Pergamon

J. Geodynamics Vol. 26, No. 2–4, pp. 245–254, 1998

PII: S0264-3707(97)00063-X
0264-3707/98 $19.00+0.00

THE KOZANI–GREVENA (GREECE) EARTHQUAKE OF MAY 13, 1995, A SEISMOLOGICAL STUDY

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(Received 13 January 1997; revised 1 June 1997; accepted 13 August 1997)

Abstract—We present a detailed seismological study of the Kozani earthquake. We relocate the mainshock with regional data at depth of 14.2 km beneath the Vourinos massif. We compute the focal mechanism by body waveform modeling at teleseismic distance and find a normal fault striking N240° and dipping 40° toward the NW with a centroïd depth of 11 km. We installed a dense network of portable seismographs around the epicentral region and located several hundreds of aftershocks. The main cluster of aftershock seismicity defines a plane dipping north at an angle of about 35°, consistent with the main-shock mechanism, while some seismic activity is also seen on an antithetic fault. Our results suggest the active fault plane to be the Deskati fault which dips at a constant angle and therefore branches on the Paleohori fault where surface breaks were observed. We also compute 181 focal mechanisms which mostly show normal faulting. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

The Kozani earthquake of May 1995 is the strongest event of the decade in Greece and occurred in a region of low seismicity. For this reason it was 'unexpected' and motivated the deployment of a portable seismological network in the epicentral region. Collaboration between French, Greek, and Italian institutions greatly increased the number of stations as the accuracy of the results. We present here a summary of our work that is already published elsewhere (Hatzfeld *et al.*, 1995, 1997) and should be discussed in the light of other observations as tectonics and geodesy. We relocate precisely the mainshock, using well located aftershocks to compute a velocity structure and station corrections. We use a body waves modeling technique to insure on the focal mechanism and centroïd depth. We locate (with an accuracy of a kilometer) more than 600 aftershocks that were recorded by a dense network (forty stations) that was installed after the mainshock.

MAIN SHOCK

Location

We compute a mean regional velocity structure (and the station corrections) that fits the arrival times at the permanent regional stations (Table 1), using as sources 50 strong aftershocks that were very well located by the local network. We also use the clear 3.4 sec S-trigger travel time delay of the SMA1 strong motion instrument located in Kozani. The location of the main shock using only regional permanent stations with residuals smaller than 2 seconds, shows some inconsistency (of several seconds) in Kozani between the seismological station KZN and the strong motion station SKZ. In KZN, we only have the P arrival time, whereas in SKZ we only have a minimum of S–P arrival delay. We cannot fit both SKZ and KZN and must eliminate the reading at KZN because we cannot trust the clock. Our final location for the mainshock is 40.183°N and 21.660°E, underneath the Vourinos ophiolite massif, at a depth of 13.6 km, with a mean RMS value that drops from 0.69 sec to 0.49 sec (Fig. 1).

Focal mechanism

The CMT solution determined by Harvard is a pure normal solution located at a depth of 16 km with one plane trending N240° and dipping 31° to the NW. We use a waveform modeling technique (Nabelek, 1984) to 43 very broad-band P- and SH-waveforms recorded at epicentral distances ranging from 30° to 90°. We compute theoretical Green's functions for a simple crustal model. We filter the records and correct for the instrumental response. We obtain a centroid depth of 11 ± 1 km slightly shallower than the depth computed by short period records, and a focal mechanism, slightly different from the CMT, that is a normal fault trending N252° ± 1° and dipping 41° ± 1° to the NW (Fig. 2). The source time function is dominated by a first large pulse of 6 sec duration followed a few seconds later by another pulse of 8 sec duration, 4 times smaller and not very well constrained. The total scalar moment is 6.2×10^{18} Nm, which is smaller than the value of 7.6×10^{18} Nm given by the Harvard CMT.

The rupture propagation likely started from the bottom of the fault. A second shock is present but not obviously different than the mainshock. The preferred fault plane dips likely 40° NW.

