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LANDSCAPE RESPONSE TO THE TECTONIC UPLIFT OF CRETE, GREECE

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ABSTRACT

In this study we used digital elevation models, tectonic data and field observations in order to recognize significant landforms related to erosion processes induced by the Neogene and Quaternary tectonic uplift of Crete. Gorges, as well as river and marine terraces were recognized in all study areas, whereas flat erosion surfaces and hanging valleys were observed in few cases. Riverbed profiles in the areas of Samaria, Zakros and Heraklio, where old normal faults are responsible for rock uplift, indicate very mature erosion style, although nick points and recent incision occur due to later fault reactivations. In the area of Ierapetra, Cha gorge developed as a result of the Ierapetra active fault, while the existence of several nick points, waterfalls and very steep profile indicate a very young erosion style. River and marine terraces occur in several altitudes representing older stands of sea or local base levels. However, lack of dating and differential uplift rates of tectonic blocks do not permit correlation between different areas. We believe that the flat erosion surfaces and the hanging valleys should be of the same late Miocene age as is the initiation of the big normal faults, thus dating the initiation and development of the majority of the gorges, and consequently the intense incision period, as Pliocene. An exceptional case is the Cha gorge that should have been developed in Pleistocene-Holocene times due to the age of the active fault. Since Messinian, estimated total uplift rates for the area of Samaria are 11.9 cm/ka, for the area of Heraklio 7.1 cm/ka and for the area of Zakros 10.8 cm/ka. We further suggest that tectonic uplift is the result of isostatic rebound of lithosphere due to upper crust thinning.

1. INTRODUCTION

It is generally known that landscape in active orogens is shaped mainly by two factors, tectonic activity and surface erosion (Skinner et al. 2004). Depending on the tectonic regime or the climate features one of these factors becomes prominent in landscape evolution.

Crete is part of the Hellenic orogen built mainly in late Cenozoic times (Bonneau 1984) by the same processes that are active today; the African – Eurasian plate convergence. It is thus being actively deformed as a result of the African plate subduction south of the island, as well as of the Anatolian plate extrusion (Meijer & Wortel 1997). Short term GPS velocities have revealed approximately 36 mm/year total convergence between African and Cretan coastlines (Mc Cluscky et al. 2000).

The neotectonic record has determined successive extensional periods all over Neogene and Quaternary times (Angelier et al. 1982, Fassoulas 2001), while only short periods of localized compressional tectonics have been recorded (Mercier et al. 1987, ten Veen & Kleinsphen 2002). Since late Serravallian times, gravitational collapse of the nappe pile resulted in the exhumation of deep crustal rocks (Fassoulas et al. 2004, Rahl et al. 2005). Extensional tectonics resulted in numerous, multi-directional, normal faults that have fragmented and shaped the island. Its elongated shape is attributed to the arc parallel and arc – normal extension (Mercier et al. 1987) during the Neogene times. Furthermore, focal mechanism analyses of south Aegean and Cretan sea have documented only crustal extension on shore, while compressional or strike-slip movements are concentrated offshore, either south of the island on the

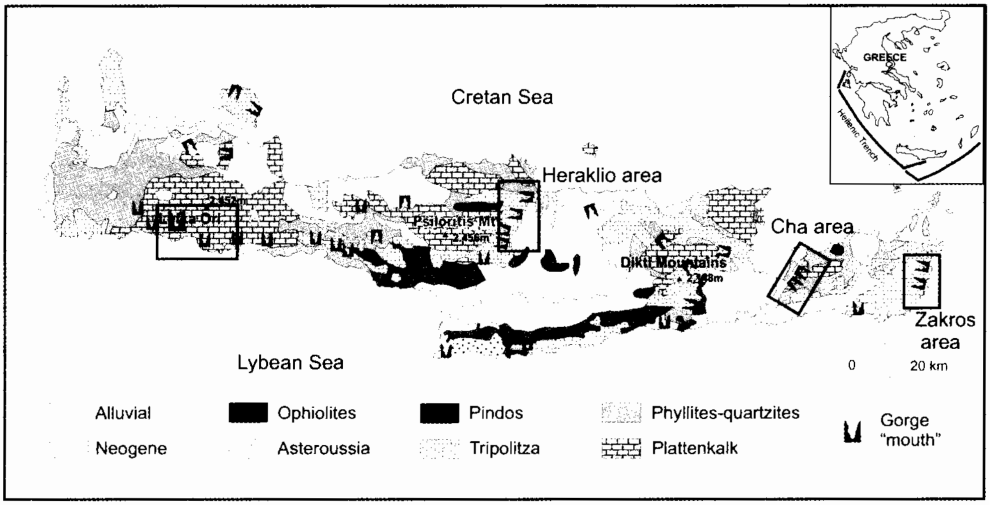

Figure 1. General geologic map of Crete based on the map of Creutzburg et al. (1977). Rectangles indicate study areas.

lower crust or northwards in the descending plate (Taymaz et al. 1989, Benetatos et al. 2004).

In Crete tectonic uplift has been documented for large areas of the island, although the whole island is under extensional regime. Meulenkamp et al (1994) have reported extensive rock uplift in central Crete during Pliocene times based on the depositional characteristics of the Heraklion basin sediments. All over the island a series of geomorphological studies based on terrace analyses (Fleming 1978, Pirazzoli et al. 1996, Lambeck 1995, Price et al. 2002) documented tectonic uplift even in Quaternary times.

An explanation for this complex tectonic situation can be found in the sedimentary flux that enters in the subduction zone. Underplatting of a large amount of sedimentary flux under Crete may account for prism overgrowth and consequently for the gravitational collapse leading to upper crustal extensional thinning (Rahl et al. 2005).

Thus, Crete is uplifted and horizontally stretched since late Miocene times building finally high mountainous areas with many summits approaching 2,5 km height and deep valleys that can sunk undersea in depths of about 3km as is the case of the Gavdos graben. This is a feature which is unique for non-volcanic islands (Rackham & Moody 1996). Intense uplift should have affected the erosion of mountainous areas forming landscape that reflect the vertical changes all over the island. Some of those are obvious when visiting the southwestern Crete, where numerous gorges run over the mountains. Furthermore, stream activity and erosion style should have also been adapted to the temporal and other changes of the uplift, recording those on the Cretan relief.

In this paper we examine the response of Cretan landscape to the long- term tectonic uplift of the island. We use modern surface (GIS based) models and river profile analyses, erosional features, neotectonic data and field observations to comment on the influence of local tectonic history in the erosion processes and the landscape development of the island, and to qualitatively approach vertical differentiations along the island. For these purposes topographic maps on the scale of 1:50000 with 20 meters isograds were used, as well as former tectonic studies and fault analyses.

