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Kalliopi Gaki-Papanastassiou, Hampik Maroukian, and Violeta Kourmpanian

THE MORPHOTECTONIC EVOLUTION OF THE SOUTHERN HALF OF KYTHIRA ISLAND (IONIAN SEA, GREECE) DURING THE QUATERNARY

Abstract: Kythira island is located between Peloponnese and Crete along the Hellenic island arc. The morphotectonic study of this island could provide useful clues about the evolution of this area. The study focused on the southern part of the island where most of the characteristic landforms of uplift are found (terraces, gorges and notches). Large scale geomorphological mapping was performed in order to determine the most significant landforms of the area such as planation surfaces, marine terraces, gorges, knick points, cliffs and notches. It is concluded that the general morphology and evolution of the southern part of the island is depended primarily on the tectonic regime of the area which is exemplified by characteristic landforms in a series of well distinguished eight uplifted marine terraces on the eastern and six in the western part, marine notches and inclined planation surfaces, gorges and knick points indicating a continuous uplift of the island during the Quaternary. Finally, an average uplift rate of about 0.13 mm/yr for the Quaternary period is determined for the study area.

Key words: morphotectonics, geomorphological mapping, marine terraces, Quaternary, Kythira island, Greece.

Introduction

Kythira is located in southern Greece between southern Peloponnese and Crete (Fig. 1). The island is mountainous with many deep valleys and pocket beaches. The area of the island is roughly 280 km^2 and the coastline has a length of approximately 52 km. The climate is Mediterranean, with high relative humidity and strong winds mainly in winter. The rugged coastal terrain is the result of tectonics and lithology with high wave energy that has shaped its shores into steep rocky cliffs with deep bays.

