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A POSSIBLE SEISMIC GAP IN NORTHERN THESSALY, GREECE AS INFERRED FROM GEOLOGICAL DATA

R. Caputo*

ABSTRACT

As a result of neotectonic, morphotectonic and seismotectonic researches it is now possible to draw a detailed map of the major active faults affecting Thessaly, a large region of continental Greece. For many of these faults, where specific studies have been carried out, also the degree of fault activity (*i.e.* the long term slip rate) can be assigned. In the present work, a brief description of the main morphotectonic features and seismotectonic characteristics of the more important faults is presented, while the recent fault activity is compared with the seismic activity of the area. The occurrence of both major (M>6.0) and minor (M6.0) earthquakes during the present century is concentrated in the southern sector and almost absent in the northern one. In contrast, according to geological and geomorphological criteria, the recent (Late Quaternary) tectonic evolution of the region does not seem to differ in the two sectors. Although palaeoseismological trenches, geodetic surveying and the record of the microseismic activity can potentially enhance our knowledge on this problem, solely based on geological (structural and morphotectonic) data, it is likely the northern sector of Thessaly represents a large seismic gap. The effects on the seismic hazard of one of the more populated regions of Greece are also discussed.

INTRODUCTION

From a tectonic point of view, the whole Aegean region can be considered as a large scale natural laboratory where any kind of deformational environment, from plastic to brittle, from deep to shallow and from extensional to compressional, has been generated. As a consequence, the unravelling of the deformational history of the region was a challenge for many geologists during the last decades. If several problems still arise for the older tectonic events, most of the scientific community feel more confident with the results of neotectonic studies. Though debates are still open, the state of art on this topic indicates a tectonic stratigraphy largely accepted by the specialists. In fact, all the major phases which affected the region, their relative and absolute chronology as well as the stress field trajectories have been clearly recognised for wide sectors of the Aegean region (*e.g.* Mercier, 1981; Mercier *et al.*, 1979; 1987; Angelier, 1977; 1979; Pavlides and Mountrakis, 1987; Sorel, 1989; Angelier *et al.*, 1981) and Thessaly is not an exception (Caputo, 1990a; Caputo and Pavlides, 1993). Indeed, also for this region of continental Greece, the structural map has been compiled and, according to a detailed

* Department of Earth Sciences, University of Florence, via G. La Pira 4, 50121 Florence, Italy.
mailing address: via Alberto Lollio 7, 44100 Ferrara, Italy.

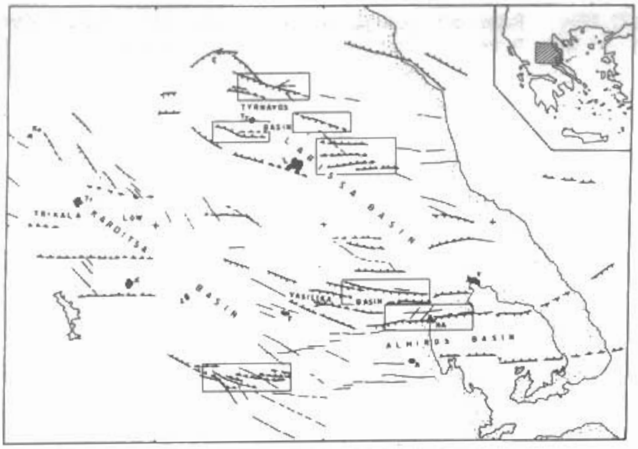

Fig. 1: Simplified tectonic map of Thessaly. The major Late Quaternary and active faults are represented in thicker lines; barbs on the downthrown side (modified from Caputo and Pavlides, 1993). Boxes and number inside refer to corresponding figures.

quantitative structural analysis, several tectonic phases have been distinguished since Miocene times. In particular, the last event started during Middle Pleistocene and it is still active in the region, where crustal deformation is characterised by generalised and pure extension, with a N10°E average direction of the least principal stress axis, σ_3.

Although the basin-and-range-like physiography of Thessaly is basically the result of the older (Oligo-Miocene) orogenic tectonism and (Pliocene - Lower Pleistocene) post-orogenic collapse (Caputo and Pavlides, 1993), also this last (Middle Pleistocene-Present) event affected the region by generating a new system of relatively small basins with a general E-W trend. This younger graben system has been superimposed onto the inherited NW-SE trending one, causing the complex blocky pattern we can see today (Fig. 1).

