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THE HYAMBOLIS ZONE: GEOMORPHOLOGICAL AND TECTONIC EVIDENCE OF A TRANSVERSE STRUCTURE IN LOKRIS (CENTRAL GREECE)

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ABSTRACT

Geomorphological and tectonic observations attest to the existence of a NE-SW fault zone transverse to the active zones in Lokris. The geometry of the 'Hyambolis fault zone' and preliminary results concerning its mode and timing of activity are presented and its role within the local and regional active tectonic grain is discussed. Moreover, this zone is placed in the context of a probable larger crustal discontinuity, the existence and significance of which are yet to be explored.

KEY WORDS: Neotectonics, geomorphology, morphotectonics, Hyambolis Fault Zone, Atalanti Fault Zone, Lokris, Central Greece

1. INTRODUCTION

Lokris is located in Central Greece, a domain that has been undergoing rapid extension of mean NNE-SSW direction since at least the Upper Pliocene (Philip, 1974, Rondogianni-Tsiambaou, 1984, Jackson and McKenzie, 1988 and many others). The region is characterised by an alpine nappe-pile structure, with overprinted neotectonic features in the form of sub-parallel WNW-ESE graben (Fig. 1), produced by normal or oblique-normal faulting and block rotation around horizontal and vertical axes (Westaway, 1991, Jackson, 1994 and others).

Geomorphological and tectonic observations, as well as more regional geological data, suggest the existence of an important NE-SW zone transverse to the active faults of Lokris, the 'Hyambolis fault zone' (HFZ, named after the ancient city of Hyambolis – Fig. 2). During the past 30 years, individual faults were mapped in various places along the HFZ -mainly at its NE part- by Maratos et al. (1967), Degardin (1972), Albandakis (1974), Rondogianni-Tsiambaou (1984), Sideris (1988, 1986) and Mettos et al. (1992). These were drawn as isolated structures each time, and usually without specific commentary; not in the context of a fault zone as proposed in this paper. Lemeille (1977) identified a set of NE-SW lineaments, on the landstrip that roughly corresponds to the HFZ and posed questions regarding their importance and age. Important reasons for the Hyambolis zone not receiving its due attention, are the lack of conspicuous features such as fault-plane outcrops, the fact that direct tectonic observations are possible on very few suitable cross-sections and its generally subdued geomorphic expression (compared to the neighbouring active zones).

In this paper, the preliminary results of a morphotectonic study of the HFZ are summarised, providing a first detailed picture of the geometrical characteristics of the Hyambolis zone as well as indications about the possible kinematic behaviour and the timing of operation of the individual constituent faults. Subsequently, the geometry of the HFZ is evaluated with respect to its possible mode of operation in the context of the regional tectonic regime and the issues raised by the existence of such a transverse fault zone in relation to the active WNW-ESE structures of the region are discussed.

2. THE NE PART OF THE HYAMBOLIS ZONE

A significant part of the Hyambolis zone is readily recognised as a major geological discontinuity, being a quite linear boundary between the alpine formations of the Chlomon mass and fluvio-lacustrine deposits of the Lokris basin (Fig. 2). In more detail, the individual faults that constitute the zone in its NE part were identified by their direct geomorphological expression in small and medium scale (1:5.000 / 1:50.000) topographic maps - namely the fault escarpments that can be observed on the NW slopes of Chlomon Mt.-, 1:33.000 airphoto analy-

