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STATIAL AND TEMPORAL EVOLUTION OF THE SEPTEMBER 1986, KALAMATA, GREECE, AFTERSHOCK SEQUENCE

K. MARKOPOULOS, A. TSELENTIS, N. VOULGARIS, J. DRAKOPOULOS *

ABSTRACT

In this paper the spacial and temporal evolution of the aftershock sequence of Kalamata, Greece, 1986 earthquake is examined, by a new technique called the method of the principal parameters (Ebbling and Michelini, 1986). This method is based on time and space cluster analysis principles. Each of the clusters to be analysed consists of m time-successive foci of a window which slides along the aftershock sequence of n-events, yielding n-m+1 sets of events. For each set of events the variance-covariance spatial matrix is constructed, and its principal parameters, i.e. eigenvalues and eigenvectors, are calculated. By interpreting this matrix as a local rupture ellipsoid, which is fitted through the foci, the method is capable of isolating different orientations of active fault planes during the evolution of the sequence.

The application of the method, to 515 well located aftershocks of the Kalamata sequence, reveals trends of the seismicity pattern which are consistent with published focal planes based on fault plane solutions. Furthermore the activation of secondary faults of different orientations has been established emphasizing the fact that the area under study is tectonically complex.

ΣΥΝΟΨΗ

Στην εργασία αυτή εξετάζεται η χωρική και χρονική εξέλιξη της μετασεισμικής σεισμικής σειράς της Καλαμάτας, κατά τον Σεπτέμβριο του 1986, με την βοήθεια της μεθόδου των χαρακτηριστικών παραμέτρων των πινάκων διασποράς. Η μέθοδος αυτή βασίζεται στις αρχές που διέπουν την ανάλυση γεγονότων που παρουσιάζουν χρονική και τοπική συγκέντρωση. Κατά την ανάλυση αυτή υπολογίζονται και συγκρίνονται τα ιδιοανύσματα και οι ιδιοτιμές των διαδοχικών πινάκων διασποράς που προκύπτουν από την μετακίνηση ενός χρονικού παραθύρου, συγκεκριμένου εύρους m γεγονότων, κατά την χρονική εξέλιξη της σειράς n γεγονότων. Θεωρώντας ότι κάθε ένας από αυτούς τους πίνακες αντιπροσωπεύει το τοπικό ελλειψοειδές διάρρηξης των m γεγονότων, αποδεικνύεται ότι η μέθοδος αυτή είναι ικανή να διακρίνει διαφορετικούς προσανατολισμούς επιπέδων διάρρηξης, που ενεργοποιήθηκαν κατά την διάρκεια της εξέλιξης της σειράς.

Η εφαρμογή της μεθόδου σε 515 καλά προσδιορισμένα επίκεντρα της μετασεισμικής σειράς της Καλαμάτας έδειξε ότι, εκτός τών ήδη προσδιορισθέντων επιπέδων διάρρηξης, υπάρχουν και δευτερεύοντα επίπεδα μέ διαφορετικούς προσανατολισμούς, γεγονός που επιβεβαιώνει την τεκτονική πολυπλοκότητα της περιοχής.

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* University of A [illegible] eothermy Division Panepistimioupolis - Ilissia, Athens 157 01, Greece.

1. INTRODUCTION

The continuous effort of getting insight into the nature of the earthquake phenomenon, leads seismologists to approach the specific problem, by either new techniques or using methods of analysis, already known from other fields, which are suitable to the seismic data involved. Thus seismic signal analysis, for example, is now performed by using techniques originally developed for electrical signal processing. In a similar way the general principles and techniques of time sequence analysis are applied to earthquake occurrence, being regarded as events along the time axis. By analogy an aftershock sequence may be regarded as a cluster in space and time. In fact the obvious interdependence of the events within the sequence and their concentration in space and time, permits us to treat them as such. Hence cluster analysis techniques (Davis 1986) could be useful in looking at the spatial and temporal evolution of an aftershock sequence.

