during the spring season (Frumkin *et al*., 2004) or the cold low pressure Cyprus systems in the winter (Ganor and Mamane, 1982). Such dust storm sources probably shut off during wetter periods when vegetation cover hinders wind erosion. The most common transportation means for the dust is during spring storms associated with shallow warm low-pressure systems. Large events are mostly associated with cold winter Cyprus low systems, which are followed by rainfall, washing the dust directly into the soil column.

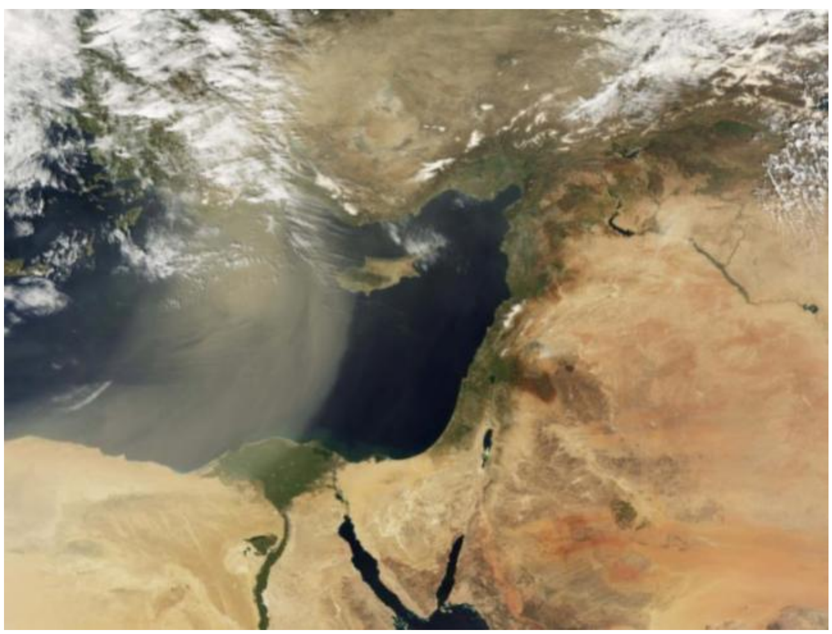


Figure 3-5 Image of dust storm in March 2008 as captured with no2 Spectroradiometer MODIS on NASA's Terra satellite, photo by NASA

Analysis of ocean and ice cores and loess sections have revealed a very dusty environment during the Last Glacial Maximum 20 ka (Goudie, 2009). This is attributed to greater aridity and the expansion of the deserts and the exposure of coastal areas due to significant sea-level fall. Dust storms are believed to have deposited 2-3 times more material during glacial times in relation to interglacial times (Mahowald *et al.*, 2006). Similarly dust storms show a decline during the African Humid Period (DeMenocal *et al*., 2000; Peck *et al*., 2004). In the eastern Mediterranean basin and north Africa, dust storms are most related to cold phases such as the Younger Dryas, Heinrich Events 1–7 and cold Dansgaard-Oeschger stadials (Moreno *et al.,* 2002; Pourmand *et al*., 2004; Jullien *et al.,* 2007).

Table 3-2 Bioclimatic zones of Cyprus (after Pantelas, 1996). M stands for the mean of the maximum temperatures of the hottest month in the year.

Altitude (m)	Bioclimatic zone	Precipitation (mm)	M (^{o}C)
<100	Semiarid hot	<400	>6
<100	Semiarid mild	<400	3-6
0-300	Hot arid	400-600	>6
300-400	Mild arid	400-600	3-6
400-900	Semi wet mild	600-900	3-6
900-1150	Semi wet cool	600-900	0-3
1150-1500	Cool wet	>900	0-3
>1500	Cold wet	>900	<0

At present, the Mediterranean climate is unique in that it is characterized by rainy, sometimes with excess rainfall winters and warm, dry summers with moisture deficits (Yaalon, 1997), a short and accurate description for climate on the island of Cyprus. The mean annual precipitation is 500 mm and occurs primarily in the months of February and March. The winter temperatures on the coast range from 0^{o} C to 25^{o} C and, from 25^{o} C to 45^{o} C in the summer.

The soil temperature regime on the coast is thermic and the moisture regime xeric. This climate was established about 2.3 million years ago as deduced from pollen data (Suc, 1984).

According to Rivas–Martinez bioclimatic classification, shown in Table 3-2, the island has a Mesophytic to Xerophytic–oceanian bioclimate with zones ranging from thermo–Mediterranean–semi arid in the lowlands to Supra-Mediterranean humid in the Troodos mountains (Barber and Valles, 1995, Andreou and Panayiotou, 2004).

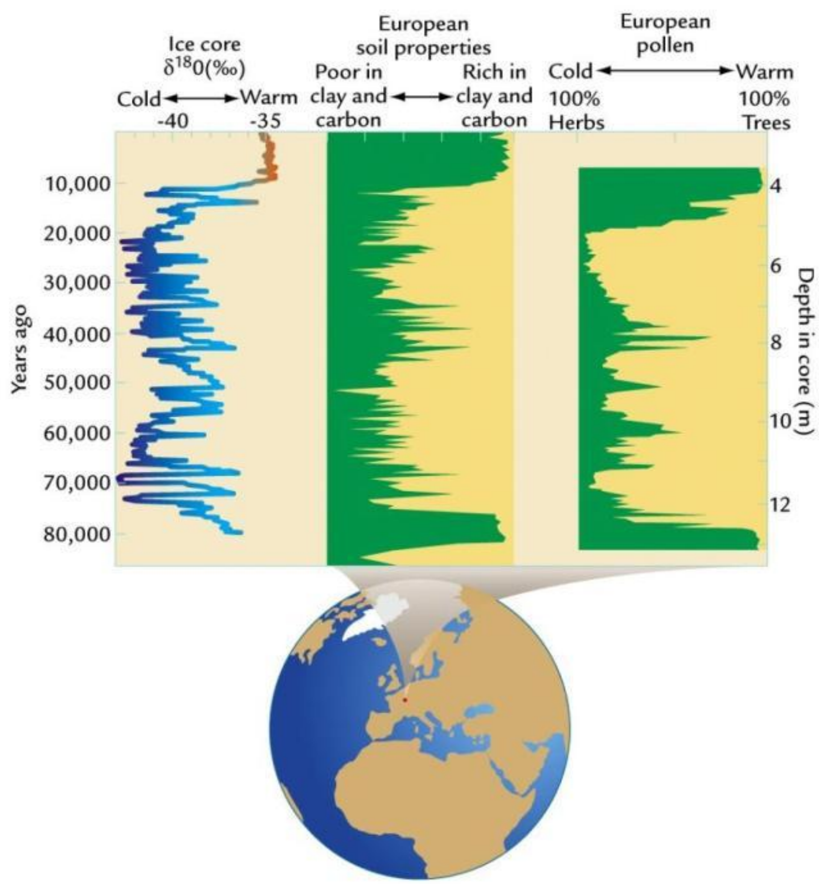


Figure 3-6 Soil clay and carbon accumulation relates well to vegetation and climate trends of the last 80,000 years (Ruddiman, 2001).

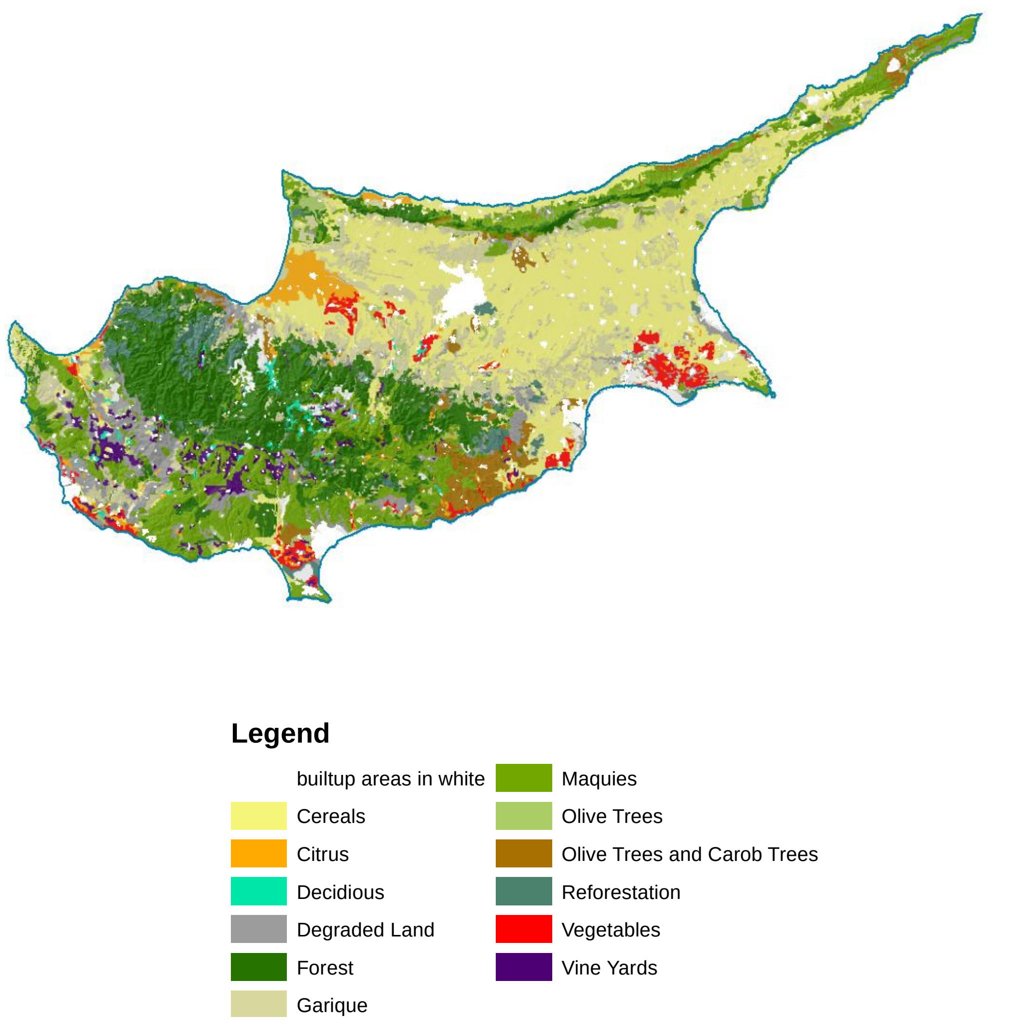


Figure 3-7 Vegetation map (Data from Ministry of Agriculture, Natural Resources and Environment).

Organic matter (plants, microbes, animals) is the most poorly known parameter in the soil forming formula for the soils on Cyprus. Cyprus soils are typically referred to as being "poor" in organic matter with little other characterization. Figure 3-6 shows the close correlation between $\delta^{18}O$, an excellent climate proxy with soil properties and pollen types for the European continent during the Upper Pleistocene and Holocene. Ice ages (and thus sea-level low-stands) are very well correlated to cold and dry conditions, leading to herb and shrub vegetation types, in contrast to wet and humid interglacial periods which correlate with the lowering of the tree line and enhanced soil development. Generally speaking, glacial epochs in the Mediterranean were characterized by Artemisia – dominated steppe environments, interstadials by forest steppe and open pine – oak forest and interglacials by mesic or evergreen oak forests (Tsedakis, 1993, Macklin *et al*. 2002). It is inferred that precipitation is the important climatic factor for this vegetation change with temperature change being of less importance (Macklin *et al*., 2002).

Table 3-3 Forest types according to Quezel classification (from Department of Forests, 2005)

Name in Quezel classification	Local description of forest type	Predominant areas of occurrence
Olea and Ceratonia Maquis	Thermophylic wild olive and carob	From sea level to 600m, from Akamas to southern Troodos foothills and the northern Pentadaktylos range
Mediterranean Conifer forest of Calabrian pine and Phoenician juniper maquis	Juniper with olive and carob	From sea level to 450m elevation, in Akamas, Episkopi, Akrotiri, Cape Kormakiti, Cape Greco and Karpasia
Sclerophyllous evergreen forest of golden oak and Kermes oak	Golden oak	From 400 – 1700 m elevation on steep slopes, typically on talus slopes in Troodos ophiolite rocks,
Deciduous riparian forest and semi-deciduous oak woodlands	Oriental plane, alder, white willow	Along streams, rivers, confined to valleys between 600-1100 m elevation
Mountain forest of Cyprus cedar and black pine	Endemic cedar, black pine and firs	Highest peaks of Troodos and Tripylos forest in Pafos forest
Oro-Mediterranean stage stands of arborescent junipers	Stinking and Grecian Juniper	Highest peaks of Troodos mountains (Chionistra 1700 -1952m elevation), Madari and Papoutsa (1400-1650m)

Dry, poorly vegetated North African deserts would increase their dust flux to the Mediterranean during these colder periods, creating sandy accumulations intercalating with red soils of the warm interglacial periods. Accumulation of loess deposits in the northern Negev desert during the last glacial period (Magaritz, 1986) and increased deposition of desert dust particles in Lake Lisan during the same period (Haliva *et al*., 2003) support the hypothesis that glacial periods are characterized by increased dust transport (Frumkin and Stein, 2004). Such interpretations have also been made by Fedoroff (1997) when studying clay illuviation on chronosequences of red Mediterranean soils in Morocco.

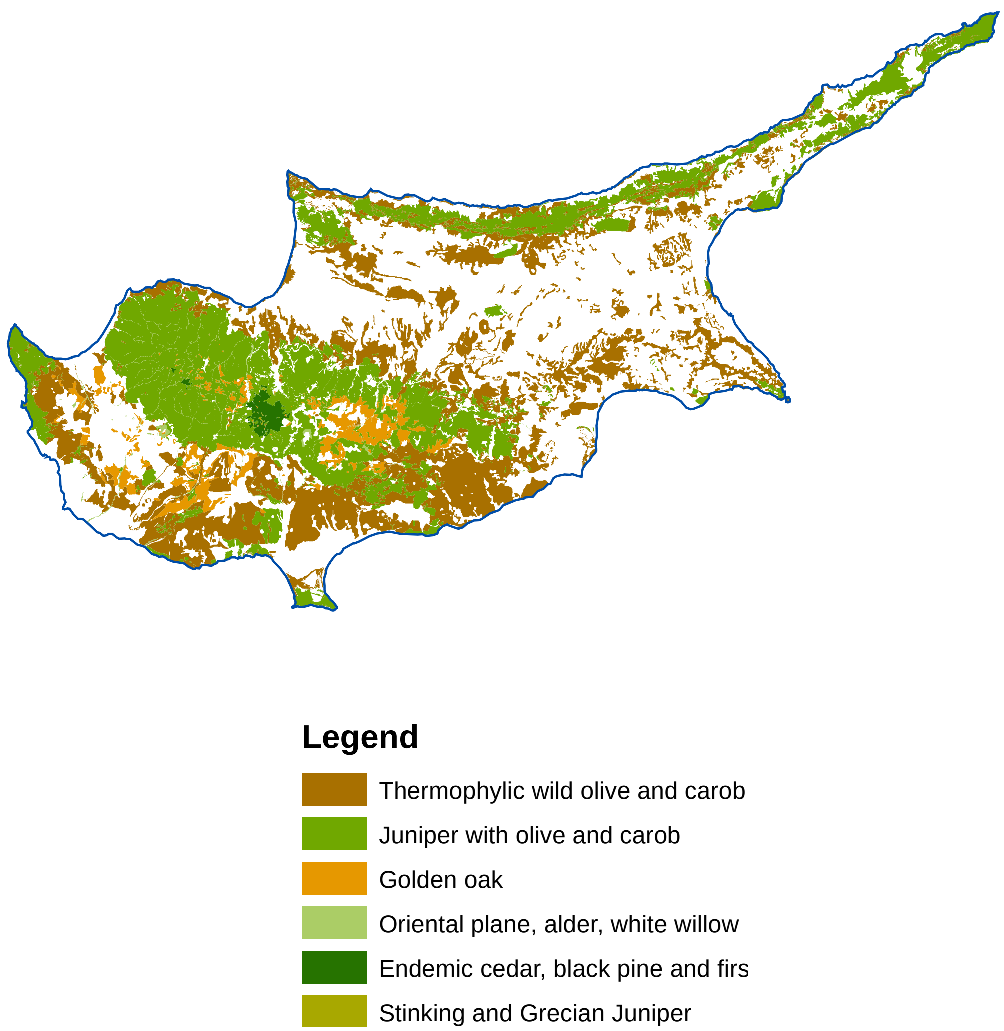


Figure 3-8 Cyprus forest types as listed in Table 3-3.

3.3 Methodology

3.3.1 Geological and soil data

It was important to compile a geological map of the study area in order to evaluate soil development and thus soil age to parent material. The Geological map of Achelia - Kouklia by Xenophontos *et al.* (1994), Agia Varvara –Pentalia by Malpas *et al.* (1999) and an unpublished map by Turner (1971a) served as a bedrock geology reference base for part of the study area. Further geological mapping was needed to cover unmapped areas between Achelia and Pegia and as far north as Kallepeia. This was an area never mapped before mainly due to the fact that it presents together with the northern sheet (Pegeia – Steni) the most geologically complicated areas in Cyprus, both lithologically and tectonically.

In the light of a microzonation study for the expanding broader urban area of Pafos and suburbs, it was considered that a geological map was needed for strategic reasons. The Geological map Pafos - Kallepeia by Tsiolakis and Zomeni (2008) was a publication that resulted from joint field mapping conducted between 2005 and 2007. Field experience with geological mapping in the coastal zone of southwestern Cyprus later proved important for understanding the geology, tectonics and thus understanding the Quaternary landscape development of the study area especially at the coastal zone. My geological mapping paid special attention to the Quaternary sequence of numerous fluvial and marine terraces and alluvial fan deposits that top the marine terrace calcarenites.

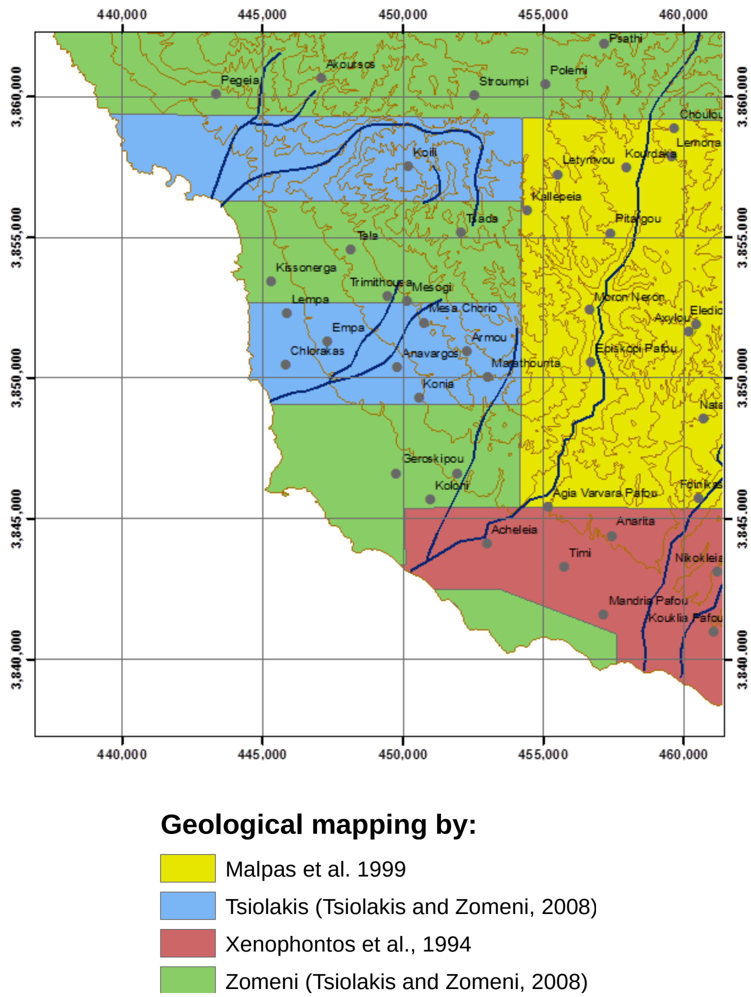


Figure 3-9 Geological Mapping conducted in the area by various authors

Two soil maps were digitized and attributed in southwestern Cyprus, the Pafos Soil map (Soteriades and Koudounas, 1968) and the Polemi Soil map (Markides, 1973). These two soil maps are the only soil map publications accompanied by memoir publications. This means that all the data regarding soil mapping, map unit descriptions, permeability testing and many soil profile descriptions and chemical analyses are included in two invaluable memoir publications. The data were input into an excel file and a GIS database in order to facilitate analysis.

3.3.2 Estimating relative soil age

The main objective was to develop a methodology by which the approximate age of a surface or a soil column can be estimated by using relative or correlation methods. A similar approach in the same study area was taken by Deckers (2002, 2003) and Deckers *et al.,* (2005) using a simplified thermoluminescence method on pottery sherds in fluvial sediments of Diarizos, Xeros and Ezousas river.

Table 3-4 Assignment of development number for the 5 items refered to in soil subseries descriptions

Descriptive item	**Assigned number**			
	1	**2**	**3**	**4**
Depth	shallow	Mod.deep	deep	Very deep
Color	Grey and yellow	/	brown	red
Clay content	No Bt horizon	/	/	Bt horizon
Petrocalcic horizon	/	/	havara	kafkalla
Degree of development	undeveloped	/	/	developed

It is assumed that certain characteristics prevail as the soil-forming processes are taking place. Soil development, i.e. the degree of horizonation, melanization, rubification, structure, consistency and accumulation of calcium carbonate, should be a function of time, just like Entisols develop into Inceptisols and eventually Aridisols in the semi - arid Mediterranean. Soil taxonomy itself classifies soils depending on soil characteristics which usually pertain to degree of soil development and thus age, especially in the USDA system of taxonomy. Soil series by themselves, with soil descriptions can be used to extract useful information about landscape development. Such an approach was taken in section 3.4.3. Table 3-4 shows how numbers were assigned to soil subseries according to these descriptive characteristics. The numbers were summed for each polygon to generate a new polygon map showing a summed-up unitless development index.

This approach was then taken further for a second approximation where the characteristics of a soil profile can be assigned numerical descriptors and eventually be entered into a kind of accounting system by which a total “degree” of development can be calculated. This development index, a unitless number can be utilized as a fast, easy and low-cost method for acquiring relative ages of soils. The soil Profile Development Index (PDI) developed by Harden (1982) is one such method. In this study a soil database was developed, soil profiles were described, sketched and photographed at various locations in the coastal region of the study area. Profile descriptions from the Pafos Soil map (Soteriades and Koudounas, 1968) and the Polemi Soil map (Markides, 1973) were added to the soil database.

Table 3-5 Properties used in calculating PDI (modified from Birkeland et al., 1991).

Process	**Soil property**
rubification	10 points for increase in hue and 10 points for increase in chroma
Color paling	10 points decrease in hue and 10 points decrease in chroma
melanization	10 points decrease in value
Color lightening	10 points increase in value
Texture change	1 point for every step towards a finer texture on the texture triangle
structure	1 point for every step towards a blocky and then prismatic structure
consistence	1 point for every step towards a firmer and/or harder consistence
carbonates	1 point for every step of stage development according to Machette (1985) shown in Table 3-6

The system used to calculate the PDI for each profile is that recommended by Birkeland *et al,* (1991) in which each property is assigned a number depending on the degree of change between soil and parent material. Properties such as texture, color, structure, Bt horizon, calcium carbonate accumulation features and parent material were used in this accounting system shown in Table 3-5.

These properties (Table 3-5) are always in relation to parent material and are calculated separately for each profile horizon. The numbering system between properties is not important to be kept consistent because the results for each property are then normalized to the maximum observed value. In this way, the profile with maximum rubification will be assigned a value of 1 for that property in that horizon. The normalized values are then added for each horizon and divided by the number of quantified properties used for that horizon. It is important here to introduce the factor of horizon thickness, where a thick horizon indicates more aging. The added normalized values are multiplied by the horizon thickness. Finally, the PDI for each point on the landscape is the sum of all these values for each soil profile. These calculations were conducted in an excel spreadsheet for 582 horizons for a total of 207 locations and then imported as point data in the ARCGIS environment.

Special attention was given to profiles located on raised marine terraces. It was important to avoid urban areas, areas of intense cultivation, and any surfaces that could be hosting materials attributed to surficial processes such as recent slope or anthropogenic processes. Surfaces in Chlorakas village were intentionally avoided because of known old practices of transferring soil in the making of market – garden land especially for the growth of vegetables (Christodoulou, 1959). From field work during geological mapping it is evident that this practice continues with the transfer of clay–rich sediment for the Mamonia Terrane in making new moisture-retaining soils for the growth of banana plants.

Table 3-6 Stages of Calcium Carbonate morphology (after Machette, 1985)

Stage	Gravel content	Diagnostic morphologic characteristics	$CaCo_3$ distribution	Maximum $CaCo_3$ content
Calcic soils				
I	High	Thin discontinuous coatings on pebbles, usually on undersides	Coatings sparse to common	Traces - 2
	Low	A few filaments in soil or faint coatings on ped surfaces	Filaments sparse to common	Traces - 4
II	High	Continuous, thin to thick coatings on tops and undersides of pebbles	Coatings common, some carbonate in matrix, but matric still loose.	2 - 10
	Low	Nodules , soft, 0.5 cm to 4 cm in diameter	Nodules common, matrix generally noncalcareous to slightly calcareous	4 - 20
III	High	Massive accumulations between clasts, becomes cemented in advanced form	Essentially continuous dispersion in matrix (K fabric)	10 - 25
	low	Many coalesced nodules, matrix is firmly to moderately cemented	Essentially continuous dispersion in matrix (K fabric)	20 - 60
Pedogenic calcretes (indurated calcic soils)				
IV	Any	Thin (<0.2 cm) to moderately thick (1 cm) laminae in upper part of Km horizon. Thin laminae may drape over fractured surfaces	Cemented platy to weak tabular structure and indurated laminae.K horizon is 0.5 – 1 m thick	>25 in high gravel content >60 in low gravel content
V	Any	Thick laminae (>1 cm) and thin to thick pisolites. Vertical faces and fractures are coeted with laminated carbonate (case – hardened surfaces)	Indurated dense, strong platy to tabular structure. Km horizon is 1 – 2 m thick	>50 in high gravel content >75 in low gravel content
VI	any	Multiple generations of laminae, breccias, and pisolites; recemented. Many case - hardened surfaces	Indurated and dense, thick strong tabular structure. Km horizon is commonly >2 m thick	>75 in any gravel content

A third approximation was attempted with using characteristics and degree of carbonate accumulation similar to the system proposed by Machette (1985). It is hypothesized that calcium carbonate accumulation progresses with time forming gravel coating, nodules, laminations and calcrete crusts (Machette, 1985). These characteristics are very distinct on the landscape of Cyprus. A descriptive method was adapted to the conditions observed in southwestern Cyprus and a matrix was assembled in which different stages of carbonate accumulation are described based on field observations. The type of carbonate accumulations that are included under each stage were observed repeatedly to occur together and thus suggesting similar time progression.

3.4 Results

3.4.1 Geology of southwestern Cyprus

In the Pafos area, the Troodos Terrane is juxtaposed with the Triassic-Cretaceous rocks of the Mamonia Terrane, forming a wide arcuate tectonic belt which can be traced along the southwestern part of Cyprus, from the Akamas peninsula in the west to the Diarizos river basin and Petra tou Romiou in the east. Mamonia Terrane rocks are exposed through erosional windows in the overlying Tertiary sedimentary rocks. Such windows are found in the Mavrokolympos river basin in the northwest and the Marathounta valley in the southeast.

The sequence of the Mamonia lithologies range in age from the Upper Triassic to the Lower Cretaceous and represents a melange that was accreted onto the hanging wall of a north-dipping subduction zone above which the Troodos ophiolite formed 90 million years ago. Subsequent collision of this subduction zone with the neighbouring Arabian Plate in the Maastrichtian was accompanied by an anticlockwise rotation of the Troodos Terrane. This rotation led to the juxtaposition of Troodos rocks with the Mamonia which further complicated the geologic structure now generally accepted as being a suture zone between the African and Eurasian Plates.

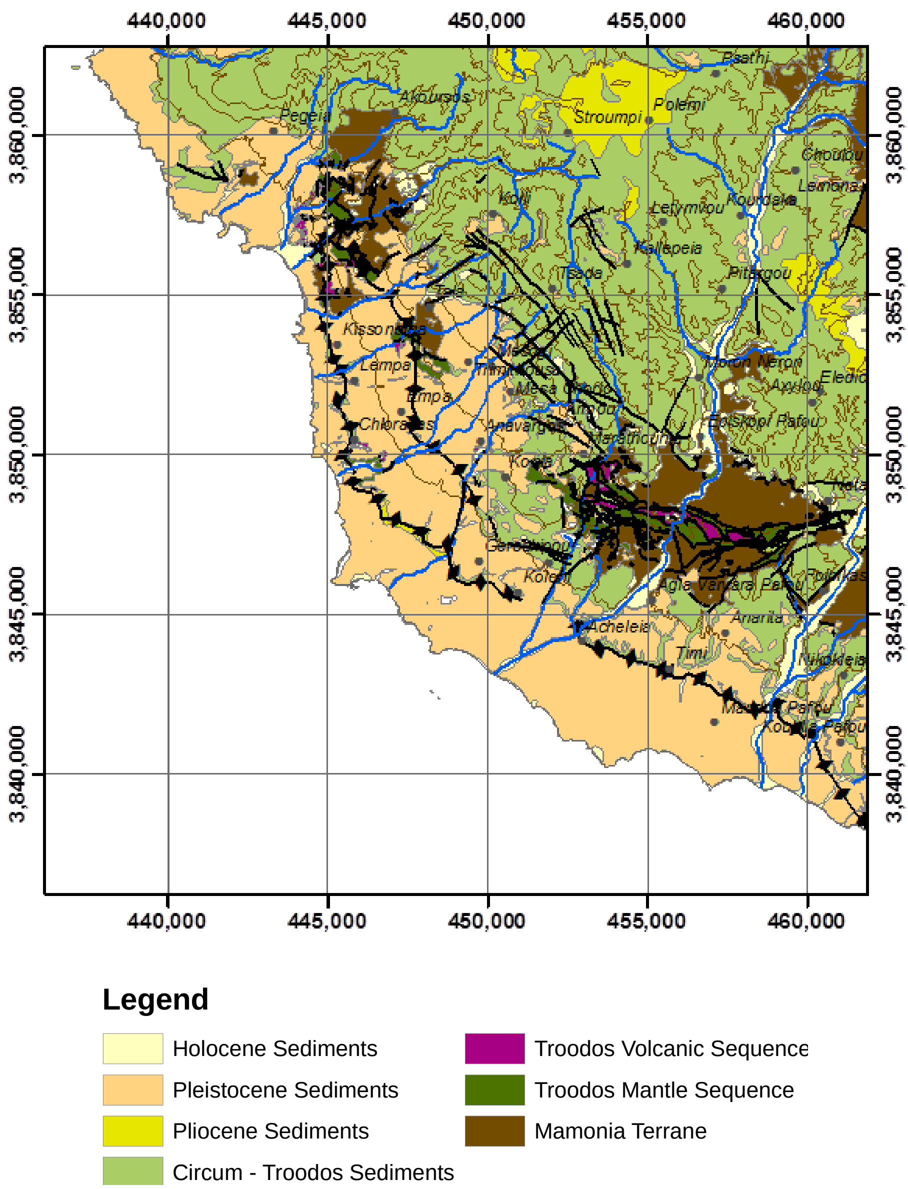


Figure 3-10 Simple geological and tectonic model of the central study area (adapted from Tsiolakis and Zomeni, 2008). Pafos thrust fault shown with a diamond symbol line. Other secondary faults shown in simple line.

The stratigraphic subdivision of the Mamonia Terrane poses problems. However, two main groups can be recognised. The Agios Fotios Group is a series of Upper Triassic – Lower Cretaceous sediments consisting of quartz sandstones, shelf and hemipelagic limestones and pelagic siliceous sediments. The Diarizos Group is an Upper Triassic – Lower Cretaceous volcano-sedimentary sequence of extrusive (pillow lavas) and minor intrusive rocks with some sediments. The Agia Varvara rocks represent Diarizos Group lithologies metamorphosed to amphibolite facies during the Campanian.

Upper Cretaceous bentonitic clays of the Kannaviou Formation, and predominately Paleogene deep marine calcareous sediments and cherts (Lefkara Formation) overlay the Troodos and Mamonia Terranes. Shallow water carbonates (Tera Member) mark the boundary between the Lefkara and Pachna Formations and present evidence for shallow seas in the Lower Miocene. Miocene Pachna Formation chalks and marls indicate a hemipelagic depositional environment. During the Messinian Salinity Crisis in the Mediterranean, gypsum and gypsiferous marls (Kalavaso Formation) were deposited onto the Pachna Formation in a basin immediately to the north of the study area. An early Pliocene Mediterranean basin transgression initiated the deposition of the Nicosia Formation marls. Subsequent Pleistocene uplift and sea level fluctuations laced the landscape with remnants of uplifted marine terraces and alluvial fans.

The major tectonic contacts within the suture zone do not show signs of reactivation in the Quaternary, at least at the surface. Quaternary deformations are mainly located along the coastline, in a zone almost parallel to the suture zone. They correspond to a major, blind thrust system extending from the Mavrokolympos fault in the northwest to the Diarizos river tributaries in the southeast. It is mostly sealed by Pleistocene deposits and ruptures the surface in a zone that extends from the village of Agia Marinouda to Kouklia in the form of an anticline. Figure 3-10 presents a geological map of this part of Cyprus and shows Pleistocene, Pliocene and older sediments (Pachna, Lefkara and Kalavaso Formations) in three separate simplified units.

3.4.2 Soils and geomorphology

Akamas remains the only undisturbed area on the island of Cyprus and is now protected with the status of a nature reserve. It is mostly uncultivated and is covered by maquis vegetation consisting of some pine trees, juniper, pistacia in the coastal parts and more woody forests at higher ground (Markides, 1975). One cannot help but want to believe that the landscape and vegetation of Akamas must have extended to Pafos and Kouklia before man started to cultivate its lowlands. These coastal lowlands consist of three prominent and broad marine terraces (MIS 5, MIS 7 and MIS 9-11) that host most of the local population. These marine platforms are topped by broad and thick alluvial fan deposits, especially MIS 7, referred to as fanglomerates in the northwestern part of Cyprus.

