Η ΜΟΡΦΟΤΕΚΤΟΝΙΚΗ ΤΟΥ ΚΑΝΟΝΙΚΟΥ ΡΗΓΜΑΤΟΣ ΤΩΝ ΣΦΑΚΙΩΝ, ΝΟΤΙΟΔΥΤΙΚΗ ΚΡΗΤΗ, ΕΛΛΑΔΑ

Tsimi C.[1], Γκάνας Α.[1], Ferrier G.[2], Δρακάτος Γ.[1], Richard J. Pope[3], Φασούλας Χ.[4]

[1] *Γεωδυναμικό Ινστιτούτο, Εθνικό Αστεροσκοπείο Αθηνών, Αθήνα 11810, Ελλάδα, christinant@gmail.com, Fax: +30 210 3490180.*

[2] *Τμήμα Γεωγραφίας, Πανεπιστήμιο του Hull, Cottingham Road, Hull, HU6 7RX, UK*

[3] *Τμήμα Γεωγραφίας του Πανεπιστημίου του Derby, Kedleston Road, Derby DE22 1GB, UK*

[4] *Μουσείο Φυσικής Ιστορίας του Πανεπιστημίου Κρήτης, Knosou Av., Ηράκλειο 71409, GR*

Περίληψη

Το ρήγμα των Σφακίων με μήκος 17 km βρίσκεται στη νοτιοδυτική Κρήτη και θεωρείται ως πρότυπο παράκτιας ανόδου και θεαματικού σχηματισμού φαραγγιών στην Ελλάδα. Αυτό το ρήγμα ξεκίνησε την λειτουργία του στο Πλειόκαινο (~ 3-5 Ma) λόγω της έκτασης του γήινου φλοιού με κατεύθυνση Β-Ν. Η δραστηριότητά αυτή συνεχίστηκε μέχρι τα μέσα του Τεταρτογενούς όπου η σεισμική δράση μεταφέρθηκε στο σεισμικό, συνθετικό, παράκτιο ρήγμα περίπου 4-6 km νότια. Σε αυτή την έρευνα παρουσιάζονται νέα δεδομένα για την τεκτονική γεωμορφολογία της περιοχής όπου χαρακτηρίζεται από τον ανταγωνισμό της ανόδου της ξηράς λόγω του ρήγματος των Σφακίων και της γενικότερης ανόδου λόγω της σύγκλισης των πλακών Αφρικής και Ευρασίας. Το σταθερό τέμαχος του ρήγματος των Σφακιών αποτελείται από ασβεστόλιθους και μάρμαρα και χαρακτηρίζεται από επιμήκεις κοιλάδες και βαθιά φαράγγια. Το κατερχόμενο τμήμα αποτελείται κυρίως από αλλουβιακά ριπίδια. Η έρευνα πεδίου απέδειξε ότι τα μικρά ρέματα που διαβρώνανε το μέτωπο του βουνού έχουν σταματήσει την κατά βάθος διάβρωση και επίσης η παράκτια πεδιάδα είναι ανυψωμένη επάνω από την παρούσα στάθμη θάλασσας από 0.2-12 m ανάλογα με τη θέση. Οι μορφοτεκτονικοί δείκτες κατά μήκος του ρήγματος (Υψομετρικό ολοκλήρωμα, Ασυμμετρία λεκάνης, Λόγος πλάτους κοιλάδας προς ύψος, Δαντέλωση στους πρόποδες των βουνών, μέση κλίση των τριγωνικών πρανών) υπολογίστηκαν με την χρήση του λογισμικού ArcGIS. Επίσης έγινε σύγκριση των αποτελεσμάτων των μορφοτεκτονικών δεικτών μεταξύ του ρήγματος των Σφακίων με το κανονικό ρήγμα του Ψαθόπυργου στο Δυτικό άκρο του Κορινθιακού Κόλπου. Οι στόχοι σε αυτή την έρευνα είναι α) να γίνει σύγκριση της επίδρασης των ρυθμών ολίσθησης στη διαμόρφωση της γεωμορφολογίας του σταθερού τέμαχους και β) να γίνει αξιολόγηση της ανύψωσης της ευρύτερης περιοχής με σύγκριση των δεδομένων από τα σταθερά τεμάχη των κανονικών ρηγμάτων.

