EARTHQUAKE RUPTURE PROCESS OF THE VOLOS-ALMIROS AREA (CENTRAL GREECE)

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A B S T R A C T

Teleseismic body wave analysis of the April 30, 1985 Almiros earthquake is applied to determine the source parameters. The obtained results are compared to those of the July 9, 1980 Volos earthquake sequence in order to interpret the rupture process. The focal mechanism obtained from long period waveform modelling (strike= 80°±5°, dip=52°±5°, rake=-115°±5°) represents a north-south extension with a moderate right lateral displacement. The centroid depth is constrained to 8±2 km, the duration of the source time function to 4 sec and the seismic moment to $2.8*10^{24}$ dyn-cm. The 300 foreshocks located by Volnet network (which represents a year's seismic activity before the Almiros earthquake) define two clusters separated by a well defined "gap" of about 8 km. This "gap" was activated during the Almiros earthquake. If we assume a rupture velocity of 3 km/sec, then the fault length is estimated to be about 12 km. Concerning these earthquakes a normal fault system with a moderate right lateral motion, dipping to the south with a length of about 55 km, is proposed, with an irregular slip motion over the heterogeneous fault plane described by the barrier-asperity model.

ΜΕΛΕΤΗ ΣΕΙΣΜΙΚΗΣ ΔΙΑΡΡΗΞΗΣ ΤΩΝ ΣΕΙΣΜΩΝ ΒΟΛΟΥ-ΑΛΜΥΡΟΥ (ΚΕΝΤΡΙΚΗ ΕΛΛΑΔΑ)

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Π Ε Ρ Ι Λ Η Ψ Η

Στην εργασία αυτή μελετάται ο τρόπος της σεισμικής διάρρηξης καθώς επίσης και ο προσδιορισμός των σεισμικών παραμέτρων των σεισμών που έγιναν στην περιοχή Βόλου-Αλμυρού. Γιά τον σκοπό αυτό εφαρμόστηκε η μέθοδος υπολογισμού συνθετικών σεισμογραμμάτων GBS και χρησιμοποιή-θηκαν δεδομένα από το παγκόσμιο δίκτυο WWSSN. Ο μηχανισμός γένεσης του σεισμού που έγινε βόρεια της πόλης του Αλμυρού υποδεικνύει κανονικό ρήγμα το οποίο έχει δεξιόστροφη οριζόντια ολίσθηση. Οι εφελκυστικές τάσεις προσδιορίστηκαν με διεύθυνση Βορρά-Νότου ενώ η σεισμική ολίσθηση υπολογίστηκε ότι είναι 10 εκατοστά με υποχώρηση του νότιου τμήματος του ρήγματος σε σχέση με το βόρειο. Το βάθος του σεισμού προσδιορίστηκε στα 8±2 km, η διάρκεια της σεισμικής πηγής στα 4 δευτερόλεπτα και η σεισμική ροπή $2.8*10^{24}$ dyn-cm. Οι 300 προσεισμοί που έγιναν στη περιοχή κατά την διάρκεια του προηγούμενου έτους και καταγράφηκαν από το δίκτυο Volnet, φανερώνουν την ύπαρξη ενός σεισμικού κενού

το οποίο ενεργοποιήθηκε με τον σεισμό του Αλμυρού. Τα παραπάνω αποτελέσματα σε συνδυασμό με αυτά που προέκυψαν από τον σεισμό του Βόλου κανοντας χρήση φραγμάτων και εμποδίων, μας οδήγησαν στο σχεδιασμό ενός μοντέλου μηχανισμού διάρρηξης.

INTRODUCTION

On April 30, 1985, a moderate earthquake of magnitude Ms=5.7 occurred in the Volos-Almiros area (central Greece). The epicentre of the earthquake was located to the north of Almiros town (39.26°N, 22.81°E) and it was close to the earthquake sequence location of July 9, 1980. Central Greece is characterised by shallow seismicity and normal faults with an extension in an approximatelly north-south direction (McKenzie, 1972, 1978; Papazachos et al., 1983; Drakopoulos and Delibasis, 1982; Papazachos et al, 1991). Following the installation of the WWSSN network, the above earthquakes were the first teleseismically recorded in this area in order to apply modelling techniques. The use of the July 9, 1980 earthquake has been difficult because of the waves overlaping resulting from the foreshock that occurred just before the main shock. Concerning the April 30, 1985 earthquake it has been teleseismically well recorded, thus synthetic seismograms can be calculated to determine the source parameters. These results are compared to those of the previous earhquakes for the definition of the rupture process.