The intermediate elevations of carbonate lithologies form steep slopes with in many places unstable ground, thin soils mostly Regosols and Lithosols on terraced country (Pachna soil series). It presents difficult mobility for the locals and no villages have ever been established in this territory. It is mostly used for agricultural activities, usually of terraced ground. The northeastern part of the study area consists of Messinian gypsum and Pliocene marl deposits in flat plateaus sometimes topped by eroded remnants of marine terrace calcarenites.

Soils in the study area are very closely related to parent material, the underlying geology; they are often refered to as geo-genetic, that is, their genesis is closely related to the geology. This is especially evident in the two erosional windows where Mamonia Terrane rocks are exposed in an arcuate mélange zone along with Troodos serpentinites and lavas. These vast areas have moon-like geomorphology, the differential erosivity of the clay rich Mamonia lithologies with the hard bedrock lithologies of the ophiolite terrane create difficult ground and make it impossible for cultivation. Soils here are thin and lithic (, they are mostly undeveloped soils with thin colluvial cover.

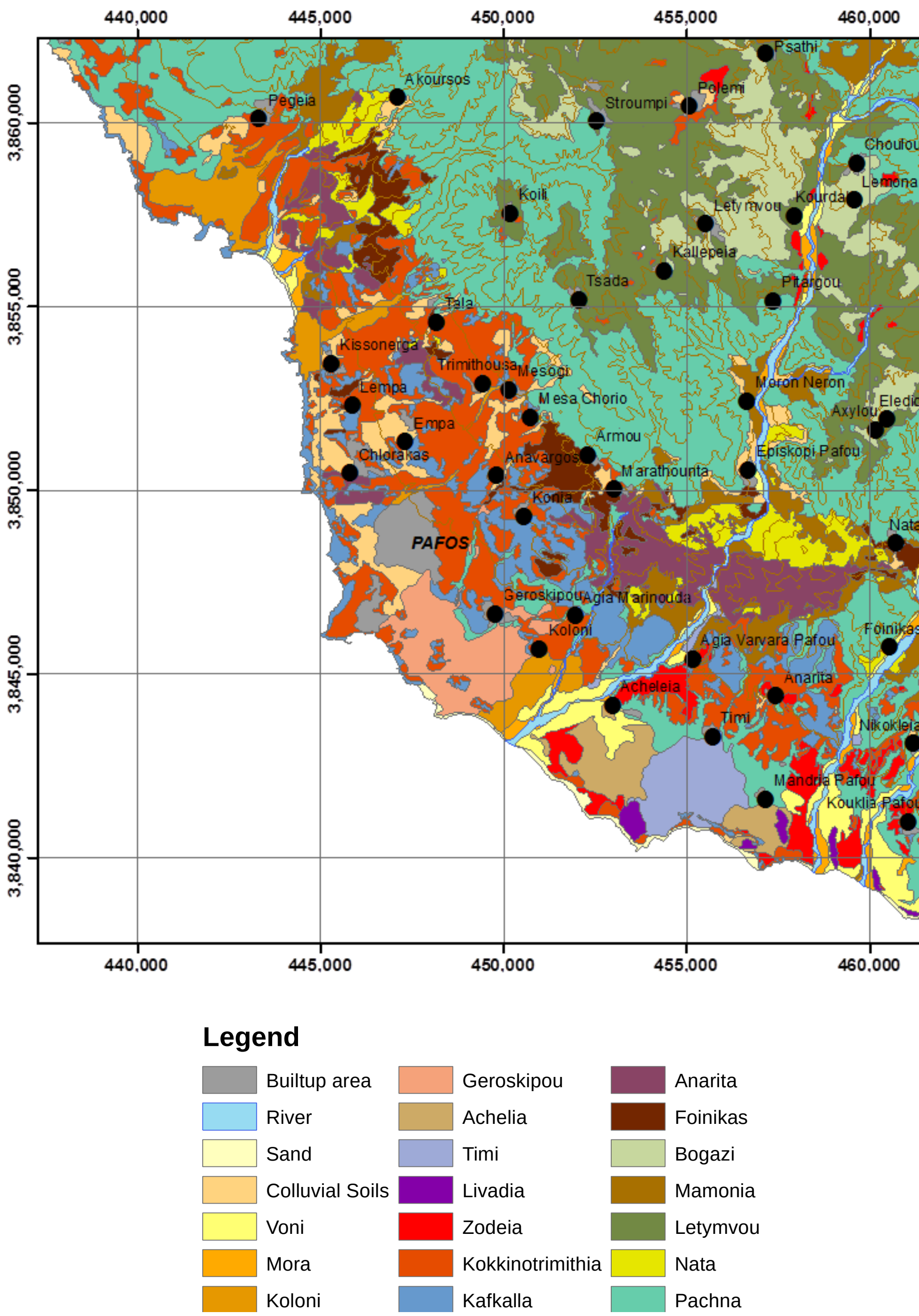


Figure 3-11 General Soil Series map of the study area, a generalized map of 777 polygons compared to 2090 polygons in the original map.

On the lower plateaus the rivers emerge from this terrain of Mamonia and carbonate lithologies into the lower plains and form alluvial terraces and alluvial fans. Some of these Pleistocene alluvial fans are capped by kafkalla. At small depths they have havara characteristics, carbonate nodules and pedogenic carbonate coated – pebbles. All of these characteristics together constitute these lanforms as resistant landforms which persist on the landscape. These calcretes (Kafkalla soil series) which usually exist in association with red soils (Kokkinitrimithia soil series) are the main focus for this study. Figure 3-11 and Table 3-7 summarize the distribution of soils and their main characteristics and associations.

Table 3-7 Main Soil Series in southwestern Cyprus with general characteristics.

Soil Series	Parent material and Soil and landscape Characteristics
Soils on surficial sediments	
Sand	Late Holocene aeolian sand in coastal regions; dunes mostly stabilized by vegetation and greatly disturbed my human activity;
Colluvial soils	Thin soils formed on gravelly slope and talus deposits
Voni (V)	Deep, heavy undeveloped soils on alluvium with a distinct buried well – developed soil at 50 cm depth showing burial of a 25-30 cm thick soil at some time which contains havara and carbonate nodules
Mora (M)	Sandy loam soils, 1 m deep forming on alluvial and fluvial terraces; show palaeohydromorphic features at depth
Koloni (KL)	Soils on thick alluvial material, undeveloped, covering havara layers at 25 cm depth, mostly developing on uplifted river gravel deltas of the Pegeia and Ezousas rivers
Geroskipou (YE)	Sandy (10%), porous soils over soft havara layers
Achelia (AH)	Deep developed soils with Bt horizon on top of a havara horizon
Timi (TI)	High density, impermeable soils consisting mostly of clay with no distinct horizonation; containing clasts from Mamonia and carbonate lithologies; contains carbonate nodules

Table 3-7 (Continued)

Livadeia (LI)	Solonetz vertisols having a natric B horizon; fine textured alkaline soils throughout, having a water table close to the surface; Hydromorphic soils, adjacent to river beds and deltas
Zodeia (Z)	Deep, dark, fine-textured soils with Bt horizon having a strong medium to coarse prismatic or blocky structure; some slickensides as well as cracks. A calcic horizon is present and the soil rests on Pleistocene alluvial fans and deltas with ophiolite lithologies
Kokkinotrimithia	Red soils (terra rosas) with Bt horizon covering kafkalla and havara outcrops (petrocalcic horizons) on plateaus, Calcaric Luvisol
Kafkalla (K)	On all lithologies, these are thick sometimes unrippable petrocalcic horizons on mostly flat surfaces of marine terraces; can be classified as an extensive Calcaric Lithosol which is exposed all over the island
Soils on sedimentary and igneous rocks	
Anarita (AN)	Regosols on Troodos ophiolite lithologies
Foinikas (PH)	On clay rich lithologies of Kannaviou Formation, they are green-colored, clay - rich Vertisols, in badlands and landslide-prone areas
Boghaz (B)	Gypsisols; medium textured soil; slightly saline and fairly high infiltration rate; on high altitudes; forming on gypsiferous rocks of the Kalavasos Formation; on slopes and cultivated mostly with vines
Mamonia (MA)	Clay - rich soils; deep to very deep; very heavy greyish brown to brown soils; overlying clays of the Mamonia Terrane formations and usually taking on the color of the parent rock.
Letymbou (LE)	Extremely calcareous soils ($CaCO_3$ >40%) generally overlying soft calcareous sediments like marly deposits of the Nicosia and Pachna Formations
Nata (NA)	Sandstones of the Mamonia Terrane; restricted to formations rich in clay or other unconsolidated non-calcareous material of the Mamonia Formation
Pachna (PA)	Calcareous soils on chalks and limestones of the Pachna Formation; a stony soil with $CaCO_3$ > 40% on hard limestone; classified as regosols

It is worth noting that the soils of Figure 3-11 and Table 3-7 are further subdivided in subseries. Each series has a range of subseries with as many as seven, their division based on characteristics of soil depth or complexity of soil horizonation.

3.4.3 Development Index, a first approximation

Five datasets were generated based on characteristics of soil subseries, depth, color, clay content, carbonate accumulation, and degree of horizonation. Results are presented in maps in the following five figures.

Deep soils (Figure 3-12) dominate the coastal lowlands and more specifically the alluvial flats on the wide flood plains like the Ezousas rive and the marine terraces, especially MIS 5e. Some deep soils form on the uplands of flat Messinian and Pliocene sediments which represent uplifted terrains. Mamonia sediments and Mamonia mélange is here interpreted as a deep soil but actually these soils are really undeveloped saprolite in these clay rich lithologies.

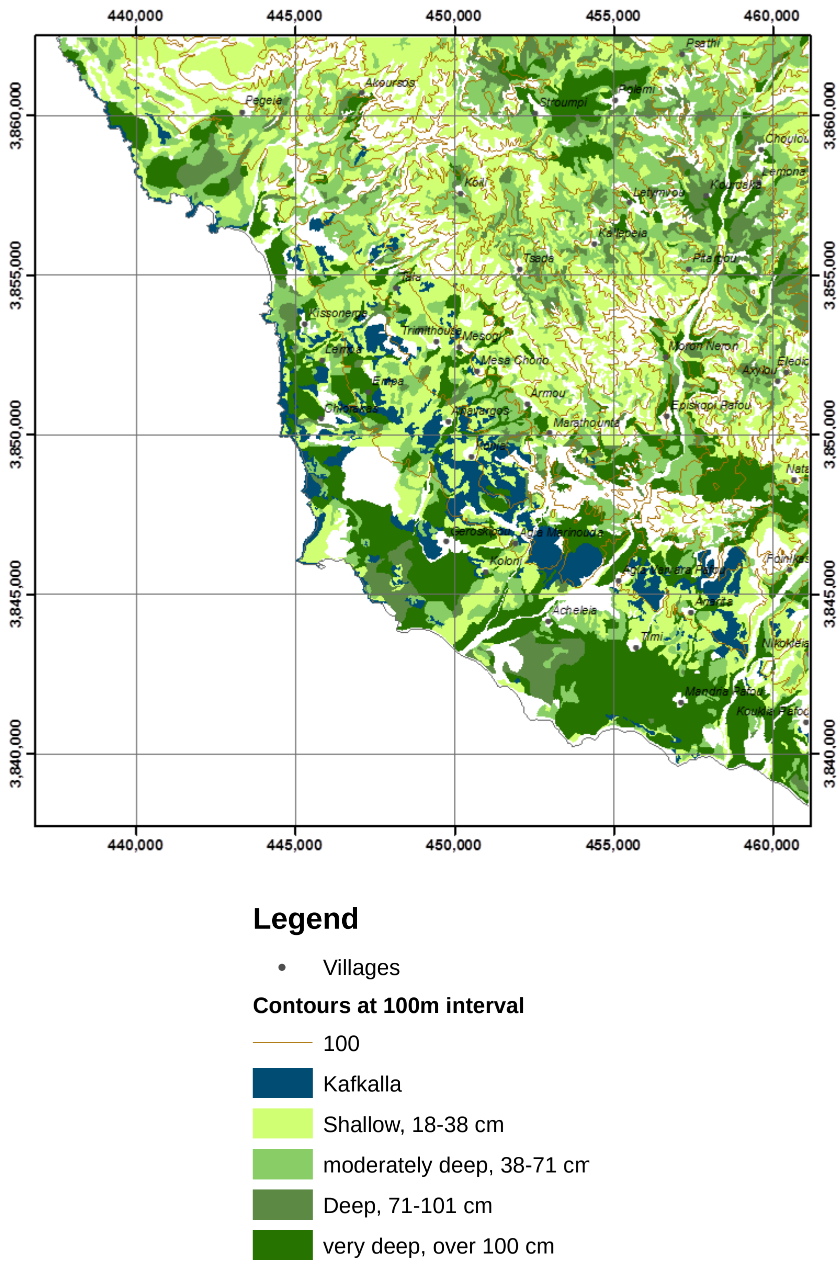


Figure 3-12 Soil-profile depth independent of soil series, blue shows exposed kafkalla.

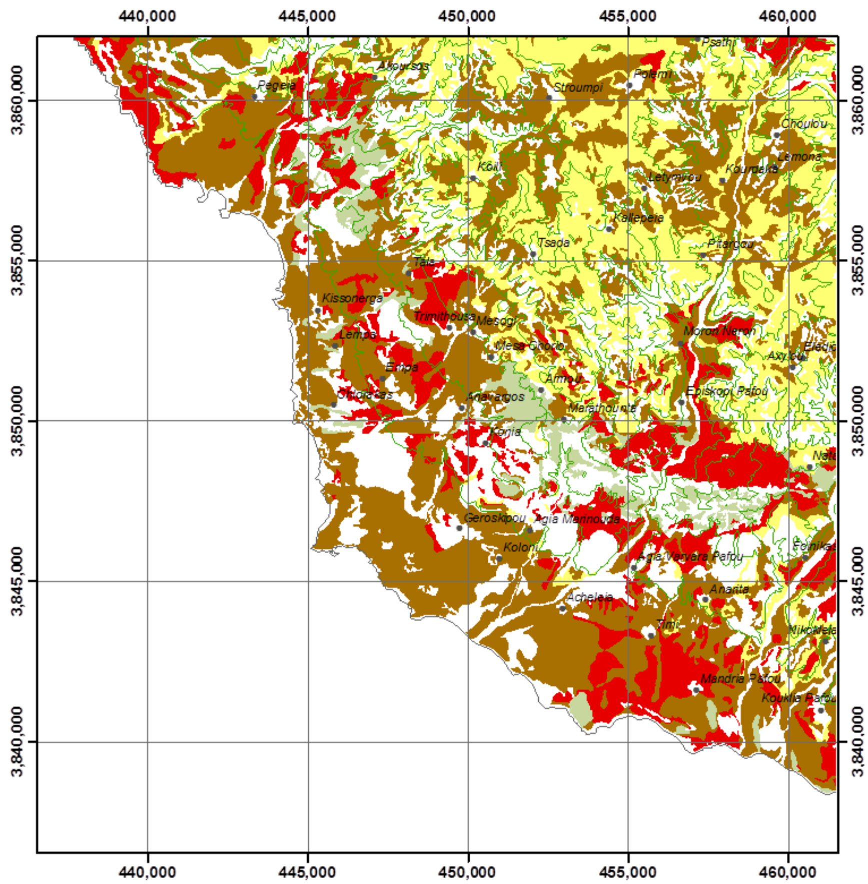


Figure 3-13 Classification of soils based on color. Printed color corresponds to the hue class of the red, brown, grey and yellow soils.

The same interpretation stands for these soils with respect to their color (Figure 3-13), the Mamonia clays are very deep red and brown mudstones misinterpreted by this simplification as soils that exhibit rubification and melanisation. Yellow soils predominate on the carbonate slopes of the Messinian Pachna Formation chalks and marls. Grey colored soils are mostly thin and stoney soils (leptic lithosols and lithic leptosols) of Anarita soil series forming on Troodos ophiolite lithologies like serpentinites, pillow lavas and other ultramafics.

Red and brown soils are mostly found on the Pleistocene coastal landforms. Kokkinotrimithia (Figure 3-14) and Timi soils series show the highest values on the color scale. Red colors of the Timi soil series is again here attributed to their connection to Mamonia clays and mudstone lithologies (Table 3-7). Numerous sections into this coastal soils were recorded in Pegeia nad Mandria beaches.

Figure 3-14 Red Kokkinothimithia soil series (luvisols) on MIS 5 terrace on the coast of Pegeia.

Clay content for upland soils seems to be directly related to bedrock geology, Pliocene marls of the Nicosia Formation, bentonitic clays of the Kannaviou Formation and Mamonia Terrane lithologies, mudstones and the mélange (Figure 3-15). These lithologies give soils of high clay content but not necessarily Bt horizons. Good Bt horizons exist on the alluvial and marine terrace soils especially on the MIS 5e terrace. On the MIS 5e terrace are a series of MIS 5a - MIS 5d aeolianites almost completely bare of any soil cover. These areas exist in a coastal zone between Pegeia, the Hellenistic town of Nea Pafos (itselt build on this aeolianite sequences) and going east all the way to the Pafos airport at Cape Zephyros. Behind these landforms small but notable depocenters of MIS 4-MIS 1 aeolian, fluvial and gravity deposits have provided parent materials for the formation of red soils with Bt horizons.

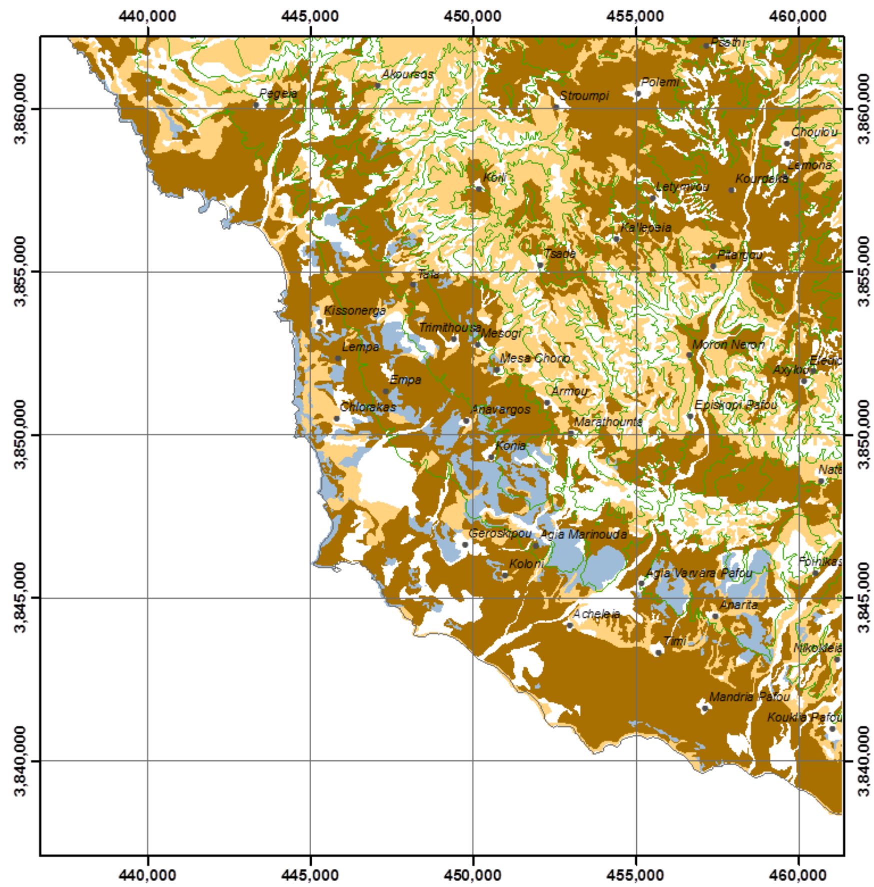


Figure 3-15 Soil texture in study area; dark brown depicts soils with Bt horizons or high clay content; light brown depicts soils with low clay content or no Bt horizon; light blue depicts exposed Kafkalla.

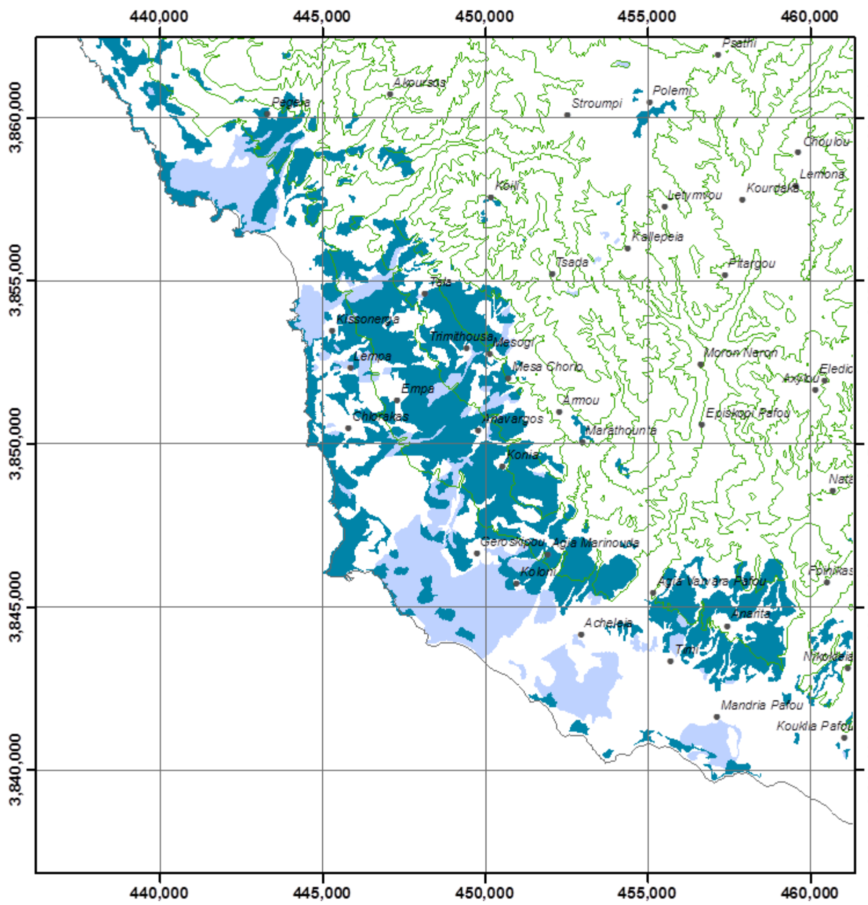


Figure 3-16 Soils with a calcic and petrocalcic horizon; light blue showing presence of havara (calcic horizon, Bk) and dark blue showing epresence of kafkalla (typically petrocalcic K horizon).

Clay content for upland soils seems to be directly related to bedrock geology, Pliocene marls of the Nicosia Formation, bentonitic clays of the Kannaviou Formation and Mamonia Terrane lithologies, mudstones and the mélange (Figure 3-15). These lithologies give soils of high clay content but not necessarily Bt horizons. Good Bt horizons exist on the alluvial and marine terrace soils especially on the MIS 5e terrace. On the MIS 5e terrace are a series of MIS 5a - MIS 5d aeolianites almost completely bare of any soil cover. These areas exist in a coastal zone between Pegeia, the Hellenistic town of Nea Pafos (itselt build on this aeolianite sequences) and going east all the way to the Pafos airport at Cape Zephyros. Behind these landforms small but notable depocenters of MIS 4-MIS 1 aeolian, fluvial and gravity deposits have provided parent materials for the formation of red soils with Bt horizons.

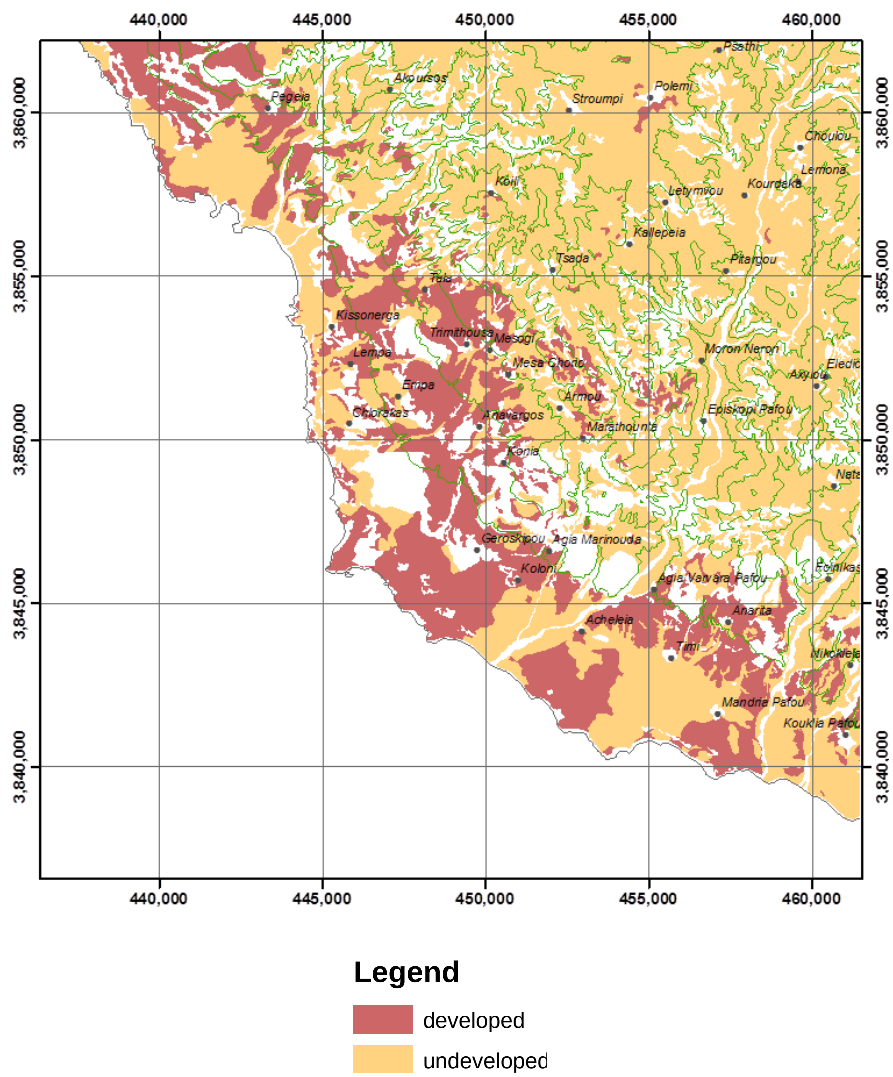


Figure 3-17 Degree of soil-profile development based on complexity and development of horizonation.

Carbonate accumulation is to a great extent more distinct in soil subseries occurring on the lower elevations, the marine platforms on reef limestones like in the case of the Pegeia or marine terrace calcarenites in the rest of the uplifted Pleistocene landforms (Figure 3-16). Pedogenic carbonate exists hand-in-hand with developed soils (Figure 3-17). Carbonate accumulation on these Pleistocene platforms mostly co-exist with some degree of pedogenic carbonate accumulation. It is important thought to note that Figure 3-16 shows landforms with havara and kafkalla accumulations only and not other pedogenic forms of carbonates like pebble coatings and nodules.

Table 3-8 Development index for soil series in SW Cyprus soils based on 5 descriptors of soil subseries

SoilSeries	Polygon count	Minimum value	Maximum value	Average value	Standard deviation	variance
Anarita	75	0	6	2.2	2.2	4.8
Pachna	507	0	10	3.5	2.7	7.3
Letymvou	224	1	7	3.7	1.5	2.2
Bogazi	190	0	8	3.9	2.6	6.9
Foinikas	50	0	6	3.9	2.0	4.1
Nata	45	0	9	5.7	2.7020	7.3
Livadia	6	6	6	6.0	0.0	0.00
Mamonia	89	0	8	6.1	2.3	5.2
Mora	49	1	8	6.3	1.7	3.2
Koloni	22	5	11	7.0	1.7	3.1
Colluvial Soils	76	6	9	7.1	1.0	1.1
Voni	61	5	8	7.2	1.0	1.1
Zodeia	75	1	11	7.5	2.9	8.4
Timi	10	8	8	8.0	0.0	0.0
Kokkinotrimithia	364	11	16	12.5	0.9	0.9
Achelia	11	12	14	13.1	0.8	0.7
Geroskipou	16	12	14	13.5	0.6	0.4

Each index value from the above mentioned five soil properties were summed for each soil subseries and then summed again for each soil series according to the scheme in Table 3-4.

Figure 3-18 shows the numerical distribution of the results in relation to the soil series. Alluvial soils of the lower landforms like Geroskipou and Achelia soil series show more advanced development than Koloni, Timi and Voni soils. Kokkinotrimithia soil series consisting of red soils also shows large numbers of a development index. It is important to note here that the red soils on marine terraces seem to have a higher development index than the Zodeia red soils on the alluvial fans which also .present the highest standard deviation from their average value.

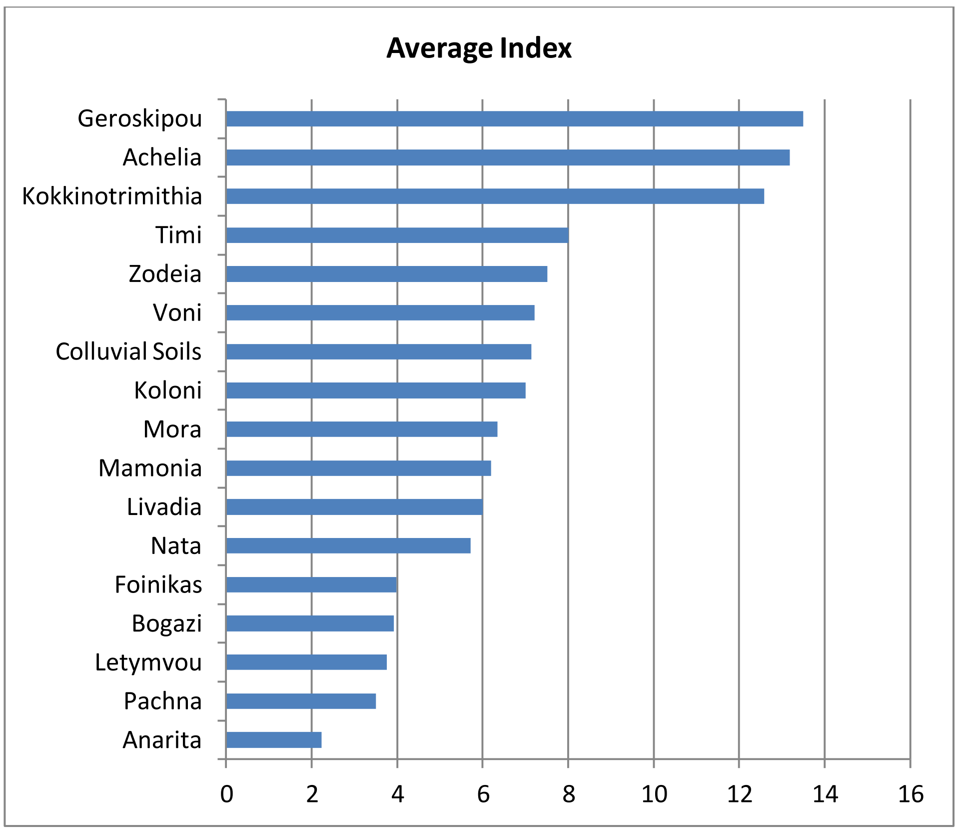


Figure 3-18 Average development index based on descriptions of soil subseries.

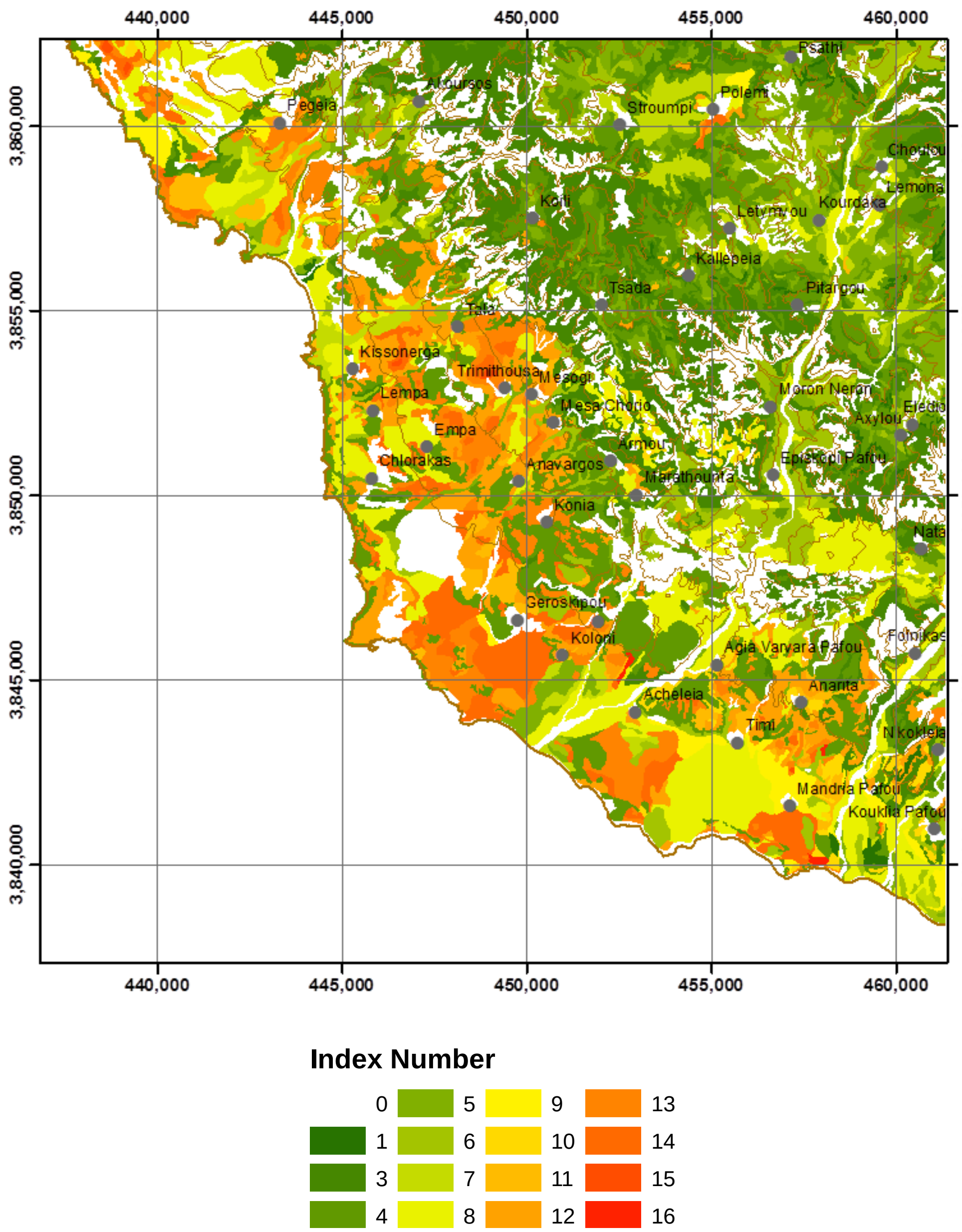


Figure 3-19 Developemnt index number based on depth, color, clay content, carbonate accumulation and horizonation of soil subseries established in Table 3-4.