MORPHOTECTONICS OF THE SFAKIA NORMAL FAULT, SOUTH-WESTERN CRETE, GREECE

Tsimi C.[1], Ganas A.[1], Ferrier G.[2], Drakatos G.[1], Richard J. Pope[3], Fassoulas C.[4].

[1] *Institute of Geodynamics, National Observatory of Athens, Athens 11810, Greece, christinant@gmail.com, Fax: +30 210 3490180.*

[2] *Department of Geography, University of Hull, Cottingham Road, Hull, HU6 7RX, UK*

[3] *Division of Geography, University of Derby, Kedleston Road, Derby DE22 1GB, UK*

[4] *Natural History Museum, University of Crete, Knosou Av., Herakleion 71409, GR*

Abstract

The E-W striking, S-dipping, 17-km long Sfakia fault is located in the south-western

Crete which is considered as a paradigm of coastal uplift and spectacular gorge formation in Greece. This fault was formed in Pliocene times (~ 3-5 Ma) because of crustal extension in the N-S direction. Its activity continued until mid-Upper (?) Quaternary where seismic faulting may have switched to the synthetic, offshore fault about 4-6 km to the south. Our work presents new data on the tectonic geomorphology of this area which is characterised by the competition of uplift due to the Sfakia fault and of regional uplift due to plate convergence. Field observations by our team showed that small streams and gullies eroding the mountain front have stopped incising and that the coastal plain is uplifted above present-day sea level from 0.2-12 m depending on location. The morphotectonic indices along the fault (hypsometric integral, drainage basin asymmetry, ratio of valley floor width to valley height (Vr), mountain front sinuosity, mean slope of triangular facets) have been calculated using the ArcGIS software. Our work shows that the tilt direction of footwall catchments changes along the footwall which is clear evidence for lack of a bell-shape, cumulative uplift pattern along an active normal fault. We also compare our results with several morphotectonic indices of the Psathopyrgos normal fault inside the Gulf of Corinth, a well-known Quaternary rift.

Λέξεις κλειδιά: Μορφοτεκτονική, Βόρειο δυτική Κρήτη, Ρήγμα Σφακιών.

Key words: Morphotectonic, South-West Crete, Sfakia fault.

1. Introduction

The Sfakia fault is located in the south-western Crete which is considered as a paradigm of coastal uplift and spectacular gorge formation in Greece (Figure 1; Pirazzoli et al., 1982; Fassoulas, 2001; Peterek A, and Schwarze J. 2004; Fassoulas and Nikolakakis, 2005). This fault is E-W striking, S-dipping, 17-km long and it was formed in Pliocene times (~ 3-5 Ma) because of crustal extension in the N-S direction. The onset of its activity is marked by the deposition of the Chora Sfakion formation (Lower Pliocene; Skourtsos et al., 2007) which is found on the hangingwall of the fault. Its activity continued until mid-Upper (?) Quaternary where seismic faulting may have switched to the synthetic, offshore fault about 4-6 km to the south. Recent estimates of footwall uplift due to co-seismic slip along the Sfakia fault are of the order of 0.8 mm/yr (Alexopoulos and Markopoulou-Diakantoni, 1996; Skourtsos et al., 2007) and is comparable to other normal fault data for central and eastern Crete (Caputo et al., 2006). In addition, the Early Pleistocene, marine sedimentary formation of Fragokastelo has been uplifted at about 0.4-0.6 mm/yr (Skourtsos et al., 2007). Fragokastelo is located in the hangingwall of Sfakia normal fault and if Sfakia was active during Middle-Late Quaternary this formation should be subsiding or be at least stable below sea level. This uplift can be explained by offshore seismic activity on synthetic normal fault(s) and/or regional uplift due to plate convergence along the Hellenic Arc. All over south Crete, one sees uplifted marine terraces and other shoreline features (Wegmann et al., 2006). Our work presents new data on the tectonic geomorphology of this area which is characterised by the competition of uplift due to the Sfakia area faults and of regional uplift.