The irregular slip motion over a heterogeneous fault plane can cause complex rupture process as shown in numerical experiments (Das and Aki, 1977; Kanamori, 1986; Kikuchi and Fukao, 1987; Papageorgiou and Aki, 1983a, b). This irregular rupture propagation was explained in terms of barriers (Aki, 1979) or asperities (Kanamori and Stewart,1976,1978). The barriers interpret the rupture nucleation before a main shock, the preparation of a fault zone for the main rupture and the occurrence of aftershocks as the release of stress concentration around barriers (Aki, 1984). The asperities are applied in areas of geometrical irregularities containing strong patches under stress surrounded by a region where stress has been released by foreshocks. The irregular rupture propagation during an earthquake can be explained by the breaking of these asperities. Both models generate high frequency seismic radiation (Madariaga, 1977,1983), important for the interpretation of strong motion records.

The Volos-Almiros earthquake sequence consists of four shocks. The first one was the foreshock (M_s=5.5) occurred on July 9, 1980, just before the main shock, to the south of Volos town (figure 1). The second was the main shock (M_s=6.3) one minute later, 8 km eastern to the foreshock, while the third one was a large aftershock (M_s=6.0) occurred twenty five minutes later and 25 km to the west of the foreshock (table 1). This earthquake sequence produced small surface breakages in the area (Papazachos et al. 1983). The fourth earthquake occurred on April 30, 1985, to the north-east of Almiros town and this is the one study applying waveform analysis method.

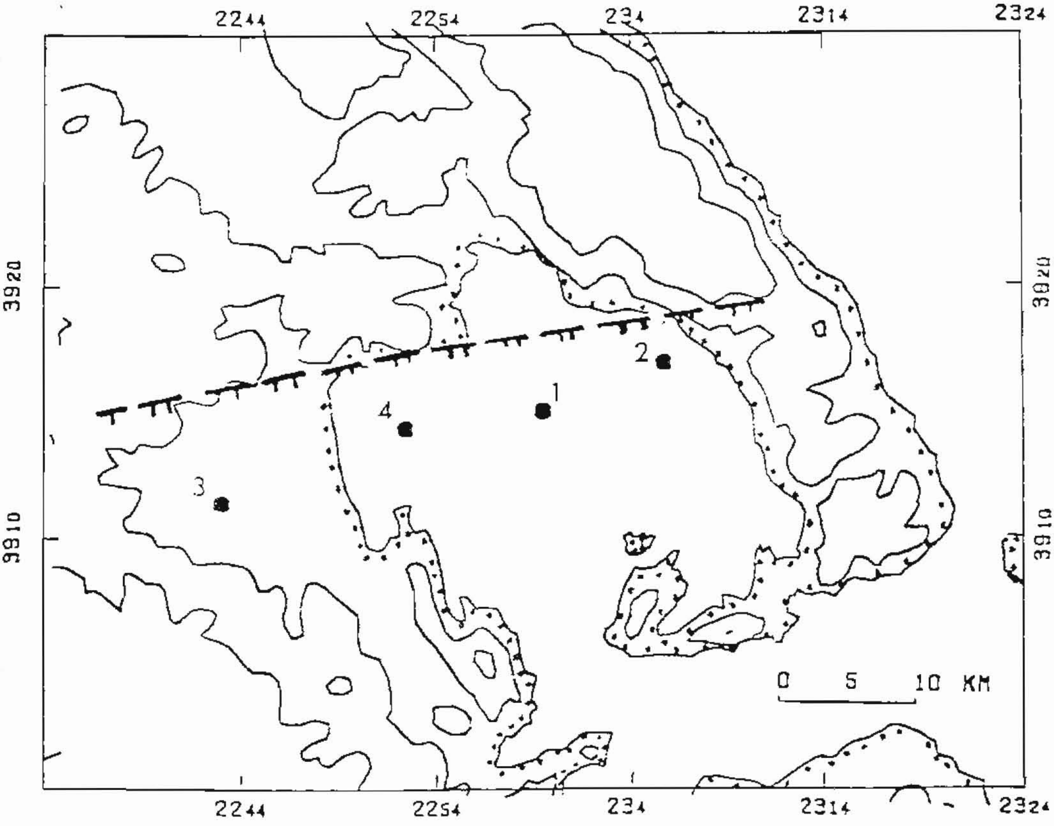

Fig.1. Location of the large earthquakes

Table 1. Epicenter determination of events with the corresponding magnitude, depth and focal mechanism.

