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Quaternary marine terraces as indicators of neotectonic activity of the Ierapetra normal fault SE Crete (Greece)

K. Gaki-Papanastassiou [a], E. Karymbalis [b], D. Papanastassiou [c,*], H. Maroukian [a]

[a] Department of Geography and Climatology, Faculty of Geology and Geoenvironment, University of Athens, Athens, Greece
[b] Department of Geography. Harokopio University, Athens, Greece
[c] Institute of Geodynamics, National Observatory of Athens, Athens, Greece

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ABSTRACT

Along the southern coast of the island of Crete, a series of east–west oriented Late Pleistocene marine terraces exist, demonstrating the significant coastal uplift of this area. Five uplifted terraces were mapped in detail and correlated with Middle–Late Pleistocene sea-level stands following the global sea-level fluctuations. These terraces are deformed by the vertical movements of the NNE–SSW trending and dipping west Ierapetra normal fault. The elevation of the inner edges of the terraces was estimated at several sites by using aerial photographs and detailed topographic maps and diagrams, supported by extensive field observations. In this way detailed geomorphological maps were constructed utilizing GIS technology.

All these allowed us to obtain rates of 0.3 mm/yr for the regional component of uplift and 0.1 mm/yr for the vertical slip movements of the Ierapetra fault. Based on the obtained rates and the existence of coastal archaeological Roman ruins it is concluded that Ierapetra fault should have been reactivated sometime after the Roman period.

1. Introduction

Marine terraces are an important element of coastal geomorphology. Their study had started by the1970s in several places of the world and has since expanded to almost all the coastal regions (Lajoie, 1986). The progress achieved is owed, to a great extent, to the development of accurate dating techniques and the establishment of the theory of the Pleistocene sea-level fluctuations. Given that marine terraces are the geological records of former sea levels, a steadily and rapidly rising coastline is the best mark for measuring major long term sea-level fluctuations and tectonic uplift. Their study could provide important information in dating fault activity and measuring rates of recent crustal deformation, which are very critical in establishing earthquake recurrence intervals, resolving the earthquake potential and evaluating the seismic hazard and risk. Following these studies, other relevant studies have been carried out at different places such as Japan, Alaska, California, New Zealand and New Guinea. In Greece, marine terraces exist in various places such as on the southern coasts of the Gulf of Corinth and along several shores of the Hellenic arc, in the southern Peloponnese and in the islands of Kythera, Crete, Karpathos and Rhodes. Among them, two regions have attracted the scientific interest: the Gulf of Corinth (Sebrier, 1977; Dufaure and Zamanis, 1980; Keraudren and Sorel, 1987) and Crete (Dermitzakis, 1969; Angelier and Gigout, 1974; Angelier, 1975). Although the study of the terraces of the Gulf of Corinth has continued (Armijo et al., 1996; De Martini et al., 2004; Mc Neill and Collier, 2004) this is not the case for Crete. Since the latter has not been studied in detailed in the last decades, it triggered our interest to study this area in the field with modern aspects of science.

Crete is the biggest and southernmost island of the Aegean sea, occupying an important position along the Hellenic arc system (Fig. 1). It has a rectangular shape with an E–W orientation. The length is about 260 km while its width varies between 60 km in the middle and 15 km at the Ierapertra graben in the east. Although Crete is an island, several mountains with peaks exceeding 2000 m exist: Lefka Mts with the highest peak at 2452 m in the west, Idi Mt (2456 m) in the central part and Dikti Mt (2418 m) in the east, a possible indication of the island's uplift through time. Along its southern coast several places exist where uplifted marine terraces occur. The most impressive are located in the eastern part of the island, having a length of almost 24 km on both sides of the city of Ierapetra. The Ierapetra normal fault is located also in the same area and is a major tectonic line with a NNE–SSW direction cutting through the whole island. The marine terraces located along the southern coast of the island, have been deformed by this fault.

This study examines the tectonic activity of the Ierapetra fault during the Late Quaternary, based on the deformation of the marine terraces in space and time and on morphotectonic observations along the fault.

* Corresponding author. Institute of Geodynamics, National Observatory of Athens, P.O. Box: 20048, GR-118 10 Athens, Greece.
E-mail addresses: gaki@geol.uoa.gr (K. Gaki-Papanastassiou), karymbalis@hua.gr (E. Karymbalis), d.papan@gein.noa.gr (D. Papanastassiou), maroukian@geol.uoa.gr (H. Maroukian).

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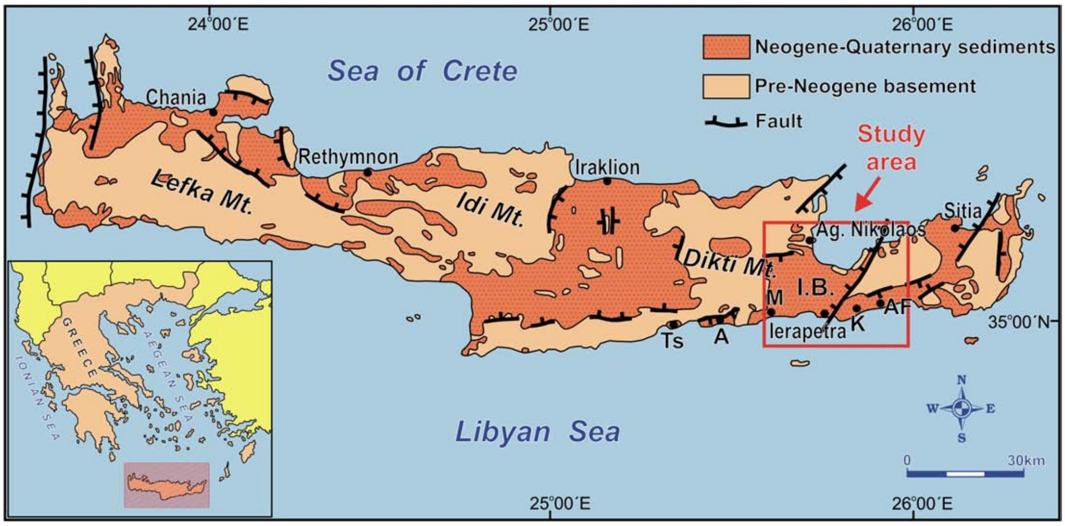