Table 1. P-Wave velocity structure

velocity (km/s)	depth (km)
5.8	0
6.2	8
7.8	30

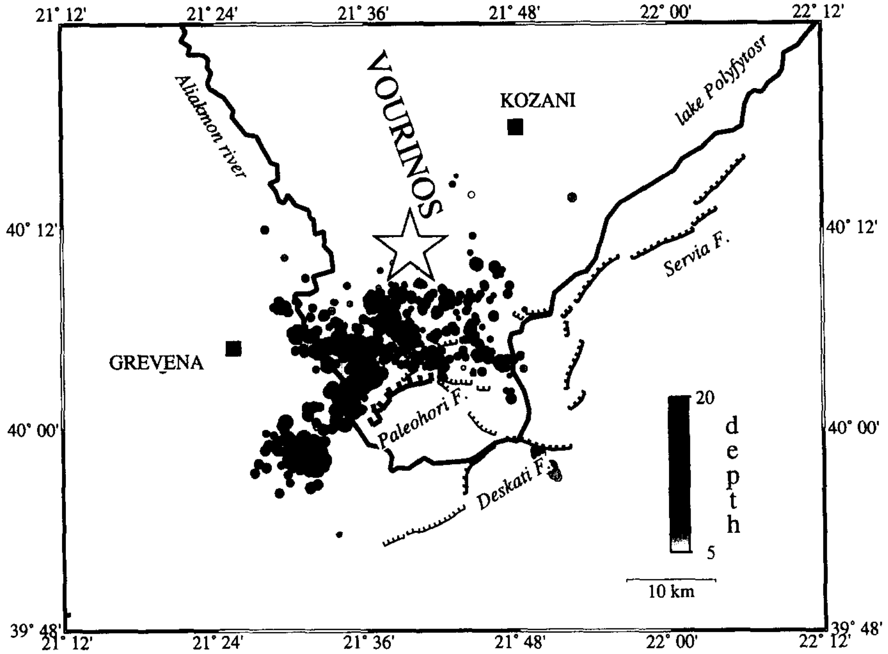

Fig. 1. Seismicity map of the 622 aftershocks recorded at more than 20 stations with an RMS smaller than 0.15 sec and located with uncertainties smaller than 1 km in terms of both epicenter and depth. The best solution for the relocated main shock is indicated by a star. The Servia and Deskati faults are plotted as thin barbed lines, whereas the surface ruptures in Paleohori during the earthquake are thick barbed line (Meyer *et al.*, 1996).

Rupture propagation

We use the strong motion record of the main-shock at Kozani near the source ($\Delta = 16$ km) to constrain the rupture directivity characteristics in matching the envelope and the spectral content of the acceleration record (Fig. 3).

We consider a fault plane striking N240° and dipping 40° with the lower edge located at 15 km depth. We define a final dislocation distribution, with a k^{-2} spectral decay. We compute the EW accelerograms at the Kozani station for four nucleation positions from the eastern edge to the western edge and evaluate only the far-field term of the P- and S-direct waves.

Positions 1 and 2, at the eastern edge of the fault which also give a good fit for the S-P travel time in the Kozani station, show a better fit in terms of directivity effects, which control frequency content and signal duration. This is in agreement with the solution proposed by Papazachos *et al.* (1995), and with our location.

AFTERSHOCKS

We deployed a temporary seismological network of 40 mobile stations around the epicentral zone within a week after the mainshock. Using the selected set of 50 well recorded events we compute a Vp/Vs ratio of 1.76, a local velocity structure that minimizes the residuals (Table 1), and mean station residuals that are applied as station corrections. Between May 19 and May 25, we locate 622 events ($1 < Ml < 3.5$) that satisfy the following