1980	07	09	02:10:19	39.25N	23.00E	5.6	13	70	45	-90
1980	07	09	02:11:56	39.27N	23.09E	6.3	16	80	45	-90
1980	07	09	02:35:52	39.16N	22.68E	6.0	18	80	45	-90
1985	04	30	18:14:13	39.26N	22.81E	5.7	8	70	45	-115

In previous studies the analysis of the events was based on macroseismic data and the P-wave first motion polarities were used for the construction of the focal mechanism. In this study teleseismic body wave modelling is combined with tectonic observations to define the source parameters and to determine the rupture process of the earthquakes in terms of barriers and asperities.

DATA AND METHODOLOGY

In order to constrain the source parameters of the main shock we generate synthetic seismograms of P and SH waveforms and then we compare them to long period WWSSN available records. For the records situated at a distance more than 30° we apply a standard inversion method that minimises the difference between the observed and the calculated seismograms in a least squares sense. For the records situated at a distance less than 30° we use the Gaussian Beam Summation method (GBS) and the EΠ86 velocity model, in order to calculate the Green's function, which represents the response of the upper mantle. The Green's function is calculated for a given epicentral distance and it contains the effect of caustics associated to the discontinuities of the upper mantle. Then this function is convolved with the source time function, the instrument response and the attenuation in order to obtain a synthetic seismogram directly comparable to the observed one by trial and error.

DETERMINATION OF SOURCE PARAMETERS

Synthetic seismograms are generated for a given epicentral distance, depth and focal mechanism and then they are compared to the corresponding observed ones. Sets of calculations were performed in a half space with a mean P velocity 5.8 km/sec. Figure 2 shows all available records with the obtained corresponding synthetic seismograms. For each station the epicentral distance is indicated in degrees and the value of the seismic moment in 10^{24} dyn-cm. A very good fit of waveforms and amplitudes is obtained for a depth of 8 km as well as a source time function of 4 seconds. The proposed focal mechanism has a strike of 80°, a dip of 52° and a rake of -115°. The mean value of the seismic moment is $2.8*10^{24}$ dyn-cm, which is similar to the one resulted from the centroid moment tensor of $3.5*10^{24}$ dyn-cm.

By fixing one of the focal mechanism parameters we explore the uncertainties for each parameter (fig. 3). For the strike variation we select the SHL station which is situated close to the one of the nodal planes and hence the synthetic seismograms are more sensitive to strike variations. The strike varies between 65° and 90° with a step of 5°. Synthetic seismograms are computed for these values and compared to the corresponding record as it is shown in figure 3a. According to this figure, when the strike is increasing the amplitude the first motion is gradually decreasing. The strike giving the best fit is 80°±5°.

The same procedure is applied on the estimation of uncertainties allowing the dip values to vary between 40° and 60° (fig 3b) and the rake variation to vary between -100° and -125° (fig. 3c). The dip which gives the best fit is 52°±5° and the rake -115°±5°. The depth is moderately well resolved, as expected for such a small and shallow event, because of the trade-off between source time function duration and depth. However P waveforms allow to constrain the depth less than 8km (fig. 3d). At a larger depth, the phases pP and pS start to appear as a separated arrival. Hence, the depth of 8 km is adopted with an estimation error of ±2 km.