2. GEOLOGICAL AND TECTONIC SETTING

The island of Crete is mainly built by a series of nappes emplaced over each other during the late Cenozoic times (Bonneau 1984). All over its extend three units i.e. Plattenkalk, Phyllites-quartz-

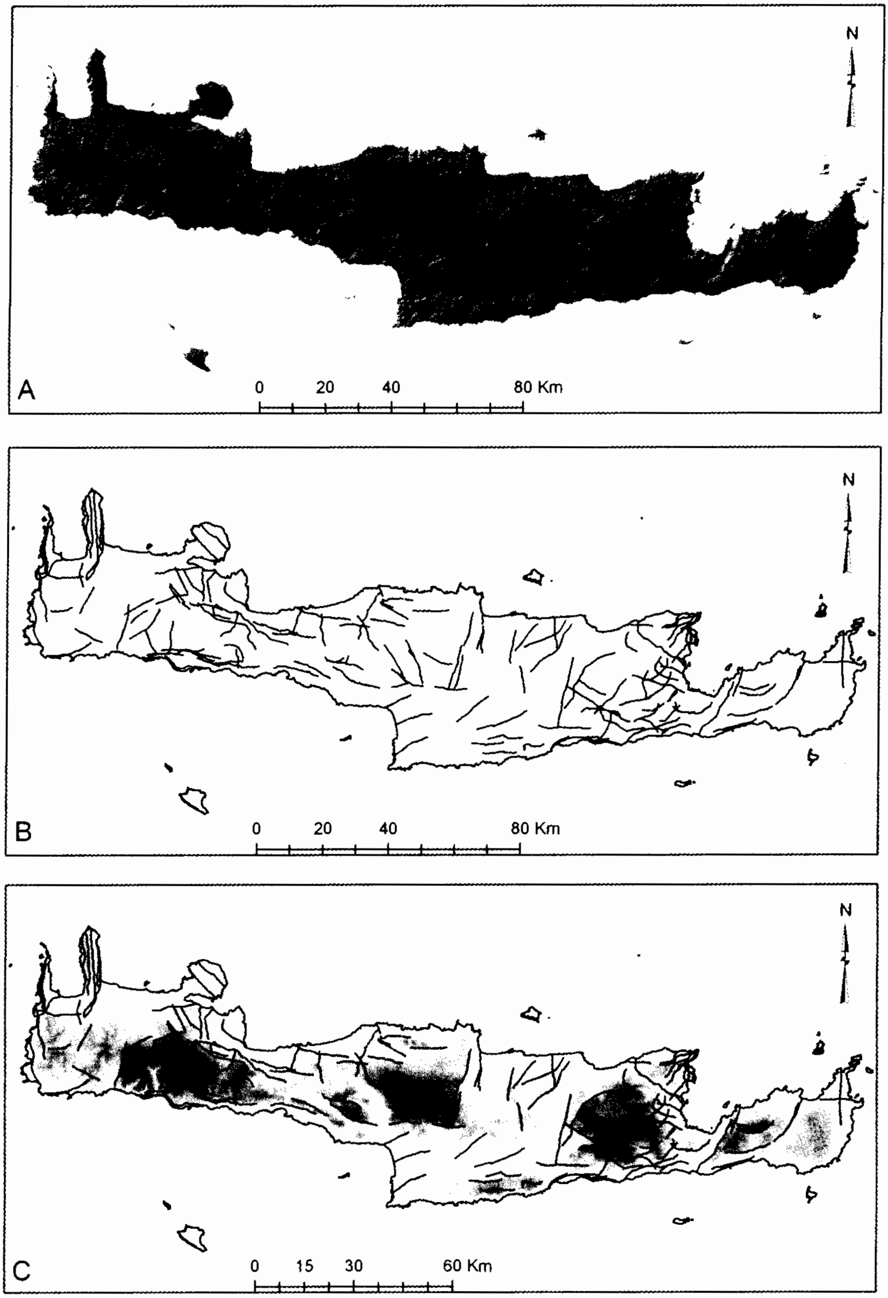

Figure 2. A., 3 D DEM of Crete, (no vertical exaggeration). B. The large post Upper Miocene normal fault zones in Crete based on Angelier et al. (1982), Papoulia et al. (1996) and Fassoulas (2001). C. A combination of DEM and the fault map of Crete to demonstrate the individual tectonic blocks.

ites and Tripolitza, crop out building the mountainous areas (Fig 1), whereas later Neogene sediments of various ages and origin occur in the tectonic basins (Meulenkamp et al. 1979).

Plattenkalk and Tripolitza nappes comprise km-thick carbonate sequences, highly karstified, separated by the impermeable Phyllite-quartzite rocks, which however have a variable thickness ranging from zero to several hundreds of meters. Thus, individual and inhomogeneous hydrogeologic conditions appear along the island, governing the water activity.

It is well documented (Angelier et al. 1982, Mercier et al. 1987, Meulenkamp et al. 1994, Fassoulas 2001) that neotectonic faulting in South Aegean is not only responsible for shaping the coasts of the island, but also for fragmenting crust into grabens and horsts initiating the first basins and mountains in the area. In most cases boundary conditions are characterized by normal faulting of various orientations (Fig. 2 B, C). Contribution of strike slip faulting in the formation of Messara basin is still controversial (ten Veen & Kleinsphen 2002, Ring & Reischmann 2002, Peterek & Schwarze 2004).

Asymmetric or symmetric extensional basins were initially formed in middle Miocene times over low-angle detachment faults that resulted to the exhumation of the lower crust (Fassoulas et al. 1994, Ring et al. 2001, Seidel 2003). Thereafter, temporal and spatial variations in stress fields resulted in multi-orientational basins that were filled by Neogene and Quaternary sediments (Angelier et al. 1982, Fassoulas 2001). The first neotectonic basins were orientated in an east-west orientation as a result of an arc-normal stretching in Late Mocene times that also accounts for the elongated shape of the island. In the upper Miocene times north-south trending normal faults resulted in north-south orientated basins and thus to an arc-parallel stretching that attributed to large-scale features as the northwestern peninsulas.. Later stress changes resulted in younger depressions as the Spili and Ierapetra grabens, where active faulting occurs (Angelier et al. 1982, Fassoulas 2001, Doutsos, & Kokkalas 2001, Monaco & Tortorici 2004).

Basin development is extending further south of the island of Crete till the European back-stop. Geophysical tomographies have documented that large depressions as the Gavdos graben, the Ptolemeous trough etc., are actually extensional basins located on the European crust rather than the plate boundaries (Bohnhoff et al. 2001). Vertical displacement in between Gavdos graben and Lefka Ori Mountains in southwestern Crete is reaching a magnitude of 5 km indicating both vertical subsidence and uplift. Outcrops of Neogene sediments in high altitudes (800m) point also to a large, post Miocene vertical uplift of certain areas of the island (Papapetrou-Zamani 1965). Meulenkamp et al (1994) suggested two periods of post-Miocene uplift in the area of Heraklion basin, based on the depositional features of Pliocene marls. The first and most intense was recorded in early Pliocene times with rates that reached temporarily 125 cm/ka, whereas the second was recorded in late Pliocene/Pleistocene times.

