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THE MAY 13, 1995, KOZANI–GREVENA (NW GREECE) EARTHQUAKE: SOURCE STUDY AND ITS TECTONIC IMPLICATIONS

D. PAPANASTASSIOU,[1]* G. DRAKATOS,[1] N. VOULGARIS[2] and G. STAVRAKAKIS[1]

[1]Institute of Geodynamics, National Observatory of Athens, 118 10 Athens, Greece
[2]Department of Geophysics and Geothermy, University of Athens, 157 84 Athens, Greece

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Abstract—At 08:47 GMT, on May 13, 1995, a strong earthquake of $M_s = 6.6$ occurred in the NW part of Greece (Western Macedonia) and caused serious damage in the Kozani and Grevena prefectures, but fortunately no fatalities. The maximum observed macroseismic intensity was IX+ of the Modified Mercalli scale. The main shock was preceded by several foreshocks and followed by intense aftershock activity lasting several months.

The Institute of Geodynamics of the National Observatory of Athens, in order to monitor and study the aftershock activity, installed a seismic network of nine (9) stations operated for a period of 50 days. Thousands of aftershocks were recorded. Based on the analysis of recorded data, a NE-SW trending zone dipping NW is defined.

In the field a surface rupture of normal slip was observed, following a NE–SW direction for a length of 8 km with a 4 cm down throw of the NW area. This break was located along a pre-existing minor normal fault, while a main fault system exists 10 km to the SE.

The focal mechanism of the main shock shows normal faulting, which is in agreement with the field observations. Moreover focal mechanisms of several well defined aftershocks were computed, showing various types of faulting. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

The broader area of Greece is part of the collision zone between the Eurasian and the African lithospheric plates and one of the most rapidly extending areas in the world. Strong earthquakes occur not only along the plate contact but also in intraplate areas. In the area of central and northern Greece, the direction of extension is about north-south.

The area of Kozani–Grevena (west Macedonia), compared to other regions in Greece, was until recently, considered to be a region of low seismicity. The only known earthquake,

*Author to whom all correspondence should be addressed.

during the historical period, that affected this region occurred in February 896 AD and destroyed the city of Veria located about 40 km NE of Kozani (Papazachos and Papazachou, 1989). During this century, 3 instrumentally recorded earthquakes (Makropoulos *et al.*, 1989) occurred close to the epicenter of the recent shock (Fig. 1), those of 1922, Dec. 7 (40.01°N–21.51°E, $M_s = 5.5$), 1943, Mar. 25, (40.41°N–21.89°E, $M_s = 5.5$) and 1984, Oct. 25 (40.11°N–21.62°E, $M_s = 5.6$).

After the earthquake of May 13, 1995, an extensive search revealed evidence of past earthquakes. 23 km south of Kozani and 5 km north of Aliakmonas river, the ruins of the ancient city of Aiani are located. This city was one of the kingdoms of ancient Upper Macedonia. Excavations, carried out since 1983, in the area, revealed that there was continuous occupation of the city from prehistoric to Roman times. The archaeologists found destruction evidence which they attributed to an earthquake, thought to have taken place during the Roman period—1st AD century—(Archaeologists of Aiani, personal