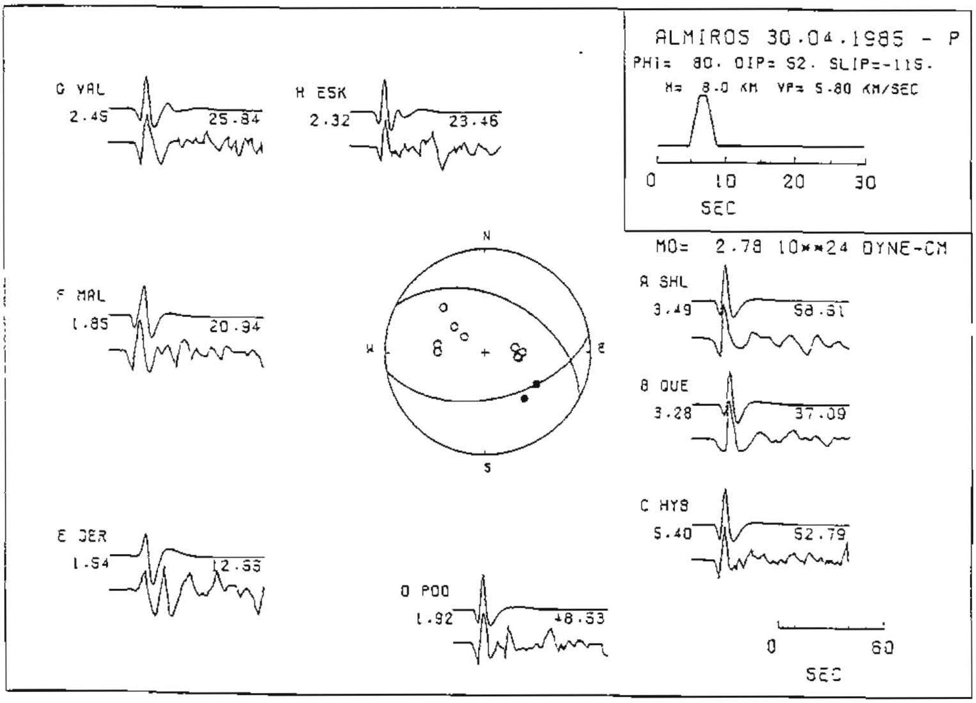

Fig.2. Modelisation of the P-waves.

SEISMICITY LEVEL

In 1983-1984 the VOLNET network was deployed in the region and it recorded many thousands of earthquakes. Figure 4a shows the seismic activity of the studied area, during this period, and distinguishes many clusters of high seismicity level: the first cluster is located northern of the city of Almiros and the second one southern of the city of Volos. Between the two clusters there is a well defined 'gap' over a width of about 8 km. Southern we distinguish two clusters also: the first one is located at the northern part of Evia showing a condensed seismic activity and the second one just to the north of the first cluster, showing a more extensive seismic activity along the coast line. To the north finally, we observe a seismic activity

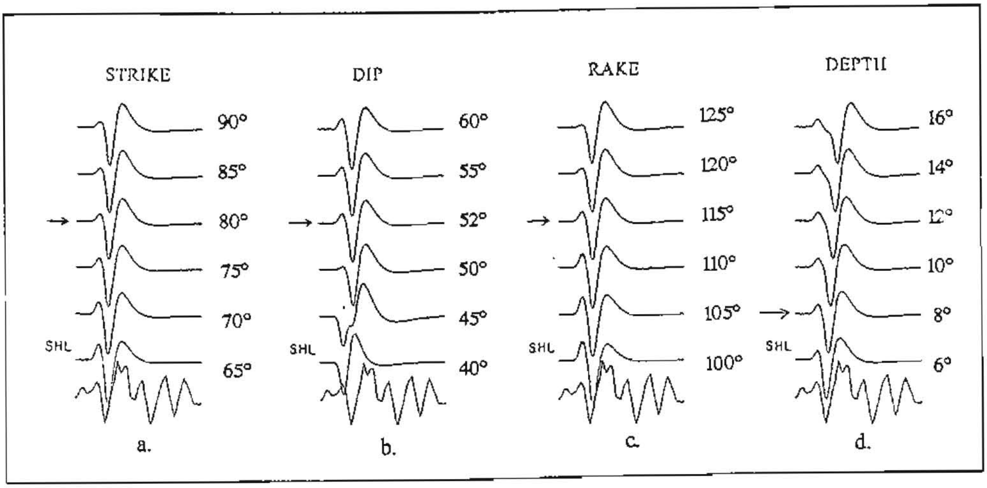

Fig.3. Modelisation of SH waves: a. strike variation; b. dip variation; c: rake variation; d. depth variation

following the topography of the area which has an orientation of about NW-SE. This seismic activity compared to the large aftershocks of the Volos 1980 earthquake sequence, shown in figure 4b, appears similarity in space distribution.