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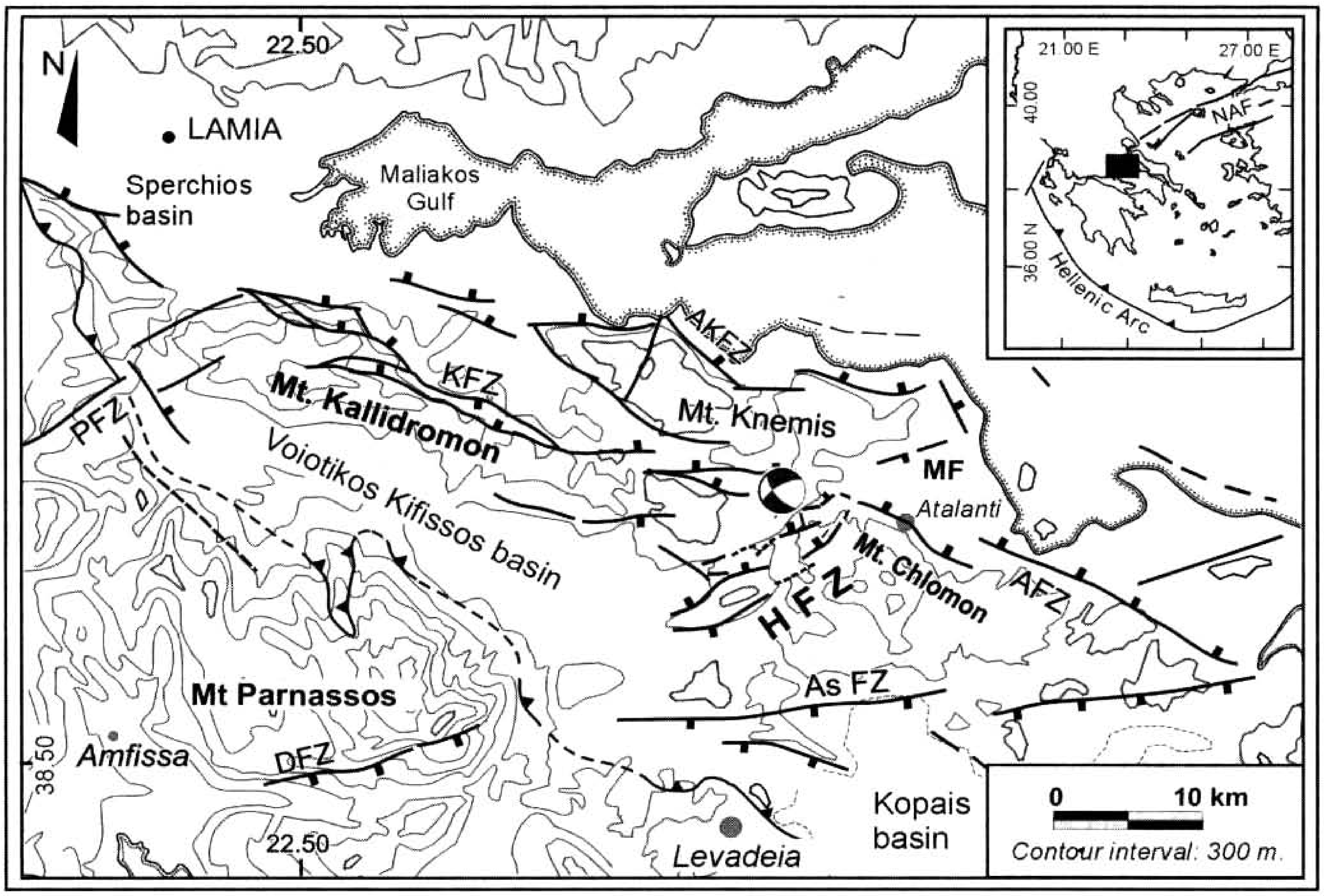

Fig. 1. Regional tectonic setting of Central Greece (modified from Richter et al., 1994, with additions from Ganas, 1997, Kranis, 1999, Kranis & Lekkas, 2000, and Palyvos, 2001). Thick hachured lines: normal faults and/or fault zones; thick lines with triangles: alpine thrusts. HFZ: Hyambolis Fault Zone, AFZ: Atalanti f.z., AKFZ: Arkitsa-Kammena Vourla f.z., KFZ: Kallidromon f.z., AsFZ: Aspledon f.z., PFZ: Pavliani f.z., DFZ: Delphi f.z., MF: Megaplatanos fault. Focal mechanism solution from Hatzfeld et al.(1999).Rectangle shows location of Fig. 2.

sis, lithological contrasts, their effect on drainage behaviour (stream alignment, across-fault differences in valley morphology), and field observations (detailed discussion in Palyvos, 2001).

The NE part of the Hyambolis zone can be subdivided in two main branches, those of Lygdeika - Ag. Sotira (faults Y5a/b and Y4 in Fig. 2) and Korakolithos - Karagiozis (Y6 and Y7), the combined effect of which is responsible for the morphological transition from the Chlomon Mt. to the Lokris basin. These two branches, together with faults of the Atalanti zone, are evidently responsible for the geometry of the Roda volcano-sedimentary sequence occurrence, which has a quite characteristic 'reverse Gamma' shape in map view.

