



Palaeoseismological investigation of the Tyrnavos Fault (Thessaly, Central Greece)

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Abstract

A palaeoseismological investigation has been carried out along the Tyrnavos Fault, an ESE–WNW trending, north-dipping normal fault representing one of the major tectonic structures bordering the Late Pleistocene–Holocene Tyrnavos Basin, Northern Thessaly, Central Greece. According to geological, structural, morphotectonic and geophysical researches, the Tyrnavos Fault has been geometrically and kinematically characterised as a typical “Aegean-type” active fault. Six trenches have been excavated and logged in detail in order to quantify the most important seismotectonic parameters, like the characteristics of past earthquakes, their ages, the elapsed time from the last event, the short-term slip-rate and the mean return period. Several samples have been also collected for absolute dating that has been performed with different techniques like TL, OSL and AMS. Sedimentological, structural and chronological data document a Late Pleistocene to Holocene morphogenic activity of the Tyrnavos Fault, which is characterised by vertical co-seismic displacements of 20–40 cm and possible recurrence interval of 2–2.5 ka. The comparison between the estimated short-term (ca. 0.05–0.1 mm/a) and long-term (0.1–0.2 mm/a) slip-rates and the elapsed time from the last earthquake suggest the occurrence of a possible seismic gap along the Tyrnavos Fault. Due to the peculiar position of the selected site at the termination of the fault scarp in the bedrock, the lateral variability in morphogenic behaviour of an active fault is also observed. The location of the fault within a highly populated region and the proximity to the third largest town of Greece (Larissa) increases the seismic hazard of the area.

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1. Introduction

The Aegean Region represents the area with the most important seismicity of the Mediterranean realm with a historical earthquake record of more than 2500 years. It has been estimated that the mean occurrence

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frequency of strong ($M \geq 6$) earthquakes is about one event every 1.7 years (Papadopoulos and Kijko, 1991). Although adequate historical documentation exists for about 500 strong earthquakes (e.g. Papazachos and Papazachou, 1997), from a seismotectonic point of view only few of them were clearly correlated to well-defined tectonic structures (Pavlidis and Caputo, 2004): in contrast to the large number of earthquakes occurring within the Aegean Region, only a small fraction of them can be associated to specific seismogenic faults (FAUST, 2001). Possible reasons for this discrepancy are the incompleteness of the historical catalogues (e.g. Stucchi et al., 2001) and the fact that not all the earthquakes can be defined as

‘morphogenic’ ones (sensu Caputo, 1993a) that is capable to produce immediate, localised and permanent effects at the Earth’s surface. Accordingly, the human perception and the consequent possibility to identify the seismogenic structure are strongly reduced. In addition, recent palaeoseismological researches in Greece (Pavlidis, 1996; Chatzipetros et al., 1998; Caputo and Helly, 2000; Koukouvelas et al., 2001) have documented that the return period of particular faults or fault segments is commonly longer than several hundred years and sometimes even longer than some thousand years.

During the last 10 years, a dedicated and multi-disciplinary research, based on palaeoseismological,

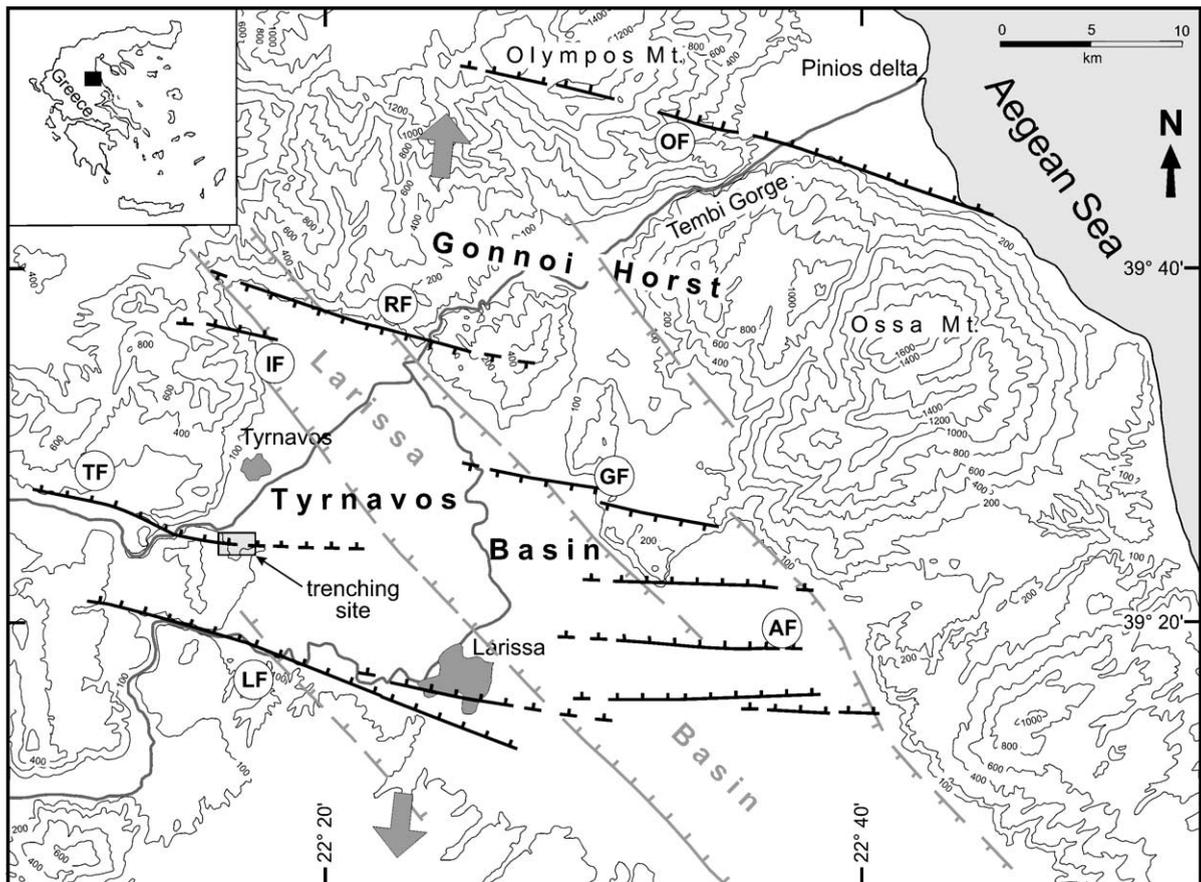


Fig. 1. Simplified tectonic map of eastern Thessaly. Black lines: active structures affecting the area since Middle Pleistocene associated to the E–W trending Tyrnavos Basin and Gonnoi Horst. Grey lines: major Pliocene–Early Pleistocene faults bordering the Larissa Basin. Barbs on the downthrown side of the faults. TF=Tyrnavos Fault; RF=Rodià Fault; IF=Ligarià Fault; GF=Gyrtoni Fault; LF=Larissa Fault; AF=Asmaki Fault; OF=Omolio Fault. Large grey arrows represent the active stress field affecting the area (Caputo, 1990).

archaeological and geophysical methods, was carried out in eastern Thessaly, Central Greece, as an effort of a holistic approach to the problem of active faulting identification (Caputo, 1990, 1994, 1995; Helly et al., 2000–2001, 2003; Caputo and Pavlides, 1993; Caputo et al., 1994). Accordingly, all major active faults have been already recognised, while the Late Quaternary activity and the principal seismogenic parameters have been qualitatively evaluated (Fig. 1). Following previous investigations, which include structural geology, morphotectonic mapping, microtopographic surveys, air photos and satellite imageries interpretation (Caputo, 1993b), ground penetrating radar profiling (Caputo and Helly, 2000) and electric resistivity tomographies (Caputo et al., 2003), the present research is an attempt of quantifying the most important seismotectonic parameters of the Tyrnavos Fault based on a palaeoseismological approach. In particular, our aim is to document the last seismic events occurred along this active structure, their possible ages, the mean return period and the elapsed time from the last earthquake.

2. Geological and tectonic framework

The tectonic architecture of Thessaly is the result of several deformational phases, though the present-day morphology of the region is basically associated to the Neogene tectonic inversion caused by the post-orogenic collapse of the External Hellenides (Caputo and Pavlides, 1993). In Thessaly, NE–SW extension (Late Miocene–Early Pleistocene) generated the so-called basin-and-range-like system (Caputo, 1990) consisting of a series of horsts and grabens bordered by NW–SE trending faults. In the study area, the major morphological and tectonic imprint caused by this crustal stretching event was the creation of the Larissa Basin (Fig. 1). The 60-km-long NW–SE trending Larissa Plain roughly coincides with this major tectonic structure.

During this extensional phase, the palaeogeography of the Larissa Plain was characterised by fluvial and mainly lacustrine conditions (Caputo et al., 1994) that persisted till Villafranchian. A permanent hydrographic network started forming only afterwards, associated to the entrenching of the Tembi Gorge

across the Olympus and Ossa Mountains, the generation of the Pinios delta (Faugères, 1977) and the permanent water outpouring from the Larissa Basin (Fig. 1).