The Late Quaternary stress field, as inferred from structural data for the northern Aegean region (*e.g.* Mercier *et al.*, 1987; Pavlides and Mountrakis, 1987; Caputo, 1990a), is in good agreement with that estimated from seismicity (*e.g.* Papazachos and Comninakis, 1978; Papazachos *et al.*, 1991) and from in-situ stress measurements (Paquin *et al.*, 1982). Unfortunately, within the studied region (Thessaly) only the focal mechanisms relative to the 1980, Volos earthquakes (main, fore- and after-shocks) are available (Papazachos *et al.*, 1983) as well as a unique in-situ measurement near Pharsala. However, the observations from both geophysical methods confirm a present-day N-S extension. Notwithstanding, from historical and instrumental records the region shows a considerable seismic activity (Shebalin *et al.*, 1974; Papazachos and Papazachou, 1989; Ambraseys and Jackson, 1990).

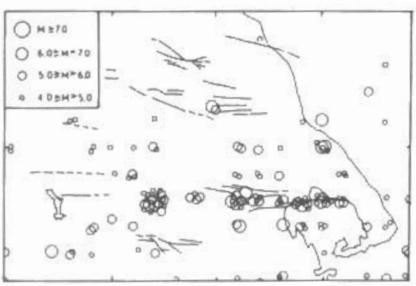

Fig. 2: Map of the epicentral distribution of Central Greece during the present century (from Comninakis and Papazachos, 1986). The major active faults of Thessaly, according to geological and morphological criteria, are also represented.

If we consider the epicentral distribution of the present century (Fig. 2), an apparent anomaly is evident for Thessaly. Indeed, in the southern sector, the seismic activity is very diffuse while in the northern sector it is almost completely absent. Very likely, two are the possible solutions. First, a northern rigid, independent and non-deforming block exists or, second, the northern region represents a large seismic gap. It is explicit that the two contrasting solutions support very different implications and consequences. Accordingly, the evaluation of the seismic hazard of one of the more populated regions of Greece would be greatly affected. The target of the present research is to contribute to the solution of this fundamental problem by using only geological means.

During the last decade, a large project aimed to the study of the recent tectonic evolution of Thessaly has been undertaken. The programme was divided in three major steps: neotectonics, morphotectonics and palaeoseismicity. The first step has been already achieved and complete data with results are published in specific papers (Caputo, 1990a; Caputo and Pavlides, 1993), while a partial description of the results obtained from the morphotectonic approach (second step) is shortly presented in the next section. As concern palaeoseismicity, work is in progress.

Late Quaternary faulting

While for the first step, the basic undertaking was the geological and structural survey in order to identify and map all major and minor tectonic structures affecting the area, the next step was to detect and separate all faults generated and activated during the last (Middle Pleistocene-Present) tectonic event (Fig. 1). In particular, a special care was spent for all the faults showing features of very recent activity. In order to understand their geometry and kinematics in detail, a different and specific approach was employed. Indeed, the morphotectonic survey for all these structures has been carried out using maps at the scale 1:5.000. The use of aerial photographs at the scale 1:33.000 was also essential to.

Most of the faults generated by this tectonic event are trending E-W to ESE-WNW and show a dip-slip normal sense of movement. Locally, NW-SE or even NNW-SSE structures, inherited from older phases, have been also reactivated as for example during the 1954, Sophades earthquake where oblique-slip motion occurred along ground ruptures of such direction (Papastamatiou and Mouyaris, 1986).

The degree of fault activity, which is expressed as the long-term average slip rate, S, has been calculated for most of the active faults and it is mainly based on the dislocation of stratigraphic markers. When data are insufficient, the freshness of the morphotectonic features are tentatively used and according to the Research Group for Active Faults of Japan (1992) the degree of fault activity has been classified as class A (10 mma^{-1} S 1 mma^{-1}), class B (1 mma^{-1} S 0.1 mma^{-1}) or class C (0.1 mma^{-1} S 0.01 mma^{-1}). All the morphological features observed along or near each of the studied faults have been also classified as fault-generated morphologies or fault-related features. Numerous examples of both types have been observed all over Thessaly. In the following, some of the more representative and active faults of the southern and northern sectors of Thessaly, respectively, are briefly described.

