The Kozani-Grevena (Greece) earthquake of May 13, 1995, M_s = 6.6. Preliminary results of a field multidisciplinary survey

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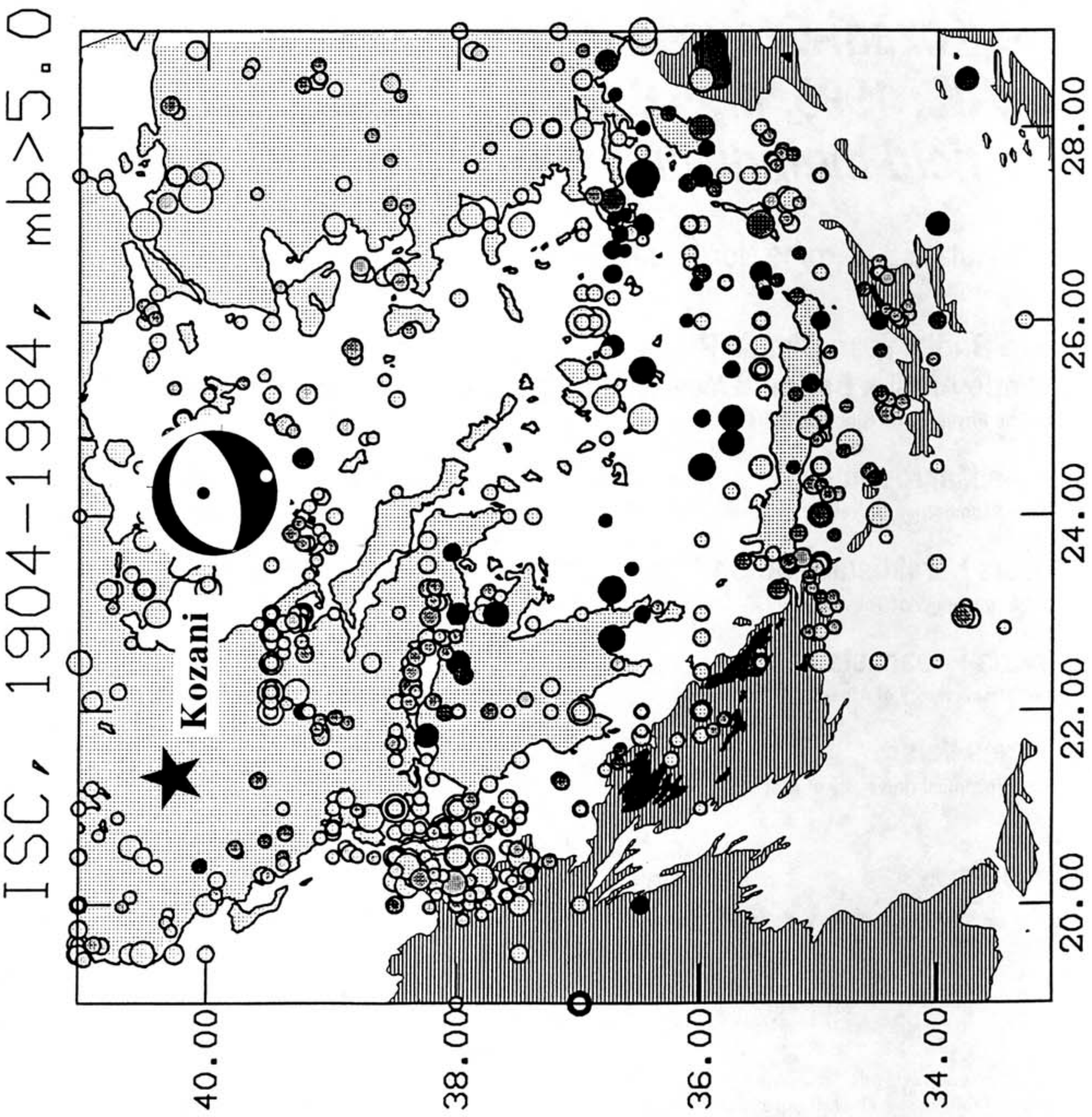
INTRODUCTION

At 08:47 on May 13, 1995, an M_s 6.6 earthquake occurred in Northern Greece and severely damaged the region around the cities of Kozani and Grevena and neighboring villages. This earthquake is the largest for the last decade in Greece, a country which experiences the highest seismicity in western Europe.

The epicenter is located in a region of very low historical seismic activity (Figure 1). The coordinates of the main shock of Kozani are 40°09.6'N 40,16 and 21°40.2'E 21,67 and the depth is about 8 km. The ISC seismicity catalog does not mention a single earthquake of magnitude greater than 5 within an area 100 km around, and the last destructive earthquake that affected this region occurred during February 896 and destroyed the city of Veria (Papazachos and Papazachou, 1989). This is very quiet in comparison to the other regions of the Aegean domain which, as a whole, exhibit a total number of about 750 earthquakes of magnitude greater than 5.0 since the beginning of the century. The CMT solution determined by Harvard is a pure normal fault at a depth of 16 km with one plane trending N240° and dipping 31° to the NW and the other one trending N70° and dipping 59° to the SE (Figure 1). The moment tensor is 7.6 x 10^{25} dyne-cm.