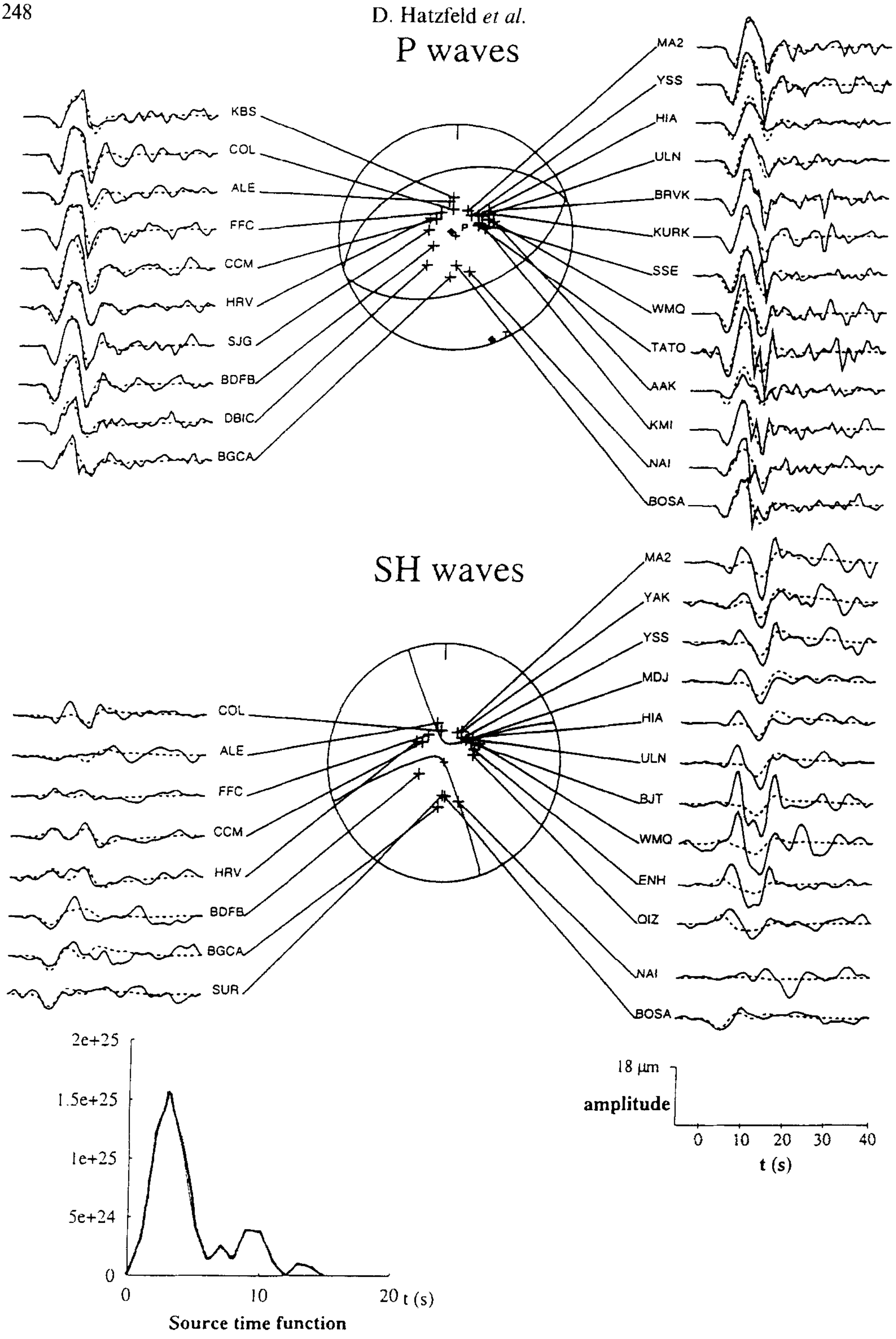

Fig. 2. Broad-band modeling of P- and SH-waveforms at teleseismic distances. The solid line is observed and the dotted line is the computed displacement. All signals were convoluted by a common VBB instrument and filtered with a Butterworth band-pass filter (0.002–0.5 Hz). The source time function shows 2 distinct pulses of 6 sec and 8 sec duration.

