TECTONO-SEDIMENTARY EVOLUTION AND RATES OF TECTONIC UPLIFT OF THE SFAKIA COASTAL ZONE, SOUTHWESTERN CRETE

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Abstract

Sfakia lies within a narrow coastal zone at the southwestern foothills of the Lefka Ori Mt. Here a segment of the South Cretan margin is preserved onshore, a structure that represents a neotectonic structure with continuous activity since the Upper Miocene. This segment is characterized by a steep, E-W striking and south facing morphological escarpment that constitutes numerous E-W and ESE-WNW striking normal faults. Since the Late Miocene, marine sequences of Tortonian, Early Pliocene and Lower Pleistocene age were deposited along the coastal zone. Since the Middle Pleistocene multiple, coalescent alluvial fans covered both the alpine basement and the marine sediments. Fault-kinematic- and stratigraphic data combined with recently published palaeobathymetry reconstructions allow us to make relable estimates of both the uplift rates of fault blocks in the study area and the period that the faults that demarcate them were active. The results show that the study area is experiencing uplift already since the Middle Pliocene and that the uplift rates of the mountainous parts are higher than those of the coastal zone. The general uplift of the coastal zone seems to be controlled by offshore normal faults, south of Sfakia.
Key words: active crustal deformation, normal fault, extension, Pleistocene, Lefka Ori, Sfakia.

Περίληψη

Η περιοχή των Σφακίων είναι μία στενή παράκτια ζώνη στο νοτιοδυτικό τμήμα των Λευκών Ορέων, στο οποίο διασώζεται τμήμα του Νότιου Κρητικού περιθωρίου. Πρόκειται για μία μακρόχρονη νεοτεκτονική δομή που άρχισε τη δράση της στο Ανώτερο Μειόκαινο και συνεχίζεται μέχρι σήμερα. Χαρακτηρίζεται από μία απότομη μορφολογική ασυνέχεια διεύθυνσης Α-Δ, που σχηματίστηκε από ρήγματα διεύθυνσης Α-Δ και ΑΝΑ-ΔΒΔ προκαλώντας εφελκυσμό Β-Ν. Από το Ανώτερο Μειόκαινο μέχρι το Κατώτερο Πλειστόκαινο αποτέθηκαν θαλάσσια, ενώ ακολούθως η ιζηματογένεση συνεχίστηκε με την απόθεση μεγάλου πάχους αλλουβιακών ριπιδίων, διαδικασία που συνεχίζεται μέχρι σήμερα. Η καλύτερη στοιχειοθέτηση της ηλικίας των θαλάσσιων ιζημάτων σε συνδυασμό με πρόσφατα δημοσιεύματα σχετικά με το βάθος απόθεσής τους και με τη χαρτογράφηση των ρηγμάτων της περιοχής, έδωσε τη δυνατότητα να προβούμε σε σημαντικές διαπιστώσεις σχετικά με τους μακρόχρονιους ρυθμούς ανύψωσης των ρηξιτεμαχών της περιοχής, όπως και για το χρονικό διάστημα που τα ρήγματα που ορί-

*ζουν αυτά τα ρηξιτεμάχη ήταν ενεργά. Από το Μέσο Πλειόκαινο όλη η περιοχή υπό-
κειται σε ανύψωση με τις εσωτερικές περιοχές να έχουν ρυθμούς έως και διπλάσιους
από εκείνους της παράκτιας ζώνης. Η γενική ανύψωση φαίνεται να ελέγχεται από
ρήγματα υποθαλάσσια νότια της περιοχής μελέτης.*
Λέξεις κλειδιά: *ενεργή παραμόρφωση, κανονικό ρήγμα, εφελκυσμός,
Πλειστόκαινο, Λευκά Όρη, Σφακιά.*

1. Introduction

Active extensional tectonics in the Aegean is accommodated by normal faulting and regional uplift producing new topography at rates higher that those of erosion and deposition (Leeder and Jackson 1993). The lateral extent of the normal faults and their associated tilted fault blocks perform a major control on the distribution of sedimentary facies in these extensional basins. This control is more obvious where the normal faults occur near sea level, which provides a reference point for the vertical motions of footwalls and hanging walls (e.g. Goldworthy and Jackson 2000, D'Agostino *et al.* 2001). The island of Crete is one of the best examples to examine the upper crustal deformation of the outer Aegean domain as the geological data show evidence of a multi-stage tectonic evolution of the island, since the Upper Oligocene (e.g. Fassoulas *et al.* 1994, ten Veen and Postma, 1999a, 1999b; Fassoulas, 1999, 2001, Peterek and Schwarze 2004, van Hinsbergen *et al.* 2006).