After a period of quiescence, a new roughly N–S extension affected the Aegean Region (Fig. 1; Caputo, 1990). This deformational phase started during the Middle(?) to Late Pleistocene and it is still active as can be deduced by the recent seismicity of the area (e.g. Ambraseys and Jackson, 1990; Papazachos and Papazachou, 1997). As a consequence of the new geodynamic conditions, a new system of normal faults was generated mainly trending E–W to ESE–WNW (Fig. 1). Although inherited extensional structures were locally or partially reactivated with an oblique-slip kinematics (e.g. Caputo, 1993c), most of the new faults cut-across pre-existing ones. At that time, the Tyrnavos Basin started developing causing the shift of the depocenter in the northern sector of the Larissa Plain (Caputo et al., 1994). From a tectonic point of view, the basin is bordered by few major faults, namely the Rodià and Gyroni south-dipping faults, to the north, and the Tyrnavos and Larissa north-dipping faults, to the south (Fig. 1).

The Tyrnavos Fault is one of the major active structures bordering the homonymous basin. It mainly affects the Triassic crystalline limestone of the Pelagonian basement but also Pliocene and Quaternary deposits (Caputo, 1990). The general trend is E–W, though it shows a slightly right-bending geometry. The well-defined fault trace has been mapped in detail for more than 12 km (Caputo, 1993b). Based on remote sensing techniques, it can be followed eastwards across the northern Larissa Plain (dashed line in Fig. 1) with a possible maximum length of about 20 km.

Both ‘fault-generated landforms’ and ‘fault-related landforms’ have been documented (Caputo, 1993b). Among the former are bedrock fault scarps, striated fault planes and fault scarps in alluvium, while the latter are represented by a valley dammed by the fault and by faulted and uplifted Late Pleistocene alluvial fans.

3. Trenches investigation

All along the eastern sector of the Tyrnavos Fault trace, a free face is exposed (Fig. 2a). Locally,

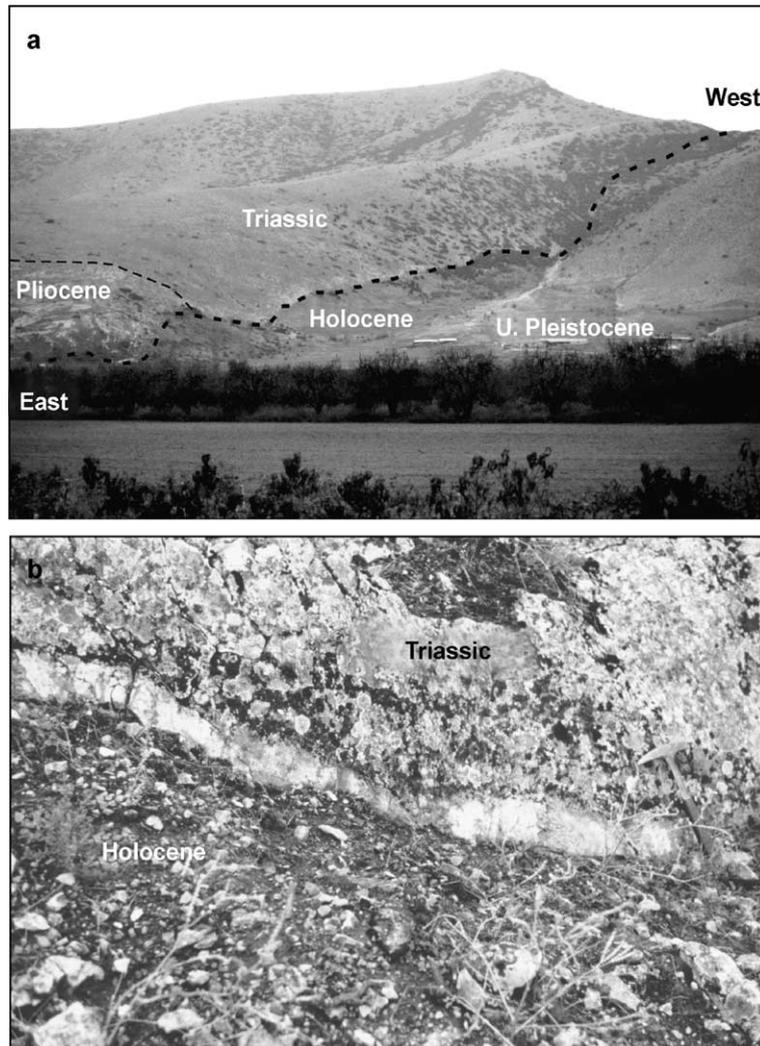


Fig. 2. (a) Morphological escarpment along the eastern sector of the Tyrnavos Fault. (b) Emergent slip surface along the eastern sector (Caputo, 1993b). Hammer for scale.

it continuously extends for several hundreds of metres along the strike of the fault with a relatively constant height of about 5–10 cm (Fig. 2b). Above this lowermost free face is a second strip with similar characteristics of continuity and uniformity. Its height is between 5 and 15 cm and it has a surface much less weathered than the above bedrock, but darker (viz. more weathered) than the lower strip. The ‘freshness’ of the bedrock cropping out along these free faces (especially the lower one), the lack of weathering on them in contrast to

the bedrock above them, the plurimetric length along strike of these surfaces, the almost constant height and their continuity along the fault denote a common and very recent origin (Caputo, 1993b). Based on this morphotectonic evidence, we selected this site along the eastern sector of the Tyrnavos Fault for our palaeoseismological investigation (Figs. 3 and 4).

The footwall block is here characterised by Late Pleistocene alluvial–colluvial sediments resting in paraconformity on Pliocene carbonate deposits that

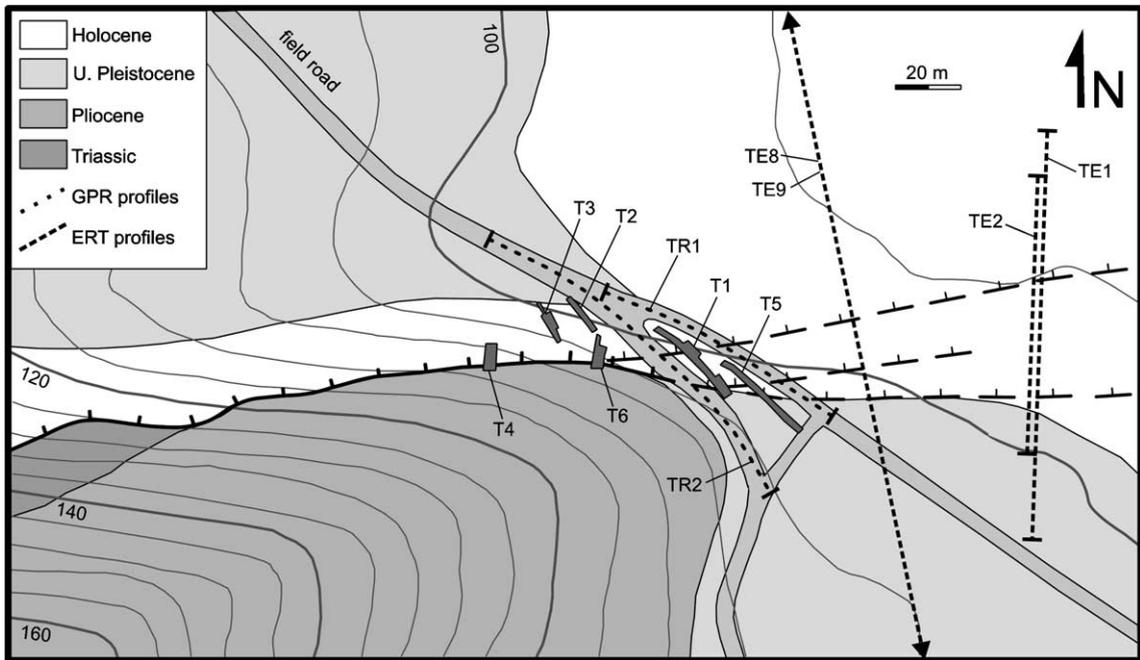


Fig. 3. Geological and structural map of the investigated site with the location of the excavated palaeoseismological trenches (labelled T#) showing the fault trace (dashed when inferred). The traces of the electrical resistivity tomographies (TE#, [Caputo et al., 2003](#)) and of the ground penetrating radar profiles (TR#, [Caputo and Helly, 2000](#)) are also shown.

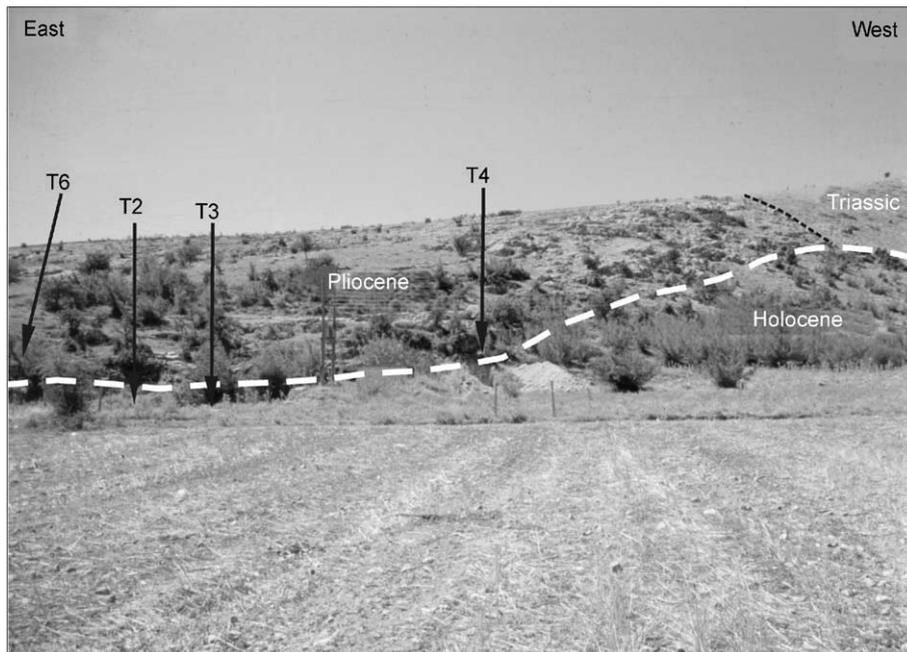


Fig. 4. Frontal (i.e. southward) view of the eastern sector of the Tynavos Fault with the location of the palaeoseismological trenches.

partly overlap, with a strong angular unconformity, the Triassic limestone. In contrast, the hanging-wall block is covered by (Late Pleistocene–)Holocene alluvial–colluvial materials of local origin.