Nea Anchialos Fault (Fig. 3)

The fault is one of the more prominent tectonic features of Thessaly (Fig. 1). It trends E-W and it clearly bounds to the north the Late Quaternary Almyros Basin which nowadays is partly submerged in the Pagasitikos Gulf. Pleistocene sediments and basalts are largely affected by normal faulting, whose geometry and kinematics indicates a N-S extension (Caputo, 1990a; 1990b). On July 9, 1980 a morphogenic earthquake (*sensu* Caputo, 1993b) of magnitude 6.5 occurred in the area. The focal mechanisms, the distribution of the seismic sequence, the shape of the isoseismal map and the ground ruptures

Fig. 3: Sketch map of the Nea Anchialos Fault. Topographic contours every 200 m. Dotted areas are Pleistocene-Holocene deposits. See Fig. 1 for location.

all indicate this major fault was activated (Papazachos *et al.*, 1983). Beyond geological and seismological data, also archaeological data have been collected in the area. A palaeochristian aqueduct crops out in the footwall block near the main escarpment along a valley which was clearly entrenched after the emplacement of the handicraft. According to the age of the handwork (3rd-4th century, P. Lazarides, pers. commun., 1990) and applying simple morphological criteria, we can tentatively infer the historic-time slip rate along the fault zone. It amounts to few millimetres per year (class A) and it is comparable to the long term slip rate estimated for geological times.

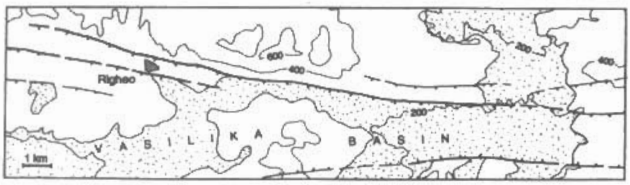

Fig. 4: Sketch map of the Righeo Fault. Dotted areas are Pleistocene-Holocene deposits. See Fig. 1 for location.

Righeo Fault (Fig. 4).

It borders to the north the eastern sector of the Vasilika Basin, a very young and narrow asymmetric graben. The fault seems to be a continuous structure with a total length of more than 20 km (Caputo, 1990a). Deposits of Late Pleistocene age are affected by this E-W trending south-dipping structure which shows a sharp and straight scarp all along its length. On March 8, 1957 within 12 hours and near the village of Velestino two earthquakes occurred with magnitude 6.5 and 6.6 (Ambraseys and Jackson, 1990; or 6.5 and 6.8, according to Papazachos *et al.*, 1982). Although no focal mechanism is available and no clear evidence of surface faulting was produced from later survey, the two earthquakes were probably generated along this major structure and one of the minor antithetic faults cropping out few km to the north (Ambraseys and Jackson, 1990; Caputo, 1990a). Though the isoseismal map as inferred from macroseismic data is probably 'cumulative' of the two earthquakes, it clearly shows an E-W lengthening (Papazachos *et al.*, 1982, in press)

Domokos Fault (Fig. 5).

It is a shortly segmented and complex fault system bordering to the south the Oligocene-Pliocene Karditsa Basin (western Thessaly). In Late Cainozoic times, the area suffered a strong brittle deformation and was severely fractured by several tectonic events that generated prevailing NW-SE trending structures. Within this inherited system, the E-W trending fault segments generated during the Late

Fig. 5: Sketch map of the Domokos Fault System. Dotted areas are Pleistocene-Holocene deposits. See Fig. 1 for location.

Quaternary extension, show a complex cross cutting relationship (Caputo, 1990a; Pavlides, 1993). During the 1954, Sophades earthquake, whose magnitude was 7.0 according to Papazachos *et al.* (1982), some of these segments have been reactivated (Papastamatiou and Mouyaris, 1986). Several ground ruptures occurred along both E-W and (N)NW-(S)SE directions showing dip-slip and oblique-slip motion, respectively. The kinematics is compatible with the N-S direction of extension as obtained from neotectonic data (Caputo, 1990a) and with an E-W trending rupture zone (Papazachos *et al.* in press), but in contrast with the poorly constrained focal mechanism presented by McKenzie (1972).

Rodia Fault System (Fig. 6).

It is a 12-15 km long complex shear zone (Caputo, 1993c) made of several segments of different directions (from NW-SE to ENE-WSW) and of probably different ages (from Pliocene to Holocene). Indeed it bounds to the north both the Pliocene Larissa Basin and the Late Quaternary Tyrnavos Basin (Caputo, 1990a). A persistent set of morphological scarps affects Late Pleistocene and Holocene alluvial deposits. The parallelism, the lateral continuity (several hundreds meters each one), the angular shape, the uniformity in vertical throw (between 0.5 and 2 m) and the constant E-W direction reflect the tectonic origin of these features. A typical basin-ward migration of faulting has been also documented. According to the displacement of dated stratigraphic horizons and other morphotectonic criteria, the estimate of the long term slip rate gives some mma^{-1} (class A). In the central segment of the fault, up to three generations of triangular facets exist thus indicating a long period of tectonic activity of this structure. No instrumental or historical earthquakes have been reported along this fault.