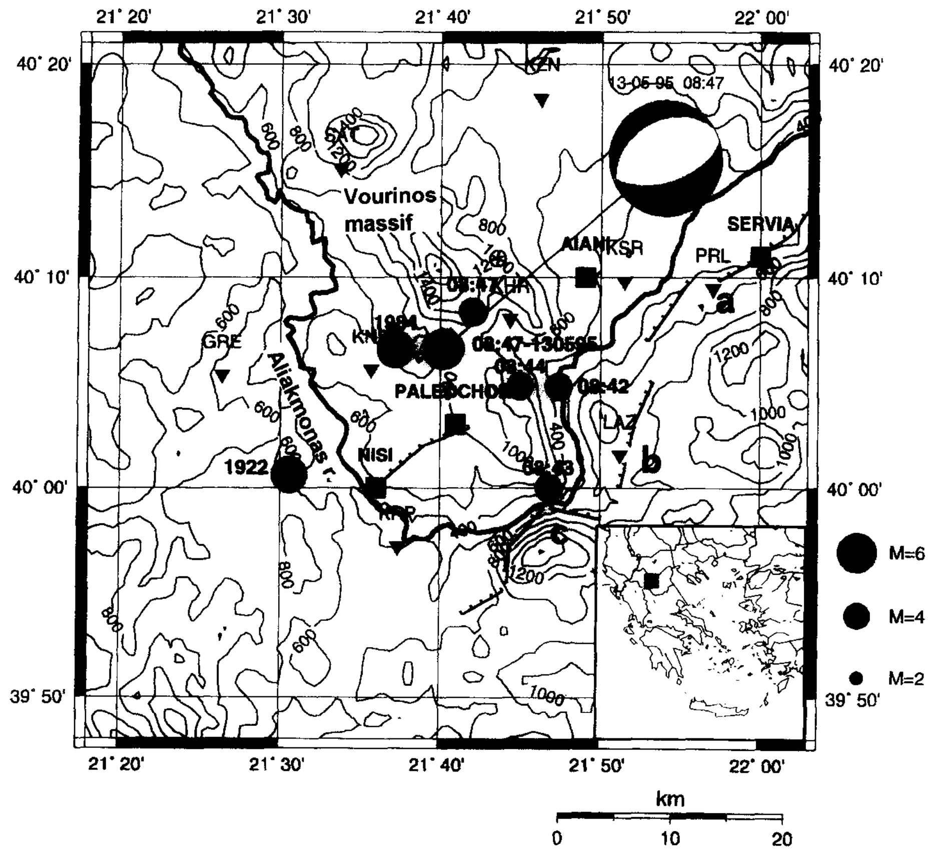

Fig. 1. Seismotectonic map of the area of Kozani-Grevena. The Servia fault zone and the observed surface break, between Paleochori and Nisi, are shown. Letters a, b, c correspond to the three segments of the Servia fault zone. Elevation contours are in m. Solid reversed triangles with names show the local seismological network, their coordinates are given in Table 2. The dark circle gives the relocated position of the main shock. Its focal mechanism is also shown. Pale circles with year are the earthquakes that occurred during this century while those with hour:minute indications are the foreshocks.

communication). The decline of the city during this period, is further evidence for the occurrence of a big earthquake. Additional information comes from the archives of monasteries located in the area. According to these written reports, during the last 3 centuries, 3 earthquakes occurred in the area of Servia, SE of Kozani: 1695, 1766 and 1852. These were strongly felt in the broader area of Servia and caused extensive damage in the city of Servia and the surrounding villages (Dimopoulos, 1994; Tsarmanidis, 1995). All this information suggests that this area is not one of low seismicity but an area of sparse seismological information.

The earthquake of May 13, 1995, occurred at 11:47 local time (08:47 GMT) on a Saturday, so public offices and schools were closed. Minutes before the main shock, significant foreshocks preceded it and forced the inhabitants to evacuate and thus no life was lost. On the contrary, the shock caused severe damage in the region south of the cities of Kozani and Grevena.

As this event was the biggest instrumentally recorded earthquake in this area of NW Greece, it was a great opportunity for many researchers, to study it from seismological and seismotectonic point of view, like Hatzfeld *et al.*, 1995, 1997; Meyer *et al.*, 1996; Papazachos *et al.*, 1996; Papanastassiou *et al.*, 1996; Pavlides *et al.*, 1995.

The Institute of Geodynamics, from the National Observatory of Athens, 18 hours after the occurrence of the earthquake, deployed a temporary seismic network of 9 stations, in order to monitor and study the aftershock activity. This network was operated for a period of 50 days. In the present paper the results of the spatial distribution and the focal mechanisms of the recorded aftershocks are presented. Moreover, tectonic observations collected in the field, results of the relocation and the focal mechanism of the main shock and macroseismic observations are also given. Finally, seismological and tectonic observations are combined, in order to obtain a better understanding of the rupture process and the regional tectonics.

GEOLOGICAL AND TECTONIC OBSERVATIONS

The geology and the tectonics of the area of Kozani-Grevena have been studied by several researchers, among them, Brunn, 1956, Pavlides and Mountrakis, 1987; Jones and Robertson, 1991.

The basement of the area belongs to the Pelagonian geotectonic unit which consists of Pre-Alpine and Alpine rocks like gneisses and schists, covered by limestones, and flysch. Over them the Vourinos massif, formed by ophiolites, is thrust having a NW–SE direction. On both sides of Vourinos, two large NW–SE trending basins orientated at, have been created, the Meso-Hellenic basin to the west and the Kozani basin to the east, filled by molassic sediments-conglomerates, sandstones, marls and silts. Over them lacustrine, fluvial and torrential deposits of Neogene age and Quaternary deposits in the form of talus cones and extended fluvial terraces are present. These sediments show significant vertical and lateral variations.