Crete occupies a fore-arc position above the north-vergent subduction zone of the Hellenic Arc along which the Africa plate is consumed under the southern edge of the Eurasian plate. Between the Upper Oligocene and Lower Miocene, the collision of the Apulian micro-continent culminated in the stacking of a thick (>10 km) pile of nappes (Bonneau 1984). The lowermost units were buried at a depth of about 20-30 km and were overptinted by HP-LT metamorphism (Siedel *et al.* 1982, Jolivet *et al.* 1994, 1996, Kilias *et al.* 1996, Fassulas *et al.* 1994). In response to roll-back of the subduction zone (Thomson *et al.* 1999) and the continuous underplating (Jolivet *et al.* 1996), the high pressure rocks were uplifted and, within a very short time span, exhumed along low-angle normal or detachments faults during N-S extension. The rapid uplift of the lower metamorphic nappes is constraint by geochronological data (Thomson *et al.* 1998, 1999) and sedimentary rocks of Middle Miocene age, which unconformably overly the high pressure rocks (Meulenkamp 1979).

After the Middle Miocene, Crete was transformed into a mosaic of asymmetrical horsts and grabens due to both temporally and spatially different modes of vertical movements (Meulenkamp *et al.* 1988). The Neogene to Quaternary sedimentary record provides clear evidence of repeated, dramatic changes in the paleogeographic configuration. In most cases these changes coincided with major tectonic events, although different ideas exist about the evolution of the stress field during that period. The complex interplay of tectonics and sedimentation resulted in a large variety of sediment types and in rapid lithological changes in both a lateral and vertical sense (Meulenkamp 1979, ten Veen and Postma 1999a, 1999b, Fassoulas 1999, 2001, Peterek and Schwarze 2004).

Most of the research concerned with the Neogene and Quaternary structural evolution of Crete focused on the extensional basins of central and eastern parts of the island (e.g. ten Veen and Postma 1999a, 1999b, Fassoulas 1999, 2001). However, research focusing on the Quaternary evolution of those areas is limited to the Messara and Ierapetra basins (e.g. ten Veen and Postma 1999a ten Veen and Kleinspehn 2003, Peterek and Schwarze 2004), due to the absence of complete sedimentary records in other areas. Our study focuses on the Sfakia region south of the Lefka Ori massif, where a segment of the South Cretan margin is preserved in a narrow coastal plain. Unexpectedly, the Midle Miocene to Holocene evolution of this segment has been characterized by multiple phases of normal faulting and episodic sedimentation. On the basis of tentative ages derived from synrift sediments, detailed mapping of the normal faults and on

recently published chronometric data we describe the tectono-sedimentary evolution for the Sfakia segment of the South Cretan margin and present new long-term rates of tectonic uplift for the area.

2. Geological Setting

Western Crete is mainly formed by the Lefka Ori (White Mountains), which reach a maximum height of 2452 metres. The Lefka Ori consists predominantly of carbonate rocks with intense karstic erosion, which is mainly fault-controlled. The highlands of Omalos and Askifou are characteristic karst forms that are covered by Quaternary continental deposits. The southern flanks of the Lefka Ori are drained by numerous streams that run through deep north-south trending canyons at Samaria, Tripiti, Klados and Imbros that extend southwards towards the sea.
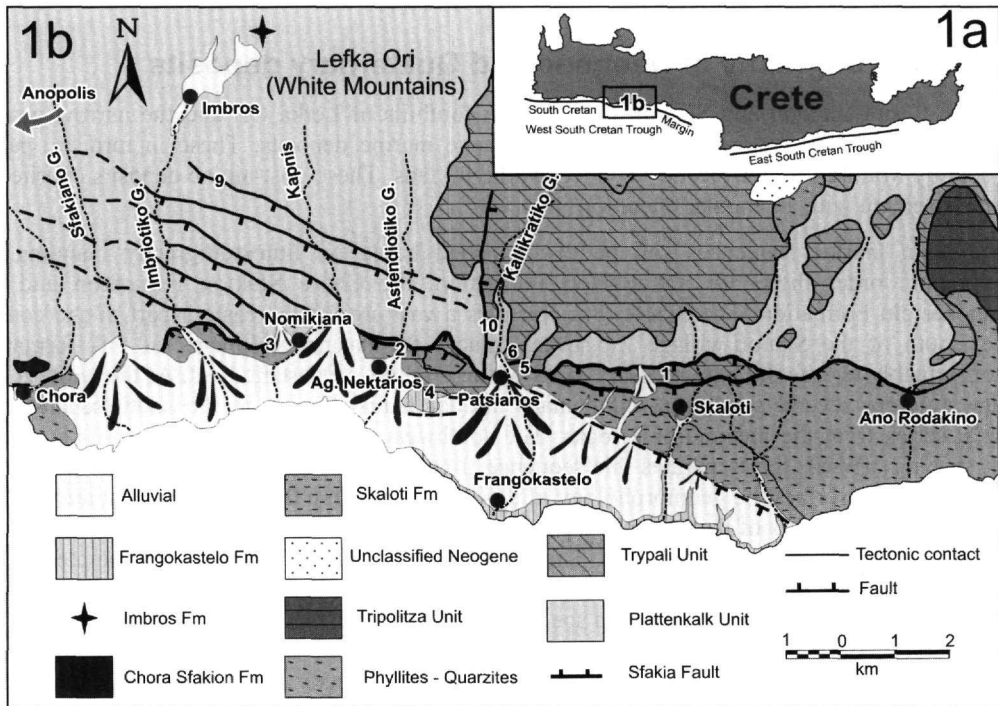

