ANNALI DI GEOFISICA, VOL. XXXVIII, N. 1, March 1995

Inference of a seismic gap from geological data: Thessaly (Central Greece) as a case study

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Abstract
As a result of neotectonic, morphotectonic and seismotectonic research it is now possible to draw detailed maps 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, the degree of fault activity (*i.e.* the long-term slip-rate) has been also assigned ranging from 0.05 to 4 mm/yr^{-1}. In the present work, the main morphotectonic features and seismotectonic characteristics of the more important faults are recalled from previous works, while the recent tectonic activity is compared with the seismic activity of the area. The occurrence of both large ($M > 6.0$) and moderate ($M \leq 6.0$) earthquakes during the present century is concentrated in the southern sector. Earthquakes have been virtually absent in the northern part of the region during the same period. In contrast, according to geological and geomorphological criteria, the recent (Late Quaternary) tectonic evolution of the region and the overall extensional rate do not seem to differ significantly in the two sectors. Although palaeoseismological trenches, geodetic surveying and the record of the microseismic activity may enhance our knowledge of this problem, on the basis of available geological (structural and morphological) data, it is likely that the northern sector of Thessaly represents a large seismic gap. The implications on seismic hazard in one of the more populated regions of Greece are also discussed.

Key words *seismic gap – morphotectonics – seismotectonics – Greece*

1. Introduction

From the tectonic point of view, the whole Aegean region can be considered a large scale natural laboratory where many kinds of deformational environments, from plastic to brittle, from deep to shallow and from extensional to compressional, have been and are generated. As a consequence, unravelling the deformational history of the region has been a challenge for many geologists during the last four decades (Brunn, 1956; Aubouin, 1959; Celet, 1962; Dercourt, 1964; Godfriaux, 1968; Mercier, 1968; Pegoraro, 1972; Lemeille, 1977; and others).

Whilst 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 on the existence of minor or local phases of deformation and their exact chronology, the state of the science on this topic indicates a tectonic stratigraphy largely accepted by 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) including Thessaly (Caputo, 1990a).

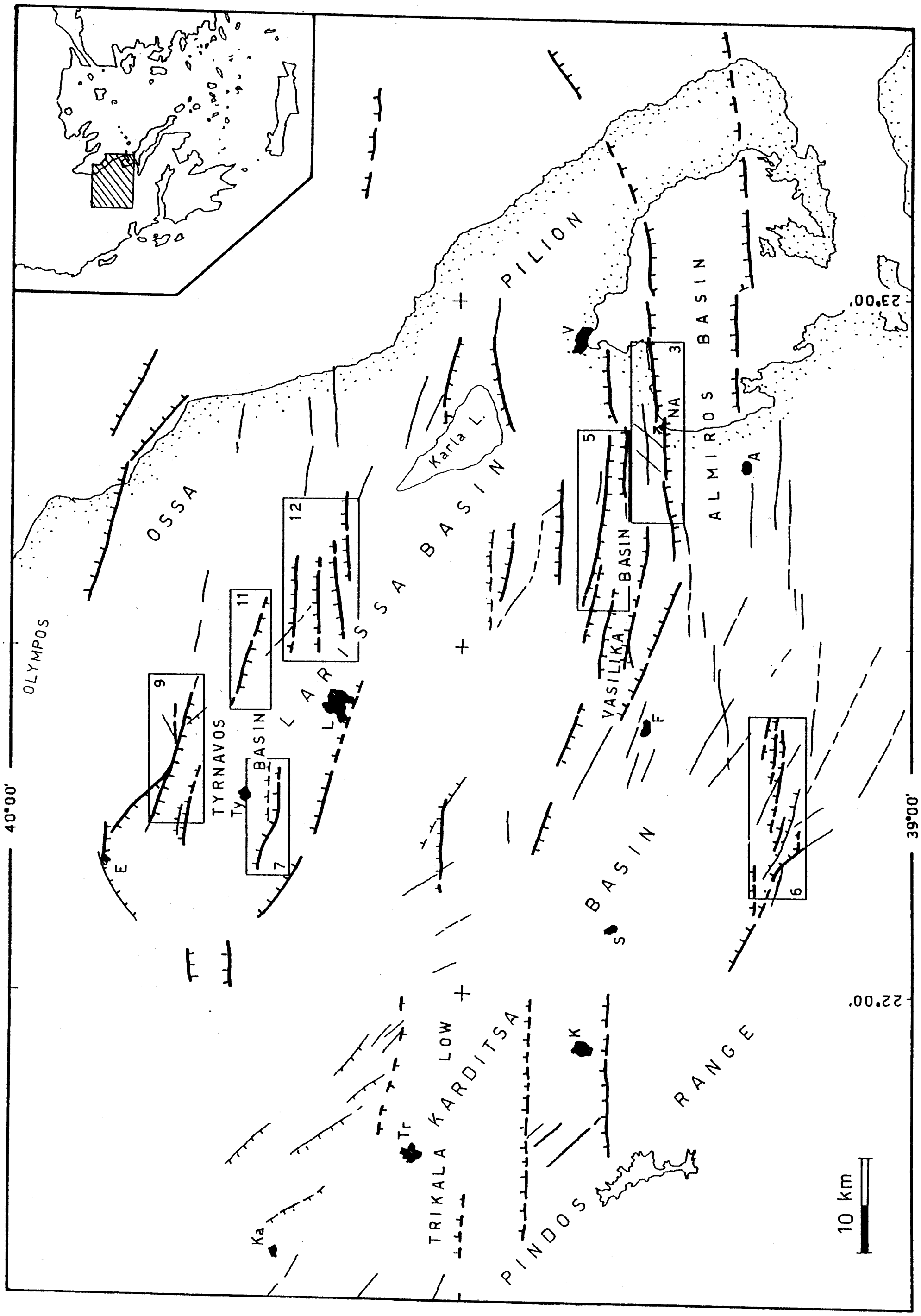

Fig. 1. Simplified tectonic map of Thessaly. The major Late Quaternary and active faults are represented in thick lines; barbs on the downthrown side (modified from Caputo and Pavlides, 1993). Boxes and number inside refer to corresponding figures.

Structural mapping has been compiled for this region of continental Greece and, according to a detailed quantitative structural analysis, several tectonic phases have been distinguished since Miocene times (Caputo, 1990a). In particular, the last phase started during Middle Pleistocene and it is still active in Thessaly, where crustal deformation is characterised by pure extension, with a N10°E average direction of the least principal stress axis, σ_3.

According to the classification suggested by the Research Group for Active Faults of Japan (RGAFJ, 1992), the degree of fault activity has been classified as class A (10 mm/yr^{-1} > $S \geq$ 1 mm/yr^{-1}), class B (1 mm/yr^{-1} > $S \geq$ 0.1 mm/yr^{-1}) or class C (0.1 mm/yr^{-1} > $S \geq$ 0.01 mm/yr^{-1}).