From morphotectonic point of view, this area is dominated by a NE–SW striking normal fault zone (Hatzfeld *et al.*, 1995; Pavlides *et al.*, 1995; Meyer *et al.*, 1996). It consists of 3 segments (Fig. 1), with a total length of 80 km and bounds the southern bank of Aliakmonas river as well as the southern shore of the Polyphyto artificial lake, oriented almost orthogonal to the structure of the Vourinos massif as well as the two basins. The northern segment of this zone (segment **a** in Fig. 1) the Servia fault, is the most prominent feature of the area, trending N 60° and dipping 60° towards the NW, while a clear, 10–20 m steep scarp exists at its front. This morphotectonic feature has been observed in many active faults in Greece and is attributed to Holocene activity (Armijo *et al.*, 1992).

Immediately after the occurrence of the main shock, the epicentral area was inspected for surface fault breaks. There was no evidence of breaks around the major Servia fault, but 10 km to the northwest, between the villages of Paleochori and Nisi, a continuous 8 km long break of normal slip was observed (Fig. 1). It was located along a pre-existing N 70° striking, 70° NW dipping normal fault that cuts the Miocene and younger sediments of the Meso-Hellenic basin. The break consisted of open fissures and small scarps with a 2–4 cm down throw slip of the NW area. At some places a vertical displacement of 10–15 cm was observed. This greater value was caused by the compaction of the soft sediments, due to the earthquake shaking. On the northeastern extension of the same fault system another segment, about 5 km long, may also have ruptured in peridotitic rocks, but the surface expression was not very clear.

The earthquake caused liquefaction at some places around the Polyphyto artificial lake and triggered small scale landslides, rock falls and slumps. Many fissures especially in soft sediments as well as at the gutters of dirt roads facing the slope were observed throughout the epicentral area.

MAINSHOCK AND FORESHOCKS ON MAY 13, 1995

The mainshock occurred at 08:47 GMT and was preceded by some significant foreshocks, ($3.5 < \text{magnitude} < 4.5$) the latest of them occurred about 15 sec before the main event. Their routine locations given by the Institute of Geodynamics have fixed depths as the solutions did not converge. In order to obtain more accurate locations and especially to resolve focal depths, the main shock and the foreshocks have been relocated by including in the data set arrival times from nearby stations belonging to the network of the Public Power Corporation, located around the Polyphyto artificial lake, and by introducing revised station corrections for the permanent network of I.G. The corrections were obtained by comparing the solutions of 54 well located aftershocks ($M \geqslant 3.0$) by the local temporary network and recorded also by the permanent network.

The obtained relocated position for the main shock (Fig. 1) is 40.12°N–21.67°E, with a depth of 15 km. The minimum standard errors are 0.3 sec for RMS, 2 km and 2.5 km for horizontal direction (ERH) and depth (ERZ) respectively. This solution is in good agreement with the geometry of the observed surface rupture (Fig. 1). This relocated position as well as those given by other Seismological Institutions like ISC, NEIC, the Institute of Geodynamics and the Geophysical Laboratory of the University of Thessaloniki are close together differing only on the obtained focal depth (Table 1). On the contrary, the solutions given by Harvard University and Hatzfeld *et al.* (1997), are located more than 30 Km towards the southeast and the west respectively. The relocated positions of the foreshocks are placed south of that of the main event while their depths are quite shallower.

CMT scalar moment given by Harvard is 7.6×10^{18} Nm and by NEIC is 4.7×10^{18} Nm

For the main shock, the record of a three-component strong motion instrument (SMA-1) operated at the town of Kozani shows a time difference of 4.4 sec between the S arrival and the triggering time (Lekidis and Theodoulidis, 1995). Assuming a mean P velocity, larger than 5.5 km/sec, and a V_p/V_s ratio of 1.78, this time difference implies that the

Table 1. Location of the mainshock given by different sources

Time	Lat.	Long.	Depth	Source
08:47:12.7	40.15	21.70	14	NEIC
08:47:20.7	39.89	21.90	15	Harvard Univ.
08:47:13.1	40.17	21.69	14	ISC
08:47:17.0	40.18	21.71	39	GI - NOA
08:47:15.0	40.16	21.67	9	Thessaloniki Univ.
08:47:14.6	40.11	21.40	14	Hatzfeld *et al.*, 1997
08:47:14.8	40.12	21.67	15	This study

hypocentre of the main shock should be located at a minimum distance of 31 km from the city of Kozani. The relocated hypocentre is also in good agreement with this observation.

The macroseismic information map was compiled from a questionnaire sent to the villages of the affected area and from field observations. The results are given on the Modified Mercalli (MM) scale (Fig. 2). The maximum intensity (IX+) was observed in the S and SW part of the epicentral zone, where most of the damage was observed and some of the villages were completely or partly destroyed. This zone is located NNW of the observed surface rupture that is at the down thrown block.