Fig. 1. General geological and tectonic setting of Crete. Letters IB stand for Ierapetra basin, A for Avri, Ts for Tsoutsouras, M for Myrtos, K for Koutsounari and AF for Agia Fotia.

Moreover based on submerged and uplifted coastal beachrocks and archaeological remains and findings, an attempt is made to clarify the Holocene activity of the Ierapetra fault.

2. Methodology

In order to present the shape of the palaeohorizontal lines defined by the mapped terraces, the elevation and the horizontal location of the inner edges of the Ierapertra terraces were determined at 143 sites selected on detailed topographic sheets (1:5000). The sites were chosen where the morphologically defined slope angle break, which identifies the terrace inner edge, is very clear. The horizontal error of the terrace inner edges is less than 20 m and the vertical uncertainty is les than ±4 m. In the field the majority of the sites were inspected for the accuracy of the location and sites where the base of the cliff was covered by thin colluvium and talus were corrected. Sites where the cliff has significantly retreated landwards due to the erosion or human modification were omitted.

Besides the mapping of the deformed terraces, detailed geomorphological mapping of the Ierapetra fault front was carried out using GIS and DTM technology through accurate analysis of Landsat satellite images, 1:33,000 air-photographs, 1:50,000 topographic sheets and 1:5000 topographic maps aided with extensive fieldwork. The DTM cell size of the grid was 15 m and the software used for this analysis was MapInfo v6.0 and Vertical Mapper v3.1. The products of these techniques, allowed the inspection and visualization of the final constructed maps.

3. Geological and tectonic setting of the area

The geology of Crete can be divided into an autochthonous basement, a system of nappes thrusted over the basement, and sediments of Neogene and Quaternary age (Fig. 1). The pre-Neogene rock succession of nappes form a pile, in which unmetamorphosed Alpine rocks are found between two metamorphic belts. High pressure metamorphism in the lower group of nappes took place during Oligocene–Early Miocene times. About one third of the island is covered by Neogene and younger sediments. The Neogene and Plio-Pleistocene sediments overly the alpine formations in discordance, and are constituted by terrestrial, fluvial, brackish and marine phases. They present great dissimilarities in age and lithology and are composed mainly of marls, conglomerates, and marly limestones. Quaternary sediments lie over all the older formations and are composed of terrestrial, marine–brackish deposits, sands, pebbles, boulders and clays, loose or slightly consolidated (Seidel et al., 1982; Papanikolaou, 1986).

Extension in the Aegean area is generally north–south, however in the southern part the present tectonics is dominated by east–west extension. The existing north–south normal faults in the area reflect this tectonic regime. The tectonics of Crete is dominated also by normal faults with this general direction (Fig. 1) placed nearly orthogonal to the east–west trending Alpine structures. Several, east–west trending normal faults, are inherited from the pre-Alpine tectonics. The active normal faults have a north–south direction and are marked by sharp scarps that in many places offset gullies on calcareous slopes or present traces of recent reactivation (Angelier, 1979b; Armijo et al., 1992).

In more detail, the largest part of the area studied is covered by a thick sequence of Neogene marine sediments and the Pleistocene deposits have a great extent. In this part of Crete post orogenic sedimentation started with the deposition of Middle Miocene terrigeneous clastics followed by Upper Miocene fluvial, lacustrine and open marine sediments, filling the Ierapetra and the other basins. Ierapetra basin is aligned at an east–west direction, parallel to the main direction of the Alpine structures. It is closed to the north by marginal east–west trending fault zones; those in the west are less clear, compared to the sharp one delineating the northern border in the east (Fig. 1). The graben is open to the south, towards the sea. The post-alpine sediments of the Ierapetra graben can be grouped into different formations, following the palaeogeographic environment and the age of deposition. They follow the general east–west geometry, which was dominant at the time of deposition, with the older sediments located at the north-western part of the graben (Dermitzakis, 1969; Fortuin, 1977; Postma et al., 1993). Quaternary deposits are discernible in the marine terraces and the coastal sediments traced mainly along the southern coastal zone and in the alluvial deposits, screes and talus cones, developed along the whole length of the Ierapetra normal fault. This fault has a NNE–SSW direction and a dip to the NW and has divided the graben having played a crucial role in the evolution of the area. Due to its activity, sediments of significant thickness cover the hanging wall, while in the footwall they exhibit less width.

4. Seismicity

The seismicity of the broader area of Crete is high and is closely related to the geodynamic processes occurring in the region, namely the subduction of the African lithosphere beneath the Eurasian plate and the stretching of the Aegean area. Following these aspects the occurrence of intermediate and deeper earthquakes, focal depth greater than 60 km, is due to the first process while shallow earthquakes with focal depth less than 60 km, to the latter. Recent studies prove that shallow earthquakes, occur mainly off the southern shores of Crete having a predominant depth of about 20 km. The intermediate events take place between 60 and 160 km depth, below the whole island with increasing depths towards the north (Papazachos et al., 2000; Meier et al., 2004; Makris and Yegorova, 2006).