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), the last (Middle Pleistocene-Present) tectonic phase also affected the region by generating a new system of relatively small basins with a general E-W trend (fig. 1). This younger graben system has been superimposed onto the inherited NW-SE trending one, causing the complex blocky pattern we can see today.

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 focal mechanisms (*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 of Thessaly only the focal mechanisms relative to the 1980 Volos earthquakes (main, fore- and aftershocks) and the 1985 Almyros earthquake are available (Papazachos *et al.*, 1983; Taymaz, *et al.*, 1991) as well as a unique *in-situ* measurement near Pharsala (see Caputo and Pavlides, 1993, for full references and detailed analyses of all available data). The observations from both geophysical methods confirm a present-day N-S extension, while historical and instrumental records from the region show considerable seismic activity (table I).

If we take into account the epicentral distribution of the present century (fig. 2), an apparent anomaly is evident for Thessaly. In the southern sector, the seismic activity is widespread while in the northern sector it is almost completely absent. It is also important to note that both large (M > 6.0) and moderate (4.0 < $M \leq$ 6.0) size earthquakes follow this distribution. Therefore, two possible and alternative solutions may be proposed to explain this pattern. First, a northern rigid, independent and non-deforming block exists or, second, the northern region represents a large seismic gap. It is implicit that the two contrasting solutions support very different implications and consequences. Accordingly, the evaluation of seismic hazard in one of the more populated regions of Greece would be greatly affected. The aim of the present research is to contribute to the selection of the correct solution by geological investigations.

The seismic gap hypothesis is commonly referred to segments of plate boundaries that have not ruptured in large earthquakes in many decades and which are the most likely sites of future large earthquakes (McCann *et al.*, 1979; Sykes and Nishenko, 1984; Bolt, 1993). Thessaly is certainly not an interplate boundary. However, I suggest the same concept can be applied to any active fault where the slip rate and the recurrence time are reasonably known and an earthquake is expected to occur in the future though of moderate size.

During the last decade, a project has been undertaken to study the recent tectonic evolution of Thessaly. The programme was divided into three major steps: neotectonics, morphotectonics and palaeoseismicity. The first step has already been achieved. Complete data with results are published in specific papers (Caputo, 1990a; Caputo and Pavlides, 1993) as are data and results obtained from the morphotectonic approach (Caputo, 1990b; 1993a; 1995; Caputo *et al.*, 1994). Indeed, the geomorphology of Thessaly is predominantly controlled by tectonic activity. Palaeoseismicity work is in progress. In the present research, to allow the analysis of the possible seismic gap in the northern part of the study area, most morphotectonic results from the above mentioned papers will be referred to.

Table I. List of the earthquakes which occurred from 510 B.C. to 1985 in Thessaly, Central Greece. Data from Comninakis and Papazachos (1982, 1986), Papazachos and Papazachou (1989) and Ambraseys and Jackson (1990).

Date			Hour	Latitude (N)	Longitude (E)	*M*
510 B.C.				39.4	22.3	7.0
1544	Apr.	22		39.0	22.4	6.6
1566	Jul.	11		39.0	21.7	6.5
1621	Feb.	24		39.4	22.0	6.2
1661	Mar.	31		39.4	22.1	6.1
1668	Aug.			39.6	22.4	6.2
1674	Jan.	26	07:	39.4	21.9	6.2
1731				39.6	22.5	6.0
1735	Sep.	01	06:	39.5	21.8	6.5
1743	Feb.	12		39.3	22.8	6.8
1766	Nov.	09		39.7	22.2	6.3
1773	Mar.	16	08:	39.3	22.7	6.6
1781	Aug.	28		39.6	22.5	6.3
1787	Jun.	19	03:	39.5	21.9	6.0
1868	Oct.	03	23:30:	39.2	23.4	6.3
1905	Jan.	20	02:32:30	39.6	23.0	6.0
1909	Jun.	15	23:30:30	39.1	22.2	5.7
1911	Oct.	22	22:31:45	39.5	23.0	6.0
1915	Jun.	04	17:22:02	39.1	21.5	5.8
1916	Feb.	06	13:14:58	39.2	23.2	5.0
1916	Feb.	06	14:39:40	39.1	23.5	5.8
1916	Feb.	06	15:17:38	39.1	23.5	5.0
1918	Sep.	06	12:32:18	39.0	21.5	4.9
1919	Feb.	25	23:33:30	39.3	23.5	5.3
1919	Feb.	26	23:04:27	39.3	23.5	5.0
1922	Mar.	15	05:12:35	39.3	22.8	4.9
1930	Feb.	23	18:19:12	39.5	23.0	6.0
1930	Mar.	31	12:33:48	39.5	23.0	6.1
1936	Mar.	26	03:07:56	39.5	22.7	5.0
1940	Oct.	21	22:02:03	39.0	22.7	4.9
1941	Mar.	01	03:52:47	39.6	22.5	6.3
1941	Mar.	01	07:51:08	39.6	22.5	5.1
1941	Mar.		15:00.55	39.6	22.5	4.9
1941	May	14	08:36:21	39.5	22.6	5.5
1941	May	16	01:27:48	39.5	22.6	5.3
1942	Jun.	01	09:01:18	39.3	22.4	5.2
1942	Jun.	01	09:17:40	39.3	22.4	5.6
1942	Jun.	01	22:10:21	39.3	22.4	5.0
1951	Jan.	21	18:51:16	39.1	23.0	4.9
1951	May	08	19:09:29	39.5	21.5	4.9
1951	Aug.	24	15:19:32	39.1	22.4	4.5
1951	Oct	13	16:42:27	39.0	23.4	5.3
1953	Apr.	13	12:51:11	39.0	22.6	4.8
1953	Jul.	03	02:37:50	39.2	23.4	4.8
1953	Jul.	03	02:45:00	39.2	23.4	4.7
1954	Apr.	25	20:03:46	39.3	22.2	4.6
1954	Apr.	30	13:02:36	39.3	22.2	7.0
1954	Apr.	30	19:33:30	39.3	22.2	5.1

Table I (*continued*).