Because of the time of the shock (11:47 local time) and of the day of the week (Saturday) most of the public administrative buildings were closed. The main shock was preceded by 5 strong (M_s = 3.5 to 4.5) foreshocks starting at 08:18 that urged inhabitants to leave their houses, and so no human lives were lost (Papazachos *et al.*, 1995). The city of Kozani, which is located only a few km north of the main shock, was nearly undamaged. In the southern and southwestern parts of the epicentral zone, however, a few villages were partially destroyed, having probably experienced MSK macroseismic intensities greater than VIII. The spatial distribution of damage appeared to be very heterogeneous, with undamaged villages neighboring partly destroyed ones by only a few kilometers. This heterogeneity is likely to be due to site effects (at least two of the most heavily damaged villages were built on narrow topographic ridges, Figure 2). Finally it should be emphasized that most of the destroyed houses were rather old and of poor design.

The Aegean region is located between the two major lithospheric plates of Europe and Africa, which have been converging in a N–S direction since lower Cenozoic time. The convergence rate is of about 1 cm/yr in this area, but the

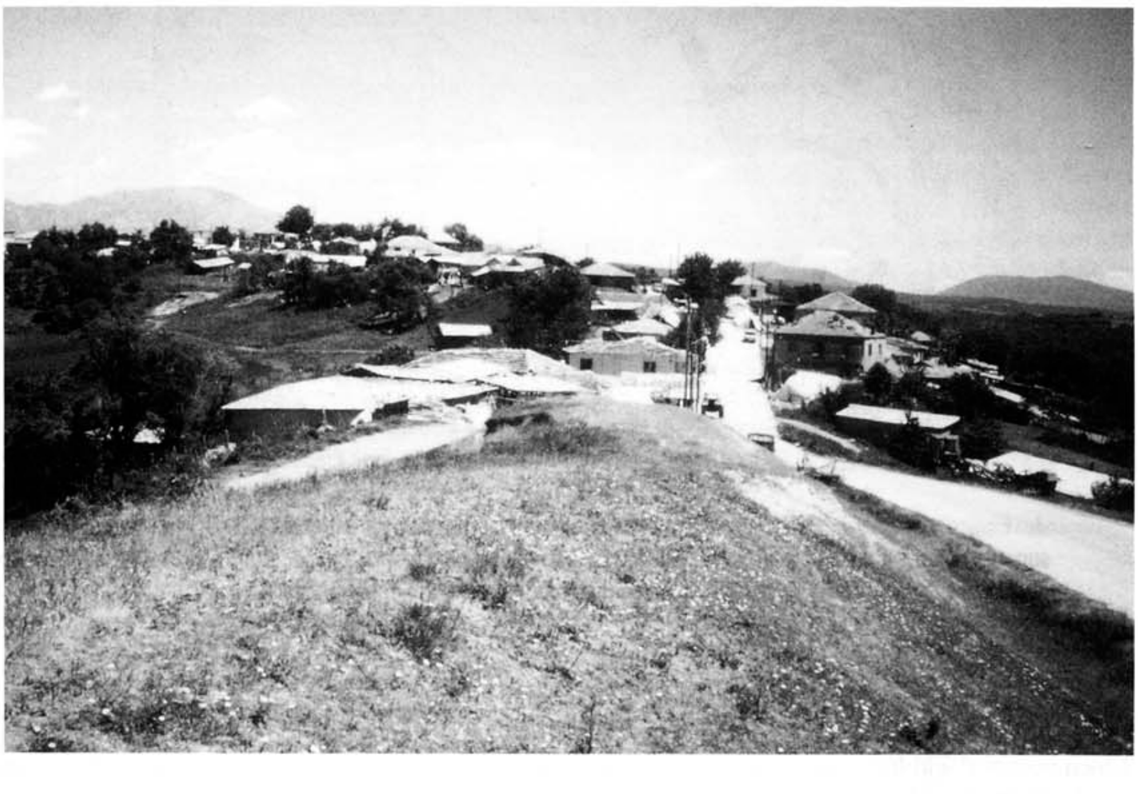


▲ **Figure 1** ISC seismicity map of the Aegean for earthquakes of magnitude greater than 5. The Kozani earthquake occurred in a region of low seismicity. The balloon is the moment tensor focal mechanism determined by Harvard for the Kozani earthquake.