Based on historical records, several great events occurred around Crete. The most destructive took place in 66 AD, 365, 439, 448, 1303, 1484, 1508, 1780 and 1815 assigned to shallow events, and in 368 BC, 55 AD, 251, 796, 1810 and 1856 to intermediate events (Guidoboni, 1994; Papazachos and Papazachou, 1997). The events of 365 and 1303 AD were among the largest events in the Mediterranean area, located northwest and southeast of Crete respectively. Additionally the events in 1508, 1780 and 1815 are mentioned as particularly having affected the study area. The shock of 1508 destroyed most of eastern Crete. Ierapetra city was ruined and was not rebuilt; until much later only a small village was constructed in its place. The violent earthquake of 1780 destroyed the fortress of Ierapetra killing all of its guard, whereas 13 villages of the area with their inhabitants were also devastated. The earthquake of 1815 was also violent in the southeast part of Crete. It caused the devastation of a great part of the city of Ierapetra.

Concerning the instrumental seismicity of the last hundred years, several earthquakes of magnitude about 6.0 were strongly felt in the city of Ieraperta, while some of them clearly originated from a close source.

However, for these strongly felt earthquakes and the previous destructive events for the city of Ierapetra, there has been no information on surface breaks or other geological phenomena accompanying the strong earthquakes, as it is very difficult to associate them with the rupture of a specific fault and especially the Ierapetra fault.

5. Morphotectonic characteristics of the Ierapetra normal fault

Ierapetra normal fault is the biggest tectonic element of eastern Crete with an inland length of more than 25 km, and has uplifted the eastern block several hundred meters related to the Ierapetra Neogene basin which is developed over the higher tectonic units of Crete now located below sea level. It is one of the most characteristic active faults of Crete that cuts through all the nappe pile. This fault should have been active at least during the early Quaternary accommodating part of the existing E–W extension in this area (Armijo et al., 1992).

The fault consists of different segments with a step-like arrangement, each one having its own characteristics (Fig. 2). The northern inland segment, between Kavoussi and Platanos villages, presents intense morphotectonic characteristics. The fault plane is very steep and its lower part is covered by screes and talus cones. They are developed in successive layers of different lithofacies depending on the size of the boulders and the type and degree of coherence of the cementing material. In general the older facies are more coherent and polymict. These lithofacies could be related to different activations of

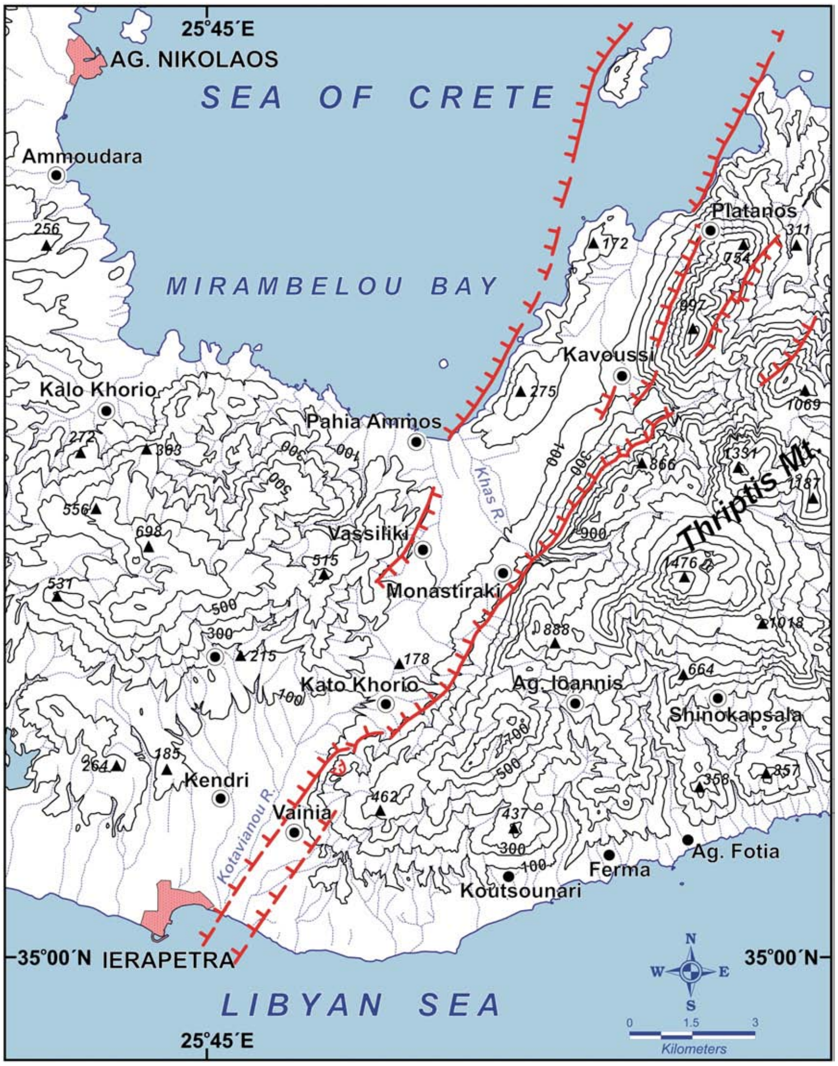


Fig. 2. Topographic map of the Ierapetra fault.