The extended sea terraces of southwestern coasts recorded important sea level changes in the order of several meters in Quaternary and Holocene times making the study of short term uplift in the areas possible (Fleming 1978 , Lambeck 1995).

The most recent and outstanding feature of rock uplift is however, the 9 meters rise of the coast in southwestern Crete as a result of either the earthquake of 365 AD with magnitude of 8,2 (Stiros 2004), or the early Byzantine Paroxism Phase (Price et al. 2002). The uplifted notches of this event can be traced allover the southern coast up to the area of Messara in central Crete (Pirazzoli et al. 1996; Photo 1a).

The neotectonic studies and terrace analyses have indicated that Crete is not reacting generally as a dipole, where western Crete is uplifted and eastern Crete is subsided (Fytrolakis 1980), but is separated into tectonic blocks which have been

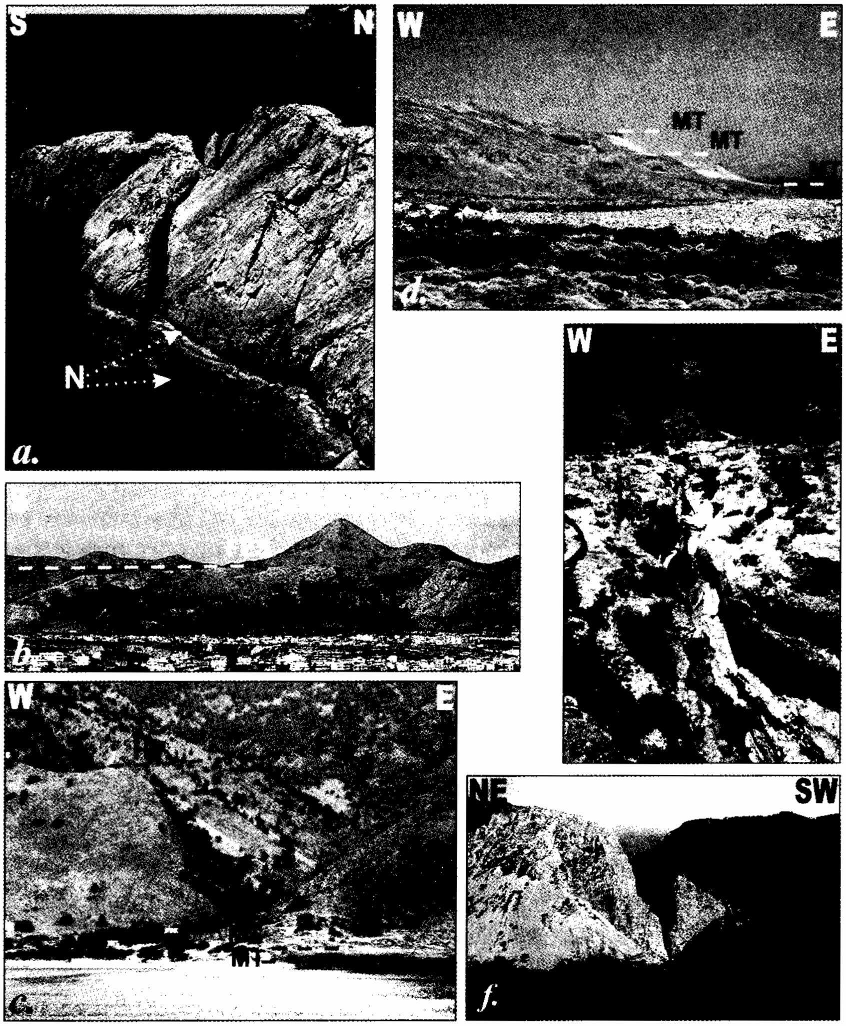

Photo 1. a. Present day and older notches at the area of Plakias (distance between notches is´ 80cm.). Higher one is attributed to the 365 AD earthquake; b. The area of Almiros gorge in Herakio showing the FES and the gorge exit (view to the west); c. The exit of Samaria gorge in Agia Roumeli beach (view to the north). Hanging valley (HV) and Holocene marine terraces (MT) are marked; d. Marine terraces (MT) in Zakros area (view to the north); e. River incision in the aggradational terrace of 70 m in Samaria gorge; f. Cha gorge and Ierapetra active fault (view to the east).

displaced and activated independently to each other through time, giving rise to differentially uplift or subsidence rates all over the island (Papanikolaou 1988). In a smaller scale, Fassoulas (2001) proposed a model for secondary basin development through time in the Heraklion basin of central Crete.

3. METHODS AND RESULTS

The response of Cretan landscape to the continuous uplift of Crete was approached in this study using GIS software (ESRI-ARCGIS) to develop a

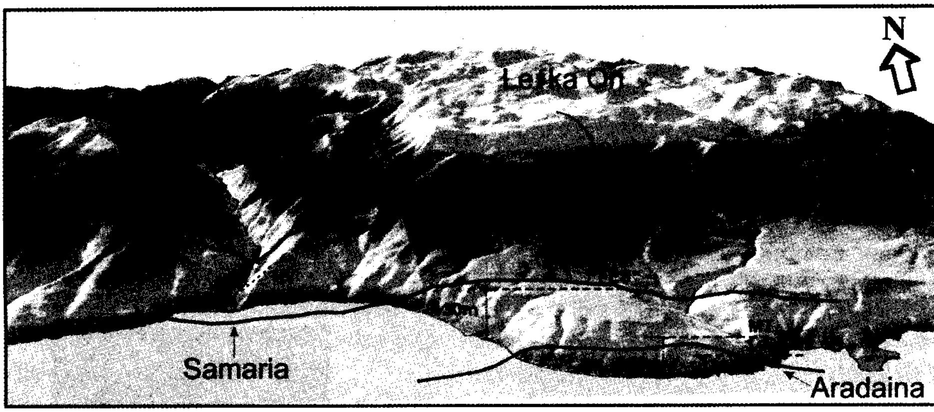

Figure 3. DEM of Samaria area and Lefka Ori Mts (no vertical exaggeration), showing hydrographic network, landforms and faulting of the area. FES, flat erosion surface; HV, hanging valley; MT, marine terraces; lines, normal faults, gray line, active fault.

reliable digital elevation model (DEM) and consequently 3D images of certain areas of Crete using different software tools (such as shading, 3D analyst etc.). Corrected and complemented topographic maps of the H.M.G.S., at a scale of 1:50000 with contour interval of 20 m (which is the highest analysis used world-wide for such scales; Pazzaglia & Brandon 2001) were used as the basement to produce DEMs.