Another reason for selecting this site for palaeoseismological trenching is the lateral termination of bedrock outcrops along the fault trace. In fact, while a cumulative fault scarp that forms after several morphogenic earthquakes remains evident for a long time in the bedrock, co-seismic free faces generated in loose deposits may quickly disappear due to both natural and anthropogenic actions.

Indeed, the eastwards continuation of the fault trace across the Larissa Plain has been inferred from the analysis of air photos and detailed topographic maps (scale 1:5000) showing a large scale 6–8 m high escarpment separating two sectors of the alluvial plain (Caputo, 1993b). However, due to continuous superficial anthropogenic manipulation no clear mesoscale escarpment can be observed but only a 5° dipping slope several tens of metres wide. Both ground penetrating radar profiles (Caputo and Helly, 2000) and electrical resistivity tomographies (Caputo et al., 2003) confirm the occurrence of different fault segments at a very shallow depth.

Following the above premises, we excavated six palaeoseismological trenches (Fig. 3). Two trenches were dug across the contact zone between the footwall Pliocene limestone and the loose Holocene deposits of the hanging-wall (trenches T4 and T6). The contact zone is associated to a bedrock escarpment. Two other trenches were entirely excavated across the smooth escarpment formed in the relatively soft Late Quaternary alluvial sediments (trenches T1 and T5). Finally, two other trenches were excavated within the Holocene deposits of the hanging-wall block in order to look for secondary basin-ward faults (trenches T2 and T3), which are common for normal faults in similar tectonic environments (e.g. Stewart and Hancock, 1990; Caputo, 1993c). Indeed, if this phenomenon has occurred along the Tyrnavos Fault, older morphogenic earthquakes would be completely ignored if only the principal contact zone is investigated. Therefore, the slip-rate and the mean return period would be underestimated with all consequences in terms of seismic hazard assessment.

As expected, the three types of trenches excavated in different locations with respect to the fault scarp show diverse results and allowed us to better evaluate the variability in morphogenic behaviour along a seismogenic structure like the Tyrnavos Fault.

Detailed microstratigraphic and structural analyses have been performed for each trench on both walls and they show coincident results. Accordingly, in Figs. 5–8, we represent only one side of each trench.

Slight variations of the matrix colour, of the size and distribution of clasts and locally observed fining upwards gradation allowed to define the different sedimentary units as labelled in Figs. 5–8. At this regard, the incipient pedogenesis observed on the top of the strata confirms the existence of temporal hiatuses in the sedimentary record. Note that labelling of sedimentary units is independent in each trench. In the following, the microstratigraphic logs will be first described, while the observed tectonic features and especially their relationships with palaeo-earthquakes will be discussed in a subsequent section of the paper.

3.1. Trench T4

This is the westernmost trench and it is N–S oriented, almost orthogonal to the local trend of the fault trace (Fig. 3) represented by more than 1-m-high scarp (Fig. 4). The trench was nearly 3 m wide and more than 10 m long, though the detailed log has been performed only for the 8 m closer to the contact zone (Fig. 5). The footwall block consists of Pliocene–Early Pleistocene oolitic calcarenite, with a subhorizontal setting and medium-to-thick layers that are locally welded together (unit *P*, in Fig. 5). These deposits were probably formed in a beach environment along the palaeo-coast of the Villafranchian Thessalian lake (Caputo, 1990). The trench intersects the fault zone and it has been excavated 2–3 m within the bedrock of the footwall block, locally softened and parted by intense vertical fracturing (faults F1 to F3, in Fig. 5). Close to the main fault plane (F4, in Fig. 5), fractures are well developed, well connected and extending much deeper. Indeed, at about 3 m depth from the top surface, fractures are open up to several centimetres and from one of these cool air blows out during the hot summer of Thessaly thus documenting underground circulation.

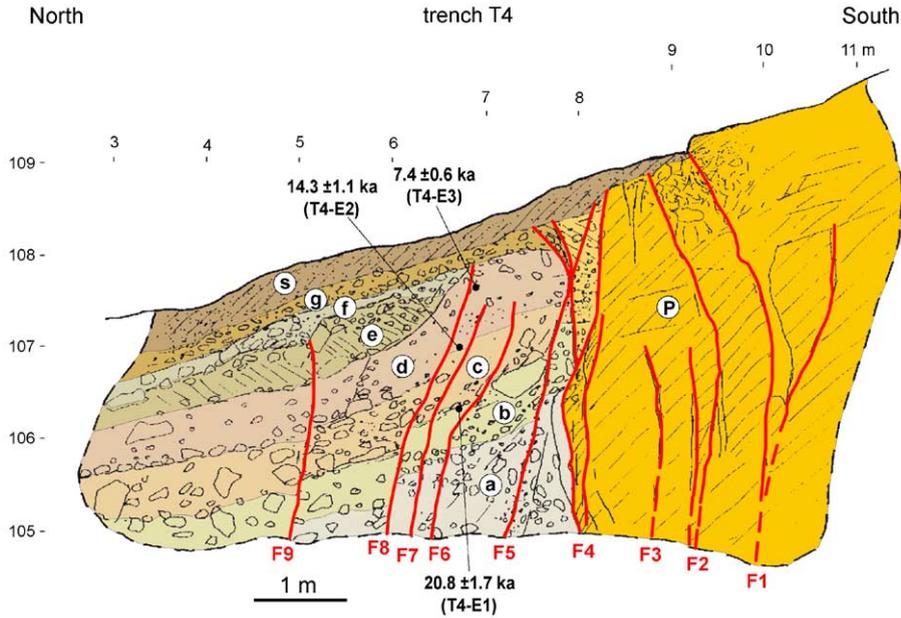


Fig. 5. Log of trench T4 (eastern wall) excavated across the tectonic contact between Pliocene–Lower Pleistocene carbonate and the latest Pleistocene–Holocene eluvial and colluvial deposits. Letters within white circles refer to sedimentary units while faults are numbered (F#). Black circles represent dated samples (see Table 1).

The sequence exposed in the hanging-wall block consists of alluvial and colluvial deposits forming at least six sedimentary units (units *a–g*, in Fig. 5). The

composition of all the detrital clasts is fairly uniform (i.e. carbonate). Clasts are from millimetres to decimetres in size and generally subangular to angular

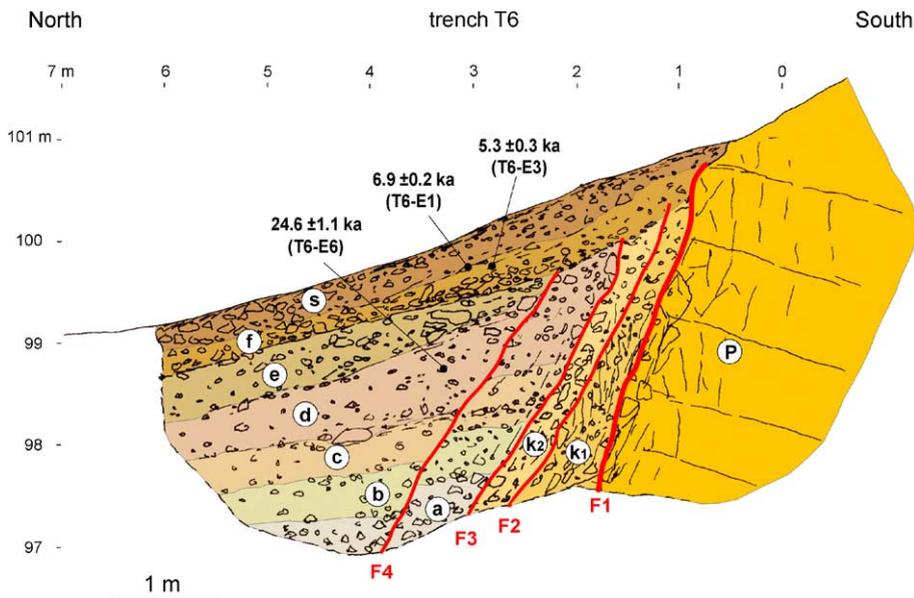


Fig. 6. Log of trench T6 (eastern wall) excavated across the tectonic contact between Pliocene–Lower Pleistocene carbonate rocks and the latest Pleistocene–Holocene eluvial and colluvial deposits. Symbols as in Fig. 5.

in shape. Matrix is commonly abundant and only locally the texture is clast-supported. The layers dip 15–20° northwards and their thickness range from 25 cm to more than 1 m, locally showing a wedge-shape geometry.

The described sequence is covered by a developing brown soil consisting of relatively organic-rich fine-grained material with scattered subangular carbonate clasts (unit *s*, in Fig. 5). The soil, which represents the present-day pedogenic layer, is about 30 cm thick, progressively thinning between faults F4 and F1 and disappearing further to the South.