Figure 1 – a) Geological map of the study area modified from I.G.M.E. (1982, 1987). b) The Sfakia coastal zone represents an onshore segment of the South Cretan margin (modified from Alves _et al._ 2007)

Within the Lefka Ori the lowermost Plattenkalk unit is underlain by the lithologically equivalent Trypali unit. Until recently, the Trypali unit was described as a massive complex of dolomitic and calcite marbles with partially tectonic breccia formations, aged Upper Triassic (Pomoni and Karakitsios 2002). Furthermore, Krahl and Kauffman (2004) revealed that the Trypali unit is a sequence of carbonate breccia, cherty marbles, meta-siliclastic sediments and massive marbles of Upper Triassic to Upper Cretaceous in age. This sequence is tectonically overlain by nummulite-bearing plated marbles of the Plattenkalk unit (Alexopoulos _et al._ 2000). Along the western flanks of the Lefka Ori, the Plattenkalk unit is overlain by mica scist, quartzite and some marble intercalations that define the Phyllites – Quarzites unit. At the southeastern foothills of the Lefka Ori, the Tripolitza and the Pindos unit are overlain the previous unit (Karakitsios 1979).

Deformation of the Plattenkalk and Trypali units was attributed to subduction related processes (Fassoulas _et al._ 2004). Variations in the magnitude and style of deformation were lithology-driven. Large, open to tight folds deform the entire stratigraphic section. In places these folds appear to be overturned, locally inverting the stratigraphy and forming large synclines and

anticlines, with fold axes trending east-west and axial planes dipping gently northward. The age of folding is constrained to the Late Oligocene – Early Miocene, as the detachment faulting separating the lower units from the non-metamorphosed upper nappes, clearly overprinted the fold structures (Fassoulas *et al.* 2004).

Since the Middle Miocene, continued exhumation of the metamorphic rocks of the lower units and the uplift of the Lefka Ori, seems to be accompanied the formation of E-W, NW-SE and NE-SW high-angle normal faulting. These faults also formed a series of asymmetrical Neogene basins within which thick sedimentation occurred. To the east of the study area, fluvio-lacustrine to shallow marine sedimentation occurred in the Plakia Basin (Meulenkamp 1979, Angelier 1979). It is suggested that these deposits are Upper Seravallian – Lower Tortonian in age and belong to the Tefelion Group (Meulenkamp 1979).

3. Lithostratigraphy of Neogene and Quaternary deposits

Between Chora Sfakion and Skaloti, the southern foothills of Lefka Ori and the narrow coastal zone are covered by Neogene to Lower Pleistocene marine deposits. These in turn are partly covered by Middle (?) Pleistocene - Holocene alluvial fans. These post-alpine deposits overlie the alpine basement with an angular unconformity.

Three main marine sequences can be distinguished based on lithostratigraphy mapping. In stratigraphic order these are: the Skaloti Formation, the Chora Sfakion Formation and the Frangokastelo Formation. The Skaloti Fm occupies a vast area at the eastern part of the coastal zone, south of the Skaloti village. In several places the basinal sediments of this formation unconformably overlie the high pressure rocks of the Phyllite – Quartzite Unit. At the western end of the outcrop, several small syn-sedimentary normal faults dipping to the south separate the basinal series from the metamorphic rocks. The southwestern border of the outcrop is a normal fault striking NW-SE that separates this sequence from another marine series, the Frangokastelo Fm. This fault describes the geomorphology of this area, separating the small hills that are built up by the marine sediments of the Skaloti Fm, from the flat area that built up by the Late Quaternary alluvial fans and the Francokastello Fm. The Skaloti Fm. consists of sands, conglomerates, marls and shallow marine limestones building a continuous series of ~170 m thick with bedding that is slightly inclined to the south. Based on a specimen of *Clypeaster* that has not been observed in the Pliocene, van Hinsbergen *et al.* (2006) placed the shallow marine deposits of Skaloti Fm. in the Upper Miocene Tefelion Group of Meulenkamp (1979). Our analysis of calcareous nannofossils strongly supports the fact that deposition occurred within a shallow marine environment during the Tortonian and thus corroborates the previous age estimates.