The footwall area of the Sfakia fault comprises mainly limestone and marble of the Plattenkalk and Trypali units and is characterised by the occurrence of rectilinear valleys and deep gorges (Figure 1). The western hangingwall area is dominated by alluvial fans along the mountain front (Nemec and Postma, 1993). To the east there is an extensive outcrop of basement (phyllites) near the village Skaloti (IGME, 1982; Figure 2) with an estimated thickness of about 400 m. Phyllites are tectonically overlain the Plattenkalk rocks which reach 1000 m in thickness (IGME, 1982) so the existence of phyllites on the hangingwall area of the Sfakia fault indicates significant vertical displacement (throw) of this fault. A complicating factor for calculating throws is the existence of the Fragokastelo normal fault (Skourtsos et al., 2007) which runs oblique to the Sfakia fault and terminates against it (Figure 1).

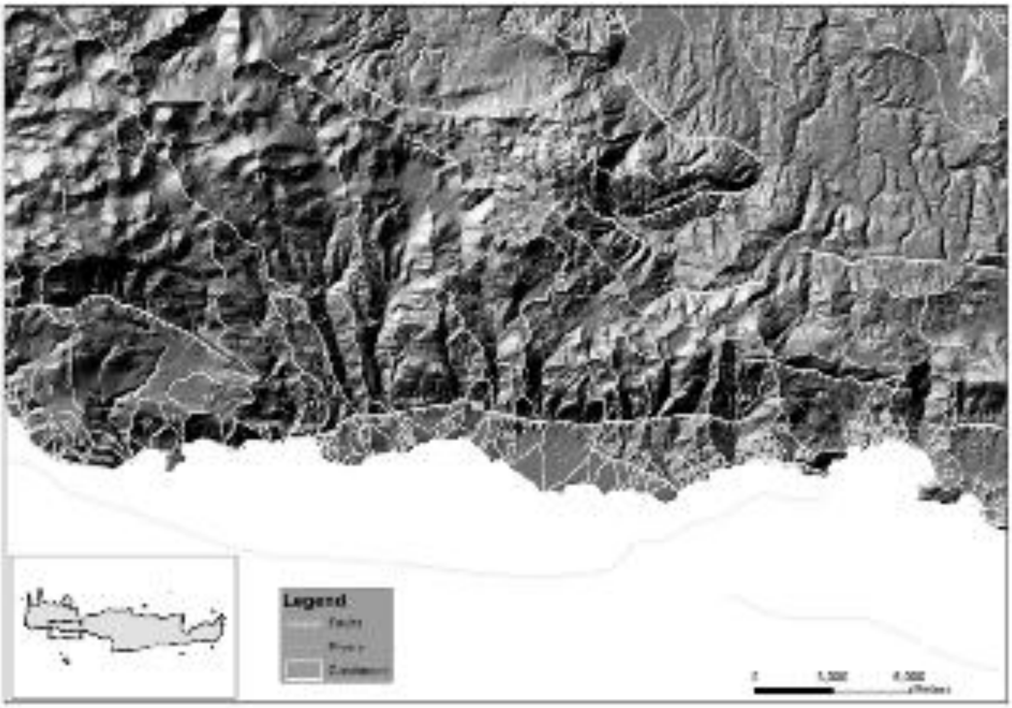

Figure 1. The study area of south-western Crete including the Sfakia normal Fault (thick white line with ticks on the downthrown side). Other normal faults are shown with their names printed, as well. Thin white lines show river catchments, main rivers and streams. Numbers indicate catchment number. Background image is a shaded relief model of Crete produced from a 20-m DEM mosaic. Illumination is from the North.

Field investigations by our team showed that small streams and gullies eroding the mountain front (Figure 2) have stopped incising and that the coastal plain is uplifted above present-day sea level from 0.2-12 m depending on location. The morphotectonic indices along the fault (hypsometric integral, drainage basin asymmetry, ratio of valley floor width to valley height (Vr), mountain front sinuosity, mean slope of triangular facets) have been calculated using the ArcGIS software. We also extended our GIS analysis to the greater western Crete area using an elevation data set of a mosaic of six 1:50000 maps sheets of the Greek Army from where we built a 20-m Digital Elevation Model (DEM). The normal faults of the greater area have been extracted by use of the DEM mosaic products (relief, slope map) and satellite images from the Landsat 7 ETM+ sensor. In this paper we will present our results for the Sfakia area only. We also compare our results with morphotectonics of active normal faults inside Quaternary rifts in mainland Greece such as the Gulf of Corinth. In particular we have analysed the Psathopyrgos fault (Tsimi et al., 2007) which is an active fault on the western Gulf of Corinth area and its footwall uplift rate has been recently determined at 1.8 mm/yr (minimum estimate; Palyvos et al., 2007). The objective is a) to compare the effect of variable slip rates on footwall geomorphology and b) to evaluate the contribution of regional uplift by comparing data from footwall areas of comparable normal fault systems.