Such a technique based on the estimation of eigenvalues and eigenvectors of the variance-covariance matrix, from the centroid of the cluster to each event, is the one introduced by Ebbling and Michelini, 1986 and further elaborated by Michellini and Bolt, 1986. The application of the method to the Friuli, Italy and Coalinga, California sequences respectively has shown this relatively simple method is capable of inferring the orientation of fault planes activated during the evolution of the sequence.

The above method will be applied to the aftershock sequence resulting from the Kalamata, Greece, September 13 1986, m_s=6.2 main shock in an attempt to contribute towards the better understanding of the mechanism involved in this seismic paroxysm that destroyed most of the city.

2. BRIEF DESCRIPTION OF THE METHOD

Although details about the method can be found in the above cited references, the main assumptions and the step by step procedure leading to the determination of the orientation of active fault planes of the aftershock sequence, may be summarized as follows.

An earthquake sequence is assumed to consist of a large number of faults within an active seismic volume embedded in the regional stress field. Each rupture causes a redistribution of the stress field and accumulation of stress on the boundary of the rupture surface and on adjacent faults. These highly stressed places are the locations where the next earthquake is on the average expected to occur (Michellini and Bolt 1986). This progressive character of the model is supported by the observation that aftershocks are clustered in both space and time, suggesting that they are dependent of each other.

From the above consideration it is expected that the analysis of the spatial distribution of time successive events could get insight into the mechanism involved, by providing additional information about the time and space evolution of the rupturing system. Based on these assumptions and observations, the method consists of studying the spread, or variance-covariance matrix, of successive sets of temporal arranged events, within the aftershock sequence. This matrix may be regarded as defining the spatial ellipsoid, fitted through the foci, whose axes are the eigenvectors of the matrix, with lengths equal to the square roots of the eigenvalues. The comparison of the successive principal components, i.e. eigenvectors and eigenvalues, is next attempted, while certain criteria for the flattening of the ellipsoid are taken into account in order to lead the comparison between the case of successive coplanar ellipsoids.

The principal parameters of each group of coplanar ellipsoids, are then averaged and projected on a lower hemisphere equal-area projection. Finally the planes perpendicular to the direction of the average of the smallest eigenvectors, represent the planes that are the best fit of the foci.

The step by step procedure to obtain the time successive fault orientation and the pattern of seismicity, shown in figure 1, is as follows:

1._ Creation of sets of m events by sliding a time window of width m, along the n events of a spherical volume, of radius r centered at depth h within the area of the aftershock sequence, arranged in temporal order. The result of this procedure is the creation of n-m+1 sets. The radius and depth of the center of the spherical volume and width m, depend on the sequence's properties (see next section).

2._ For each one of the m successive events, the distance from the centroic of the set is calculated and averaged over the m events, formulating thus the spread matrix of the set. That is:

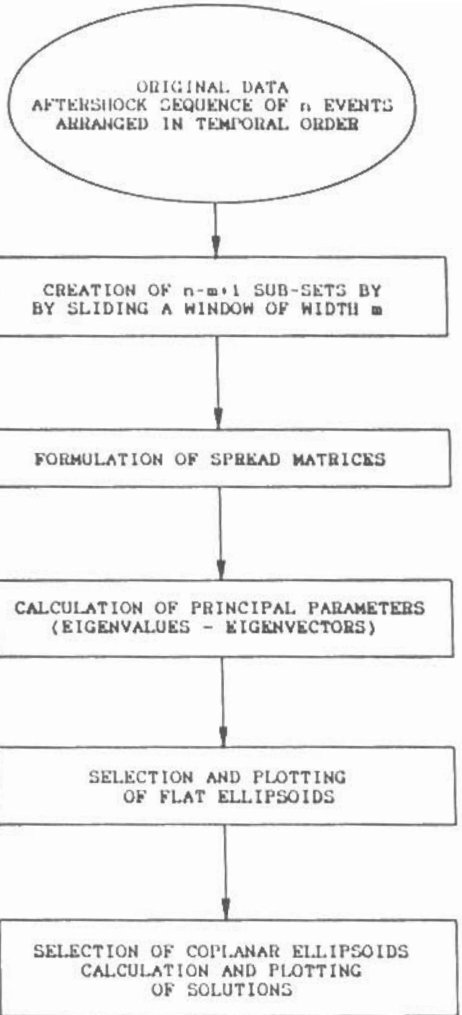
$$l_{ij}=l_{ji}=1/m \sum_{k=1}^{m} (x_{ki}-\bar{x}_i)(x_{kj}-\bar{x}_j) \quad (i,j=1,2,3) \quad , \quad \bar{x}_i=1/m \sum_{k=1}^{m} x_{ki} \quad (i=1,2,3)$$