Fig. 3. The front of Ierapetra fault seen from a distance. The Ha gorge is also seen.

the fault. The middle segment at Monastiraki, has an eastward step. This segment has a N 30° orientation while the dip of the fault surface is about 70° with pure dip slip slickensides (Karotsieris et al., 2000). The fault plane is covered largely by screes and talus cones but near Monastiraki where the mouth of Ha gorge is located, the fault plane is very clear (Figs. 3, 4). A band of light colour is observed along the base, having a width of about 100 cm, which is associated with the Holocene activity of the fault, giving a minimum uplift rate of 0.1 mm/yr at least for this period. The southern segment, south of Kato Khorio, as it crosses soft rocks is not very clear, but could be traced in two different parallel segments creating an unstable zone where a landslide has occurred (Figs. 2, 5). One of its segments is on the continuation of the Monastiraki segment and the other is located further east. The continuation and the recent activity of the western segment, covered now by the alluvial deposits of Ierapetra plain, is proven by the presence of beachrocks uplifted by 1–2 m, located just east of Ierapetra city. Ierapetra fault extends into the sea towards both the north and south of Crete.

The drainage systems on both sides of the fault zone of Ierapetra differ significantly in what relates to basin extent and stage of development (Fig. 2). In the eastern side (Mount Thriptis), the main channels exhibit a parallel drainage type with short lengths and are still in a young stage of development. On the other hand, the drainage networks of the western side present a more extensive and well-developed system with one network prevailing (Geroutas R.) having a more mature stage. The characteristic development of Kotavianou R. extending only on its western half is one more indication of the continuous activity or reactivation of the Ierapetra fault which has not permitted the eastward extension of the drainage network and basin. Following the deep downcutting of the torrents and the formation of a

Fig. 4. Close up of the Ha gorge. The light colour stripe visible at the base of the fault scarp indicates recent reactivation.

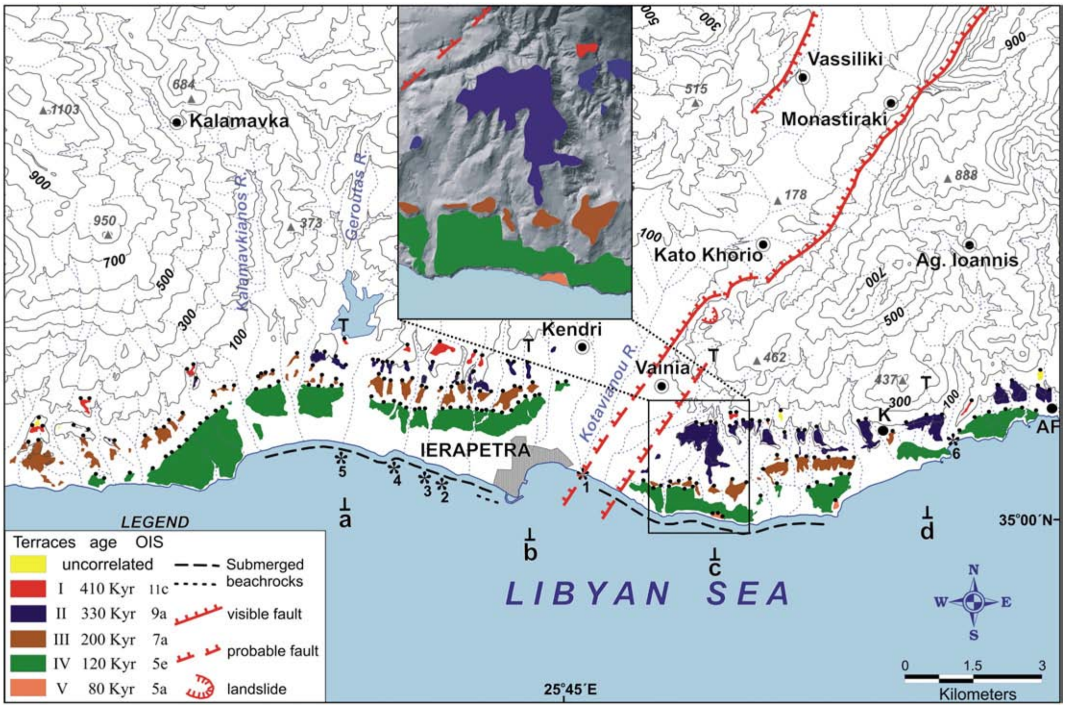


Fig. 5. Morphotectonic map of the Ierapetra area in which the deformed marine terraces and the Ierapetra fault are shown. Black dots indicate the sites of the inner edges where their elevations were estimated. Sections a, b, c and d used in the study are also shown. Numbers indicate coastal natural and artificial features discussed in the text. Letters AF and K stand for Agia Fotia and Koutsounari respectively. The inset is part of the DEM produced for the study area.

steep topography, there is an increased frequency of rockfalls intensified by the friable and intensely strained conglomerates.

6. Marine terraces

Marine terraces are excellent morphological markers and have been used world-wide to recognize past sea-level changes. An emerged marine terrace is a complex morphological feature, characterized by erosional and depositional elements. It is bounded landward by an inner edge representing the palaeoshoreline correlated to one of the main interglacial Oxygen Isotope Stages or Substages (OIS) ascribed by the global eustatic curve (Imbrie et al., 1984; Aharon and Chappell, 1986; Chappell and Shackleton, 1986; Chappell et al., 1996; Zazo, 1999). The correlation of uplifted Quaternary marine terraces and palaeoshorelines with the main interglacial highstands can be done only in areas where significant geological and morphological evidence suggests the existence of a long-term continuous uplifting process at a regional scale, even though it is characterized by variable rates since the formation of the oldest marine terrace. The hypothesis that the mean uplift rate during the investigated time period is high enough to preserve the marine terraces, permitted the dating of the terrace sequence and the evaluation of the uplift history of raised coastal regions (Westaway, 1993; Armijo et al., 1996; Zazo et al., 2002; Tortorici et al., 2003). The surface extension of the terraced surfaces depends on the duration of the sea-level stand, the erodability of the local rock layers and the original morphology. In the Aegean area, these are preserved because of sufficient coastal uplift. Dating their exposure, therefore, provides a way to date the uplift. For recent marine terraces ^{14}C has been used to determine the age of emplacement of certain markers, in other cases U-series measurements on shells has also been used. However in the Aegean it is difficult to find datable material on those surfaces, commonly marine shells, as these are in most cases abrasion surfaces with only a thin cover.

