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Transverse fault zones of subtle geomorphic signature in northern Evia island (central Greece extensional province): An introduction to the Quaternary Nileas graben

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Abstract

Reconnaissance level geomorphological observations in the northern part of Evia (Euboea) Island, suggest that a major topographic feature, the 17 km long and 15 km wide Nileas depression (NDpr), corresponds to a previously undetected graben structure, bounded by fault zones of ENE–WSW to NE–SW general strike. These fault zones have been active in the Quaternary, since they affect the Neogene deposits of the Limni–Histiaia basin. They strike transverse to the NW–SE active fault zones that bound northern Evia in the specific area and are characterised along most of their length by subtle geomorphic signatures in areas of extensive forest cover and poor exposure.

The NDpr was formed during the Early–Middle Quaternary, after the deposition of the Neogene basin fill. During the Middle–Late Quaternary, the NW–SE fault zones that bound northern Evia have been the main active structures, truncating and uplifting the NDpr to a perched position in relation to the northern Gulf of Evia graben and the submarine basin on the Aegean side of the island. The present-day morphology of the NDpr, with an interior (floor) comprised of Middle Pleistocene erosional surfaces extensively dissected by drainages, was shaped by erosion during this uplift. Judging from their geomorphic signatures, the fault zones that bound the NDpr must have been characterised by low or very low rates of activity during the Late Quaternary. Yet, that they may still be accommodating strain today is suggested by moderate earthquakes that have been recorded within the NDpr.

The fault zone at the SE flank of the NDpr (Prokopi–Pelion fault zone) may be very important in terms of earthquake segmentation of the active NW–SE Dirfys fault zone that controls the Aegean coast of northern Evia, given that the intersection between the two presents striking morpho-structural similarities with the intersection of two fault zones with the same directions on the mainland (the Atalanti and Hyampolis fault zones), which is known to have acted as a barrier to the propagation of the Atalanti earthquake ruptures in 1894.

Keywords: Tectonic geomorphology (morphotectonics); Neotectonics; GIS; Digital elevation models; Evia (Euboea) Island; Central Greece

1. Introduction — aim of study

A geomorphological approach in studies of neotectonics and active tectonics can prove invaluable in diverse tectonic settings, scales and time-frames,

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providing data and understanding otherwise difficult or impossible to collect (e.g., Keller and Pinter, 1999; Burbank and Anderson, 2001). This can be true even for reconnaissance level studies in areas relatively well-studied from a geological point of view, such as the extending domain of central Greece (Fig. 1). Geomorphological observations can provide important hints of neotectonic structures that may be obscure due to lack of appropriate fault exposures, lack of lithological contrasts across them and dense vegetation cover.

A system of WNW–ESE to NW–SE normal fault zones and associated graben or half-graben (e.g., Roberts and Jackson, 1991; Jackson, 1994), accommodate in central Greece the most recent (Quaternary) phase of a long-lasting extension established in the broader back-arc area of the Hellenic arc (Fig. 1) as early as the Early Miocene (e.g., LePichon and Angelier, 1978; Mercier et al., 1989). The northern part of Evia (Euboea) Island (Fig. 1) is a strip of land between two major Quaternary graben, the northern Gulf of Evia (NGE) and a tectonic basin located offshore in the Aegean.

Recent geomorphological and geological field studies identified a major ENE–WSW neotectonic fault zone on the mainland side of the NGE. The "Hyampolis fault zone" (HFZ in Figs. 1 and 2a — Kranis et al., 2001; Palyvos, 2001; Kranis, 2002; Maroukian et al., 2002) strikes transverse to the dominant, WNW–ESE to NW–SE normal fault zones (the presently active AFZ and AKFZ, and the probably inactive KAFZ in Fig. 1), has a geomorphic signature that is complicated in close view and, few outcrops of its constituent faults. It has played an important role in the recent phase of the neotectonic evolution of the area, being a structural boundary to at least two major NW–SE fault zones (KAFZ and AFZ), and the Plio-Pleistocene Renghinion (or Lokris) basin (between the KAFZ and AKFZ — Philip, 1974; Mettos et al., 1992; Kranis, 1999). Furthermore, the HFZ apparently acted as a barrier to the propagation of the 1894 earthquake rupture of the Atalanti f.z. (Ganas et al., 1998; Palyvos, 2001; Pantosti et al., 2001 — AFZ in Figs. 1 and 2a). Thus, its presence has an indirect impact on seismic hazard, since it is a structure that exerts control on the earthquake segmentation of the seismogenic fault system that bounds the NGE to the SSW.

In view of the above, we carried out a morphotectonic reconnaissance on northern Evia Island (Fig. 1), at the prolongation of the HFZ across the NGE, in order to examine whether similar transverse structures are to be