Date			Hour	Latitude (N)	Longitude (E)	*M*
1954	May	01	02:41:54	39.3	22.2	4.7
1954	May	03	17:46:11	39.3	22.2	4.6
1954	May	04	16:43:20	39.3	22.2	5.6
1954	May	04	16:45:27	39.3	22.2	5.7
1954	May	04	23:44:54	39.3	22.2	5.0
1954	May	05	00:58:05	39.3	22.2	4.6
1954	May	05	02:58:49	39.3	22.2	4.6
1954	May	07	08:33:15	39.3	22.2	4.5
1954	May	09	16:13:02	39.3	22.2	4.7
1954	May	09	20:13:20	39.3	22.2	4.6
1954	May	16	15:58:48	39.3	22.2	4.5
1954	May	17	11:17:12	39.3	22.2	4.5
1954	May	25	22:03:32	39.3	22.2	5.6
1954	May	28	07:43:02	39.3	22.2	4.9
1954	Jun.	05	14:05:32	39.3	22.2	5.0
1954	Jun.	16	22:08:00	39.3	22.2	4.6
1954	Jul.	09	23:17:01	39.3	22.2	4.5
1954	Aug.	05	03:48:22	39.5	22.0	4.8
1954	Dec.	02	18:29:47	39.4	22.6	4.6
1955	Jan.	03	01:07:03	39.2	22.1	5.6
1955	Jan.	08	07:53:01	39.2	22.0	5.1
1955	Feb.	21	19:46:44	39.4	23.1	4.9
1955	Apr.	19	16:47:19	39.3	23.0	6.2
1955	Apr.	21	07:18:19	39.3	23.1	5.8
1955	May	13	19:54:32	39.3	23.0	4.8
1955	Oct.	09	14:19:22	39.0	22.8	4.6
1956	Jan.	21	09:50:55	39.5	22.2	4.9
1956	Mar.	13	20:21:14	39.5	21.5	4.5
1956	Mar.	26	22:51:00	39.5	21.9	4.5
1956	Mar.	28	11:39:15	39.5	21.9	4.6
1956	May	18	22:08:28	39.0	22.8	5.1
1956	Jun.	26	06:27:40	39.5	22.2	5.0
1956	Nov.	02	16:04:33	39.3	23.1	5.6
1957	Mar.	08	12:14:14	39.3	22.7	6.5
1957	Mar.	08	12:21:13	39.3	22.6	6.8
1957	Mar.	08	12:54:06	39.3	22.7	4.9
1957	Mar.	08	20:30:40	39.3	22.7	4.5
1957	Mar.	08	20:37:57	39.3	23.0	5.4
1957	Mar.	08	23:35:09	39.2	22.8	6.0
1957	Mar.	09	04:01:42	39.3	22.6	4.7
1957	Mar.	09	10:29:36	39.3	22.7	4.5
1957	Mar.	11	07:19:14	39.3	22.7	4.6
1957	Mar.	11	09:31:14	39.3	22.7	5.2
1957	Mar.	11	13:26:50	39.3	22.7	4.7
1957	Mar.	11	13:39:36	39.3	22.6	5.2
1957	Mar.	24	06:24:07	39.6	22.9	4.7
1957	Mar.	26	23:23:30	39.3	22.7	4.6
1957	Mar.	28	22:26:01	39.3	22.7	5.5
1957	May	12	07:52:31	39.3	22.7	4.8
1957	May	13	06:34:33	39.4	22.6	4.7

Table I (*continued*).

Date			Hour	Latitude (N)	Longitude (E)	*M*
1957	May	21	13:24:18	39.4	22.8	5.6
1957	Jun.	27	07:10:55	39.4	22.7	4.8
1957	Jul.	13	03:31:41	39.4	22.7	4.6
1957	Sep.	17	21:10:30	39.5	23.0	4.6
1957	Sep.	20	02:19:24	39.5	23.0	4.9
1957	Sep.	21	16:50:22	39.5	23.0	4.6
1957	Oct.	24	22:45:10	39.4	23.1	4.5
1957	Oct.	25	02:18:33	39.4	23.1	4.5
1957	Nov.	27	03:08:04	39.2	22.6	5.6
1959	Apr.	25	09:31:00	39.5	22.8	4.7
1959	May	14	00:55:54	39.8	23.3	4.5
1960	Jun.	03	02:31:06	39.0	23.2	4.5
1961	Jan.	28	07:18:16	39.4	22.0	4.9
1962	Sep.	24	23:30:10	39.3	22.0	4.7
1965	Jun.	03	18:31:51	39.7	23.2	5.0
1966	Feb.	05	02:01:45	39.1	21.7	6.2
1966	Feb.	05	02:11:08	39.2	21.9	5.0
1966	Feb.	05	02:58:01	39.1	21.9	5.3
1966	Oct.	21	16:17:04	39.5	22.1	4.7
1966	May	04	04:46:19	39.5	21.5	4.5
1966	May	04	13:13:36	39.8	21.5	4.5
1966	May	04	13:31:08	39.6	21.3	4.8
1966	May	05	06:26:38	39.6	21.5	4.7
1966	May	09	08:0:47	39.7	21.4	4.6
1969	Feb.	21	18:39:57	39.1	21.9	4.6
1969	May	16	07:27:01	39.1	21.8	5.2
1971	Jun.	20	02:04:07	39.1	21.8	4.5
1975	Apr.	18	20:59:10	39.0	23.4	4.5
1976	Feb.	22	12:02:53	39.4	22.1	5.2
1976	Feb.	22	22:01:49	39.4	22.1	4.8
1976	Feb.	22	22:54:35	39.4	22.1	4.8
1976	Aug.	19	22:36:25	39.1	22.1	4.5
1977	Apr.	05	17:15:09	39.3	23.3	4.5
1977	May	13	18:17:44	39.1	23.5	5.0
1978	Jan.	31	06:39:19	39.3	22.9	4.6
1979	Feb.	07	10:16:48	39.6	23.3	4.7
1979	Jun.	21	02:09:53	39.6	22.2	4.5
1980	Jan.	21	07:47:03	39.3	22.9	4.7
1980	Jan.	25	23:08:15	39.2	23.0	4.5
1980	Jul.	04	20:20:16	39.3	22.9	4.9
1980	Jul.	05	05:34:37	39.2	23.0	4.5
1980	Jul.	05	08:06:10	39.3	22.9	4.5
1980	Jul.	06	05:34:43	39.2	22.9	5.1
1980	Jul.	07	16:04:42	39.3	22.9	4.9
1980	Jul.	08	02:59:31	39.2	22.9	4.6
1980	Jul.	09	02:10:20	39.3	22.9	5.4
1980	Jul.	09	02:11:57	39.3	22.9	6.5
1980	Jul.	09	02:35:52	39.2	22.6	6.1
1980	Jul.	09	06:01:48	39.3	22.9	5.1
1980	Jul.	09	06:11:07	39.2	23.0	4.5

Table I (*continued*).