On the Lygdeika-Ag. Sotira branch, fault Y5b (Fig. 2) was mapped in detail by Sideris (1986, 1988) as the contact between the Roda volcaniclastics and the Chlomon carbonates. It has produced an escarpment up to 300 m high, which is today in a retreated position (even so, steep slopes are preserved at places). No geomorphic evidence of recent (Holocene) ground ruptures was identified at its base. The escarpment is dissected by drainage networks that are in a youthful stage on the uplifted block, with deep 'V' valleys carved into an old planation surface - morphology indicative of Middle to Late Pleistocene fault activity. In part, this could also be due to lowering of their local base level by differential erosion across the fault (the hanging-wall volcano-sedimentary formations are more erodible, and a wide flat-floored valley has formed).

At its prolongation towards the NE, fault Y5b probably splays into two branches that bound the mountain-peak of Roda, corresponding to characteristic (albeit smoothed) knickpoints on the Roda ridgeline. Towards the SW, the escarpment of Y5b is characterised by a systematic decrease in height, and from a point on, although the fault can be continuously traced as a distinct lineament (fault Y5a), the polarity of the relief associated with it is reversed, with Skarfi (645 m) on the NW side and elevations 85 m lower on the SE. Farther SW, the relative relief across Y5a becomes as low as 20 m. This behaviour cannot be attributed to exogenetic processes operating after the fault-block movements (e.g. stream erosion), because on the SE side of faults Y5a and Y5b the pre-faulting relief is well preserved (an erosional surface of probable Miocene age, extensive remains of which can be seen as interfluves of the streams now dissecting it – Fig. 2). It can only be logical to assume that