3.2. Trench T6

Trench T6 is oriented N10°E, roughly orthogonal to the local trend of the fault trace, here emphasised by a scarp similar to that observed in trench T4, though fairly more weathered. The trench is nearly 3 m wide and about 10 m long, but the detailed log has been performed only for the 6 m closer to the contact zone (Fig. 6). Again, the bedrock of the footwall block consists of Pliocene–Early Pleistocene oolitic calcarenite dipping about 15° to the south (unit *P*, in Fig. 6). Fracturing within the bedrock is here less intense than in trench T4 and consequently the medium-to-thick layering of the carbonate sediments is more evident. On the other hand, the contact zone observed in trench T6 is much sharper than in T4 and dips 70–75° northwards. The cataclastic process appears much more localised and thus more intense. As a consequence, the mechanical process of fracturing of the bedrock has generated a real fault-gouge generally fine-grained and with relatively abundant matrix (unit *k*₁, in Fig. 6) delimited by faults F1 and F2. Locally and especially in the deepest sector of the trench, a well-defined cleavage can be observed, consisting of numerous shortly spaced shear-planes oriented either parallel to the main contact surface as well as subvertical that we interpret as Riedel structures synthetic to the dip-slip normal displacement occurring along the fault. Unit *k*₁ is about 80–100 cm thick at 3 m depth and it progressively thins upwards till disappearing near the surface. In direct contact with this fault-gouge, there is a shear zone mainly consisting of Quaternary materials and characterised by the isorientation of the long axis of the irregularly shaped pebbles (unit *k*₂, in Fig. 6).

The materials belonging to the hanging-wall block are represented by organised clastic deposits dipping 15–20° to the north, separated in at least six sedimentary units (units *a–f*, in Fig. 6). The lithology of clasts is similar to that observed in trench T4. Particles are from millimetres to few decimetres in size and subangular to angular in shape. Layers show more clearly a fining upwards gradation. Texture is commonly matrix-supported though locally the coarse-grained lower portion of the layers is clast-supported. The clay–silty matrix is yellowish to light brown in colour. Single strata have a thickness varying from 30 cm to slightly more than 1 m, while a progressive thickening seems to occur toward the shear zone (viz. wedge-shape geometry). The typical organic-rich brown soil (unit *s*, in Fig. 6) overlies the colluvial succession and in the footwall block is strongly reduced to few centimetres quickly disappearing south of fault F1.

3.3. Trench T1

In contrast to T4 and T6, trench T1 has been completely excavated within the alluvial deposits across the smooth escarpment aligned with the fault trace observed along the bedrock–sediments contact (Fig. 3). The trench is 35 m long, 1.5–2.5 m deep and 1–3 m wide (Fig. 7). Due to the occurrence of a country road, the trench is slightly curved and oriented between N56°W and N38°W, thus oblique to the trace of the fault (Fig. 3).

Seven alluvial layers are distinguished (units *a–e*, in Fig. 7). It is noteworthy to say that the whole sedimentary succession has a general northward dip progressively increasing with depth from about 5° to almost 30° thus generating a fan-shape geometry. By considering that these values likely correspond to apparent angles due to the orientation of the trench, the general dips are certainly higher.

In the lowermost and southernmost section, the trench shows the oldest deposits consisting of prevailing yellow-whitish clays belonging to the Pliocene–Early Pleistocene lacustrine deposits (unit *P*, in Fig. 7). These materials represent a facies laterally equivalent of the previously described oolitic calcarenite but formed in deeper water conditions (Caputo, 1990). The top surface of these deposits is subhorizontal in the southernmost section of the

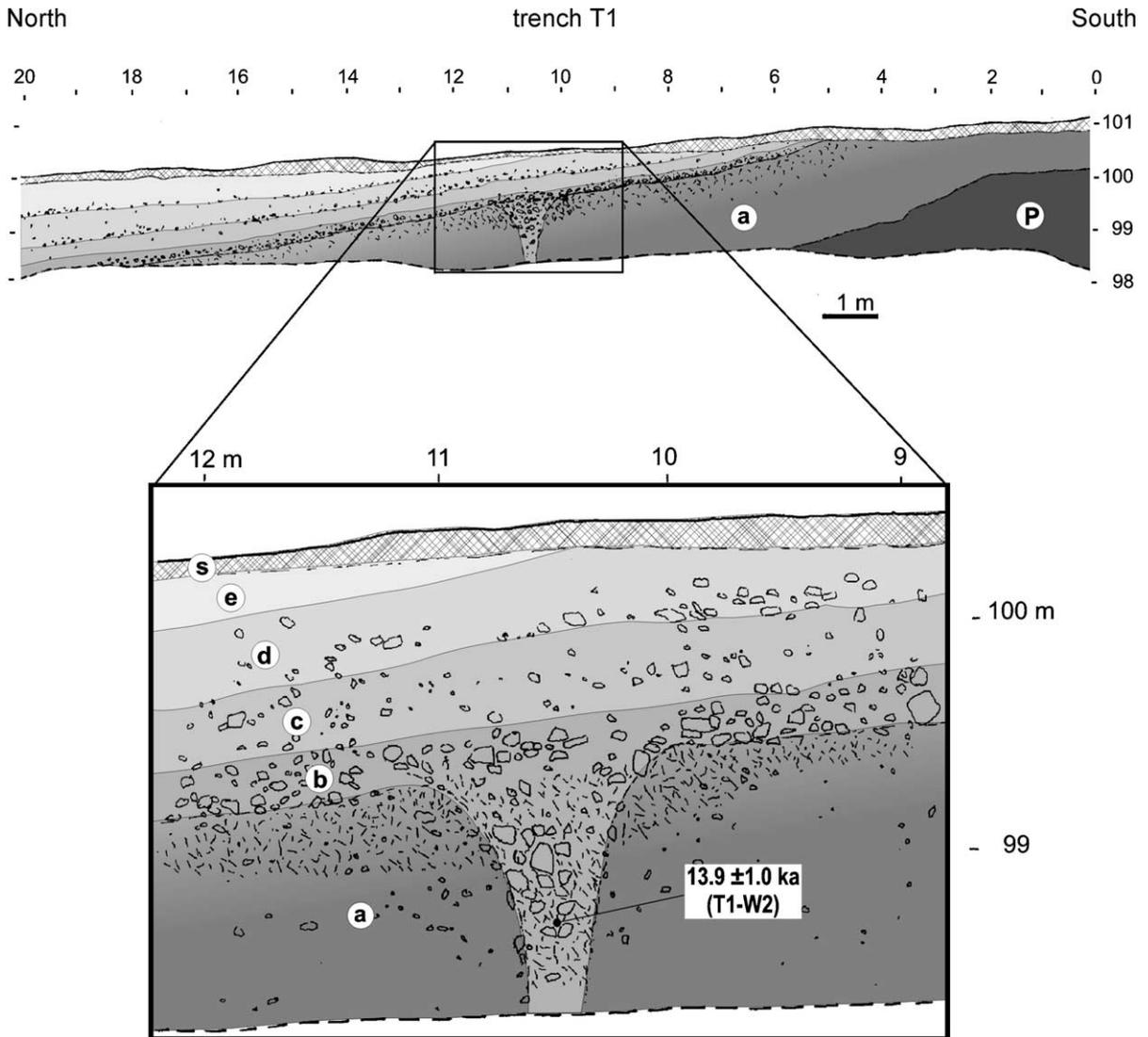


Fig. 7. (a) Log of trench T1 (western wall) excavated across the smooth morphological escarpment. (b) Detailed view of the central sector of the trench. Symbols as in Fig. 5.

trench, while further north it abruptly dips about 30° northwards rapidly deepening of more than 1.5 m and thus disappearing from the trench wall.

Unit *P* is overlain by yellowish-reddish fine sand and silt with a relatively large amount of mud content (unit *a*, in Fig. 7). Clasts from millimetres and up to few centimetres in size are present but rare. Especially in the uppermost part of this layer (0–25 cm), whitish carbonate-rich patches are diffuse. This material indicates that unit *a* possibly corresponds to the B-

horizon of a calcic soil therefore suggesting a long sedimentation break before deposition of the overlying units. In the southernmost section of the trench, the thickness of the layer is strongly reduced to less than 1 m, while the lack of pedogenesis on the top horizon and the disappearance of the carbonate-rich level suggest the occurrence of a localised erosion process. In contrast, due to a general dip of about 15° , the layer thickness progressively increases northwards becoming more than 1.5 m thick.