Date			Hour	Latitude (N)	Longitude (E)	*M*
1980	Jul.	09	16:06:01	39.2	22.9	4.5
1980	Jul.	10	19:39:03	39.3	22.9	5.4
1980	Jul.	15	00:31:42	39.3	23.1	4.7
1980	Jul.	15	11:34:54	39.3	23.1	4.8
1980	Jul.	16	00:06:59	39.3	22.6	5.0
1980	Jul.	24	10:44:12	39.3	23.0	4.7
1980	Jul.	29	20:41:31	39.3	23.0	5.0
1980	Aug.	11	09:16:00	39.3	22.7	5.3
1980	Aug.	12	01:41:06	39.3	22.7	4.8
1980	Sep.	26	04:19:21	39.3	22.8	4.8
1980	Oct.	21	02:35:43	39.3	23.0	4.6
1980	Oct.	21	04:07:18	39.3	23.0	4.8
1981	May	06	00:18:25	39.3	22.8	4.8
1982	Aug.	05	11:05:44	39.3	23.0	4.6
1984	Dec.	07	00:09:24	39.3	22.9	4.5
1984	Dec.	15	09:01:22	39.9	22.7	4.8
1985	Apr.	30	18:14:13	39.3	22.8	5.8
1985	Sep.	21	10:13:11	39.0	22.3	4.8

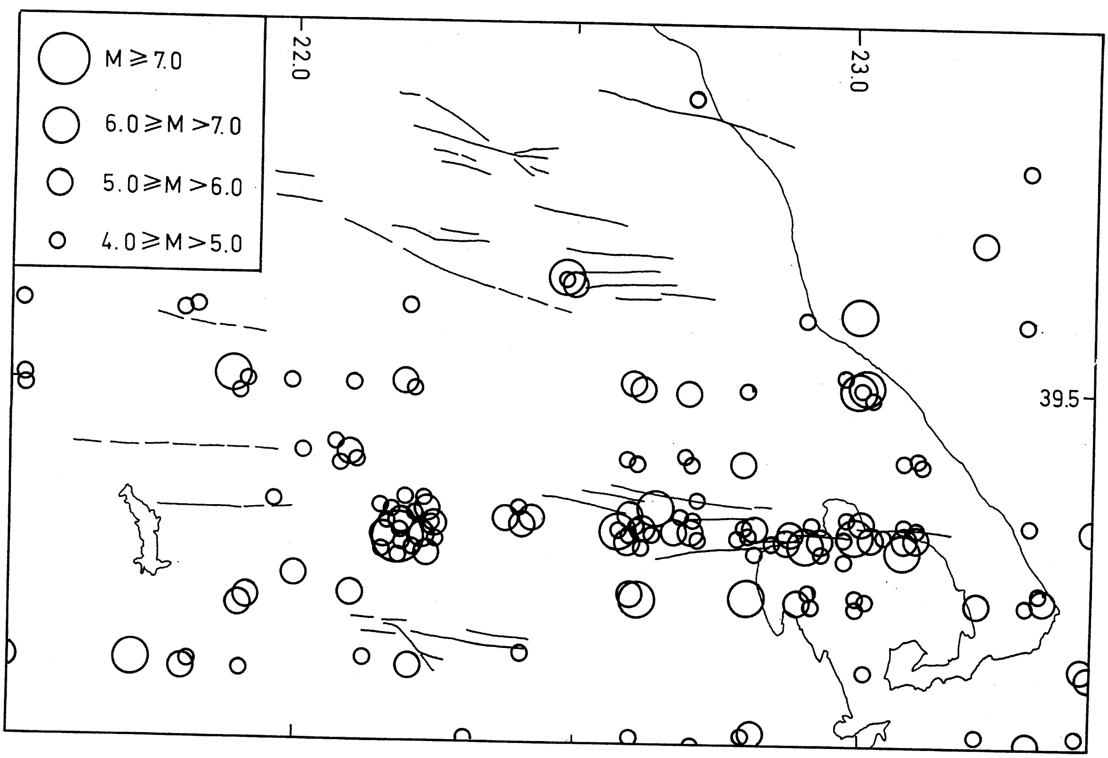

Fig. 2. Map of the epicentral distribution of Central Greece for the period 1901-1985 (from Comninakis and Papazachos, 1986). The major active faults of Thessaly, have been simplified from fig. 1.

2. Late Quaternary faulting

While for the first neotectonic investigations, geological and structural mapping was undertaken 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 phase (fig. 1). In particular, special care was taken for all faults showing features of very recent activity. In order to understand their geometry and kinematics in detail, a different specific approach was employed. The morphotectonic survey of all these structures was carried out using maps at the scale 1:5000, and aerial photographs at the scale 1:33 000.

Most of the faults generated during the Middle Pleistocene-Present tectonic phase trend 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 (M = 7.0) where oblique-slip motion occurred along ground ruptures of such direction (see lateron).

The degree of fault activity, which is expressed as the long-term average slip-rate, S, has been estimated for most of the active faults and this is mainly based on the amount of displacement of stratigraphic markers. When stratigraphic data are not sufficient for dating, the «freshness» of the morphotectonic features are tentatively used. All the morphological features observed along or near each of the studied faults were also classified as fault-generated morphologies or fault-related features. Numerous examples of both types were observed all over Thessaly. In the following sections, the most representative active faults of the southern and northern sectors of Thessaly are briefly described.

2.1. *Nea Anchialos Fault* (fig. 3)

The Nea Anchialos Fault is one of the more prominent tectonic features of Thessaly (fig. 1). It trends E-W and it bounds the northern margin of the Late Quaternary Almyros Basin which nowadays is partly submerged in the Pagasitikos Gulf. Pleistocene sediments and basalts are affected by normal faulting, the geometry and kinematics of which indicate N-S extension. On July 9, 1980 a morphogenic earthquake, that is a seismic event able to generate surficial deformation along the fault it activates (Caputo, 1993b), with magnitude 6.5 occurred in the area (fig. 4). The focal mechanisms, the distribution of the seismic sequence, the shape of the isoseismal map and the ground ruptures indicate that this major fault was activated during the quake (Papazachos *et al.*, 1983). As well as geological and seismological

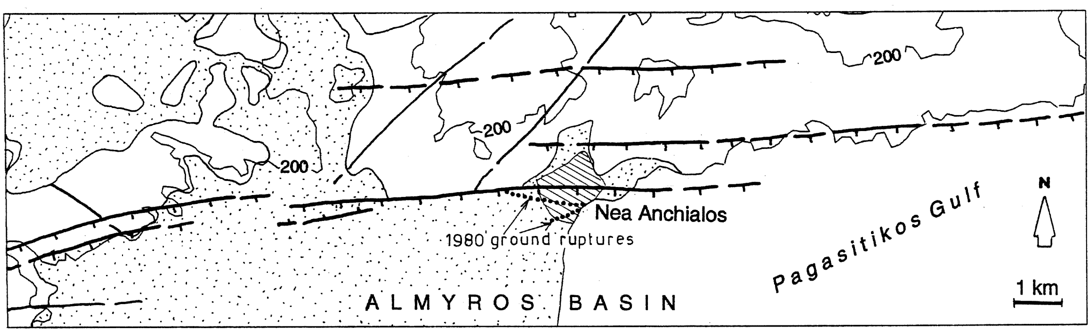

Fig. 3. Sketch map of the Nea Anchialos Fault. Topographic contours every 200 m. Thick lines represent major Late Quaternary faults with barbs on the downthrown side. Dotted lines represent the ground ruptures which occurred during the 1980 Volos earthquake (M = 6.5). Dotted areas are Pleistocene-Holocene deposits and Quaternary basalts. See fig. 1 for location. Modified from Caputo (1990a).