The Chora Sfakion Fm. is observed immediately northeast of Chora village and comprises a 5 m thick sandy deposit of Lower Pliocene age, which overlies coarse conglomerates of unknown age or marbles of the Plattenkalk Unit. It has been suggested that this small outcrop of deep marine deposits is Lower Pliocene in age (van Hinsbergen 2004) and is equivalent to Finikia group of Meulenkamp (1979).

The Frangokastelo Fm. occupies the central part of the coastal zone. According to Sissingh (1972), this formation comprises two distinct sedimentary sequences. First, immediately east of Frangokastelo, a coastal cliff exposes a 35 m thick marine sequence comprising blue-green clays and limestones. Second, close to the village of Agios Nektarios, a sequence comprises of limestones with pebbles, both rounded and angular, with intercalations of clays and clayed marls (Meulenkamp 1969, Sissingh 1972, Driever 1984). According to Meulenkamp (1969) both formations have features that are very different from other marine formations outcropping to the east of the study area or to the central and northern parts of the island of Crete. Although the stratigraphic position of the formation is uncertain, it has been tentatively placed in the Middle Pliocene by Meulenkamp (1969). The same outcrops were dated Late Pliocene by Hinsbergen *et al.* (2006).

Due to uncertainties regarding the age of the Frangokastelo Fm., we made an attempt to date these marine sequences using calcareous nannofossils. Our results show that both outcrops of the Frangokastelo Fm are much younger than previous age estimates. The sequence close to Agios Nektarios is assigned to the Lower Pleistocene [biostratigraphic zones MNN19c and MNN19d which provide an age range of 1.66-1.25 Ma (Lourens *et al.* 2004)]. In comparison, the sequences close to Frangokastelo is assigned to biostratigraphic zones MNN19d and MNN19e, providing an age range of 1.62-0.97 Ma (Lourens *et al.* 2004)]. Thus, the data strongly suggest a Early Pleistocene age for the Frangokastelo Fm. The deposition of the blue-green marls took place under open marine conditions. The Agios Nektarios sequence has low-angle dips to the east, whereas the bedding of the Frangokastelo show dips to the west.

Marine sediments are not only found in the foothills of the Lefka Ori, but also occur in the main mountain zone at altitudes in excess of 1000 m. These sediments occur as isolated outcrops of lithified limestones and conglomerates with shallow marine faunas, which are separated from the Plattenkalk and Trypali units by normal faults. Van Hinsbergen (2004) proposes that these marine sediments closely resemble those exposed in southwestern Crete and probably correspond to the Serravalian – Tortonian Topolia Fm. of the Prina Group (Meulenkamp 1979). Alexopoulos and Marcopoulou-Diakantoni (1996) described also Lower Pleistocene marine fauna in a residual outcrop a few km northeast of Imbros (Imbros Formation).

The alluvial fan zone occupies essentially the whole of the coastal piedmont between Chora Sfakion and Skaloti, and comprises multiple coalescent fan complexes which together form an extensive bajada (Fig. 1). Those fan systems occupying the western half of the piedmont are classically telescopic in planform, with low gradient distal segments nested within increasingly steeper medial segments. In comparison, the eastern piedmont fans display both limited telescopic segmentation and radial segmentation. Irrespective of the style of segmentation, all fans share two distinctive attributes. First, the fan head zone is permanently entrenched. Second, with the exception of the youngest fan deposits and recent channel fills, an immature soil has formed on the majority of fan surfaces (Nemec and Postma 1993).

The exposed marine sequences located stratigraphically beneath the earlier stages of the fans have been assigned to Biozones MNN19c-e (1.66-0.97 Ma). Consequently, the basal debris flow deposits are likely to have been emplaced no earlier than the later part of the early Pleistocene. Optically Stimulated Luminescence dating of coarse silts and fine sands provide maximum ages of c.143 ka BP for the stage 2A surfaces of the Sfakia fan and c.94 ka and c.70 ka for the basal and middle stage 2C of the Patsianos fan (Pope *et al.* in press). Besides, archaeological data strongly suggests that the stage 3 mudflows exposed within the distal portion of the Patsianos fan were emplaced during the pre-historical period [5.5 to 3.0 ka BP (Sphakia Survey 2002)]. Finally, Venetian artefacts contained within the stratigraphically higher fine-grained hyperconcentrated flows suggest that these deposits were emplaced c.1.0 ka BP (Pope and Wilkinson unpublished data).