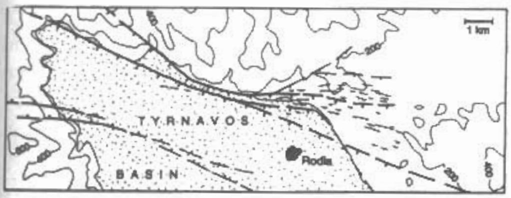

Fig. 6: Sketch map of the Rodia Fault System. Morphotectonic scarps as thin barbed lines. Dotted areas are Pleistocene-Holocene deposits. See Fig. 1 for location.

Tyrnavos Fault (Fig. 7).

Located in the homonymous Tyrnavos Basin, it is a 12 km long north-dipping normal fault affecting substratum rocks as well as Pliocene and Late Quaternary sediments (Caputo, 1993a). It is segmented in three parts with E-W and ESE-WNW strikes. The detailed structural analysis demonstrates that this fault was activated and generated in response to the Middle Pleistocene-Present tectonic regime. Both bedrock fault scarps and fresh fault scarps in unconsolidated deposits have been observed. But other fault-related morphologies such as a dammed river valley, truncated scree fans and the differential erosion of scree fans on the two sides of the fault, indicate a very young age of tectonic activity. Several stratigraphical and morphological criteria, allow the estimate of the long term slip rate ranging between 0.14 and 0.4 mma^{-1} (class B). According to the seismogenic parameters as derived from field investigations,

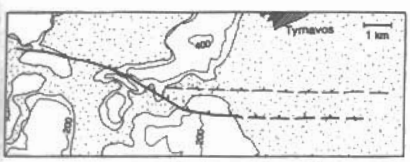

Fig. 7: Sketch map of the Tyrnavos Fault. Dotted areas are Pleistocene-Holocene deposits. See Fig. 1 for location.

the characteristic earthquake magnitude of the Tyrnavos Fault is 5.8-6.1 (Caputo, 1993a), consistent with that estimated for the 1731 earthquake (M=6.0; Papazachos and Papazachou, 1989) and located in this region. No younger seismic events have been recorded.

Gyrtoni Fault (Fig. 8).

It is parallel and synthetic with, but smaller than, the Rodia Fault. It is a 12-13 km long south-dipping normal fault with an ESE-WNW strike (Caputo, 1990a). The fault forms a several meters high scarp in poorly consolidated deposits of late Villafranchian(?) and younger age. Flat lying sediments cropping out in the footwall block show features related to syn- and post-sedimentary seismic activity (*i.e.* seismites). The western segment of the fault sharply dissects the northern sector of the Pinios alluvial plain where the river presents a diffuse meandering, with both abandoned and active segments, near the fault scarp (Caputo *et al.*, in press). According to morphological, archaeological and historical data, the southern block had a very recent subsidence and so is the tectonic activity (Helly *et al.*, in press). The long term slip rate is probably very low and the fault possibly belongs to class C.

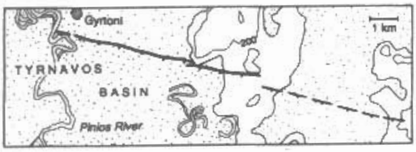

Fig. 8: Sketch map of the Gyrtoni Fault. Dotted areas are Pleistocene-Holocene deposits. See Fig. 1 for location.

Chasambali Fault System (Fig. 9).

It is a set of north-dipping minor faults antithetic to the Gyrtoni Fault. In Late Quaternary times, these faults played a crucial role for the palaeogeographic evolution of the area. In fact, they constrained the Pinios River to flow in the northern sector of the Larissa Plain which paradoxically stands at an altitude of 20 to 40 m higher than its southern sector (ex Karla Lake; Caputo *et al.*, in press). These faults affect latest Pleistocene and Holocene deposits and their recent morphogenic activity is confirmed by archaeological data (Helly *et al.*, in press). Some ground cracks several meters long and few centimetres wide recently opened along the Kastri Fault showing that very low but not instrumentally recorded seismic activity exists. The macroseismal epicentre of the 1941, Larissa earthquake (M=6.3) has been tentatively located in this area (Galanopoulos, 1950). In the bedrock NE of Larissa a series of ruptures striking NW-SE have been reported after the earthquake, but their relation with the seismogenic fault has not been established (see Ambraseys and Jackson, 1990). Also along the Asmaki Fault numerous ground ruptures occurred and this suggests that the seismogenic structure could have been one of the faults of the Chasambali E-W trending system. The morphologically estimated long term slip rate is low and all three faults belong to class C.