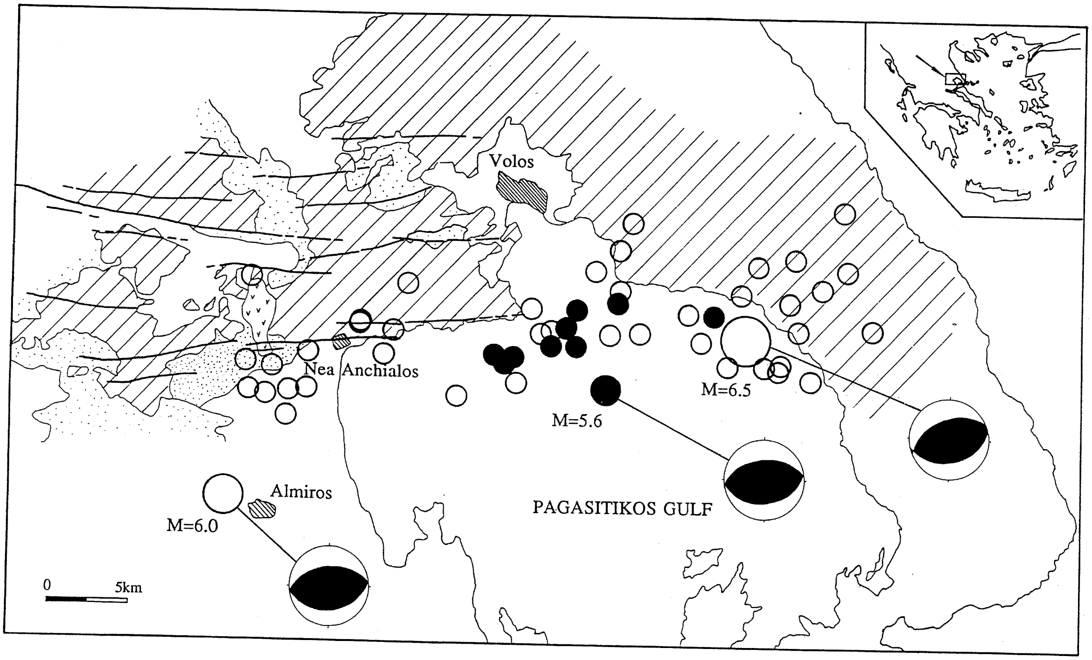

Fig. 4. The distribution of the epicenters of the shocks with $M \geq 4.2$ of the Volos 1980 seismic sequence (modified from Papazachos *et al.*, 1983). Full circles: fore-shocks; open circles: after shocks. The computed relative focal mechanisms are shown.

data, archaeological data have also been collected in the area. A palaeochristian aqueduct crops out in the footwall block near the main escarpment along a valley which was naturally entrenched clearly after the construction of the structure (Caputo, 1990b). According to the age of the construction (3rd-4th century A.D., P. Lazarides, personal communication, 1990) and applying simple morphological criteria, the historic-time slip-rate along the fault zone was tentatively inferred (Caputo, 1990b). It amounts to 2-3 mm/yr (class A of RGAFJ, 1992) and is comparable to the long-term slip-rate estimated for geological times responsible for the genesis of the Almyros Basin (Middle-Late Quaternary).

2.2. *Righeo Fault* (fig. 5)

The Righeo Fault forms the northern border of the eastern sector of the Vasilika Basin, a Late Quaternary narrow asymmetric graben (fig. 1). The fault seems to be a continuous structure with a total length of more than 20 km. Deposits of Late Pleistocene age are affected by this E-W trending south-dipping structure which shows a sharp straight morphological scarp from several tens to hundreds of metres high along its length. On March 8, 1957 near the village of Velestino two earthquakes occurred seven minutes apart 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 mapping, the distribution of the macroseismic epicenters of the main shock and of the aftershocks (Ambraseys and Jackson, 1990) strongly supports the hypothesis that the Righeo Fault was the seismogenic structure of the 1957 Velestino earthquakes (Caputo, 1990a). Though the isoseismal map inferred from macroseismic data is probably

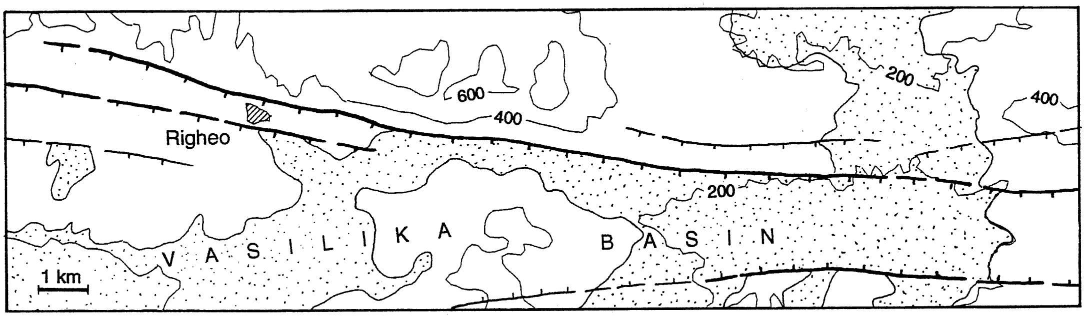

Fig. 5. Sketch map of the Righeo Fault. Topographic contours every 200 m. Thick lines represent major Late Quaternary faults with barbs on the downthrown side. Dotted areas are Pleistocene-Holocene deposits. See fig. 1 for location. Modified from Caputo (1990a).

«cumulative» of the two earthquakes and thus doubtful, it clearly shows an E-W trending seismic structure (Papazachos *et al.*, 1982). Although no exact slip-rate has been computed, according to morphotectonic criteria, the fault is certainly within the range of classes A or B.