3.1. Geometry of Normal Faults

3.1.1. Sfakia Fault

The morphology of the study area is dominated by a morphologically well-expressed fault scarp (termed the Sfakia Fault), which forms a steep south-facing escarpment (Fig. 2). The fault represents the eastern onshore segment of the South Margin Fault that forms the southwestern coastline of Crete (Fig 1). The length of this fault is more than 15 km with its western tip close to Ano Rodakino. Two segments can be recognized: First, a 7 km long western segment between Chora and Agios Nektarios village. Second, a 8 km eastern segment between Patsianos and Ano Rodakino. The segment between Agios Nektarios and Patsianos looks to represent a significantly bend of the Sfakia fault.

Figure 2 – The Sfakia fault expressed as a steep south-facing, morphological discontinuity striking E-W and separating a narrow coastal zone from the eastern foothills of the Lefka Ori massif. View to the east

The main feature of the hanging wall of the western segment is the presence of thick alluvial fans, which cover the metamorphic rocks of the Phyllite-Quartzite Unit. The gravels of the younger alluvial fans have been deposited over the high-pressure rocks of the Phyllites – Quartzite Unit in the hanging wall of the fault and the marbles of the Plattenkalk Unit that form the footwall. These gravels are unfaulted and therefore most probably seal the Sfakia fault. On the contrary, the debris flows of the first stage of the westernmost fan (Sfakia fan) that has been deposited directly above intensely fractured marbles of the Plattenkalk Unit have small internal faults that are parallel to the strike of the Sfakia fault. If such faults were not produced by gravity sliding, it is possible that they reflect fault activity during deposition. Studies of the kinematics of the individual faults that formed within this segment indicate an N-S to NNE-SSW direction of extension (Fig. 3, locations 2-4).

The eastern segment of the Sfakia fault is more linear than the western and its damage zone is noticeably wider, reflecting the presence of intensely faulted carbonate breccias of the Trypali unit along its trace. Two parallel faults define the thickness of the damage zone. The southern one is a low-angle normal fault with an eroded fault scarp juxtaposing the Phyllites – Quartzite Unit and the Trypali Unit. The northern one is a high-angle normal fault that juxtaposes the latter unit and Upper Cretaceous marbles of the Plattenkalk Unit. The difference in the dip angle of these two faults is believed to owe to antithetic block rotation of the southern fault block. The analysis of the slickenside lineations of both faults indicates the predominance of N-S directed extension (Fig. 3, location 1). At the western tip of it (or what) (location 5 in Fig. 1), where two faults strike NW-SE and NNE-SSW, fault kinematic data indicate NE-SW extension (Fig. 3).

3.1.2. Frangokastello Fault

The Frangokastelo fault is observed in the hanging wall of the Sfakia fault, northeast of Frangokastelo. The position of the fault is marked by a morphological discontinuity running NW-SE that separates the Skaloti fm in the northeast from the Frangokastelo Fm in the southwest. Its presence is also reinforced by borehole data from the Eggion Veltioseon Service of the Chania Prefecture. Fault displacement at the Frangokastello Fault led to the creation of the accommodation that was filled by the Frangokastelo Fm. Close to the expected trace of the fault; high-angle normal faults offset the Skaloti Fm beds and tilted pebbles and gravels beds within conglomerate units, reveal its normal character.