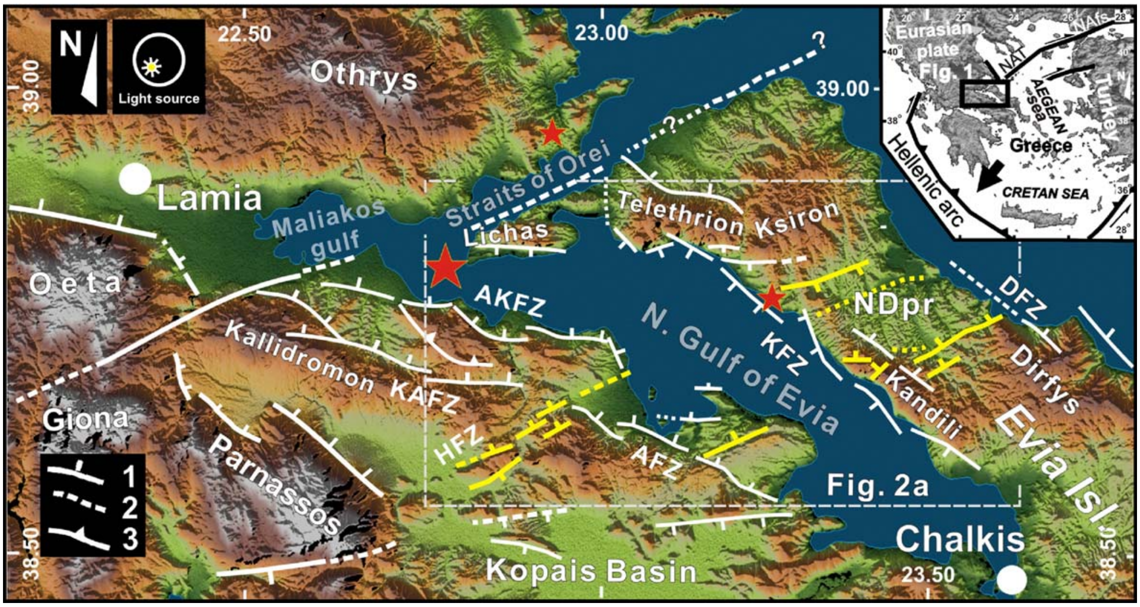

Fig. 1. Inset: Location of study area. NAfs: North Anatolian fault system, NAT: North Aegean Trough, thick arrow: the relative motion of the Aegean and S. Greece with respect to a stable Eurasia. Main neotectonic fault zones in N. Evia and Lokris, based on this study, Kranis (1999) and Palyvos (2001). Included faults modified from Philip (1974), Lemeille (1977), Katsikatsos et al. (1978, 1980, 1981, 1984), Rondogianni (1984), Mettos et al. (1991), Ganas (1997), Galanakis et al. (1998) and Lekkas et al. (1998). The ENE–WSW fault zones discussed or introduced in this study in different colour. Background DEM: NASA's 90 m SRTM. AKFZ: Arkitsa–Kammena Vourla f.z., AFZ: Atalanti f.z., DFZ: Dirfys f.z., HFZ: Hyampolis f.z., KAFZ: Kallidromon f.z., KFZ: Kandili f.z., NDpr: Nileas depression, Stars: Neogene and Quaternary volcanic centres, 1: (oblique) normal faults, 2: probable f.z. traces, 3: apparently reverse fault (rotated normal fault).