2.3. *Domokos Fault System* (fig. 6)

The Domokos Fault System is a shortly segmented complex fault system bordering the southern edge of the Oligocene-Pliocene Karditsa Basin (Western Thessaly, Caputo, 1990a). In Late Cainozoic times, the area suffered a strong brittle deformation and was severely fractured by several tectonic phases that generated the prevailing NW-SE structures. Within this inherited system, the E-W trending fault segments generated during the Late 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 were reactivated (Papastamatiou and

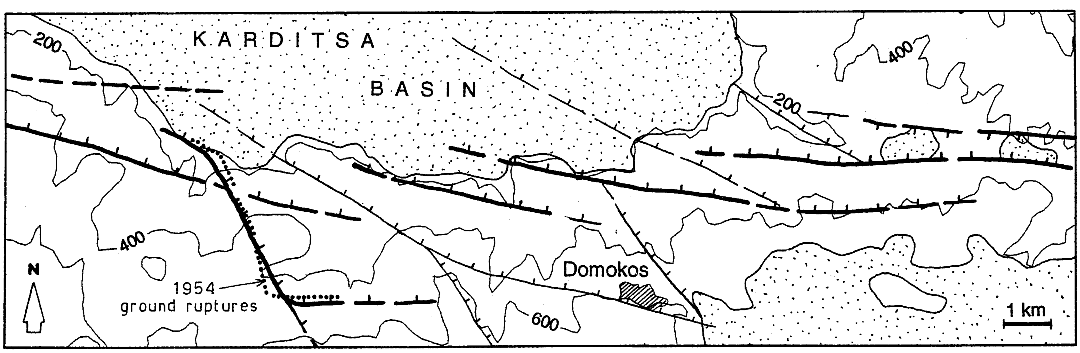

Fig. 6. Sketch map of the Domokos Fault System. Topographic contours every 200 m. Thick lines represent major Late Quaternary faults with barbs on the downthrown side. Dotted lines represent the ground ruptures which occurred during the 1954 Sophades earthquake ($M = 7.0$; modified from Papastamatiou and Mouyaris, 1986). Dotted areas are Pleistocene-Holocene deposits. See fig. 1 for location. Modified from Caputo (1990a).

Mouyaris, 1986). Several ground ruptures occurred along both E(SE)-W(NW) and (N)NW-(S)SE directions showing dip-slip and oblique-slip left-lateral motion, respectively, with maximum throws of 90 cm. The observed kinematics are compatible with the N-S direction of extension as obtained from neotectonic data. This is in contrast with the focal mechanism presented by McKenzie (1972) which is probably unreliable because based on short period seismic recordings. Moreover, the distribution of the epicenters (main and aftershocks) based on macroseismic data (Ambraseys and Jackson, 1990) confirms the existence at depth of an E-W trending seismogenic zone reaching the surface *via* inherited structures and thus generating about 30 km of discontinuous ground ruptures along an average N120°E direction. As for the Righeo Fault, also in this case the slip-rate ranges within classes A or B.

2.4. *Tyrnavos Fault* (figs. 7 and 8)

A 12 km long north-dipping normal fault, located in the homonymous Tyrnavos Basin (fig. 1), affects substratum rocks as well as Pliocene and Late Quaternary sediments. It is segmented in three parts with E-W and ESE-WNW strikes. Detailed structural analysis demonstrates that this fault was activated and generated in response to the Middle Pleistocene-Present tectonic regime (Caputo, 1993a). Both bedrock fault scarps and fresh fault scarps in unconsolidated deposits were 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 an estimate of long-term slip-rates ranging between 0.14 and 0.4 mm/yr^{-1} (Caputo, 1993a) corresponding to class B of RGAFJ (1992). According to the fault geometry and the seismogenic parameters as derived from field investigations, 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 seismic events have been recorded more recently.

2.5. *Rodia Fault System* (figs. 9 and 10)

This is a 12-15 km long complex fault zone 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 (fig. 1). A persistent set of morphological scarps (fig. 10) affects Late Pleistocene and Holocene alluvial deposits: the parallelism, lateral continuity (several hundreds meters each), angular shape, uniformity in vertical throw (between 0.5 and 2 m) and constant

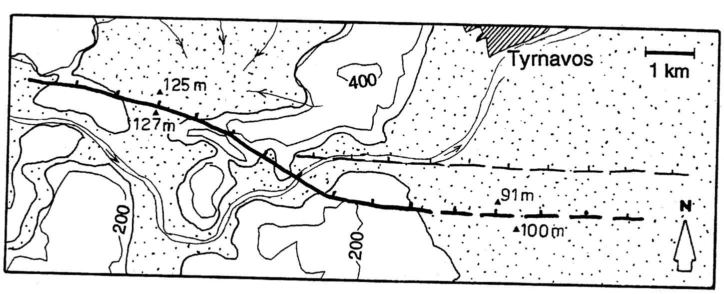

Fig. 7. Sketch map of the Tyrnavos Fault. Topographic contours every 200 m. Local altitudes in meters above sea level. Dotted areas are Middle Pleistocene-Holocene deposits. The major stream flowing eastwards is the Titarissios River. See fig. 1 for location. Modified from Caputo (1993a).

Fig. 8. Aerial photograph of the Tyrnavos Fault. Small arrows indicate streams flowing into the dammed valley, an alluvial plain whose drainage is constrained by recent faulting.

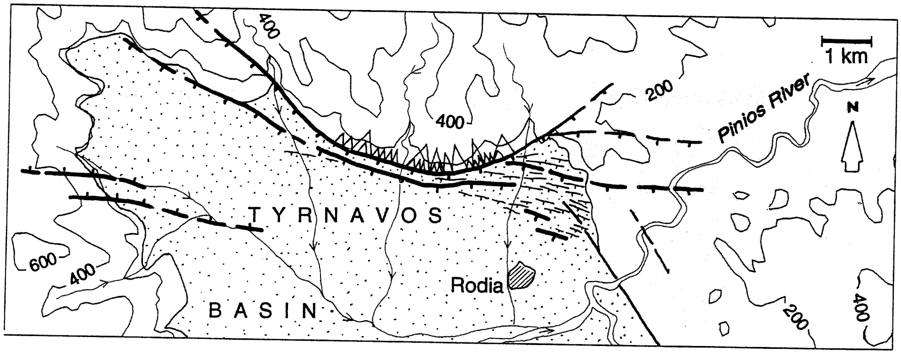

Fig. 9. Sketch map of the Rodia Fault System. Topographic contours every 200 m. Thick lines represent major Late Quaternary faults with barbs on the downthrown side. Morphotectonic scarps are represented as thin barbed lines. Triangular facets are also shown on the footwall block. Dotted areas are Late Pleistocene-Holocene deposits. See fig. 1 for location. Modified from Caputo (1994).

E-W direction of these scarps reflect their tectonic origin (Caputo, 1995). A typical basinward migration of faulting was also documented where the last morphogenic faulting affects Early Holocene deposits. According to the displacement of stratigraphic horizons and to other morphotectonic criteria such as morphotectonic scarps, triangular facets (fig. 10) and the thickness of shear zones in Upper Pleistocene deposits along faults, it is possible to estimate the long-term slip-rate as 1-4 mm/yr^{-1} (class A of RGAFJ, 1992). 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 located along this fault. However, two events (1766 and 1781 A.D.) with estimated magnitude of 6.3, were reported in the Northern Larissa plain (Papazachos and Papazachou, 1989). As a working hypothesis, one (or both) of these events could have occurred along this fault system.