Along the coasts of southern Crete, marine terraces, abrasion platforms and raised notches are present at various locations. In the area of south-east Crete, an east–west oriented coast, Angelier and Gigout (1974) and Angelier (1975) recognized the existence of Late Pleistocene uplifted wave-cut surfaces and thin depositional platforms at several locations, carved into pre-existing Mio-Pliocene marine sediments. More precisely they have mapped at a scale of 1:50,000, three main terraces, at areas located just east of Ierapetra city up to the Agia Fotia area and at two sites, Tsoutsouras and Arvi, located 25 km west of Ierapetra (Fig. 1). Following their work, another terrace located at higher elevations was occasionally visible, but due to the inadequate preservation was not mapped by them. More specifically, in the area of Koutsounari, east of Ierapetra (Fig. 2), they reported the existence of the three terraces, the lower one at 4 to 20 m, the middle one at 35 to 45 m and the highest at 65 to 100 m. They also state the existence of a fourth younger raised abrasion platform at elevations of 2–3 m.

Table 1
Radiometric dates and the associated errors provided by Angelier (1979a)

Terrace	Radiometric method	dated fauna	Altitude m	Age Ka
Higher	$^{230}Th/^{235}U$	Spondylus	70	≥250
Lower	$^{231}Pa/^{235}U$	Pectenidae	10	109^{+22}_{-12}
		Callista Chione	10	$130^{+\infty}_{-65}$
	$^{230}Th/^{235}U$	Pectenidae	10	131^{+9}_{-7}, 103^{+6}_{-6}
		Pectenidae Spondylus	20	114^{+15}_{-7}
		Callista Chione	10	90^{+5}_{-3}
Abrasion platform	$^{230}Th/^{235}U$	Spondylus	4, 2.5	52^{+6}_{-5}, 47^{+5}_{-5}, 43^{+2}_{-2}

The dated fauna, the altitude of the samples and the corresponding terrace are also stated.

Fig. 6. Beachrocks east of Ierapetra city uplifted up to 1.5 m.

The observed fauna differs between the terraces. In the lower one (4–20 m) a great number of sea shells exist like: *Cantharus viverratus Kien*., *Conus testudinarius Mart*., *Polinices lacteus Guild*., *Patella safiana Lmk*. and *Strobus bubonius Lmk*. which confirm a Late Pleistocene age, corresponding to OIS 5e, for this terrace where corals are also abundant (Fig. 5). At the higher terrace (65–100 m) the common existence of the shell *Spondylus gaederopus Linne*, did not however permit its dating. In the middle one the fossils were very few. In the following work by Angelier (1979a) radiometric $^{230}Th/^{235}U$ dating was performed. The reported dates are presented in Table 1. We should mention that Angelier in his work does not give specific information on the precise location where the dated samples were collected.

7. Correlation in time of the terraces and uplift rates of the Ierapetra terraces and fault

In this study we have tried to determine the tectonic activity of the Ierapetra fault during the Late Quaternary based on the deformation of the marine terraces located along the south-eastern coast of Crete in space and time and on morphotectonic observations along the fault. Following our detailed field work in the area extending 24 km east and west from Ierapetra city, from Agia Fotia in the east to Myrtos in the west, five Quaternary marine terraces were recognized. Four, well preserved terraces numbered I–IV starting from the highest and oldest towards the youngest and lowermost, deformed by the Ierapetra fault have been mapped in detail (Fig. 5). In addition to these well defined terraces, at some other points located on both walls of the fault, there exists some evidence of one more, older terrace situated at higher elevations. The lack of continuity of this terrace made precise mapping and correlation difficult. Furthermore, recent modification of the land, mainly of the hanging wall, due to the construction of greenhouses, is also a reason of poor preservation. Terraces II, III and IV correspond to the higher, middle and lower terraces defined by Angelier (1975, 1979a) and Angelier and Gigout (1974). Moreover, in some places on the footwall a fifth lower and younger terrace (V) was mapped, at elevations of about 2–8 m, which coincides to the abrasion platform mentioned by Angelier (1975, 1979a) and Angelier and Gigout (1974), while very near the fault trace there are uplifted beachrocks up to a height of 1.5 m (location 1 on Figs. 5 and 6) (Fig. 7).

Fig. 7. Close up of the 120 Ka old marine terrace (IV) in the Ierapetra area, composed mostly of corals.