3._ For each of the n-m+1 sets, the principal parameters, i.e. the eigenvectors and eigenvalues, are computed and stored for further processing.

4._ Because we are mainly interested for flat ellipsoids, only the eigenvectors with $T_1/T_3 \geq a$ and $T_2/T_3 \geq b$, where T_1, T_2, T_3 are the eigenvalues of the major, intermediate and minimum axis respectively, are selected and stored (for the values a,b see next section).

5._ The average major and minimum eigenvectors of each solution are next plotted in a lower hemisphere equal-area projection. From this plot it is possible to see the spatial migration of successive foci and to define a general trend.

6._ Next the successive coplanar ellipsoids are selected and averaged. This selection is performed by comparing the ellipsoid's orientation with the first, or reference ellipsoid, requiring that the major and minimum axis of the ellipsoid under comparison satisfies certain tolerance limits (see next section). The first ellipsoid that does not satisfy the criteria, is regarded as the



Σχ. 1.: Λογικό διαγραμμα της μεθόδου των χαρακτηριστικών παραμέτρων.

Fig.1.: Flow chart of the principal parameters method.

new reference ellipsoid in the next comparison whereas the previous ones represent now a solution of coplanar ellipsoids.

7._ Finally, in order to isolate the average seismicity trends during the sequence, the planes perpendicular to the direction of the average smallest eigenvalues are plotted on a same type of projection as before.

3. DATA SET

After the September 13 Kalamata, Greece, earthquake, a network of 16 portable seismic stations was installed covering the affected area.