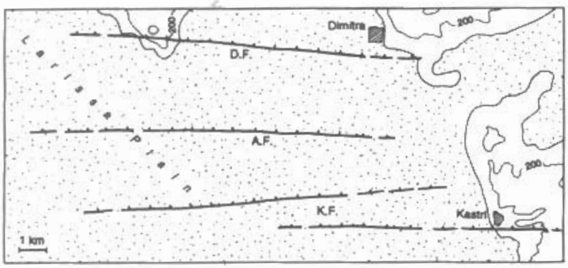

Fig. 9: Sketch map of the Chasambali Fault set. Dotted areas are Pleistocene-Holocene deposits. See Fig. 1 for location.

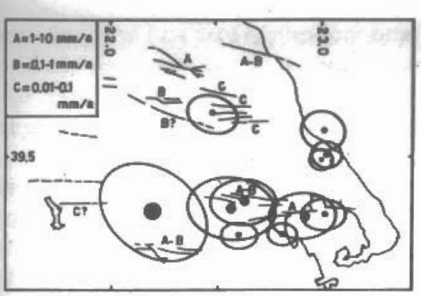

Fig. 10: Tentative reconstruction of the seismogenic volumes associated to the major earthquakes (M>6.0, full circles) occurred during the present century. In these volumes, the tectonic stresses are supposed to have been temporarily released due to the shocks. For the major active faults of Thessaly, the degree of activity is also represented. A similar recent tectonic activity between the northern and southern sectors of the region is clear. In contrast, the distribution of the present-day seismic activity is concentrated to the south and thus the north represents a possible seismic gap.

DISCUSSION

The results of the neotectonic, morphotectonic and seismotectonic researches recently carried out in Thessaly, show that several Late Quaternary faults affected the region, while for most of them a very recent tectonic activity has been demonstrated (Caputo, 1990a; 1990b; 1993a; 1993b; Caputo *et al.*, in press). All these active faults consist of complex shear zones and are always more or less segmented. They are made of prevailing newly generated E-W trending segments but also of older inherited NW-SE trending structures. Also in other regions of Greece, similar multi-fractured seismogenic areas have been recently described (Pavlides, 1993).

According to the map of Late Quaternary and active faults of Thessaly (Caputo and Pavlides, 1993) the fault density and the distribution in the northern and southern sectors does not differ significantly (fig. 1). Also, if we consider the important parameter of the long term slip rate which has been estimated for most of the faults, the recent morphotectonic activity of the region seems uniform and similar for the two sectors (Fig. 10).

On the other hand, from the distribution of the epicentres relative to the earthquakes of the present century (Fig. 2), it is clear that only the southern structures have been reactivated. In particular if we take into account the major shocks occurred during the last few decades, whose associated morphogenic faults have been identified, the same geographically diversified seismic behaviour is manifest. With the exception of the 1941, Larissa morphogenic earthquake and the few not well located earthquakes of northern Pilion region, all events occurred in the southern sector.

As a consequence of an earthquake, the crustal volume around the hypocenter suffers a strong stress release. In Fig. 10 there are tentatively represented the volumes associated to the major (M>6.0) earthquakes occurred in Thessaly during this century assuming they are roughly proportional to the magnitude and related to the geometric parameters of the associated faults. Within these volumes, the tectonic stresses are supposed to have been suddenly and temporarily released. According to the distribution of the active faults and their degree of fault activity, it is possible the northern sector represents a large seismic gap.

The work is still in progress in order to perform the third step of the project (*i.e.* palaeoseismicity of Thessaly). Several potential sites have been recognised along most of the previously described active faults where the digging of exploratory trenches, microstratigraphic studies and sampling for radiochronological dating will be preferably carried out. This new investigating approach will probably enhance our knowledge concerning the last few thousand years of seismic activity along these faults and potentially will enable us to estimate a much shorter long term slip rate and a more precise return period for morphogenic earthquakes.

In the northern sector of Thessaly, further and complementary research is certainly required. At this regard, geodetic surveying of these structures by classical surface techniques or by advanced satellite supported methodologies (GPS, VLBI *etc.*) and the installation of a local network of seismographs for recording the microseismicity of the area will be extremely useful and they are welcome. Nonetheless, from the present research, solely based on geological (structural and morphotectonic) data, it is clear that the northern tectonic structures induce a seismic hazard for the area much higher than previously supposed. If we consider also the dense population in the surrounding region, particularly being so close to the city of Larissa, and the soft materials on which most of the buildings in this area are constructed, the northern Thessaly area is likely to have a high potential seismic risk.

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