The topography of the hanging wall of the fault is flat where thin alluvial deposits unconformably overlie the Early Pleistocene marine deposits of the Frangokastelo Fm. The Patsianos fan formed at the mouth of the Kalliktatiko gorge and shows evidences of marine and aeolian sands interfingering with the alluvial deposits. The maximum ages provided by OSL dating of those sands are c.94 ka and c.70 ka.
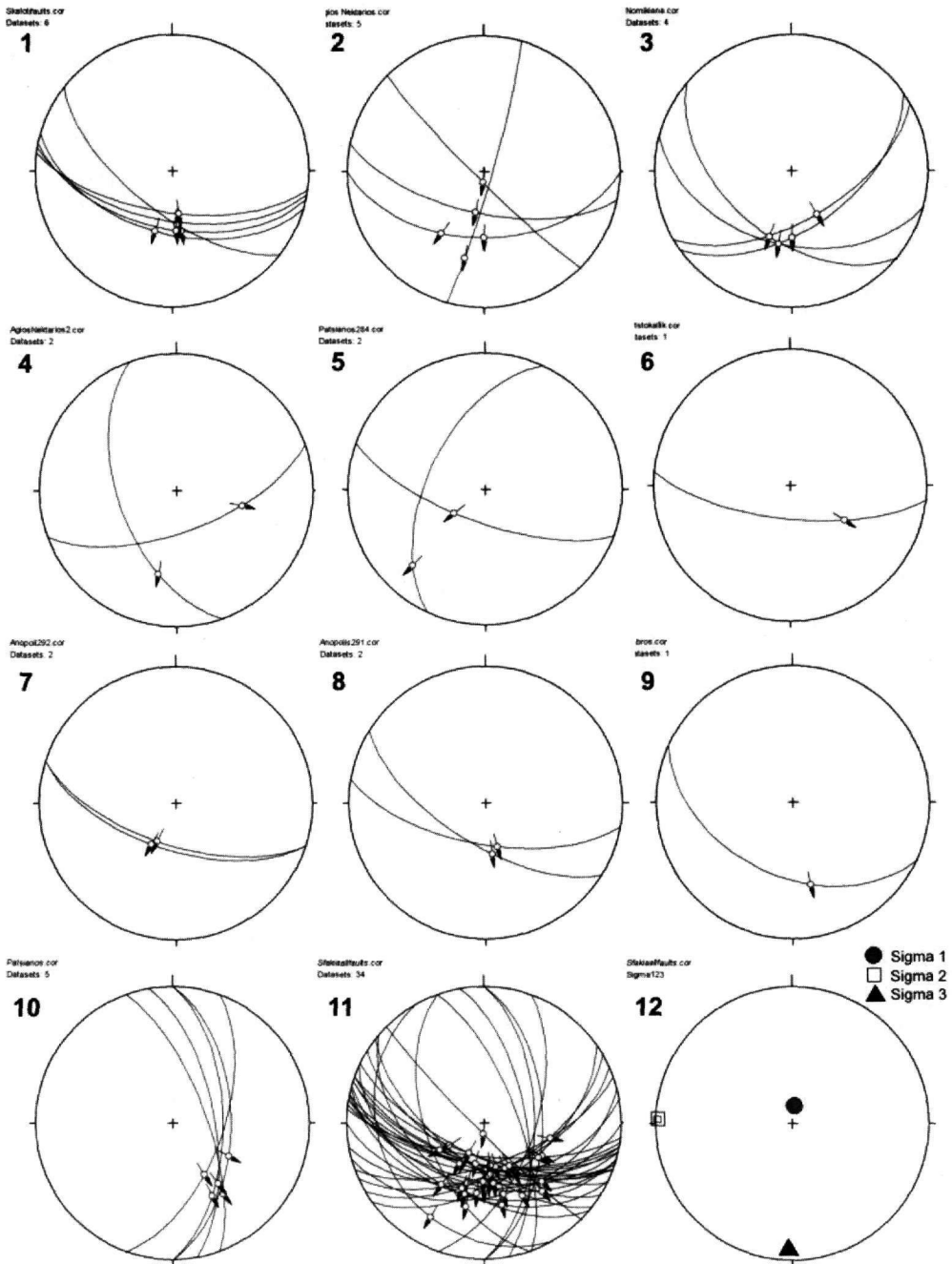
Figure 3 – Fault-slip analysis (P/T method, program Tectonics FP 1.159) performed on kinematic data. Numbers represent the measurements localities, which can be seen in figure 1. The locations 7 and 8 are north of the Anopolis settlement, northwest of Chora. Number 11 shows all the measurements that were used to calculate the mean stress axes of number 12.

3.1.3. Patsianos Fault

The Patsianos fault is a distinctive structure on the footwall of the Sfakia fault running parallel to the Kallikratiko gorge. It strikes N-S and has an high-angle dip to the east. It is a normal right-slip fault that has caused the subsidence of the eastern fault block by 300 m, as shown by the offset of the tectonic contact between the Trypali and Plattenkalk Units. The fault truncates the E-W and NW-SE trending faults that are observed at the southern tip of it. The analysis of the fault-kinematic data indicates an NW-SE directed extension (Fig. 3, location 10).

3.1.4. Faults on the Footwall of the Sfakia Fault

On the footwall of the Sfakia fault a series of parallel normal faults can be observed up to the north of Anopolis (NOT ON THE MAP), striking NW-SE to WNW-ESE and having high-angle dips to the south forming southwest facing, 40-100 m high escarpments. At their base, these escarpments show fault planes with slickensides and juxtaposition of thin colloudvial wedges. It is interesting to note that their throw seems to decrease towards the south-east, where these faults tend to link with the Sfakia fault. In the hanging wall of these two faults, antithetic faults were formed at 50-200 m distance from those. These have higher dips than the main faults and demarcate small hanging-wall grabens. The presence of deep valleys normal to these grabens allows to see that the rocks between the antithetic faults is intensevely fractured by near vertical small faults, as if the grabens had been formed by collapse. The study of the fault-kinematic data shows that they are either pure-normal or normal-left-slip faults (Fig. 3, locations 7-9).