Figure 2. Field photograph of the Sfakia mountain front near the village Skaloti. Black arrows show the position of the fault scarp. Note that the face of the scarp is eroded indicating fault inactivity. Rocks on the foreground are mica schists of the phyllite unit. Photograph taken on 30 May 2007. View to the west.

2. Materials and Methods

The main data set, which we used, is a Digital Elevation Model (DEM) with resolution 20 x 20 m. From those data we produced slope maps, shaded relief maps and TIN models of the landscape. The software that was used was ArcGIS™ v.8.1 for Windows. We digitized on-screen a) the boundaries of catchments (287), b) the courses of streams c) the boundaries of triangular facets developed on the footwall area of the Sfakia faults and d) the traces of normal faults as mapped by Skourtsos et al., (2007) and by our own field work. Several faults were located precisely by collecting fault plane coordinates using field GPS. The calculated morphometric indices of this study are the following:

• Hypsometric integral (HI; Figure 3)

$$HI = \frac{H_{mean} - H_{\min}}{H_{\max} - H_{\min}} \qquad (1)$$

Where Hmean, Hmax and Hmin are the mean, maximum and minimum elevation, respectively.

• Drainage basin asymmetry (AF; Figure 4)

$$AF = 100 * (Ar/At) \qquad (2)$$

Where Ar is the size of area in the right sub-catchment of main river and At is the area of whole catchment.

• Ratio of valley floor width to valley height (Vr; Figure 5)

$$Vr = \frac{2V_{fw}}{(h_1 - h_3) + (h_2 - h_3)} \qquad (3)$$

Where Vf is the width of the valley floor, h1 and h2 are the elevations of the right and left drainage divide and h3 is the elevation of the valley floor.

Where Vf is the width of the valley floor, h1 and h2 are the elevations of the right and left drainage divide and h3 is the elevation of the valley floor.