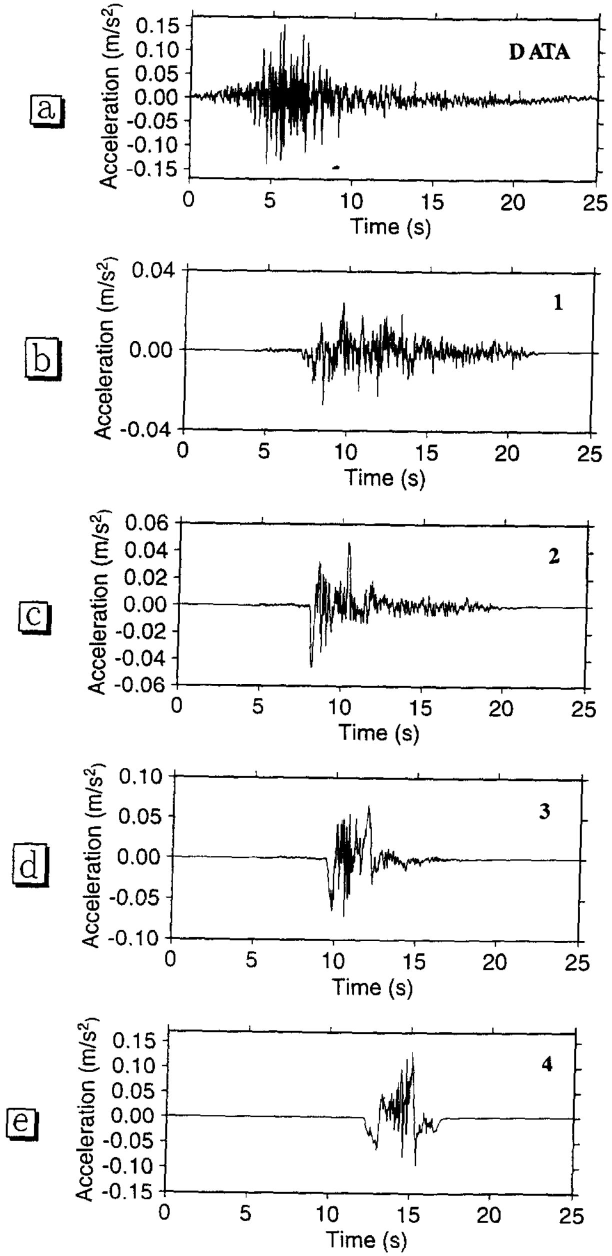

Fig. 3. Comparison between observed and modeled accelerations for the EW component in Kozani. a) SMA1 record of the EW component. b) to e) Synthetic accelerograms computed for four different nucleation positions from the east (accelerogram 1) to the west (accelerogram 4). The best fit is for a nucleation point at eastern location.

criteria: number of readings greater than 20, RMS smaller than 0.15 sec, and uncertainties in both epicenter and depth smaller than 1 km (Fig. 1).

The seismicity, ranging between 5 and 15 km depth, is concentrated north of the Deskati Fault and also north of the surface ruptures observed during the main-shock (Pavlides *et al.*, 1995; Meyer *et al.*, 1996). It defines two clusters which are separated by a local minimum of activity. The largest cluster (about 20 km wide) dips roughly to the north and is limited by the surface breaks. A second cluster, about 10 km wide, is located south-west of the main cluster near the city of Grevena but is dipping toward the south, in the opposite direction to that of the main cluster.

We compute two vertical sections trending perpendicular to the surface faults (Fig. 4). Section 1 is located across the main cluster. It clearly shows a deepening of the aftershocks toward the north from 5 to 15 km. According to our relocation, the main-shock is reported at the bottom of the fault plane. We also observe a well-defined cluster, with opposite dip, that is connected to the main cluster at 7 km depth. The dip of the main cluster is about 40° toward the north and would cut the surface approximately around the Deskati Fault and therefore south of the surface breaks. The antithetic branch reaches the surface near Siatista in the valley which cuts the mount Vourinos.

Section 2 runs across the western cluster, beneath Grevena, which appears to deepen

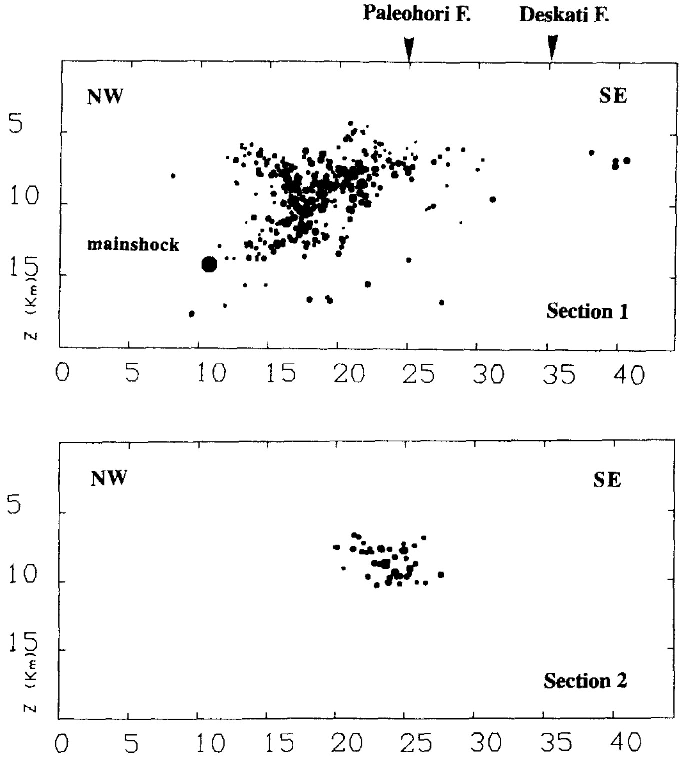

Fig. 4. Cross sections trending perpendicular to the surface breaks. Section 1 is across the main cluster, section 2 is across the Grevena cluster. The surface traces of the Deskati Fault and the ruptures near the Paleohori fault are indicated when available.