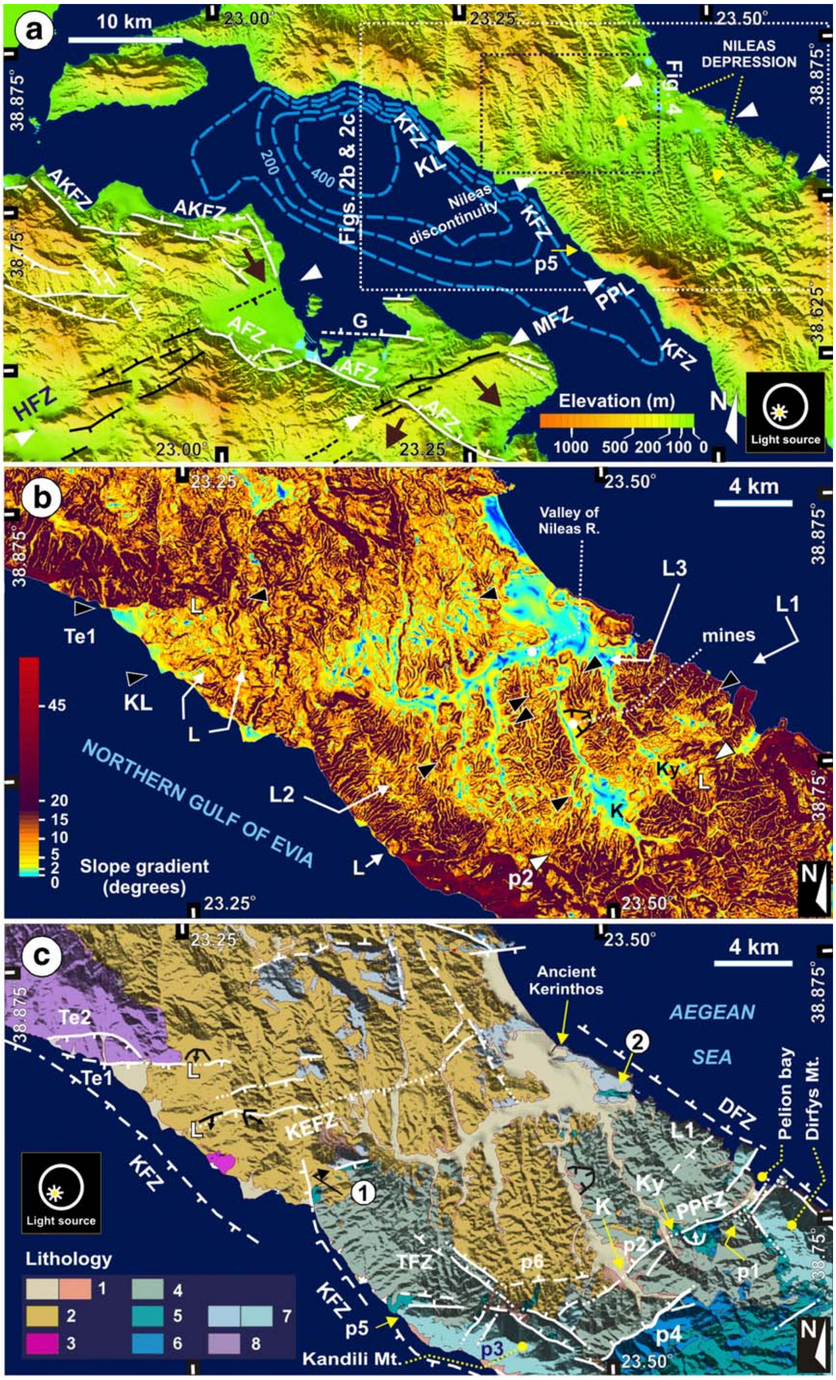

Fig. 2. (a) Hill-shaded DEM of the northern Gulf of Evia area (30 m resolution, interpolated from 20 m contours of 1 : 50,000 maps). Arrowheads mark geomorphic discontinuities discussed in the text, dark arrows on the mainland indicate block tilting. (b) Slope map of the Nileas depression area. Colour scale optimized for the portrayal of the lineament p2. L: landslides. (c) Hill shaded model of the Nileas depression area, overlaid with lithologies from Katsikatsos et al. (1978, 1980, 1981, 1984) and traces of faults following geomorphic signatures. Faults in maps of the bibliography without important geomorphic expression have been omitted for clarity. 1 and 2: Quaternary valley fill/alluvial fans and cones (resp.), 2: Neogene deposits (Limni–Histiaia basin), 3: Miocene volcanics, 4: ophiolites, 5 and 6: schist–chert melange and included carbonates (resp.), 7: Triassic–Jurassic (Sub-Pelagonian), 8: Permian–Triassic metamorphics (Pelagonian unit). KEFZ: Kechriae f.z., PPFZ: Prokopi–Pelion f.z., KFZ: Kandili f.z., DFZ: Dirfys f.z., HFZ: Hyampolis f.z., AFZ: Atalanti f. z., MFZ: Malessina f.z., AKFZ: Arkitsa–Kamena Vourla f.z. Faults Te2, TFZ, p1 and p3 from Katsikatsos et al. (1978, 1980, 1981, 1984), p4 from Lekkas et al. (1998). Mainland faults NW of the HFZ simplified from Philip (1974) and Kranis (1999), SE of the HFZ from Rondogianni (1984), Ganas (1997) and Palyvos (2001).

found further north-eastwards, or not. We will present reconnaissance level geomorphological observations which suggest that such ENE–WSW structures most probably exist (for earlier inferences see Leontaris and Delibasis, 1987) and are responsible for a large-scale geomorphic feature, a 17 by 15 km wide depression that crosses all of northern Evia. Extensive forest cover and lack of suitable outcrops has hampered the recognition of these structures in the past, and along most of their length, also obstructs their direct verification at present.

2. Methodology

For the purposes of our reconnaissance, we developed an extensive Geographical Information System (GIS) database for northern Evia and the neighbouring mainland, that included 1 : 50,000 scale topography from maps of the Hellenic Army Geographical Service (HAGS) (and 1 : 5000 scale, for part of the study area), geological information from maps of the Institute of Mineral and Geological Exploration (IGME) and, an up-to-date synthesis of mapped neotectonic faults. From the digitised topographic contours, digital elevation models (DEMs — e.g., Weibel and Heller, 1991) of 30 and 5 m resolution were interpolated for all and part of the study area (respectively), in order to benefit from the advantages in terrain visualisation DEMs offer (e.g., Burrough, 1986).

We extracted standard morphometric derivatives from the DEMs (slope gradient and aspect — see, e.g., Franklin, 1987) and produced hill-shaded relief maps, topographic profiles and 3D views for detection of possible fault-related geomorphic discontinuities by visual inspection (see, e.g., Oguchi et al., 2003; Ganas et al., 2005, or Florinsky, 1996 and Jordan, 2003 for examples of quantitative approaches) and comparison with the existing geological data. A pair of panchromatic SPOT images (30 m resolution) was also examined stereoscopically for the same purpose, whereas subsequent field reconnaissance was carried out to ground-truth the recognised geomorphic features and, to search for outcrops — if any — that would allow the direct verification of inferred fault zones.

Because of the medium resolution of the assembled database and the important degree of dissection of the study area, our reconnaissance focused on broad-scale geomorphic discontinuities. Given that indirect evidence should always be treated with caution, we note that in the following, the argument for a given geomorphic discontinuity to qualify as probable signature of a neotectonic fault zone is the co-occurrence of several indications, in combinations that do not favour other interpretations. These indications, e.g., linearity and association with marked changes in terrain elevation, drainage anomalies and lithological changes, as well as alignment or parallelism with known neotectonic structures (see, e.g., Vandenberghe, 1990; Goldsworthy and Jackson, 2000; Ganas et al., 2005), if taken separately, may not be conclusive or, discriminative between fault zones active in the Quaternary and older tectonic discontinuities.

3. Overview of geology and neotectonic structure

The northern part of Evia is dominated by Lower Miocene to Upper Pliocene fluvio-lacustrine deposits of the Limni–Histiaia basin (Fig. 2c), which was formed during the earlier neotectonic phases of the region (e.g., Guernet, 1971; Mettos et al., 1992). Basement formations include a Permian–Triassic volcaniclastic complex at the base of a thick sequence of Triassic–Jurassic carbonates (the “Sub-Pelagonian” unit), and an ophiolite nappe, emplaced in the Late Jurassic–Early Cretaceous (e.g., Guernet, 1971; Katsikatsos et al., 1986; Scherreiks, 2000). These Mesozoic formations were also folded during the main phase of the alpine orogeny (Paleocene–Eocene in this part of the Hellenide units).

Previous neotectonic studies in the Limni–Histiaia basin propose two main neotectonic phases: (a) Miocene–Early Pliocene NE–SW extension and (b) Pleistocene NNW–SSE to N–S extension (Mettos et al., 1991, 1992; Galanakis et al., 1998). Between these two phases, Mettos et al. (1991) propose a phase of strike-slip faulting around the Late Pliocene–Early Pleistocene. According to Mettos et al. (1991, 1992) the Limni–Histiaia basin was formed during the earliest extensional phase by normal faults with a NW–SE or E–W main direction, whereas the younger phase is accommodated by either new faults trending NE–SW to ENE–WSW or the pre-existing NW–SE and WNW–ESE faults (with a sinistral oblique component of displacement — Roberts and Jackson, 1991). During this latter phase, the NGE graben was formed by NW–SE to WNW–ESE normal fault zones (e.g., Philip, 1974; Lemeille, 1977; Rondogianni, 1984; Roberts and Jackson, 1991; Mettos et al., 1992).

4. The Nileas depression at northern Evia

A distinct feature of the broad-scale morphology of N. Evia is a rectangular area of low-lying, strongly dissected terrain, extending between Mts Kandili and Dirfys (to the SE) and Mts Telethrion and Ksiron (to the NW — Figs. 1 and 2a). This low-lying area will be called "the Nileas depression" (NDpr). The Nileas river which flows through it towards the Aegean Sea (Figs. 2b, 3 and 4), is the trunk of the largest drainage network of Evia (Fytrolakis et al., 1988; Leontaris and Gournellos, 1991), which is attracted to the depression from the N and S.