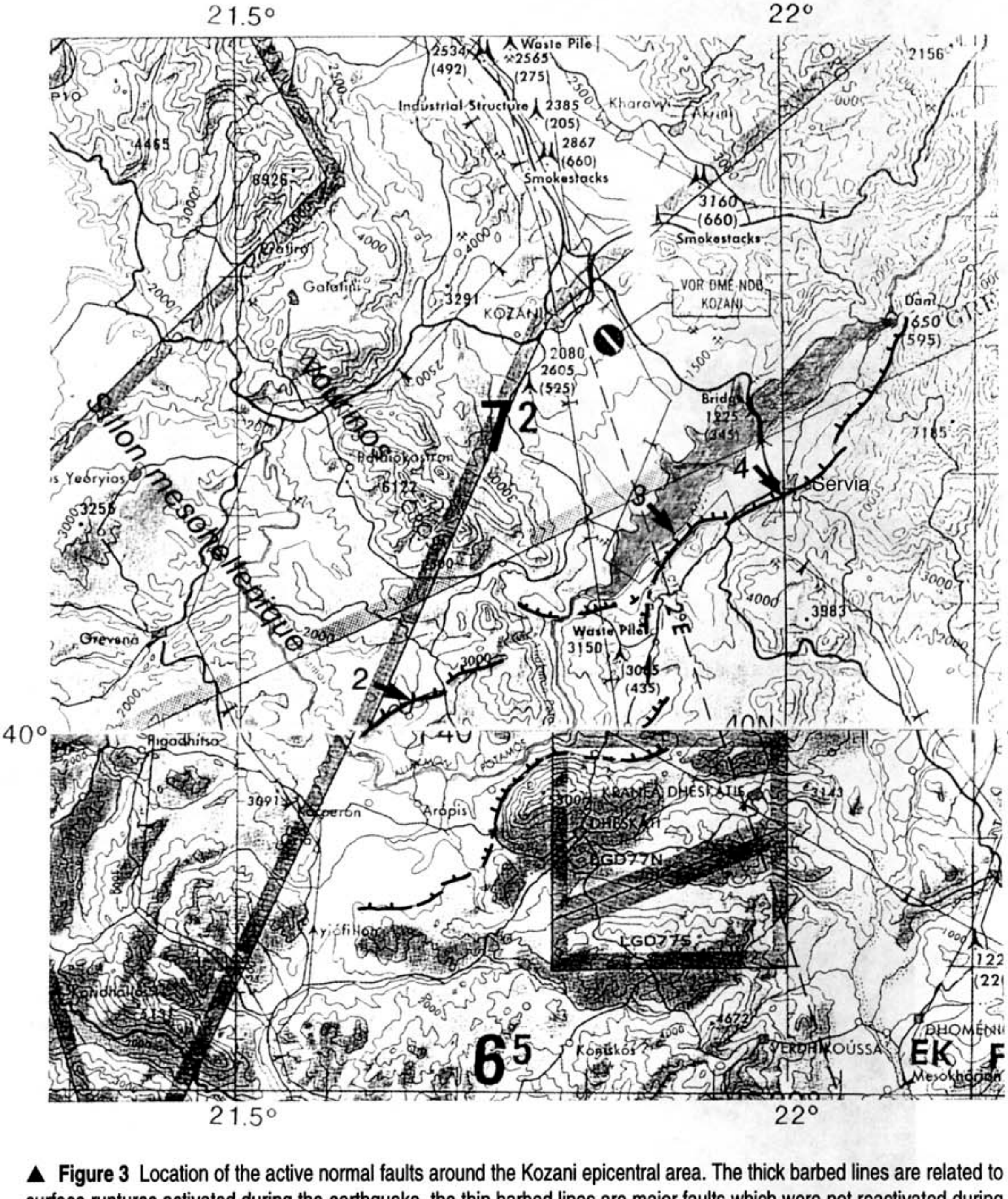
motion across the Hellenic trench, which is the southern boundary, is very much faster at about 5–7 cm/yr (McKenzie, 1978; Le Pichon and Angelier, 1979). This difference in relative motion is likely due to two causes: the westward motion of Turkey along the North Anatolian Fault and the internal deformation that affects the Aegean (i.e., Mercier *et al.*, 1976). Seismicity is therefore concentrated along the boundary of the Hellenic trench, but it also affects internal zones of the Aegean such as the Peloponnese, the Gulf of Corinth and the North Aegean Sea. Focal mechanisms show reverse faulting along the Hellenic trench with the shortening trending NE–SW, but mostly N–S extension within the southern Aegean and dextral strike slip motion along the NE trending North Aegean Trough.

Normal faulting is common within the Aegean, but usually exhibits N–S extension as in the Mygdonian graben during the 1978 sequence of magnitude 6.5 (Soufleris and Stewart, 1981), in the Gulf of Corinth during the 1981 se-

▲ **Figure 2 a and b** Examples of damaged houses located on a ridge near Grevena.