Soil series on upland landforms of bedrock lithologies score the lowest development index numbers except Tera limestone lithologies in Pegeia forming flights of marine terraces hosting some thin but red Kokkinotrimithia series soils. The results of this first approximation are shown in Figure 3-19. Index numbers range from zero on steep slopes and built-up areas, to 3-5 on upland carbonate bedrock, 6-9 on young fluvial deposits and 10-15 on older fluvial deposits and marine terraces. Figure 3-20 is a reliability map for the first approximation showing the degree to which some soil series on the ophiolitic and clay-rich formation lithologies cannot offer reliable locations for this method of approach.

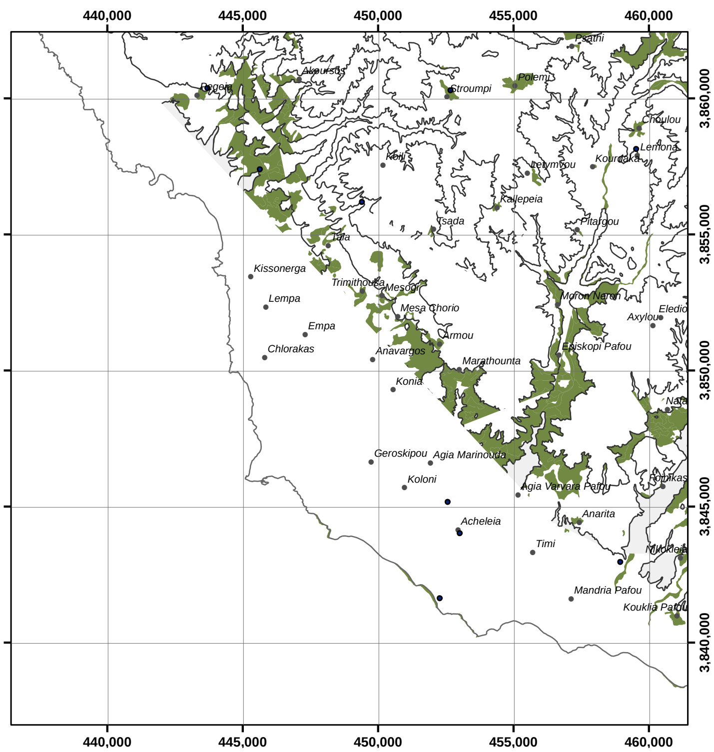


Figure 3-20 Reliability of the first approximation.

3.4.4 Profile development index, a second approximation

Similar to development index calculated in the previous section, PDI results appear low in the upland areas. Some higher PDI values show up on fluvial terraces and narrow fault basins south and southeast of Tsada village in the center of the study area. Colluvial slopes below marine terraces have low PDI (0-10) like the slopes below Achelia and Timi villages. High PDI values are more common on the MIS 5, MIS 7 and MIS 9 terraces. The lack of sufficient data points in the broader urban area of Pafos which extends from Geroskipou to Anavargos and Empa does not allow for a complete picture of the whole extent of the coastal zone. A data point density of 1.8 points/km^2 is probably not high enough to make PDI data in this dataset useful for making valid interpretations.

Table 3-9 PDI results for all the soil series in the study area.

Soil Series	Point count	Min PDI	Max PDI	Average PDI	Standard deviation
Colluvial Soils	25	23.5	92.5	41.1	13.6
Livadia	7	29.5	63.0	39.5	11.3
Kokkinotrimithia	12	21.8	51.2	36.4	10.6
Mora	2	34.3	36.5	35.4	1.6
Voni	17	20.6	58.4	33.7	9.2
Koloni	11	16.7	49.1	33.6	10.9
Pachna	26	8.9	70.8	30.5	15.7
Geroskipou	11	21.0	38.1	29.3	4.7
Bogazi	9	20.3	43.1	28.5	8.4
Achelia	7	14.7	39.5	28.4	10.6
Anarita	3	13.3	40.0	28.0	13.5
Timi	11	13.6	34.5	27.4	6.2
Letymvou	39	7.9	49.8	26.7	9.9
Zodeia	8	8.5	50.4	25.5	12.9
Nata	5	0.0	48.3	25.0	20.1
Mamonia	9	5.3	29.5	21.7	8.0
Foinikas	5	3.8	31.3	21.2	10.5

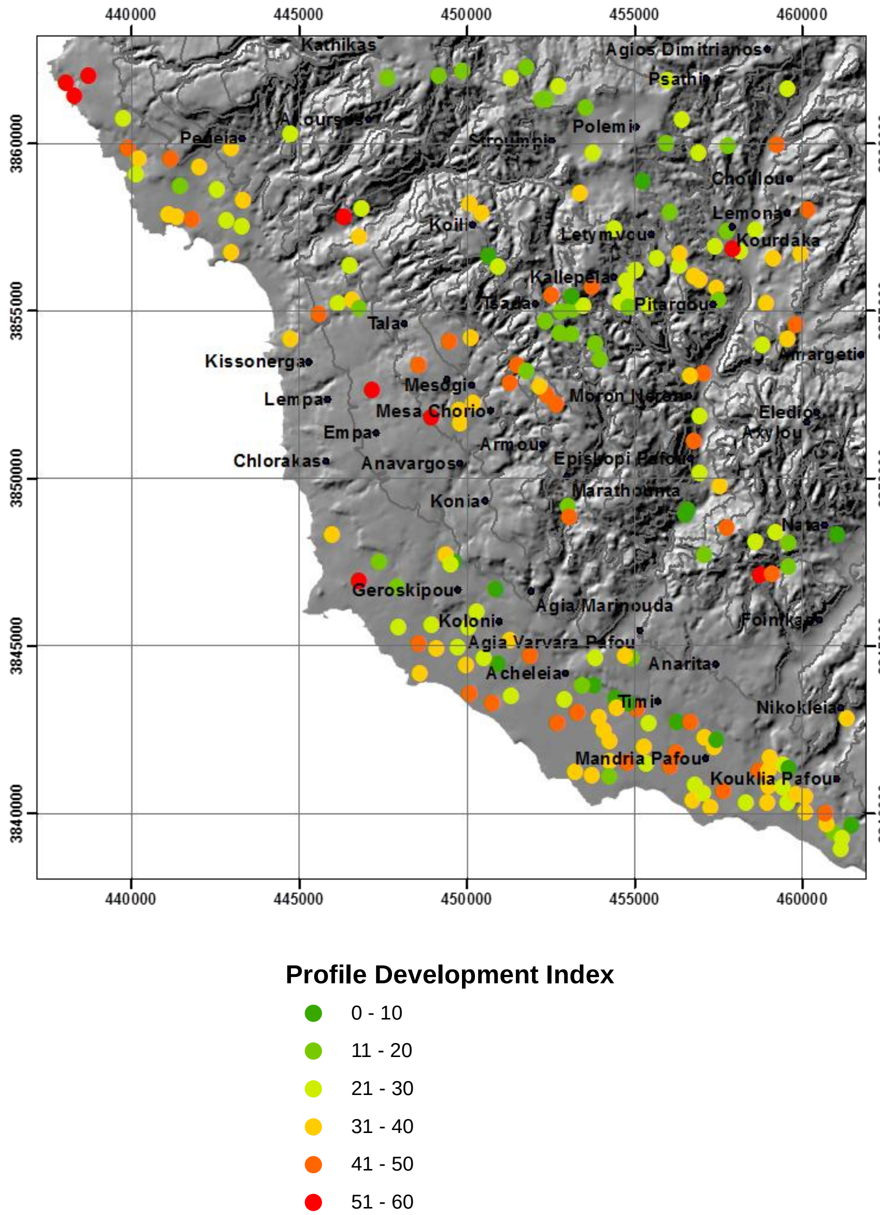


Figure 3-21 Profile development index based on Harden method (1982) for 207 soil profiles.

Zodeia soil series developing on older Pleistocene alluvial fan surfaces together with the younger alluvial soils show continuous addition of material which drops the PDI values at these locations.

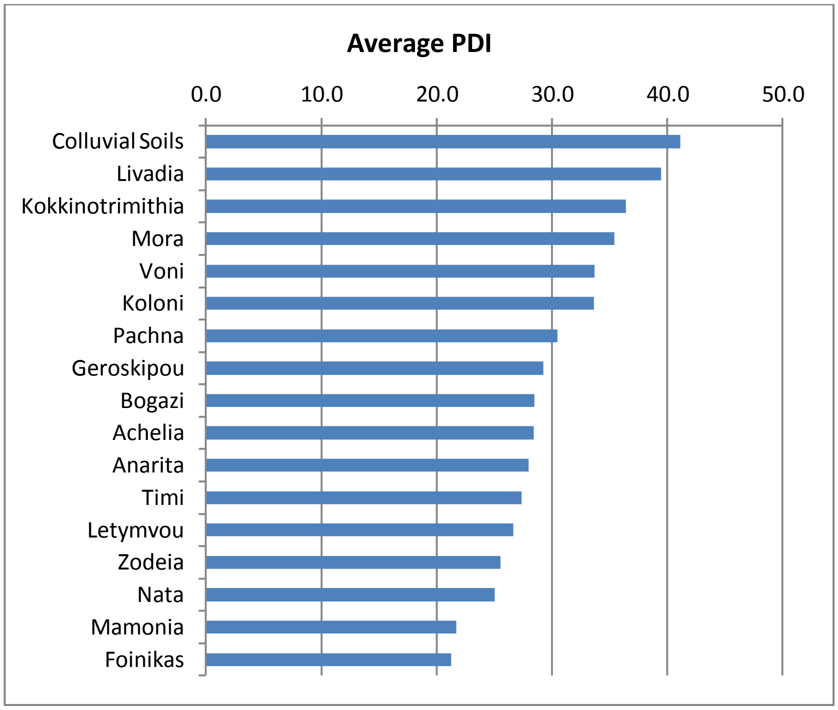


Figure 3-22 Average PDI number for each soil series.

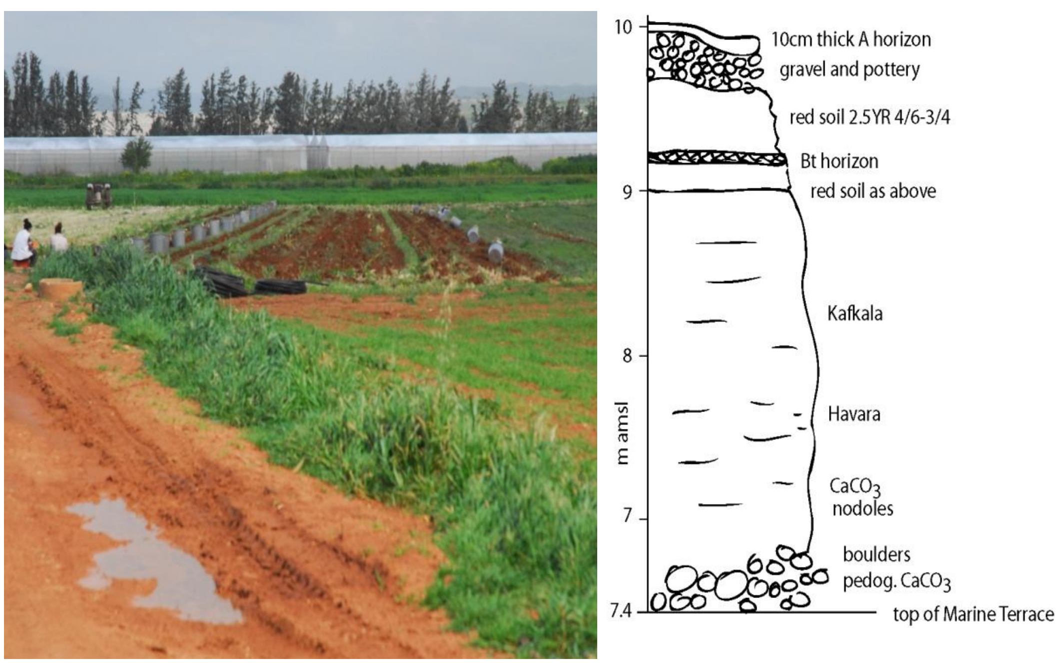


Figure 3-23 Mandria MIS 5e terrace topped with 1m thick red soil of the Kokkinotrimithia soil series and a PDI of 45-55.

3.4.5 Carbonate development stage, a third approximation

Carbonate accumulation in southwestern Cyprus is present on almost all surfaces in some form. Accumulation initiates with tiny disseminated carbonate nodules, just visible to the naked eye. With time it concentrates along ped surfaces and small fractures along which roots are found. Carbonate precipitation favours plant roots or gravel surfaces. Small nodules start to form and grow. Similarly, carbonate accumulates in laminar sheet – like forms which during the initial stages appear like soft and porous carbonate accumulations similar to a soft chalky texture, referred to as havara. Laminar accumulations may thicken and harden becoming impervious and thick Bk horizons. Gravel deposits may become cemented when carbonate coatings coalesce and root coatings may form root casts. At this advanced stage of laminar build-up, the accumulations are referred to as kafkalla and are similar to a hard cap rock like a limestone. Both havara and kafkalla layers may contain cemented sands, gravels or colluvial material that were at some point added to the surface of the profile.

Figure 3-24 Cemented gravels on the Stage V alluvial fan at Kouklia which is estimated to be equal to age or older than MIS 9, pencil for scape.

The above is a simplified description of how the accumulation of carbonate material progresses over time. In any profile, a combination of the above may be seen. Nodules and laminar accumulation may be growing at different levels of the same profile or a havara layer may be capped by a buried soil which in turn may be capped by a kafkalla layer. It becomes evident that accumulation goes on during the process of soil formation, erosion or burial. Accumulation occurs in the soils which form over a variety of parent materials but also occur on parent materials like marine and aeolian calcarenites.

Table 3-10 Carbonate development stage for SW Cyprus

Stage	**I**	**II**	**III**	**IV**	**V**	**VI**
Disseminated carbonate						
coatings on peds / fractures						
Some coatings on gravel						
Very small nodules (< 2 mm)						
thin coatings on gravel (<1 mm)						
small nodules (3-10mm)						
laminar accumulations (<5 mm)						
Thick laminar accumulations (1-3 cm)						
thick coatings on gravel (1-2 cm)						
Medium nodules (1-3 cm)						
havara layer (5-20 cm)						
Thin kafkalla layer (<5cm)						
large nodules (3-5 cm)						
Root casts						
cemented gravels						
medium havara layer (20 -40 cm)						
Thick kafkalla layer (10-20 cm)						
Extremely large nodules (>5 cm)						
Very thick Kafkalla layer (>20 cm)						
Thick havara layer (>45 cm)						
Cemented and capped gravels						

After observing numerous locations in Cyprus and 200 locations in the study area, Table 3-10 was assembled in which different stages of carbonate accumulation are described. The carbonate accumulations that describe each stage were observed repeatedly to occur together. Nodules and gravel coatings are characteristic of the deeper horizons and sometimes occur together when the soil profile consists of both finer materials and gravel. These nodules seem to be the first signs in carbonate accumulation. Nodules are never found alongside gravel that has no carbonate coating. It is observed that nodule growth in the soil matrix progresses with accumulation of carbonates on gravel.

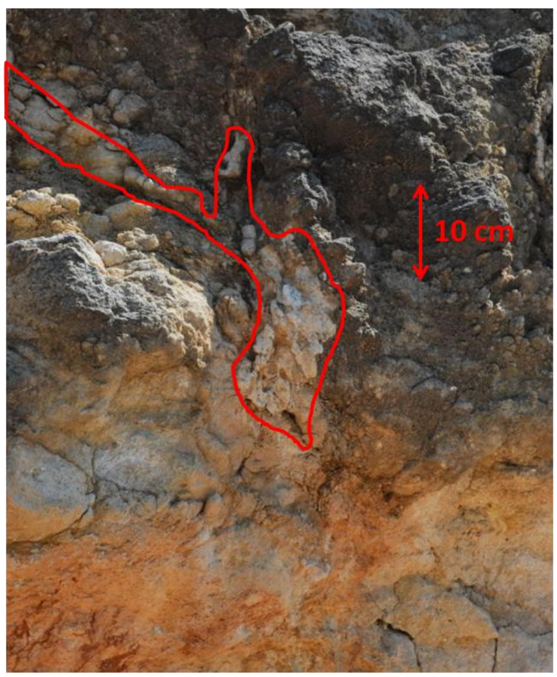


Figure 3-25 Carbonate precipitation around fossil root in MIS >13 (?) in the Kathikas section of Figure 3-29.

Laminar accumulations are common in the upper soil profile and their beginning stage is in the form of mm-thin, discontinuous sheets of soft carbonate material. These laminar accumulations that later will develop into havara and kafkalla layers begin to appear in the profile at Stage III. These laminar accumulations grow in extent and thickness over time but it is not clear if their preferential extent is up or down in the profile. Nodules, gravel and ped coating continue to develop after the laminar accumulations begin to form. These laminar accumulations do not provide an obstacle for movement of carbonates to the lower part of the profile. Some of these nodules can grow into thick root casts up to 6-7 cm wide (Figure 3-25).

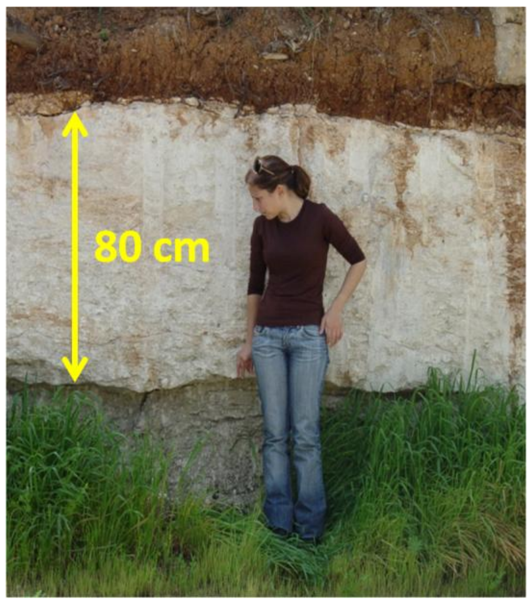


Figure 3-26 A lacustrine deposit with a Stage VI accumulation of an 80 cm havara layer in downtown Pafos MIS 9 terrace.

In Stage IV, laminar accumulations begin to develop into havara layers of soft and friable carbonate material. These havara layers can reach a thickness of 80 cm (Figure 3-26). A thin, kaflalla layer that may form will be at the surface. The kafkalla will progressively grow vertically down and cement havara layers into a harder carbonate layer. Eventually, it will become very hard, what local soil scientists call and map as “unrippable” kafkalla.

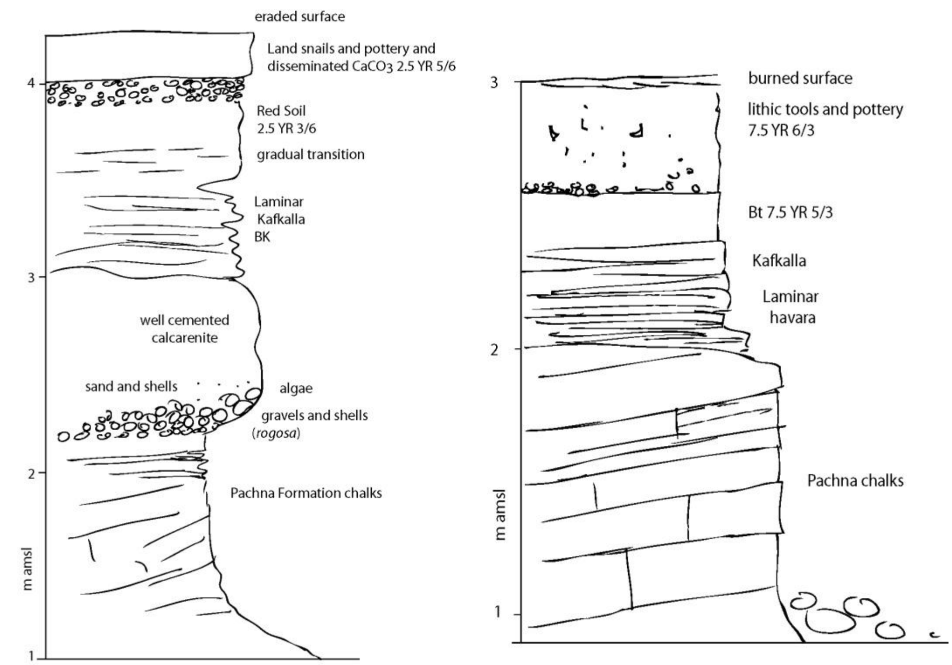


Figure 3-27 MIS 5a-d terraces on the Pegeia shoreline with a transition between havara and kafkalla. The higher MIS 5e terrace is shown in Figure 2-12.

Sometimes the boundary between the havara and kafkalla layers is a smooth transitional one. Figure 3-27 shows two such examples from the MIS 5 terrace on the coast of Pegeia in the Thalassines Spilies location. Here, there is a sharp boundary between the cemented marine calcarenite and the carbonate accumulations on top. On some other marine terrace calcarenites and aeolianites kafkalla will form alongside cementation of the marine or aeolian deposit (Figure 3-28).

During all of the above, progressive movement from one stage to the next, materials may continue to be added to the soil profile. In colluvial soil profiles and profiles in active alluvial fans, the picture becomes more complicated as new material is added. This observation is to be expected because river downcutting and headward erosion, especially on an uplifting landscape, will generate cycles of new depositions (Muhs, 2000).

Figure 3-28 Kafkalla cap on MIS 5 (5c and 5d) aeolianite deposits west of Pafos. Tombs (appr. 2000 BP) are carved in the softer calcarenite below, taking advantage of the kafkalla cap as a stable roof.

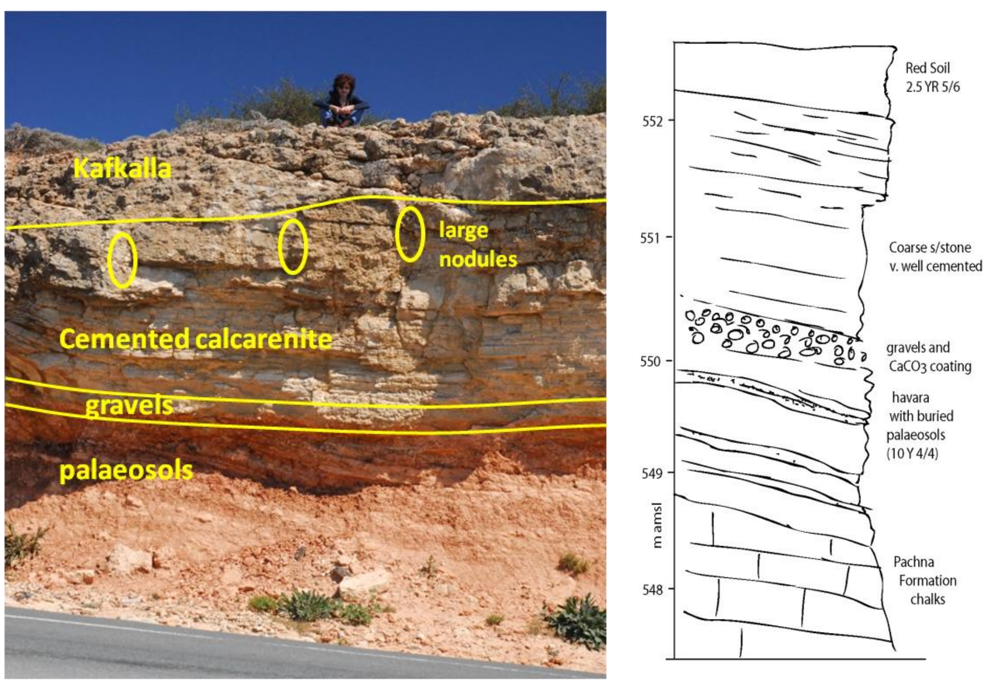


Figure 3-29 Section of an MIS 13 (?) marine terrace just below the village of Kathikas at 550 m.a.s.l. Person for scale at top of section.

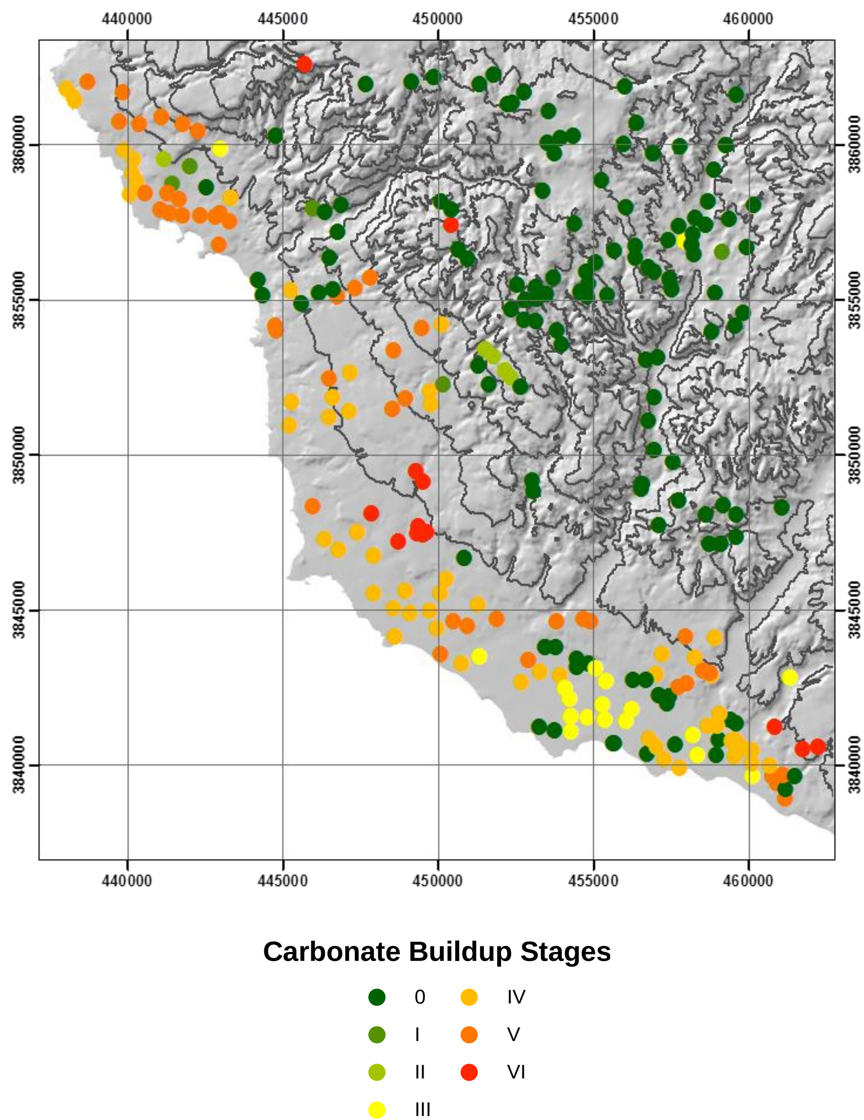


Figure 3-30 Carbonate buildup for 270 soil profiles.

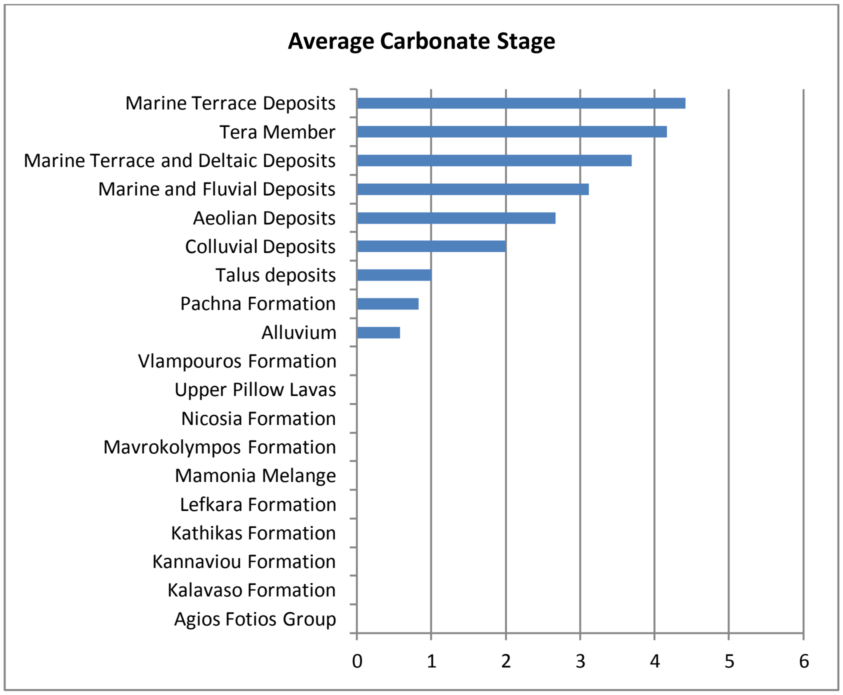


Figure 3-31 Average carbonate stage with respect to parent material.

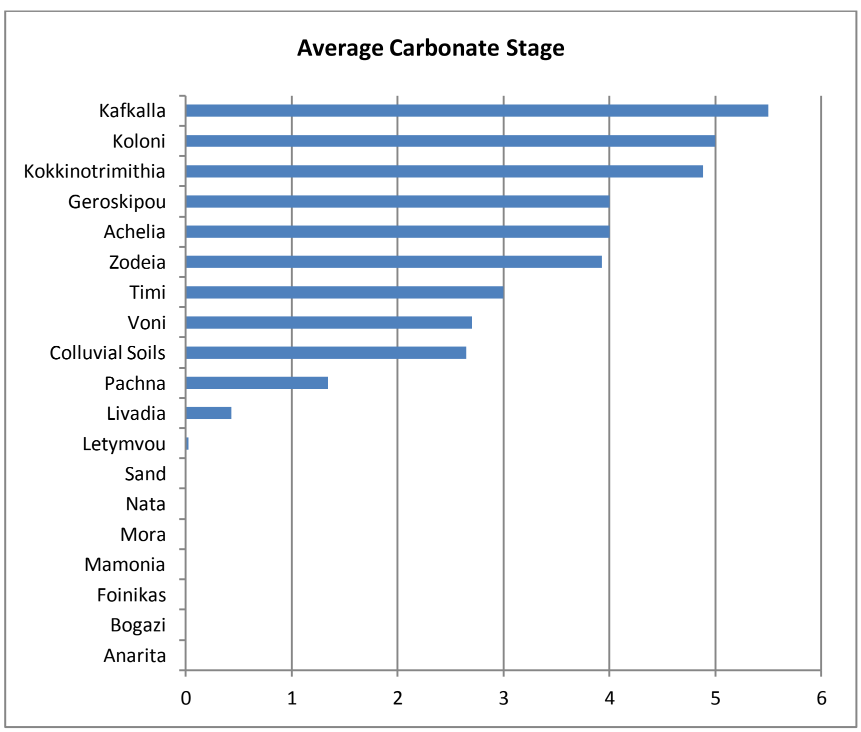


Figure 3-32 Distribution of Carbonate accumulation in relation to soil series.

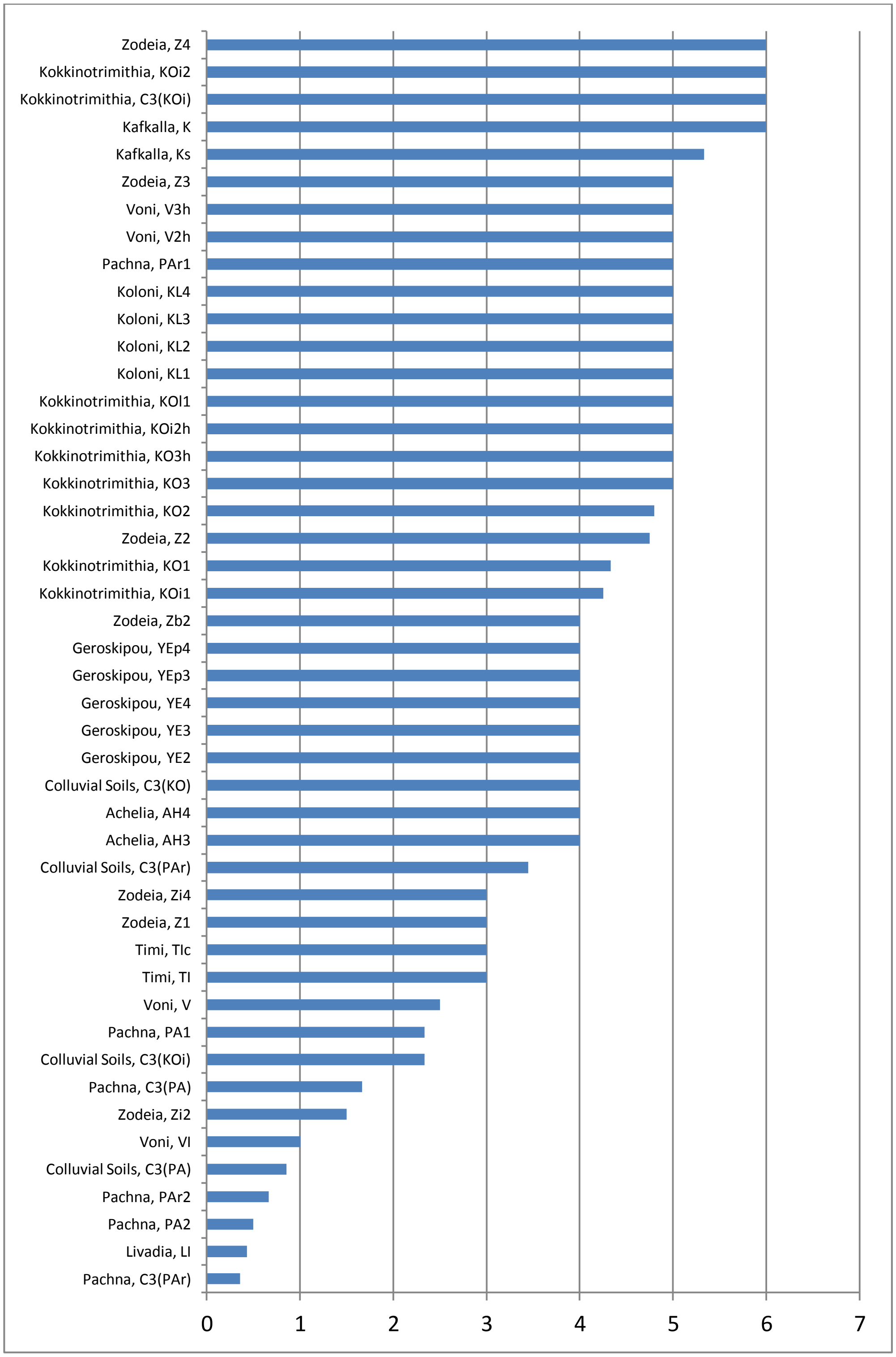


Figure 3-33 Distribution of Carbonate accumulation in relation to soil subseries.