4. Uplift Rates

Stratigraphic and tectonic data emerging from our research coupled with recent palaeobathymetric reconstructions (cf. van Hinsbergen *et al.* 2006), allow us to reconstruct the post-Early Miocene geological history of the Sfakion coastal piedmont.

The Upper Miocene sediments that are found at altitudes of ~200 m at the eastern domain of the coastal zone, unconformably overly metamorphic rocks of the Phyllites – Quartzites Unit. Furthermore, van Hinsbergen *et al.* (2006) proposed that given the relationship between depth and %P [fraction of planktonic foraminifera among the total foraminiferal population (cf. van der Zwaan *et al.* 1990)], the deposition depth for this formation is 59 m. The Lower Pliocene sands of the Chora Sfakion were deposited at a depth of 800 m according to the method of van Hinsbergen *et al.* (2006). By comparison, the Frangokastelo Fm. formed at depths of 500-750 m based upon the method of van der Zwaan *et al.* (1990). Today these formations are found at altitudes of ~50 and 120 m, respectively. The presence of the Early Pleistocene (Calabrian) marine fossils northeast of the Imbros settlement at attitudes of 1000 m (cf. Alexopoulos and Marcopoulou-Diakantoni 1996), indicates that the mountainous domain has been uplifted ~1100 m since the Calabrian given that these organisms lived in waterdepths of 30-100 m. This gives an uplift rate of 80cm/ka for this fault block.

It is interesting to note that the Skaloti Fm contains the oldest marine sediments, yet appears to have been uplifted just 300 m to reach its present position. In comparison, younger formations appear to have been uplifted by more than 600 m. This suggests that following the deposition of the Skaloti Fm, subsidence of the study area during the latest Miocene – Lowest Pliocene was of the order of 700 m, and was coincident with activity along the Sfakia Fault (Fig. 4A-B). This in turn led to the exposure of the fault scarp where the sands of Chora Sfakion Fm. were deposited on the alpine basement (Fig. 4B). During the Middle Pliocene to Early Pleistocene, gradual uplift of the order 50-300 m occurred, after which the Frangokastelo Fm. was deposited (Fig. 4C). Although the sediments at Imbros and Chora Sfakion were both deposited on the footwall of the Sfakia fault, differential uplift (600 – 900 m uplift at Chora and 1100 m uplift at Imbros) probably reflects the accumulated offsets of the NW-SE faults observed in the north of the Sfakia fault. Moreover, comparison of the Lower Pleistocene sediments indicates that deposition of the

Frangokastelo Fm occurred at depths of 500-750 m, while sedimentation at Imbros occurred at depths of 30-100 m (Fig. 4C). Consequently, at the time of deposition there was a height difference of 400-720 m. However, their present height difference is 900-950 m, indicating that this difference has increased by 180-500 m after the Early Pleistocene (Fig. 4D). The lowest value of this difference (180 m) can be explained by activity of the NW-SE faults between the outcrops of the Early Pleistocene marine deposits alone. For the highest value (500 m) displacement on the Sfiaka fault must have occurred too.
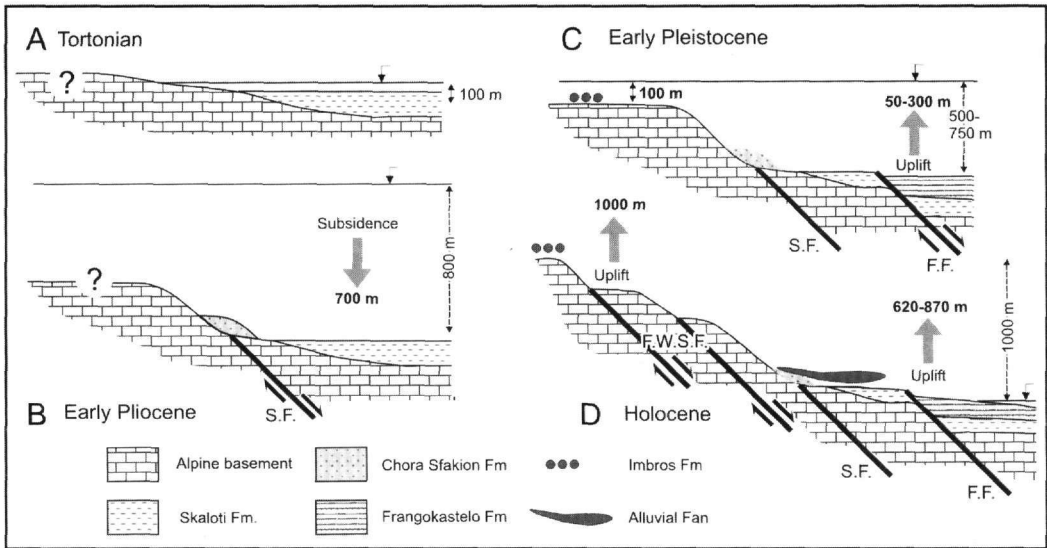