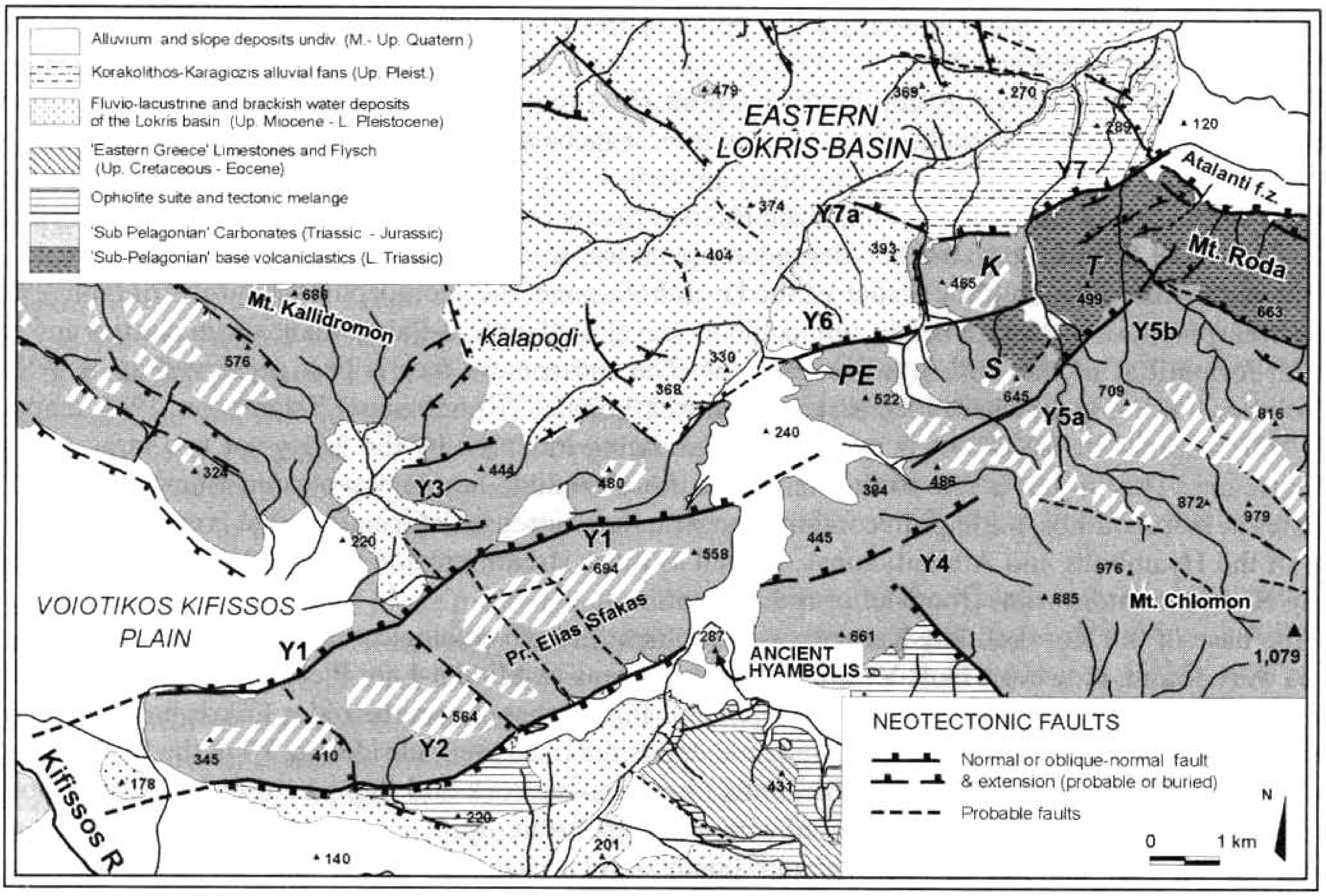

Fig. 2. Geological– neotectonic sketch map of the area crossed by the HFZ. Geology after Maratos et al. *(1965, 1967), Sideris (1986), Kranis (1999) and Palyvos (2001). Faults from Kranis (1999) and Palyvos (2001). Thick white lines indicate remains of the Chlomon Miocene relief.*