4.1. The SE flank of the Nileas depression

Viewed at a broad scale (Fig. 2a), the boundary between the NDpr and the higher terrain to its SE, is a subtle 12–13 km long geomorphic discontinuity of NE–SW to ENE–WSW general trend, which runs almost all across N. Evia (the "Prokopi–Pelion lineament" — PPL in Fig. 2a). A striking characteristic of the PPL is its general alignment with a known NW to NNW facing neotectonic normal fault zone on the mainland (the Malessina f.z. —MFZ—in Fig. 2a, Katsikatsos et al., 1978; Rondogianni, 1984). The MFZ has been active in the Quaternary and corresponds to a quite continuous NW-facing escarpment in Pliocene deposits and a very well-defined back-tilted surface on its footwall (Palyvos, 2001 — Figs. 2a and 3). In the following, we will propose that the PPL is also in all probability the expression of a neotectonic fault zone (the PPFZ).

At its NE tip (Pelion bay), the PPL corresponds to NW-facing normal faults (faults p1 in Fig. 2c — Katsikatsos et al., 1981). The Pelion Bay, a drowned valley along faults p1 and antithetic ones on the NW side of the bay, corresponds to a large and abrupt step both in terrain elevation and lithology (Fig. 2a and c). It essentially marks the NW termination of the highest mountain range of Evia (the Mt. Dirfys range — Fig. 1). On the SE side of the bay, Triassic–Jurassic carbonates reach elevations higher than 1000 m (Fig. 2a). On the NW side, after the occurrence of a small carbonate horst, the coastal range becomes much lower, not exceeding 350 m in elevation and, consists exclusively of ophiolites for a distance of over 5 km to the NW. The ophiolites (above the carbonates in the tectono-stratigraphy of the area, tectonically emplaced in Jurassic times) have been eroded away on Mt Dirfys.

Whereas faults p1 belong to a zone that according to Katsikatsos et al. (1981) continues to the SW up to point Ky (Fig. 2c), the PPL abruptly ceases to be associated with impressive morphology from the point where carbonates no longer comprise its footwall. From that point on, the PPL runs through much softer lithologies (intensely tectonised ophiolites and melange), as a subtle geomorphic discontinuity (p2 in Fig. 2b and c).

We propose that the fault zone mapped by Katsikatsos et al. (1981) could well be extending farther SW along all of p2, through an area of extensive forest cover and lack of outcrops, all the way to the fault zone that bounds Mt. Kandili to the NE (TFZ in Fig. 2c — Katsikatsos et al., 1978). Between points Ky and K, p2 corresponds to a degraded escarpment, in front of which

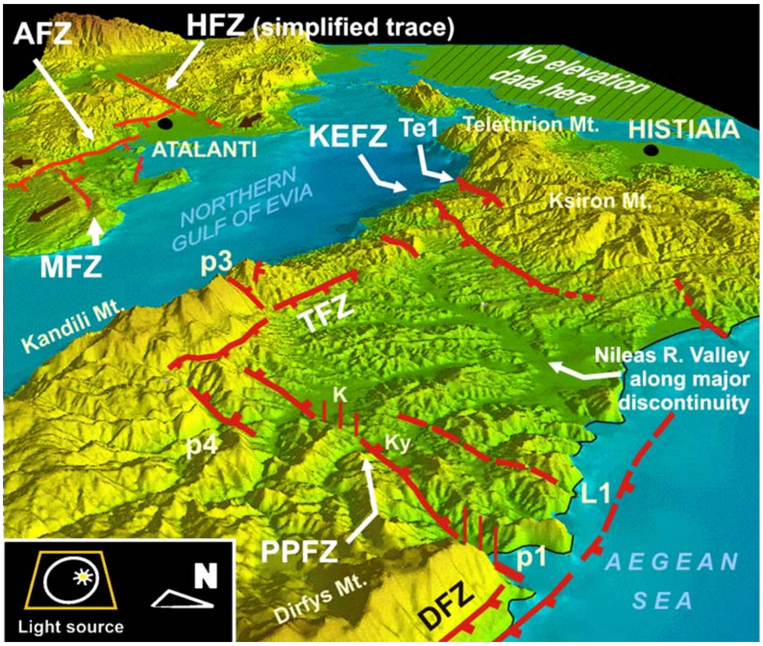

Fig. 3. 3D view of the N. Evia DEM and the Nileas graben. Fault zones as in Fig. 2.