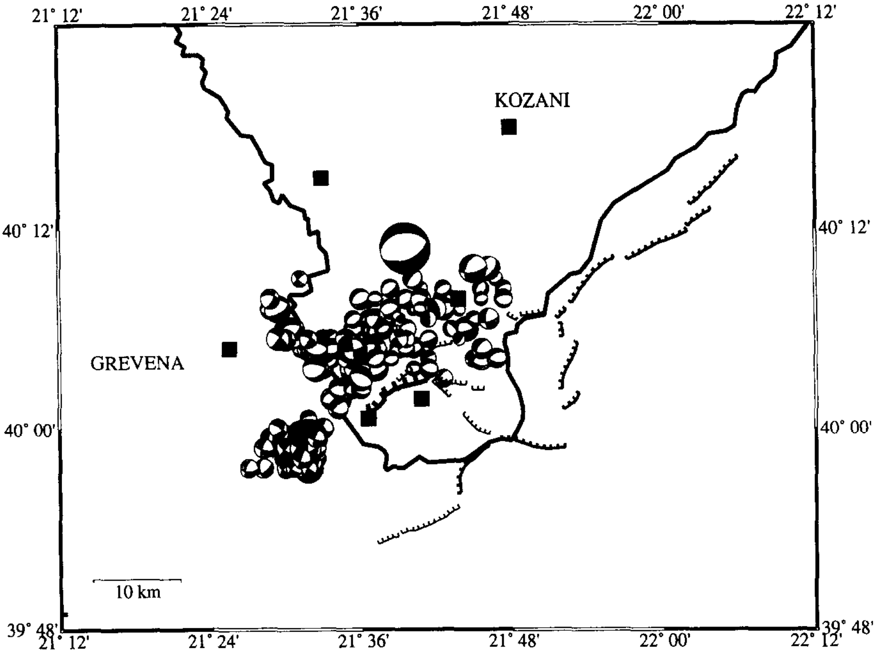

Fig. 5. Map of the focal mechanisms computed for the aftershocks. The biggest balloon is the mechanism computed for the main-shock in this study. Most of the aftershocks are normal faulting similar to the mainshock. We observe a few strike-slip solutions mostly located to the west of the main cluster. Therefore the western part of the fault, with and antithetic fault and strike slip mechanisms, appears to be more complex than the eastern part.

toward the south. The dip cannot be measured accurately but is similar to the antithetic cluster of section 1, suggesting that both clusters could be related to the same fault.

We also compute 144 focal mechanisms with a minimum of 20 polarities and add 35 solutions computed for the western cluster for which we release the criteria (Fig. 5). Most of the solutions are consistent with the main-shock and show normal faulting. A few solutions are strike-slip motions (belonging generally to the western cluster) with a T axis trending roughly NW–SE similar to the normal faulting mechanisms. A few mechanisms are associated with the 'antithetic' fault seen in section 1. They show the same pattern of normal faulting as the northward dipping cluster.

DISCUSSION AND CONCLUSIONS

Our study precises a few points regarding the Kozani earthquake.

(*a*) *The slip and surface of the fault*

The static moment of the main shock is $6.2\mathrm{x}10^{18}$ Nm. Given the surface of the fault (425 km^2, if we assume a length of 25 km and a depth greater than 5 km) obtained by the aftershock seismicity, we can compute a mean slip on the fault. Assuming a rigidity of $3.6\ 10^{10}$Pa, the average displacement on the fault is therefore of 0.5 m. However, it could be

0.25 m if the main fault reached the surface and affected the Grevena cluster which dips in the opposite direction. This displacement is slightly less than computed from geodesy (Clarke *et al.*, 1996) and Radar Interferometry observations (Meyer *et al.*, 1996).