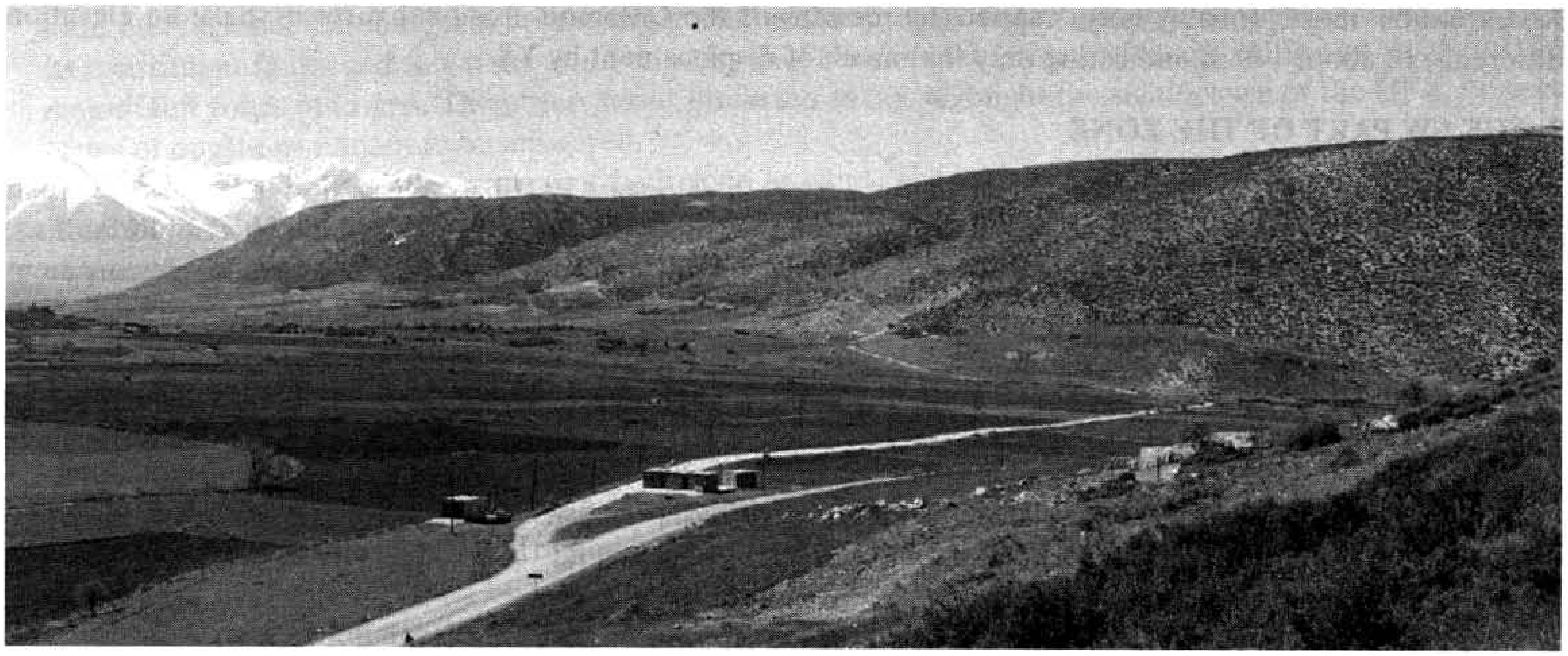

Fig. 3. View of the Hyambolis fault escarpment (fault Y2), and the erosional surfaces that constitute the top of the Pr. Elias Sfakas horst. The fortified hill of ancient Hyambolis is visible at the right hand side of the photograph.

this palaeo-relief (the 'Chlomon surface') extended into the area of Pr. Elias and Skarfi (the 'flat' hilltop of Skarfi is probably a remnant of this relief), so it can be utilised as a datum whose vertical displacements depict the deformation caused by the faults since its formation.

The Chlomon surface is tilted predominantly towards the SW (rather than towards the SE), a fact that points to influence primarily by the Atalanti zone (AFZ footwall backtilt). The observed displacement along fault Y5a/b could imply that it is a structure predating the formation of the Chlomon Late(?) Miocene relief (hence the – practically- zero offset at its SW end), and has hosted later movements of increasing magnitude towards the active Atalanti fault zone, accommodating the uplift of the Chlomon block (which is uplifted by AFZ, and bounded by HFZ on its NW side).

Farther SE, Y5a steps over to the Ag. Sotira fault (Y4) that corresponds to a smooth slope of increased profile concavity, without morphological discontinuities at its base (only gentle saddles between it and the hills to the NW). Being difficult to attribute to other processes (e.g. fluvial erosion) or differential erosion (it is developed exclusively in carbonates), and, given the fact that is in good alignment with the general strike of the Hyambolis zone, it is inferred to be the –degraded- geomorphic expression of a fault belonging to it.

In the Karagiozis-Korakolithos branch of the Hyambolis zone, the geomorphic 'signature' of fault Y7 is a 3.8 km long escarpment of moderate height -up to 150 m- developed on Sub-Pelagonian volcaniclastics and carbonates, with formations of the Lokris basin against it. The escarpment face is best preserved at its WSW part (Korakolithos – K in Fig. 2) where it consists of alpine carbonates (Rondogianni-Tsiambaou, 1984, mapped this part of Y7), whereas its ENE part is more degraded, being indented by the valleys of two large and several smaller streams. This in part is due to the somewhat more erodible lithology (volcaniclastics) compared to the carbonates at Korakolithos, perhaps in combination with more intense deformation that is expected at the intersection of the Hyambolis and Atalanti zones, as well as more stream erosion potential the closer we get to the uplifting Roda mountain front (footwall of the Atalanti fault).

At the base of the Korakolithos-Karagiozis escarpment, no morphological indications of Holocene ground ruptures were found. However, fault Y7 affects a quite extensive Middle-Late Pleistocene fluvio-torrential formation (Korakolithos-Karagiozis alluvial fan deposits – Fig. 2) that covers the older Lokris basin fill in front of the escarpment (from which it has been derived, and deposited in an area subsided by Y7 in the M.-L. Pleistocene – Palyvos, 2001). The tectonic nature of the contact between bedrock and these Late Pleistocene deposits was verified at a small roadcut where it is exposed with a low apparent dip.

Fault Y6 has been mapped by Rondogianni-Tsiambaou (1984), as a distinct boundary between formations of the Lokris basin and the alpine carbonates of Pr. Elias. The latter are intensely tectonised along the fault, favouring the development of small strike valleys that have masked the original escarpment morphology. At the longitude of Pr. Elias, the fault is associated with a minimum of 200 m vertical displacement, which decreases rather abruptly to the ENE upon crossing a small transverse fault bounding Korakolithos to the W. Skarfi and Korakolithos -most probably both 'capped' by remains of the Chlomon erosional surface-, have an elevation difference of about 140 m, indicating only that much of displacement by Y8.