Figure 4c shows the foreshock activity in the year 1985 (during the fourth months before the main shock) and figure 4d the aftershock activity of the 15 days following the main shock. We observe a moderate seismic activity before the occurrence of the main shock which is very close to the aftershock location distribution. The aftershock distribution covers an area of about 15 by 10 km and we distinguish some preferential orientation striking NE-SW. The depth varies between the surface and 20 km. On the basis of aftershock distribution we estimate the length of the fault 12 km, the width 15 km and the coseismic slip 10 cm. Taking an elastic modulus 3*1011 dyn/cm^2 we obtain a seismic moment of $5.4*10^{24}$ dyn-cm.

DISCUSSION

The July 9, 1980 earthquake sequence occurred to the south of the town of Volos. For this event small surface breakages have been observed to the eastern part of the apparent fault indicating normal fault striking E-W, with a downthrown block to the south (Papazachos et al., 1983). Taking a mean displacement of 40 cm, 20 km for the average fault length, 15 km for the fault width and an elastic modulus $3*10^{11}$ dyn/cm^2 we obtain a seismic moment of $3.6*10^{25}$ dyn-cm which is approximately the expected value of an earthquake of magnitude M_s=6.3. According to these values and to the foreshock event we estimate that the length of the rupture zone is about 28 km (fig. 5) and the length of the aftershock is about 15 km. Between the two estimated faults a 'gap' of about 8 km can be observed. This 'gap' is also well presented in figure 4a.

According to the NOA or ISC location the April 30, 1985 earthquake occurred in the defined 'gap' area. The calculated seismic moment is $2.8*10^{24}$ dyn-cm and the duration of the source time function is 4 seconds. Taking a 3 km/sec velocity rupture we estimate the length of the fault of about 12 km. This value is consistent with the observed seismic 'gap'. The proposed focal mechanism is in agreement with the tectonic observations and shows an E-W normal fault with a moderate right lateral component of motion. The fault plane is striking N80°E and dipping 52° to the south.

Three fault plane solutions of the July 9,1980 earthquake sequence, have been proposed by Papazachos et al. (1983) using the P-wave first motion polarities. The main event and the main aftershock show identical pure normal faults striking N80°E. The focal mechanism of the foreshock shows a normal fault striking N75°E with a moderate left lateral motion. One nodal plane, of the above solutions, dipping to the north is well constrained by the P-wave first motion polarities but the auxiliary plane is not. Concerning the azimuth of the fault plane of the foreshock, it is in agreement with the azimuth of Almiros fault plane but the proposed left lateral motion is not consistent with the right lateral motion proposed in this study.

The fault plane solutions based only on the P-wave first motion polarities could show the mechanism of the fault but in general they are not often a well constrained solution. The focal mechanism of the Almiros earthquake is composed using wave form analysis and thus the nodal planes are well constrained. Because of the uncertainties of the three Volos focal mechanisms, we rotate the nodal planes in order to obtain orientations similar to those of the Almiros nodal planes. According to these remarks we propose a homogeneous normal fault system with a moderate right lateral motion, dipping to the south with a length of about 55 km which is in agreement with the tectonic observations (Papazachos et al. 1983).

An irregular slip motion over a heterogeneous fault plane is observed in the Volos-Almiros area during the 1980-1985 earthquake sequence that can be explained by the barrier-asperity models, illustrated in figure 5. The completely shaded fault plane corresponds to a uniformly stressed fault (fig. 5a) before the earthquake sequence. The rupture of the Volos main shock was initiated by the foreshock that took place approximately in the middle of the fault releasing a moderate energy. The figure 5b shows the fault plane containing unbroken strong patches after the foreshock. These patches are called "barriers" (Aki, 1979; Papageorgiou and Aki, 1983a,b). This barrier model explains the occurrence of an earthquake as the release of stress concentration around barriers (Aki, 1984). The shaded region in figure 5b is stressed and the blank is slipped. Then the rupture propagated to the eastern part of the fault while the western part remained unbroken. Figure 5c shows the fault plane