The resolution of these digital models limits the detailed approach of topographic data, however, on the other hand enables a thorough recognition of past structures and features, smoothing the recent and small scale erosion features. We worked initially with the digital models analyzing certain topographic features, as watershed areas, riverbed profiles and the coastal area morphology, combining structural and topographic data, and finally incorporating field observations to check and testify laboratory results.

For this purpose we focused our study to certain areas of the island using as criteria the occurrence of long stream systems, the presence and age of large-scale fault zones, and the proximity to the coastal zone. The areas include the Samaria National Park territory in southwest Chania Province, the Heraklion area at the eastern slopes of Psiloritis Mountains, the Ierapetra graben and the Zakros coastal zone at the eastern part of the island (Fig 2).

The westernmost locality, Samaria area, is located at the southern part of Lefka Ori Mountains, the largest mountainous area in the island with several summits over 2 kms asl. The famous Samaria gorge is drained by a stream initiating at the high topographic levels of Lefka Ori, mouthing at the southern coast near Agia Roumeli village (Fig 3). Lithologies include mainly the Plattenkalk unit (Fig. 1). The coastal zone in the area is dominated by east-west trending normal faults that have created the steep slopes of Lefka Ori and the deep graben structures between Crete and Gavdos. The age of this graben is considered to be middle Miocene (Angelier et al. 1982, Bohnhoff et al. 2001), whereas fault activity appears diachronous, as seismicity is still present in the area (Papoulia et al. 1996)

The second, study area, Heraklion area represents the transition zone from Psiloritis Mountains to the Heraklion basin in central Crete (Fig. 4). Several streams spring out from the mountains entering to the lowland area, continuing their way to the northern coast towards the gulf of Heraklio. In few places streams have developed gorges, such as the Almiros gorge to the north, Gonies gorge in the middle and Kroussonas gorge to the

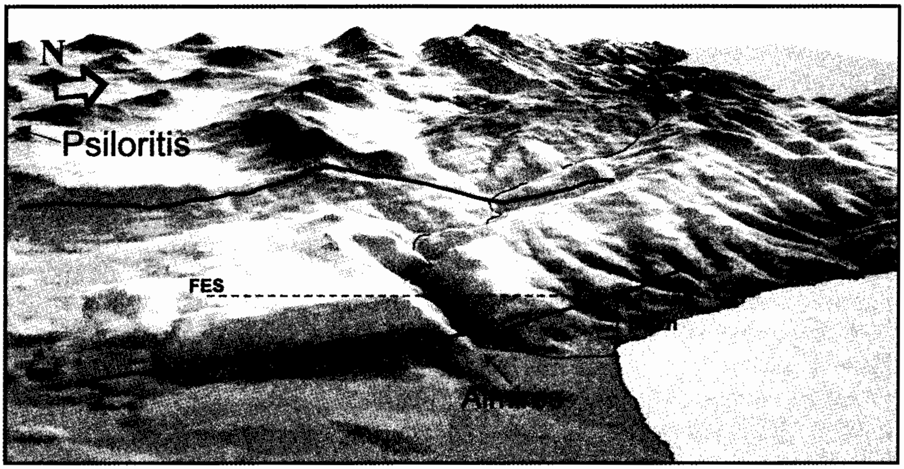

Figure 4. DEM of Heraklio area and Psiloritis Mts (no vertical exaggeration), showing hydrographic network, landforms and faulting of the area. FES, flat erosion surface; lines, normal faults.

south. The transition zone is formed by a series of north-south trending normal faults of late Miocene/ Pliocene age (Fassoulas 2001). Rocks cropping out in the area include the carbonate series of the Tripolitza nappe, the underlying carbonates of the Plattenkalk unit and also the Miocene and Pliocene sediments of the Heraklion basin.

Ierapetra graben is characterized by the presence of the northeast-southwest trending Ierapetra active fault (Angelier et al. 1982, Papoulia et al. 1996), which forms the vertical cliffs at the western Thripti mountains (Fig 5). An impressive and very narrow gorge develops from the fault scarp upwards to the Thripti mountains, while, thick alluvial fans (screes) cover in several places the fault scarp. Again, Plattenkalk carbonates appear in the area covered by a thin sequence of Phyllite-quartzite rocks and Tripolitza carbonates (Fig. 1). Early Miocene and Quaternary sediments are filling the Ierapetra graben (ten Veen 1998).

Finally, in Zakros area, large north-south trending normal faults, probably of late Miocene/Pliocene age (Fassoulas 2001), fragment and lower down the relief towards the Lybian sea (Fig. 6). Main

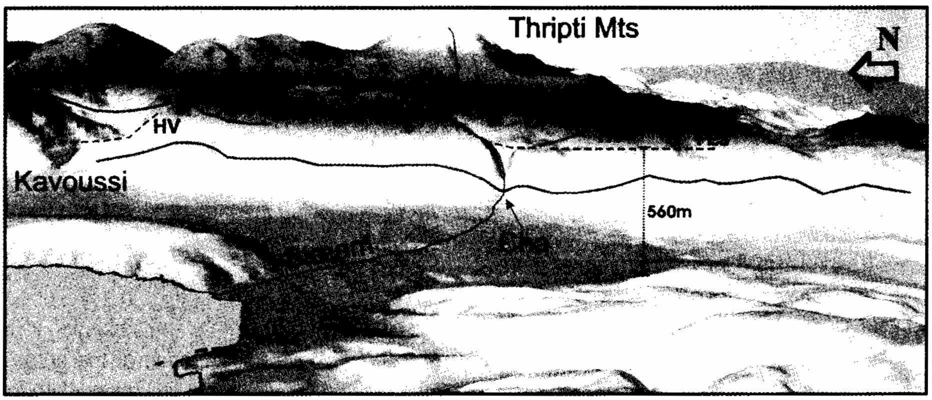

Figure 5. DEM of Ierapetra area and Thripti Mts (no vertical exaggeration), showing hydrographic network, landforms and faulting of the area. FES, flat erosion surface; HV, hanging valley; grey lines, Ierapetra active fault.