3. THE SW PART OF THE ZONE

Conspicuously in alignment with the Hyambolis zone, the elongate Pr. Elias Sfakas Mt. is a landform shaped by NE-SW normal faults on either side – a horst, uplifted by the Souvala fault (Y1) and the Hyambolis fault s.s. (Y2) (Fig. 3). Fault Y1 is partly visible as a lineament in air-photographs, at the base of a 8.8 km long escarpment of considerable steepness and 300 m max. height, exclusively developed on alpine carbonates. The presence of the fault is also suggested by the development of an elongate doline along its strike, as well as the attraction of small streams that follow the weakened zone of fractured carbonates. Again, no slope disruptions indicating recent ground ruptures were observed at the base of the escarpment.

Maratos et al. (1967) and Albandakis (1974) mapped smaller synthetic and antithetic faults paralleling Y1 (area Y3), which bound elongate occurrences of the Lokris basin deposits. One such fault was directly observed at a small outcrop, juxtaposing basement carbonates against Early Pleistocene deposits of the Zeli formation (Ioakeim & Rondogianni-Tsiambaou, 1988).

Fault Y2 has equally well expressed morphology as Y1, the 7.5-km long Hyambolis escarpment (Fig. 3), which follows a NE-SW course on its NE part and subsequently bends to an E-W direction (a behaviour seen at the SW tip of Y1 also). Field evidence (outcrops where splays of the fault were seen affecting Early Pleistocene formations, but also somewhat younger slope deposits), attest to Y2 being a neotectonic fault with activity in the M. Pleistocene and perhaps early Late Pleistocene. Morphological indications of ground ruptures younger still were not observed.

A characteristic feature of the Pr. Elias Sfakas horst is its staircase morphology oblique to the Hyambolis zone, lowering towards the W. Two distinct –albeit gentle– "steps" separate remains of erosional surfaces that constitute the top of the horst. The steps were found to be the product of NW-SE faults that have displaced what was once a single planation surface, probably the same relief as in Chlomon, Skarfi and Korakolithos. These faults may have acted as compartmental en-echelon structures, dividing Pr. Elias Sfakas into three "mini-blocks" that were subjected to differential vertical displacements during the operation of the Hyambolis zone.

4. DISCUSSION AND CONCLUSIONS

The Hyambolis fault zone can be associated with regional tectonic, geomorphological and geological characteristics. HFZ was found to be a linear SE boundary for the present occurrences of the Lokris basin fill: all the contacts between the basin deposits and alpine rocks were found to be tectonic, i.e. NE-SW to ENE-WSW, NW-dipping faults belonging to the zone.

As far as the active tectonic fabric is concerned, the HFZ is evidently a boundary to the Kallidromon and Atalanti fault zones, readily discernible in small-scale maps or satellite images as a limit to their geomorphic expression (the Kallidromon range and the Roda/Chlomon mountain). More specifically, the Atalanti zone cannot be securely traced within the Lokris basin (e.g. Ganas, 1997, Ganas et al., 1998), and recent studies (Pantosti et al. 2001, Palyvos, 2001) identify its WNW termination as being distinctly abrupt, corresponding to a large geomorphic and lithological 'step'. This step coincides exactly with the intersection of AFZ and HFZ (more specificaly, the Karagiozis fault - Y7). Upon intersecting Y7 the Atalanti fault exhibits a dramatic deficit in long-term slip towards the NW, being associated with only minor escarpments in the Lokris basin. The alpine formations uplifted in the Roda footwall completely disappear NW of Y7, where only Plio-Pleistocene formations can be seen, at much lower elevations.

A structure possibly related to the prolongation of the HFZ towards the NE could be the Megaplatanos fault (MF in Fig. 1), proposed by Ganas (1997). This fault has no direct geomorphic expression, but it has been located under the recent deposits of the plain by geophysical investigations (Tz. Memou, IGME internal report) and coincides with the linear NW boundary of the Atalanti plain, which is also a limit for the Knemis mountain range (sensu lato). In Ganas & White (1996), the Megaplatanos fault is drawn longer than in Ganas (1997), extending along the HFZ, as a normal fault downthrowing its SE block, that 'bounds and predates the AFZ'.

The SW part of the HFZ and its probable prolongation towards the SW is related to an important regional geomorphic feature. That is to say, the HFZ, together with the (partly buried) "Aspledon fault zone" (AsFZ in Fig. 1 – discussed in Palyvos, 2001), define a triangular-shaped uplifted area which constitutes the boundary between the Kopais and V. Kifissos basins (the Kifissos river is characteristically restricted there to a narrow valley).