Taking into account the tectonic setting of the area, the total amount of uplift should be the result of movement on the Ierapetra fault and the regional uplift component. In order to better define the deformation pattern of the area, the traces of 143 inner edges of the palaeoshorelines have been projected in an E–W direction, perpendicular to the fault trace, for a length of about 24 km (Fig. 8). In this projection the palaeoshorelines I–IV display increasing elevations from E to W, a geometry suggesting a tilting to the E, and a clear normal fault deformation crossing the Ierapetra fault. In order to quantify the uplift rates of the terraces and the Ierapetra fault, we have

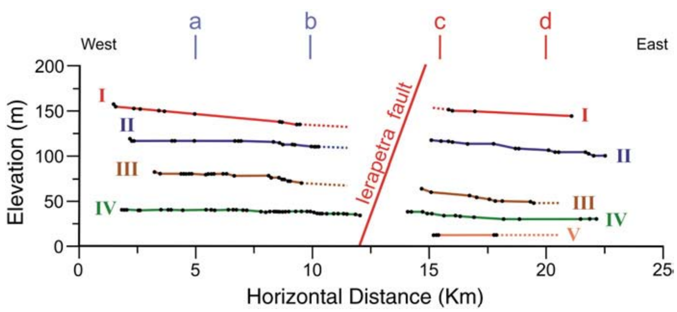


Fig. 8. Vertically projected east–west profiles of the palaeoshoreline elevations, occurring both on the footwall and the hanging wall of the Ierapetra fault. The fault trace is also given. Letters a, b, c and d indicate the sites of the sections used in Fig. 9.

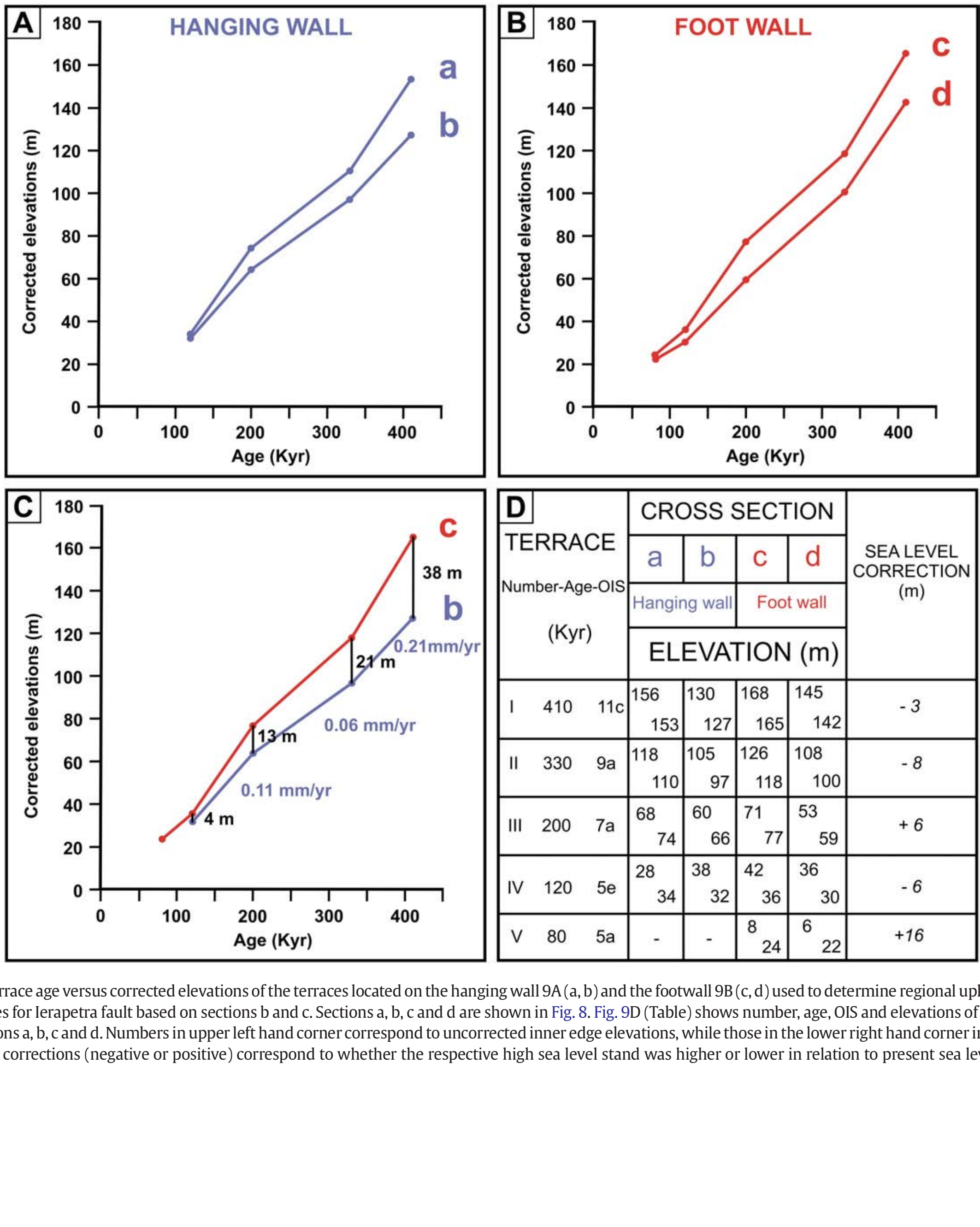
identified the elevation of the inner edges along four profiles constructed across the marine terraces, two from the hanging wall (a, b) and two from the footwall (c, d) Sections a and d are located far from the fault, while b and c are in its vicinity (Fig. 9). Sections a and d, free from fault movements, were used to determine uplift rates of the terraces. The elevations of the inner edges allow the precise estimation of the amount of uplift, from the given elevation of sea level at the time of their formation. This implies the correlation of the elevation of every terrace, to a specific interglacial OIS given by a sea-level curve. However, this is not an easy task, as there are great differences between the various published sea-level curves concerning the height and age of the highstand sea-level peaks (Zazo, 1999; Caputo, 2007). Given the uncertainty on the precise elevations and the accuracy of the duration of the highstands, we have tried to use uplift rates that are constant through time in order to assign dates to the terraces, an approach that is consistent with the results of other works (Armijo et al., 1996; Morewood and Roberts, 1999; Houghton et al., 2003). The dates of the marine terraces of Ierapetra are those provided by Angelier (1975, 1979a) and Angelier and Gigout (1974) and they have already been presented.