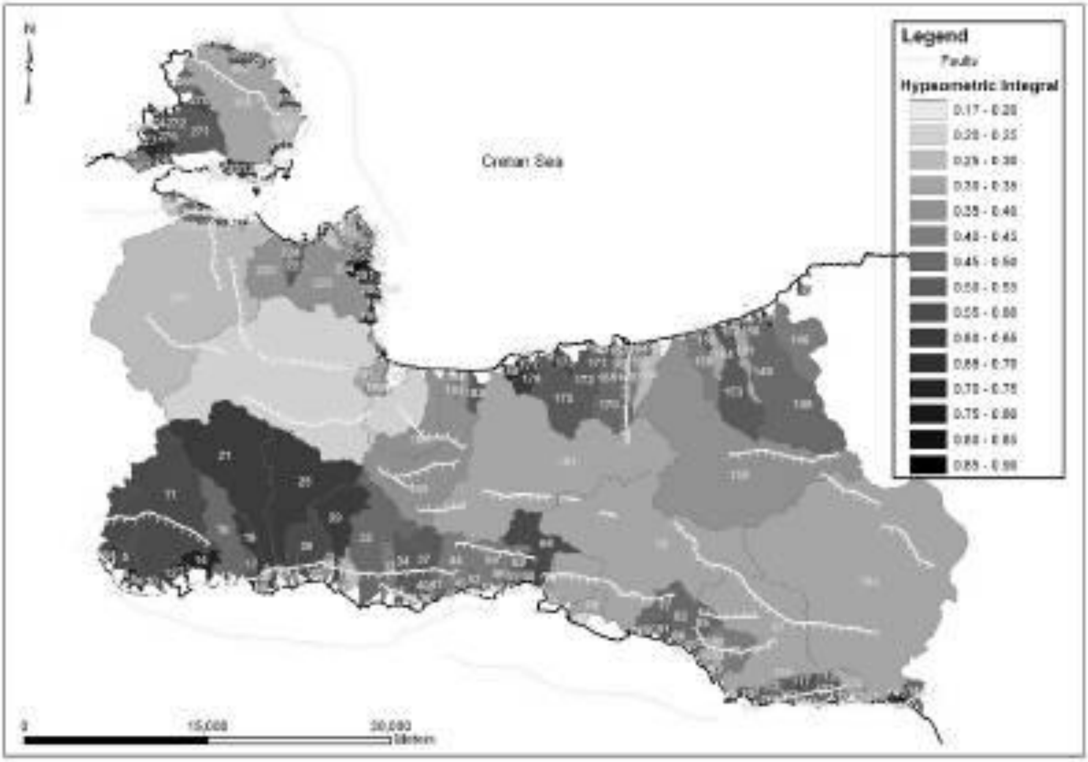

Figure 3. The map indicates the spatial distribution of the Hypsometric Integral based on DEM elevations of catchments. The Sfakia area catchments are indicated by numbers 18 to 44. The light grey color means low topography and the dark grey color means high topography. The white lines are the normal faults (ticks on the downthrown side). Note in the Sfakia fault area that the size of catchments decreases to the east.

3. Results and Discussion

Our results on the distribution of the morphotectonic indices along the Sfakia Fault include:

a) High values of the H.I index are mapped on the western end of the fault (0.64). Low values (H.I < 0.4) are mapped on catchments that are cut by the fault.

b) The Asymmetry map reveals strong tilt to the east and moderate tilts to the west. The AF index reaches 0.86 (Sfakia gorge catchment 21; west part), 0.74 and 0.71 (catchments 26 and 28; middle), 0.81 and 0.79 (catchments 31 and 37; east). A drastic change in the tilt direction occurs in the middle of the fault. AF values for catchments 26 and 28 (see above) indicate tilt to the east but the neighbouring catchment of Asfendou (Figure 4, number 29) shows AF=0.21 indicating strong tilt to the west. It is notable that this switch in tilting directions occurs almost in the middle of the fault where one would expect the opposite behaviour if a typical displacement-length relationship was established as in the Psathopyrgos fault case (Tsimi et al., 2007).

c) The Vr ratio (Figure 5) ranges from 0.08 to 2.02, both values characterising limestone-incised valleys. Vr values below 1 are characteristic of active regions; however, we suggest that such values can be sustained along inactive normal faults if the area is undergoing uplift due to regional processes such as plate convergence and/or the migration of fault activity is relatively new (let's say 100000- 300000 years). An interesting point to be further investigated is that the Vr ratio does not increase with distance from the fault scarp as is the case with active faults such as the Heliki Fault in the Gulf of Corinth area (Verrios et al., 2004). This may be due to either a) incorrect positioning of the fault scarp on the DEM image b) stop of tectonic activity (i.e. footwall uplift) resulting in termination of down-cutting and c) contribution of regional uplift which does not necessary follows the same pattern as the fault-specific uplift.