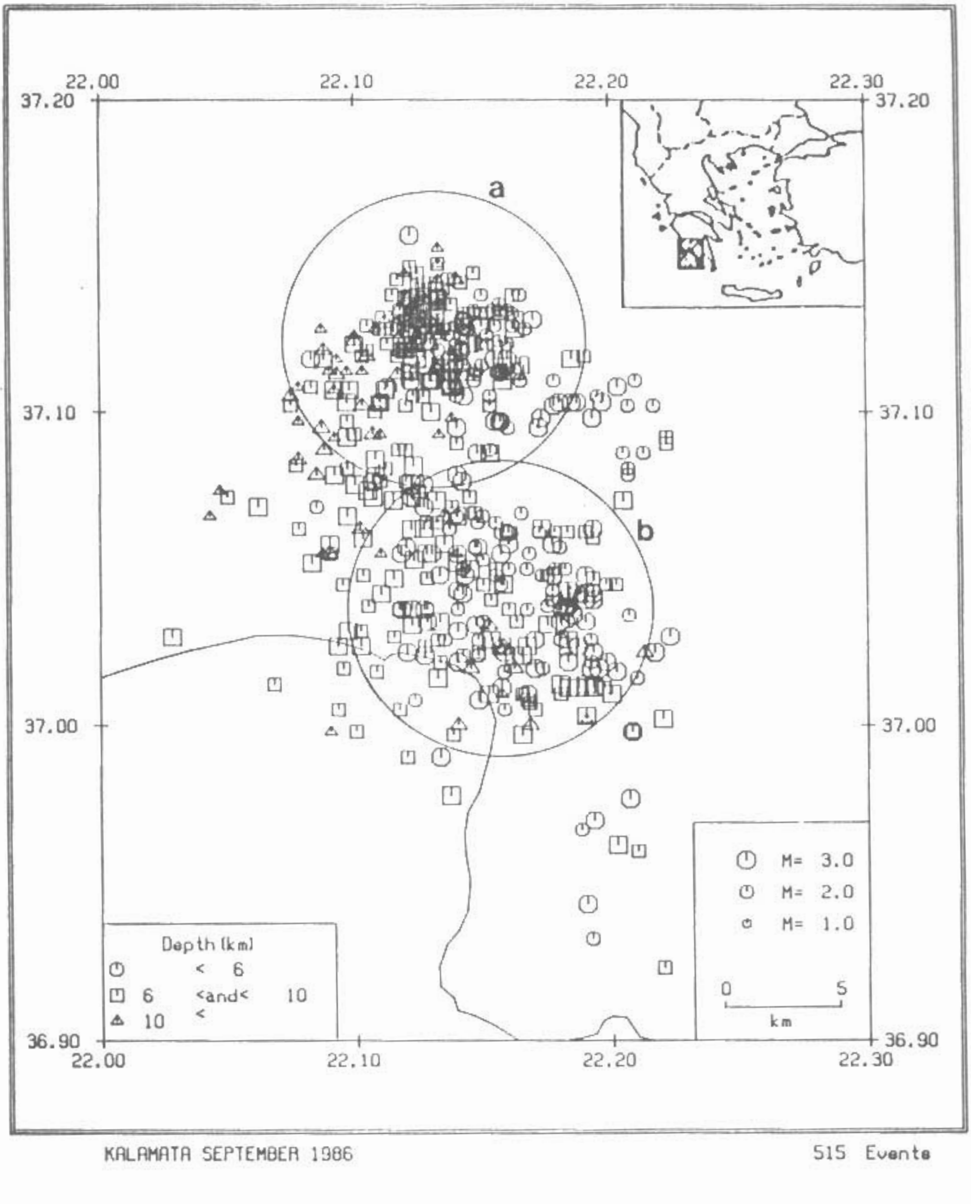
Over the period of the first two weeks more than 1500 aftershocks were recorded. These events were located with the HYPO71 computer program (Lee and Lahr, 1975). Using as location quality criteria : RMS<0.15 sec, ERZ<1.2 km, ERX<0.6 km, ERY<0.6 km and in addition at least 5 P-wave and 2 S-wave readings for each event, a total number of 515 events, with depths ranging from 0 to 12 km, were selected for further processing. The spatial distribution of these events is shown in figure 2.

From figure 2 it can be seen that the aftershocks are mainly clustered into two areas: the northern cluster (a), north of the Kalamata city, containing the hypocenter of the main shock and the southern one (b), containing the major aftershock. Based on the above observation and taking also into account that the cluster analysis method requires clusters to be as dense as possible, it was decided to study these two areas separately.

As it was mentioned in the previous section, before sampling, the radius and depth of the center of the spherical subvolume, has to be defined. These quantities depend on the cluster's density and the depth of the events. Thus for the northern cluster a radius of 6.6 km and a center depth of 6.7 km were selected, while for the southern cluster the radius and center depth were set to 6.7 and 7.0 km respectively.

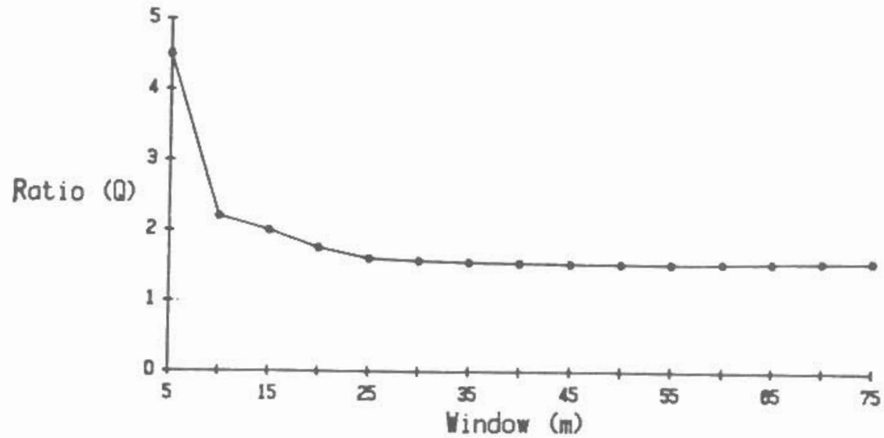
A second requirement of the method is to define the optimum width m of the sliding window. This choice is dictated by the fact that for smaller windows the spread of the eigenvectors is caused by a small number of foci used, while for larger windows information about the rupture directions may be lost due to smoothing caused by averaging a large number of events. In practice the optimal width is chosen by calculating the average ratio Q between the intermediate, T_2, and smallest, T_3, eigenvalues of the scatter matrices, for different window widths. By plotting the Q values for different values of m, the smallest value of m for which Q is nearly equal to the constant value is chosen. As it can be seen from figure 3, in our case a value of m=25 was chosen for both cases.