Table 3-11 Estimated age constraints for carbonate stages in southwestern Cyprus. Dark blue shows average values, light blue shows extent of deviation.

	Carbonate Stage						
MIS	**1**	**2**	**3**	**4**	**5**	**6**	**No of points**
5a -5c							6
5e							3
5-7							59
7							13
9							18
11							15
13							7
15							1
>17							1

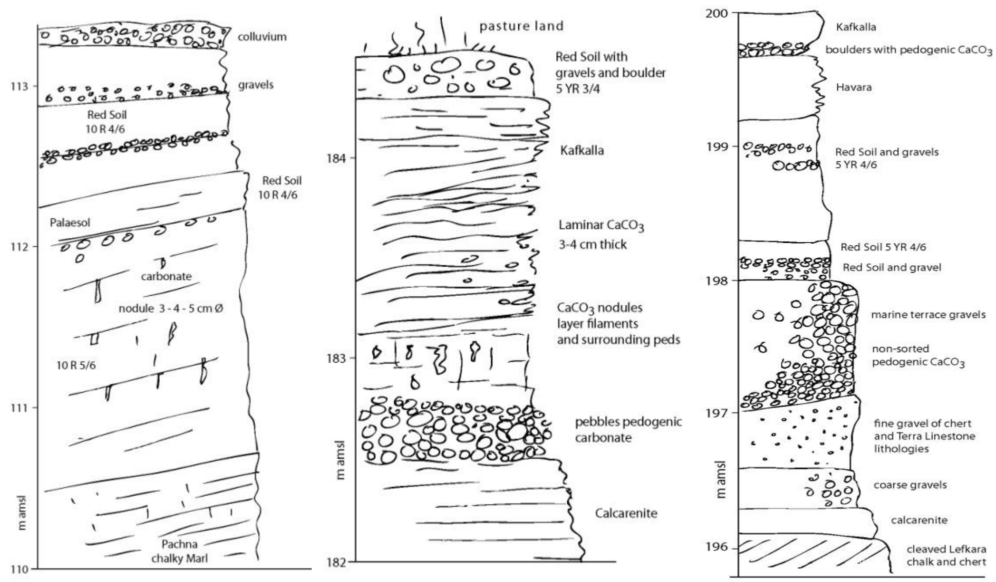


Figure 3-34 Pegeia MIS 7 marine terrace (on the left), MIS 9 terrace (in the middle) and MIS 11(on the right).

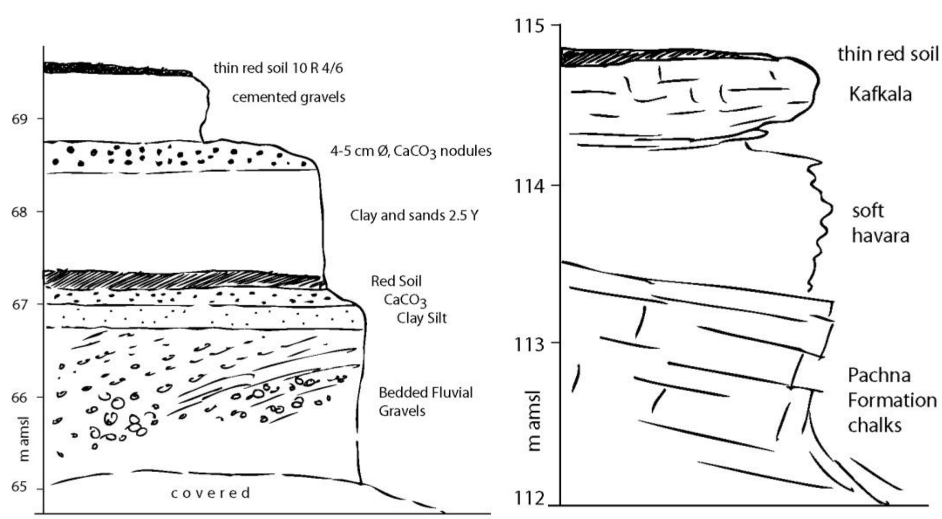


Figure 3-35 Fluvial sediments (left) and section below housing development (right), both on MIS 9 in Anarita

3.5 Discussion

The soils in SW Cyprus have developed on a wide variety of parent materials. The three approaches described above were employed in order to provide understanding for the development in the Pleistocene landscape in southwestern Cyprus. It is hypothesized that development index is an indication of time progression in the soil profile.

The redness and iron content of Mediterranean soils is closely linked with the term “terra rossa” (meaning red earth), the Mediterranean climate and its unique coastal geomorphology (Schaetzl and Anderson, 2005). Initially related pedogenetically to their limestone bedrock substrate, abundant on Mediterranean coasts, they were later renamed red fersialitic soils in the French soil taxonomy system (S.E.C.S., 1966) and Chromic and Calcic Luvisols in the FAO soil taxonomy system (FAO-UNESCO, 1989) after it was decided that they were almost independent of their bedrock type but relied a lot on Saharan dust inputs. Studying Jerusalem speleothems and their Sr and U isotope systems, Frumkin and Stein (2004) revealed a precisely dated record of Saharan dust inputs into the eastern Mediterranean being correlated with terra rossa soils development. Modern dust accretion rates in Israel are as much as 22-39 mm/ka in the semi-arid zone (Yaalon and Ganor, 1975).

Calcification is one of the most obvious pedogenic processes in semi – arid environments. Referred to as “caliche” in the desert soils of the southwestern United States and “havara” and/or “kafkalla” in Cyprus, it is more commonly referred to as calcrete or Bk for petrocalcic horizons (Soil Survey Staff, 2010). Havara comes from the Arabic word “huwwar” meaning soft, white stone (Redhouse, 1968). In contrast, kafkalla is a local Greek word meaning a hard, rocky, bare or stony surface. These calcaric soils and petrocalcic (Bk, K) horizons are common in Mediterranean soils of thermic and xeric regimes where evaporation exceeds precipitation. If there is enough water to translocate the calcium and/or magnesium carbonates, and a supply of carbonates is available, a calcic horizon will form. Field work by Gile and others in New Mexico helped create the first four-stage calcium carbonate development system (Gile *et al*., 1966). It was later expanded by Machette (1985) to include six stages of development (Table 3-6).

Sources of calcium ions are usually carbonate rocks, but aeolian inputs and biogenic sources are also important and believed to be the most important source (Gile *et al.*, 1966; Machette, 1987; Mayer *et al*., 1988). Four of the proposed models for the formation of the calcic horizon are the insitu dissolution and reprecipitation model, the upward capillary rise model, the biogenic model (Ferris et al., 1994) and the wetting front model (Schaetzl and Anderson, 2005). The calcification process on the island of Cyprus probably involves a combination of the above mentioned models. The purpose of this project was not to investigate the processes behind calcification but to use calcic horizons as clues to the degree of soil development.

Machette (1978, 1985) showed that calcic horizons and their progressive development in about six stages can be used as a tool to approximately date calcic soils in Quaternary sediments in the semi-arid parts of the southewestern United States (Table 3-6). Parameters like horizon/parent material carbonate content, thickness, depth and the overall horizon characteristics are used to evaluate the rate of accumulation and ultimately the age of the soil. He correlated accumulation rates with attained morphological stage and showed that development stage equates time. Similarly, Pleistocene alluvial fans in Spain hosting well – developed calcretes show variable stages of development but also have a strong impact on the response of alluvial fans to surficial processes.

Havara and Kafkalla are very well known in Cyprus especially to farmers who need to deal with these hard soil horizons in ploughing. The Department of Agriculture included kafkalla outcrops in soil mapping and differentiated surfaces with rippable and unrippable kafkalla. Pantazis and Soteriades (1961) and Pantazis (1973), have studied these petrocalcic horizons and measured $CaCO_3$ contents ranging from 75 – 90 % with a mineral residue up to 10%. Minerals include quartz, chalcedony, chert, opal, feldspars and zeolites. In addition small fragments of rock as well as sand, gravel and foraminifera are present. The provenance of these minerals is always the surrounding geology. Petrographic analysis showed small calcite crystals along cracks and in cavities suggesting *in situ* formation.

Shirmer (1998) has used havara horizons in southern Cyprus (Kalavaso colluvial sequences) as age proxies for correlating soil horizons and talus surfaces to central European climatic events and stages. It is premature in the Quaternary research on the island to make the assumption that central European glacial and interglacial periods created such strong climatic events in Cyprus as they did in central Europe. He has dated 27000 year old havara accumulations over 32000 year old buried soils in Kalavasos valley. Similarly, havara from the Larnaca area have yielded ages of 15,860 and 13,900 years (Gifford, 1978). In Japan, Maejima *et al.*, 2005 applied similar methods using meteoric ^{10}Be to date soils on raised marine terraces. He concluded that terra rossa soils were the oldest in age.

An experiment conducted in Pafos by the University of Oxford compared the maps of four independent soil scientists in their attempt to map soils in the coastal zone from Timi to Mandria (Bie and Beckett, 1973). The mappers used air - photo interpretation methods and were provided soil-profile descriptions. The results showed that the mappers used different strategies for interpreting the same landscape. Subjective decisions with regard to soil polygons, their shape, size and soil associations and relation to landscape position are common and can differ from mapper to mapper depending on experience and field of expertise. Additionally, there seems to be a range of factors that can contribute to complicating the use of soil properties as relative-age indicators. Topography, landscape position and the degree to which a location is subject to inputs from surficial or aeolian processes is important in soil formation and produce soil variety on the landscape.

It is in this context that the 3rd approximation was attempted. It was important to identify a soil process that would help capture the relationship of time to soil formation and landscape development. Item specific descriptions like color and carbonate accumulation can offer more simplicity to relative – age methods when the item described is a strong indicator of age and simple to describe and classify according to a well – defined model.

3.6 Conclusions

Soils in the southwest of Cyprus are similar in genesis to other soils in Cyprus. Local soil scientists like to refer to Cyprus soils as geo-genetic, a term that gives emphasis to the parent material factor of the soil forming equation. The geology in this part of the island with a 0.35-0.65 mm/year uplift rate is dominated by steep carbonate slopes and numerous marine terraces in the lower coastal areas. Soil properties are time-honored methods in Quaternary geology for determining relative ages of landforms (Muhs, 2000). In this context, soil properties were used in trying to understand soil distribution on Quaternary surfaces in southwestern Cyprus. Three approaches were used. The first approximation involved decoding the soil map and soil descriptions, the second approximation involved using a profile development index number and the third concentrated in using carbonate accumulation.

Some simple soil properties such as soil depth, redness, clay content and carbonate content can potentially become useful relative age indicators (Markewich and Pavich, 1991). Carbonate bedrock slopes host mostly regosols and calcisols with the exception of soil formation, or rather soil accumulation, behind man-made dry stone terraces and on fluvial terraces. Terrains in clay-rich rock formations have developed very poor and thin soils with little horizonation and with color and texture similar to parent material. Well-developed soils have formed on all coastal geomorphological surfaces in southwest Cyprus and some stable surfaces in the bedrock upland country. These soils are deeper, darker in color, show more carbonation and higher clay content.

Profile development index (PDI), an index number quantifying soil properties is a method for comparing the soil profile with the parent material. This method was used to measure the degree of soil development on this landscape and was concluded that coastal terraces and alluvial fans have the highest PDI numbers. PDI numbers range between 30-60for coastal soils and lower than those values for soil profiles in upland bedrock landforms.

In addition, these coastal soils, mostly chromic luvisols and cambisols have substantial calcium carbonate accumulation. Development of Bk and K horizons, locally known as havara and kafkalla, have been used to correlate soil profiles across toposequences. Carbonate builtup stages were customized for the soil environment in the southwest of Cyprus from empirical knowledge. Stage V and stage VI is mostly common on the higher terraces of MIS 7 MIS 9 and MIS 11.

Figure 3-36 On the left, a thick havara – kafkalla cap on the fanglomerate formation in Achna, and on the right calcrete development and red palaeosols on a MIS 11+ marine terrace in Paralimni, both locations in southeastern Cyprus.

Similarly, stage VI surfaces on marine terraces in other parts of the island appear on MIS 9 and MIS 11. The distribution of havara but especially kafkalla points to Pleistocene surfaces of marine terraces, alluvial terraces and alluvial / colluvial fans. It is generally accepted that these pedogenic features are associated with Mediterranean red soils (Chromic petroxeralfs or Luvisols), locally known as terra rosas. Mapping of these deposits by Pantazis and Soteriades (1968) reveals that there is a close association between calcium carbonate accumulation and red soils on the whole island. Figure 3-37 is nothing more than a map of the distribution of red soils and carbonate buildup on the whole island. Time since subaerial exposure of a stable surface must be the most important factor in this soil forming equation.

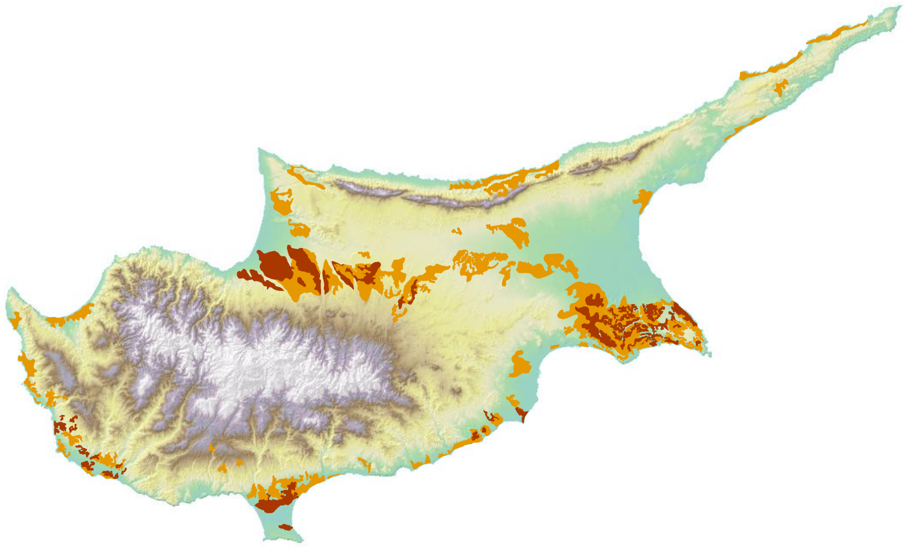


Figure 3-37 Distribution of luvisols (red soils) shown in red brown and Kafkalla (petrocalcic horizon) shown in light brown, (based on the Soil Map of Cyprus (1999), Soil and Water Use Section, Department of Agriculture).

4 Geomorphology and geoarchaeology of Palaipafos

This chapter focuses on the southeastern part in the soilscape of Chapter 3 (**Error! Reference source not found.**) and attempts to understand the landscape of the ancient polity of Palaipafos which is located in the heart and environs of what is today the village community of Kouklia. The geomorphological study area is shown with a red outline, small black dots are modern villages and the ancient Palaipafos urban landscape is shown with a black solid square in the same figure. The Pafos catchment area is shown with a blue outline and forms what is also believed to be an influence area for the southwest of Cyprus.

The principal attraction to this study area is archaeological. Palaipafos, known since the Medieval period as Kouklia (from *kovocle, kouvouklion*), was a prosperous and long-lived polity since the Late Bronze Age and played a significant role in the history of southwestern Cyprus throughout Antiquity. Geoarchaeologically, the study area becomes significant due to its coastal location, its geomorphological character and its close relation to tectonics, coastline evolution, regional archaeometallurgy and continuous human occupation and land use. Copper deposits and ancient slag heaps are located and studied in area shown with a yellow box (**Error! Reference source not found.**). The diversity of the geomorphology units on the landscape of Palaipafos (red box) is evidence for the tectonic and climatic dynamics of its environment and form, together with the copper slag heaps of the northern part of the catchment area, the focus of this Chapter.

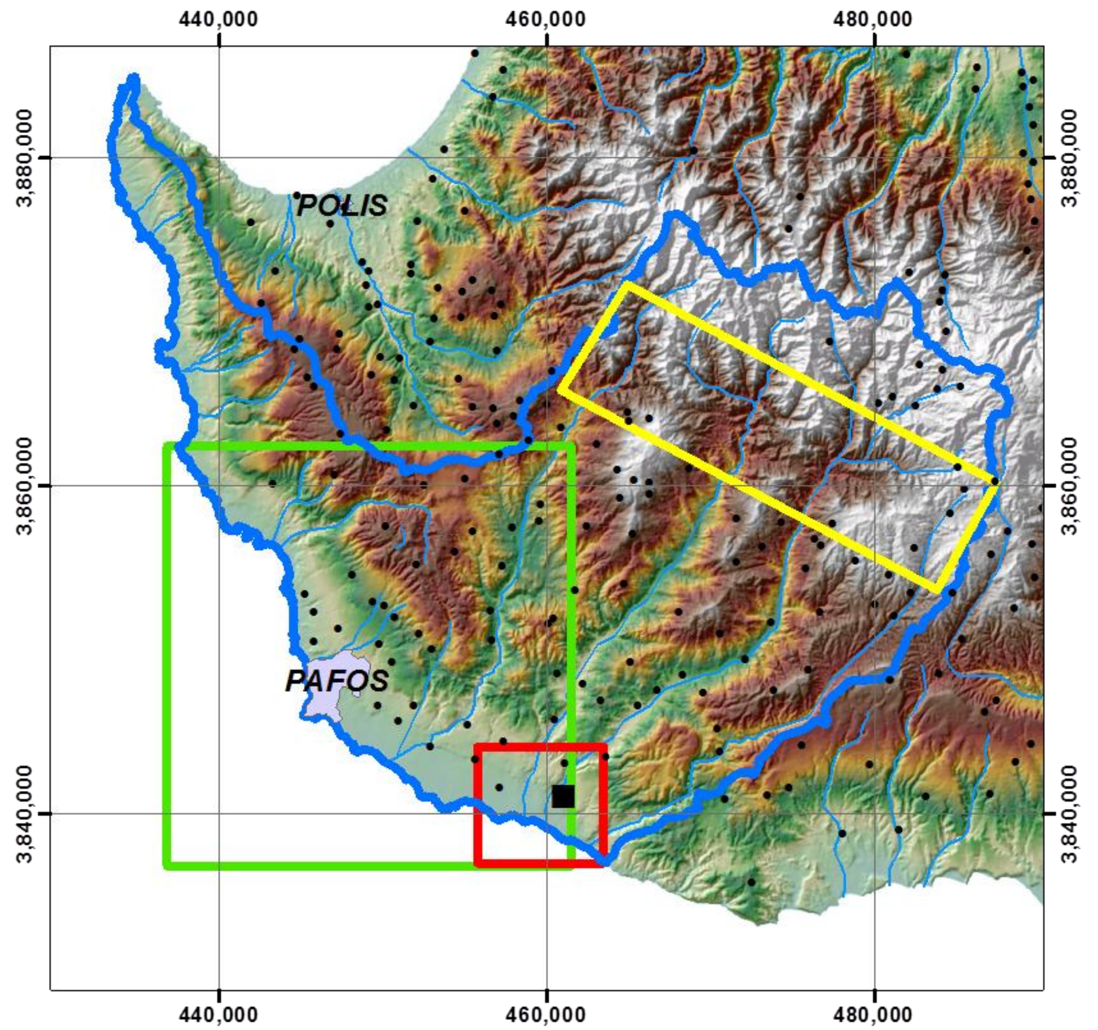


Figure 4-1 Digital elevation model of southwestern Cyprus. Study area of Chapter 3 is shown with green box, Pafos catchment area is shown in blue outline, study area of ancient slags is shown with yellow box, geomorphological map area is shown with red box, small black dots are villages and the black solid square is the urban landscape of Palaipafos. The grey-shaded areas are the towns of Pafos and Polis. The grid is in meters.

4.1 Main Objectives

One of the most significant attributes of Palaipafos in relation to other ancient polities was its ability to sustain human occupation almost continuously for about 4000 years to this day. This longevity renders the area a venerable source of important archaeological information (Iacovou, 2008). Environmental factors affecting human occupation of coastal Mediterranean sites are mostly relating to geology and tectonics, sea–level change, tsunami hazard and patterns of climate and land use change. This chapter provides an evaluation of the significant environmental factors that play a key role in the resistence of the Palaipafos landscape. The objectives of the work presented in this chapter are:

- To understand the landscape of the area and its evolution during the Quaternary and to identify those geomorphic signals that give clues to human land use in the last 4000 years,
- To understand the degree to which the landscape is resistant,
- To make suggestions for the sustainability of the archaeological sites against natural and anthropogenic hazards.

4.2 Methodology

A large geodatabase was created for the documentation of geographical data and their interpretation in a geographical information system. ARCGIS™ was used for storing the database and for making spatial analysis and interpretation. Tha data stored included topographic, administrative, archaeological, geological, geomorphological and soil data.

Archaeological data, much of it created with high topographic accuracy (Agapiou 2010), was collected and analysed in the course of a University of Cyprus applied science project (2007-2010) entitled “A long-term response to the need to make modern development and the preservation of the archaeo-cultural record mutually compatible operations”, (Iacovou *et al.*, 2009; Agapiou *et al.*, 2010). The importance of human occupation on the coastal front becomes significant when attempting to reconstruct coastline evolution. A dense point file with elevation data resulting from photogrammetric methods was provided by the Lands and Surveys Department of the Ministry of Interior. Digital elevation models from these data and digital elevation models from topographic maps published in the 1970’s were used as a first approximation in interpreting the landscape.

Air photographs of 1957, 1963, 1994 and satellite images of 2003 and 2008 were then used to aid the delineation of geomorphic units, to look for recent landscape change, mostly man induced and to identify features presently concealed by vegetation or artificial fill. Written sources were searched for evidence of land use change and references to environmental events such as droughts, tsunamis, floods, earthquakes and other environmental variables.

4.2.1 Geological and geomorphological mapping

Geomorphological mapping was conducted with field surveys. Satellite images with contour data were printed and used as field sheets. Mapping was conducted in the spring after harvest and in the autumn after ploughing for maximum visibility. Special attention was paid to surficial sediments and their significance on the landscape. Finalization of map units was done after extensive field mapping which included outcrop section descriptions. Field work focused on identifying features or associations that pointed to human occupation or recent (historical) deposits. The goal was to produce a geomorphological map, as a tool for geoarchaeologists and geomorphologists for the understanding of this Pleistocene landscape and its response to prolonged human occupation in the Holocene.

Study of soil profiles across the landscape were also conducted for extrapolating age estimations based on knowledge acquired from the previous chapter. Profile descriptions and human artefacts like pottery sherds, gave invaluable information on the chronostratigraphy of profiles. Artefacts, mostly pottery sherds provided reliable maximum age for Upper Holocene deposits. In order to understand the Quaternary landscape evolution of the area, it was also important to create a coastline evolution map of palaeoshorelines and assign approximate dates to each one. Archaeological and geochronological data were used but also PDI and calcrete accumulation data from the previous chapter which covers this area. Coastline evolution become important in attempting to identify possible locations for the Bronze Age harbor of Palaipafos.

Natural resources and their relative importance and proximity to the site were evaluated based on years of intimate knowledge of bedrock geology in southwestern Cyprus. A copper slag database was composed by merging published data with data from the archives of the Cyprus Geological Survey; both were verified in the field and new locations were added. Charcoal was dated with the ^{14}C method for two samples of charcoal in copper slag deposits and for one sample in a coastal alluvial fan.

4.3 Geological setting

The ancient polity of Palaipafos in SW Cyprus, lies on the eastern edge of a 30 km long collisional zone between autochthonous Turonian Troodos terrane and the allochthonous Carnian-Campanian Mamonia Complex. This collisional zone is made evident from a surficial expression of an impressive anticline just a few meters east of Palaipafos. The coastal lowlands of the ancient polity to the south and the Diarizos river to the west, create a unique Quaternary environment of deltaic, aeolian, alluvial, gravity and marine sediments.

4.3.1 Geology

Presently located 2.1 kilometers from the coast, Palaipafos is spread on a number of small plateaus – mesas which overlook the Mediterranean Sea to the south. The area west of Petra tou Romiou, which includes the Hapotami valley and also Palaipafos, marks the boundary between the Circum-Troodos Terrane in the east and the Mamonia Terrane in the west. Consequently, it is a region of very diverse geology with evidence of Quaternary tectonic activity along the coast.

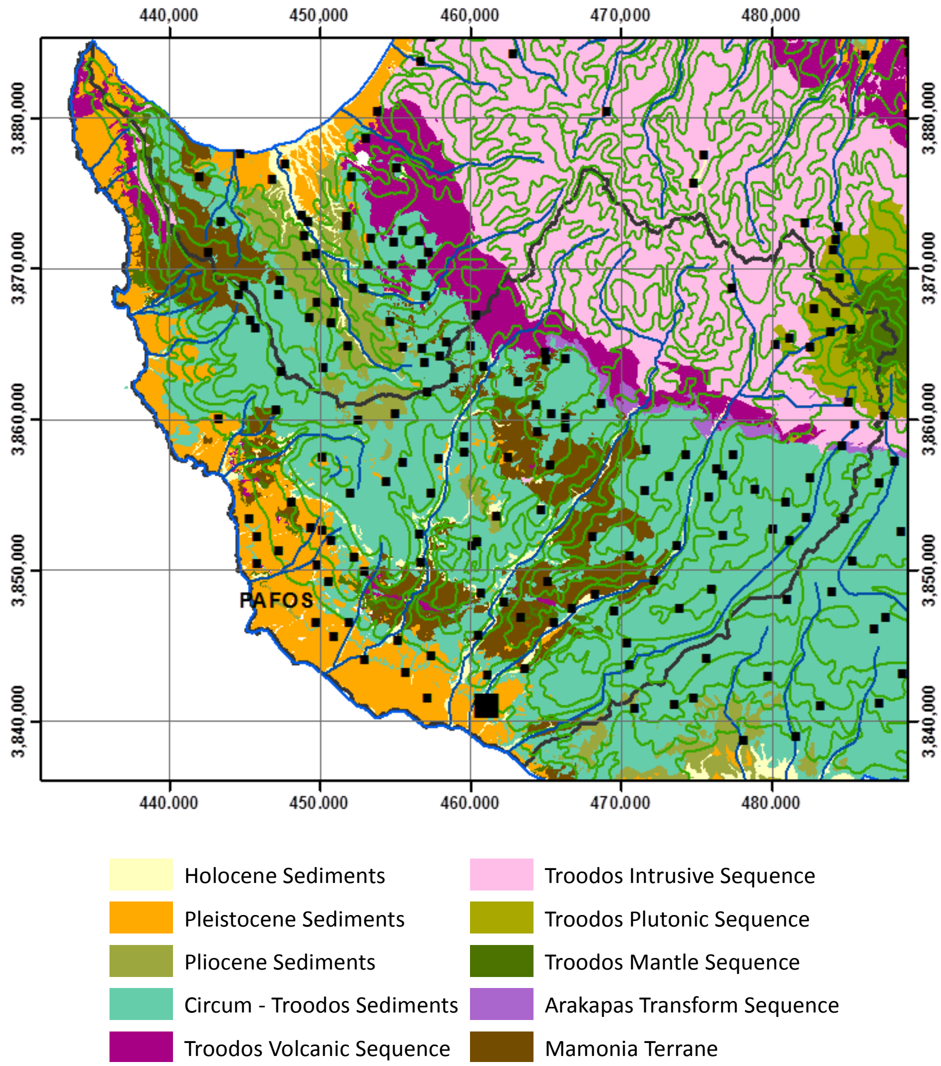


Figure 4-2 General geology of the Palaipafos catchment area (boundary shown in black). Small squares are villages with the big square in the south being Palaipafos (modern Kouklia village).

The Petra tou Romiou location marks the first exposure of Mamonia Terrane in western Cyprus. Petra tou Romiou which literally means the Rock of the Greek, are a set of large, white re-crystallized Upper Triassic reef limestone exotic blocks containing small basaltic pillow lavas. According to traditional belief, Aphrodite, the goddess of love, ascended from the sea waves at this location which is also the type section for Petra tou Romiou Formation. The reefal limestones are believed to represent small carbonate build-ups formed on seamounts and small volcanic islands associated with oceanic crust that formed during the opening of the Tethyan ocean basin. Late Triassic dark-colored rocks that make up the point in the foreground (Figure 4-3) belong to the Agios Fotios Group and Fassoula Lavas of the Diarizos Group of the Mamonia Terrane which include volcaniclastic sandstones, tuffs, pillow lavas and lava breccias in a matrix of thinnly-bedded, radiolarian cherts and mudstones.

Figure 4-3 The Petra tou Romiou location with Petra tou Romiou Formation limestones forming sea stacks and Diarizos and Agios Fotios Group lithologies forming the laced coastline.

Inland, the Maestrichtian bentonitic clays of the Kannaviou Formation (Figure 4-4) are deformed together with the older Mamonia rocks having being deposited during the juxtaposition of the Mamonia Terrane during this time. West of this location in the Hapotami river valley, Kathikas Formation overlies the collisional zone of the juxtaposed Mammonia Terrane. Kathikas Formation (Figure 4-5) consists of debrites containing numerous clasts of

Mamonia and Troodos Terrane lithologies in a sand and clay matrix (appears on the map (Figure 4-2) as one unit with Mamonia Melange due to scale).

Figure 4-4 Kannaviou Formation below marine terrace gravel deposits between Hapotami and Petra tou Romiou.

Figure 4-5 Kathikas Formation in Hapotami Valley with its variegated-colored bedding and badlands morphology.

The deformed rocks are overlain unconformably by the post-Maestrichtian pelagic carbonates of Lefkara Formation and Pachna Formation. This unconformity marks the end of significant tectonism during the geologic evolution of the island and the onset of a tectonically quiescent period for southern Cyprus until the Pliocene. Lefkara Formation chalk predominates east of the Petra tou Romiou location and Pachna Formation chalks predominate west of this location. The Lefkara Formation chalks along this geological zone boundary, deposited on Kannaviou Formation bentonitic clays and Mamonia Terrane clays are severely faulted causing many small landslides. The ancient polity of Palaipafos is located on well-cemented gravel deposits on top of Pachna Formation chalks just west of this region.

Pliocene sediments (Nicosia Formation marls) are not occurring in this part of the coast. Uplifted marine terraces at elevations as high as 200 m are evidence for an Upper Pleistocene uplift rate of 0.2 mm/year in the vicinity of Palaipafos (Chapter 2). The coastal lowlands present a depositional environment of diverse marine, deltaic, fluvial and aeolian deposits due to the existence of two large river mouths, an active fault and a fluctuating coastline. These Quaternary deposits will be discussed in detail in the Geomorphology section (section 4.6).

4.3.2 Tectonics

Although western Pafos presents fascinating opportunities for tectonic and palaeoseismology studies (Tsiolakis and Zomeni, 2008) it is not the purpose of this study to document these tectonic structures. Nevertheless, it is important to consider tectonics and historical earthquakes as a significant factor for the landscape development of the area of Palaipafos which has been occupied for the last 4000 years. Catastrophic events are common interpretations for settlement abandonment in antiquity. Earthquakes are considered by early travelers (most of them on their pilgrimage to the Holy Land) as a primary reason for settlement abandonment and/or destruction. Cotovicus (1599) refers to Palaipafos:

> "Palaipafos, founded by King Paphos, son of Pygmalion, lies on the south coast near the promontory Zephyrium. This city, so famous in poetry, was destroyed by frequent earthquakes; traces of ruins show what was its former greatness.

> Here was the celebrated temple of Venus in which persons of both sexes sacrificed naked to Venus: tradition holds that it fell at the prayer of Apostle Barnabas.

Although the state of the ruins was as a rule the result of human factors (e.g. reuse of worked stone for the building of the Medieval cane sugar refinery at Kouklia (Maier *et al*., 2004), earthquakes did occur in Palaipafos, and there is a rich history of earthquakes as shown in **Error! Reference source not found.**.

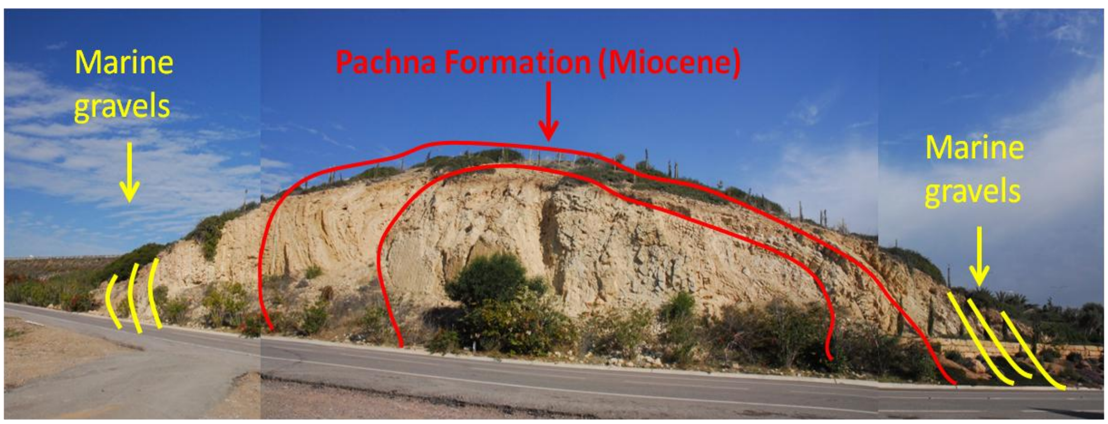


Figure 4-6 Kouklia fold deforming Pachna Formation chalks, indicating a southwest – northeast stress regime. Marine gravels are of Quaternary age. Road for scale, view towards northwest.