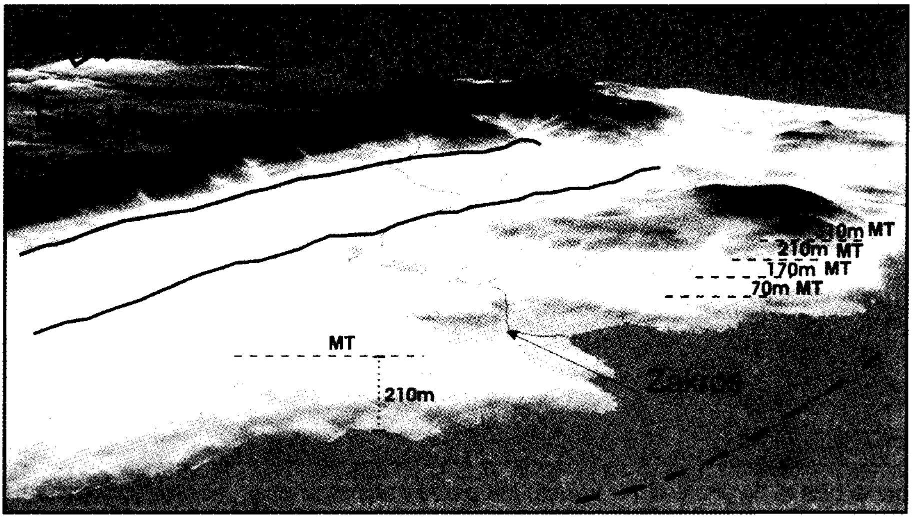

Figure 6. DEM of Zakros area and Sitia Mts (no vertical exaggeration), showing hydrographic network, landforms and faulting of the area. MT, marine terraces; lines, normal faults, dashed line, possible active fault (Papoulia et al. 1996).

lithologies comprise the Tripolitza carbonates and the purple phyllites of the Phyllite-quartzite nappe (Fig. 1). Local streams initiated in the Sitia Mountains form a gorge (Deads gorge with Nekropolis inside) at the lower topographic block, mouthing at the Zakros gulf and the adjacent Minoan palace.

3.1 Landforms

Two kinds of surface features have been recognized by the analyses of 3D DEMs and field observations in the study-areas. These concern direct basal level indications, such as flat erosional surfaces (FES) and hanging valleys, or indirect basal level indications related to sea level changes, like marine terraces and notches.

Erosional surfaces in the Mediterranean area and Crete are well known for the Mio-Pliocene time interval (Delrieu et al. 1993 and references therein) related with the sea level fall in the Mediterranean basin. In Crete, Mio-Pliocene erosion has also been recorded with high incision magnitude in evaporite beds, but has lasted only for 100.000 years (Delrieu e al. 1993) meaning that only river incision may had been produced. In the study areas the most outstanding FES (paneplane?) is recognized in the Heraklion area. The flat surface occurs at about 340 meters asl., on top of Mesozoic and of late Tortonian limestone (Fig. 4, Photo 1b). The adjacent Almiros gorge has been incised under this surface into the Mesozoic limestone.

Another, nevertheless not so well preserved FES occurs in the area of the Ierapetra graben on the Mesozoic limestone of Thripti mts. This surface stands out at about 560 meters asl. and Cha gorge has also been incised under this surface (Fig. 5). Furthermore, two hanging valleys (one related with Cha stream and the other one with the nearby Kavoussi stream) can be recognized in the area at the same altitude, indicating that earlier erosion in the streams had reached basal level before the initiation of the present day Cha and Kavoussi gorges.

In the area of Samaria (Fig. 3) a FES occurs at the altitude of 630 meters and a hanging valley is preserved above the entrance of the gorge at a lower altitude in respect to the others (140 m.).

Aggradational and degradational marine terraces were recognized in several areas both from

DEMs and field observations. Although marine terraces are related either to global sea level changes or local rock uplift, the rate of generation (and preservation) of new terraced landscape, reflecting the uplift rate pattern is balanced by the rate at which terraces are eroded by channels or by hill-slope processes (Anderson et al. 1999). In the study areas two factors have counteracted for their preservation; the lithology of bedrock, which is limestone everywhere, not permitting fast mechanical erosion, and the low precipitation rates (especially for central and eastern Crete).

In the area of Samaria marine terraces occur in several altitudes with the lower of them standing approximately 2,5 meters over the sea level, being formed in late Holocene times (Price et al. 2002, Pirazzoli et al. 1996). Earlier degradational terraces occur at 300 and 120 meters asl (Fig. 3). The last one is maybe comparable with the hanging valley at the entrance of Samaria which occurs at 140 meters asl (Photo 1c). Terraces in the area of Zakros are more and better preserved than other places shaping a coastal zone in the form of successive stairs (Fig. 6; Photo 1d). Aggradational terraces rich in late Pleistocene mammal fossils occur in the lower levels (lower than 70m; Lax 1996), whereas, degradation terraces occur in higher levels. These widest terraces occur at 70, 170, 210 and 310 meters asl, marking successive sea level stands.

3.2 River activity

Climate in Crete is characterized as typical Mediterranean with a wet season accumulated mainly in winter months (Pennas 1977). The abrupt relief changes, as well as the geographical position of the island account for the high discrepancies in precipitation distribution along the island. Generally, precipitation decreases from northwest to southeast, ranging from 1200 mm in western Crete to 500 mm in eastern Crete (Pennas 1977).

This type of climate was established in Pliocene but Mean Annual Temperature (MAT) and average precipitation were higher than in our days (5° C and 400 – 1000 mm more per year; Brown & Lomolino 1998). Regardless the short, although dramatic climate change in Messinian, similar to present day temperatures and quite higher precipitation (maybe at about 1000 mm more) occurred during late Miocene times in Crete (Sachse et al. 1999, Zidianakis et al. 2004).

Supposing quite higher precipitation rates in former times, erosion should have been also more intense than present. The occurrence of manly carbonate rocks in the mountainous areas accounts for intense karstic erosion and the formation of the main landscape features of the island (gorges, caves, plateaus). In places where impermeable rocks crop out (as is the case of western Chania territory) deep valleys have been formed. The vertical uplift is indicated by the intense river incision all over the island, but is better exposed in the abundant gorges. These valleys develop normal to the large fault zones as a result of footwall uplift in respect to the present mean sea level (Fassoulas et al. 2004)

Analyses of the riverbed profiles in the most characteristic of these gorges were demonstrated using DEMs and field observations. In most cases the rivers/streams drainage old valleys that later were affected by normal fault activity. A considerable bending of stream direction is observed on the topography, mainly at the hangingwall where rivers are reorientated parallel to the direction of the newly formed basins. This is more evident at the Psiloritis eastern slopes. Running eastwards Agia Irini, Gonies and Almiros streams drainage old, hanging valleys that were formed by late Miocene normal faults (Fassoulas 2001). Entering in the hangingwall of the north-south trending faults the streams turn northwards running off towards the Cretan sea (Fig. 4). The same happens in Ierapetra grabben by the initially westwards running streams that turn northwards entering in the hangingwall, possibly due to higher displacements at the northern part of Ierapetra fault (Fig. 5). In the area of Samaria the hangingwall is under the sea