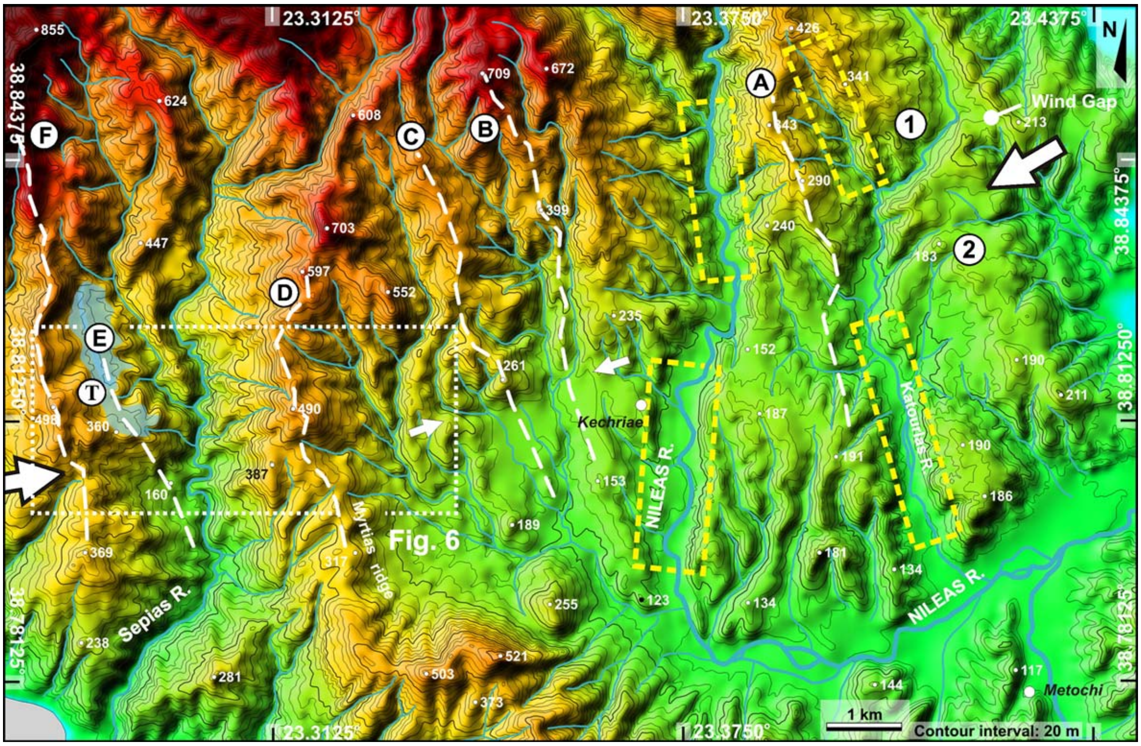

Fig. 4. Topographic map of the geomorphic discontinuity of Kechriae (indicated by large arrows) and surrounding area. Dashed lines labeled A to F: Traces of respective profiles in Fig. 5. Thick dashed line rectangles indicate major deflections of the Nileas and Katourlas rivers at their intersection with the Kechriae f.z. (KEFZ). Smaller arrows point to possible smaller stream deflections along the fault zone. T: terrace group in the Sepias R. valley interrupted at the KEFZ (by a combination of fault displacement and landsliding). 1 and 2: elbow of capture and marked stream alignment (resp.), indicating NE–SW splays of the KEFZ.

a marked widening of the valley of Kireas R. (K) is observed. This feature is inside a 3-km-wide zone where similar morphological anomalies characterise also two other valleys immediately to the NE of Kireas (wider valleys, lower slope gradients of the valley walls — Figs. 2b and 3). This zone of widened valley stretches does not appear to coincide with important lithological changes. It is bound by the PPL to the SE, whereas a lineament can also be drawn as its NW boundary (L1 in Fig. 2b). A lineament like L1 could be non-tectonic, merely connecting receding heads of rejuvenation due to lowering of relative base-level. Yet, the three rivers in question are of different sizes, making such a regular alignment of rejuvenation heads seem an unlikely coincidence. Furthermore, the NE part of L1 follows two perfectly aligned and asymmetric valleys: their NW sides/flanks, which are markedly higher the SE ones, essentially correspond to a SE-facing escarpment (dashed fault in Fig. 2c).

Immediately to the SW of point K, p2 coincides with the SW limit of the Neogene deposits preserved in the NDpr (Katsikatsos et al., 1981). On the higher terrain to the SE of p2, Neogene deposits have been almost completely eroded, reappearing only after 8 km to the SE (outside Fig. 2c), at substantially higher elevations (600 m and higher), suggesting that p2 — in combination perhaps with other faults to its SW — is associated to a large down-step (ca. 200 m) of the base of the Neogene basin fill.

The area to the SE of the SW-most stretch of p2 is occupied by Sub-Pelagonian limestones and ophiolites, whereas ophiolites and Neogene deposits are found to its NW (Fig. 2c), an arrangement that is compliant with a fault zone down-throwing to the NW. Such a fault zone could be obscured by the fact that p2 is followed by a strike valley (densely vegetated). The straight NW boundary of a major occurrence of limestones farther SE, has been re-appraised as a p2-parallel fault (p4 in Fig. 2c) by Lekkas et al. (1998), with the same sense of vertical displacement, providing indirect support to this interpretation.

In a way similar to the termination of Mt. Dirfys, the NW termination also of Mt. Kandili (Figs. 2c and 3) is quite abrupt. Known NW-facing normal faults (p3 in

Fig. 2c — Katsikatsos et al., 1978) coincide with an impressive, 400 m high facet on limestones. Yet, the final transition to ophiolites and lower elevations to the NW, coincides with an E–W escarpment (p5 in Fig. 2a) at the base of which Katsikatsos et al. (1978) have mapped a fault zone (p5 in Fig. 2c, trace modified at its E part), whereas a second fault in front of its base (dashed in Fig. 2c) is also probable, judging from stream alignments. We note that a fault zone with the same E–W strike as p5 could be present to the N of the TFZ/PF intersection (p6 in Fig. 2c), bounding to the N an area where ophiolites and melange are found under Neogene deposits and also between p2 and p4 (not drawn), roughly at the prolongation of p5. Such E–W faults are present also to the N of the AFZ/MFZ intersection at the mainland, the main one (G in Fig. 2a — Rondogianni, 1984) being responsible for a basement high to its S, at the hangingwalls of AFZ and MFZ.

4.2. The NW flank of the Nileas depression

The Nileas depression is flanked to the NW by Mt. Ksiron (990 m) and the SE part of Mt Telethrion (969 m), which constitute an ENE–WSW zone of high terrain (Figs. 1 and 2a) with fault-bounded outcrops of basement rocks (Fig. 2c). To the SE of this mountain range, systematically lower-altitude terrain forms a 3–4 km wide, ENE–WSW-directed zone of morphological transition towards the interior of the NDpr. On its NW side, the NDpr is occupied by a dissected low-lying terrain with accordant interfluves at around 180–200 m elevation (Fig. 4) and remnants of successively lower erosional surfaces (this is also the case for a large part of the SE side of the depression). Fytrolakis et al. (1988), mention four groups of surfaces and probable small vertical dislocations by faults.

At an appropriately broad view, the boundary between the erosional floor of the NDpr and the higher terrain to its NW stands out as a 13 km-long ENE–WSW morphological lineament (the "Kechriae Lineament" — KL in. Fig. 2a and b). The KL is essentially an intensely dissected escarpment up to around 120 m high (Fig. 4) in easily erodible Neogene deposits, relatively steep remnants of which can be discerned at very few places and only for short distances. Dissection also of the terrain in front of the escarpment base further obscures its topographic signature, which is best displayed by successive profiles along interfluves (Fig. 5a).