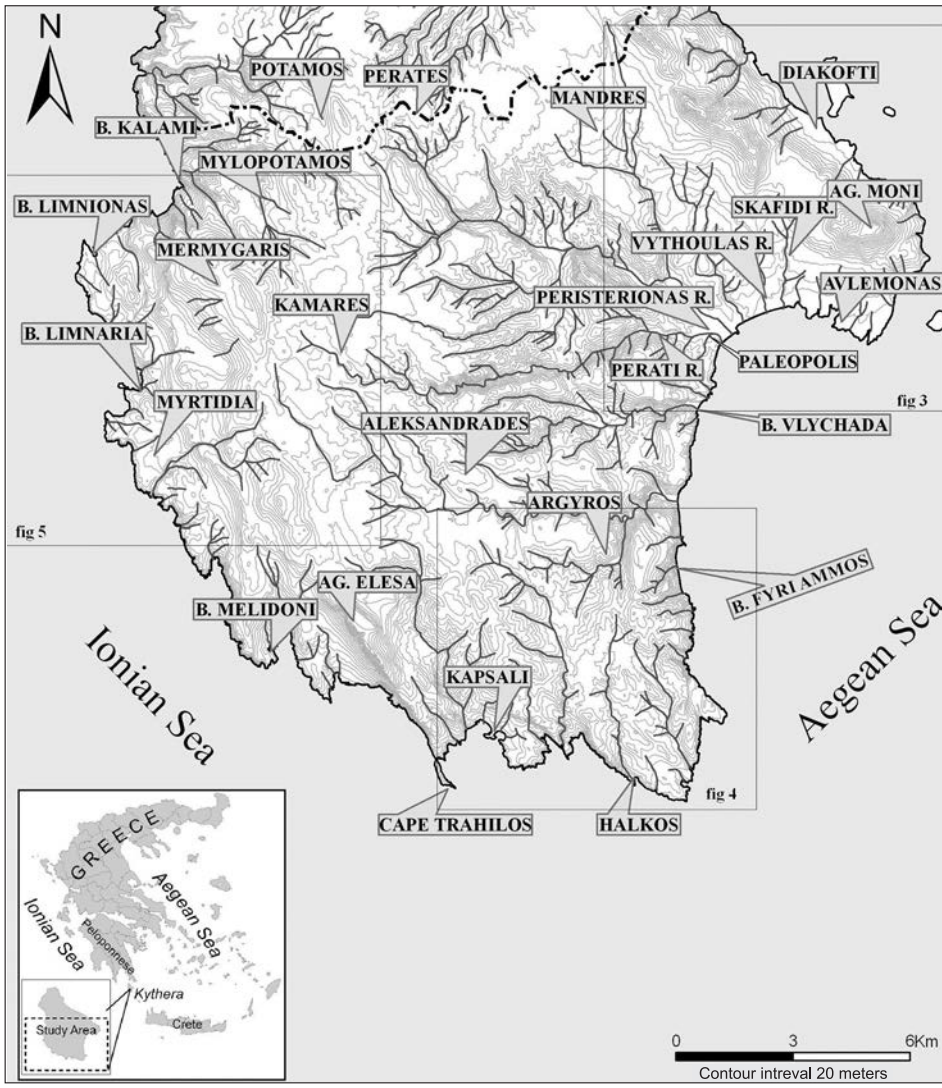

Fig. 1. Topographic map and location of the study area

In this study, geomorphological observations along the coastal zone of the central and southern part of Kythira island were realized. A combination of G.I.S techniques and field work lead to the mapping of particular coastal landforms such as coastal terraces, gorges, slopes, knick points, cliffs, notches and the understanding of the evolution of the coastal and inland environment during the Quaternary.

Detailed coastal geomorphological mapping was accomplished at a scale of 1:5 000 and maps were created tracing and depicting coastal landforms of the study area. Various maps were produced at different scales including a map of the drainage networks and a geomorphological map depicting coastal terraces, palaeo-surfaces and other coastal features.

Geology and Tectonics

The geological structure of the island of Kythira (Fig. 2) constitutes the metamorphic crystalline basement, the geotectonic unit of Tripolis unconformably overlying the former, the Pindos unit overthrust upon the Tripolis unit and the post-Alpine formations (Manolessos 1955; Geological map of Kythira island – IGME, 1966; Theodoropoulos 1973; Meulenkamp et al. 1977; Verykiou-Papaspyridakou 1986; Papanikolaou and Danamos 1991; Danamos 1992).

The crystalline basement is highly folded and occupies the northern part of the island. Due to the erosion of the overlying cover of the Pindos unit, tectonic windows outcrop in some parts of the island. The base of the Tripolis unit is composed of clastic sediments of upper Paleozoic-Triassic age with flysch at the top. Most of this unit is composed of carbonate formations which create the elongated main mountain masses in the eastern and western part of the island. Large parts of the island are covered by these rocks and especially in the western part reach the sea creating abrupt cliffs due to the existing offshore faults. Pindos unit is an extensive tectonic nappe of Mesozoic-Tertiary age, which covers almost a third of the island and is mainly located in the central and southern part of the island between the elongated mountains of the Tripolis unit. The post-Alpine formations are composed of Neogene and Quaternary deposits. Neogene sediments extend mainly in the southern part of the island and are primarily marine with intercalations of fluvial and lacustrine deposits. The latter are composed of sandstones, marls, marly limestones and conglomerates of transgressive (at the top) and regressive (at the bottom) origin. The Quaternary sediments are largely terrestrial (sands, gravels, scree and fluviotorrential deposits) and occupy mainly the central part of the island.

Concerning the tectonics of Kythira, an older pre-Alpine phase is distinguished, which folded the metamorphic crystalline basement having an axis of ENE-WSW direction, followed by an Alpine phase responsible for the folding and faulting of the Tripolis and Pindos units. Post-Alpine tectonism with NNW-SSE trending faults created today's terrain observed in the SW and NE parts of the island. These faults resulted in the genesis of grabens and horsts, the most notable being the main basin located in the south-central region of the island. This basin was filled with marine sediments during the Neogene. Quaternary fault tectonism is associated with the N-NE subduction of the African plate underneath the Aegean area. This tectonic regime is extensional and has resulted in the uplift of the island which, being close to this plate boundary, is in a highly seismogenic area (Lyberis et al. 1982). Many earthquakes in recorded history have had their epicenters around or on the island, like those of 800 AD, 1750, 1798, 1866, 1903, and 2006.