RECORDING AND ANALYSIS OF AFTERSHOCKS

After the occurrence of the main shock a portable seismic network was deployed. Before the noon of the next day the whole network was in operation. This network consisted of 8 smoked paper instruments (Sprengnether MEQ-800) equipped with 1 Hz vertical seismometers complemented by the 3-components permanent station of the Institute of Geodynamics in Kozani (Fig. 1, Table 2).

The aftershock activity was continuously monitored for a period of 50 days, from May 14 through July 4. The activity was intense during the first week and more than 1000 events of $M_L > 1.5$ were recorded per day.

No detailed information about the velocity structure of the area was available. Thus, in order to find a reliable velocity model, 74 well recorded aftershocks were selected, with more than seven (7) P wave and two (2) S wave readings and with a magnitude of $Ml \geqslant 3.0$. This set would be a representative sample of all the aftershocks both in location and depth. The Vp/Vs ratio was firstly estimated from Wadati diagrams, constructed using events with more than 5 S-readings and was found to be 1.78 ± 0.05. The events were relocated first at different half-space models and then at layered velocity models. Every time the standard errors (RMS, ERH, ERZ) were checked. The final chosen velocity model, given in Table 3, yields a smaller RMS than any one of the tested models. Comparable mean velocities and V_p/V_s values were found also for the same area (Hatzfeld *et al.*, 1997) as well as in adjacent areas (King *et al.*, 1983; Kiratzi *et al.*, 1987).

AFTERSHOCK DISTRIBUTION

The network provided a satisfactory coverage of the aftershock area and allowed for well resolved hypocentres and reliable individual focal mechanism determination. Initially,

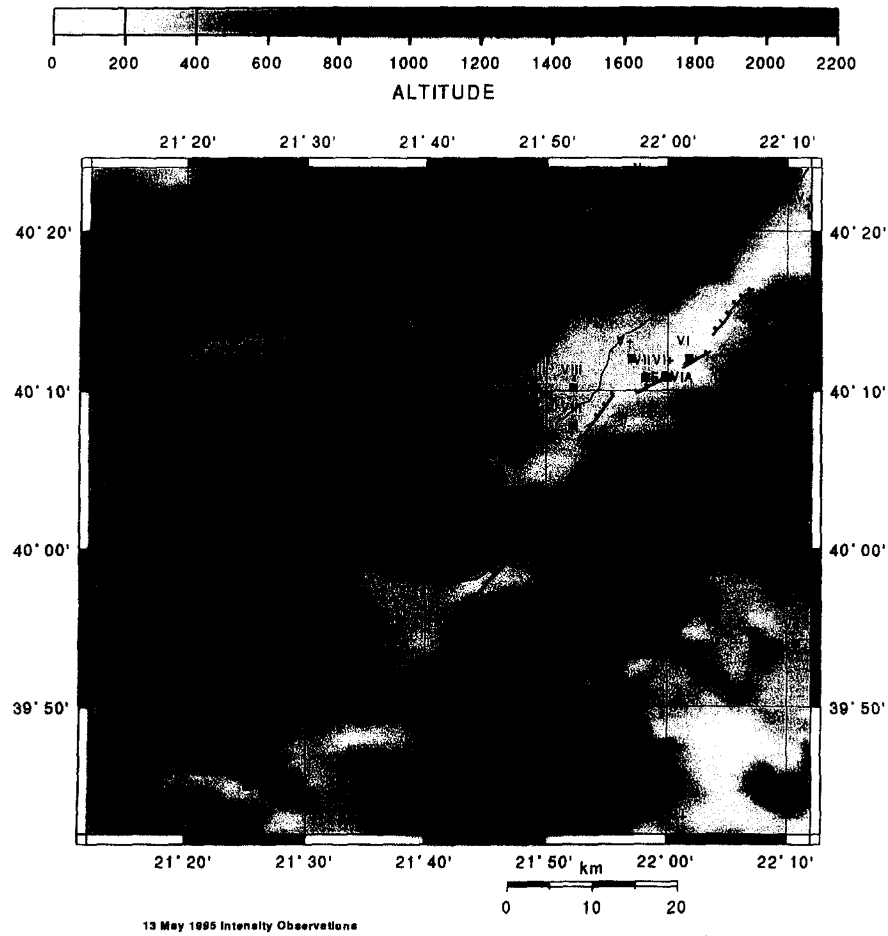

Fig. 2. Map showing the distribution of the macroseismic intensities. The observed surface rupture and the main fault zones are also shown. Solid circle gives the location of the main shock.