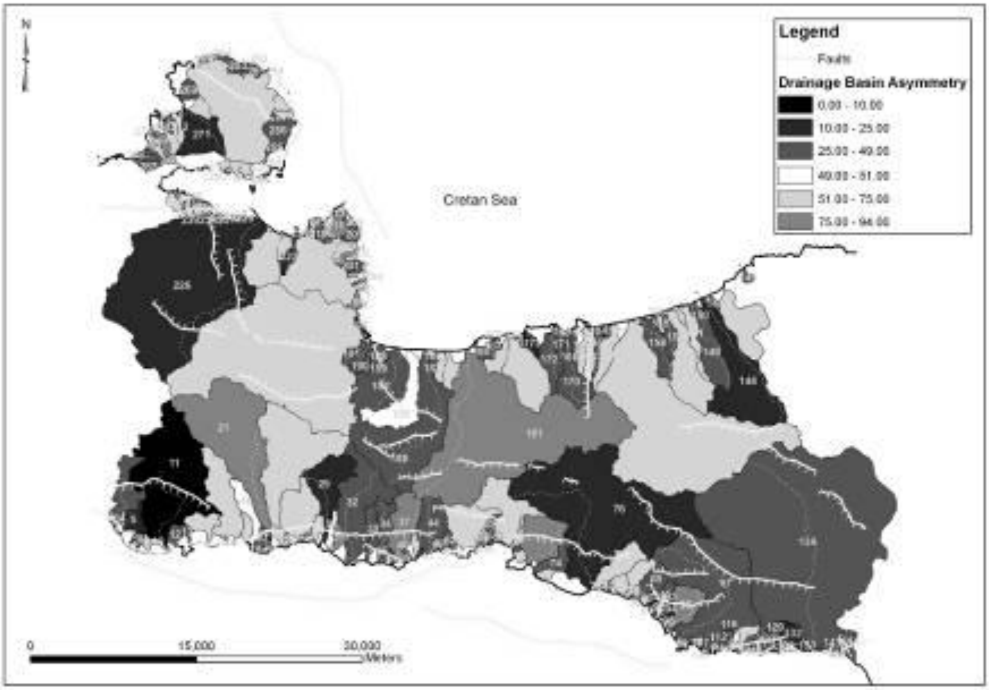

Figure 4. The map indicates the spatial distribution of the drainage basin asymmetry. The light color indicates values larger than 50% and means catchment's tilt to the left of the flow direction. Dark grey color indicates catchment's tilt to the right of the flow direction. The Sfakia area catchments are indicated by numbers 18 to 44. The white lines are the normal faults.

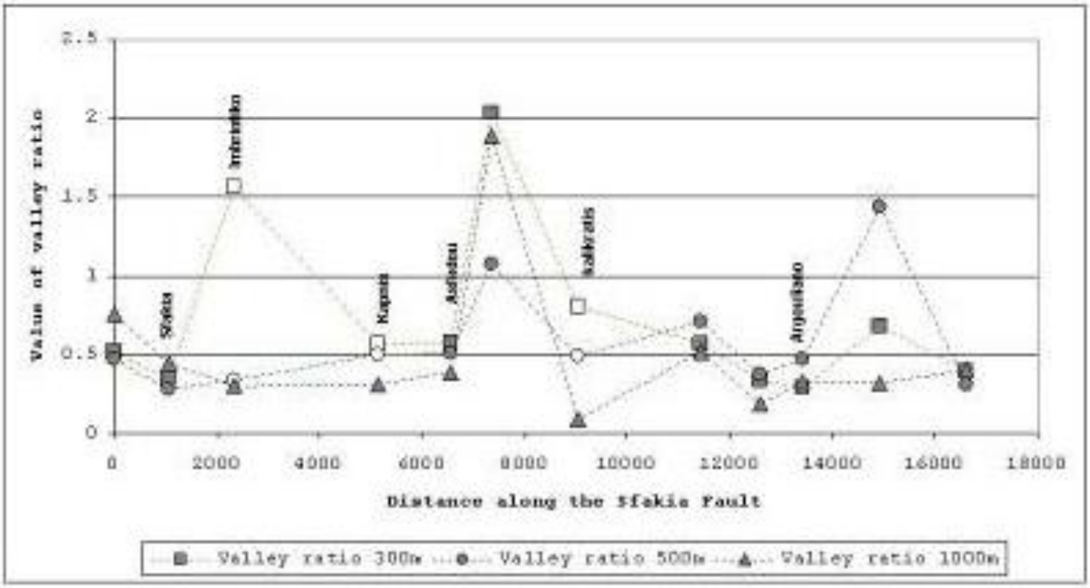

Figure 5. Graph showing the distribution of the ratio of valley floor width to valley height (Vr). The square points indicate values at 300 m distance from the Sfakia Fault while circles indicate values at 500 m distance and triangular points indicate 1000 m, respectively. The grey color means that the lithology of the valley is limestone. The white color means that the lithology of the valley is alluvial fan, scree or talus. The position of the Sfakia fault was determined by the break in morphological slope.