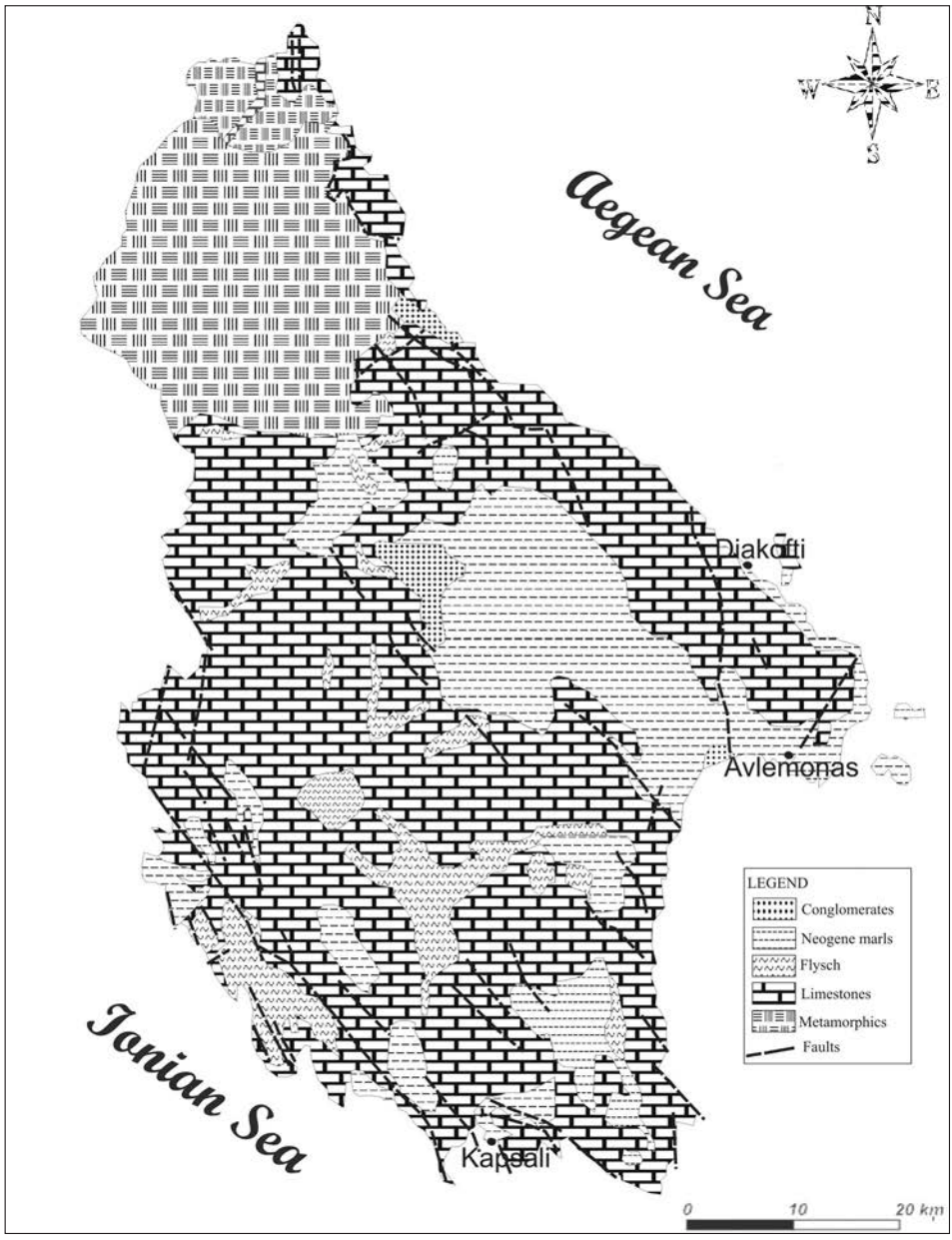

Fig. 2. Geologic map of Kythera island based on Danamos (1992) and field observations

Geomorphology

The general morphology of the island is owed mainly to the recent fault tectonics, as the island of Kythira is located near the edge of the Aegean microplate and the subducting African plate. Another factor is the lithology which has resulted in a rugged topography in the eastern and western part of the study area (limestones) and the easily erodable formations in the south-central part of the island (Neogene marls).