Table 2. Coordinates of the local seismological network

Station	Code name	Coordinates		
Grevena	GRE	40.09°N	21.44°E	530 m
Kozani	KZN	40.31°N	21.77°E	900 m
Siatista	SAT	40.25°N	21.56°E	830 m
Kaisaria	KSR	40.16°N	21.86°E	630 m
Karpero	KRP	39.35°N	21.62°E	490 m
Knidi	KND	40.09°N	21.60°E	675 m
Khromio	KHR	40.13°N	21.74°E	640 m
Lazarades	LAZ	40.03°N	21.85°E	660 m
Prosilio	PRL	40.16°N	21.95°E	540 m

Table 3. Local velocity model

Velocity (km/sec)	Depth (km)
5.5	0
6.0	10
6.5	20
8.0	40

more than 2000 events, having at least five (5) P wave and one (1) S wave readings, were selected and located using the HYPO 71 computer program (Lee and Lahr, 1975). Next, in order to get an aftershock catalogue with precise locations and homogeneous distribution, 740 events with at least six (6) P and two (2) S readings and standard errors RMS < 0.2 sec, ERH < 1.5 km and ERZ < 2.0 km were selected (Fig. 3). The majority of the events is located SW of the main shock and N–NW of the observed surface breaks. On both ends of

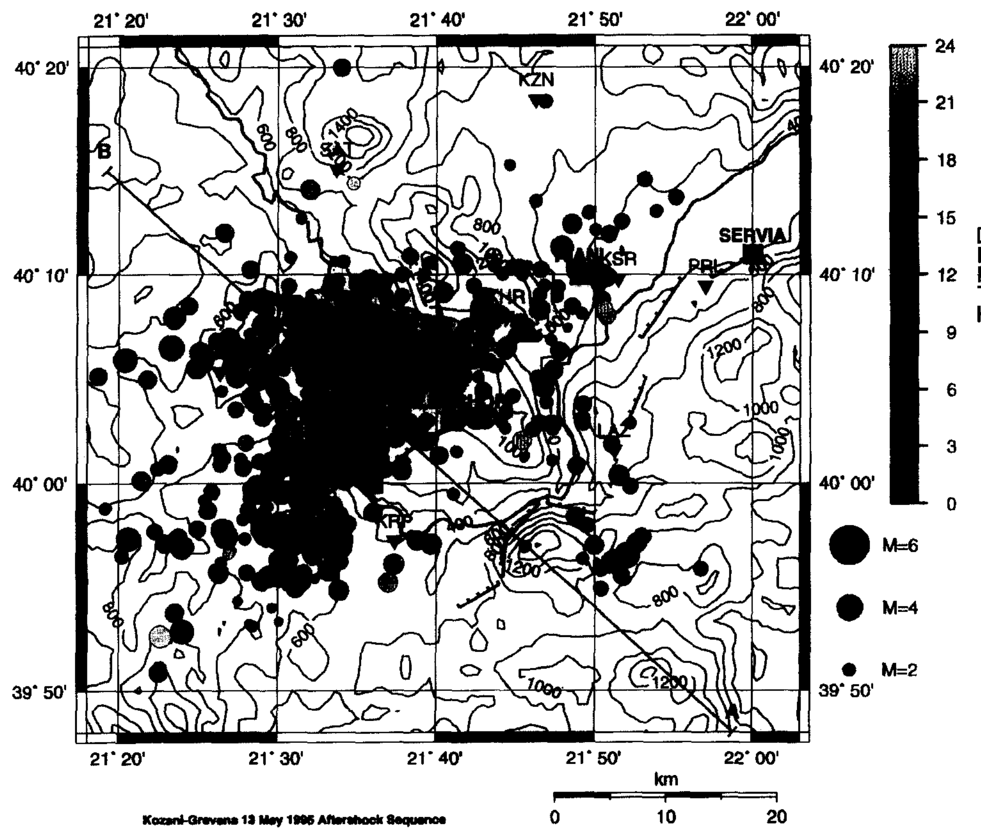

Fig. 3. Map view of the 740 well located aftershocks. Star gives the location of the main shock. The observed surface rupture and the main fault zones are also shown. Line gives the direction of the cross section given in Figure 4.

the observed surface rupture, two clusters of activity have been observed. The one located at the western end is larger and well defined, while the other at the eastern end is directed towards the northeast with a diffused spatial distribution. At the eastern end, just south of the Paleochori village, another group of aftershocks could be distinguished, following an almost linear trend with a NW–SE direction.