Firstly, we have modeled the elevations of inner edges of terrace IV, with the existing dates as these are the most reliable and abundant. These range between 131 (+9, −7) and 90 (+5, −3) Ka, strongly suggesting that it was formed 125 Ka ago, during the prominent sea-level highstand corresponding to OIS 5e. This highstand began possibly 132 Ka when sea level reached ~6 m above present mean sea level. High sea level was sustained until 120 Ka and then fell rapidly (Chen et al., 1991). As the corrected elevations of the inner edge of this terrace are located between 30 and 34 m (sections a and d) the resulting uplift rate would be about 0.3 mm/yr (Fig. 9).

By applying this uplift rate to the younger highstand 5a, at 80 Ka, an elevation of 24 m for the inner edge is obtained. Taking into account that the elevation of the inner edge of the terrace is at 6 m and that this highstand was lower than the present msl by about 16 m (Schellmann et al., 2004; Schellmann and Radtke, 2004; Dumas et al., 2006; Caputo, 2007) we could assign the OIS 5a to this terrace.

For terrace III there are no radiometric dates. The elevation of its inner edge varies between 53 and 68 m. By using the uplift rate, ages between 177 Ka and 227 Ka are obtained. During this time period the major OIS 7a existed, at 200 Ka, located at about 6 m below present msl, while the immediately previous OIS 7c has an age of 240 Ka and an elevation correction of 20 m (Schellmann et al., 2004; Schellmann and Radtke, 2004; Caputo 2007). The OIS 7a at 200 Ka was adopted, as more appropriate, for terrace III.

For terrace II an indication of only an age greater than 250 Ka is given (Angelier, 1979a). The inner edges of this terrace are located at



TERRACE Number-Age-OIS (Kyr)			a (Hanging wall)	b (Hanging wall)	c (Foot wall)	d (Foot wall)	SEA LEVEL CORRECTION (m)
I	410	11c	156 / 153	130 / 127	168 / 165	145 / 142	- 3
II	330	9a	118 / 110	105 / 97	126 / 118	108 / 100	- 8
III	200	7a	68 / 74	60 / 66	71 / 77	53 / 59	+ 6
IV	120	5e	28 / 34	38 / 32	42 / 36	36 / 30	- 6
V	80	5a	-	-	8 / 24	6 / 22	+16

Fig. 9. Diagrams of terrace age versus corrected elevations of the terraces located on the hanging wall 9A (a, b) and the footwall 9B (c, d) used to determine regional uplift rates. Fig. 9C shows the vertical uplift rates for Ierapetra fault based on sections b and c. Sections a, b, c and d are shown in Fig. 8. Fig. 9D (Table) shows number, age, OIS and elevations of the inner edges of the terraces used in sections a, b, c and d. Numbers in upper left hand corner correspond to uncorrected inner edge elevations, while those in the lower right hand corner in corrected elevations. The applied sea level corrections (negative or positive) correspond to whether the respective high sea level stand was higher or lower in relation to present sea level.

elevations between 108 to 118 m. Using the same technique, the age of 330 Ka, which corresponds to the 9c OIS, is obtained for this terrace. By applying an elevation correction of −8 m, the data match quite well. (Schellmann et al., 2004; Schellmann and Radtke, 2004;).

Finally, for the higher and older terrace I, we assign the age of 410 Ka which corresponds to the previous prominent OIS 11c. Given that this highstand was about 3 m above present msl, this implies that the inner edges of this terrace should be located at elevations of about 125 m, which are not far way of the elevations of the inner edges measured for this terrace (Rohling et al., 1998; Caputo, 2007). This difference in elevation may be due to a possible change in the uplift rate or due to the extended erosional period of the inner edges of the terrace which are not well preserved.

By using sections b and c, information of the tectonic history of the Ierapetra fault since the formation of the earliest mapped palaeo-shoreline was obtained. These sections show that the inner edges of the same terrace located on both sides of the fault are displaced with vertical offsets decreasing from the oldest terrace to the youngest one. The obtained vertical slip rate for the Ierapetra fault, for the period 120–200 Ka is 0.11 mm/yr, for the period 200–330 Ka is 0.06 mm/yr while for the last period 330–410 Ka is 0.21 mm/yr. A mean value of 0.10 mm/yr is reasonable to assign for this area, in relation to the estimated Holocene rate.

8. Holocene deformation on coastal formations

Along the coast of Ierapetra, on both sides of Ierapetra fault, submerged beachrock formations are found at several places. At a number of sites specific observations could be made based on field investigation and maps of the Greek Hydrographic Service (scale 1:10.000) and various other references, showing the underwater relief of the area.

On the hanging wall of the fault, just west of Ierapetra city, two distinct series of submerged beachrocks are found (Fig. 5). A shallower one located along the whole coast, at depths of 1–1.5 m and another one located in a limited area, just west of Ierapetra city, at depths of about 3 m. East of the city, on the footwall, only one line of beachrocks is obvious, at depths of about 1.5–2 m (Mourtzas, 1990). Moreover, on the footwall where the fault enters into the sea, uplifted beachrocks exist at elevations 1–2 m.