2.6. *Gyrtoni Fault* (fig. 11)

This fault is parallel and synthetic with, but smaller than, the Rodia Fault (fig. 1). It is a 12-13 km long south-dipping normal fault with an ESE-WNW strike. The fault forms a 5 to 8 m high scarp in poorly consolidated deposits of probably late Villafranchian age (Daniela Esu, written communication, 1992). 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 meanders, near the fault scarp. According to morphological, archaeological and historical data, the southern hanging-wall block was subsiding throughout the Late Holocene, thus confirming a very recent tectonic activity (Helly *et al.*, 1995). A first estimate of the long-term slip-rate indicates a value below 0.1 mm/yr^{-1}. The fault thus belongs to class C.

2.7. *Chasambali Fault System* (fig. 12)

The Chasambali Fault System comprises a set of north-dipping minor faults antithetic to the Gyrtoni Fault (fig. 1). In Late Quaternary times, these faults played a crucial role in the palaeogeographic evolution of the area (Caputo *et al.*, 1994). 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

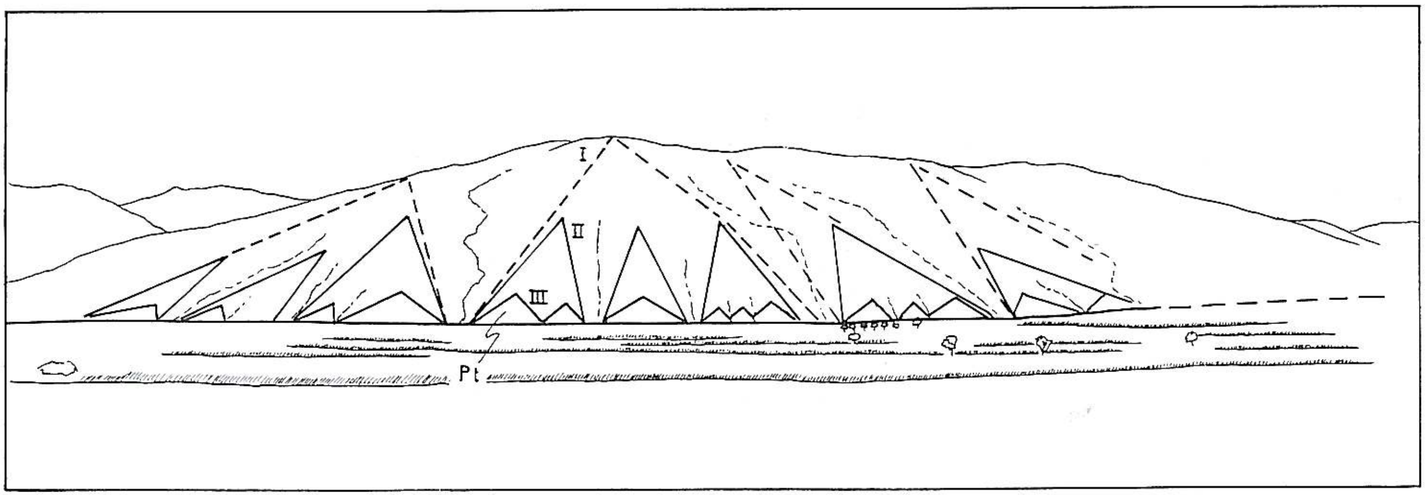

Fig. 10. The central sector of the Rodia Fault System: three generations of triangular facets are visible in the footwall block, while several morphotectonic scarps affect Late Pleistocene and Holocene deposits in the hanging-wall block.

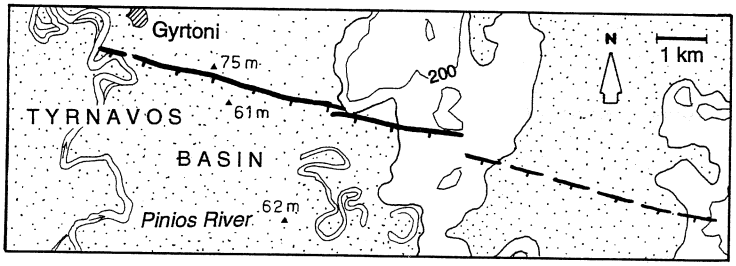

Fig. 11. Sketch map of the Gyrtoni Fault. Topographic contours every 200 m. Local altitudes in meters above sea level. Some abandoned meanders of the Pinios River are also shown. Dotted areas are Pleistocene-Holocene deposits. See fig. 1 for location. Modified from Caputo *et al.* (1994).

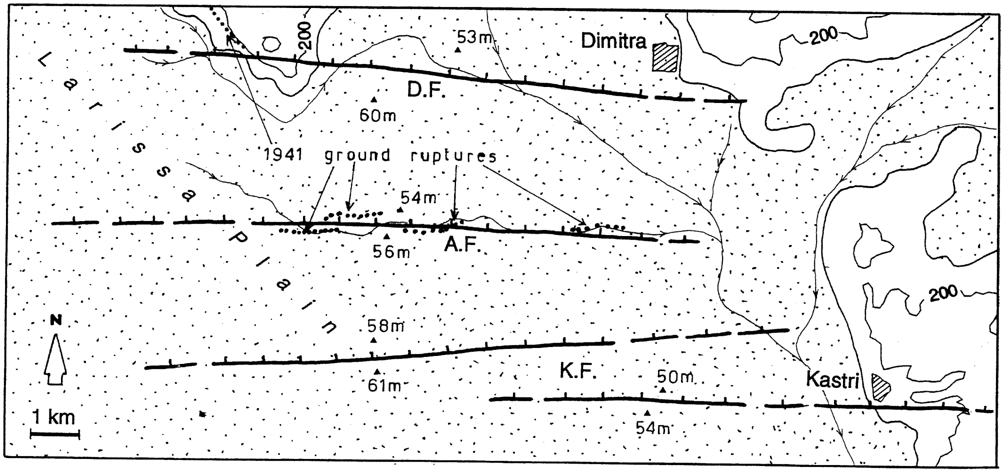

Fig. 12. Sketch map of the Chasambali Fault set. Topographic contours every 200 m. Local altitudes in meters above sea level. Dotted lines represent the ground ruptures occurred during the 1941 Larissa earthquake (M = 6.3). Dotted areas are Late Pleistocene-Holocene deposits. K.F. = Kastri Fault, A.F. = Asmaki Fault, D.F. = Dimitra Fault. See fig. 1 for location. A tectonically controlled hydrographic network is evident. Modified from Caputo *et al.* (1994).