Along a cross section (Fig. 4), perpendicular to the fault trace, the main cluster appears as a clear zone located north of a fault plane dipping to the NW. This zone can be extended towards the surface near the mapped surface rupture, while the majority of the aftershocks are located in the depth range of 10–20 km. Considering this observation as well as the hypocentre and the focal mechanism of the main shock, the seismogenic fault plane appears to have a steeper dip (60°–70°) near the surface, and gradually decreases (30°–40°) down to a depth of about 10–15 km.

FOCAL MECHANISMS

By using *P* wave polarities from the permanent network of the Institute of Geodynamics and those provided by the International Agencies, the fault plane solution for the main shock was determined. The solution (Fig. 1) is related to pure normal faulting on planes having directions 240°N and 72°N, dipping 35° to the NW and 56° to the SE respectively. The first plane coincides with the geometry of the surface faulting. The CMT solution determined by Harvard also suggests pure normal faulting with planes trending 240°N and 70°N dipping 31° to the NW and 59° to the SE respectively. This solution is almost identical to the one determined in this study.

For the determination of the focal mechanisms of the aftershocks the polarities of the local stations were used. The solutions of 53 well constrained mechanisms are presented (Fig. 5, Table 4), with a variety of types indicating the complexity of the tectonics of the area and the activation of different sub faults. To the north of the surface rupture, the majority of them show normal faulting, although some solutions show reverse faulting. Nevertheless in all solutions a plane with a NE–SW direction, dipping to the NW, similar to that of the main shock is observed. West of the Vourinos massif, there is a group of

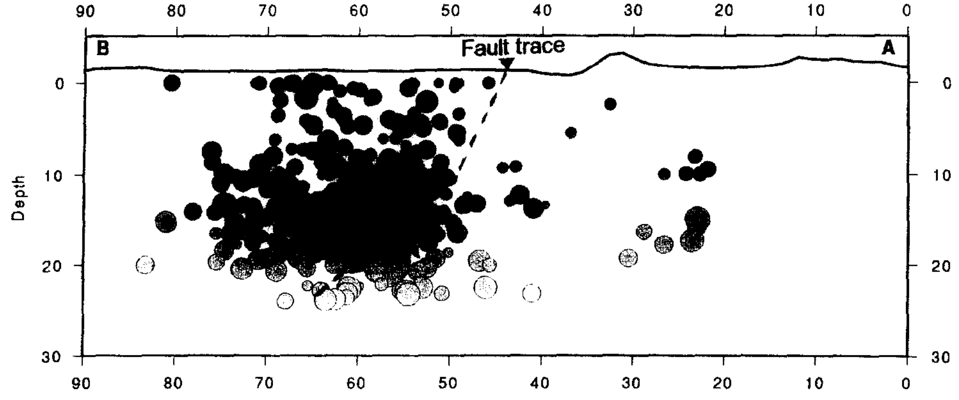

Fig. 4. Cross section perpedicular to the surface break. Star gives the location of the main shock. The assumed geometry of the ruptured fault is also shown.