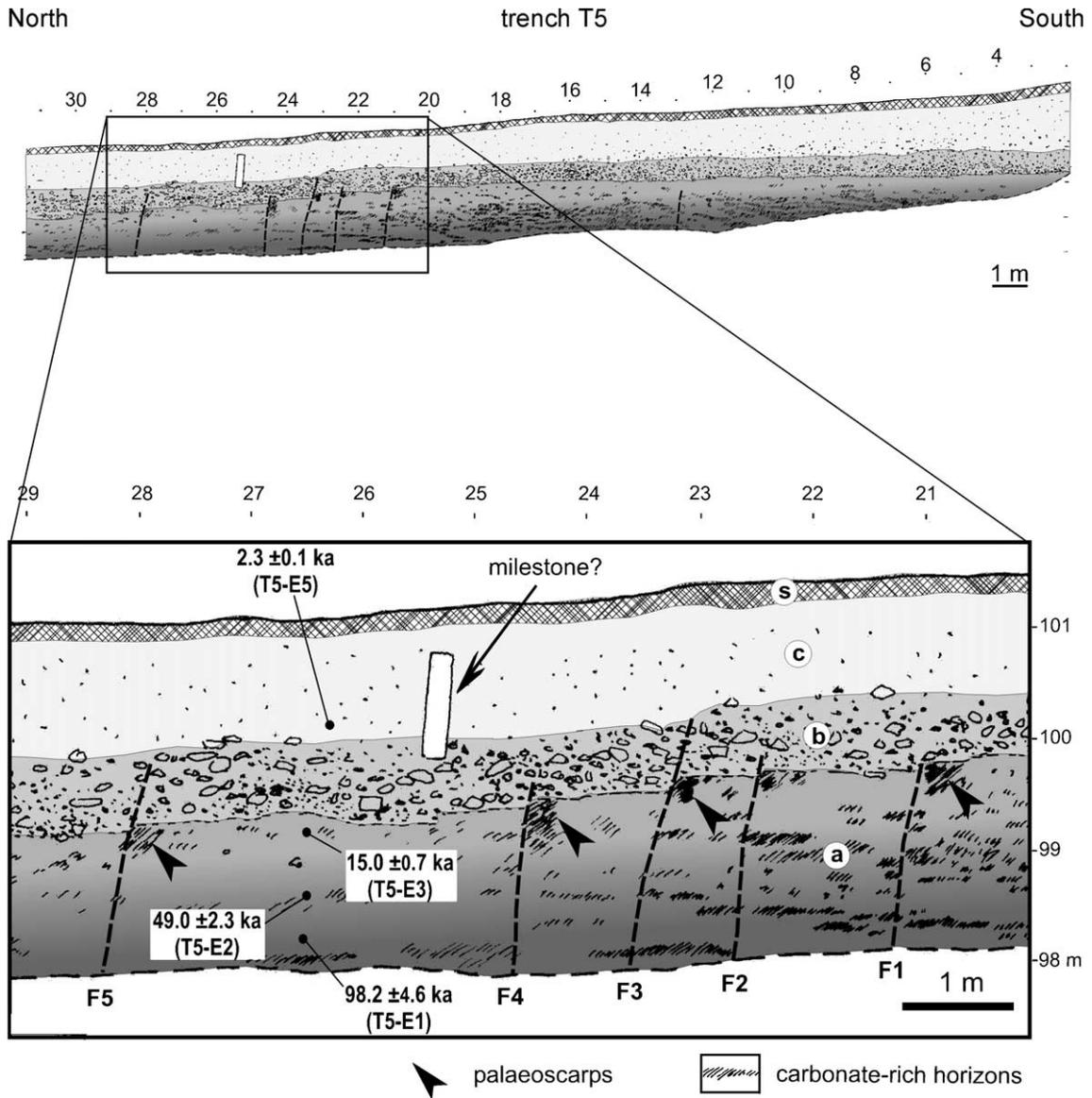


Fig. 8. (a) Log of trench T5 (western wall) excavated across the smooth morphological escarpment (see Fig. 3). (b) Detailed view of the northern sector of the trench. Symbols as in Fig. 5.

Unit *a* is overlain by 20–30 cm thick alluvial deposits (unit *b*, in Fig. 7) consisting of subangular to subrounded pebbles from millimetres to few decimetres in size floating in a reddish-brown clay-silty matrix. Also in this case, according to the roughly constant thickness and the more or less uniform sedimentary facies, this alluvial layer has been clearly eroded in the southernmost section of the trench

exposure. A cone-shaped structure crosses unit *a* and is filled by unit *b* sediments. On the two sides, an anomalous concentration of whitish carbonate-rich cement occurs. In this case, it is likely that part of the carbonate material is of diagenetic origin and associated to a process of near surface evaporation of the water table with the consequent precipitation of the water ionic content. This latter aspect and the general

geometry of the structure are interpreted as co-seismic tectonic features associated to a superficial fracturing process.

Unit *b* is overlain by a brown-grey layer (unit *c*, in Fig. 7) consisting of scattered angular to subangular pebbles (1–10 cm) floating in a sandy–clayey matrix. Also in this level, carbonate-rich patches, nodules and crusts occur. The layer is eroded in the southernmost section of the trench. According to vertical slight variations of the matrix content, to the distribution of the coarser detrital particles suggesting a fining upwards texture gradation, two further layers can be recognised (units *d* and *e*, in Fig. 7). Their dip progressively decreases to 5° and both units are eroded in the southern section. Finally, the whole trench wall is capped by an incipient brown soil about 5–15 cm thick (unit *s*, in Fig. 7).

3.4. Trench T5

Similar to trench T1, also trench T5 has been entirely excavated within the alluvial deposits across the eastern escarpment (Fig. 3). The exact location of this trench has been determined according to the results of a ground penetrating radar investigation showing several ruptures and cumulative dislocations of the dielectric horizons thus documenting the occurrence of growing faults at very shallow depth (Caputo and Helly, 2000). The trench is 36 m long, 2 m wide and 3–3.5 m deep (Fig. 8). It has been excavated parallel to a field road trending N50°W that is oblique to the fault trace (Fig. 3).

Notwithstanding the detailed log of the trench walls, only few layers can be distinguished (*a* to *c*, in Fig. 8) showing an overall stratigraphic succession roughly similar to trench T1, though the deeper Pliocene–Early Pleistocene yellow-whitish clays have not been reached in trench T5. The excavated sedimentary sequence begins with 1.2–1.6 m thick layer of yellowish-reddish sandy silt with a variable amount of clay content (unit *a*, in Fig. 8). Whitish carbonate-rich patches are frequent within these materials, locally resembling a subhorizontal but discontinuous layering. At places, real carbonate nodules have been observed. Clasts from millimetres up to few centimetres are rare. Also in this case, this unit could represent the B-horizon of a calcic soil, though local concentrations of this carbonate material

(Fig. 8) could have been enhanced by a co-seismic fracturing process.

On top of this silty layer, there is a 40–60 cm thick alluvial deposit consisting of subangular to sub-rounded clasts from millimetres to few decimetres in size and with abundant reddish-brown mainly muddy–silty matrix (unit *b*, in Fig. 8). Unit *b* is overlain by a layer of yellowish to light brown sand and silt with some clay content (unit *c*, in Fig. 8). Scattered small clasts are present but no particular internal sedimentary structure is observed, thus differing from trench T1. The thickness is about 1 m. The trench wall is capped by the typical active brown soil about 10 cm thick (unit *s*, in Fig. 8).

3.5. Trenches T2 and T3

As mentioned above, in order to document possible secondary branches typically associated to a superficial basin-ward faulting phenomenon, we excavated two more trenches (T2 and T3) within the alluvial sediments of the hanging-wall block (Fig. 3). The sequence exposed in these trenches is similar to that observed in trenches T1 and T5, consisting of prevailing alluvial sands with few coarser carbonate clasts. These trenches did not show any clear evidence of surface rupturing at least in the upper part of the sequence (3.5–4 m). The lack of any fracture in these trenches assures that all Late Quaternary co-seismic ruptures affecting this sector of the Tyrnavos Fault occurred within the major shear zone observed in trenches T4 and T6. As a consequence, the logs will not be described and discussed in more detail.

4. Dating

In order to better specify the period of morphogenic activity and to attempt dating single past earthquakes, numerous samples have been collected (Figs. 5–8). The samples were analysed with different techniques like thermo-luminescence (TL), optically stimulated luminescence (OSL) and accelerated mass spectrography (AMS). All samples consist of sandy–silty sediments, except sample T6–E1 being the shell of a continental Mollusc. Despite the large number of samples collected, only relatively few could have been

Table 1
Samples collected from palaeoseismological trenches and relative ages in ka BP

Trench	Sample	Material	Unit	Age (ka) BP	Error (\pm ka)	Method	Lab.	Lab.#
T1	T1–W2	se	b	14.0	1.0	TL	BJ	T1.2
T4	T4–E1	se	b	20.8	1.7	TL	BJ	T4W-1
	T4–E2	se	d	14.3	1.1	TL	BJ	T4W-2
	T4–E3	se	d	7.4	0.6	TL	BJ	T4W-3
T5	T5–E1	se	a	98.2	4.6	OSL	CT	t5e1
	T5–E2	se	a	49.0	2.3	OSL	CT	t5e2
	T5–E3	se	a	15.0	0.7	OSL	CT	t5e3
	T5–E5	se	c	2.3	0.1	OSL	CT	t5e5
T6	T6–E1	sh	f	6.9	0.2	AMS	UGA	10360
	T6–E3	se	f	5.3	0.3	OSL	CT	t6e3
	T6–E6	se	d	24.6	1.1	OSL	CT	t6e6

Sample: label used in the present note; *material*: se=sediment; sh=shell; *unit*: letters refer to sedimentary units as labelled in the figures corresponding to each trench (Figs. 5–8); *method*: TL=thermoluminescence; OSL=optically stimulated luminescence; AMS=accelerated mass spectrography; *lab.*: CT=Department of Physics, University of Catania, Italy (resp. O. Troja); UGA=Center for Applied Isotope Studies, University of Georgia, Athens, USA (resp. R. Culp); BJ=Institute of Geology, State Seismological Bureau, Beijing, China (resp. C. Shaoping); *lab#*: sample label used in the laboratory.

successfully dated, mainly due to techniques limitations. Further details for each dated sample are listed in Table 1.