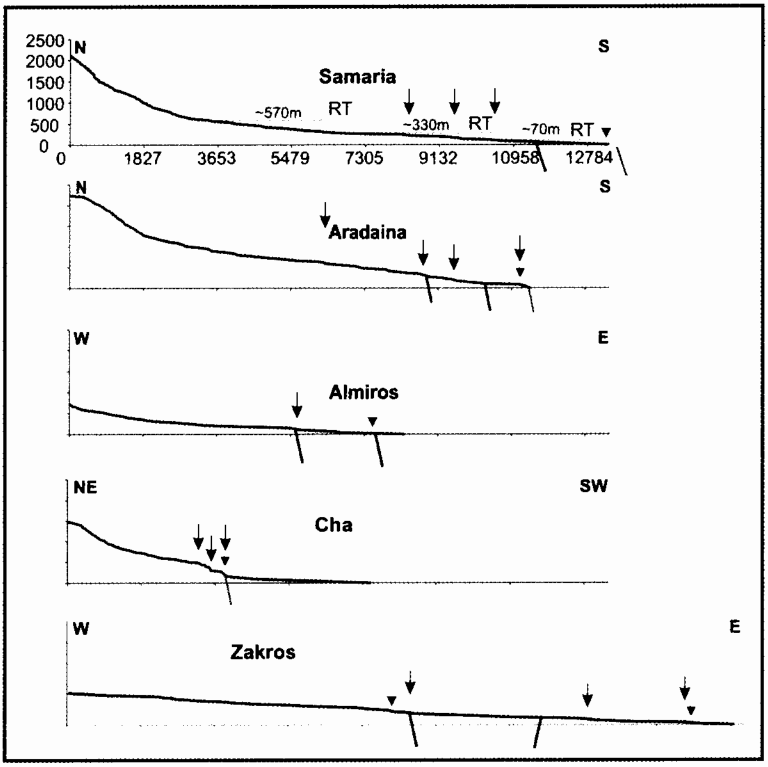

Figure 7. Riverbed profiles of gorges in study areas. RT, river terraces; triangles indicate gorge exits (mouths); arrows show nick points; straight lines, the fault trace; grey straight lines, active fault trace.

level, however this pattern occurs also undersea with both the Aradaina and Samaria streams that initially run southwards turning submarine westwards, and forming canyons in the Gavdos graben (T. Tselepides, Hellenic Center Marine Research, personal communication). Only in Zakros stream this pattern is not so well developed, although bending and reorientations occur (Fig. 6).

Riverbed profiles were plotted against main fault traces in order to examine possible interactions between tectonics and erosion (Fig. 7). In most cases profiles exhibit a concave inclination that trend asymptotic to the basal sea level. Only Zakros stream in the area of Zakros depict an almost straight profile indicating probably a constant uplift rate for the upstream area. In the other cases long erosional records with minor or major changes along profiles are indicated. In Almiros stream in the area of Heraklion the profile is subdivided into two parts by the western fault presenting a nick point at about 200 meters. However, erosion in the lower part has already reshaped the profile into a typical concave one indicating a long duration of incision. No river terraces were observed in the gorge.

Nick points occur mainly in the profiles of Ierapetra area and secondary in Samaria area; however, overall profiles are quite different among them. Riverbeds in Samaria area present a similar, very gentle inclination and almost along half of their profiles appear nearly horizontal. Gorges' exits appear at the present sea level (Photo 1c), and some of them (e.g. Aradaina) continue directly under sea. This style indicates old erosion processes and deep river incision (exceeding in places 800 meters in depth) that have managed to smooth the riverbed parallel to the present basal plane. However, erosion in the area has been affected by repeated uplift phases as is indicated by the several nick points and aggradational terraces existing mainly in Samaria gorge (Fig. 3). Most of these preserve coarse, well stratified fluvial sediments that were later degradated and incised by the river activity. The highest appears at an altitude of about 570 meters, the next at 330 and 300 m and finally the lower one at 70 meters. The latest and most outstanding terrace extents from the narrowest part of the gorge, the famous Portes to the coast and at this part the river has incised about 6-8 meters in depth (Photo 1e).

Cha gorge in the area of Ierapetra develops at the footwall of the Ierapetra active fault and its exit appears as a thin V-shaped valley just on the fault scarp (Photo 1f). The gorge is very narrow at the exit (about half a meter) and its sides are about 200 meters high, while its riverbed is very irregular and very steep in parts forming repeated waterfalls of three to fifteen meters high, small lagoons and vertical cliffs. Even at its exit, at the fault scarp, a small waterfall of about 4 meters develops towards the hangingwall.

The older tectonic blocks, such as the coastal area of Samaria which exposes an overall fault displacement of 5 km and a total uplift of at least of 630 meters (Fig 3), show thus a very mature erosion profile with nick points related possibly to later reactivation of several onshore and most important, off shore faults. Younger tectonic blocks (recognized by the ages of the main bounding faults) as is the case in the areas of Heraklio and Zakros, present on the other hand rebirth processes. In these areas total uplift is at least 340 and 310 meters respectively. Finally, the most recent tectonic blocks as is the case of the active Ierapetra graben indicate very young erosional profiles and initiation of deep river incision. Hanging valleys in close proximity to the present coastal area at 560 meters altitude, as well as the early Miocene age of the filling sediments indicate however that uplift in the area should have initiated quit earlier, possibly in late Miocene-Pliocene times.

4. DISCUSSION

4.1 Gorge development

Earlier studies have indicated that gorges, and thus river incision in Crete appear in the footwall of normal faults zones, which are responsible for large vertical displacements (Fassoulas et al. 2004). The age and activity history of these fault zones (Angelier et al. 1982, Fassoulas 2001) have a more direct influence to the style and the magnitude of erosion, than the accumulative precipitation in each area. This imply that Samaria and the nearby gorges should have been initiated much earlier than the other gorges studied in this work, and were probably fully developed in Pliocene times. Later tectonic reactivation should account for the minor nick points and subsequent river incision in the area. The Almiros and Zakros gorges, as well as all the gorges of the island that are related with late Miocene/Pliocene north-south trending faults should thus have been initiated and been developed in Pliocene times, resulting in a rebirth of landscape and riverbed profile. The Cha gorge, which is related with the late Pliocene - Pleistocene Ierapetra fault (Fassoulas 2001) is thus one of the youngest features in Cretan landscape, being in a youth stage and still developing continuously.

Intense gorge development should thus have happened in Pliocene times, a period where large vertical movements in the area of Crete have been recorded. Meulenkamp et al (1994) argue for an intense subsidence period in the Messinian/Pliocene boundary that may have reached a magnitude of 1000 m, followed by two intense uplift periods in Pliocene times. The most rapid uplift occurred in early Pliocene times reaching a rate of 125 cm/ka.