Table 4. Focal parameters of the events plotted in Fig. 5

No	Date	Time	Lat N	Long E	Depth	Mag.	az1	dp1	az2	dp2	azp	dpp	azt	dpt
1	95 517	22:58	40.02	21.61	17.5	2.7	120	45	7	69	69	14	322	48
2	95 517	23:51	39.97	21.56	18.2	3.4	50	35	230	55	320	10	140	80
3	95 518	1:10	40.05	21.58	14.0	2.3	135	35	302	55	37	10	188	78
4	95 518	12:40	40.03	21.57	8.1	2.8	60	45	212	48	52	75	315	1
5	95 518	21:11	40.10	21.57	9.1	2.8	60	45	254	45	243	82	337	0
6	95 519	1:30	40.06	21.55	17.3	3.4	90	70	210	35	157	19	37	54
7	95 519	12:29	40.05	21.71	19.5	3.3	45	75	306	61	269	31	173	9
8	95 520	11:45	40.08	21.61	16.3	2.4	40	25	282	77	354	29	217	52
9	95 520	14:41	40.14	21.71	16.1	2.1	90	15	259	75	351	30	165	59
10	95 520	20:35	39.98	21.54	18.3	3.7	65	70	198	27	3	60	139	22
11	95 521	2:40	40.10	21.64	15.5	1.9	150	60	262	56	114	48	207	2
12	95 521	4:42	40.05	21.62	13.7	2.3	95	35	320	63	33	15	270	62
13	95 521	7:21	40.11	21.74	16.4	2.8	90	55	191	73	56	37	317	11
14	95 521	13:28	40.06	21.57	17.7	2.9	185	65	294	54	241	6	145	45
15	95 521	23:48	40.14	21.59	18.0	2.4	120	75	218	61	75	31	171	9
16	95 522	00:25	40.14	21.59	21.0	2.5	190	75	85	55	55	20	140	8
17	95 522	0:54	40.05	21.72	20.0	2.1	290	75	187	51	54	14	156	38
18	95 522	3:57	40.13	21.61	11.9	2.5	120	70	221	61	78	35	172	5
19	95 522	4:35	39.93	21.84	9.9	2.3	120	40	242	65	355	14	108	56
20	95 522	5:30	40.00	21.55	16.0	2.5	320	70	66	52	276	41	16	10
21	95 522	12:19	40.03	21.58	13.3	2.7	135	55	10	51	345	58	252	2
22	95 522	12:22	40.04	21.57	13.2	3.1	5	90	275	60	234	20	135	20
23	95 522	12:26	40.03	21.58	16.8	2.5	30	90	300	70	256	13	163	13
24	95 523	1:16	40.17	21.81	22.4	3.0	90	75	215	24	25	55	164	27
25	95 524	6:17	39.96	21.49	18.5	2.8	335	65	225	54	98	6	194	45
26	95 524	10:30	40.00	21.52	9.8	2.6	95	70	342	43	321	48	213	15
27	95 524	10:45	40.11	21.46	15.4	3.0	120	30	353	71	65	22	295	57
28	95 524	17:34	40.08	21.55	18.7	3.3	65	65	308	46	182	11	287	52
29	95 524	19:17	40.11	21.48	13.5	2.2	10	50	251	60	214	53	313	6
30	95 524	22:90	40.09	21.57	12.8	2.4	235	85	327	60	187	24	285	16
31	95 525	4:50	39.99	21.50	16.6	3.1	120	80	211	80	75	14	345	0
32	95 525	8:48	40.10	21.70	15.0	2.9	260	80	125	14	358	34	157	53
33	95 526	21:34	40.12	21.63	8.1	2.6	210	50	82	54	53	60	147	2
34	95 527	1:10	40.12	21.76	10.7	2.2	35	55	260	44	247	65	145	5
35	95 527	4:90	40.10	21.67	13.1	2.3	90	40	244	52	102	75	345	6
36	95 527	16:17	40.08	21.69	16.3	2.7	305	60	45	72	172	8	268	34
37	95 528	6:80	39.98	21.56	15.8	2.6	310	60	203	64	257	2	165	41
38	95 528	13:15	40.12	21.64	10.4	2.1	120	30	255	67	134	62	1	19
39	95 529	16:51	40.12	21.63	10.4	2.6	75	50	239	41	37	81	157	4
40	95 529	17:19	40.11	21.63	7.8	1.9	35	80	296	50	263	34	159	18
41	95 529	20:80	40.11	21.60	17.1	2.9	120	65	218	71	80	31	348	4
42	95 530	2:10	40.14	21.52	14.4	2.4	50	20	230	70	320	25	140	65
43	95 530	2:14	40.08	21.58	15.6	2.4	150	75	252	51	103	38	205	14
44	95 530	4:70	40.00	21.55	16.4	3.0	310	65	200	54	73	6	169	45
45	95 530	6:45	40.08	21.48	20.7	3.2	0	60	259	72	216	34	312	8
46	95 530	20:46	39.95	21.54	18.9	2.9	315	60	208	64	262	2	170	41
47	95 531	18:34	40.03	21.58	16.8	2.7	185	80	93	80	49	14	139	0
48	95 6 2	16:80	40.09	21.79	17.9	2.7	15	40	285	90	227	32	342	32
49	95 6 3	10:20	40.11	21.60	26.6	3.2	95	60	195	72	58	34	322	8
50	95 6 4	20:15	40.10	21.42	7.4	3.0	135	70	236	61	93	35	187	5
51	95 6 4	23:28	40.16	21.56	10.7	2.3	120	65	223	63	81	38	172	1
52	95 6 5	18:28	40.09	21.31	9.7	2.6	20	30	272	80	212	47	339	29
53	95 6 6	4:35	40.15	21.48	13.4	3.7	35	30	170	67	49	62	276	19