In the central and southern part of the island an extensive limestone palaeosurface of Neogene age is observed, which constitutes a tectonic graben having a NW--SE direction and dipping to the SE, with its highest point at 410 m in the northwest (Kamares) and the lowest point at 220 m in the southeast (Argyros). Noteworthy are the residual erosional limestone forms west of the palaeosurface, at Mermygaris (506 m) and Agia Elessa (472 m). In the area of the airport, this surface has its largest extent, at elevations ranging from 280 to 325 m, shaped partly on limestones and partly on Pliocene marine formations. This surface should correspond to the coastline of the early Pliocene epoch, during the deposition of the marly sediments. This hypothesis is supported by residual Pliocene outcrops on the limestones at elevations of about 340 m in the area of Mandres (Fig. 1).

In Kythira, contrary to Peloponnese and Crete, no karstic surface forms like poljes and dolines exist. This is owed to the presence of the compact limestones of Tripolis zone uplifted mountain masses, while the limestones of Pindos zone are not karstified and form the palaeosurface of the island. Nevertheless, within the Tripolis limestones some big caves exist in the southern part of the island.

In the southeastern part, the drainage networks that have developed on limestones have an E-W direction, while their downstream parts are rejuvenated due to the uplift of the area. In the more recent networks (Bythoulas, Peristerionas) the main axis has a NW-SE direction and have developed on the Neogene formations. It is worth mentioning that the upper parts of these networks were already in existence in Pliocene times but with the uplift of the Neogene formations during the Pleistocene these networks extended their channels to the SE. In the western part, the growth of the NE-SW trending networks is limited, as a consequence of Quaternary tectonism. In the NW, the Mylopotamos drainage network has a rejuvenated downstream part probably owed to the Plio-Pleistocene uplift and and a few SE-NW trending tributaries located on Pindos limestones and flysch formations.

The present morphology of the coasts is not only the result of tectonic factors but also the nature of rocks and the erosive intensity of sea waves. The southern part of the island of Kythira is mostly composed of steep slopes (Photo 1) with some pocket beaches in between (Photo 2) and two extensive sandy beaches in the east (Avlemonas, Paleopolis) (Photo 3) and a tombolo at Kapsali. Uplifted notches and sea caves are observed on the cliffs on the sides of pocket beaches. They are located in the areas of Avlemonas (Photo 4), Fyri Ammos and Halkos (Photo 5) at 40 cm, Limnaria at 60 cm while uplifted sea caves exist west of Avlemonas at Skafidi remma (Photo 6) and in Melidoni beach.

The most important geomorphological feature in the southern part of the island which gives clues in the understanding of the palaeogeographic evolution of the

study area, is the existence of uplifted marine terraces mainly in the areas of Diakofti, Avlemonas (Fig. 3 and Photos 4 and 7), Palaeopolis, Vlychada and Fyri Ammos (Fig. 4) in the east and at Myrtidia (Photo 8) and Limnaria in the west (Fig. 5). Most of the terraces have been carved in pre-existing Neogene formations. In the east, eight well developed marine terraces can be distinguished at 4-24 m, 24-40 m, 40-72 m, 60-80 m, 76-140 m, 136-196 m, 176-204 m and 240-296 m extending in an E-W