The area along the KL is quite unfavourable for direct geological observations in the field, being forested and generally lacking appropriate natural or

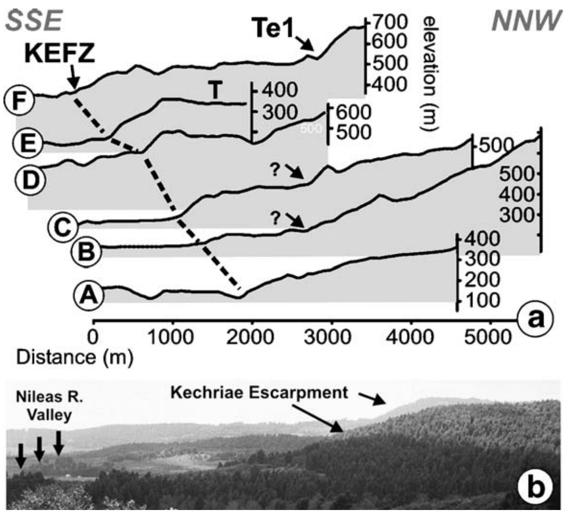

Fig. 5. (a) Topographic profiles demonstrating the degraded Kechriae escarpment and the flat-lying erosional relief in front of it (A–C). Profile traces in Fig. 4. KEFZ: general trace of the Kechriae f.z., T: interrupted terrace group in the Sepias R. Valley (Fig. 4). Te1: fault bounding the Telethrion Mt. (traced in Fig. 2c). (b) View of the escarpment and the flat erosional relief in front of it (view to the WSW). The dense vegetation cover typical of the area is also visible.

artificial exposures (see, e.g., Fig. 5b). Still, the co-occurrence of specific geomorphic (indirect) indications suggests that the Kechriae escarpment is in all probability controlled by a fault zone, the "Kechriae fault zone" (KEFZ — Palyvos et al., 2002). Such indications recognizable at 1 : 50,000 scale are: (a) it has a linear trace, (b) it is not restricted to the edge of the flat-lying terrain inside the NDpr but, it also traverses the NGE–Aegean Sea divide (Figs. 3 and 4 and profiles D–F in Fig. 5), (c) exactly at its trace, marked deflections of the Nileas and Katourlas Rivers occur (Fig. 4) in Neogene deposits, any lithological inhomogeneities inside of which are unlikely to have produced drainage anomalies at this scale, on rivers of this size and (d) its W part parallels a major neotectonic fault zone with the same sense of vertical displacement (Te1 in Fig. 2c, the boundary of Mt. Telethrion to the S — modified from Katsikatsos et al., 1984).

In closer view, two splays at the easternmost part of the KEFZ (Fig. 2c) are suggested by (a) an elbow of capture (e.g., Sparks, 1986) and (b) aligned streams (1 and 2, respectively in Fig. 4) across both of which the terrain is down-stepping (one fault drawn in Katsikatsos et al., 1980 also). At its W part, the KEFZ is associated to large down-stepping of the divides of the Sepias R. valley (100 and 150 m, Fig. 4 and profiles D and F in Fig. 5), suggesting that is has hosted substantial displacements since the Middle–Late Pleistocene, at least in this area. Within the valley, it coincides with an abrupt interruption of a group of terraces at elevations of 320–380 m (T in Fig. 4 and profile E in Fig. 5).

The aforementioned are recognisable on 1 : 50,000 scale and, taken together, appear suggestive enough at a reconnaissance level. In Fig. 6, we give an example of what the details of the morphology look like in the Sepias R. valley, in a hill-shaded relief model of a DEM interpolated from 4 m topographic contours of very detailed (1 : 5000) HAGS maps. Recent fast incision by Sepias R. (due to uplift by the offshore KFZ and any unknown component of regional uplift) into a wide and flat old valley floor (T in Fig. 4), has resulted in a steep-sided, deep valley in Neogene deposits, which has been widened by extensive landsliding (some large landslides noted also in Katsikatsos et al., 1980). The trace of the KEFZ and two additional fault zones with the same direction (1 and 2–3 resp. in Fig. 6) are quite eloquently "etched" by landsliding along them. The geomorphic signature of the KEFZ (1) is quite complicated, apparently consisting of several small escarpments aligned with or trending oblique to an ENE–WSW to E–W principal displacement zone, whereas other fault zones (intersecting the KEFZ) may also have contributed as pre-existing failure planes for mass-movements. That the geomorphic signature of fault zones 2 and 3 in Fig. 6 is not due to randomly located landslides is suggested by the fact that 2 crosses the W valley divide, whereas f.z. 3 is continuous across both sides of the valley. At the prolongation of escarpment 3 towards the E valley divide, an aligned stream and the SE limit of an outcrop of basement limestones occurs (see Fig. 2c — only fault 3 is drawn).

To the E of the Sepias valley, apart from small stream deflections and captures along the base of its escarpment (Fig. 4), the KEFZ is not as distinct in the 1 : 5000 topography, probable reasons for this being: (a) several intersections with faults striking oblique or transverse to the KEFZ and the effect these have had in determining the fluvial erosion or mass-wasting that has been intensively acting on the Neogene deposits, or, (b) a complicated fault zone pattern; the KEFZ need not necessarily correspond to one main fault where deformation was localized. It may be a zone consisting of faults arranged in a more complex pattern, which can obscure its geomorphic signature in closer view, particularly if fault slip rates have been low in the recent geological past (the same maybe true for the PPFZ also).