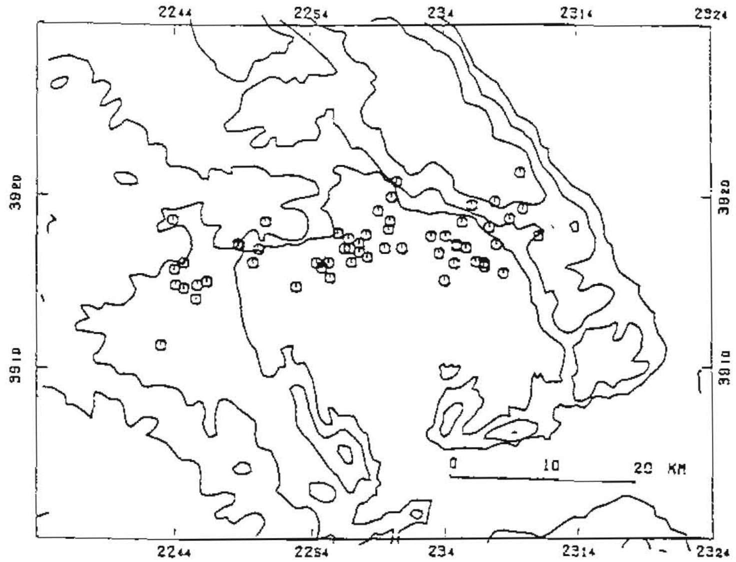

Fig.4a. Map of seismicity for one year period of time;

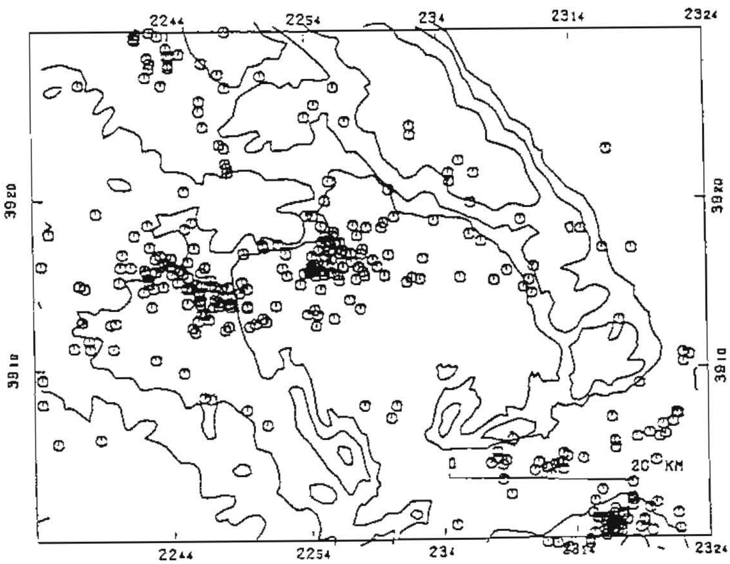

Fig.4b. Large aftershocks distribution of the Volos earthquake sequence.

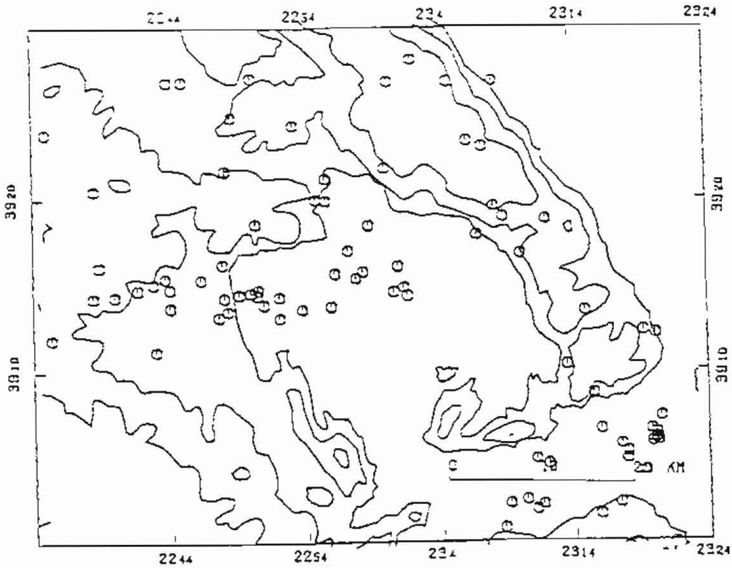

Fig.4c. Foreshock distribution of the Almiros earthquake;