Our attempt in dating single past earthquakes faced two major problems. First, the short-term sedimentation rates observed in the trenches are about 0.1–0.05 mm/a (Fig. 9a). As a major consequence of these relatively low rates, sedimentation is highly condensed. Second, due to the subaerial conditions of the investigated site, a slow sedimentation rate also

implies that the sedimentary units were exposed to deeply working weathering phenomena and pedogenic processes along with a more or less intense bioturbation of the whole uppermost section. Because of the condensation and natural mixing of the sediments, though originally deposited in distinct units, the sampling operations are somehow problematic. Moreover, due to the short transportation distance of the clasts down slope, it is likely that a complete bleaching of the grains has been prevented. Accord-

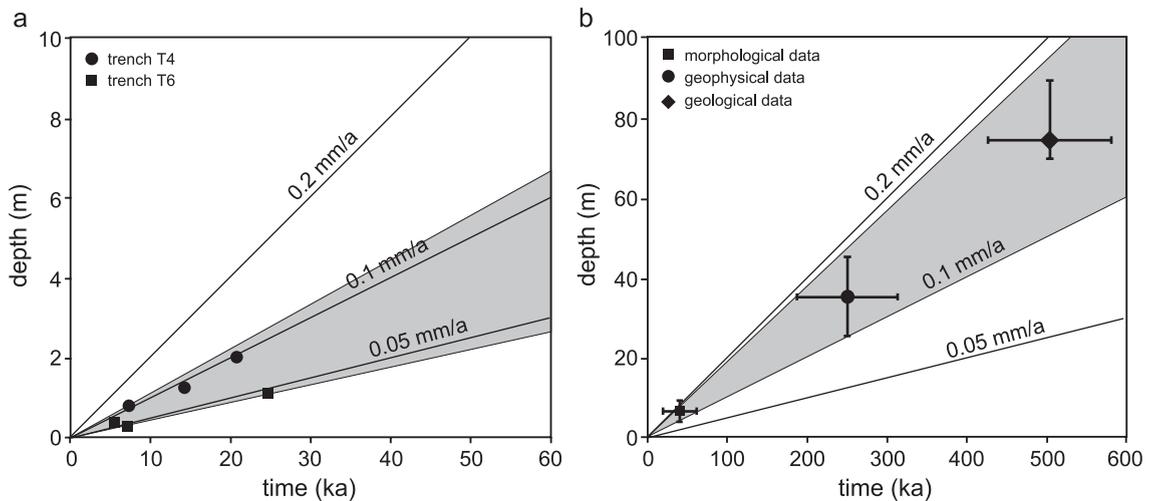


Fig. 9. (a) Short-term (latest Pleistocene–Holocene) slip-rate obtained from trenches T4 and T6. Error bars (see Table 1) lay within the symbol dimensions. (b) Long-term (Middle–Late Quaternary) slip-rates. In both diagrams, the 0.2, 0.1 and 0.05 mm/a slip-rate curves are represented for reference. The shaded areas represent the inferred ranges.

Table 2

Seismic events inferred from trench T4, based on the detailed analysis of the log, the available ages and the assumptions discussed in the text

Number of event(s)	Affected units (hanging-wall)	Accommodation space (unit)	Activated fault branch	Vertical displacement per event	Age (ka BP)
1	a–g	30 cm (s)	F1–F5	ca. 30 cm	<7.4
1	a–f	ca. 25 cm (g)	F4–F5	ca. 25 cm	<7.4
At least 2	a–d	ca. 60 cm (e–f)	one event F6 to F9 one event mainly F4	30 cm ?	(<7.4 ?)
At least 2	a–c	70–80 cm (d)	mainly F4	max 40 cm	one event <14.3 and >7.4 one event <20.8 and >14.3
At least 2	a–b	60–70 cm (c)	F4 and F6 to F8	max 30–40 cm	<20.8 and >14.3
At least 2	a	ca. 70 cm (b)	F4	max 30–40 cm	>20.8
At least 3 (possibly more)	(a)	>150 cm (a)	F4	max 40–50 cm	>20.8

For the stratigraphic units and faults referred to in the table see Fig. 5.

ingly, the interpretation of the obtained samples' ages must be attentive and the obtained values should be considered as indicative.

Beyond the obtained absolute ages, during the excavation of trench T5 (Fig. 8), at a depth of about 1–1.5 m from the surface, we found a stone with sides 80, 50 and 15 cm long, respectively. It consists of carbonate material, probably mined from the nearby Pliocene limestone. The almost regular parallelepiped shape and its vertical orientation clearly indicate an anthropogenic origin. Indeed, it probably represents a rudimentary milestone or possibly a boundary stone. Due to the lack of any incision on its sides, the stone has not any real archaeological interest nor it can be dated accurately. However, it represents a very useful

information concerning the possible time range of units *b* and *c*, being younger than about 6–7 ka BP (the lower boundary of the Neolithic period).

5. Palaeoseismological evolution

Notwithstanding the chronological problems, following some straightforward assumption we can obtain important information about the seismotectonic behaviour of the Tyrnavos Fault and its palaeoseismological evolution during late Quaternary. Firstly, the investigated trenching site has a very limited source area for the production of sediments (see map and frontal views in Figs. 3 and 4,

Table 3

Seismic events inferred from trench T6, based on the detailed analysis of the log, the available ages and the assumptions discussed in the text

Number of event(s)	Affected units (hanging-wall)	Accommodation space (unit)	Activated fault branch	Vertical displacement per event	Age (ka BP)
1	a–f	20 cm (s)	F1 (and F2)	20 cm	<6.9–5.3 (close to 5.3)
1	a–e	20–25 cm (f)	F1–F3	20–25 cm	>6.9–5.3
Probably 2	a–d	ca. 50 cm (e)	F4 (possibly F1–F3)	20–30 cm	<24.6 and >6.9–5.3
At least 2 (possibly 3)	a–c	ca. 90 cm (d)	F1–F3	max 40–50 cm (30–40 cm)	one event <24.6 one event >24.6
At least 2	a–b	70–80 cm (c)	F1–F3	max 30–40 cm	>24.6
Probably 2	a	ca. 70 cm (b)	F1–F3	max 20–30 cm	>24.6
At least 2 (possibly more)	(a)	>90 cm (a)	F1–F3	max 40–50 cm (20–30 cm)	>24.6

For the stratigraphic units and faults referred to in the table see Fig. 6.

Table 4

Seismic events inferred from trench T1, based on the detailed analysis of the log, the available age and the assumptions discussed in the text

Number of event(s)	Affected units (hanging-wall)	Warping/diffuse shear (unit)	Tectonic feature	Vertical displacement per event	Age (ka BP)
At least 2	a–d	50–60 cm (e)	warping (tilting, erosion)	?	<14.0
At least 2	a–c	40–50 cm (d)	warping (tilting, erosion)	?	<14.0
At least 1	a–b	30–40 cm (c)	warping (tilting, erosion)	?	<14.0
At least 1	a	25–30 cm (b)	warping (tilting, erosion)	?	<14.0
1	a	20–30 cm opening (a)	opening structure (and warping?)	5–10 cm (?)	>14.0
Several	a	>150 cm (a)	warping (tilting, erosion)	?	>14.0

For the stratigraphic units referred to in the table see Fig. 7.

respectively), while the local and broader geological conditions do not favour at all the widespread accumulation of alluvial and colluvial materials. Accordingly, we assume that the deposition of some tens of centimetres thick sedimentary units, as observed in the palaeoseismological trenches T4 and T6, was preceded by the creation of a comparable amount of accommodation space (viz. vertical displacement along the fault). Moreover, the existence of incipient soils on top of the different sedimentary units confirms the occurrence of a sedimentary hiatus. Therefore, we assume that each sedimentary layer recognised in the hanging-wall corresponds to at least one morphogenic seismic event (sensu Caputo, 1993a). In other words, each layer corresponds to at least one earthquake that co-seismically ruptured the topographic surface thus producing a free face and a bedrock scarp, while the incipient soils should represent the inter-seismic periods.

Secondly, based on the ‘magnitude versus surface rupture length’ empirical relationship specifically proposed for the normal faults of the Aegean Region (Pavlidis and Caputo, 2004) and assuming that the

Tyrnavos Fault is reactivated all along its length, the maximum expected magnitude is 6.6–6.7. Conversely, by using the vertical displacement versus magnitude relationship, the maximum displacement associated to such an earthquake is 50–60 cm. We should also take into account that the maximum vertical displacement commonly occurs in the central sector of a fault (e.g. Cowie and Scholz, 1992), whereas the trenching site is located further to the East (Fig. 1) and vertical displacement is probably the 60–70% of the maximum one. Accordingly, it is reasonable to assume that the thicker layers, say 1 m or more, observed in trenches T4 and T6 correspond to multiple events even if it is not possible to recognise and separate distinct sedimentary units. The difficulties in separating layers could be due to (i) the low sedimentation rate, (ii) a relatively short inter-seismic interval, (iii) climatic variations or a combination of these factors.

Based on the detailed analysis of the trench logs and the available chronologies and following the above assumptions, the number of events, the vertical displacement per event and the possible age (or time window) of the most recent earthquakes are inferred

Table 5

Seismic events inferred from trench T5, based on the detailed analysis of the log, the available ages and the assumptions discussed in the text

Number of event(s)	Affected units (hanging-wall)	Accommodation space (unit)	Tectonic feature	Vertical displacement per event	Age (ka BP)
2 (?)	a–c	50–60 cm (c)		?	<2.3 (?) <Neolithic
At least 1	a–b	10–20 cm (c)	F3 (F5?)	10–20 cm	<15.0 and >2.3
2 (?)	a–b	ca. 40 cm (b)		?	<15.0 and >2.3
At least 1	a	ca. 20 cm (b)	F1, F2, F4 and F5	max ca. 20 cm (probably less)	<15.0 and >2.3
Several	a	60–70 cm (b)		?	<15.0
Several	a	>180 cm (a)		?	between >98.2 and <15.0

For the stratigraphic units and faults referred to in the table see Fig. 8.