Fig. 4 – Schematic cross sections representing the evolution of the study area after the Tortonian

Useful uplift estimates can also be based on the uplift rates of the Sfakia fault blocks from the Late Pleistocene onward. According to van Hinsbergen *et al.* (2006) the deposition of the Fragokastelo Fm took place at depths of 500 - 750 m, whereas today it is found at altitudes of up to 120 m. This suggests that the uplift rate of the hanging wall of the Sfakia fault is 46 – 64 cm/ka since the Early Pleistocene. This means that the hanging wall is uplifted with a rate that is 1/2 to 4/5 of the rate of footwall uplift. The difference between the uplift rates is due to the presence of the faults that are located in the north of the Frangokastelo Fm, including the Sfakia fault. Therefore, the whole study area has experienced uplift since the Middle Pliocene, but an increase in the rate of uplift is observed between the southern coastal regions and the northern mountainous areas of the Lefka Ori massif. This increase is mostly due to the NW striking faults, and much less due to the Sfakia fault, at least for the period after the Middle Pleistocene, as the materials of the alluvial fans seem to seal this fault. Such suggestions of uplift rates have been proposed for central Crete, where some parts have been uplifted 1000-2000 m since the Late Pliocene (Meulenkamp *et al.* 1994).

5. Discussion - Conclusions

The study area is characterized by the presence of a steep south-facing morphological discontinuity striking E-W that separates a narrow coastal zone from the eastern foothills of the Lefka Ori massif. This steep escarpment is interpreted as a normal fault that represents the eastern and onshore segment of the south fault margin of Lefka Ori mountain range. As testified by (post-alpine) marine sediments deposited on the hanging wall, the Sfakia Fault is a major and long-lived neotectonic structure that invoked the subsidence of the Skaloti Fm and which became active after the Tortonian and remained active until the late Pleistocene.

The Sfakia Fault and other faults, found both in the footwall and hanging wall, show that the deformation was caused by extension in a N-S to NNE-SSW direction, i.e., normal to the long axes of the arc and parallel to the main direction of the compression stresses in that part of the outer Aegean Arc. Although, the majority of faults are normal, some faults (e.g. the Patsianos Fault) exhibit a significant horizontal slip component, which may indicate the presence of wrench tectonics. Alternatively, it is possible that such faults are formed by the same tectonic regime responsible for differential uplift parallel to the mean strike of the South Cretan Margin, including the Sfakia Fault. It is clear that most faults in the southeastern foothills of the Lefka Ori Mountain have kinematic data indicative of N-S to NNE-SSW extension at least from the Late Pliocene to the present. This observation is consistent with the results of Papazachos and Papazachos (2000) and Doutsos and Kokkalas (2002) who suggested NNE-SSW extension in central western Crete.

As far as the palaeogeographic evolution is concerned, the stratigraphic data show the deposition of marine sediments during the whole post nappe extension until the Lower Pleistocene. After the Lower Pleistocene a significant proportion of the hanging wall of the Sfakia fault was emerged and deposition of the first alluvial fans commenced. Nemec and Postma (1993) described the development of the alluvial fans in three stages concurrent with profound climate changes during the Quaternary: an earlier Late Pliocene to Late Pleistocene stage, a mid-Pleistocene stage and a later Holocene stage. The presence of Lower Pleistocene marine deposits underlying the alluvial fans proves that the oldest stage of the alluvial fans development took place sometime in the Middle Pleistocene, while the second stage of the Sfakia fan deposition is tentatively dated to around 143ka (Pope *et al.* in press).

The evolution that is described in the previous section shows that after the Upper Miocene the study area is progressively sliced into numerous faults blocks (Fig. 4) as if the area suffers gravitational collapse. The normal faults that define the numerous fault blocks cause N-S extension while the general uplift of south-western Crete is due to offshore normal faults, in the south of the study area. This collapse seems to be caused by compression perpendicular to the arc taking place in the medial and lower crust from the intense resistance of the subducted plate (Le Pichon *et al.* 1982, 1995, Mascle *et al.* 1998, Peterek and Schwarze 2005).

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7. References

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