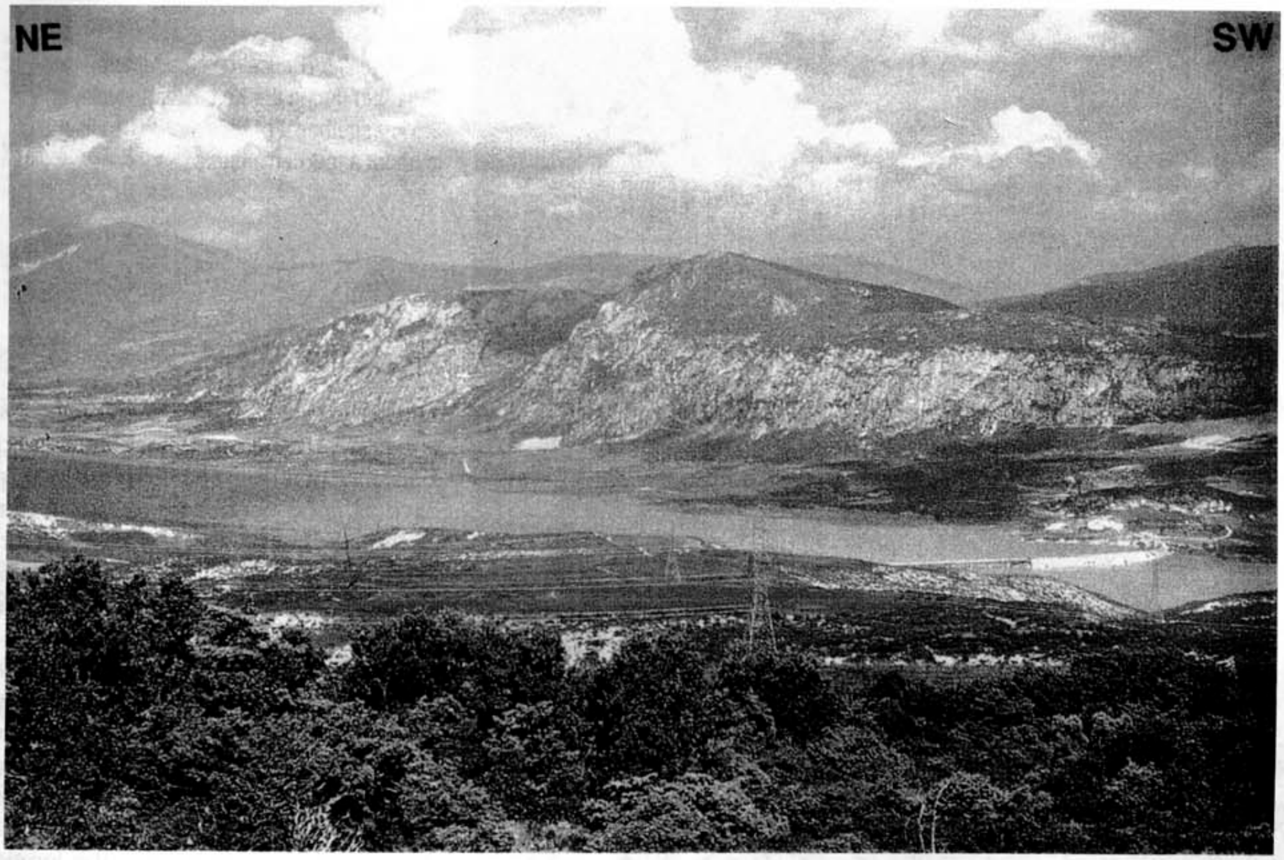
quence of magnitude 6.7 (Jackson *et al.*, 1982) or around the Gulf of Volos during the 1980 sequence of magnitude 6.5 (Papazachos *et al.*, 1983). The NW–SE extension exhibited by the Kozani earthquake is therefore puzzling within the tectonic pattern of the Aegean domain. Finally, it should be emphasized that these 3 sequences mentioned above in-



▲ **Figure 3** Location of the active normal faults around the Kozani epicentral area. The thick barbed lines are related to the surface ruptures activated during the earthquake, the thin barbed lines are major faults which were not reactivated during the earthquake. Number 2 is the location of the surface rupture shown in Figure 5, number 3 is the location of Servia fault shown on Figure 4.

cluded multiple earthquakes of similar magnitude (6.0 to 6.7) which occurred within 6 weeks, and therefore the probability of a strong aftershock was high.

The Aegean area is one of the most rapidly deforming regions in the world and therefore forms a very fundamental natural laboratory for the study of continental tectonics. Extensive tectonic studies have been conducted for the last decade by French teams, in collaboration with Greek institutions, in several regions of the Aegean. Because this earthquake was located in an unusual area and because field studies of strong earthquakes are considerably enhanced by including surface ruptures, total deformation and aftershock



▲ **Figure 4** View of the Servia fault looking toward the ENE from the Vourinos mountain. The difference in elevation is about 500 meters.

studies (thereby associating tectonicists, geodesists and seismologists), we decided to conduct a multidisciplinary study of the Kozani earthquake.

TECTONICS

The earthquake epicenter is located east of the Vourinos ophiolite mountain close to the western termination of the Servia fault which cuts the Miocene and sometimes younger sediments of the Mesohellenic basin. The Servia fault is a normal fault, trending N60° and dipping 60° toward the NW. It is a very important feature which appears in the topography as a 800 m difference in elevation (Figures 3 and 4). On this fault, we observed Holocene scarps of about 10 to 15 m, attesting to active displacements during the last 10,000 years.

We looked for surface ruptures due to the main shock but did not find any evidence of breaks around the major Servia fault. On the other hand, we observed some fresh scarps of about 2 to 4 cm of normal slip and some fissures (Figure 5) southwestward of the Servia fault between the villages of Paleohori and Nission. These deformations affect a 15 km long narrow zone in the continuation of the Servia fault and form an en-échelon system of faults. It is therefore likely that the main shock affected the southwest termination of the Servia fault. Among the two possible fault planes given by the CMT solution, the one striking N240° and dipping 31° toward the NW is the most likely to have ruptured.

GEODESY

Knowing the magnitude and scalar moment of the earthquake we modeled the deformation that should be observed at the surface using a simple dislocation model (Figure 6). This computation predicts co-seismic displacements of a few centimeters at the surface. The existence of a geodetic network of pillars installed during the 70's and whose accuracy is of about 5 cm gave a good opportunity to study the displacements associated with the earthquake.

We had only 4 Ashtech and 2 Trimble receivers available at the time of the earthquake, so we decided to collaborate with a team from Oxford (G.B.) who brought 8 Ashtech receivers.

The principal purposes of the geodetic measurements were to:

1) determine the co-seismic displacement field associated with the earthquake by re-measuring the existing geodetic network,
2) study the pre- and post-seismic displacement field in case of a strong aftershock sequence,
3) follow the post-seismic deformation,
4) infer rheological parameters for the ductile lower crust from the long-term post-seismic deformation.