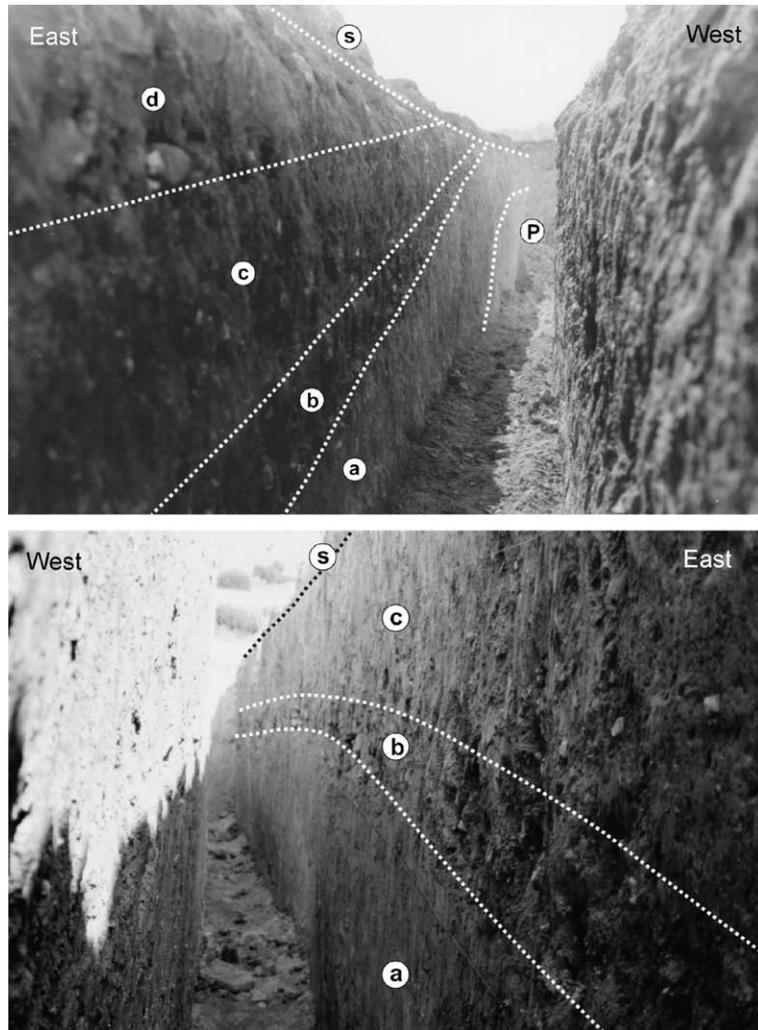


Fig. 10. (a) The southern sector of trench T1 showing the bending of unit *a*, the progressive northward tilting of the overlying units and their erosion towards the south. (b) The central-southern sector of trench T5 showing the bending of units *a* to *c* in correspondence with the smooth escarpment observed at the surface.

(Tables 2–5), thus documenting repeated re-activations of the Tyrnavos Fault during Late Pleistocene and Holocene times.

As mentioned above, the trenches excavated in different locations with respect to the fault scarp show diverse results, while both trenches excavated across the bedrock scarp (T4 and T6) show a comparable evolution (Tables 2 and 3). In particular, from the logs analysis (Figs. 5 and 6), we can infer the following palaeoseismic evolution. Firstly, units *a–d* are sedimentologically equivalent in the two trenches and are

affected by 10–11 morphogenic events. These palaeoearthquakes are older than ca. 7–8 ka BP and, by assuming as a first approximation a roughly uniform slip-rate (viz. sedimentation rate), they occurred within the last few tens of ka (latest Pleistocene). From the same two trenches we can also document the occurrence of two younger events that re-activated the Tyrnavos Fault since ca. 7–8 ka, though the last morphogenic earthquake probably occurred closer to 6.9–5.3 ka than Present (Fig. 6; Table 3). It is noteworthy that each event or group of events

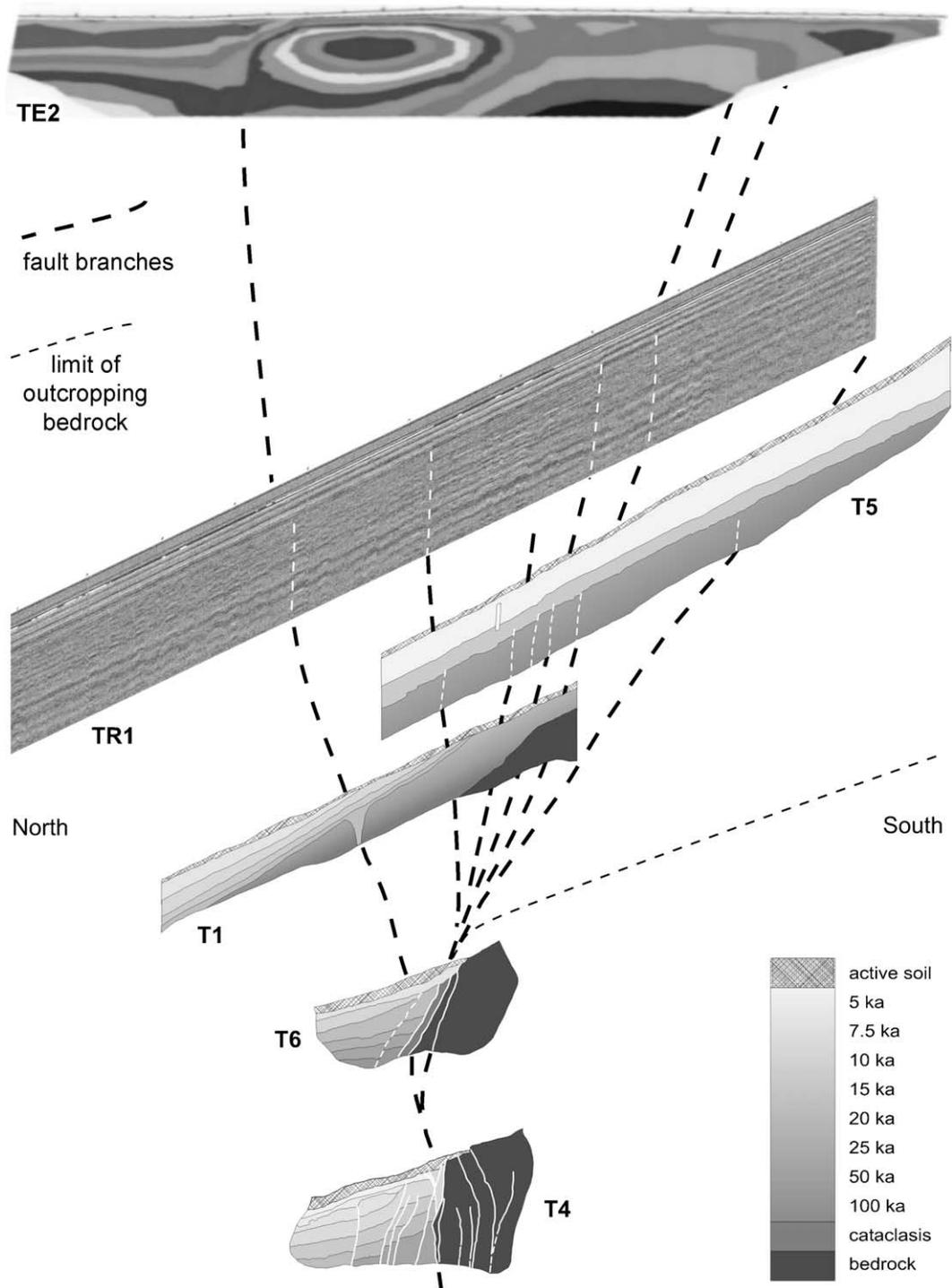


Fig. 11. Perspective view of the four trenches (present paper), a GPR profile (TR1; from [Caputo and Helly, 2000](#)) and an electrical resistivity tomography (TE2; from [Caputo et al., 2003](#)). The grey scale in the palaeoseismological logs is purely indicative of the age.

observed in the two trenches has a comparable amount of vertical displacement.

In contrast, the detailed analysis of trenches T1 and T5 (Tables 4 and 5) excavated across the smooth escarpment does not show the same sharp shear zone as in the previously discussed trenches, where co-seismic deformation is highly concentrated. The only evidences of co-seismic surface ruptures are the opening fracture (trench T1, Fig. 7) and the small syn-sedimentary faults (trench T5, Fig. 8).

Also in this case, the stratigraphic logs of the two trenches are comparable. In particular, unit *a* coincides in both trenches and units *b–c* of trench T1 correspond to unit *b* of trench T5. Because the observed co-seismic features affect the interface between unit *a* and *b*, they are probably associated to the same seismic event. Based on the available absolute ages, this morphogenic earthquake occurred about 14–15 ka BP.