We also compared our findings to the results we obtained from the morphotectonic analysis of the Psathopyrgos normal fault in the western Gulf of Corinth area (Tsimi et al., 2007). Our results are comparable because both footwall areas were studied from 1:50000 scale digitised DEMs. For this purpose we summed several key observations along one graph (Figure 6). Figure 6 shows the distribution of three (3) indices along strike of the two faults, namely the H.I index, the mean slope angle of catchments and the A.F index. Psathopyrgos shows high values of H.I (>0.5), and a switch in A.F about 5 km to the west of the origin the section. Sfakia shows both high and low H.I values along strike. However, Sfakia show opposite behaviour in terms of tilt direction of the footwall catchments. In Figure 6b we see that catchments from distance 0 to 8500 m along strike show high values of AF indicating tilt to the east, while from distances 8500 to 17000 m the tilt direction switches to the west. This result is inconsistent with an isolated fault growth model where footwall basin asymmetry follows the cumulative displacement which has elliptical (or bell-shaped) geometry (Schlische et al., 1996). This change in tilt direction occurs in the centre of the fault with a converging mode and it can be regarded as evidence for fault inactivity. If large earthquakes (M>6) had recently occurred along the Sfakia fault then the footwall uplift would be greater in the centre and less at fault tips so the tilt direction would diverge at fault centre. On the contrary, this diverging asymmetry is what we observe in Psathopyrgos where the tilt direction agrees with the long-term slip distribution along the fault (Tsimi et al., 2007; Figure 6). Both faults show a similar distribution of slope angles of catchments.

In terms of comparing the effect of long-term (100000 to 1 million years) uplift rate on the present-day morphotectonics of both normal faults we note the following: a) H.I values along Psathopyrgos (fastest uplift; 1.8 mm/yr) are greater than 0.5 whereas H.I values along Sfakia range from 0.25-0.64. In addition, the range of H.I values along the Psathopyrgos fault is small as they range from 0.50-0.65 while along Sfakia they range from 0.25-0.64 b) The spread of AF values is again larger for Sfakia (0.21 to 0.86) than for Psathopyrgos (0.39-0.61). We think this difference is not due to the uplift (slip) rate difference (1.8 vs. 0.8) but to the combination of a) regional uplift pattern and b) normal fault activity migration to the south. This hypothesis may be supported by the fact that AF values in the western part of Sfakia are generally greater than those from the eastern part (Figure 6) and numerous field observations by us (i.e. Figure 2) and other workers that the Sfakia mountain front is not actively incising. Fault migration to the south would imply that the Sfakia fault now constitutes the footwall area of the active fault(s) so the present-day uplift pattern would depend on the exact location of the active fault, its geometry and its distance. We also suggest that the effect of regional uplift along Psathopyrgos (if any) is negligible.

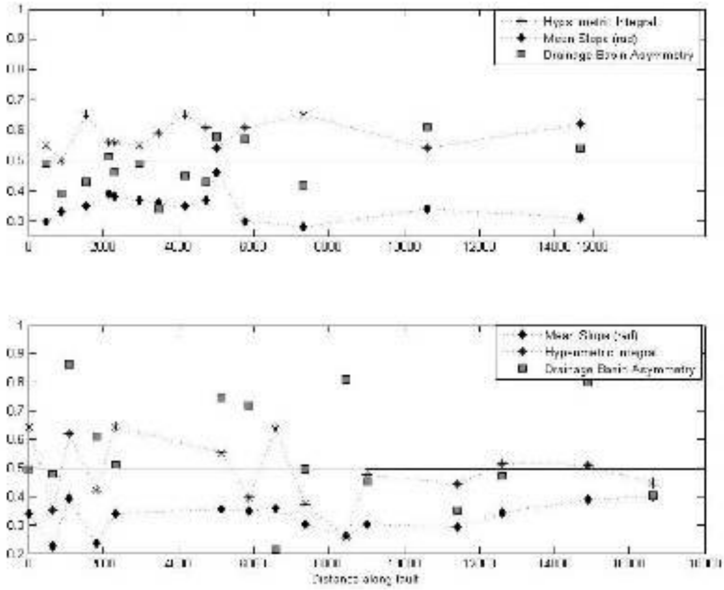

Figure 6. Diagram indicating variation of three (3) indices along strike Top) Psathopyrgos Fault Bottom) Sfakia Fault. Slope values are mean slope angles of catchments in radians. Note that the Psathopyrgos section is oriented east-west but the Sfakia section is west-to-east.