▲ **Figure 5** Typical surface rupture observed during the Kozani earthquake at 2.5 km southeast of Paleohori. The offset is about a few centimeters.

SEISMOLOGY

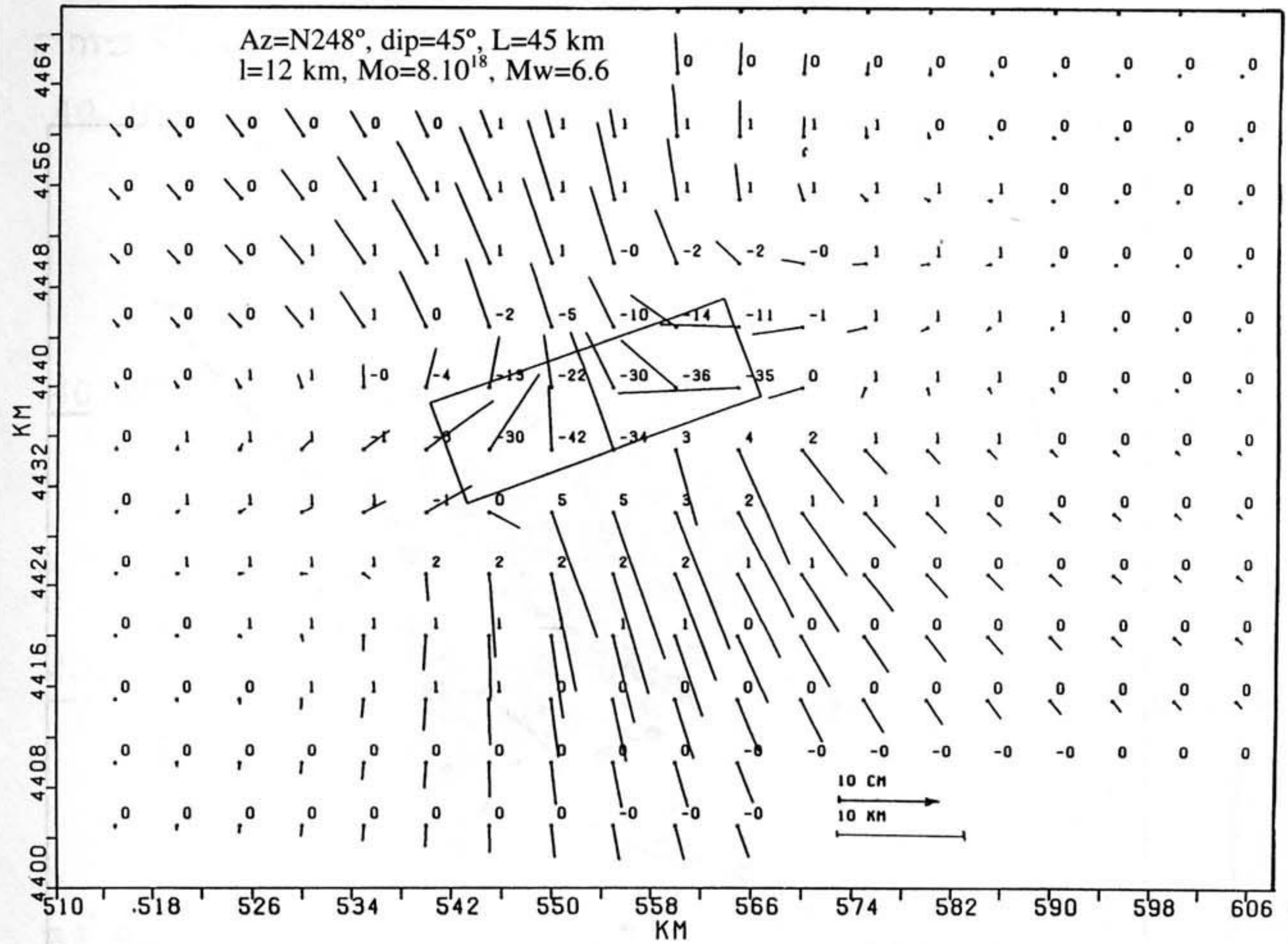
The permanent reliable seismological station closest to the main shock was located at a distance of 80 km, and therefore we do not have as good control on the depth of the earthquake as on the epicenter. Unfortunately, most of our digital stations were not available at this period of time, so we decided to deploy over the epicentral area 15 smoked MEQ800 Sprengnether, 10 1-D TAD digital, 5 3-D Lennartz digital and 6 strong-motion instruments. We decided to enter into a collaboration with seismologists from the Instituto Nazionale di Geofisica of Roma who added 10 3-D digital units (Figure 7). In this paper we present only the locations obtained with the 10 1-D digital instruments.

The deployment of the instruments was intended to create a network as spatially homogenous as possible, so we mixed all the instruments in the field. The first instrument was installed on May 15, but the bulk of the network was really operating on May 18 and completed on May 19. The network was pulled out on May 25. Preliminary location of aftershocks was performed routinely from permanent stations by the Seismological Observatory of Thessaloniki. The seismic activity was rather high with more than one event per minute located mostly on the southwestern termination of the Servia fault.