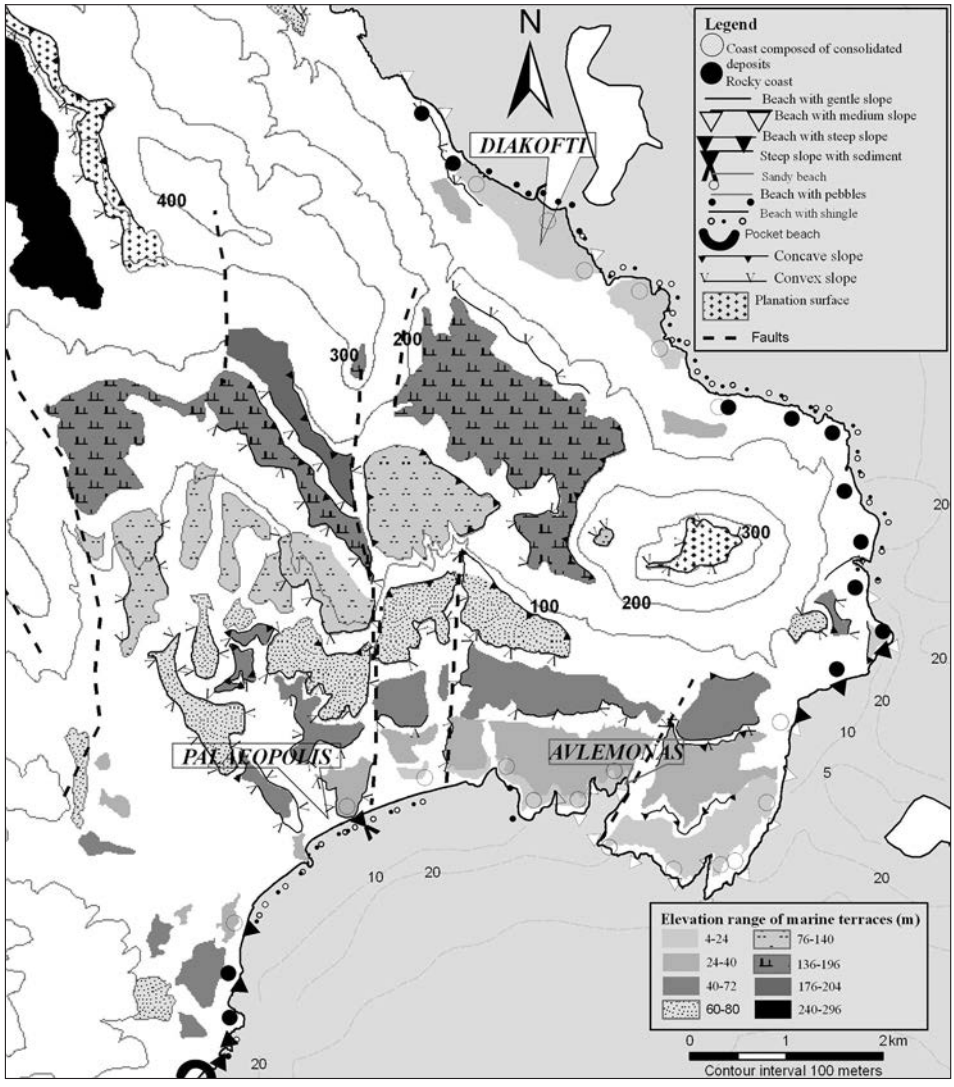

Fig. 3. Geomorphological map of the eastern part of the study area

direction, which have been displaced by a series of normal faults having a N-S direction and dipping to the west (Fig. 3 and Photo 7).

In the western part of the island in Melidoni – Myrtidia (Photo 8) – Limnionas area, six marine terraces exist at 4-40 m, 40-76 m, 80-120 m, 124-160 m, 190-240 m and 240-280 m (Fig. 5).