In Crete compressional tectonics take place in the lower crust, while in the upper crust extensional tectonics prevail (Taymaz et al. 1989, Benetatos et al. 2004). This extensional regime

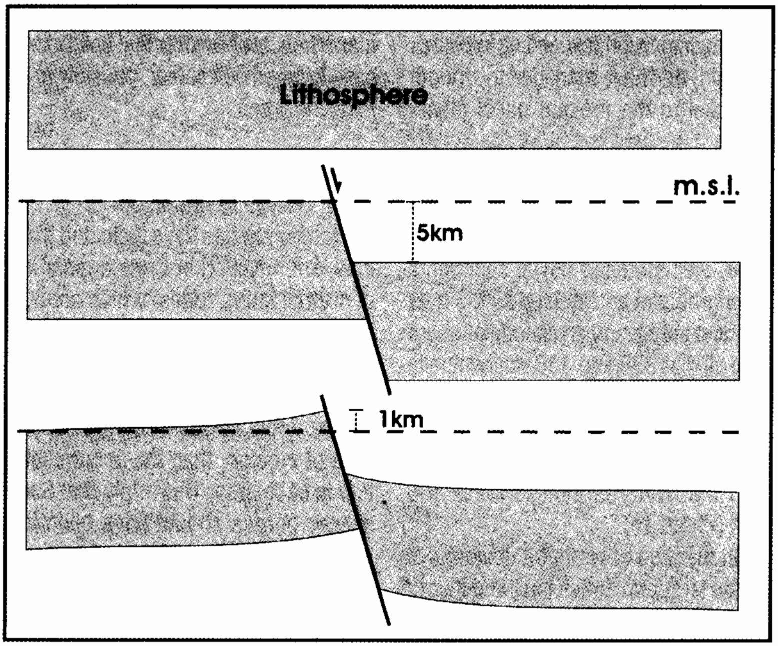

Figure 8. Simplified model for isostatic response of lithosphere to crustal thinning caused by normal faulting.

act to compensate the sedimentary flux underplatting in the subduction zone and to attain a balanced wedge shape (Rahl et al. 2005). Thinning of crust and the resulting negative load on Earth's crust can induce regional isostatic response of lithosphere and thus uplift of the flanks of the grabens (Masek et al. 1994). Footwall uplift in Cretan grabens can thus be interpreted as the result of the isostatic rebound of lithosphere due to the thinning of crust. In the area of Samaria and the adjacent Gavdos graben vertical displacement along the coastal zone faults, only based on the topography, is probably exceeding 5 kms. In similar cases, numerical models (Burbank and Anderson 2001) predict that uplift of the flanks is about 20% of the fault vertical displacement. Applying to Samaria area graben about 1 km uplift of footwall can be inferred (Fig. 8).

4.2 Erosion record

The study of both river and marine related features on the Cretan landscape indicated that several successive phases of stable sea level periods were alternated with periods of intense sea level changes. Coming to recent times, in Pleistocene and Holocene many terraces and old sea level stands are preserved in coast lines all over Crete (Pirazzoli et al. 1996, Price et al. 2002).

It is well known (Holmes 1957) that marine terraces are formed by wave cutting, degradation and aggradation processes under long periods of stable sea level stand. Thus, both FESs, hanging valley levels and marine terraces represent periods of stable sea levels stands, following either periods of high rock uplift rates or global sea level changes. In the area of Samaria, the lower most terraces that exist at altitudes not higher than several meters were dated as late Holocene (Pirazzoli et al. 1996, Price et al. 2002), whereas, in the area of Zakros only terraces in altitudes lower than 70 m contain late Pleistocene mammal fossils (Lax 1996). These facts indicate that the higher terraces occurring in several places along Crete should be linked to pre Pleistocene rock uplift or

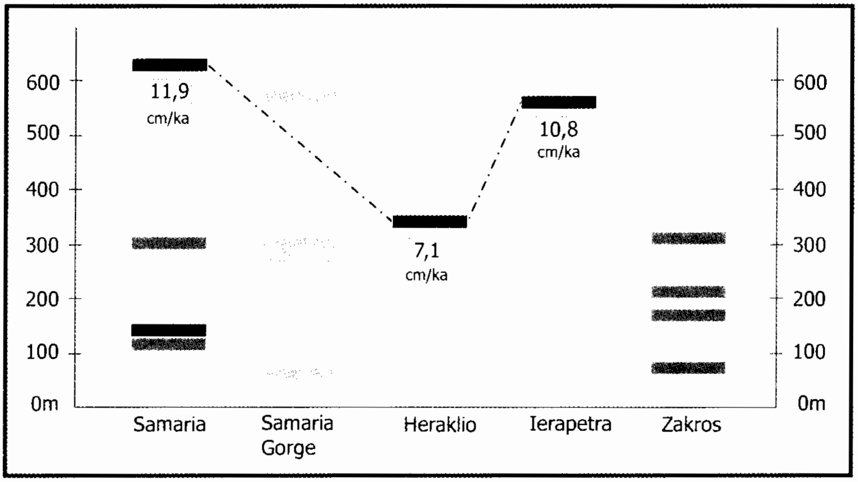

Figure 9. Diagram showing main erosion surfaces in study areas and possible correlations in respect to altitude. Dark lines present FES; dark grey lines, marine terraces; light grey lines, river terraces. Number in boxes indicate total uplift rates since Messinian.

sea level changes or both. However, sea level records during the late Tertiary times (Prentice & Matthews 1988) show that sea level was never higher than present. This implies that presence of marine terraces at high altitude is the result of differential rock uplift.

The most pronounced stable erosion period was recognized at the boundary of Miocene-Pliocene all over the Mediterranean (Delrieu et al. 1993). This period with more humid and tropical climate than today, was accompanied by intense erosion that predates the Messinian Salinity crisis and the dramatic climate changes in the Mediterranean basin. The dramatic fall of regional sea level in such a short period of a few hundreds of thousands years (Krijgsman et al. 1999) can not account for the intense river incision and gorge development, as this requires high precipitation and longer time for kartsic erosion to operate. However, it could have resulted to the submarine continuation of Samaria and other gorges of the area in great depths in the Gavdos graben, where only soft, Neogene sediments occur.

We suggest that large FESs, as well as hanging valley stands should be related to the late Miocene intense erosion period and that the initiation of gorge development should postdate the Messinian Salinity Crisis. This is documented by the fact that in the area of Heraklio FES degradation has been developed both on the Mesozoic and the late Tortonian – Messinian limestone, as well as by the later river incision and gorge development under the FESs.