In order to achieve these goals we designed the following strategy of observations (Figure 6). Four receivers were devoted to continuous monitoring around the epicentral zone. During short sessions of about 2 hours, we measured about 70 existing pillars for which we expect an accuracy of about 1 cm. We designed a 150 km long profile across the fault zone which was observed during 8 hour sessions. This profile was complemented by two shorter profiles on each side.

These observations will be compared with the original angular observations obtained for the pillars in the 70's. Moreover, radar interferometry techniques will be performed to infer a detailed map of deformation.

During the 6 days when the TAD stations were in operation, we were able to locate 673 earthquakes that were recorded by more than 8 stations. Among these, 423 have a root mean square error in time smaller than 0.15 sec and uncertainties both in depth or epicenter smaller than 2 km. The seismicity map (Figure 7) shows that the majority of aftershocks are located south of the main shock as determined by the Seismological Observatory of Thessaloniki and north of the surface breaks that were observed after the earthquake. We observe two different clusters that seem to be separated by a small gap. The depth of the earthquakes ranges from the surface to 23 km, with a maximum in depth distribution at 9 km.



▲ **Figure 6 a)** Surface displacements predicted for the Kozani earthquake and computed using a simple dislocation model. Arrows are horizontal displacements, numbers are vertical displacements, in cm. The rectangle is the horizontal projection of the fault plane. Coordinates are UTM.

We computed aftershock cross sections about 10 km wide perpendicular to the fault surface breaks (Figure 8). The sections located in the easternmost part of the cluster clearly show a deepening of the events toward the NW. Earthquakes do not concentrate on a narrow fault zone dipping to the NW, but the upper limit of seismic activity defines a plane dipping 45° and reaching the earth's surface close to the place where the surface ruptures were observed. The earthquake activity is therefore restricted to the footwall of the active fault. Further to the southwest, the cross sections show a more complex pattern, especially for the western cluster, which seems to support a southeast dipping plane.

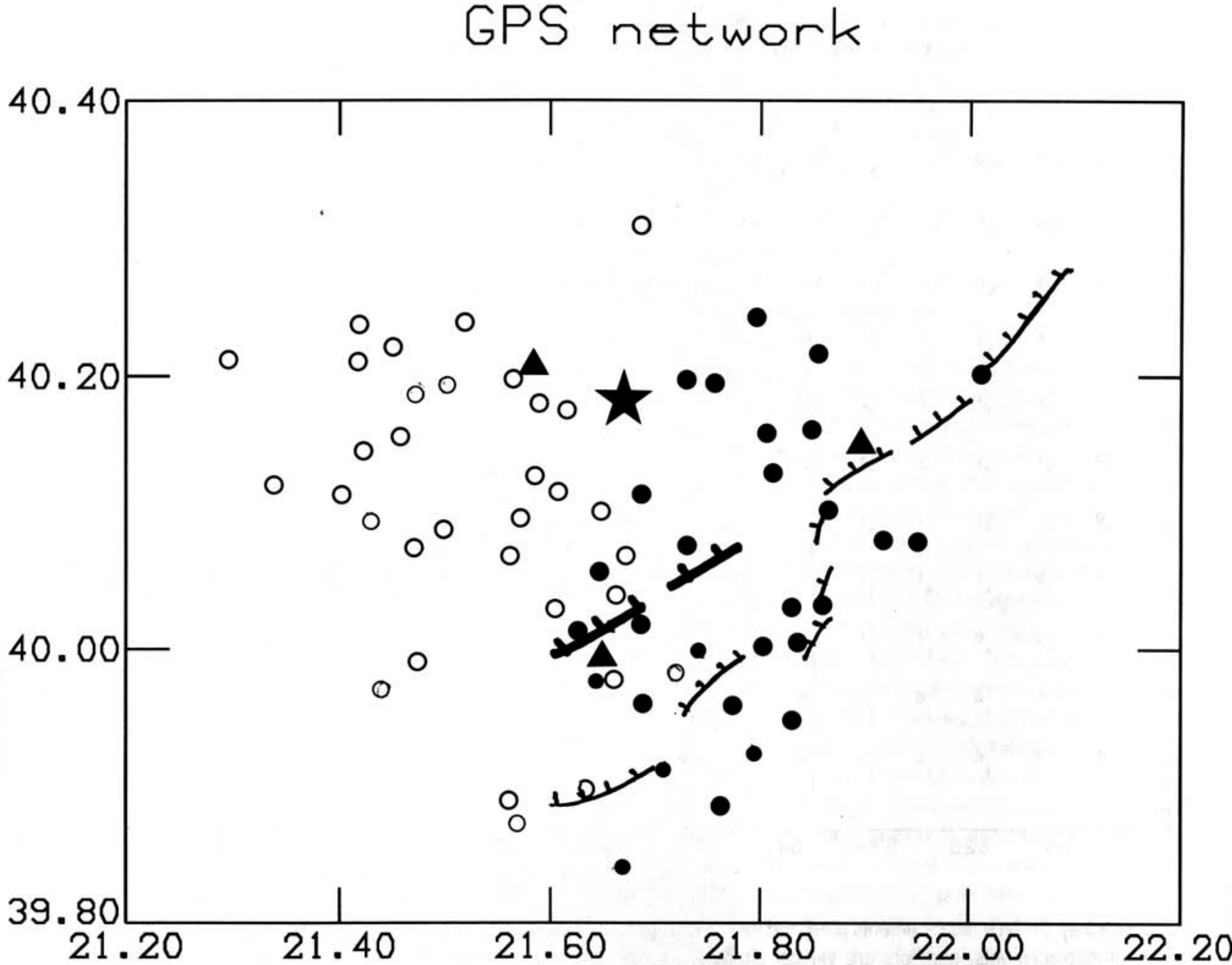
DISCUSSION AND CONCLUSION

The objectives of the coordinated field research were 1) to study a strong earthquake in a region of low seismic activity combining tectonic, geodetic and aftershock investigations and 2) to infer consequences for the geodynamics of the area. We present here very preliminary results which will be developed more fully within the next few months.