(*b*) *The main fault*

A flat plane of constant dip (about 35°) through the aftershocks of section 1 would cut the surface around the Deskati Fault. This dip is consistent with the dip of the fault plane inferred from body wave modeling. It favors the Deskati fault to be the active fault. However, such a shallow dip is uncommon for normal faults and does not fit the observed dip of the Deskati Fault observed at the surface. And no breaks were observed during the earthquake around the Deskati fault but along the Paleohori fault. Our observations suggest that the aftershocks are located on the deepest part, that experienced the largest slip, of a wider fault plane of the Deskati fault which branches toward the surface to the Paleohori fault. We observe some complexity (most of the strike-slip mechanisms) on the western part of the fault around Grevena, and not at the eastern end as it is inferred from satellite imagery (Meyer *et al.*, 1996).

(*c*) *The antithetic cluster*

Part of the aftershocks concentrate on a plane which dips southward and is therefore of reverse polarity as compared to the main cluster. Some mechanisms were computed for this cluster and also show normal faulting, striking the same a the main cluster. The extension of this plane reaches the surface in the vicinity of the main road between Kozani and Grevena, near Siatista, where a valley cuts the Vourinos massif. But no surface breaks were observed in this area. The approximate surface is of 40 km^2 that represents about 8% of the main fault surface. This antithetic fault could be the origin of the second pulse in the source time function, which represents only 15% of the total moment, and the slip on this antithetic plane should be therefore of comparable extend for both the main and antithetic faults.

(*d*) *A possible model*

The Kozani earthquake probably did not rupture one simple plane dipping northward from the surface (Fig. 6). The main shock probably occurred on a 40° northward dipping fault plane, whose upper edge is located at a depth of 5 km beneath Paleohori. This is consistent with the smallness of the surface ruptures and with the coseismic ground deformation (Clarke *et al.*, 1996; Meyer *et al.*, 1996). The rupture started on the eastern part and at the bottom of the fault and propagated toward the southwest.

The surface breaks in Paleohori are located at the vertical projection to the surface of the upper edge of the aftershock seismicity. They could be due to branching of the Deskati fault to the Paleohori fault toward the surface. This favors the Deskati fault to become active in the prolongation of the Servia fault.

An antithetic cluster offset by a few km toward the south-west is also present which could be related to the presence of a second pulse representing 15% of the total energy released. We have no evidence on the timing of the antithetic fault as compared to the main fault.

This complexity looks like the Corinth earthquakes in 1981 or the Thessaloniki sequence of 1978 which affected several adjacent segments of the main fault, but the offset between the 2 faults is smaller here than for Corinth or Thessaloniki.

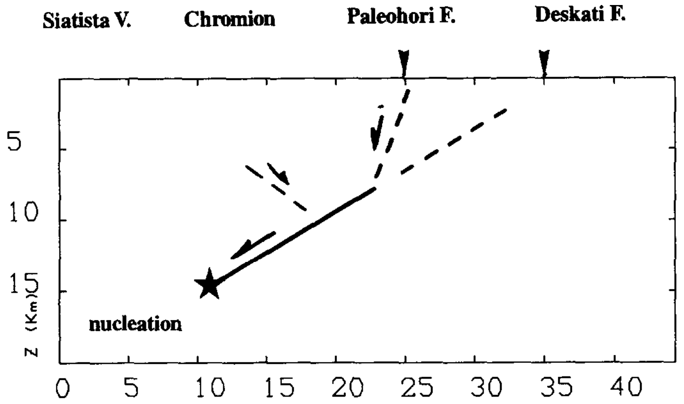

Fig. 6. Possible model for the Kozani earthquake. The nucleation of the fault started on the bottom of the fault and propagated toward the surface and the East. The active fault dips at an angle of about 40° toward the North. The slip occurred on a fault located in the prolongation of the Deskati fault, but surface breaks occurred on the Paleohori fault. Most likely the Paleohori and the Deskati faults branch at depth. The antithetic fault could be the result of volume readjustment.

Acknowledgements—We would like to thank the local authorities for their efficient help during the field work. The PPC of Greece for communicating their data. We had fruitful discussions with R. Armijo, P. Briole, G. King, H. Lyon-Caen, B. Meyer, B. Papazachos, B. Parson, J.-C. Ruegg, D. Sorel, & P. Vergely. We benefited of a great help in the field from R. Guiguet, A. Paul, P. Voidomatis, D. Diagourtas, I. Kassaras, I. Koutsikos, R. Azzara, M. Di Bona, S. Baccheschi, P. Bernard, and C. Papaioannou. This work was supported by the PNRN-INSU program of CNRS, from EC Environment Program, contracts EV5V-CT94-0413 and EV5V-CT94-0513. V.K. was supported during his visit to Grenoble by the Service Scientifique of the French Embassy in Athens.

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