4. Conclusions

Our work presents new data on the tectonic geomorphology of the Sfakia area (western-south Crete) which is characterised by the competition of uplift due to the Sfakia area faults of the order of 0.8 mm/yr and of regional uplift. The main morphotectonic indices along the Sfakia fault (hypsometric integral, drainage basin asymmetry, ratio of valley floor width to valley height (Vr)), have been calculated using the ArcGIS software. We found that a) the basin asymmetry factor does not follow the long-term slip profile along strike (Figure 6), instead it shows a converging tilt in the middle b) Vr ratios while remaining low do not increasing upstream as do in other normal faults (Helike). This evidence suggests that the Sfakia normal fault is inactive. We also observe that high uplift rates on footwall areas of normal faults tend to produce catchments with hypsometric integral values > 0.5 and that a component of regional uplift would tend to disturb the bell-shape profile of isolated footwall geometry and produce highly asymmetric catchments. Finally, low Vr ratios (< 0.5) developed on carbonate rocks can still survive along inactive normal faults.

Acknowledgements

This research is funded by the General Secretariat of Research and Technology of Greece and NERC, UK. We thank Andrei Gosar, Manolis Skourtsos, Spiros Pavlides and Andy Banks for comments during field trips in western Crete. We also thank Odisseas Christou and GEOINFO Ltd for supplying the DEM data for Crete.

References

Alexopoulos, A. and Macropoulou-Diakantoni, A. 1996: La presence du Calabrien au plateau Impros (Crete occidentale, Greece) et sa signification pour l'evolution tectonique de Crete. Rev. Paleobiol., 15(2), 349-355.

Caputo R, Monaco C, Tortorici L., 2006: Multiseismic cycle deformation rates from Holocene normal fault scarps on Crete (Greece). Terra Nova, 18 (3), 181-190.

Fassoulas, C.G., 2001: Field Guide to the Geology of Crete, Heraklion 2001, ISBN 960-367-008-1.

Fassoulas, C., and Nikolakakis, M., 2005: Landscape Response to the tectonic uplift of Crete, Greece. Bulletin of the Geological Society of Greece, 37, 201-207.

IGME, 1982. Geological map of Greece, Sellia sheet (1:50000 scale).

Nemec, W. and Postma, G. 1993: Quaternary alluvial fans in southwestern Crete: sedimentation processes and geomorphic evolution. Special Publication of the Association of Sedimentologists, 17, 235-276.

Palyvos, N., Sorel, D., Lemeille, F., Mancini, M., Pantosti, D., Julia, R., Triantaphyllou, M., De Martini, P.M. 2007: Rewie and new data on uplift rates at the W termination of the Corinth rift and the NE Rion graben area (Achaia, NW Peloponnesos). 11th International Conference of the Geological Society of Greece, Athens 24-26 May 2007

Peterek A, and Schwarze J. 2004: Architecture and Late Pliocene to recent evolution of outer-arc basins of the Hellenic subduction zone (south-central Crete, Greece). J. Geodynamics, 38 (1): 19-55.

Pirazzoli PA, Thommeret J, Thommeret Y, Laborel J and Montaggioni LF, 1982: Crustal block movements from Holocene shorelines: Crete and Antikythira (Greece). Tectonophysics, 86, 27–43.

Skourtsos, E., Pope. and Triantaphyllou, M. V. 2007: Tectono-Sedimentary evolution and rates of tectonic uplift of the Sfakia coastal zone, southwestern Crete. 11th International Conference of the Geological Society of Greece, Athens 24-26 May 2007

Schlische RW, Young SS, Ackermann RV, Gupta A., 1996: Geometry and scaling relations of a population of very small rift-related normal faults. Geology, 24 (8), 683-686.

Tsimi, Ch., Ganas, A., Soulakellis, N., Kairis, O. and Valmis, S., 2007: Morphotectonics of the Psathopyrgos active fault, Western Corinth rift, Central Greece. 11th International Conference of the Geological Society of Greece, Athens 24-26 May 2007

Verrios, S., Zygouri, V., and Kokkalas, S. 2004: Morphotectonic analysis in the Eliki fault zone (Gulf of Corinth, Greece). 10th International Conference of the Geological Society of Greece, Thessaloniki 15-17 April 2007

Wegmann, K.W, Pazzaglia, F.J, and Fassoulas, C., 2006: Chronostratrigraphy of Late Quaternary marine terraces of Crete, Greece: vertical tectonics and implications for seismic slip on the Hellenic subduction zone. Geological Society of America Abstracts with Programs, 38, (7), 508.