The southern compressional stress regime of Cyprus is reflected onshore in the Pafos district with a fault system, that runs from the northwest (Pegeia) to the southeast (Geroskipou), almost parallel to the coast, and then turns southeast to Kouklia and crosses the coastline just below the village of Kouklia and west of Petra tou Romiou (Figure 3-10). It surfaces on the Kouklia coastal road section as an anticline, deforming Pachna Formation chalks and Quaternary marine gravels (Figure 4-6), where it was first identified and mapped by Xenophontos et al. (1994). The marine gravels are deposited on top of a marine abrasion platform on the Pachna ormation chalks, are cemented and contain marine fauna (Figure 4-7).

Figure 4-7 Deformed slightly cemented Quaternary marine gravels on the eastern flank of the Kouklia fold, deposited on a Pachna Formation chalk marine abrasion platform (hand of person on abrasion platform).

Later mapped and studied by Soulas (2001, 2003) and the NEOCYP Consortium (2005), it was revealed that it follows the base of the MIS 7 terrace, crosses the village of Agia Marinouda and ends just below the Geroskipou MIS 7 terrace, expressed as a 105^{o} E trending fold, where it was mapped by Zomeni in Tsiolakis and Zomeni (2008). The fold at Kouklia was trenched and logged (Figure 4-8) in 2004 by Tsiolakis from the Geological Survey and Soulas with Morisseau (NEOCYP Consortium, 2005). The movement on the structure was at the time estimated to be of Quaternary age. Two marine terraces were identified in the trench as being faulted. Unfortunately, the sediments did not present any opportunities for geochronology.

Based on Kinnaird (2008), colluvial deposits and buried palaeosols on the north – dipping side of the fold at Geroskipou, give luminesence dates of 68.7 ± 28.2 ka at the base of the succession, at 33.03 ± 6.74 ka in the middle of the succession and at 6.68 ± 4.0 ka at the top of the succession. This verifies ongoing tectonic movement after the deposition of MIS 5e 125,000 years ago.

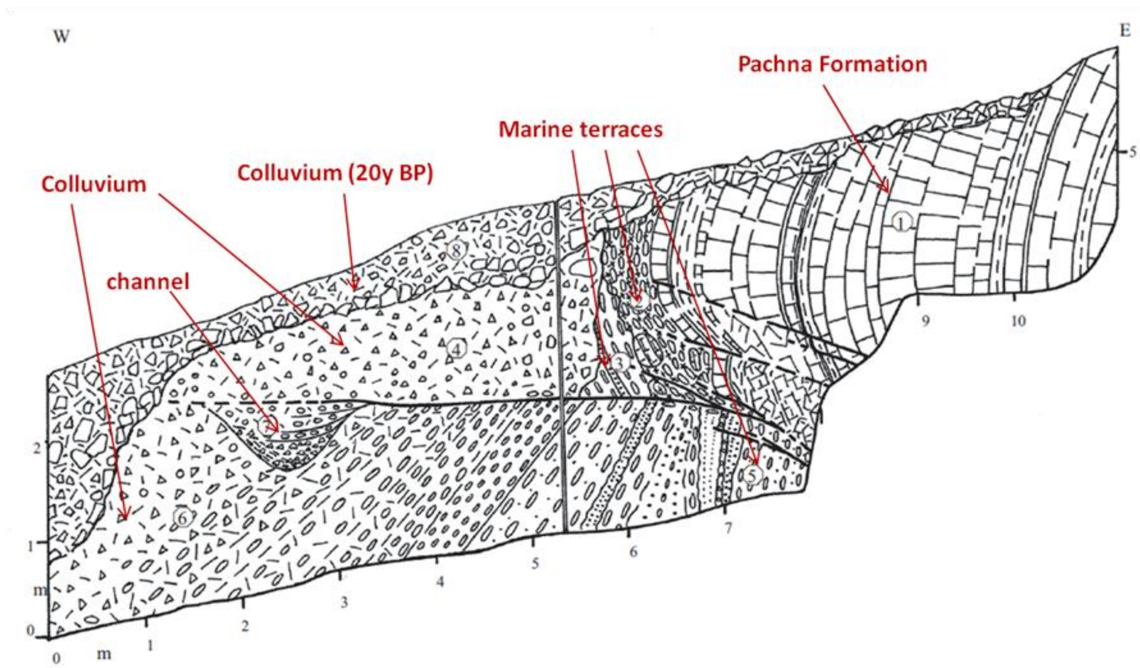


Figure 4-8 Trench log on the west flank of the fold (NEOCYP Consortium, 2005). The folded Miocene strata is thrusted over the MIS 5e and MIS 7 terraces.

4.4 Natural resources and the foundation of Ancient Pafos

The exploitation of natural resources and raw materials and their proximity to a site is of primary significance in the establishment of a new settlement. The foundation of Ancient Pafos during the transition from the Middle to the Late Bronze Age was directly related to the copper trade: Palaipafos is believed to have been founded as a gateway for the export of copper resources (Iacovou, 2012). Its location proximal to running water, forest resources and good agricultural land must have provided added advantage for the people and the polity of Palaipafos. The following section is diachronic in focus, incorporating cultural activities from the earliest, prehistoric settlers to present day.

4.4.1 Ore deposits, mining and ancient slag heaps

The extraction of copper ore and the production of copper on the island of Cyprus in antiquity has gained a lot of attention in both geological and archaeological studies. Until recently, however, almost all archaeological attention had focused on the copper resources and copper smelting in the northern Troodos foothills (Given and Knapp, 2002), and in relation to ancient polities of the central and eastern part of the island, like Tamasos, Enkomi, Salamis, and Kition. Copper ore was mostly mined from pillow lava exposures which are much better exposed in the northern foothills. Copper slags in the northern foothills are found at similar elevations as copper slags in Pafos but the terrain in Pafos is more difficult than the terrain in the northern Troodos foothills. Copper, however, was also exploited from the extensive exposures in the sheeted diabase rocks in the western part of Troodos, in what is known as the Pafos forest.

Figure 4-9 Dedicatory inscription dated to the first century BC from the sanctuary of Palaipafos.

Despite the fact that the urban nucleus of the ancient polity has only recently become the target of a long-term archaeological investigation, the evidence of slag found in the sanctuary in association with Late Bronze Age pottery hints to the copper industry providing the export economy of Palaipafos since its establishment during the second millennium BC. The metals´ economy continued to have the same primary significance for as long as the island was divided into many autonomous kingdoms, and also afterwards when it became a colony first of the Ptolemies and later the Romans. During the Roman period, Cyprus produced and exported large quantities of copper. The importance of Cyprus as a copper source for the Roman Empire is shown by the fact that pure copper was described as *Aes Cyprium* by the Romans, namely Cypriot copper and also by Pliny's statement that copper was discovered in Cyprus (Kassianidou, 2011).

The alphabetic inscription on the base of a first century BC statue from the sanctuary of Aphrodite describes the primary importance that the copper industry continued to have for the Ptolemies' colonial administration. The inscription mentions that the statue was dedicated to Potamon, a Cypriot who had held the high office of antistrategos and was also director of the copper mines of Cyprus, shown below in original text:

> «ΑΦΡΟΔΙΤΗ ΠΑΦΙΑ ΤΟ ΚΟΙΝΟΝ ΤΟ ΚΥΠΡΙΩΝ ΠΟΤΑΜΩΝΑ ΑΙΓΥΠΤΟΥ, ΤΟΝ ΑΝΤΙΣΤΡΑΤΗΓΟΝ ΤΗΣ ΝΗΣΟΥ ΚΑΙ ΕΠΙ ΤΩΝ ΜΕΤΑΛΛΩΝ, ΤΟΝ ΓΥΜΝΑΣΙΑΡΧΟΝ ΕΥΝΟΙΑΣ ΧΑΡΙΝ».

Even if the ancient copper slag deposits in the Palaipafos polity are fewer and smaller in relation to other locations in Cyprus (Figure 4-10), the picture becomes quite impressive after extensive bibliographical research and a few survey field trips. Table 4-1 lists the size and age (where known) of the copper slag heaps in the broader Palaipafos polity. During this study, copper slag pieces were also discovered amongst the beach gravels on the Palaipafos coast just east of the mouth of the Diarizos river (Figure 4-11). These slag pieces, probably derived from some metallurgical activity at the head of the catchment basin of Diarizos or Xeros, made their way down the coast in the Diarizos river, judging from the rounded shape they have.

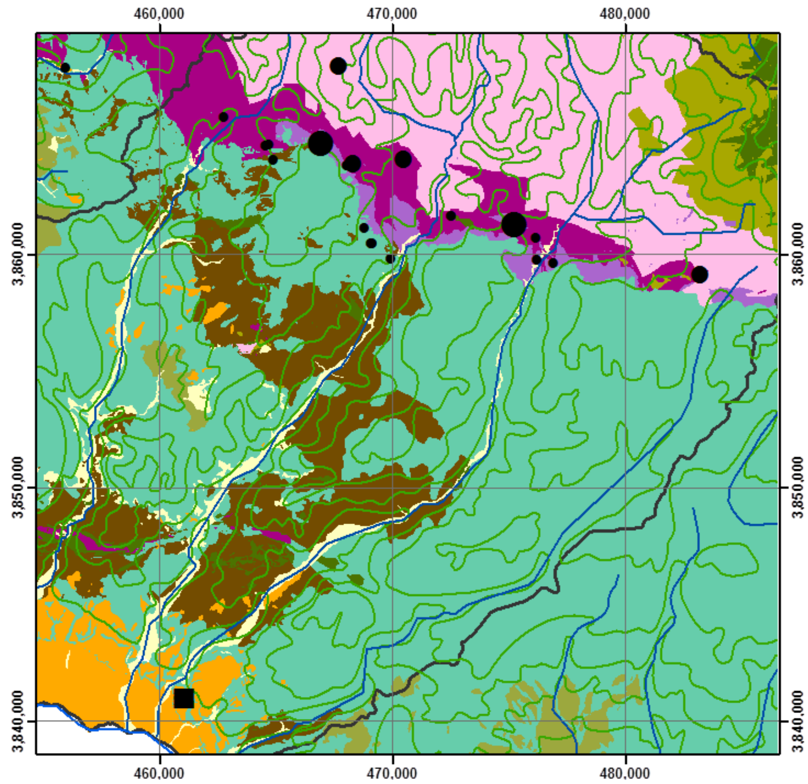


Figure 4-10 Map of ancient copper workings, small dots depict small heaps,medium dots depict medium heaps and large dots depict large heaps. Colors correspond to the geological map of Cyprus (see Chapter 2).

Figure 4-11 Rounded pieces of copper slag found in the beach deposits on the Palaipafos beach.

The unique characteristic of the copper slag heaps of the Pafos area is that they are numerous and testify to substantial metallurgical activity. The heaps are small but spread over the mountains in an almost even distribution. The heaps occur in the pillow lava deposits of the Troodos Ophiolite Terrane and some in the lava series of the Arakapas Terrane. The pillow lavas of the Arakapas Terrane extend in a 2-3 km wide zone from the Limassol Forest all the way to the village of Panagia to the west. Their affinities are similar to the Troodos lavas and the fault zone in which these two terranes meet is characterized by lava breccias and undulating terrain. In the Vretsia and Pano Panagia area volcanic vents lie along 340^{o} fault lines in an area where 340^{o} dykes are abundant (Gass *et al.*, 1994).

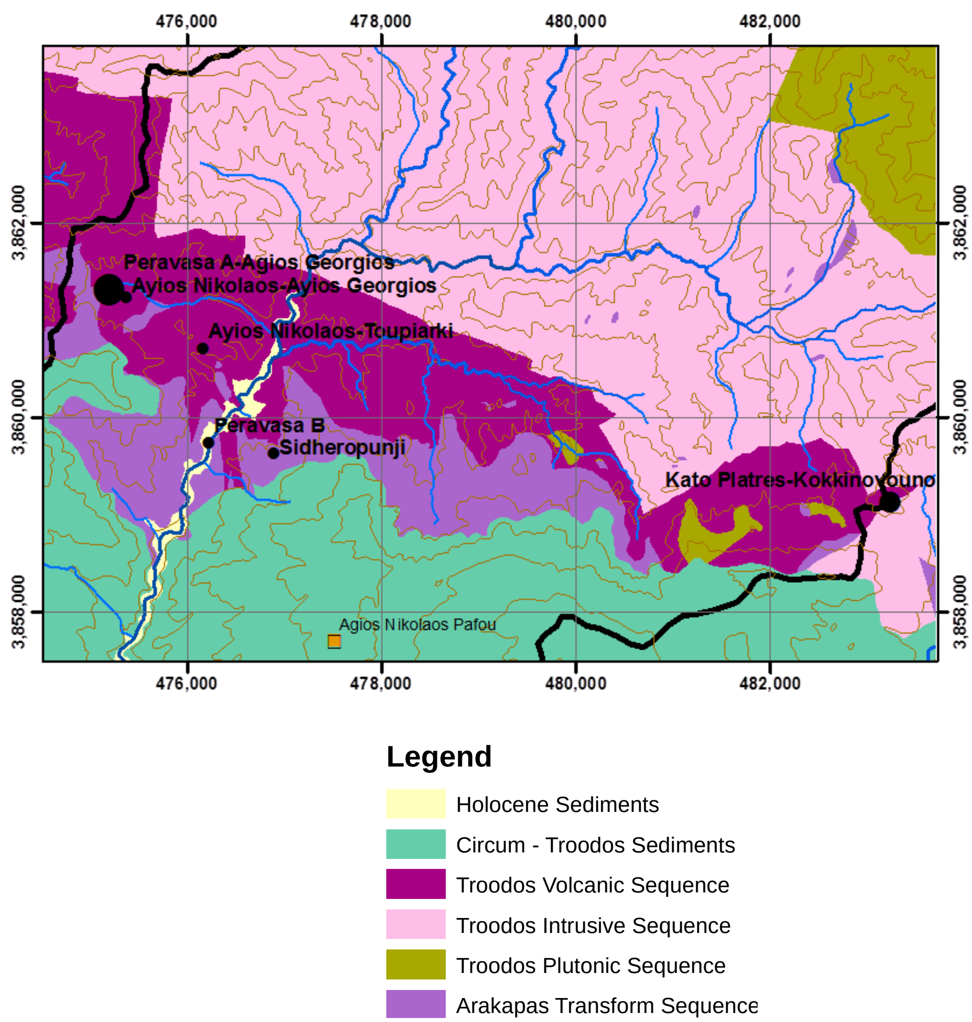


Figure 4-12 Copper slag in the Diarizos river.

The Petalas orebody in Peravasa was mined in the 1950's and consists of an orebody with an estimated size of 100,000 tonnes averaging 30% sulphur and 0.75% copper. This orebody is associated with the Peravasa slag heaps adjacent to the Peravasa Forest station (Figure 4-13, Figure 4-14, Figure 4-15). The modern Vretsia mine (Figure 4-17) at the Mala location explored a 200,000 tonne orebody with 25-43% sulphur 0.45 - 0.55% copper and 0.30% zinc. These modern mines utilized the same deposits available in antiquity to the ancient miners of the Palaipafos polity.

Figure 4-13 Large heap of ancient copper slag at Peravasa, terraced and reforested by the Forestry Department.

Figure 4-14 Pieces of slag, ochre, stone tools and bricks lay on the Peravasa terraced slag heap.

Figure 4-15 The base of the Peravasa heap was dug and charcoal – bearing slag pieces were sampled for ^{14}C analysis.

Copper did not cease to be a high-value material during the Iron Age (on Cyprus begins around 1100 BC). Iron has more widespread demand at this time. Iron ore, originating from many of the same mines as copper, is friable and easy to process compared to copper. With iron being vulnerable to corrosion, copper and bronze continued to be preferred for the manufacture of cultural objects and household items. Iron was widely used for weaponry.

Figure 4-16 Sideropungi slag piece and sample geochronology point

Iron is abandunt on the surface and its extraction and processing easier than copper production. Iron–rich deposits are gossans (80% Fe) and deposits of umbers and ochre (up to 20-30%), always associated geologically with the upper pillow lava deposits. These deposits are also self–fluxing. Their abundance as surface outcrops shift the metals industry from site specific copper sites to the more geographically dispersed iron ore sites. Metallurgy is easier both technologically and in the sense of manpower. The oxidizing characteristic of iron makes its use limited to the use for tools and weapons. Copper production continues since copper and bronze are excellent materials for the making of cooking and religious ware, jewelry, coins and art, items intended for long time use. The copper slags of the broader Pafos area appear to be rich in manganese, an element often used as flux material during the smelting process, which was common practice during the Roman / Late Roman period (Kassianidou, pers. com., 2012).

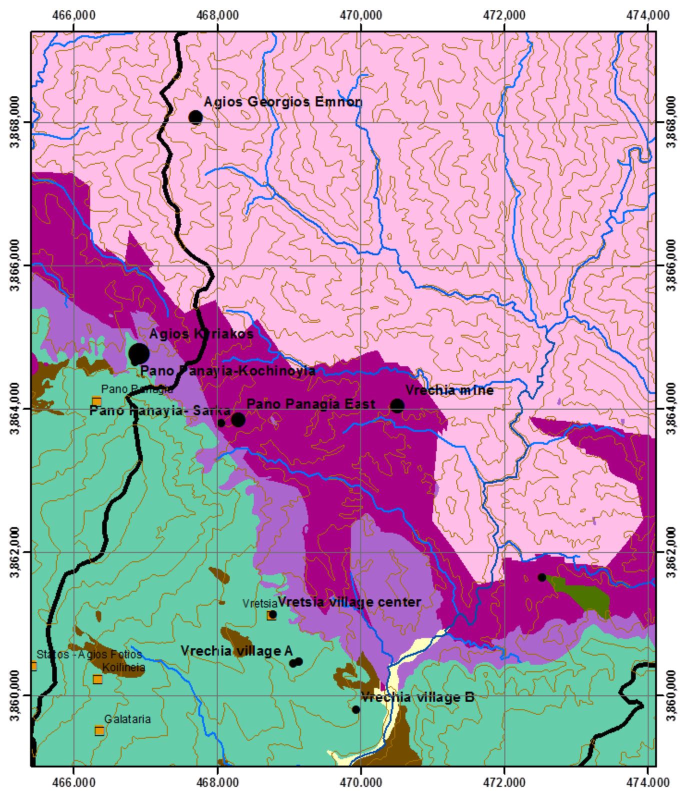


Figure 4-17 Copper slag locations in the Xeros drainage basin

Figure 4-18 Pano Panagia slag has been quarried for road foundation material.

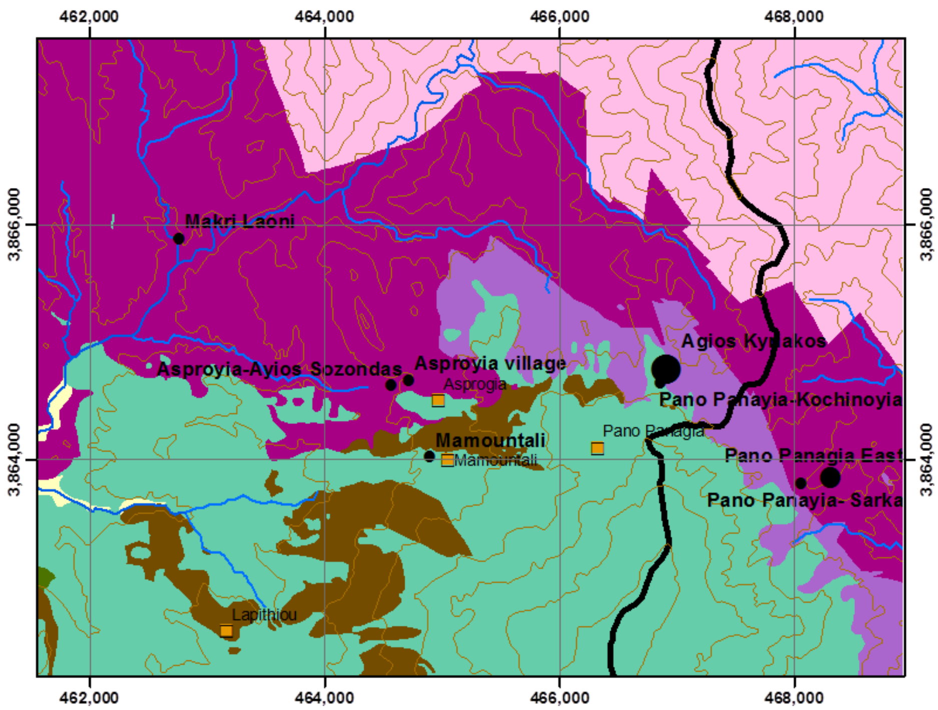


Figure 4-19 Copper slag locations in the Ezousas river drainage basin.

Table 4-1 Ancient slag locations in the broader Palaipafos Polity area

Name and location	**size**	**description**	**Reference and chronology**
Sideropunji (Figure 4-16)	1 medium heap	Small heap preserved, the rest spread in vineyard and used for building vineyard terrace	365 ± 35 AD, charcoal, ^{14}C (this study)
Vretsia village	2 medium heaps	Spread in village	This study
Vretsia	2 medium heaps	In fields southeast of village	This study
Agios Georgios, Peravasa (Figure 4-13)	Very large heap	7-10 m tall heap, up to 50 m in diameter terraced and planted by Forestry Department, by Agios Georgios chapel at Peravasa Forest Station	315 ± 50 AD, charcoal, ^{14}C, (Zwicker, 1985, 1986) 365 ± 35 AD, charcoal, ^{14}C (this study)
Ayios Nikolaos-Ayios Georgios"	Large heap (2,500 m^3)	By Peravasa Forest Station in Argakin tis Skourkas river	Rupp *et al.* (1984) Gale *et al.* (1998)
Ayios Nikolaos-Toupiarki	small	On the road to Peravasa Forest Station	Rupp *et al.* (1984), ceramics suggest Byzantine - Medieval
Peravasa, Arminou dam	small	Buried by water of modern reservoir	Gale *et al.* (1998)
Asproyia	small	In village, Destroyed by modern earthmoving	Gale *et al.* (1998)
Makri Laoni	patch in field	Northwest of Asproyia	Gale *et al.* (1998)
Mamountali	patch	Mamountali village	Gale *et al.* (1998)
Kioni	patchy	Neo Chorio on road to Akamas	Gale *et al.* (1998)

Table 4-1 (Continued)

Name and location	**size**	**description**	**Reference and chronology**
Agios Kyriakos, Kokkinoyia Panagia (Figure 4-20, Figure 4-21)	Large heap (875 m^3)	On the side of mountain close to a monolith menir of Agios Kyriakos chapel ruin	Gale *et al.* (1998)
Panagia Sarka (Figure 4-18)	2 large heaps (2650 m^3)	East of Pano Panagia village, in Khandakas river	Rupp *et al*. (1984)
Agios Georgios ton Emnon, Panagia	medium	Panagia village	Gale *et al.* (1998)
Asproyia-Ayios Sozondas"	Small-medium	24 mining adits associated with a gossan in pillow lavas in the Lakkos tis Sterajas valley with slag heap	Rupp *et al.* (1984)
Kato Platres-Kokkinovouna	patchy	Mining adits and possible refining site with some slag	Rupp *et al*. (1984) Roman provenance
Agios Ioannis Pafou	medium		Geological Survey Archives

Figure 4-20 Agios Kyriakos slag heap, east of Panagia village.

Figure 4-21 Perforated monolith used in animal-driven olive presses, at Agios Kyriakos, slag heap is located in the background.

4.4.2 Building Stone and stone tools

Important since Neolithic times, stone tools were significant in sustaining life. Used in agricultural activity, preparing food, general housekeeping, and later in metallurgy, these raw materials are mostly derived of hard ophiolite lithologies such as diabase and gabbro. Chert was the first geological resource needed by the Neolithic settlers. Chert was used to make small tools for hunting, skinning animals, harvesting and preparing food (Simmons and Reese, 1993). Chert was used until recently in the making of doukani, wooden panels with chert pieces inserted in slots at its bottom side and pulled by animals on threshing floors over harvested cereals for the separation of the grain from the straw. Chert is abundant in Upper Cretaceous – Palaeocene Lefkara Formation chalks in bands and nodules (Figure 4-2). Boulder-size chert pieces, resistant to erosion, are also found in alluvial deposits in the Diarizos and Xeros river channels.

Figure 4-22 Local and imported stone.

Figure 4-23 The sanctuary ruins of ashlar blocks constructed with Pachna Formation Calcarenites (Upper sub-littoral facies).

River boulders, usually diabase, found in the Diarizos and Xeros lower river beds were used to make grinding tools. Umber, ochre, and terra verde from the vicinity of the pillow lavas were mined and used as pigment color. Umber was also later used as a flaxing agent in copper smelting. Marl was mined until recently from the nearby Pachna chalks, mostly the clay-rich horizons, and processed in lime kilns for the making of house plaster.

Figure 4-24 Marbles, chalks and calcarenites used as elaborate building blocks now stored in the museum area.

Carbonate rocks and conglomerates of the Pachna Formation, as well as marine terrace calcarenites, offered abandant sources for building material, monoliths, statues, pillars, temple ashlar blocks and various tools. During the Roman period, elaborate mosaics (Figure 4-26) were crafted with a wide variety of materials, local and imported (Michaelides, 1989). Imported Quaternary vesicular basalts from the Levant were popular grinding stones on Cyprus (Elliot *et al*., 1986; Xenophontos *et al*. 1988; Williams *et al*., 1991). Pieces have been found scattered in the study area and the Museum area (Figure 4-25). A basalt artefact from the Kouklia-Evreti alalysed by Xenophontos *et al*. (1988) revealed Levantine affinities (Syria, Palestine, Jordan). Limestones, marbles and granites from outside sources must have arrived on ships and exchanged for other goods. The fact that the ancient Cypriots imported rock materials on such a geodiverse island confirms that during periods of prosperity trading patterns were advanced and complex.

Figure 4-25 Quaternary basalt piece imported from the Levant area at the Kouklia museum.

Figure 4-26 Mosaic depicting Leda and the swan, adjacent to the sanctuary, dating to the end of the 2nd century – beginning of the 3rd century AD.

4.4.3 Forest resources

Abundant, sustainable and easily accessible forest resources of wood were available for construction, fuel and copper. There are no renewable forest resources in the coastal lowlands. Any forest resources in this coastal area, especially the zone between the Diarizos and Hapotami rivers which is the most easily accessible by people living on the Palaipafos mesa, must have been the first to be used and exhausted. Forest of juniper and pine at higher elevations, close to Palaipafos and away from the inhabited alluvial fans is still available today. Wood for copper smelting must have been used only in the close vicinity of the copper smelting furnaces. In the case longer trips were needed for wood resources, it is believed that charcoal instead of wood could have been transported for longer distances with more ease. The fact that charcoal is primarily found in copper slag deposits and never unburned wood is a fact pointing to this direction (Kassianidou, pers. com, 212).

Forest hunting must have added significantly to the diet of the Palaipafos area. In wells used later as dump sites (vothroi), 5,000 pieces of animal bones were excavated by Maier in the Palaepaphos-Evreti wells showing preference for wild fallow deer in the meat diet (Maier, 2004). Besides deer, Halstead (1977) has also identified bones of various birds, but also of domesticated animals like cow, sheep, goat, equid and dog. Halstead (1977) concludes that the abandunce of follow deer bones can reflect that forest hunting was going on.

4.4.4 Clay resources

Clay deposits were an important resource for making pottery, and Cypriots have been manufacturing pottery since the Late Neolithic. Southwestern Cyprus has extensive outcrops of clay-rich formations especially in the Mamnonia terrane. King (1987) sampled clay raw materials at 29 locations and correlated geochemical signatures from neutron activation analysis with pottery sherds in southwestern Cyprus. Using discriminant function analysis, he concluded that surficial sediments like alluvium and clay horizons from soil profiles were preferred sources for pottery clay instead of clay from rock formations. He also speculated that these surficial sediments have a more diverse admixture of clay types and offer better raw materials for pottery products. In Palaipafos, elaborate and decorated pottery accompanied many burials in the Skales and Asprogi cemeteries (Figure 4-27).

Figure 4-27 Pottery from Palaipafos Skales location, both 10^{th}-11^{th} century BC, photographs taken from Flourentzos (1996).

Sugar cane industry pottery demanded large clay resources in the Medieval period based on the finds of sherds in 24 sites in the broader area of Palaipafos and nearby Achelia village (Gregory, 1987). As much as 6,700 pieces of clay moulds for sugar cane production and of pithoi were collected from Stavros locality alone attesting to the big demand for pottery.

4.4.5 Agricultural land and industrial crops

The alluvial fan plateau and the coastal lowlands must have been attractive to the first inhabitants and founders of Palaipafos during the Bronze Age. Hosting thick and red soils (Figure 4-30), these soils can easily sustain production of crops intended for local consumption. The olive press at Stillarka locality is evidence for agricultural activity in Antiquity. In the Medieval period, the coastal lowlands sustained sugar cane cultivation for processing and export of sugar. The Pafos lowlands, extending from Geroskipou to Palaipafos (modern Kouklia) and even including the small valley of Hapotami river just east of Kouklia, are very well known as established chifliks, presently organized into agricultural research estates. In 1959, the Kouklia chiflik had a total area of 2,860 donums (3.82 km^2 or 382 ha), 99% of which was listed as cultivable and irrigated (Christodoulou, 1959).

During the Roman period, rural population on Cyprus was divided into free farmers (the coloni) and the slaves (ascripticii), a system established by the Romans and later adapted by the Christians (calling them parici and enapographi respectively). Enapographi worked on these organized farms (Christodoulou, 1959). Chifliks, as they are still known today, are agricultural estates established in the feudal system by the Franks and renamed chifliks by the Ottomans. They were owned by the religious institutions (Greek or Latin church or the Moslem Evqaf), the king’s people or the king himself. They were managed by the local chief and passed down to family members. They usually employed large numbers of local agricultural workers.

The British colonial government dissolved these estates in 1945 by purchasing the land from the owners and turned most of them into agricultural research institutes. In the Palaipafos area, there are two such research institutes, one in Achelia and one in Kouklia.The Hapotami chiflik, in the Hapotami valley, belonged to the Monastery of Sinai of Egypt until the 1950’s when it was sold to a private owner who cultivated bananas and vines. In the late 1970’s it became the “Venus Rock Estate” which was later developed into the Secret Valley community with almost 600 housing parcels.

It is remarkable that unlike almost every other place on Cyprus, the study area does not have stone-built terraces outside the ancient or present urban nucleus of Palaipafos. Only a few check dams are present in two smaller streams in the lowlands. Preservation of soil on the slopes seems not to have been an issue for the people in Palaipafos. Fertile soil resources are plentiful in the coastal lowlands and the flat plateaus. The 1994 agricultural census (Department of Statistics and Research, 1994) classified Kouklia as one of the most agriculturally rich communites in the Pafos district with a total of 12357 donums (16.53 km^2, 1653 ha) of agricultural land, 30% of which are irrigated. Of this agricultural land, 28% is cultivated with annual crops, 10% with permanent cultivations, 4% remains fallow land and the rest is not cultivated, or classified as private forest land or scrub land. Kouklia compares well with the other 120 communities in the Pafos district and is listed second only after Pegeia (19812 donums) in total agricultural area (Department of Statistics and Research, 1994).

In 1788 Kyprianos (Kyprianos, 1788) writes:

> "This village is today called Kouklia. It is one of the first on the island in terms of productivity, it produces cotton, silk and other necessities like wheat and barley. Sugar cane was cultivated until the times of the Venetian rule, producing large quantities of sugar. There are many signs of antiquities and of its natural beauty. It was considered one of the most important polities of those times. There were until today, tombs of the ancient people underground, around 1490, a king's body was discovered …"

Palaipafos must have been self–sufficient during Antiquity with production centered on cereals across the vast flat, fertile lands in its lower plain. In contrast to Kyprianos, the Spaniard Ali – Bey of Abbasii, son of Othman Bey of Aleppo, visits the village of Kouklia in 1806 and writes (Ali – Bey, 1806):

> "The principal tenant of Couclia expected us, and had prepared a great dinner. He complained that the Sultana, the owner of the farm, would spend nothing in repairs (here referring to the village and the Sanctuary). Every day the place grew more ruinous. He pays twenty purses (ten thousand piastres) a year. Very few trees still remain. But one can guess from the water courses that there were formerly large gardens, as well as palaces and buildings of vast extent."

More than half a century later, between 1874 and 1875 Di Cesnola pays two visits to Palaipafos in search of ancient treasures. He writes:

> "Gently sloping from Kouklia towards the shore, there is a fine and fertile plain belonging to the castle; this plain must formerly have been thickly wooded, and was doubtless the grove spoken of by Homer. At the moment I am writing, it is covered with ripe barley, and seems a sea of gold. A few hundred yards from the coast are the remains of another temple, the foundations of which are also oblong. This must have been the Temple of Venus built to commemorate the spot on which for the first time the beautiful goddess is said to have appeared to the Cyprians…"

Cesnola (1877) refers to the Hellenistic olive press workshop at Stillarka, a coastal location between the Xeros and Diarizos rivers. Some worshipping practice may have taken place hand-in-hand with olive oil production with religious beliefs lasting longer than the factory itself. It is not known when the olive press was abandoned (Maier *et al.*, 2004) but it is worth noting that olive trees are presently not dominant on the coastal landscape. The perforated monoliths (Figure 4-28), usually referred to as menirs, are widespread in southwestern Cyprus and some other coastal locations. They are believed to function as weight levers for olive pressing during the production of olive oil or possibly pressing of grapes for wine making (Hadjisavvas, pers. comm., 2012).

Figure 4-28 Perforated monoliths and olive oil tanks excavated at Stillarka location. Modern aggregate crushing plant in the background.