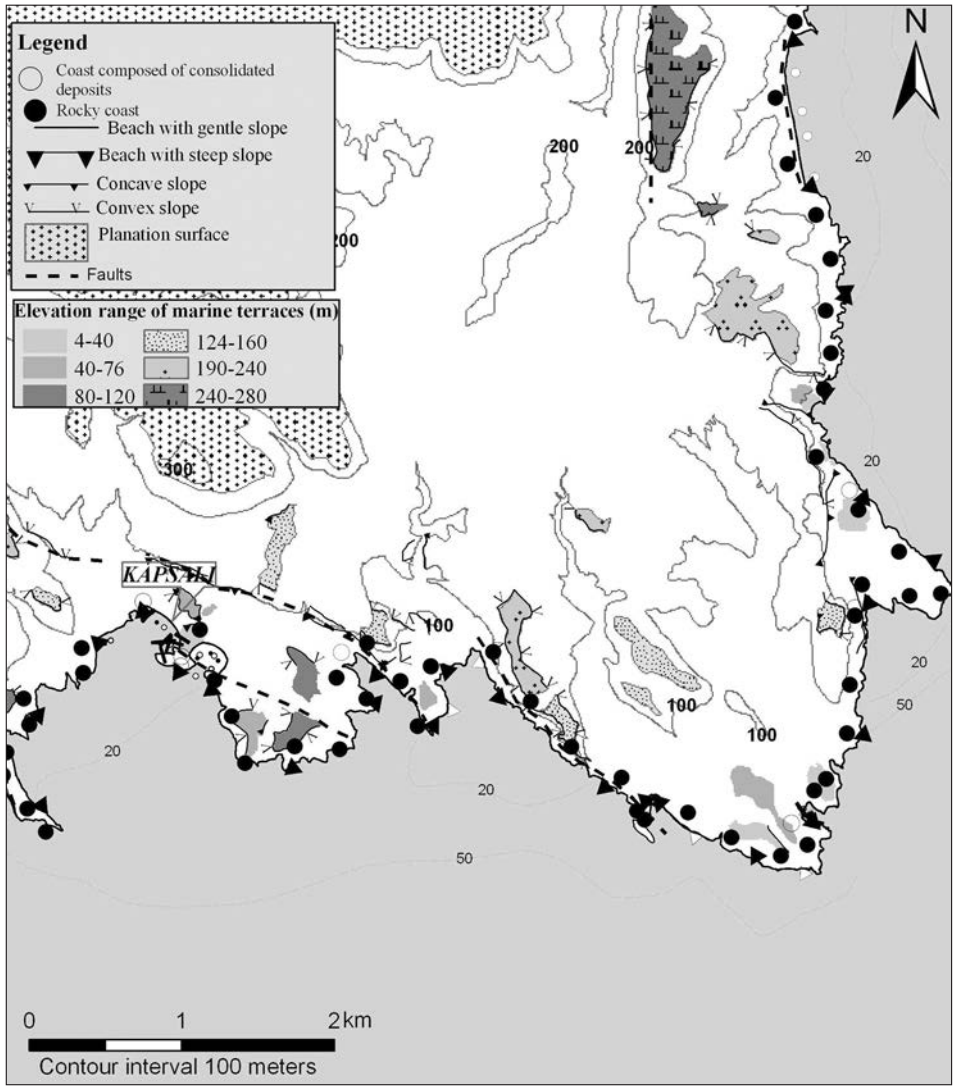

Fig. 4. Geomorphological map of the southern part of the study area

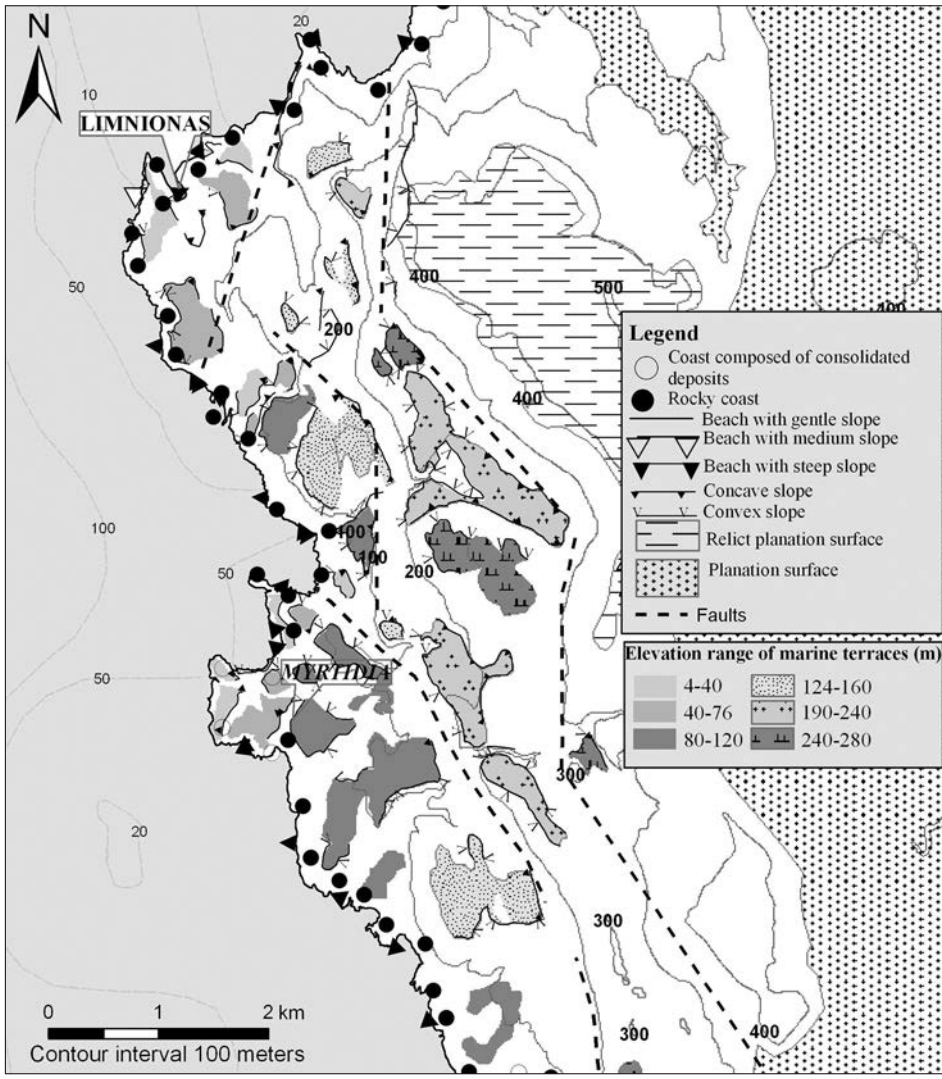

Fig. 5. Geomorphological map of the western part of the study area

The general tilt of the island from north to south during the Quaternary is proven by the differences in the elevation of the older terraces been located higher in the north and lower in the south in both the eastern (Avlemonas-Palaeopolis) and the western (Melidoni – Myrtidia – Limnionas) parts of Kythira.

Having no dates of the marine terraces is impossible to associate ages on them and reveal uplift rates. However, these uplifted Pliocene marine formations can pro-

Photo 1. Coastal cliffs at Limnionas, west Kythera

Photo 2. Pocket beach at south Kythera

Photo 3. The Palaeopolis Beach. In the left middle ground, the formations are uplifted marls and conglomerates

Photo 4. Marine terraces at 2 and 4 m and a notch at 0.4 m, at Avlemonas

Photo 5. Coastal cave carved in limestones at Fyri Ammos with a 0.4 m notch, south-east Kythera

Photo 6. Marine notch and a sea cave at 0.4 and 2 m respectively and a 24 m marine terrace at Skafidi remma, east Kythera

Photo 7. Marine terraces at 24-40, 40-72 and 60-80 m in the broader area of Avlemonas, east Kythera

Photo 8. View of the third terraces 80-120 m at Myrtidia, west Kythera

vide indirect uplift rates. Given that this area should have been submerged in the beginning of the Pleistocene, 2.6 million years ago, and is uplifted up to 340 m today, a minimum mean uplift rate of about 0.13 mm/yr is estimated.

Palaeogeographic evolution of the study area during the Quaternary

The start of fault tectonism during the Upper Miocene signals the beginning of taphrogenesis that is observed in the southcentral part of the island along the Potamos-Avlemonas axis which is synchronous with the culmination of doming (Danamos 1992).

The tectonic depressions received the clastic fluvio-terrestrial sediments from erosion and locally lacustrine deposits as exemplified by the Upper-Miocene conglomerates in the Neogene basin of Potamos-Avlemonas (Theodoropoulos 1973; Meulenkamp et al. 1977).

During the Pliocene, the geodynamic regime remains steady leading to the continuation and development of the same phenomena broadening and widening of the central tectonic graben and the formation of other smaller ones mainly in the southern part of Kythira. This way, the Pliocene sediments (marls, sandstones, conglomerates,) were deposited in parts of the island including echinoids (Manolessos 1955; Theodoropoulos 1973) under shallow-water conditions.

During the Quaternary, the broader area of the island uplifted at least 250-300 meters due to fault tectonism following the reactivation of NW-SE trending faults. This emergence resulted in the Neogene formations to dip to the southeast with their highest elevation in the northwest (340 meters) near Perates village just west of the airport.