With respect to the western trenches, because of the different local sedimentary conditions, it is not possible to correlate each stratigraphic unit to specific co-seismic events and consequently to measure the induced superficial displacement. Nevertheless, due to the geological context of the investigated site and based on the palaeoseismological evolution of T4–T6, also in the eastern trenches the syn-sedimentary tectonic activity of the Tyrnavos Fault is confirmed by some large-scale features. In particular, in trench T1 (Figs. 7 and 10a) we can observe, firstly, the bending of the interface between the Pliocene–Early Pleistocene lacustrine deposits (unit *P*) and the overlying alluvial sediments; secondly, the variable degree of erosion of the overlying layers (units *a–e*) in the southern sector; thirdly, the fan-shape geometry of these deposits and the associated progressive northward tilting with depth; fourthly, that the base of each layer is marked by the occurrence of coarser pebbles, possibly indicating a temporarily higher energy of the local relief; fifthly, the persistence of a broad escarpment at the surface. From all these features, we infer that through time the northern sector of the plain progressively subsided with respect to the southern one where uplift and erosion occurred. As a consequence, a general bending of the surface was produced (Fig. 10b). Because this process was repeated several times during latest

Pleistocene–Holocene and because of the location of the trench (Fig. 3), it is likely that this phenomenon was caused by as many morphogenic earthquakes (Table 4). At this regard, GPR profiles carried out parallel to the eastern trenches (Figs. 3 and 11) clearly document several syn-sedimentary fault branches up to few metres from the surface (Caputo and Helly, 2000).

The occurrence of multiple morphogenic earthquakes affecting this sector of the plain is also supported by the extremely low sedimentation rate observed in trench T5 showing only 2.5 m of alluvial deposits in about 100 ka (Fig. 8). Although Quaternary climate variations could have played a role, the low rate of accommodation space is likely due to its location within the footwall block (viz. the uplifted sector of the plain; Fig. 3). Also, electrical resistivity tomographies carried out across the plain (Figs. 3 and 11) confirm the eastwards continuation of the fault (Caputo et al., 2003), thus providing further evidences of its Late Quaternary activity.

In summary, among all the earthquakes documented by the palaeoseismological analyses, only one event is well constrained in all four trenches (Tables 2–5). Based on the sedimentological observations and following the more reliable absolute ages obtained with the OSL method (Table 1), this earthquake occurred around 14–15 ka BP and caused the open structure in trench T1 (Fig. 7), ruptured the top of unit *a* in trench T5 (Fig. 8) and generated some of the accommodation space for unit *d* in trenches T4 and T6 (Figs. 5 and 6). Possibly, during the last 14–15 ka, five events ruptured the Tyrnavos Fault, two of which occurred during the last 7–8 ka. Therefore, a rough estimate of the mean recurrence interval since the latest Pleistocene is 2.5 ka, while the mean co-seismic vertical displacement is between 20 and 40 cm.

6. Discussion

The major outcomes obtained from the present research are at least two. First, we document the late Pleistocene–Holocene seismic activity of the eastern sector of the Tyrnavos Fault and we infer some of the most important seismotectonic parameters like the above-mentioned mean recurrence interval and mean

vertical displacement, but also a short-term slip-rate of 0.05–0.1 mm/year (Fig. 9a). As concerns the magnitude of these palaeoseismic events, following the ‘magnitude versus maximum vertical displacement’ relationship and according to the inferred co-seismic displacements (Tables 2–5), estimated magnitudes are 6.3–6.5 (Pavlidis and Caputo, 2004). Conversely, following the ‘magnitude versus surface rupture length’ relationship and assuming that the entire structure was re-activated (ca. 20 km; Fig. 1), higher magnitudes are obtained (6.6–6.7). This apparent discrepancy is due to the fact that the maximum vertical displacement generally occurs in the central sector of seismogenic faults (e.g. Cowie and Scholz, 1992) and therefore the co-seismic dislocations occurring at the investigated site are probably 30–40% smaller. Because in seismic hazard evaluations a worst-case scenario is certainly more meaningful, we assume the higher values as the maximum expected magnitude.

As a second major outcome of this palaeoseismological investigation, we document for the first time the abrupt change in morphogenic behaviour along strike of a seismogenic structure. In fact, along the bedrock–sediments contact, deformation is highly concentrated within a relatively thin shear zone due to the strong mechanical contrast between the two blocks (Fig. 11). In contrast, when the fault generates a sediment–sediment contact near the surface, co-seismic deformation is much more distributed and the co-seismic ruptures propagating upwards commonly spreads out into several minor branches each characterised by a lower amount of displacement. If the total co-seismic displacement between the two blocks is few tens of centimetres, as documented in trenches T4 and T6, it is likely that not a unique fault rupture forms at the surface and even in a palaeoseismological section a throughout fracture is hardly observed. In these conditions, single events are easily missed while only the cumulative effects can be inferred from a several metres wide shear zone producing a large-scale bending of the superficial layers.

In order to have a more complete understanding of the Quaternary seismotectonic evolution of the Tyrnavos Fault, we also take into account independent data about the cumulative displacement during longer time periods. Firstly, a 6–8 m high escarpment affecting the latest Pleistocene (?) alluvial plain can be observed east of the trenching site as well as in the western sector

(Caputo, 1993b). Secondly, electrical resistivity tomographies across the central sector of the Tyrnavos Fault (Caputo et al., 2003) document a displacement of several tens of metres of a Middle(?) to Upper Pleistocene alluvial fan. Thirdly, some bore-holes drilled 1.5 km east of the investigated site on both sides of the fault trace found that the contact between the Pliocene–Lower Pleistocene lacustrine sediments and the Middle Pleistocene–Holocene alluvial deposits is at depth of 52 m in the footwall block and more than 125 m (the base was not penetrated) in the hanging-wall block. Considering the relative altitudes, the post-Early Pleistocene displacement is more than 75 m.

According to the above-estimated amounts of displacement and their possible ages and assuming a tectonic origin, we can estimate 0.1–0.2 mm/year of long-term (Middle–Late Quaternary) slip-rate (Fig. 9b). It is noteworthy that these values are nearly twice those obtained from the palaeoseismological investigation representing a short-term (latest Pleistocene–Holocene) slip-rate (Fig. 9a). The variation in slip-rate could be explained as a result of a decrease of morphogenic activity along the Tyrnavos Fault during the latest Pleistocene. This hypothesis implies that the Tyrnavos Fault has begun a period of relative quiescence. However, due to (i) the fairly constant and uniform geodynamic conditions affecting the whole Aegean Region during Late Quaternary (Mercier et al., 1989; Pavlidis and Mountrakis, 1987; Caputo and Pavlidis, 1993), (ii) the relatively young age of the Tyrnavos Fault, (iii) the perfect orientation of this structure with respect to the present-day regional stress field (Caputo, 1990) and (iv) the strong instrumental seismicity both North (e.g. 1995—Kozani and 1978—Thessaloniki) and South (e.g. 1999—Athens, 1995—Aigion, 1982—Corinth, 1980—Volos and 1954—Sophades) of the investigated area, we think this is probably not a likely hypothesis.

As an alternative explanation for the difference between the short- and long-term slip-rates, we suggest that the Tyrnavos Fault is presently characterised by a lack of vertical displacement. In other words, a strong morphogenic earthquake could occur in the next future to compensate this gap. At this regard, we should also take into account that the last seismic event documented in trenches T4 and T6 is chronologically constrained between 6.9–5.3 ka BP and present. As discussed above, it probably occurred closer to the

older time limit (Table 3), therefore some thousands of years ago. Because the estimated mean recurrence interval is about 2.5 ka, this implies a relatively high seismic hazard. Obviously, this latter interpretation will bring with it serious implications for the seismic risk assessment of the area which is one of the most populated regions of Greece where the city of Larissa, the third town of the country, is only 15–20 km far from a possible future epicentre and the large majority of the settlements within the area stand on alluvial deposits commonly characterised by higher values of the peak ground acceleration.

7. Concluding remarks

Thessaly as well as large sectors of the broader Aegean Region are characterised by numerous and variously oriented inherited tectonic structures (e.g. Pavlides, 1993), a relatively shallow Moho (Makris, 1977) and a mainly extensional tectonic regime (e.g. Mercier, 1976; Caputo and Pavlides, 1993). These crustal and geodynamic conditions strongly influence the maximum dimensions of the seismogenic structures that are commonly no longer than 15–25 km (Aegean-type faults).

Consequently, the maximum seismic magnitude these tectonic structures can generate is about 6.6–6.7 and only exceptionally up to 6.8 (Pavlides and Caputo, 2004). A further consequence of these seismotectonic characteristics is that the maximum possible displacement that can occur as co-seismic surficial rupture directly caused by the seismogenic fault is of some tens of centimetres (Pavlides and Caputo, 2004). In other words, the morphogenic potential (sensu Caputo, 1993a) of most of the Aegean-type active faults is commonly quite weak.

In fact, while the cumulative effects of the co-seismic deformation can be commonly observed and tentatively quantified, seismogenetic (viz. co-seismic) surface ruptures affecting loose deposits seldom produce important morphological variations sufficient to induce a sudden sedimentological change along the fault trace and therefore to be stratigraphically recorded. As a consequence, this seismotectonic behaviour characterising most of the Aegean-type faults is generally not able to induce a sharp sedimentary variation on the two sides of the plane. This aspect

is reflected in fairly contrasting geoelectrical and sonic characteristics of the two fault blocks (Caputo and Santarato, 1997; Caputo et al., 1998; 2003). Indeed, even palaeoseismological trenches sometimes do not allow to clearly distinguishing the occurrence of surficial ruptures. We think that this intrinsic investigation problem is common to all the areas with a seismotectonic behaviour similar to Thessaly, like most of the Aegean-type faults.

We should also not forget that since the last 2000–5000 years Thessaly has been densely populated and that most of the lands have been farmed or used for pasturage (Helly, 1970, 1983, 1991). Consequently, even the possible evidence of historical morphogenic earthquakes could have been easily destroyed by human activities without eventually leaving any clear trace at the surface.

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