On the down thrown block, at a distance of 2.6 km from the fault and 40 m from the coast, at about 2 m below sea level the existence of beachrock is reported containing plenty of ceramic shreds including also the neck of an amphora of the 2nd century BC, (position 2 in Fig. 5), (Mourtzas, 1990). At another site, at a distance of 3 km from the fault and 80 m from the coast, at 3.5 m below sea level, a beachrock with an amphora of the same period was found, (position 3 in Fig. 5). At a distance of 3.7 km and at a depth of 1.5 m, beachrock is found where a cooking pot from the Classical period (5th–4th century BC) is incorporated (position 4 in Fig. 5). In the same block, at a distance 5 km and at a depth of 1–1.5 m, graves were found of the Minoan period, 2500–1800 BC, covered by beachrock, (position 5 in Fig. 5) (Dermitzakis and Theodoropoulos, 1975).

On the eastern uplifted block, there is a place by the coast at a distance 7 km from the fault where a rock-carved fishtank of Roman age is located, (position 6 in Fig. 5 and Fig. 10). According to archaeologist Davaras (1974) its present position implies an uplift of the coast of about 50 cm while Flemming and Pirazzoli (1981) attribute the present position to a subsidence of the coast of about 20 cm.

9. Discussion–conclusions

The geomorphological analysis of the Ierapetra area, permitted us to identify five uplifted marine terraces, correlated to five main OIS of the eustatic sea-level curve in the period 410–80 Ka before present.

The uplifted terraces are characterized by a continuous uplift since the segments of the marine terraces located on the hanging block are

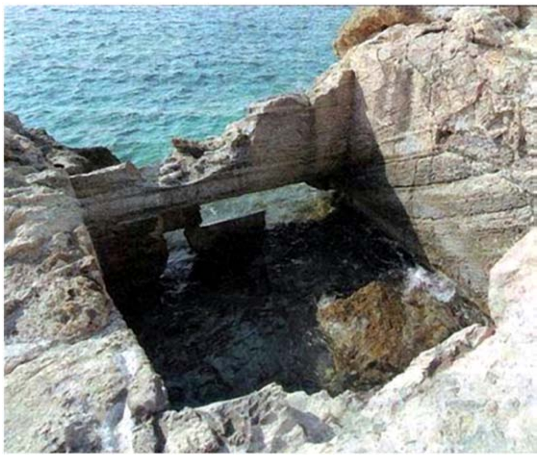


Fig. 10. The rock carved Roman fish tank.

still elevated above sea level. The obtained rate of uplift is 0.3 mm/yr. This value is similar to the regional component of uplift 0.2 mm/yr found and adopted also at other places of the Aegean, particularly in the Corinth gulf (Collier et al., 1992; Armijo et al., 1996; De Martini et al., 2004). In our case we believe that the estimated rate of 0.3 mm/yr is adequate as this area is situated closer to the active subducting margin than the Gulf of Corinth.

The analysis of the terraces located both on the hanging wall and on the footwall of Ierapetra fault indicates that this fault has been active since 410 Ka. Its movements are characterized by slow rates, about 0.1 mm/yr.

Although these obtained values of activity have been estimated for time intervals corresponding to the periods between the major interglacial peaks of the eustatic curve, they approximate the combined vertical movements of Ierapetra fault and the regional uplift, giving a total uplift rate of the order of 0.4 mm/yr.

Along the coast of Ierapetra, on both sides of the fault, submerged beachrock formations are found at several places, but it is not easy to date or correlate them and obtain absolute rates of the fault movements. However, based on the existing archaeological remains and findings some comments could be made concerning the Holocene movements of the Ierapetra fault. Trying to elucidate the Ierapetra fault activity during this period, besides the total tectonic rate, the eustatic sea-level rise should also be taken into account.

As it has already been mentioned, a Roman fishtank exists on the footwall. Assuming an age of about 2000–1700 yrs BP for the fishtank and using the total estimated uplift rate of the area of 0.4 mm/yr, a total uplift of less than 1 m is derived for the tank. In the Aegean area sea-level rise of almost 50 cm during the last 2000 yrs has been considered adequate (Flemming and Webb, 1986). It is concluded that the fish tank has been uplifted by almost 30–50 cm, in accordance with the observations of the archaeologists. This uplift could be associated with a reactivation of the Ierapetra fault, which took place after the Roman period.

On the hanging wall there are several places where beachrock is found at depths of 2 to 3.5 m containing ceramic shreds, an amphora and a cooking pot of the 5th to 2nd centuries BC. Even more, at shallower depths of 1 to 1.5 m the existence of a grave of the Minoan period (2500–1800 BC) is reported covered with beachrock. It is also given, that in the last 2500 years sea level has risen by almost 1 m and more than 3 m in the last 4000 years (Lambeck, 1996). It is obvious that the present position of these underwater archaeological findings should be attributed to the combined action of the Ierapetra fault and the eustatic sea-level rise. Having no precise knowledge on the original location of these beachrocks, it is very difficult to estimate the proportion of the eustatic and tectonic component that affected the area and led these formations to take their present position. However, in the vicinity of the fault on both sides, the submerged beachrock shows a more or less apparent correlation concerning their depth position. Those located on the uplifting side are reported to be at smaller depths, about 1–2 m below present msl than those of the down dropping block, 1–4 m. It is clear that the submergence of these formations should be primarily eustatically controlled, but their displacement could be related to the reactivation of the Ierapetra fault.

Concerning the uplifted beachrock on the uplifted block at the point where the fault enters the sea, its location is attributed to recent fault reactivation. Taking into account the heights of 1–1.5 m and its nearness to the fault, uplift age of 2000 yrs seems acceptable, proposing an earthquake after Roman times in accordance with our observation further west at the Roman fish tank.

Although Ierapetra fault seems to be one without high activity, the intense morphology of the fault zone, indicates that a future reactivation could cause severe damage in the broader area, like similar recent cases from other parts of Greece such as in Athens in 1999 and at Grevena in1995.

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