As for the ratios of T_1,T_2,T_3, which define the flattening of the acceptable ellipsoids (see step 4 of previous section), the values of $T_1/T_3 \geq 2.5$ $T_1/T_2 \geq 2.0$ and $T_2/T_3 \geq 1.5$, were chosen in order



Σχ. 2.: Χωρική κατανομή της μετασεισμικής σειράς. Οι περιφέρειες σημειώνουν τις υπό εξέταση περιοχές.

Fig.2.: Spatial distribution of the data set. Location of the examined subvolumes.



Σχ. 3.. Γραφική παράσταση του λόγου T_2/T_3 σε συνάρτηση με το εύρος του χρονικού παραθύρου m.

Fig.3.: Plot of the T_2/T_3 ratio versus window width m.

to obtain a satisfactory resolution.

A final requirement of the method is to define the tolerance limits for which successive ellipsoids can be regarded as coplanar (see step 6 previous section). In our case the values of 10° and 30° for the angles of major and smallest eigenvectors respectively, were chosen.

4. RESULTS AND DISCUSSION

For the two subvolumes considered in this study, see previous section, the eigenvectors with the largest (U_1,+) and the smallest (U_3,Δ) eigenvalues have been plotted on a lower hemisphere equal-area projection in figure 4 (a,b). This plot represents the results after the conclusion of step 4 in section 2, showing the migration and general trend of successive flat ellipsoids. For each of these subvolumes the results are as follows:

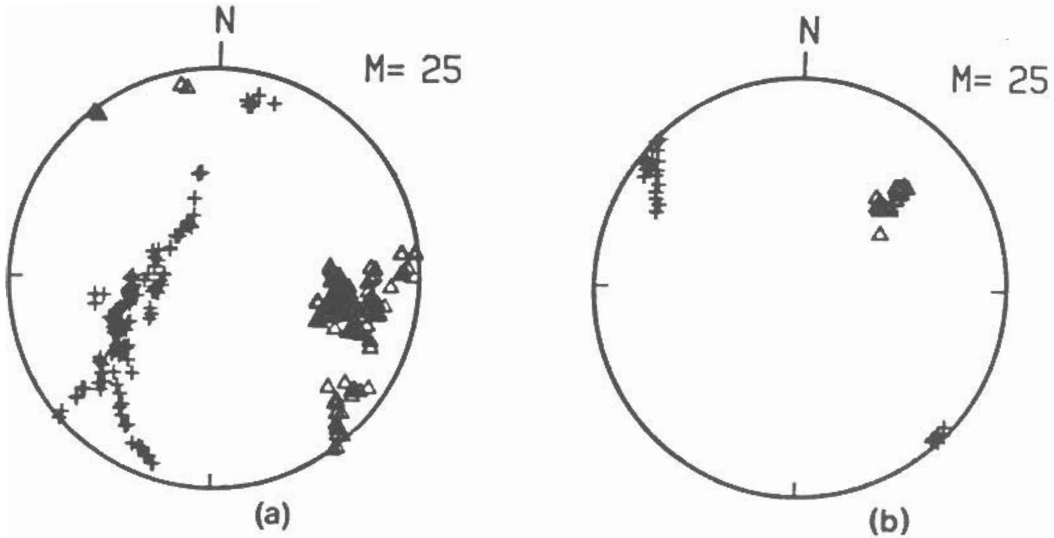
I._ Northern cluster: From figure 4a, it can been seen, that the smallest eigenvectors, which are perpendicular to the focal plane, are in the ESE part of the projection, showing that the expected planes will have a dip ranging from 45° to 90° and a strike ranging from a N-S to a NE-SW direction. This is confirmed by figure 5 where the solutions resulting from the averaging of successive coplanar ellipsoids are plotted on the same type of projection. In this figure two types of solutions can be distinguished:

a._ A solution with an average strike N32°E ±4° and an average dip of 81° ±7° (solution type A). This planes were activated at the beginning (solutions 1,2) and reactivated at about the middle (solutions 10,11) of the sequence. This type of solution is in agreement with the solution proposed by Papazachos et al. 1986 for the focal mechanism of the main shock of this series.

b._ Another type of orientation is represented by solutions 4,5,6,7,9,13-21, which display an average strike of N5°E ±13°.This general group can be subdivided into three subgroups, B_1,B_2,B_3 with average dips of 47°±3°, 63°±5° and 85°±5° respectively. These solutions are similar to the one suggested by Delibasis et al., 1987.

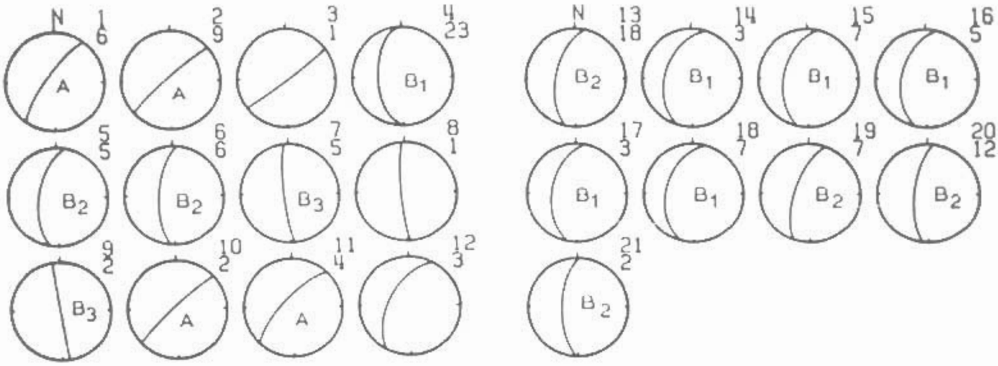
In addition, figure 6 represents the fault type solution combined with the depth and time evolution of the sequence. Thus from this figure, we can see that the type A solution starting from shallower depths at the beginning of the sequence, appears again in the middle of the sequence but this time at much greater depth. Another feature to be noted is the rapid increase of the depth of foci towards the middle and a gradual decrease towards the end of the sequence.

II._ Southern cluster: In figure 4b, where the largest (+) and smallest (Δ) eigenvectors, calculated for the second subvolume, are plotted, the overall picture is different,from that of the previous cluster, with the smallest eigevectors appearing in a highly concentrated group in the NE sector of the projection, showing that all expected solutions of coplanar ellipsoids should be very similar, displaying NW-SE strike and an average dip of about 50°.



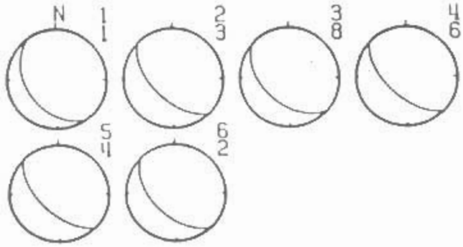
Σχ. 4.: Προβολή των μενίστων και ελαχίστων ιδιοανυσμάτων τών ελλειψοειδών με $T_1/T_3 \geq 2.5$ γιά την βόρεια (a) και νότια περιοχή (b).

Fig. 4.: Lower hemisphere equal area projection of the maximum (+) and minimum (Δ) eigevectors, with $T_1/T_3 \geq 2.5$ for the northern (a) and southern (b) clusters.