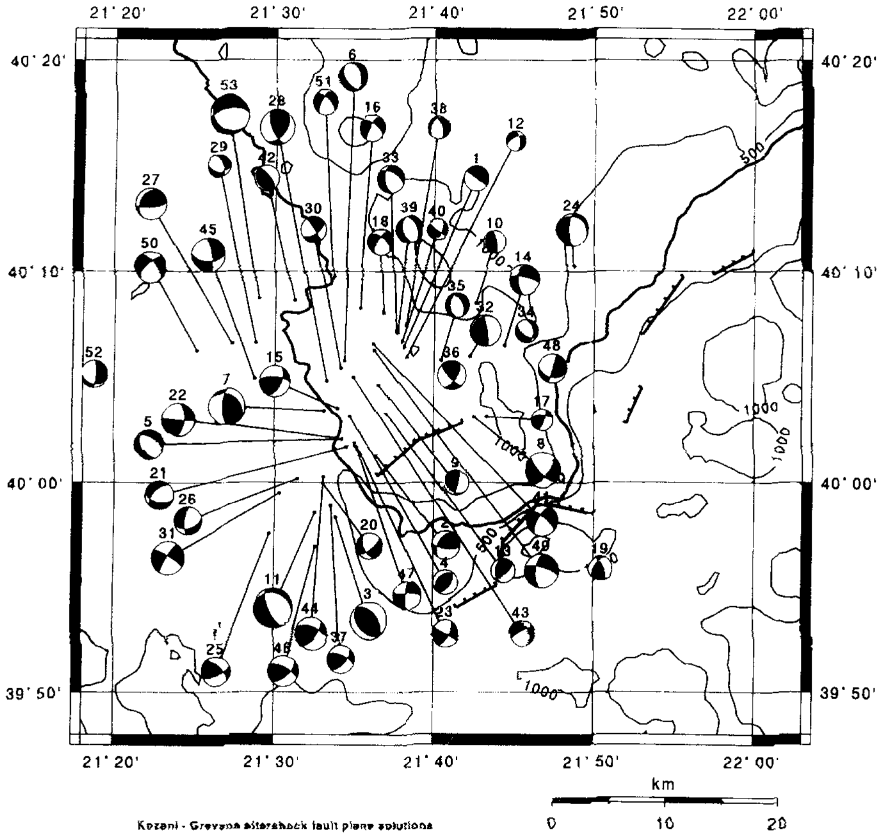

Fig. 5. Determined fault plane solutions for the 53 aftershocks. The observed surface rupture and the main fault zones are also shown.

aftershocks, aligned at a NW–SE direction, parallel to the western front. The focal mechanisms of this group show normal faulting at planes having directions NW–SE, dipping to the NE or SW. The cluster of the aftershocks located at the western end of the surface rupture show a variety of mechanisms either normal or reverse type. In all the solutions a significant horizontal component of movement is observed. At the group, located east of the rupture, normal faulting is dominant on planes having directions NW–SE and NE–SW.

CONCLUSIONS

The distribution of the aftershocks and the determined focal mechanisms of the main shock, as well as of some aftershocks, are in good correlation with the observed surface rupture. These observations confirm the view that the earthquake was caused by the reactivation of an existing minor normal fault, having a N 70° direction and dipping about 70° to the NW near the surface, located 10 km northwest of the main Servia fault zone. The mapped surface rupture had a length of $\cong 8$ km, was of normal slip with a down throw movement of the NW area of about 4 cm. In this area most of the destruction was also observed.

The distribution of the damage was very heterogeneous both within the same village and at very closely located villages, where macroseismic intensity differs considerably. This is probably due to site effects since the soil of the region is not homogeneous and strong vertical and lateral variations are observed. An additional factor, for locally increased damage levels, could be attributed to the topographic effect, since some of the heavily damaged villages were built on very narrow topographic sedimentary ridges.

The majority of the aftershocks are located in the north of the fault, on the hanging wall among 10 and 20 km in depth, while their focal mechanisms show normal faulting with planes compatible to those of the main event. The main shock and the foreshocks occurred at the northern extremity of the aftershock zone, indicating that the rupture initialized at that part and afterwards propagated to the SW.

The results show that this earthquake sequence displayed some peculiarities. The earthquake ruptured part of a secondary fault, while the main and most important faults of the area did not rupture. The calculated seismic moment 7.6×10^{18} Nm by Harvard or 4.7×10^{18} Nm by NEIC are significantly larger than the one that can be calculated from the relatively small extend of both the aftershock zone and the surface break. This may suggest that the slip at the depth could be greater, or that some faults may have ruptured at depth without reaching the surface.

Meyer *et al.* (1996), proposed a model for the faulting of this earthquake by combining information from field observations and surface deformation deduced from SAR interferometer. They implied that the slip at the depth was 1 m, while some other tear faults should have ruptured at depth. They also suggested that the main event reactivated under the extension of an old thrust plane with a NW-SE strike and NE dip extended SE of the eastern end of the rupture at Paleochori. Results from this study, like the spatial distribution of the aftershocks and the obtained focal mechanisms, suggest that this reactivation exists not only in this area but extends as well in a NW direction.

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