1) Source properties

To the northeast of the cluster, the aftershocks define a clear zone of seismic activity bounded by a discontinuity. The plunge of the discontinuity (45° to the NW) is steeper than the fault plane inferred from the main shock (30°) but smaller than the dip (60°) observed at the surface for the Servia fault. The discrepancy between the dip deduced from the main shock and from the aftershocks could be due to a flattening of the fault at depth, consistent with a steepening of the fault at the surface, and supporting the idea of a listric fault.

The length of the surface breaks is about 15 km. The surface of the main cluster is about 25 x 25 = 625 km². If we accept a scalar moment of 7.6×10^{25} dyne-cm, we find a mean displacement on the fault of 35 cm. According to scaling laws, this displacement is smaller than that expected for an earthquake of this magnitude. However, it is consis-



▲ **Figure 6 b)** Location of the Geodetic GPS network surveyed after the Kozani earthquake. The star is the epicenter of the main shock. The open circles are British receivers, the solid circles are French and Greek receivers, the triangles are permanent receivers. The thin barbed line is the active Servia fault, the thick barbed line is the surface break.

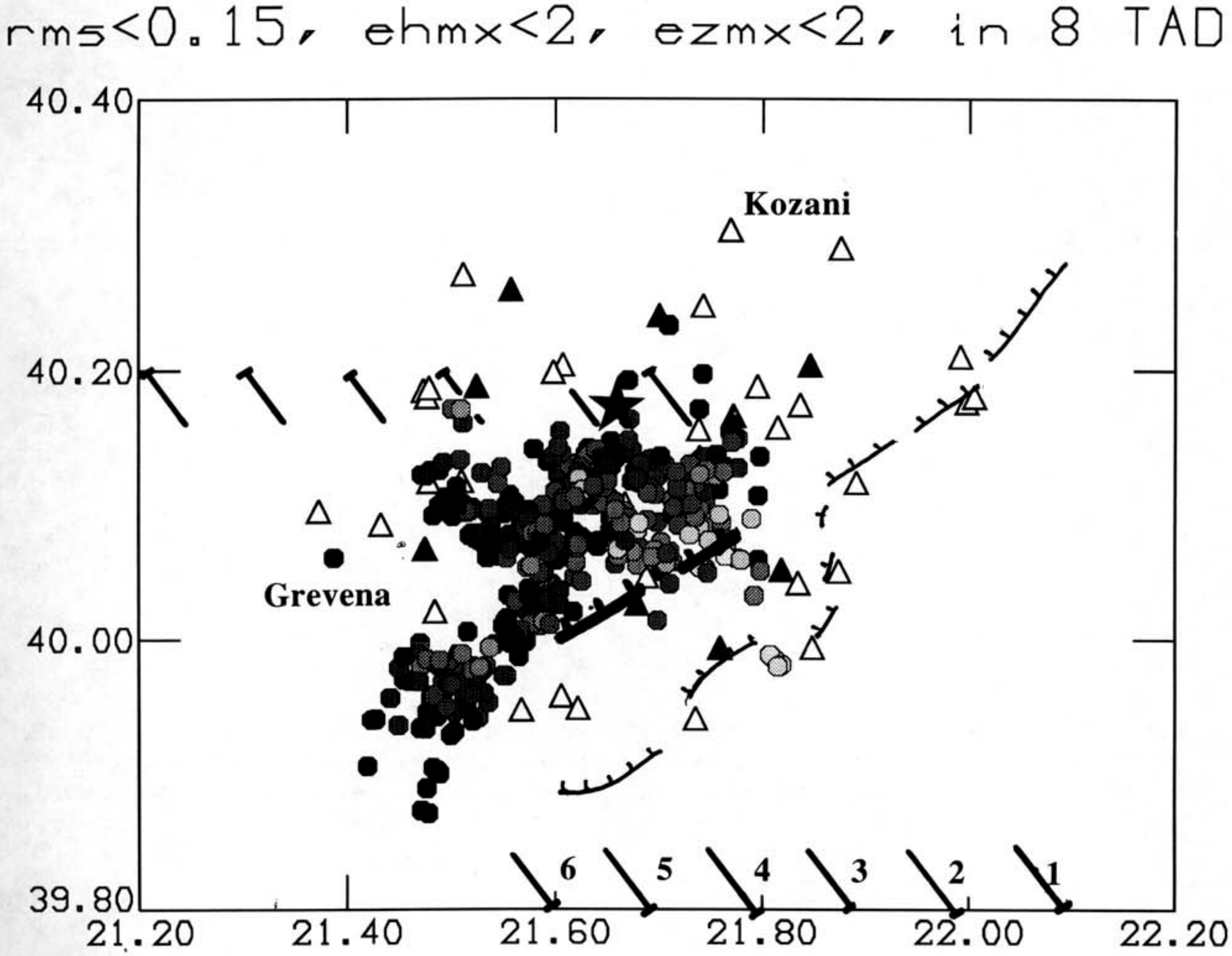
tent with the very small displacements observed at the surface and supports the idea that the rupture did not reach the surface.