In the central and southern parts of the island, a Neogene calcareous palaeosurface is observed which composes a NW-SE trending tectonic graben reaching up to 410 m in the north-west (Kamares) whilst the lowest elevation is found at 220 m in the southeast, Argyros area.

In the southeastern part of the island, the drainage development is limited. The direction of the networks on the limestones is NW-SE and their upstream section is rejuvenated following the uplift of the area while the younger streams (Vythoulas, Peristerionas) are in earlier stages of development having a NW-SE flow direction. In the west, there is a limited development of streams with NW-SE orientation due to Pleistocene fault tectonism. Northwest of Mylopotamos, there is an E-W flowing main channel with SE-NW trending tributaries which formed when the tectonic horst started uplifting during the Plio-Pleistocene.

The presence of eight in the east and six in the west uplifted coastal terraces indicates the intense fault tectonism of the Quaternary. During the last glacial period sea level dropped about 125 m (18 000-20 000 years BP) which resulted in deep downcutting of the drainage systems following the lowering of base level. The ensuing sea level rise in the Holocene drowned many coastal areas including valleys until the sea reached near its present level 5 000 years ago. Today's coastal morphology is determined by fluvio-torrential deposition and coastal erosion thus forming sandy

beaches in the east (Avlemonas) and an indented coastline with pocket beaches in other parts of the island.

The Neogene deposits are found in an elongated tectonic graben having NW-SE direction, being created by the action of normal faults of the same direction and delimit the Neogene deposits from the upper Cretaceous limestones of Pindos unit. Near Alexandrades, roughly 2 Km east of the fault, the hypsometric difference of the current watercourses from the palaeosurface is roughly 100 m. A residual outcropping of Pliocene marls at 204 m means that the throw of the fault in the region of Agios Grigorios is exceeded more than 100 m and agrees with altitudes of other marly outcrops in the SE part of the island.

In the western part of the island, several parallel faults of N-S direction were observed, that have dissected the area and have created smaller basins filled with Neogene sediments. In the southern part of the island exists a normal fault extending from Cape Trahilos till Limnionas. The general dip of the southern part of the island is to the south-east.

Conclusions

– The presence of uplifted marine terraces, eight in the east and six in the west, is owed to Quaternary fault tectonism. The planation surface (280-324 m) is observed in the east and corresponds to the older Pliocene sea level. The whole set of the western terraces is located about 40-50 m higher than the eastern ones. This is primarily owed to the proximity of the western area to the active subduction zone existing west of the island. However, the geomorphological evolution of the eastern coastal terraces is affected by the existence of local faults, having an almost N-S direction dissecting perpendicularly the palaeoshorelines. On the contrary, in the western coastal terraces the local faults are parallel to the palaeoshorelines.
– In Pliocene times, the configuration of Kythira island was completely different. In the central and southern part of the island a Neogene old limestone planation surface is observed corresponding to a NW-SE trending tectonic graben. Its highest elevation (410 m) is located in the northwestern tip of the palaeosurface whilst the lowest point in the southeast reaches 220 m.
– In Quaternary times, the island was uplifted a few hundred meters and took its present shape, with a general tilt from NW to SE.
– Considering the highest position of the raised Pliocene formations (340 m) and that their uplift occurred during the Quaternary ($2.7 \cdot 10^6$ years), we conclude that the minimum uplift rate is about 0.13 mm/yr.
– The drainage networks are characterized by rejuvenation in their upstream parts on the palaeosurface and extension in the new downstream parts mostly on Pliocene formations.
– The intense fault tectonism during the Quaternary together with the variable lithology (limestones – marls – conglomerates) and eustasy have controlled the coastal and fluvial evolution of the island of Kythira. In the NE-ESE, there are more coastal landforms and fewer cliffs while in the W-NW the slopes are steeper and wave energy much higher.

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Kalliopi Gaki-Papanastassiou, Hampik Maroukian, and Violeta Kourmpanian
University of Athens
Department of Geography and Climatology
Faculty of Geology and Geoenvironment
Panepistimiopolis, GR-15784, Athens, Greece
e-mail: gaki@geol.uoa.gr
e-mail: maroukian@geol.uoa.gr