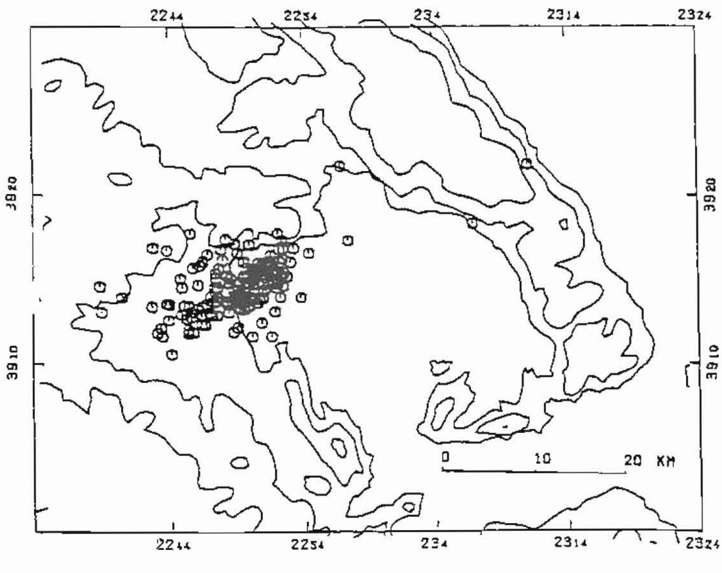

Fig.4d. Aftershocks distribution of the Almiros earthquake.

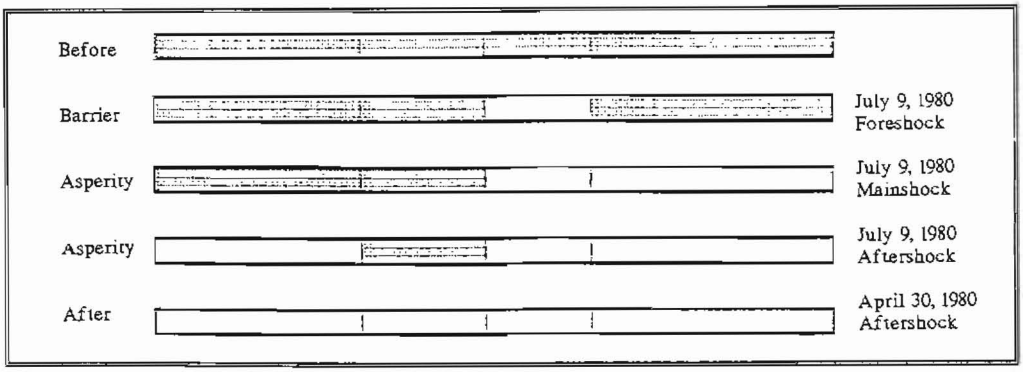

Fig.5. Rupture propagation model.

containing strong patches under stress surrounded by a region where stress has already been released by the foreshock. These strong patches are called "asperities" (Kanamori and Stewart,1976, 1978). A few hours later, this earthquake sequence provoked a rupture propagation to the extreme western part, leaving an unbroken asperity behind (fig. 5d). Finally the Almiros earthquake provoked a rupture propagation in the last unbroken patch and as a result the fault plane became a uniformly stressed fault (fig 5e).

CONCLUSIONS

The Volos-Almiros earthquake sequence consists of four distinct events. The long period waveform modelling of Almiros event suggests that the fault broke in a relatively coherent manner over a distance of about 12 km. The epicentre of this event is close to Volos sequence and occurred in the well defined "gap". The obtained fault mechanism phi=80°, dip=52°, rake=-115°, represents a north-south extension with a right lateral motion. The calculated coseismic slip is 10cm with a fault plane dipping to the south. The three Volos earthquakes produce normal faults striking E-W. These orientations could be adapted to that proposed in the present study, in order to obtain a homogeneous set of focal mechanisms. Finally, a rupture propagation model is proposed in terms of barriers and asperities in a total length of about 55 km.

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