5. Discussion

5.1. Timing and present rates of activity of the fault zones at the flanks of the Nileas depression

The Neogene deposits are affected by the proposed fault zones at the flanks of the NDpr, suggesting that the latter was formed after their deposition, in the Early–Middle Quaternary. Whether the bounding fault zones

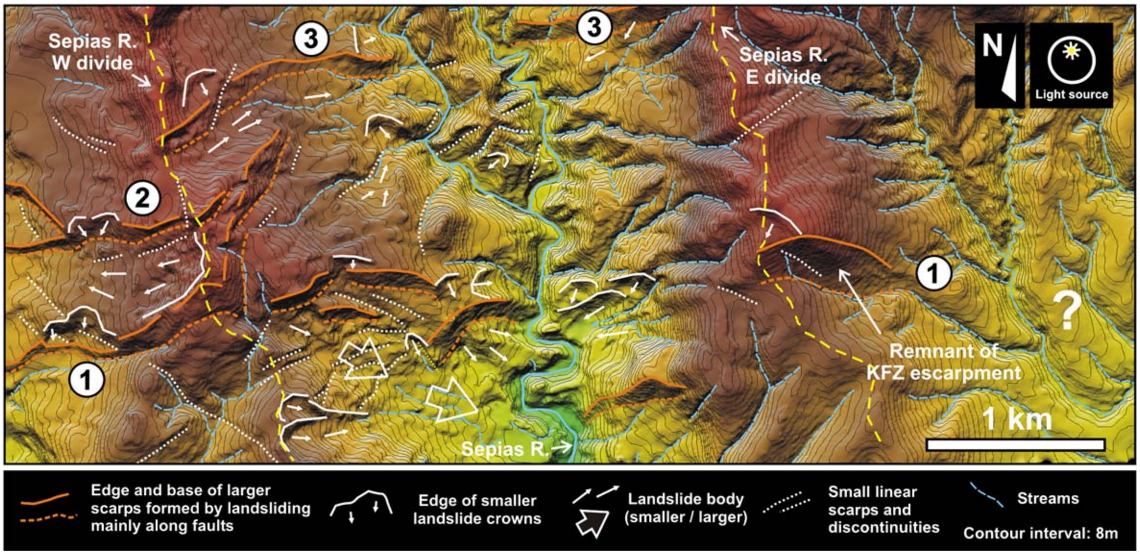

Fig. 6. Detailed view of the geomorphic signature of the KEFZ at its western part (Sepias valley). Landsliding along the KEFZ (1) and faults parallel or oblique to it (2, 3) has been the dominant geomorphic process (primarily responsible for the observed larger scarps along these faults). Large question-mark indicates the absence of geomorphic indications of the KEFZ at the right-hand side of the figure. Underlying DEM (5 m resolution) constructed by interpolation of 4 m contours digitised from 1:5000 scale HAGS maps (for clarity, only the 8 m contours are plotted).

have a longer history than the NDpr, that is, if they may have controlled the sedimentation of part of the Neogene deposits that occur inside it, is an open question.

As far as the Middle–Late Quaternary is concerned, the geomorphic evolution of N. Evia at the broader area of the NDpr has been dominated by the presently active NW–SE coastal normal fault zones, the KFZ on the NGE side, and the DFZ on the Aegean side (Figs. 1 and 2a). These zones are responsible for the elongate shape of the island at this area. The NDpr has been uplifting in-between them, to be found today in a 'perched' position relative to the submarine basin of the NGE and the basin located offshore the Aegean coast of N. Evia. This recent uplift is also responsible for the formation of the erosional surfaces at the floor of the depression. If we consider the Holocene uplift rate estimate of 0.6 mm/yr for the Aegean coast by Maroukian et al. (2001) at ancient Kerinthos (Fig. 2c), the main surface system within the NDpr (180–200 m) may have been graded to sea-level high-stands of oxygen isotope stages 9 or 7 (roughly 350–200 kyr).

Which has been the role of the fault zones at the flanks of the NDpr in this period? The geomorphic signature of the Kechriae fault zone (KEFZ), is subtle along most of its length. Furthermore, the 100 m-high steps at the divides on either side of the Sepias valley can be due to sympathetic slip along the KEFZ, in the vicinity of the nearby active Kandili f.z. (KFZ in Fig. 2a), rather than an indication of repeated activation of the whole KEFZ in recent times. Regarding the PPFZ, whereas there is marked lithological contrast across p2 at its SW part (limestones vs. Neogene deposits), there is no important step in elevations, implying that the bulk of activity of p2 pre-dates erosion that occurred at least as early as the late Middle Pleistocene. Thus, inactivity or very low vertical displacement rates can be assumed for the SW part of the PPFZ during the Late Pleistocene–Holocene. The relatively well-expressed escarpment at the central part of p2 between K and Ky is mainly a fault-line scarp, the result of exhumation (e.g., Bosi et al., 1993) during the formation of the erosional surfaces that occupy the interior of the NDpr.

Still, just how low are the slip rates of the NDpr-bounding fault zones at present, remains to be quantified. Subtle geomorphic signatures can be misleading in easily erodible lithologies, or, due to complicated fault zone geometry. Flat erosional surfaces that can be recognized on the KEFZ footwall (e.g., Fig. 5b foreground, right), might be after all displaced remnants of the quite young (Middle Pleistocene) surface system that occupies a large part of the interior of the NDpr. Both the KEFZ and PPFZ are oriented at high angles to the NNW–SSE to N–S present direction of extension (Mettos et al., 1991, 1992; Galanakis et al., 1998). Futhermore, the concentration of moderate magnitude earthquakes inside the NDpr (Papanastassiou et al., 2001 and earthquake catalogues of the National Observatory of Athens), as well as the micro-earthquake activity recorded by Hatzfeld et al. (1999), suggest that the NDpr faults may still be accommodating some amount of strain today. The preferred nodal planes of focal mechanisms of the above micro-earthquakes inside the NDpr (predominantly dextral strike- and oblique-slip), are interestingly aligned with the ENE–WSW direction of the fault zones proposed herein (Hatzfeld et al., 1999; Kiratzi, 2002). Furthermore, Voreadis (1932) discussing the intensity VI–VII earthquakes that struck northern Evia in 1931, concluded that the responsible structure was a major ENE–WSW tectonic discontinuity running along an "elongate land-strip from Agia Anna to Limni". This landstrip, which according to G. Voreadis "is the result of (tectonic) subsidence", is actually the NW part of the Nileas depression, whereas the tectonic discontinuity in his figure extends to the mainland along the Hyampolis zone.