In the absence of marine and river terrace dating, no direct correlation among them can be made. Only in Samaria area some river terraces, such as those existing at 570m and 300 m could be correlated with the marine terraces of 630m and 300 m occurring at the coastal zone. Also, the hanging valley at 140 m and the marine terrace at 120 m should represent an erosion phase related probably with the Pleistocene interglacial periods. In addition, as differential uplift has been the case for most of the study areas, it is also impossible to reconstruct a detailed uplift or/and erosional path either for each tectonic block or for the whole island (Fig. 9). However, taking the assumption that most of the extended FESs and the hanging valley stands have been develop in the late Miocene time, and considering a global fall for the late Tortonian time (6 ma) of about 86 meters (Prentice & Matthews 1988, May et al. 2002), a total uplift rate since that time can be approached. Thus, for the Samaria area a rate of 11.9 cm/ka has been estimated, for Heraklio area 7.1 cm/ka and for Ierapetra area 10,8 cm/ka. These rates are similar with the long term uplift rates of Heraklion basin sediments suggested for the Pliocene period by Meulenkamp et al. (1994).

5. CONCLUSIONS

A combination of digital elevation model analyses, neotectonic data and field observations of certain tectonic blocks all over Crete was performed to recognize significant landforms related to the tectonic uplift of the island. The effect of river incision was studied in the deep gorges that developed in the footwall of large normal faults, while marine erosion was recognized in nearby coastal areas.

River profiles appear to be directly dependent to the age and tectonic history of the fault zones that have formed the uplifted tectonic blocks. Old fault zones of late Miocene age have produced mature erosion profiles that lie asymptotically to the basal, sea level plane. Later reactivations have attributed to the formation of nick points and active incision processes. Samaria area gorges belong to this case having been initiated probably in late Miocene/Pliocene times and developed fully in the Pliocene. Younger fault zones of late Miocene/Pliocene age created river profiles that show rebirth of the landscape (as is the case of Almiros in Heraklio), or long term, continuous uplift that has not been reshaped by erosion yet (Zakros case). These gorges were probably initiated and developed in the Pliocene. In cases of active faults (Cha gorge) profiles are in a youth stage with several nick points as a result of the recent reactivation.

Extended, flat erosional surfaces were recognized in the areas of Heraklio, Samaria and Ierapetra, associated in few cases with nearby hanging valleys at the same altitudes. These landforms depict the late Miocene (Tortonian/ Messinian) erosional period that was followed by the dramatic sea level fall of the Messinain salinity crisis and the fast crustal uplift of early Pliocene. Gorges developed under these surfaces as a response of the landscape to the differential uplift of Pliocene and later periods. Total uplift rates since the Messinian period were roughly estimated at 11.9 cm/ka for the area of Samaria, 7.1 cm/ka for the area of Heraklio and 10.8 cm/ka for the area of Zakros.

The differential uplift of the footwall in the normal fault zones of Crete is probably the result of isostatic response of lithosphere to crustal thinning of the upper crust.

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ΠΕΡΙΛΗΨΗ
Η ΑΝΤΑΠΟΚΡΙΣΗ ΤΟΥ ΑΝΑΓΛΥΦΟΥ ΣΤΗΝ ΤΕΚΤΟΝΙΚΗ ΑΝΥΨΩΣΗ ΤΗΣ ΚΡΗΤΗΣ

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Στην εργασία αυτή χρησιμοποιούμε ψηφιακά μοντέλα αναγλύφου, τεκτονικά δεδομένα καθώς και στοιχεία υπαίθρου με σκοπό να αναγνωρίσουμε σημαντικές μορφές του αναγλύφου που προκαλούνται λόγω της έντονης διάβρωσης κατά τη διάρκεια των Νεογενών και Τεταρτογενών τεκτονικών ανυψώσεων της Κρήτης. Φαράγγια, ποτάμιες και θαλάσσιες αναβαθμίδες αναγνωρίστηκαν σε όλες τις περιοχές μελέτης, ενώ σε ορισμένες περιπτώσεις διαγνώστηκαν επιφάνειες επιπέδωσης και κρεμαστές κοιλάδες. Τα προφίλ των ρεμάτων στις περιοχές της Σαμαριάς, της Ζάκρου και του Ηρακλείου, όπου η τεκτονική ανύψωση ήταν αποτέλεσμα παλιών κανονικών ρηγμάτων, φανερώνουν ένα πολύ ώριμο στάδιο διάβρωσης, αν και σε ορισμένες περιπτώσεις παρατηρήθηκαν σημεία καμπής και κατά βάθος διάβρωση, πιθανόν ως αποτέλεσμα πρόσφατων επαναδραστηριοποιήσεων των ρηγμάτων. Στην περιοχή της Ιεράπετρας όπου το φαράγγι του Χα αναπτύσσεται στην κυριολεξία πάνω στην επιφάνεια του ενεργού ρήγματος, το προφίλ του ρέματος είναι ε στάδιο νεότητας με έντονα σημεία καμπής, μικρούς καταρράκτες και έντονη κλίση. Παράλληλα, ποτάμιες και θαλάσσιες αναβαθμίδες απόθεσης εμφανίζονται σε διάφορες περιοχές υποδεικνύοντας παλαιές θέσεις του βασικού επιπέδου ή της στάθμης της θάλασσας. Η απουσία όμως λεπτομερών χρονολογήσεων, καθώς και η διαφορική τεκτονική ανύψωση των επιμέρους τεκτονικών τεμαχών δεν επιτρέπει προς το παρόν συσχετισμό μεταξύ των διαφόρων θέσεων. Πιστεύουμε όμως ότι οι επιφάνειες επιπέδωσης και οι κρεμαστές κοιλάδες πρέπει να είναι ίδιας Άνω Μειοκαινικής ηλικίας όπως είναι και τα μεγάλα ρήγματα που προκάλεσαν τη σχετική ανύψωση. Η έναρξη της έντονης διαβρωτικής διαδικασίας που δημιούργησε την πλειονότητα των φαραγγιών θα πρέπει συνεπώς να έλαβε χώρα στο Πλειόκαινο. Εξαίρεση αποτελεί η περιοχή του φαραγγιού του Χα που σύμφωνα με την ηλικία του ενεργού ρήγματος θα πρέπει να έλαβε χώρα στο Πλειστόκαινο/Ολόκαινο. Οι εκτιμούμενοι ρυθμοί συνολικής ανύψωσης από το Μεσήνιο και έπειτα είναι για την περιοχή της Σαμαριάς 11,9 cm/ka, για την περιοχή του Ηρακλείου 7,1 cm/ka και για την περιοχή της Ζάκρου 10,8 cm/ka. Η τεκτονική ανύψωση πιστεύουμε ότι είναι το αποτέλεσμα της ισοστατικής επαναφοράς της λιθόσφαιρας που προκαλείται από την λέπτυνση του άνω φλοιού.