To the west, the aftershocks define a small cluster with a slight southwestward dip. It is separated from the main cluster by a gap. This cluster was still active during the last part of our deployment. It could be due to a stress increase at the western termination of the fault and suggests that rupture propagated southwestward.

2) Seismotectonics

The Kozani earthquake happened at the western termination of the very important and recently active Servia fault. The mechanism is a normal fault, with a slip vector trending NW at about 340°. The Servia fault has the same trend as the North Aegean Trough which is the western termination of the dextral strike slip North Anatolian Fault. The motion on this fault is consistent with tectonic observations on Quaternary faults located in northern Greece around Florina (Pavlides and Mountrakis, 1987). However, the direction of the extension indicated by the focal mechanism of the Kozani earthquake (NW–SE) does not fit with the NS extension dominant in the Aegean.

At this early stage, it seems clear that the preliminary results of this multidisciplinary study confirm the peculiarity of the Kozani earthquake. Further work will include a) the relationship between the earthquake, the Servia fault and the tectonics of northern Greece, b) the comparison of the geodetic measurements with previous surveys, c) the use of all the seismological stations for focal mechanisms computation. ■



▲ **Figure 7** (opposite, top) Seismological network installed around the epicentral zone, and seismicity map of the most reliably located events by the TAD stations. The shade of the symbols is a function of the depth of the earthquakes. We note two clusters separated by a gap. The location of the active fault (thin barbed line), the surface breaks (thick barbed line), and the cross sections are reported.

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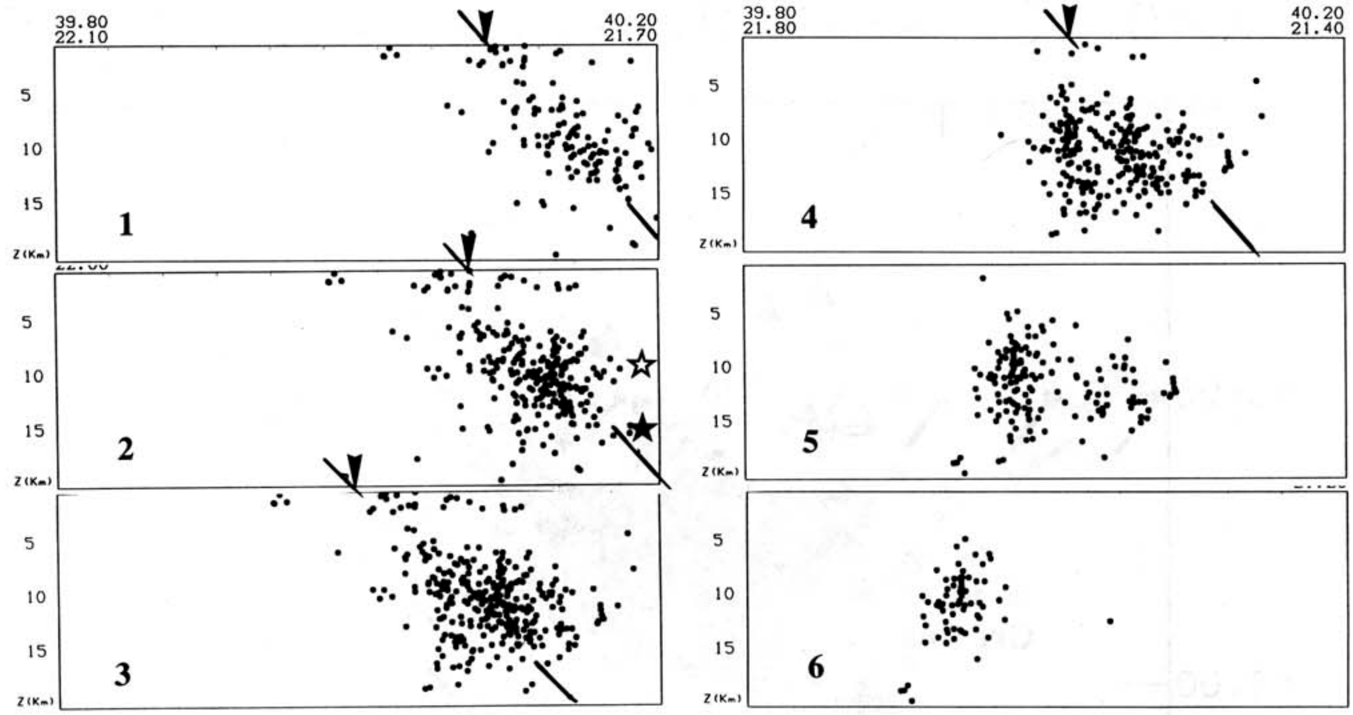

▲ **Figure 8** (opposite, bottom) Cross sections perpendicular to the surface breaks showing the two clusters of aftershocks. The arrows are the trace of the fault breaks seen at the surface. The line indicates the 45° dip toward the NW. The open star is the location of the mainshock determined by the Seismological Observatory of Thessaloniki, and the solid star is the location of CMT solution determined by Harvard.

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