5.2. Effect on the segmentation of active fault zones

The important uplift of Mt Dirfys at the SE side of the PPFZ at Pelion bay is mainly due to the activity of NW–SE faults of the Dirfys f.z. (DFZ in Figs. 1 and 2c) that bound to the NE and SW the Triassic–Jurassic carbonates that comprise Mt Dirfys. The intersection of the DFZ with the PPFZ is responsible for a marked decrease in the cumulative footwall uplift of the former (and thus, also in its cumulative displacement) — a change noted also by Leeder and Jackson (1993). A very similar example exists at the mainland (Fig. 2a) with fault zones of the same strike and polarity. The NE segment of the Atalanti f.z. (AFZ) exhibits the largest cumulative uplift (Ganas, 1997; Ganas et al., 1998), being backed by a mountain more than 1000 m high, where the lowermost Mesozoic formations emerge. Yet, upon intersecting the transverse Hyampolis zone (HFZ) and exactly because of this intersection, the cumulative displacement of the AFZ dramatically decreases. The Mesozoic formations on its footwall give way to Neogene deposits and elevation drops at around 400 m (Kranis et al., 2001; Palyvos, 2001).

As mentioned in the introduction, the HFZ/AFZ intersection is a known earthquake segment boundary (e.g., DePolo et al., 1991) for the AFZ, as is common with such intersections (e.g., Turko and Knuepfer, 1991). This fact assigns particular interest to the PPFZ/DFZ intersection, especially considering the suggestion of Stiros et al. (1992), about recent uniform coseismic uplift of a 70 km long stretch of the Aegean coast of Evia and the implications this would have for the maximum expected earthquake magnitude in the region.

5.3. The Nileas Discontinuity

At the prolongation of the Hyampolis fault zone on the mainland (HFZ in Figs. 1 and 2a), a major tectonic discontinuity of the same WSW–ENE trend (the "Nileas Discontinuity", or ND) traverses all of northern Evia, buried along most of its length by the Nileas River alluvium (Katsikatsos et al., 1980). The Nileas River has a N–S direction at its upper part but, it exhibits a conspicuously sharp bend and attains an ENE–WSW direction in its lower reach within the NDpr, when it meets with the ND (Fig. 2b and c). The ND corresponds to an important change in the pre-Neogene basement lithologies across the valley: a zone 6–9 km wide paralleling the discontinuity to the S is occupied almost exclusively by ophiolites, whereas for at least 12 km to its NW only Sub-Pelagonian carbonates (and their basement, in Telethrion Mt.) can be observed under the Neogene cover (Fig. 2c).

Katsikatsos et al. (1980) identify the ND as an Eohellenic (Late Jurassic to Early Cretaceous), SE-dipping thrust of the ophiolites and associated melange of deep sea sediments over the Sub-Pelagonian formations. The occurrences of Sub-Pelagonian limestones and schist–chert melange just south of the discontinuity are considered as formations that were 'swept' by the over-thrusted ophiolites. On the other hand, Fytrolakis et al. (1988) proposed that a neotectonic structure could exist along the valley of Nileas, based on the observation that young terraces in the Nileas tributary valleys exist only at the NW side of the discontinuity, a fact that could be implying uplift of that area relative to the one SE of the discontinuity.

It is a fact that the only areas where the ND is not buried by Holocene deposits are locations 1 and 2 in Fig. 2c. The existence of a thrust at (2), does not rule out the possibility of a neotectonic fault buried under the alluvium of the valley that is found just to its S. At location 1, the ND is not equally well exposed; its cartographic trace suggests a tectonic contact between limestones and melange rocks that is sub-vertical, a fact that does not necessarily imply a neotectonic origin, though. We can only comment, that the alignment of the ND with the Hyampolis f.z. on the mainland and the ND-parallel neotectonic structures we propose at the flanks of the NDpr, as well as two other possible ones inside the depression (L2 and L3 in Fig. 2b, through Neogene deposits) provide a context in which, the possibility that the ND might be a structure (inherited or not) that has been active in the neotectonic period as part of an ENE–WSW fault system together with the HFZ, perhaps may be left open. No important cumulative vertical displacements during the Middle–Late Quaternary can be proposed, based on the fact that the erosional surfaces at the "floor" of the NDpr are generally found at the same elevations across the discontinuity.

6. Conclusions

Reconnaissance level geomorphological and geological observations on northern Evia Island, suggest that a major geomorphological feature, the 17 km long and 15 km wide Nileas depression (NDpr), corresponds to a graben structure bound by important fault zones of ENE–WSW to NE–SW general direction. These (the Kechriae f.z. — KEFZ — and the Prokopi–Pelion f.z. — PPFZ —, the latter partially mapped in the past by IGME), are characterised by a subtle geomorphic signature in areas of extensive forest cover and generally poor exposures. The PPFZ and KEFZ strike transverse to the NW–SE active fault zones that bound northern Evia Island in the specific area and are aligned with or trending parallel to transverse structures on the mainland coast. They have been active after the deposition of the Neogene deposits of the Limni–Histiaia basin, forming the Nileas depression during the Early–Middle(?) Quaternary.

During the Middle–Late Quaternary the NW–SE coastal fault zones that bound northern Evia have been the main active structures, truncating and uplifting the Nileas depression in a perched position in relation to the northern Gulf of Evia and the submarine basin on the Aegean side of the island. The present-day morphology of the depression, with an interior (floor) comprised of late Middle Pleistocene erosional surfaces, was shaped by erosion during this recent uplift.

In the above recent period, the fault zones that bound the Nileas depression apparently are characterised by low rates of vertical displacement, judging from their geomorphic signature. However, moderate earthquakes and focal mechanisms of micro-earthquakes inside the depression suggest that these fault zones may still be accommodating strain also today.

The intersection between the fault zone at the SE flank of the depression (PPFZ) and the active NW–SE Dirfys f.z. (DFZ) offshore Evia, presents striking morpho-structural similarities with the intersection of two fault zones with the same directions on the mainland (the Hyampolis f.z. and the presently active and seismogenic Atalanti f.z.). The fact that the latter intersection is known to have acted as a barrier to the 1894 rupture on the Atalanti fault zone, suggests that the PPFZ/DFZ intersection may play a similar role in the earthquake segmentation of the Dirfys fault zone.

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