A flat and broad coastal feature is characteristic of coastal communities in Cyprus but especially characteristic of coastal Pafos communities. From Kissonerga to Kouklia, communities (Kissonerga, Lemba, Emba, Ktima, Geroskipou, Koloni, Agia Marinouda) are usually located on the upper terrace of Marine Isotope Stage 7 and have their agricultural parcels and pasture lands in the lower Marine Isotope Stage 5 terrace. These coastal lowlands have favourable mild winter climate.

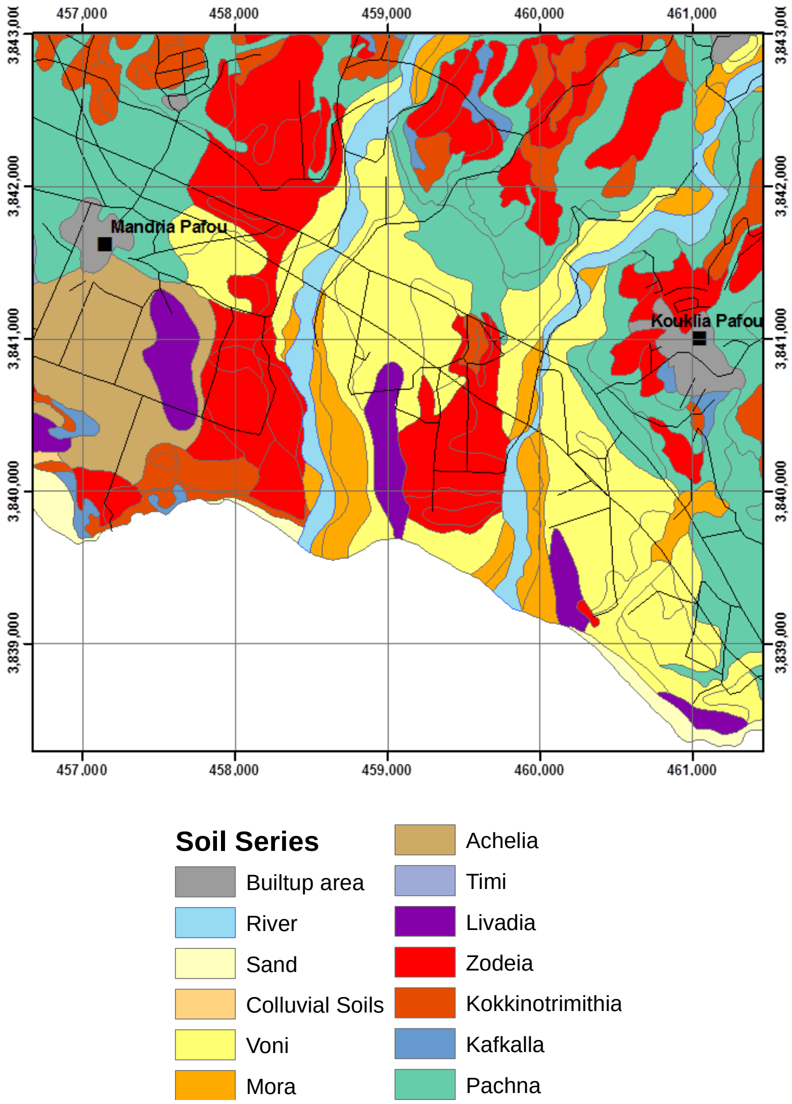


Figure 4-29 Soil map of the study area (from Soteriades and Koudounas, 1968).

The coastal lowlands of Palaipafos are even more suitable for agriculture based on the fact that the lower valleys of Xeros and Diarizos rivers provide irrigation water and broad flood plains with rich soils. These soils, were presented in the previous chapter and shown here in more detail in Figure 4-29, include the Zodeia and Kokkinotrimithia red soils on the older alluvial fans and on the Kafkalla petrocalcic horizons of marine terraces, deeply developed Achelia and Voni alluvial soils, and the more recent Mora soils on the active flood plains of the two rivers. Livadia soils are hydromorphic, vertic (50% clay) and saline soils and are not suitable for agriculture without the construction of artificial drains due to the high water table (at <1 m depth during summer). Figure 4-30 summarizes all of the soil property information, taking into consideration topography and plots what is premium and good agricultural land.

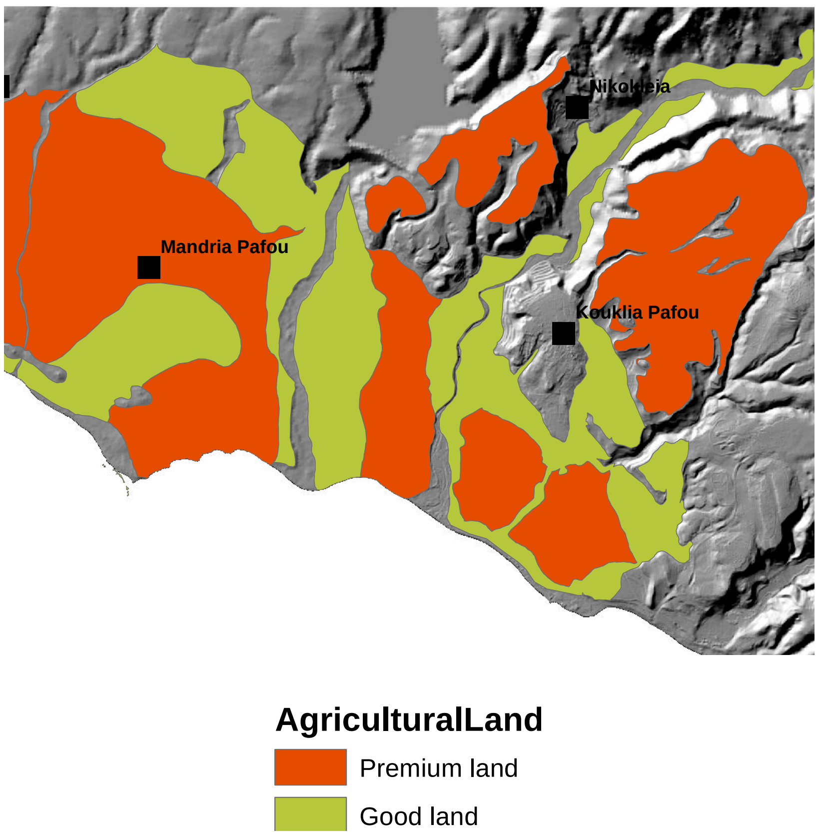


Figure 4-30 Premium and good agricultural land based on soil properties and topography.

Palaipafos, is also known for two important industrial crops, cotton and sugar cane. Cotton is a low water demand crop but sugar cane is a crop high in water demand and needs irrigation. Kouklia grew cotton and sugar cane for export. It even developed a sugar cane processing plant producing what used to be called *Polvere di Cipro,* it was of excellent quality, well bleached and refined (Christodoulou, 1959). Sugar cane industry demanded large clay resources for the production of specialised vessels that were not reusable. Their fragments were recorded in 24 sites in the broader area of Palaipafos and nearby Achelia village (Gregory, 1987). The 6,700 pieces of clay moulds for sugar cane production from Stavros attest to the size of the industry (Maier *et al*, 2004).

Production of sugar cane continued until the 17th century (Christodoulou, 1959), just before the beginning of the peak of Little Ice Age in Europe (1690 – 1760 AD, see Table 1-4). Lower temperatures during the Little Ice Age may have reduced sugar cane production and motivated the local Kouklia chiflik chief to concentrate in growing cotton instead. The reference of Ali – Bey in 1806 to abandoned water courses suggests the existence of water irrigation canals using water from the two rivers. Cane sugar was gradually abandoned when the road to India was opened and sugar came to Europe from the far east.

Figure 4-31 The sugar cane refinery at Stavros, just below the Manor House.

Cotton was another important industrial crop, this one rain–fed, intensively cultivated in Kouklia, Episkopi, Lefka and Kythrea. It soon replaced sugar cane cultivation because of the lower demands for water and was cheaper and easier to grow. During Venetian times cotton was exported to Venice, England and Holland (Christodoulou, 1959).

4.4.6 Water resources

It is remarkable how today the Diarizos river is classified as the drainage basin collecting the second largest amount of rainfall and having the second highest annual river runoff after the Kouris. Located on the eastern high banks of the Diarizos river mouth, Palaipafos has benefited from the availability of the water resources of Diarizos for many centuries. The Xeropotamos river to the west also drains from the Troodos mountains and provides premium agricultural land especially in the alluvial fans and flood plains between the two rivers. If a geographer or simply a politician were to choose a new town location in this century, amongst the many eastern Mediterranean locations, Palaipafos would score very high on this list just because of the significance of water to sustaining life in the semi – arid Mediterranean.

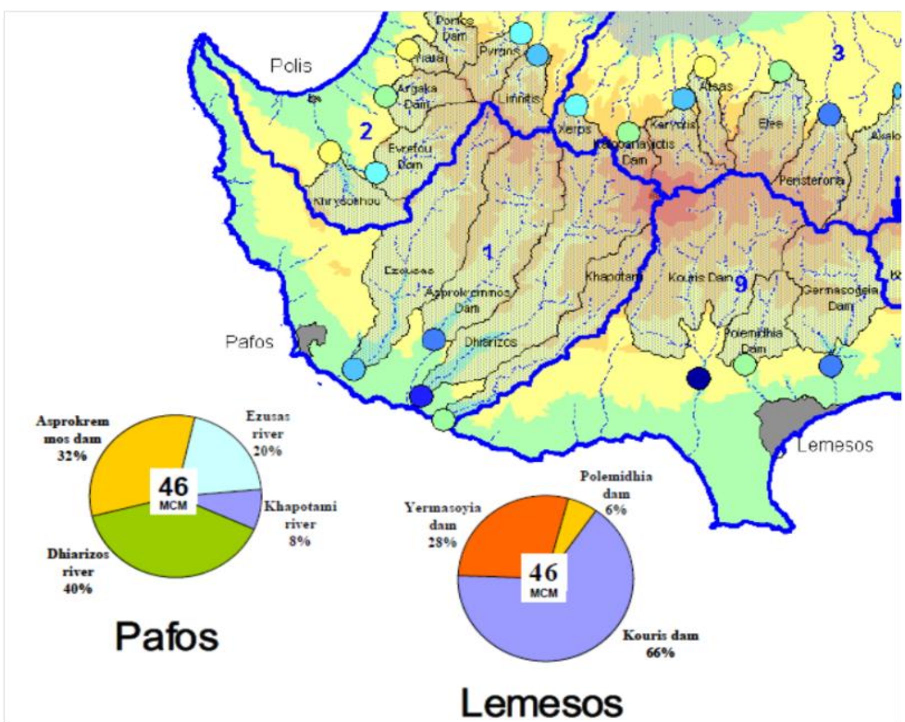


Figure 4-32 Mean annual surface runoff by watershed in the hydrological region of Pafos and Lemesos (from Rossel, 2002)

The hydrological region of Pafos has 24% of the total distribution of Cyprus surface runoff by hydrological region (Figure 4-32). The results of a recent FAO report (Rossel, 2002) show that the Pafos hydrological region has, together with the Lemesos hydrological region, the highest mean annual surface runoff of 46 million cubic meters of water each. From those 46 million cubic meters of water of the Pafos hydrological region, Diarizos has 40% of it (about 18.4 million cubic meters of water).

The proximity of Diarizos river and Hapotami river to Palaipafos must have sustained agriculture in the lower plateaus. The sugar refinery at Stavros is strategically located just above the Diarizos flood plain. Local bedrock, the chalks and marls of the Pachna Formation are not rich aquifers and the existence of surface water is here deemed important. Chains of wells, also known as qanats in the Middle East and Persia, and common in the rest of Cyprus, especially in the Mesaoria Plain, are a water resource system are not present here.

In post World War II times, water resources were demanded in the lower coastal alluvial fans and the Diarizos and Xeros river flood plains which host excellent soils suitable for agricultural use. During the late 1940’s, sub-surface dams were constructed in the Diarizos river channel near Kouklia (Christodoulou, 1959). These are constructed after the removal of gravel from the river bed and the construction of a sub – surface dam on bedrock. Horizontal water flow stopped when reaching the dam and water was forced to the surface where it was collected for irrigation purposes.

4.5 Archaeology and history up to the present

Palaipafos has been closely associated with the worship of the goddess Aphrodite. Pafos, where the goddess has her temple, is the only Cypriot state mentioned by Homer in the Odyssey (Karageorgis, 1989). The goddess, referred to as “Kypris” was worshiped at the sanctuary of Palaipafos which acted as the most important religious centre on the island. However, it is necessary to make a distinction between Palaipafos (meaning “Old Pafos”) which today refers to the modern village of Kouklia, and New Pafos, locally refered to as Nea Pafos, a large coastal town, some 17 km to the north-west. The goddess was not addressed in Cyprus as Aphrodite until the end of the fourth century BC (Karageorgis, 2005).

The worship of Kypris is closely linked to copper. Bronze statuettes of a female figure standing on an ox-hide ingot are thought to be some of the earliest representations of the deity that protects the copper industry. King Kinyras of Cyprus is her lover and priest and is most widely known as the inventor of tools and metallurgy (Iacovou, 2008b).

Palaipafos was one of the first sites to draw the attention of the Cyprus Exploration Fund in 1888—a decade after the island had been ceded to Great Britain. A second British mission, the British Kouklia Expedition, went out to Palaepaphos in the early 1950s under the epigraphist Terence Mitford of the University of Saint Andrews and J. H. Iliffe, the Director of the Liverpool Museums (Catling, 1979). In 1966 a Swiss-German Expedition took over and, besides investigating the sanctuary, it also excavated the Medieval cane sugar refinery—the finest industrial archaeology project to have been attempted in Cyprus to this day (Maier and Wartburg, 1985; Maier and Karageorghis, 1984). Meanwhile, ever since the 1960s, the Department of Antiquities has been conducting rescue digs, mostly of tombs, often on a daily basis although tomb robbers work harder on a nightly shift. After more than a century of field operations, "the city site of Late Bronze Age Palaepaphos still awaits excavation" (Karageorghis 1990).

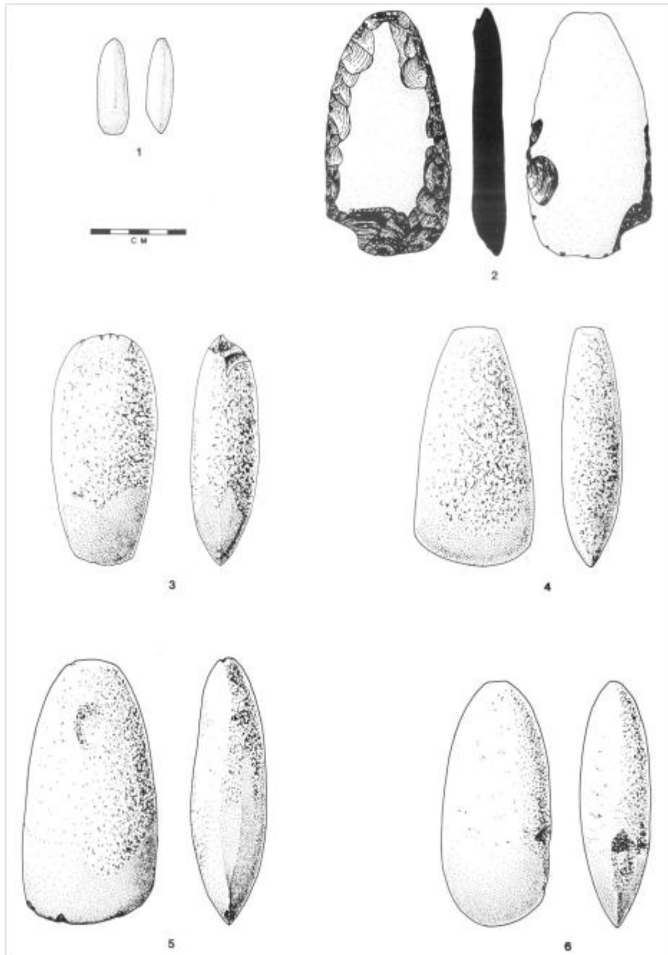


Figure 4-33 Ground and rough stone artifacts from Kouklia – Liskovouno. 1. Microgabbro chisel, 2. Diabase flaked adze, 3&4. Gabbro axes, 5&6. Diorie and microgabbro axes. Illustration from Fox (1987).

Many travelers have visited and described the sanctuary of Aphrodite. In addition to the sanctuary and the village of Kouklia, some travelers and historians have reported on other antiquities like the monuments at Styllarka, a coastal location between the mouths of Xeros river and Diarizos river. Peristianis (1930) mentions that Guillermard and Hogarth (1889) had interpreted these monuments as olive presses or olive mills.

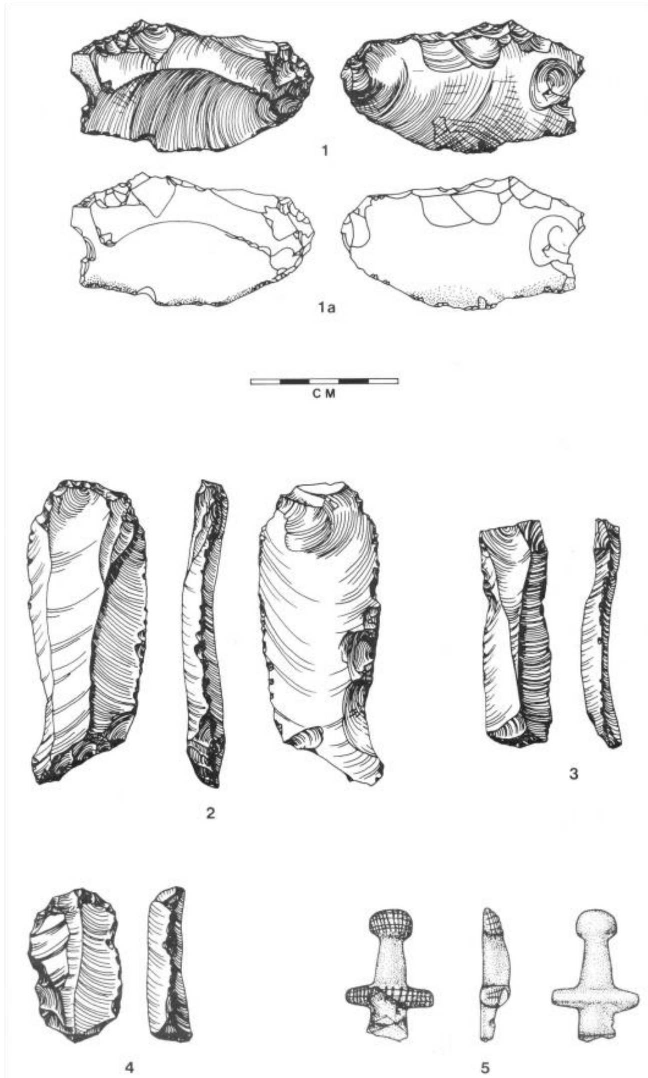


Figure 4-34 Chipped and ground stone artifacts from Kouklia – Liskovouno. 1. Chert sickle blade, 2. Chert retouched blade, 3&4. Chert and scrapers on blades, 5. Picrolite cruciform pendant fragment. Illustration from Fox (1987).

A different perspective in archaeological research was introduced by Rupp (1981, 1982, 1984, 1987a, 1987b, 1987c, 1993, 2004); Rupp et al. (1984, 1986, 1992, 1993) who tried to survey the three main drainage basins in the Palaipafos area including the smaller basin of Hapotami in the east and have published various reports on this Canadian Palaipaphos Survey Project-CPSP (Rupp, 1987a). The study was one of the first on the island to make observations on geomorphology, soils, copper slags, and generally make an attempt to incorporate these spatial and geomorphological relationships into archaeological analysis.

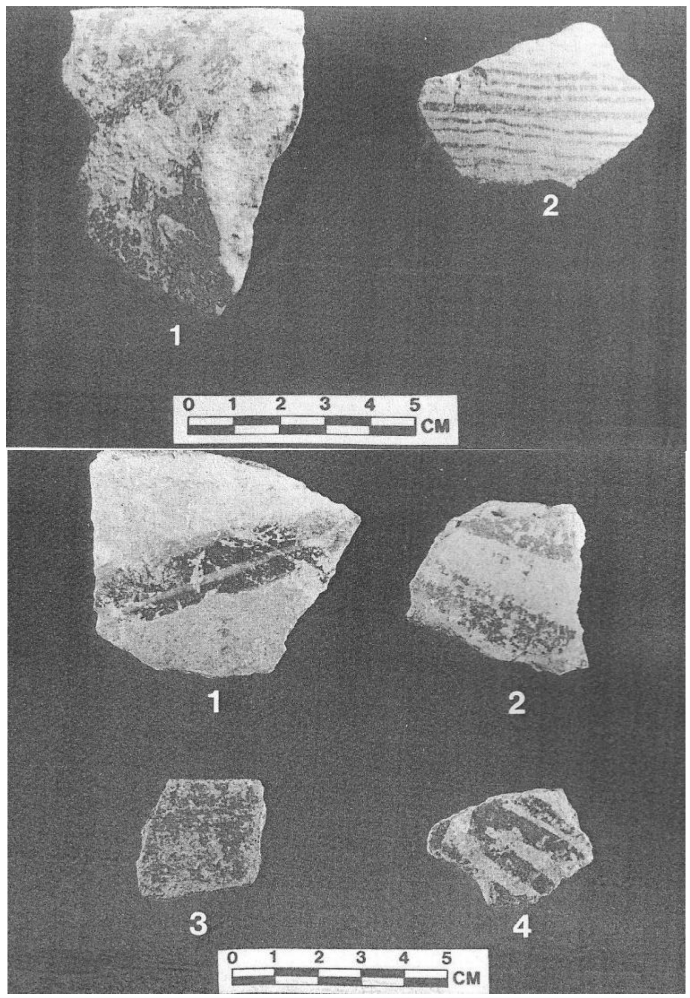


Figure 4-35 Ceramics from Kouklia – Liskiovouno (Fox, 1987).

Figure 4-36 Early photograph of the sanctuary by Deschampes (1898)

Figure 4-37 Illustration from Deschampes (1898) of the coastal location of Styllarka and the two mega-monolithic monuments.

The first signs of occupation in the immediate vicinity of Palaipafos is on the coastal site of Liskovouno where ceramic Neolithic tools, like chert blades and stone axes, pottery and picrolite pendants (Figure 4-33, Figure 4-34, Figure 4-35) had been discovered by Maier and

Wartburg (1985) and documented by Fox (1987) and Rupp *et al.* (1987). This site is located 11-13 meters above present sea – level above what appears to be an old coastline (Rupp et al., 1987). The artifact scatter is 6,000 m^2, the phosphorous soil analysis shows an occupation extension over a 1,400 m^2 area. The location of this settlement becomes important in relation to Late Holocene coastline evolution (Figure 4-38).

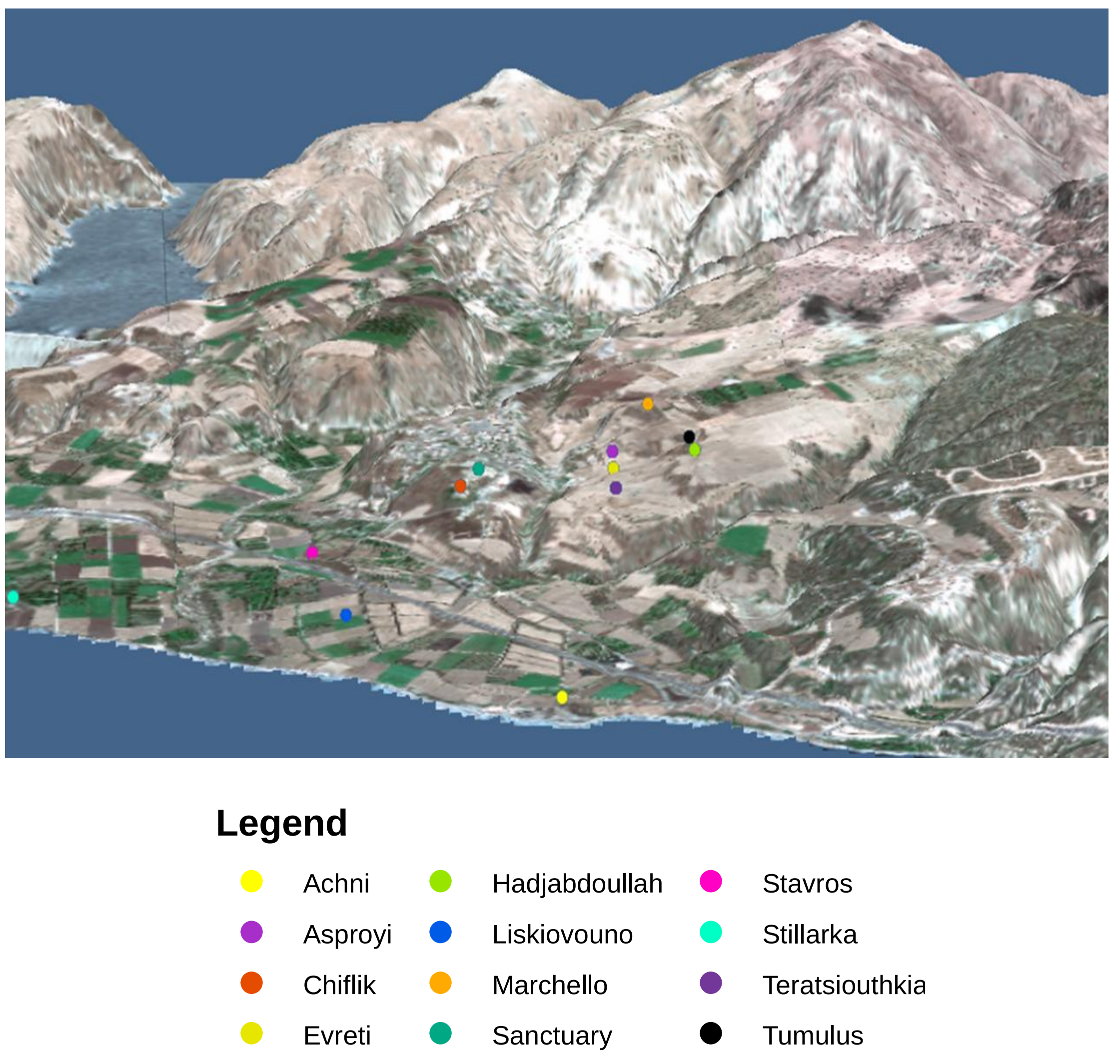


Figure 4-38 3-D scene of the Palaipafos area with vertical exaggeration

Iacovou and the Archaeological Research Unit of the University of Cyprus recently led a new survey of Palaipafos, under two project umbrellas, one titled “The Palaipafos urban landscape project” and the other titled “A long-term response to the need to make modern development and the preservation of the archaeo – cultural record mutually compatible operations” (Iacovou, 2008a). The project conducted geophysical surveys and excavations. The survey which began in 2006, took a step forward in understanding the Palaipafos area, the distribution of the archaeological sites on the surrounding plateaus and the relationships between them as parts of a town and not as individual monuments.

Figure 4-39 The walls of Marchello, location shown in Figure 4-38.

Agapiou (2010) created a relational and spatial database for the broader Palaipafos region and showed that most Bronze Age sites are located in the Diarizos valley and along the coastal lowlands. In the immediate vicinity of Palaipafos Neolithic occupation is evident in the coastal zone, just below the sanctuary in a location named Liskiovouno. Archaeological chronology from burial grounds in sites of the vicinity of the urban core of Palaipafos suggest that the polity of Palaipafos was apparently founded in the 2nd millennium BC.

Figure 4-40 The Frankish Manor house to the west of the temple, overlooking the coastal lowlands, location shown in Figure 4-38.

Figure 4-41 The palatial building of Hadjabdoullah as it stands taday, location shown in Figure 4-38.

Figure 4-42 The tombs at Arkalou (Palatia tis Rigainas, meaning palaces of the Queen), below Hadjabdoullah.

4.6 Geomorphological Interpretation

The polity of Palaipafos operated a complicated terrain in the sense that it does not lie on a gently flat area like Engomi or an extensive flat high plateau like Kourion or a low lying coastal location like Marion, Salamina or Soloi. It occupies small mesas on a small boxed area bordering, the Diarizos river in the west, a hilly carbonate terrain on the east, a highly incised valley of Diarizos in the north and the coastal lowlands in the south. The geomorphological regions in the vicinity of the polity have large differences between themselves, both in the sense of bedrock geology, surficial units and soils, and the resulting landscape (Figure 4-43). The following sections describe the different Geomorphological units as they were mapped between 2007 – 2012.

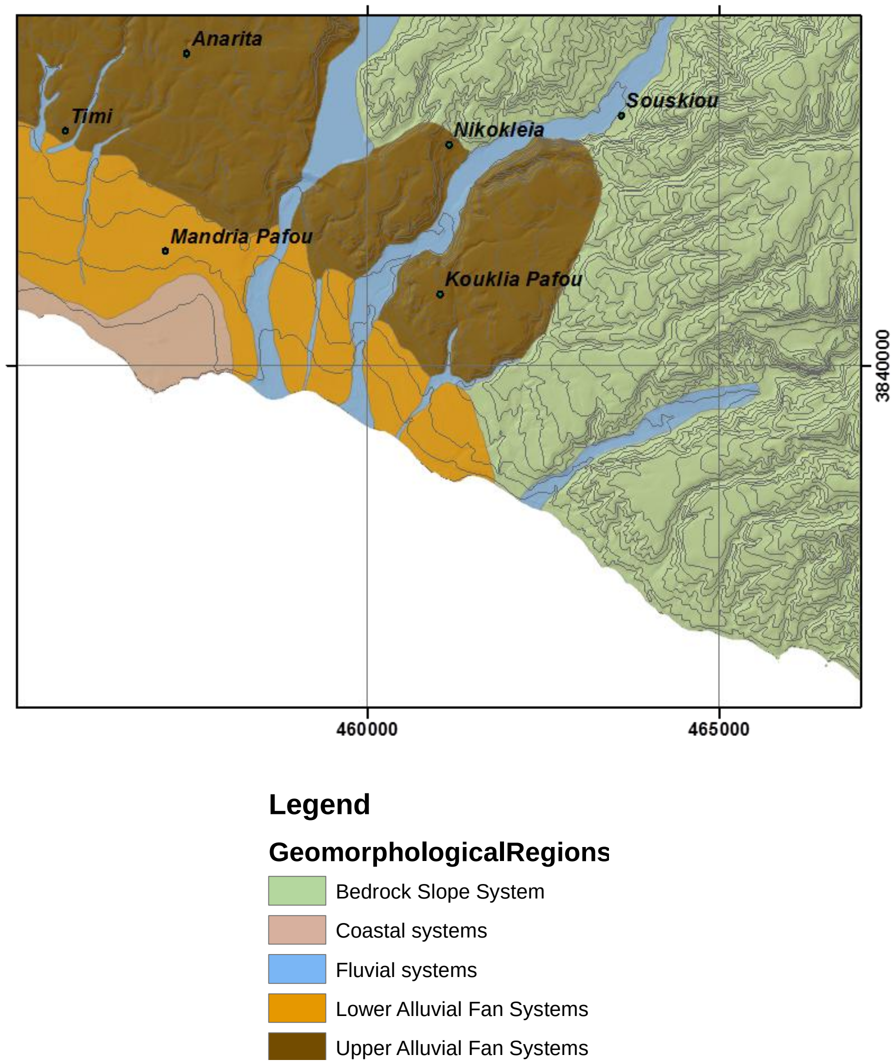


Figure 4-43 Geomorphological regions of the broader Palaipafos (Kouklia) area.

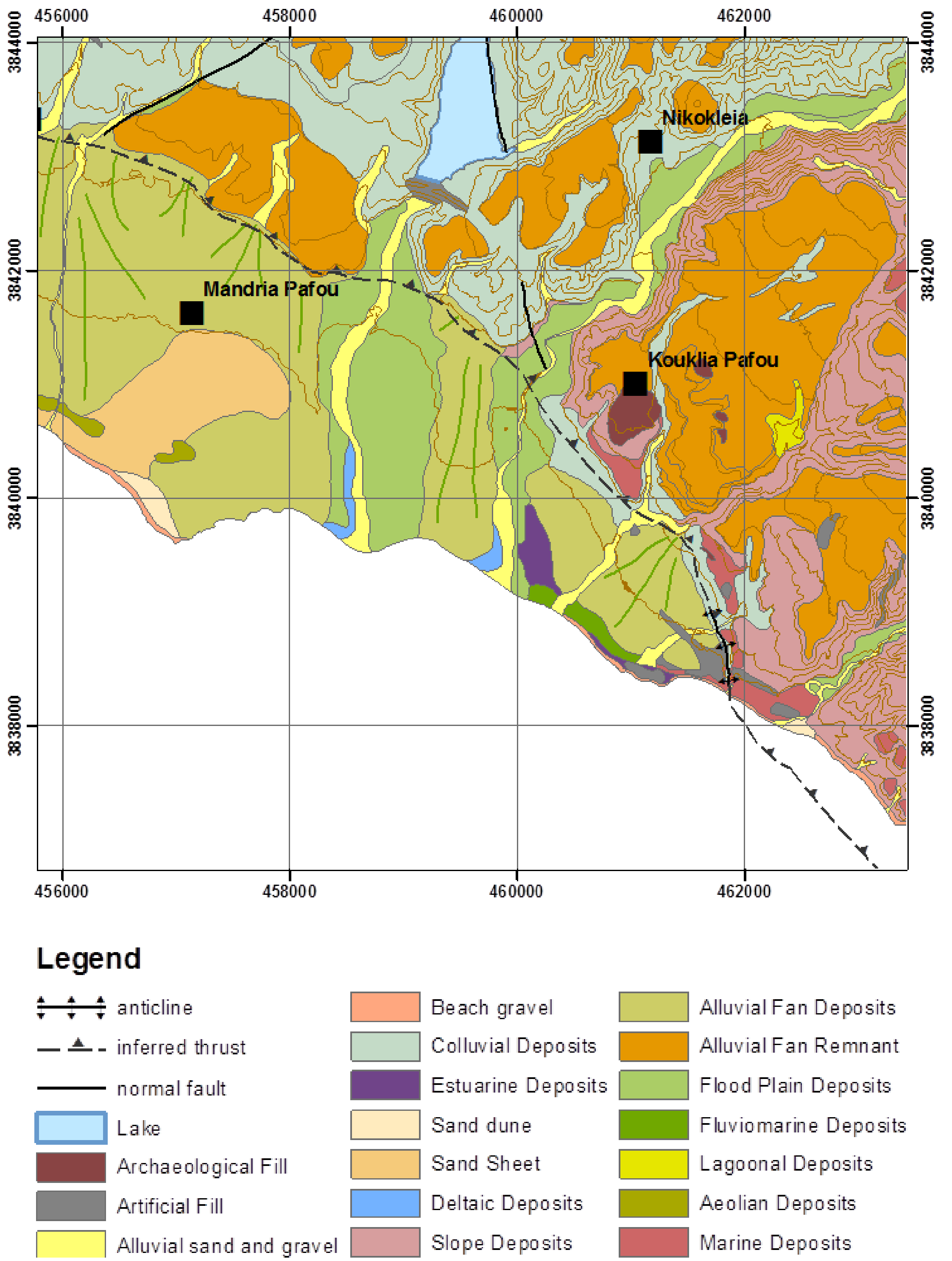


Figure 4-44 Geomorphological map of the broader Palaipafos area.