All the aforementioned point towards the realisation of the existence of a fault zone that participates in the local and regional tectonic grain both actively and passively, in the sense that it both hosts tectonic episodes on its constituent faults and functions as a boundary that controls the propagation of faulting on the WSW-ENE major fault zones in Lokris. The observations discussed so far, highlight the significance of the HFZ; however a series of questions remain to be answered.

A first question regards the type of fault zone at hand. The series of NE-SW to ENE-WSW, left-stepping Hyambolis faults constitute a ~2.5 km wide deformation zone, of 17 km visible length. This zone is intensely segmented, with the lengths of the constituent faults not exceeding 5 km. The overall pattern of the faults within the deformation zone could be representative of a structure that accommodates considerable proportion of strike-slip movement. More specifically, such configuration of over- or underlapping left-stepping faults, oriented oblique to the primary deformation zone they belong to, is found in brittle structures where the amount of strike-slip offset is at least equal to dip-slip (McCoss, 1986, Tron and Brun, 1991, Richard et al., 1995). Moreover, the results of a microseismicity survey in central Greece showed that a good quality focal mechanism located at the SE tip of the Lokris basin (and probably related to fault Y6 (Figs 1 and 2) is almost pure dextral strike-slip (mechanism # 180 in Hatzfeld et al., 1999). For these reasons, we tend to believe that the overall kinematics of the HFZ could be oblique-slip to strike-slip, accommodating significant proportion of dextral offset. This doesn't necessarily mean that the kinematics of every constituent fault is strike-slip: it is well known that zones of this type may comprise series of en echelon normal faults (extensive analysis in Biddle & Christie-Blick (Eds.), 1985).

A second important point pertains to the timing of activity of the Hyambolis zone. Abundant evidence speaks of M. Pleistocene deformation, reaching into the Late Pleistocene at some faults (e.g. Y7 and probably Y1 and Y2). This immediately classifies the HFZ into the active tectonic features. The fact that the morphological expression on many constituent faults is subdued and the absence of geomorphological indications of marked Holocene earthquake activity can be due to a number of reasons (or combination of them), such as: (i) a significant, if not most, part of the deformation during the Late Pleistocene and Holocene is accommodated through creep, and not during morphogenic earthquakes (Caputo, 1993); moreover, recent research has shown that in this type of tectonic environments earthquake activity and fault lengths can be significantly smaller than in others, as for instance orthogonal rifting (Clifton and Schlische, 2001) (ii) the slip rate of the zone is quite low (the neighbouring AFZ, which is evidently more active, has a low slip rate already (e.g. Ganas, 1997, Pantosti et al., 2001), and (iii) the zone is intensely segmented and the overall strain pattern can be expressed through minor tremors (M<2), isolated or in clusters. This has been the case for another transverse fault zone in the region, parallel to the HFZ, the Pavliani fault zone (PFZ in Fig. 1), the activity of which was identified through local microearthquake networks (Burton et al., 1995) and neotectonic mapping (Kranis, 1999, Kranis & Lekkas, 2000).

A major issue arising is whether the HFZ is just a 17-20 km-long structure found only in Lokris and N. Boeotia, or it is part of a larger, crustal-scale structure. This question was posed by Kranis (1999) and the landstrip that corresponds to the HFZ was found to lie on the trace of NE-SW lineament (arguably a deformation zone) that includes the Delphi fault zone (DFZ in Fig. 1) the ENE-WSW neotectonic fault proposed by Fytrolakis et al. (1988), which affects the main stretch of Nileas river in N. Evia. The location and trend of this large-scale zone could suggest that it might be somehow related to the westward propagation/extrusion of the Anatolian block into the Aegean region (e.g. Jackson, 1994). The geometric and kinematic character of the HFZ might be considered, to some degree, representative of the overall character of this crustal-scale structure; should this be the case, it may function as the SE boundary of a broad shear zone that hosts rigid to semi-rigid block rotations around horizontal and vertical axes (Jackson, 1994). The NW boundary will then approximately coincide with the PFZ (Kranis and Lekkas, 2000) and the rotating blocks are represented by the elongated WNW-ESE mountains (Mts. Kallidromo and Knemis) within Lokris.

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