(ex Karla Lake). These faults affect the latest Pleistocene and Holocene deposits and their recent morphogenic activity is also confirmed by archaeological data (Helly *et al.*, 1995). Some ground cracks several meters long and 2-3 cm 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 = 6.1) was tentatively located in this area (Galanopoulos, 1950). In the bedrock NE of Larissa a series of ruptures striking NW-SE were reported after the earthquake and tentatively assumed to be the seismogenic fault by Ambraseys and Jackson (1990). However, numerous ground fractures also occurred along the recently recognised Asmaki Fault (Caputo *et al.*, 1994) suggesting that one of the segments of this E-W trending fault system could have been the seismogenic structure of the

1941 Larissa earthquake. Because the dissected topographic surface of this area is Holocene (Caputo *et al.*, 1995), 0.1 mm/yr^{-1} is a minimum value for the long-term slip-rate assigning the fault to class B.

3. Discussion

The results of the neotectonic, morphotectonic and seismotectonic research recently carried out in Thessaly, show that several Late Quaternary faults affected the region, and that for most of them a very recent tectonic activity can be demonstrated (Caputo, 1990a,b; 1993a; 1995; Caputo *et al.*, 1994). All these active faults consist of complex shear zones and are commonly segmented. They are made of newly generated E-W trending segments but also of older inherited NW-SE trending structures. Similar multi-fractured seismogenic areas have recently been described in other regions of Greece (Pavlides, 1993).

According to the map of Late Quaternary and active faults of Thessaly (fig. 1) the fault density and distribution pattern in the northern and southern sectors does not differ significantly. Also, if we consider the important parameter of the long-term slip-rate which was estimated for most of the faults, the recent morphotectonic activity of the region seems uniform and similar for the two sectors (fig. 13).

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, or prevailingly, the southern structures have been

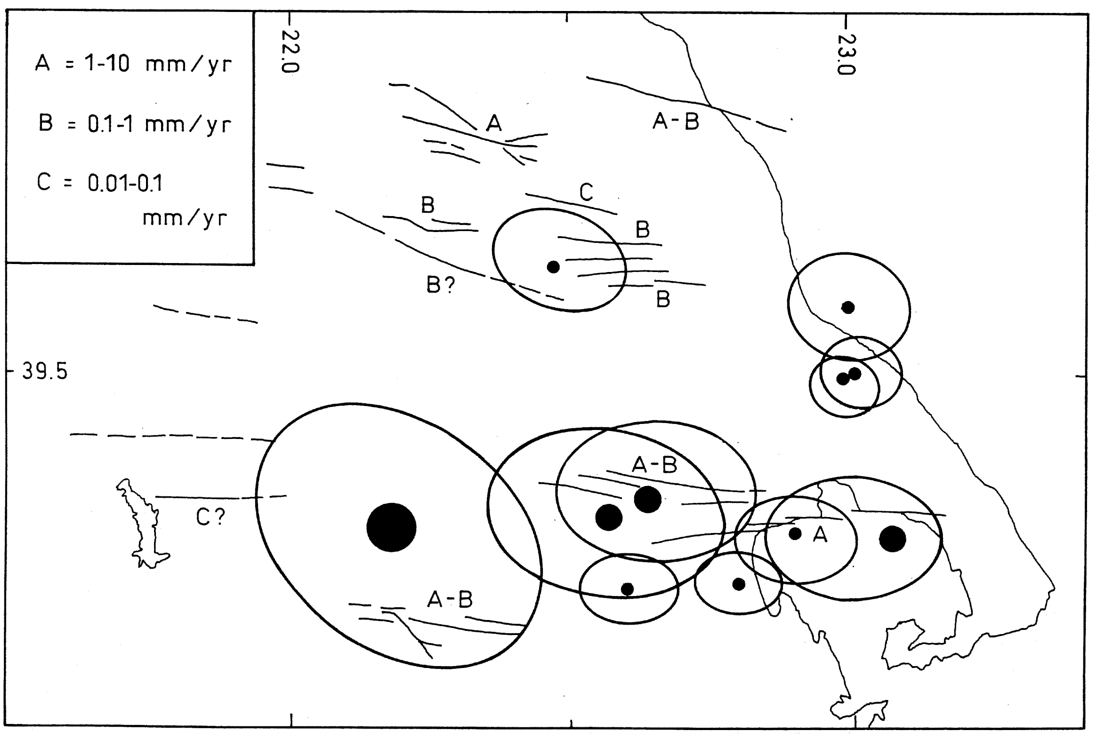

Fig. 13. Sketch map with the possible seismogenic volumes associated with the major earthquakes (full circles) which occurred during the present century. Within these volumes the tectonic stresses were probably mainly released. For the major active faults of Thessaly, the degree of activity as classified by RGAFJ (1992) is also represented. See text for discussion.

reactivated. In particular if we take into account the major shocks which have occurred during the last decades, whose associated morphogenic faults have been identified, the same geographically N-S diversified seismic behaviour is manifest. With the exception of the 1941, Larissa earthquake ($M = 6.1$), all the seismic events with magnitude higher than 6.0 occurred in the southern sector.

As a consequence of any earthquake, the crustal volume around the hypocenter suffers a strong stress release. In fig. 13, the volumes associated to the major earthquakes which occurred in Thessaly during this century are tentatively represented assuming they are roughly proportional to the magnitude, they are related to the geometric parameters of the associated faults as well as to the ground ruptures which occurred and the distribution of the aftershocks. Similar maps based on the degree VIII isoseismals and the rupture zones (Papadopoulos, 1992) are comparable to the proposed one.

In conclusion, it is very likely that the recurrence time of seismic events is of the order of few hundred years. This is a direct consequence of, first, the small size of the faults (generally less than 20 km), second, their intrinsic capacity to trigger earthquakes of moderate to small magnitude and, third, the relatively high slip-rates (classes A and B of many faults). Accordingly, and from the distribution of active faults, the hypothesis of a large seismic gap in the northern sector of Thessaly seems confirmed.

Work is still in progress 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 carried out. Although the data already collected and analysed in the present research support the proposed conclusions, this new investigating approach will enhance our knowledge concerning the Late Holocene seismic activity along these faults and potentially will enable us to estimate a short-term slip-rate and a more precise return period for morphogenic earthquakes.

In the northern sector of Thessaly, further complementary research will certainly be useful. In 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 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.

Acknowledgements

Thanks to Spyros Pavlides for the numerous discussions and to Michele Caputo for many useful comments. Reviewing by Richard Collier, Mustapha Meghraoui and Daniela Pantosti has been appreciated. Daniela Esu is also warmly thanked for the paleontological datings along the Gyrtoni fault. The research was supported by several sources among which are the Italian Ministry of the University (personal grants and funds to Mario Boccaletti), the European Community (Stimulation Action Project, contract No. SC1*0056), the Italian National Council of Research (CNR-*Centro di Geologia* of Florence) and NATO.

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(received March 18, 1994;
accepted October 18, 1994)