4.6.1 Artificial fill and Archaeological fill

The artificilial fill unit consists mostly of transferred earth materials used for foundations of roads and residential areas. More recently, artificial fill appears in the form of transported soil mostly for the purpose of landscaping in recreational areas like the area of the golf courses in Hapotami valley.

Man – made fill also occurs at archaeological sites. In these areas man – made fills from historic times form deposits rich in archaeological remains (Figure 4-45). These deposits contain transferred earth, broken pieces of building materials such as drafted blocks, bricks, roof tiles, floor tiles and pieces of pottery and tools. It constists of layers of building material formed over time due to the continuous occupation of a site and the construction of new buildings over older ones. In this way a stratigraphic sequence from older to younger can be expected. In Cyprus we do not have tell formations (thick accumulations from continuous site occupation) as in the near east, occupation moves around the landscape and relocates (Iacovou, per. comm., 2012). Many times, parts of this archaeological fill material is redeposited as piles of excavated material adjacent to archaeological excavations and can be up to 3-4m thick.

Figure 4-45 Archaeological fill in front of the western entrance to the Catholiki church.

4.6.2 Fluvial and gravity deposits

Colluvial slopes dominate the landscape west of the Diarizos river like they do in other areas of Cyprus. The material on these colluvial slopes are derived from the marly deposits in the the Pachna Formation, a facies much more erodible than the harder chalk facies found on the foundation bedrock where Palaipafos is situated. Poorly sorted silt to gravel-sized material deposited by gravity mostly on sloping ground forms these uncemented slope deposits in the eastern part of the study area.

Alluvium in the river beds of Xeros and Diarizos consists of sand gravel and boulders. The channel is braided in the lower 300 m of its elevation profile and numerous gravel bars form inside the channel. Two elevated fluvial terraces occur at elevations slightly higher than the main flood plain deposits. As many as seven fluvial terraces are traced on the eastern banks of the Diarizos river on the steep slope just below the village. These fluvial deposits are deposits outside the presently active channel. These fluvial terraces have in the last 30 years been terraced and planted with orchards. Alluvial fans are built on the lower reaches where the Diarizos and Xeros rivers exit the thrust – bend anticline zone just below the MIS 7 terrace and enter the lower coastal reaches. Some of the younger fans show active accumulation through the Ottoman period.

Figure 4-46 Gravel in the Diarizos river and adjacent fluvial flood plain. Channel straightening is visible with artificial levve on west (left) bank of river.

Figure 4-47 Pleistocene alluvial fan unit over Pachna Formation chalks just below the foundations of Marchello.

On the higher plateaus, 3-4 m thick alluvial fans were deposited during the Pleistocene (Figure 4-47). The Pleistocene alluvial fan on which the broader urban nucleus of Palaipafos grew is now deprived of almost all its original soil cover. If one walks, drives or ploughs the land on this alluvial fan one will remember from experience how this part of the landscape is rich in large boulders, mostly Mammonia and Troodos lithologies and is littered with pottery sherds and other artefacts. Only one location to the north of the sanctuary, by the town's football stadium shows that there is preservation of the original soil cover compared with the adjacent location on Hadjabdullah (Figure 4-48). Caclium carbonate nodules at depth attest to the age of this alluvial fan being equivalent to MIS 9. The gravels on this Pleistocene alluvial fan are the source material for the construction of the tumulus described in section 4.6.7. In contrast, alluvial fans in the eastern part of the study area, just west of Hapotami river, host thick soils and buried palaeosols (Figure 4-49).

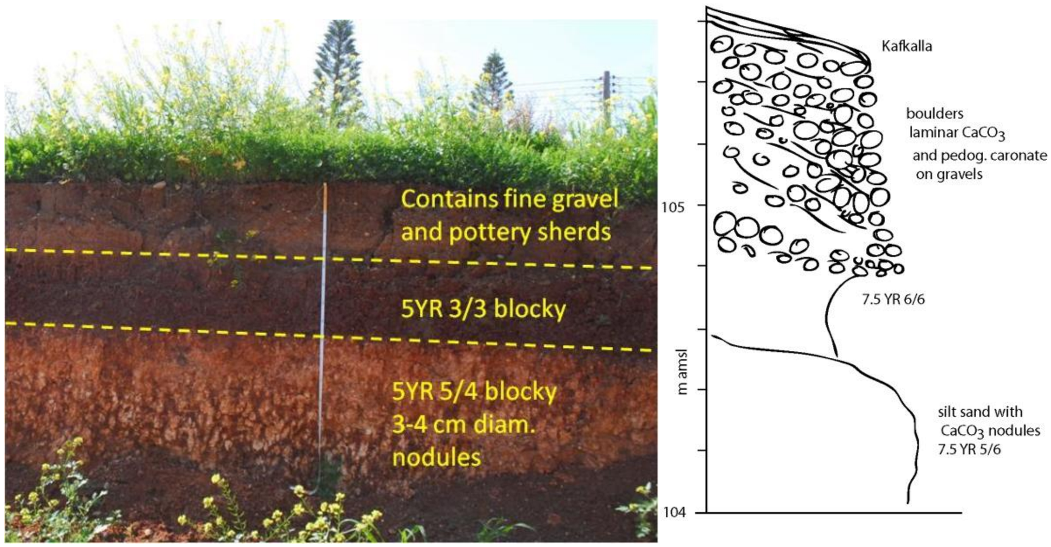


Figure 4-48 Kouklia soil section just north of the sanctuary of Aphrodite (left) and below Hadjabdullah (right), both on fluvial gravels equivalent to MIS 9.

Figure 4-49 Palaeosols on the Pleistocene alluvial fan in Hapotami valley.

4.6.3 Marine and aeolian deposits

Marine terraces in the Palaipafos area were mapped and results are presented in Chapter 2. In the Palaipafos area, from the west of Xeros river to the Petra tou Romiou Formation, marine terraces consist of gravels and sands rich in marine fauna. Calcarenites similar to the thick calcarenites of Timi and Pafos are not present here. These terraces, elevated in heights from 20 – 200 m are the result of marine processes at the eastern side of the two large river mouths which supplied the coastal zone with clastic material similar to the material found on the beaches of Mandria and Kouklia today. MIS 11, 9 and 7 occur at elevations of apr. 92m and 72 m and 44 m and Table 4-2 shows MIS 5 terrace drilled through at a collar elevation of 24m.

Table 4-2 Borehole log of the 5e marine terrace buried under Upper Pleistocene and Holocene surficial sediments drilled during the study in the Kouklia Agricultural Research Estate in November 2011.

depth		Lithological description	color
from	to		
0	2	Silty sand with some gravel (up to 3-4cm diameter), many roots	10YR 6/3
2	4	Partly cemented sand and gravel with clay matrix. Cementation increasing with depth	10YR 6/3
4	5	Partly cemented silty clay and gravel	10YR 6/3
5	6	Silt	10YR 5/3
7	9	Calcarenite, Quaternary marine terrace	10YR 7/6
9	15	Marly chalk of the Miocene Pachna Formation	

4.6.4 Fluviomarine and deltaic deposits

On the coastline, sea-level change and land progradation has created an area broadly underlain by fluviomarine sediments - marine and fluvial gravels with associated buried soils. One such recently formed alluvial fan of silts and clays on top of gravels (Figure 4-50) lies at the 0 – 10 m elevation and is here referred to as the Ottoman fan. Similar sections with accumulations of fluvial gravels have been dated by Deckers (2005) in the Diarizos river in the proximity of the sugar cane refinery at Stavros. Thermoluminesce on pottery sherds yielded a maximum age of 1613 AD. Deckers had interpreted this section as an indication of flood events. Similar 4-5 m thick flood deposits in Eastern Mesaoria (cover 14th-16th century mills in Alykos and Gialias rivers (Devillers, 2005). During this study, a charcoal sample in the Ottoman fan from about 65 cm below the surface gave an Ottoman date of 1670 ± 30 AD. Decker's correlation with Christodoulou's reference to the "Kouklia dam breaching in twenty places" because of flooding is unfortunate because Christodoulou (1959) was referring to the Kouklia dam in the village of Kouklia in Ammochostos District (eastern Cyprus). Kouklia village in Pafos never had a dam constructed in the 1940's but Deckers, nevertheless was correct in her chronology.

Figure 4-50 Geochronology sample site for the Ottoman alluvial fan on a coastal cross section.

Coastal erosion continuously cuts back a fresh section into the fan. Winter storms of 2012 exposed another section (Figure 4-51) with the charcoal layer more thick and prominent. There is no doubt of the similar age of the two charcoal layers because a few meters to the east of Figure 4-51 a clay smoking pipe dating again to the Ottoman period (Iacovou, per. com.) was found in the same stratigraphic position (Figure 4-52). The Ottoman pipe confirms the ^{14}C age and provides a maximum age on the fan and is similar to Ottoman pipes found in the Stavros sugar refinery site (Wartburg, 2001).

Figure 4-51 The “fire event” over the flood event in the Ottoman alluvial fan.

Figure 4-52 Ottoman pipe in coastal alluvial fan, *in situ* before removal and after removal with scale.

Deltaic deposits in the vicinity of the Diarizos and Xeros river deltas are a combination of coastal, aeolian and fluvial sediments deposited in river mouth environments. Gilbert type gravel deposits are common. These deposits can be found in the prograding deltas below the elevation of the main highway.

4.6.5 Estuarine deposit

This is an enclosed deposit of clay with a high content of organic matter, mapped as the Livadia soil series on soil maps. The organic matter was calculated as 2.37% in the Laboratory of the Cyprus Geological Survey. It is an estuarine deposit now uplifted at an elevation of 2+ meters a.m.s.l.. The water table is very high and the associated deposit is mapped as having hydromorphic features. The extent of the deposit is much bigger than what appears today. A typical profile of the eastuarine deposit is shown in Table 4-3.

Table 4-3 Description of a typical profile in the estuarine deposit.

Depth (cm)	description
0-20	10YR 4/2, blocky, firm, saturated clay
20-46	10YR 5/2 Medium heavy clay, saline, strong prismatic structure, plastic, mottles
46-66	5Y 5/1 Glei horizon, saline, porous, prismatic structure, mottles

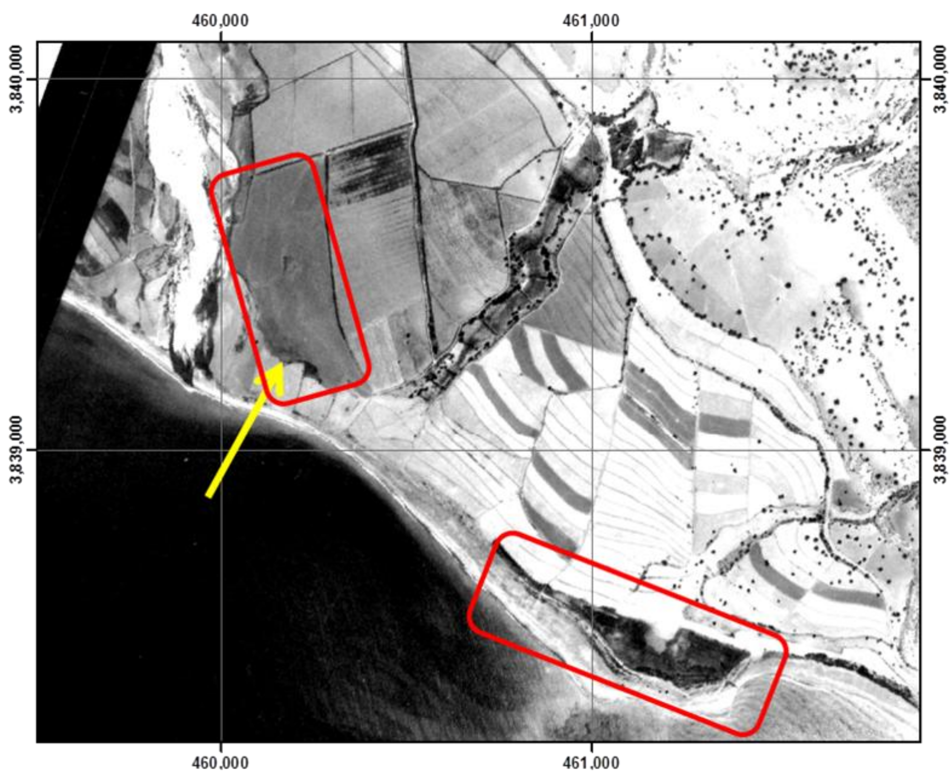


Figure 4-53 Aerial photograph of 1957 showing estuarine deposit (in red boxes) and palaeoshoreline (pointed to by yellow arrow).

Three activities have transformed the coastal landscape in recent years. Gravel extraction activities on the coast for producing aggregates for the construction industry in the 1970's has redistributed the gravel deposits. The estuarine deposit has been covered by the gravels in order to gain access back and forth along the beach. In addition, farmers have transferred soil over the estuarine deposit and behind the gravel bar in order to lengthen their fields and cover the estuarine hydromorphic soils that served no agricultural benefit. These are the "infested lakes" that Kyprianos was referring to in the 16th century, that have in the 20th century been literally obliterated. Only hydromorphic soils at depth can attest to the existence of these low flats and lakes and their extension to the west, almost as far west as the bed of the Xeros river.

Figure 4-54 Wider view of the estuarine deposit with beach gravel artificial fill in the foreground.

The abandonment of the gravel pits after government regulation in the 1980's forbade natural gravel extraction, let the estuarine low flat become a dumpsite for garbage, especially construction materials. The third activity that has changed the coastal landscape in the vicinity of the estuarine deposit is the most recent construction of a fishery farm adjacent to the Achni location. The farm owners have redistributed gravel over the estuarine deposit in an attempt to reclaim estuarine land for the installation of the fish tanks. The only evidence that does exist for the estuarine deposit is the small low flat just to the east of the fishery and to the south of Achni.

Figure 4-55 Surface sampling of the estuarine deposit in summer showing salt crust and salt tolerant plants.

4.6.6 Tsunami deposits

Tsunami deposits have been identified in western Cyprus by Kelletat and Schellmann (2001) and Noller *et al.* (2005, 2011), see section 1.5.7 for island – wide information. It is worth here repeating the reference from Ogerius Panis and Marchisius Scriba (ca 1294 AD), who wrote about a tsunami event in Lemesos and Pafos which is believed to have taken place in May 1222 AD (Rohricht, 1882):

> "... at Cyprus, the sea was lifted up by the shock and rushed inland; the sea in places opened up in huge masses of water big as mountains and surged inland, razing buildings to the ground and filling villages with fish ... Baffa (Pafos), they say, suffered most ... the harbor dried up and then the town was submerged by the sea ... the town and its castle were completely ruined and its inhabitants wiped out …"

Figure 4-56 Tsunami sediments in the bottom 20 cm in a section in the southeastern part of the study area.

It is reasonable to assume that such a tsunami event in Pafos and Lemesos must have hit the Palaipafos coast since it is located in between these two locations. Figure 4-56 shows a tsunami deposit 4 km west of Petra tou Romiou. Similar deposits had been identified on the same stretch of coast (3-4 km west of Petra tou Romiou) by Kelletat and Schellmann (2001) and Schellmann and Kelletat (2001). Schellmann and Kelletat (2001) had mapped these same deposits with 40 cm diameter boulders at elevations as high as 4m above present sea–level at the exact same location.

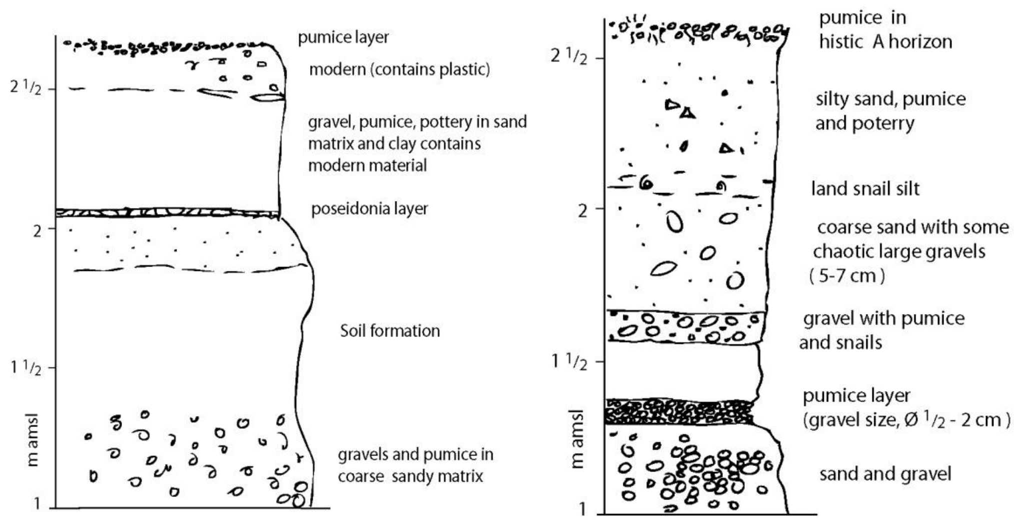


Figure 4-57 Coastal wave-cut section 500 m west of Diarizos river, containing pumice layers. Sections are 50 m apart.

The deposits of Figure 4-56 are about 20 cm thick in the exposed section, and consist of a chaotic, mostly bimodal sediment. The finest material is sand sized and the largest clasts reach up to 10 cm diameter rounded and flat boulders. The boulder to sand ratio is 60:40 and the boulders are well rounded material from the foreshore. These tsunami deposits can be mistaken for storm deposits but with a closer look they are different. Storm deposits are imbricated, well-sorted and graded suggesting many storm waves achieving a depositional process. Boulders and gravel in a chaotic fashion in a sandy matrix suggest a very short “dump event” such as a tsunami (Kelletat and Schellmann, 2001; Schellmann and Kelletat, 2001).

Some pumice layers have been mapped by the author in the Akamas peninsula which are similar to the ones seen here in these coastal deposits. Figure 4-57 shows an example of such a pumice layer, here being 10 cm thick in a section 500m west of the Diarizos river. With Cyprus not having local sources of pumice, it is hypothesized that this pumice material has reached the coasts of Cyprus either by travelling on the sea surface from the Aegean or the Italian volcanoes or by tsunami events (section 1.5.6. is relevant).

4.6.7 The tumulus site

By far the most impressive geomorphological anomaly in the area considered to be part of the urban environment of the ancient polity, especially during the first millennium BC, is a 5 m high rounded hill on one of the plateaus (Figure 4-58). It is located on the third mesa with Kaminnia and Marchello on the north and Hadjiabdoullah on the south. It has an elliptical base with a 60 m short and a 100m long axis (Figure 4-59). It reaches a height of 5 meters and its volume is estimated to be about 30,000 m^3 and consisting of transferred material.

It consists of an artificial pile of gravel and boulders in a sand and clay matrix and is believed to have been constructed in antiquity.This material is derived from the surface of the Pleistocene alluvial fan that the Marchello and Hadjabdullah sites are built on. It can be considered a work of ancient engineering but the reasons behind its construction are unknown. Besides one known attempt by Maier, who sank some trial trenches on the side but reported no results (Figure 4-60), the Palaepaphos project tried twice to approach the tumulus with different geo-equipment (including a geo-radar) (Sarris *et al*., 2006) but identified no anomalies.

Figure 4-58 The tumulus, an artificial hill on the third mesa, red line depicting original surface of alluvial fan before the construction of the tumulus.

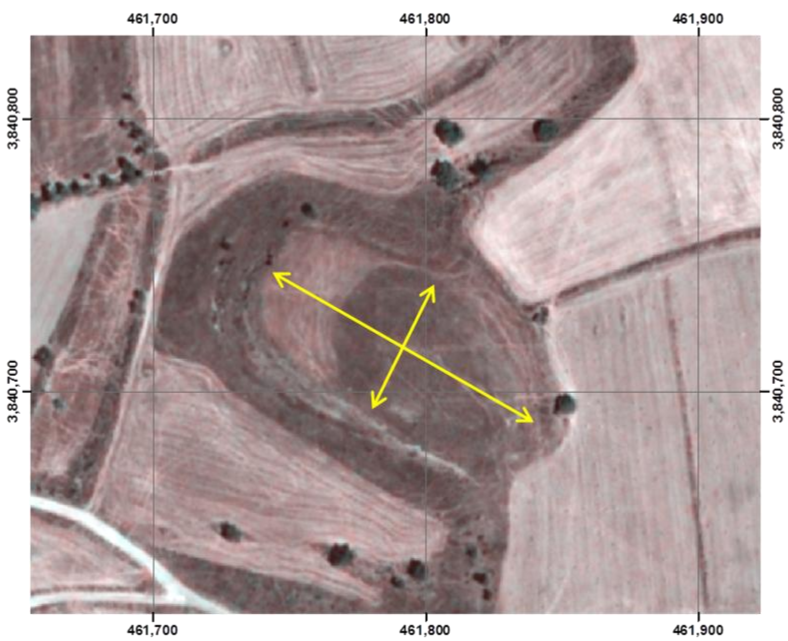


Figure 4-59 Plan view of the tumulus showing rough measurements of 60 m in short axis, 100 m in long axis, a perimeter of 280 m making a conical shape for a 5,960 m^2 footage.

Figure 4-60 Signs of human intervention, possibly by tomb robbers in search for easy access to the center of the tumulus.

A similar but much higher tumulus had been excavated by Karageorgis (1968) near the ancient polity of Engomi, in the Salamis necropolis between 1965 and 1966. A 10 metre high tumulus with a 50 metre base diameter of earth (Figure 4-61) was removed to uncover the so-called cenotaph of Nicocreon, the last king of Salamis. Cenotaphs (empty tombs) are usually built in honor of people whose bodies were buried elsewhere. The excavation of the Salamis tumulus revealed an off-centered exedra (elevated flat floor) of mud bricks measuring 11.5 by 17 metres with a pile of rocks in its center covering the remains of a pyre of numerous unbaked clay statues (Figure 4-62).

Figure 4-61 The tumulus at Salamis (eastern Cyprus) before excavation, (Karageorgis, 1968).

Karageorgis (1968) interprets this structure as an erection in honour of the dead. But according to Diodorus it was Nikokles of Paphos the last king of Paphos, and his whole family that had committed suicide. The monument at Salamis has recently been reinterpreted as constructed by Demetrios Poliorcetes (Mbourazelis, in press). The tumulus covering the exedra (platform) was constructed for a single occasion and never disturbed. It remains to be investigated by archaeologists whether the tumulus feature in Palaipafos was constructed in a similar context.

Figure 4-62 The tumulus at Salamina (eastern Cyprus) after excavation, (Karageorgis, 1968).

4.7 Discussion

In the case of Palaipafos, the action of the Diarizos river, the evolution of the coastline in the last 500,000 years and human activity have left strong imprints on the landscape. The movement of water and sediment on the coast, on the flood plain and in the fields (by farmers) is the greatest and longest-lasting physical process shaping the landscape of Palaipafos. In this way, farmers and residents of Palaipafos have become a geomorphic force together with gravity, weathering and tectonics. It becomes necessary to bridge the gap that is left between the history of human occupation usually dealt with by archaeologists and the history of landscape evolution usually dealt with by geomorphologists.

4.7.1 Landscape evolution and the possible harbor site

Palaipafos, as has only recently been claimed (Iacovou 2008; 2012), was founded as a gateway for the export of copper. Therefore, it must have founded as a harbour facility during the Late Bronze Age (mid second millennium BC). The first historian to make mention of a port in the area of Palaipafos was Strabo of Amasia (Strabo, AD 19), a Greek historian and geographer (64/63 BC – ca AD 24), who wrote in Book XIV of his "Geographia" about the "*ΰφορμος"* (translated as anchorage by Liddell and Scott, (1994)) on the coastline of Palaipafos:

> "At Kourion is the commencement of the voyage towards the west in the direction of Rhodes; then immediately follows a promontory, whence those who touch with their hands the altar of Apollo are precipitated. Next are Treta, Boosura, and Palaipafos, situated about 10 stadia from the sea, with an anchorage and an ancient temple of the Paphian Aphrodite; then follows Zephyria, a promontory with an anchorage, and another Arsinoe, which also has an anchorage, a temple, and a grove. At a little distance from the sea is Hierocepis."

In 2002, the Department of Oriental Collections of the Bodleian Library, Oxford, acquired an Arabic manuscript by an unknown author titled "Kitab Ghara'ib al-funun wa-mulah al-uyun" (The Book of Curiosities of the Sciences and Marvels for the Eyes). It is believed to date to the first half of the 11th century, after 1020 and before 1050, and was most probably written in Egypt. It contains maps of islands and ports in the eastern Mediterranean, including Sicily, Cyprus, and the coasts of Asia Minor. The island of Cyprus is represented with a square shape divided into 36 boxes, 29 of which contain information. The text in the boxes refers to harbors, their topography, their churches, the number of ships that can be accommodated, and information with respect to sailing winds. A simplified version of the map is provided in English by the Bodleian Library (Figure 4-64). It is not known if the information on this map is original or a copy from an older source. Is it possible to claim that in the worst period of the Middle Ages (1020 – 1030 AD) a survey of Cyprus took place?

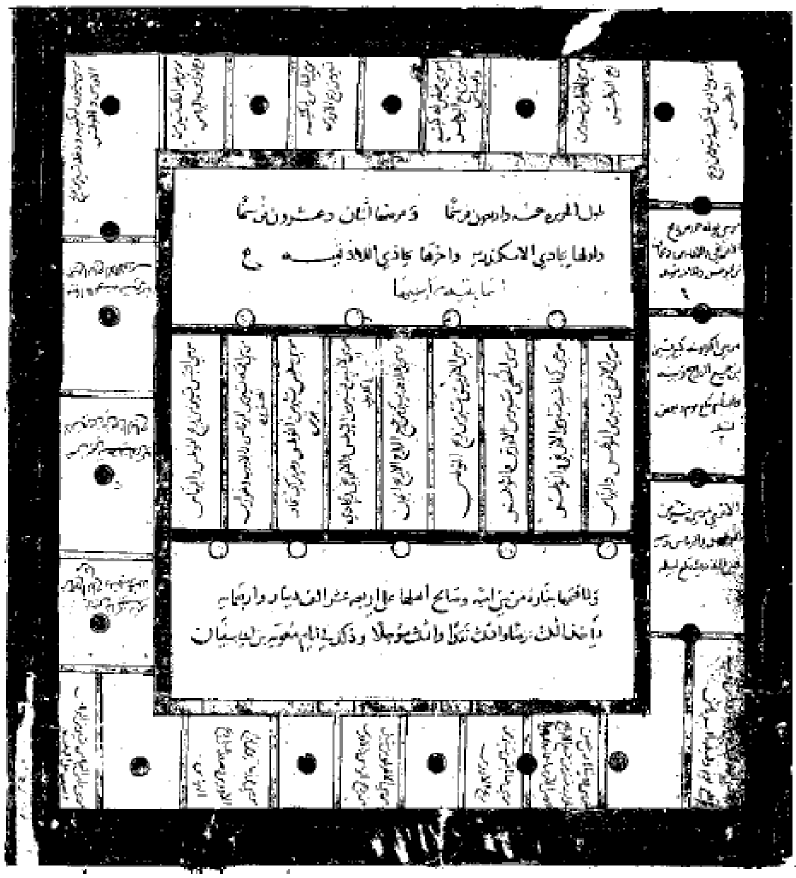


Figure 4-63 The map of Cyprus from the Book of Curiosities of the Sciences and Marvels for the Eyes (Anonymous, 11th century).

Seven hundred and fifty years later Archimandritis Kyprianos in his Chronicle of Cyprus (Kyprianos, 1788) writes:

> "The famous temple of this goddess was damaged together with the city from the big earthquakes and then again rebuilt by Agapinoras, even better. There used to be a lake, large as a port which accepted ships, which filled up and was deserted by the sea, some lagoons remained which after filling up with rain water during harvest caused bad air, and because of this there followed a lot of disease from the stillness of the waters."

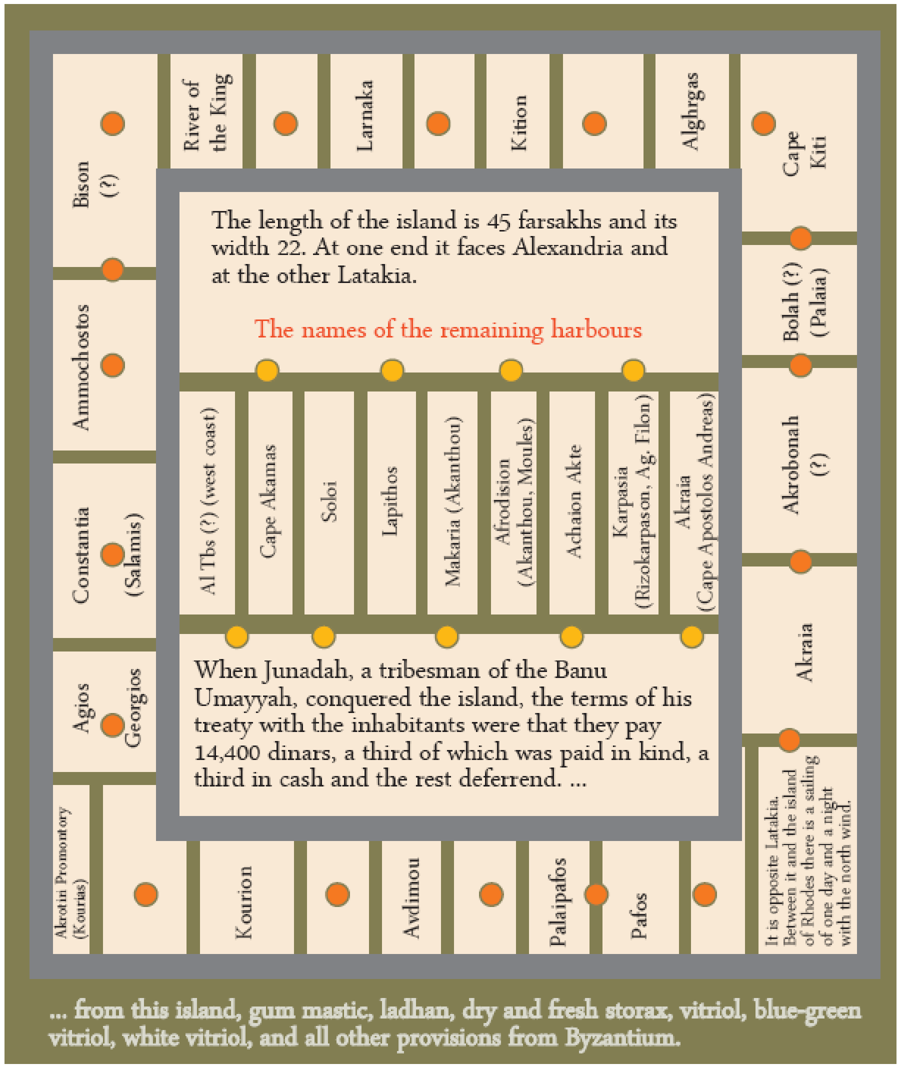


Figure 4-64 Simplified English version of the map of Cyprus from the Book of Curiosities of the Sciences and Marvels for the Eyes (Anonymous). Translation by the Bodleian Library at Oxford University.

He goes on to say that the town of Palaipafos conducted “large trade”. There is no doubt that an anchorage did exist in Palaipafos. The question here is whether all of these authors refer to the same site, that is to say, did the location of the harbor change as coastal geomorphology changed? Sakellarios (1890) refers to the harbor of Palaipafos with this account:

> "Her harbor, where pilgrims visiting the temple of the goddess, coming from the sea, is now called Achni. At this location, not rarely, in the summer, ships sail in, for the export of the local products. From here, 200 meters away, on the sea between the rivers Vocarios (Diarizos river) and Xeros there are 2 conical monoliths, which Hammer considered to be remnants of an ancient port, which never existed."

Sakellarios is referring to Von Hammer who had visited and described the site in 1811. Censola, in 1877 writes of his 1875 visit to Kouklia:

> The river Bocarus (Diarizos river), now called by another name , still waters the plain, silently flowing a little south of these ruins (he is referring to Stillarka), and empties itself into the sea… Some 750 yards south-east of this temple, beyond the river Bocarus, some peasants of Kouklia by chance, about fifteen years ago, laid bare several vaults, in which they found, according to my informant, "wonderful things", but I was unable to learn what those wonderful things were."

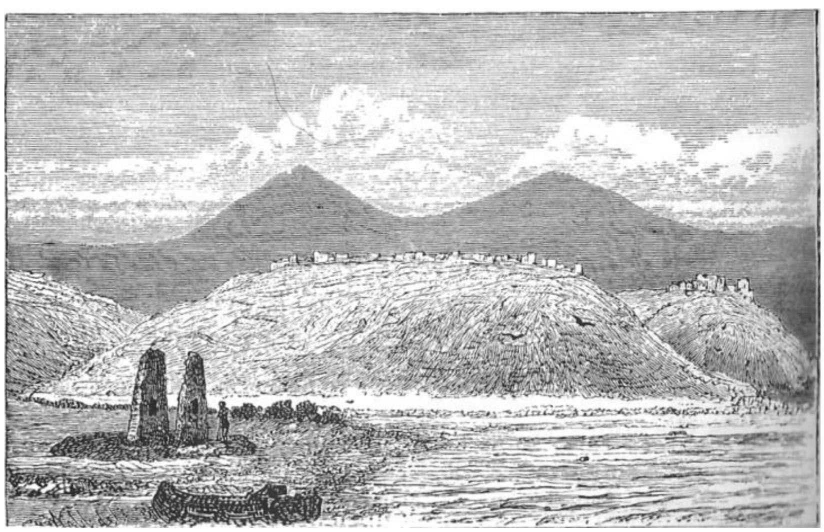


Figure 4-65 Illustration of Stillarka locality from Di Cesnola (1877).

Iacovou has suggested that the establishment of the monumental sanctuary at the beginning of the 12th century BC on the lower terrace of Palaepaphos was conditioned by its close spatial and visual relation to the original port lagoon, since the copper trade was managed through the temple, both at Kition and at Palaipaphos (2008a; 2012). She therefore posits as a possible harbor location the site of Loures, adjacent to the sanctuary, at an elevation of 50 m. The location of a harbor at such an elevation implies an uplift rate of 14.3 mm/year if one assumes a constant uplift rate since circa 1500 BC, the foundation period of Palaipafos. It would be more reasonable to assume an uplift rate much lower than that considering the regional geochronology results and uplift rates presented in Chapter 2.

The margins of large deltas seemed to have been attractive locations for harbors, e.g. Marseilles on the Rhone river delta and Alexandria on the Nile river delta, (Marriner and Morhange, 2007). If one considers that hydraulic cement was not discovered until Roman times, it is reasonable to assume that a port location would have to offer natural protection for ships sailing in and anchoring. The silting of Engomi, which caused it to move to a new port site at Salamis and the silting of the two ports Kition had in the late Bronze Age and of its neoria in the Classical period (now 400m from the sea) (Marriner and Morhange, 2007) does not necessarily predict the same fate for the Palaipafos harbor.

The coastal area of Palaipafos, located at the footwall of a thrust fault, is considered to be undergoing subsidence instead of uplift (NEOCYP Consortium, 2005). The presence of uplifted marine terraces and the coastal estuarine deposit elevated at a height of 2-3 m today defies this claim at least for the Upper Pleistocene and the Holocene. The MIS 11, 9 and 7 terraces are found at 92 m, 72 m and 44 m. An uplift rate of 0.215 mm/year predicts these elevations for these terraces and fixes Upper Pleistocene rate at this value (Table 4-4). West of Xeros river, at Mandria, these terraces are found at higher elevations (section 2.6.1) and a 0.35 mm/y uplift rate was calculated.

Some time after the deposition of the MIS 7 terrace the Pafos thrust fault has folded the MIS 7 terrace. The MIS 5e terrace was deposited at the foot of this fold and follows the thrust fault to the west. In the vicinity of Palaipafos it is buried under the alluvial fan which has developed below this fold presently mapped as the Voni soil series. The terrace, its elevation and thickness has been verified by a borehole drilled inside the Kouklia Experimental Agricultural farm (**Error! Reference source not found.**). The elevation of the MIS 5e palaeoshoreline is estimated to be at 23-24 m.

Table 4-4 Agreement between predicted and mapped marine terraces for a 0.215 mm/year uplift rate.

age	years BP	RSL	mapped elevation (m)	uplift rate (mm/year)	predicted elevation (m)	total uplift (m)
MIS 11	402000	6	92	**0.215**	92.43	86.43
MIS 9	330500	5	72	**0.215**	76.0575	71.0575
MIS 7	216000	-3.5	44	**0.215**	42.94	46.44

After the end of MIS 5e 125,000 years ago, the sea level peaked again to -20 m during MIS 5c and to -19 m during MIS 5a. These terraces and all the younger ones are now submerged. During the Last Glacial Maximum sea level dropped to as much as -120 m below present sea – level. At that time broad alluvial fans and soils developed below the fault and over the buried 5e terrace below Palaipafos. At some time after the formation of MIS 5e and the beginning of the Holocene, uplift begins in the immediate vicinity of the Kouklia fold.

Figure 4-66 shows a simplified cross section

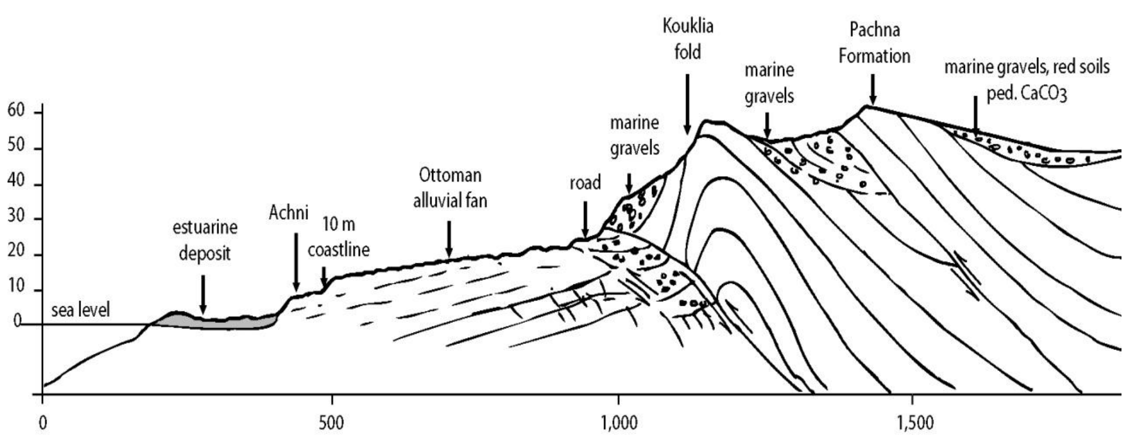


Figure 4-66 Cross section from the location of the estuarine deposit below Achni to the Fault-bend fold on the old Kouklia road.

In order to estimate this uplift rate, the following points had to be taken into consideration:

1. The relative sea level is that predicted in Israel by Sivan *et al*., (2001), Lambeck *et al*., 2004b, and Galili *et al*., (2005) (shown in Table 4-5),
2. sea–level during the occupation period of Liskiovouno (4600-3900 BC) had to be below this location which is 13 meters above present sea - level,
3. no sea–level postdating Liskiovouno occupation period could possibly “flood” the Liskiovouno site,
4. an ancient harbor requires a water column of at least 1.5-2 m depth to be functional,
5. there is a functioning harbor between the Late Bronze Age – Hellenistic period,
6. the coastline is below the Stillarka locality during this period,
7. it is possible that the harbor location shifted,
8. there needed to be enough duration of a constant sea – level to form the 3 distinct palaeoshorelines seen at 4-4.5 m, 8 m and at 9.5-10 m above present sea – level,
9. there is a harbor when Strabo visits Palaipafos during the Roman period,
10. Palaipafos is situated about 10 stadia (1800m) from the sea when Strabo visits it,
11. there is a harbor between 1020 – 1030 AD when the Book of Curiosities is written,
12. there were lagoons instead of a harbor when Kyprianos writes in 1788,
13. Cesnola refers to tombs, 750 yards (685m) SE of Stillarka, on the eastern bank of Diarizos. This site had to be above water in 1875 AD,
14. when Sakellarios visits Palaipafos in 1890 AD, the prevailing tradition is that an abandoned port is located at Achni.

Various uplift rates were used in a trial and error method for the Holocene and elevations of palaeoshoreline were back-calculated for each time period. The resulting elevation of shorelines vs time were tested to see if they satisfy the above conditions (Table 4-5). An uplift rate of 2.1 mm/year satisfies all of the above. Antonioli *et al*., (2006b) has estimated similar Holocene uplift rates at St. Alessio and Taormina in eastern Sicily to be 2.4 mm/y and at Scilla in southwestern Calabria to be 2.1 mm/y. A lower uplift rate does not offer any explanation for the 10 m high palaeoshoreline which seems to be carved directly into the alluvial fan deposits. It is also possible that here lies the exposure of the MIS 5e terrace, with the sea – level revisiting at this time this elevation creating a new shoreline angle into this resistant calcarenite.

Table 4-5 Palaeoshorelines in relation to the present coastline for the Palaipafos lowlands.

Age	**Years BP**	**relative sea level**	**coastline elevation**	**uplift (m)**	**uplift rate (mm/year)**
	8900	-35	-16.31	18.69	2.1
	7850	-16	0.485	16.485	2.1
	7000	-7	7.7	14.7	2.1
Neolithic	6000	-6	6.60	12.6	2.1
	5700	-2.5	9.47	11.97	2.1
	4000	0	8.40	8.4	2.1
Bronze Age	3900	0.5	8.69	8.19	2.1
Iron Age	3200	0	6.72	6.72	2.1
Hadjabdullah	2600	0	5.46	5.46	2.1
Achni	2400	0	5.46	5.46	2.1
Hellinistic	2300	-1.6	3.44	5.04	2.1
Roman / Strabo	2000	0	4.20	4.2	2.1
300-600 AD	1400	0.5	3.44	2.94	2.1
1200 AD	800	-0.5	1.18	1.68	2.1
1300 AD	700	0	1.47	1.47	2.1
Venetian	500	0	1.05	1.05	2.1
	300	-0.25	0.38	0.63	2.1
Ottoman	220	0	0.46	0.462	2.1
Sakellarios	110	0	0.23	0.231	2.1
present	0	0	0.00	0	2.1

The sea level reached -2.5 m around 5700 yeas BP (Galili *et al.*, 2005). Right about this time humans occupy the Liskiovouno location which is almost right on the coastline shown with a red line in Figure 4-68. A possible landing site from the sea would be a proto – harbor at locations marked as box nos. 1 and 2 in Figure 4-68. Small bays exist in the Xeros and Diarizos river mouths as the fast rising sea – level quickly floods the coastline until about 5000 BP. Coastlines are sharp and beaches are flooded as quickly as they form. On a global scale coastlines are complicated and lacy as sea level is rising fast. As sea level rise slows down coastlines fill in from fluvial clastic material and indented morphology becomes more linear. After about 5000, coastlines begin to prograde.

When Palaipafos is first occupied in the (MCIII/LCIA) Late Bronze Age the coastline is at 8.7 m above the present one, shown with a yellow line in Figure 4-68. A shallow proto – harbor could exist in what is marked as box nos. 1 or 2. In the area of box no. 2 an estuarine deposit now exists hosting what is classified as a vertisol of the Livadia soil series (also shown on Figure 4-53). This possible harbor location would be just below the Palaipafos Sanctuary of Aphrodite which was constructed soon later. This small cove at the mouth of the eastern bank of Diarizos would create a small harbor with a 3-4 m deep water column.

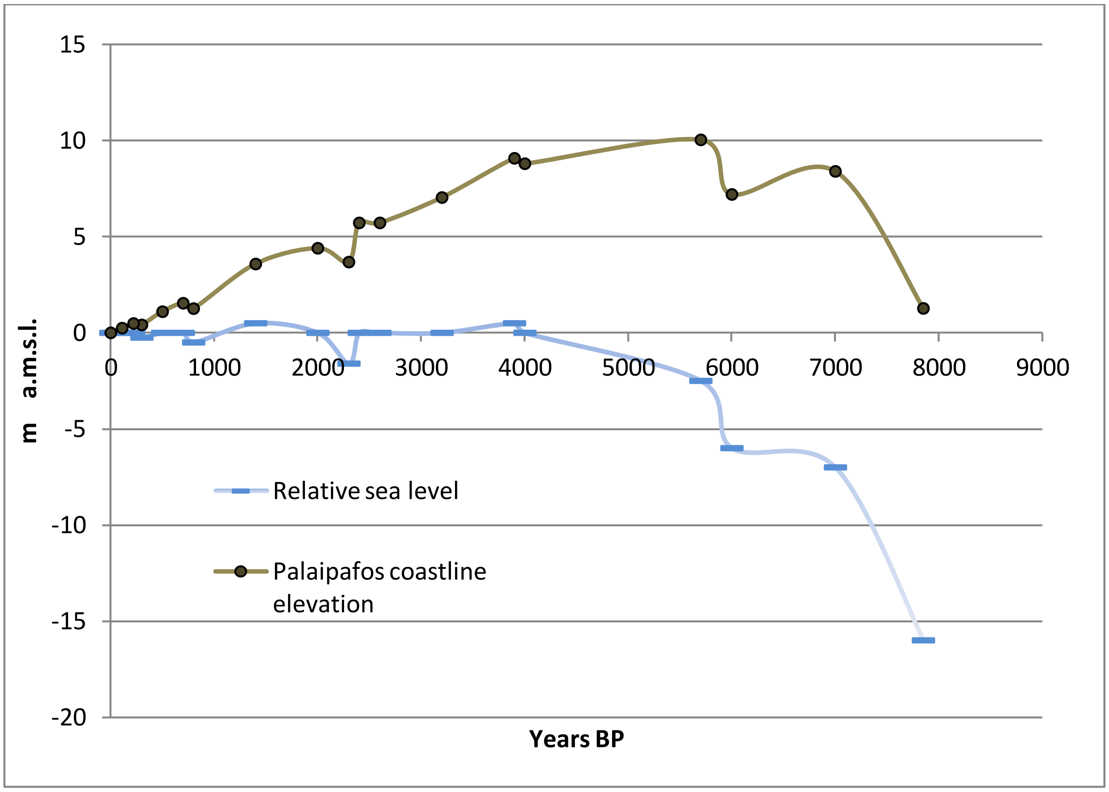


Figure 4-67 Relative sea–level and height of abandoned palaeoshorelines in Palaipafos.

"The Dark Ages Drought Event" in Syria which initiated the abandonment of Ugarit started between 1265-1000 BC and ended between 930-765 BC (Kaniewski *et al.*, 2010). Such aridity in the eastern Mediterranean could have initiated an alluvial derived sediment pulse, inducing rapid infilling in many of the Levant's estuaries and estuarine proto – harbors, like the one attested in Tyre (Marriner *et al.*, 2007b). Rapid infilling during this period in the Levantine estuaries (Morhange *et al.*, 2005) has caused relocation of coastal populations and the abandonment of estuarine harbors. This may explain the move from Enkomi to Salamis and the abandonment of the Hala Sultan Tekke harbor (now a Salt Lake) around 1100 BC.

A sea–level drop of 1.6 m (Toker *et al.*, 2011) must have dried the harbor site in the Hellenistic period. Did this environmental change trigger the shift of the population from Palaipafos to Nea Pafos in the west? Sea – level reached present levels in the Roman period, but continuous uplift probably did not re-establish the use of the harbor in its original state but at the location of box no. 3. By then, it would be a silted - in harbor. Had the harbor already been relocated at Achni? Any other location between box no. 3 and Achni would be exposed to more sea weather.

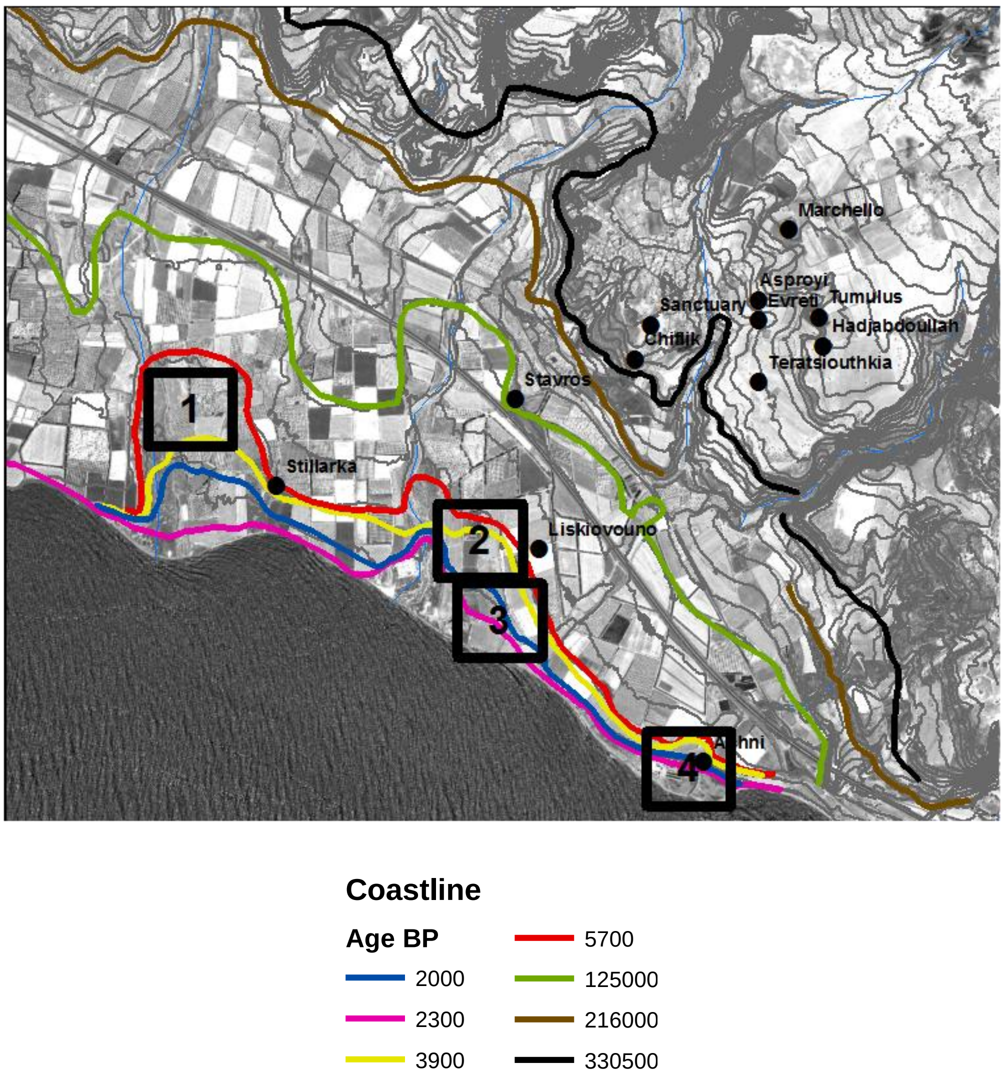


Figure 4-68 Map of coastline evolution with a Holocene uplift rate of 2.1 mm/year with possible locations of a harbor.

The Roman period is a prosperous time for Palaipafos but it was no longer a royal capital or a port of export; only a sanctuary town. The sanctuary is considered an important pilgrimage and it served since the Ptolemaic period as the centre of the united colony of Cyprus now showing its allegiance to the new rulers. Radiocarbon dates of charcoal from copper slag deposits in the mountains of Diarizos and Xeros give dates of 315 ± 50 AD (Zwicker, 1985; 1986) and 365 ± 35 AD (this study).

It would be wrong to make premature conclusions on the location of this very important ancient harbor without the necessary field palaeoenvironmental and geological investigations. Whereas from the geomorphological mapping it seems that the estuarine deposit (shown as box no.4) serves as an excellent candidate for the last location of an ancient harbor, it remains a promising area for future geoarchaeological investigations and an excellent opportunity to make the shift from theoretical to practical harbor geoarchaeology on Cyprus.

The question that remains is whether a 2.1 mm/year uplift rate can be considered possible or extreme. In Western Crete, ancient Phalasarna harbor shows a sudden uplift of around 6.6 m about 1530 years BP, probably during the seismic event of 365 years AD (Pirazzoli et al., 1992). In the case that this uplift was not co-seismic, uplift rate would amount to 4.3 mm/year. In Cyprus, Yon (1991, 1994) and Dalongeville *et al.* (2000) found fossil sea levels at an altitude of 2 - 3 m above m.s.l., which were dated on marine shells, 4830 ± 50 years BP giving an uplift rate of 0.33-0.42 mm/year and 865 ± 45 years BP at 1 m, south of Larnaca, giving an uplift rate of 1mm/year.

It is not unreasonable to assume that in the immediate vicinity of an active fault, co-seismic uplift did occur during the last 100,000 years. Historical earthquake archives attest to such destructive earthquakes in a zone from Pafos to Lemesos. Kinnaird's (2008) chronology of colluvial – palaeosol sequences on the north side of the fault – bend fold in Agia Marinouda and Geroskipou shows evidence for at least 5 tectonic events between 70,000 – 12,000 BP.

4.7.2 Geohazards and sustainability of archaeological heritage on the coast

Humans have themselves become a geohazard in their own environment (Morhange and Marriner, 2010). The construction of Arminou dam on the Diarizos river has deprived the fluvial system of sediment load. The flow on the river is controlled by the dam and water is never allowed to flow downstream unless the dam is overflowing during a good rainy year. In any other case the valuable water of the dam is used for irrigation systems. The decreased water and sediment load will have two effects downstream.

The dam acts like a flood control system, a great advantage for human occupation downstream. In contrast, the lack of flood waters deprives the flood plains of the Diarizos downstream of sediment input. The soils in the lower plateaus are, since the construction of the dam are on a decreased sediment budget. The fertile soils of the lower plateaus will not receive any additions other than the sediment added to the system from surficial sheet flow and sediment from small tributaries downstream from the dam.

Secondly, the coastal system is deprived of sediment being added to the system from the Diarizos and Xeros rivers. Sediment transport along the coast is mostly from the west. Any change in river load west of Palaipafos will affect the coastal system in Palaipafos. It is anticipated that coastal erosion that is now evident from comparing airphotographs from 1957, 1963, 1994 and recent Quickbird images, will go on (Figure 4-69). As much as 55 m of retreat has taken place from 1957 to 1963 at the site of the estuarine deposit. The coastal alluvial fans are being cut back by wave action revealing new cross sections into this deposit. Any vulnerable cultural information contained in these fans will have to be rescued periodically. It is proposed that frequent visits to the coastline will help document and sample any new information as new sections are revealed.

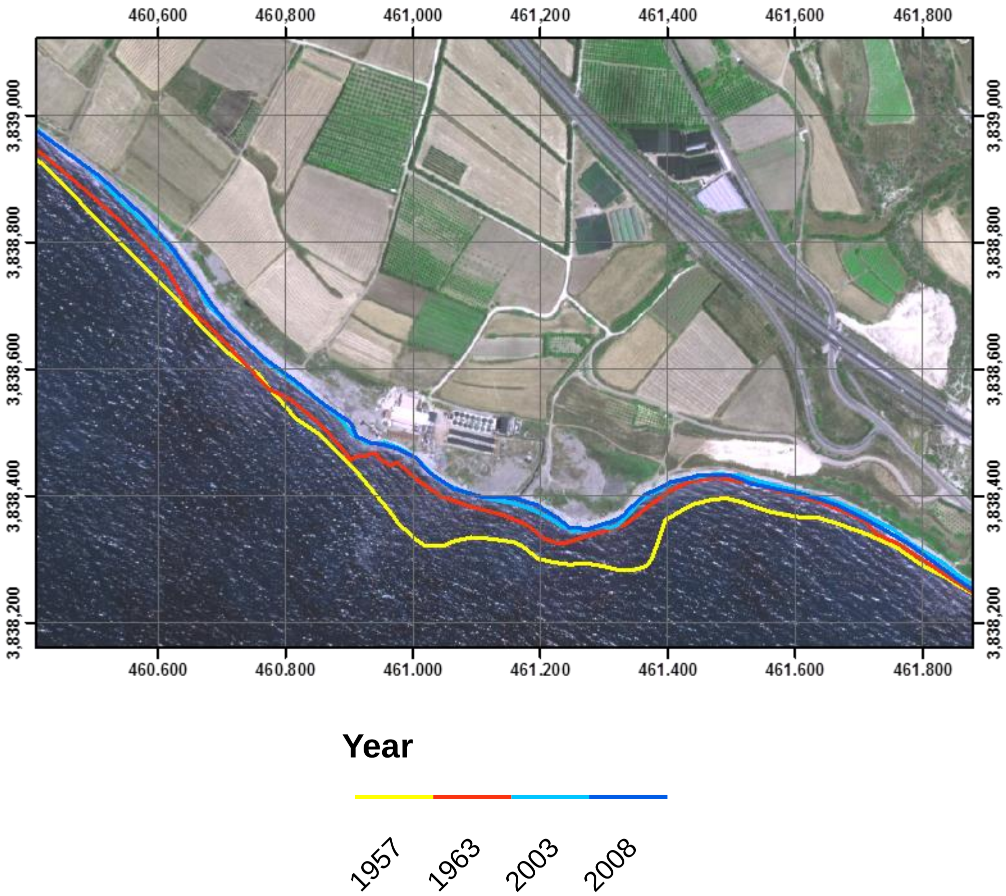


Figure 4-69 Coastline retreat since 1957 (can be compared to Figure 4-53).

4.8 Conclusions

Landscape resistence is a property which provides the opportunity to continue to support the existence of an entity on the landscape, here being the community of Palaipafos – Kouklia. A sustainable system is simply one that allows you to last (Chesworth, 2010). It is here attempted to refute the claim that one could make in that the success and prosperity of the Palaipafos polity was a result of its well-known and important sanctuary to the goddess Aphrodite. Geological and other environmental factors are believed to have contributed to the success of this ancient polity. Geomorphological and geological data have revealed the fact that there are indeed other factors that need to be considered.

Table 4-6 Significance of geological and environmental factors.

factor	**signifigance of factor**
Foundation conditions	high
Water resources	high
Copper resources	high
Sea-level change	high
Earthquake hazard and risk	moderate
Forest resources (wood, hunting)	moderate
Soil resources and agricultural land	moderate
Pasture land	moderate
Marine resources	moderate
Climatic change	moderate
Tsunami hazard and risk	low

It is profitable to start with a simple model of natural factors that play key roles on the landscape and the people who live on the landscape. The factors shown in Table 4-6 are those factors that in antiquity would help sustain human occupation at a given site based on the idea that an area with geological resistance to erosion provides those foundation conditions that help sustain its infrastructure. If Palaipafos were build on the loose sediments of the coastal lowlands and not the 80 m high plateau it would have suffered river erosion and silting and more damage during earthquake shaking and tsunami events in Antiquity. Instead, it is strategically located just overlooking the most extensive and thick alluvial deposits of the Diarizos river below, where thick, well developed fertile soils sustain agricultural productivity with sufficient irrigation from the river.

Table 4-7 Possible causes and effects on the Palaipafos landscape.

Time	Possible cause	Possible effect
1628 BC	Tsunami caused by Santorini eruption (Goodman-Tchernov *et al.*, 2009)	Possible destruction of coastal structures, if any
Late Bronze age	Late Bronze Age Collapse in Cyprus "The Dark Ages Drought Event" in ancient Ugarit, Syria (1200-825 BC), social instability in E Mediterranean, arid conditions in SE Mediterranean (Kaniewski *et al*., 2010)	The economic Crisis that forced the abandonment of other sites worked in favour of Paphos and Kition, possible silting of a Bronze Age harbor induced by aridity
Hellenistic	Sea – level fall of 1m	Hellenistic harbor is abandoned
Byzantine	Earthquakes, Byzantine Paroxism	Destruction of the urban fabric
Byzantine 900-1200 AD	Climate change, Mevieval Warm Period,	Shift to sugar cane cultivation and sugar refinery industries, stress on the riparian, agricultural landscape, stress on water resources
Frankish period 1202 AD	Tsunami in Southwestern Cyprus	Destruction of nearshore Nea Pafos by tsunami, including maybe coastal structures (if any exist) in Palaipafos
Ottoman	Climate Change, Little Ice Age	Slow abandonment of the sugar cane cultivation and other agricultural land, large volumes of sediment build coastal alluvial fans

Table 4-7 lists those factors that may have been important during the history of the site. Beginning with the big catastrophic tsunami event of the 1628 BC in Santorini (Thera) which must have reached the coast of Palaipafos (Goodman-Tchernov *et al*., 2009), any coastal habitation or even a proto-harbor would have suffered damage. The tsunami would have reached the Palaipafos coast 70 minutes after the eruption and eventual collapse of the Santorini volcano.

The increased aridity in the eastern Mediterranean between 1200 BC - 825 BC (Kaniewski *et al.*, 2010), would created a shift in vegetation cover that must have caused increased soil erosion in the Diarizos river basin that would silt up a Bronze Age harbor in the mouth of the river. The harbor site may have moved to serve the increased population attracted from other abandoned sites on the island. A drop of sea-level of as much as 1 m in the Hellenistic period would cause abandonment of yet another harbor site. Earthquakes and possibly more tsunamis caused great damage in all coastal towns up to the Byzantine period. Goodman-Tchernov *et al.*, (2009) have logged two more tsunami deposits in the Eastern Mediterranean, one in the Roman period around 115 AD, and one in the Late Roman – Early Byzantine period, around 551 AD.

With Palaipafos becoming less and less significant as a site after the establishment of Nea Pafos, it is climate change that sets in to play a key role on the landscape. Extensive agricultural activity in the Frankish and Venetian periods is highly dependant on the running water of the Diarizos river. Diarizos drainage basin presently collects the second highest total precipitation and has the second highest river discharge on the island. This added advantage together with the fertile soils on the lower broad alluvial fans and flood plains of the Diarizos and Xeros rivers must have attracted the attention of the Franks and the Venetians. Extensive sugar plantations and sugar refinery continued until the beginning of the Ottoman period coinciding with the beginning of the Little Ice Age.

One cannot forget that Palaipafos, what today we call Kouklia, is located by a coastal geomorphosite, the Petra tou Romiou location, the birthplace of Aphrodite. Petra tou Romiou is a high-ranked geomorphosite, protected by Cyprus law because of its aesthetic value but also the importance of the site for the understanding of the geological evolution of the island. Maybe it is this natural beauty that attracted the first settlers and maintained this location as an attractive occupation ever since, this being the social dimension of landscape and is better left to the social scientists.

5 General Conclusions

The uniqueness of Cyprus is partly due to the fact that, as a preserved ophiolitic complex with a hydrated core, it behaves like a diapirically uplifting entity. Coupled with the nearshore tectonic activity of the Cyprus arc collision zone, there exists a dynamic environment of landscape evolution. Repetitive Quaternary sea level change has created coastal features that due to continuous uplift have been preserved as flights of marine and fluvial terraces.

Marine Isotope Stage (MIS) 5 through MIS 13 terraces have been identified along the coast, mapped and dated. Palaeoshoreline elevation, an excellent indicator for a past sea – level was used to calculate an Upper Pleistocene uplift rate for various coastal sectors. Marine terraces are preserved very well on hard lithologies like reef limestones and carbonate rocks of Upper Cretaceous – Miocene age. Coastal landscapes built on Messinian gypsum deposits and Pliocene marl deposits have poor development and poor preservation of marine terraces.

Western and southwestern Cyprus presents the highest uplift rates of 0.35-0.65 mm/year with other sections demonstrating uplift of 0.07-0.15 mm/year. This Pleistocene tectonic signal for the last 125,000 years is being attributed to an offshore subduction/collision system to the southwest of Cyprus, an active system, as evidenced from the seismic activity offshore and the surface expression of a blind thrust fault and a recently activated anticline in the Pafos region. Small differences in uplift rates between coastal sectors are attributes to coastal tectonic activity.

Dated geomorphic surfaces and soil chronosequences are invaluable to earth scientists. Once knowledge on chronosequences is established, they provide a reliable tool for extrapolating soil knowledge to undated surfaces and deriving conclusions on other landscape processes and finally, landscape evolution. This idea is based on Davis's concept of the geomorphological cycle where landscapes evolve from a young to a mature stage (Davis, 1909). In the case of Cyprus, the results provide new information on the geomorphology and tectonics of the coastal Pleistocene geomorphic surfaces of southwestern Cyprus, their stability and maturity, with valuable applications to seismic hazard assessment and soil resources management.

Soil chronosequences and geology in southwestern Cyprus were studied in order to understand the Quaternary development on this uplifting landscape. Soil development is usually used as a relative method for dating marine terraces. Here the opposite is attempted. Soil characteristics on dated marine terraces are used as a tool for understanding soil developmet in southwestern Cyprus. Soil maps and soil profile properties were used to calculate a profile development index (PDI), a method often applied to geomorphic surfaces as a relative dating method. Geochronology of marine terraces was used as the closest approximation to correlating these results to real age estimations.

Well-developed soils were shown to dominate the coastal landscape and dominate the surfaces of marine terraces. These soils show horizonation, rubification and accumulation of calcium carbonate. This calcification is in the form of disseminated $CaCO_3$, accumulation along peds and fractures, nodules ranging in size from a few millimeters to a few centimeters, laminar accumulations that can reach 50 cm thickness (locally known as havara), and hard petrocalcic horizons that can reach a thickness of 1 m and are locally known as kafkalla. It was found that accumulation of calcium carbonate is a function of time and the development stage can be correlated to the age of the soil.

Geomorphologic mapping focused on the southeastern part of the Pafos thrust fault, the only point on the landscape where this otherwise blind fault is exposed on the surface as an active anticline. This is the coastal location of the important and prosperous Late Bronze Age polity of Palaipafos, a polity of impressive organization that has sustained human occupation from 1600 BC until today. It is here attempted to refute the claim that the success and prosperity of the Palaipafos polity was a result of its well-known and important sanctuary to the goddess Aphrodite.

Human occupation in Palaipafos concentrated on the Middle Pleistocene alluvial fan plateaus of the big Diarizos drainage basin. It is strategically located just above the MIS 5 marine terrace where the most extensive and thick alluvial deposits of the Diarizos river are hosting thick, well developed fertile soils. The water from Diarizos, the drainage basin with the highest rainfall and highest discharge on the island provided for sustainable agriculture and industrial agriculture over the centuries. Carbonate rocks forming the foundation rock for the ancient polity and the modern town of Kouklia resist erosion from the river and continue to stand and dominate the landscape.

Inland, pillow lavas have been mined for copper, numerous piles of ancient slag attest to archaeometallurgical activity and the belief that Palaipafos could not have been such a prosperous polity in the Late Bronze Age if it had not produced and exported copper itself. Its coastal location, unlike other ancient polities like Tamassos and Idalion, provided for the ability for Palaipafos to manage this resource from the stage of production to the stage of export. The location of this proto - harbor though, is unknown and is believed to exist under the gravels of the Diarizos river mouth or buried by the estuarine deposits, if not eroded away. It is concluded that bedrock resistance, but especially excellent soil and water resources have contributed to the resilience of this landscape and its society over time.

About 70% of the population of Cyprus lives or works in the coastal zone of the island. In addition to the local population, 2 million tourists visit the coastal region every year. Airports, ports, power plans, and 6 and of 7 towns are all located exactly adjacent to the coastline. The coastal plains also constitute the main agricultural areas because they are made up of Quaternary sediments which host some of the most important aquifers and fertile soils. Earthquakes, tsunamis, erosion and other improper land management practices are issues creating concerns if this zone will continue to sustain modern human occupation.

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