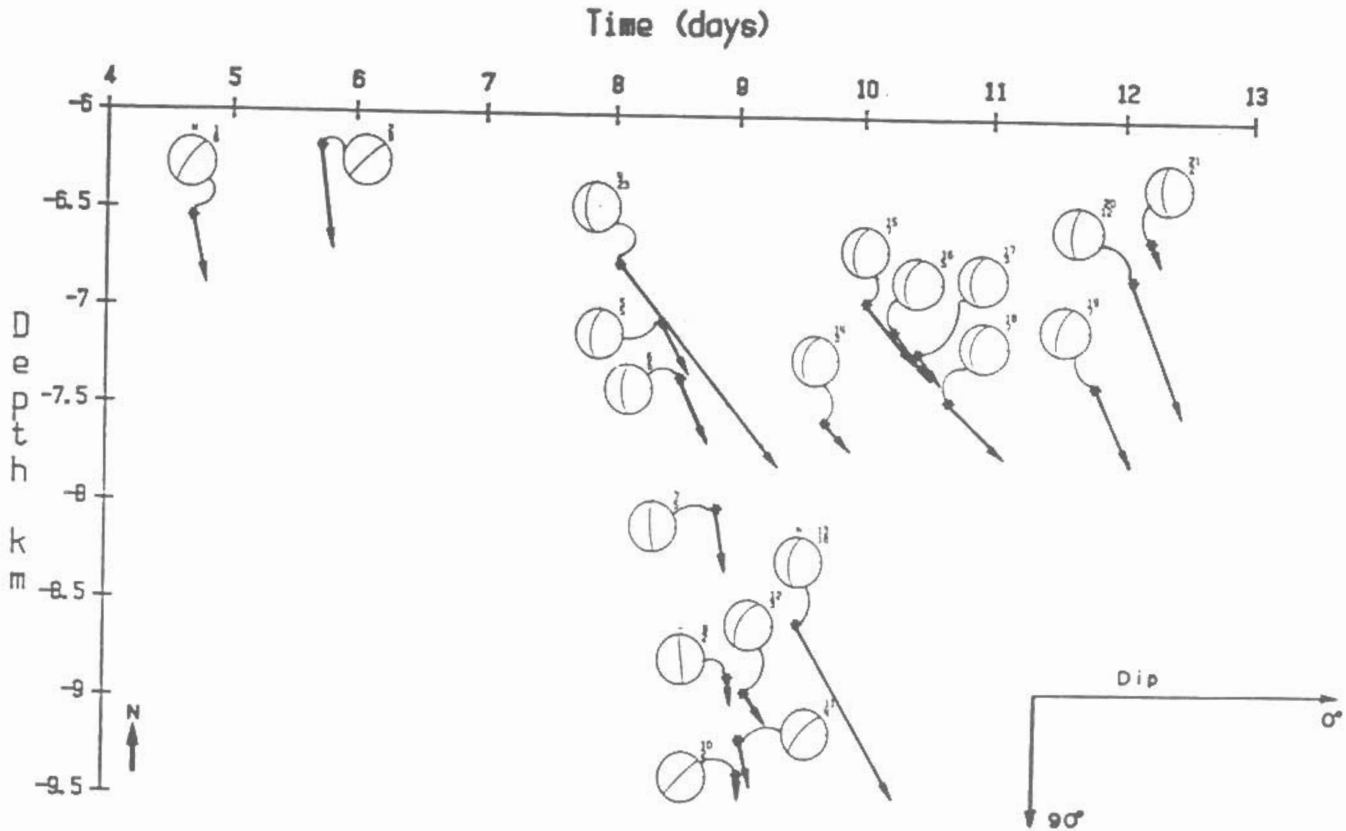
Σχ. 5.: Προβολή των λύσεων για την βόρεια περιοχή (A και B_1, B_2, B_3).

Fig.5.: Lower hemisphere equal-area projection of the average of successive coplanar ellipsoids for the northern cluster. Solution type A and B_1, B_2, B_3.



Σχ. 7.: Προβολή των λύσεων για την νότια περιοχή.

Fig.7.: Lower hemisphere equal area projection of the average of successive coplanar ellipsoids for the southern cluster.



Σχ. 6.: Γραφική παράσταση των διαφόρων λύσεων σε συνάρτηση με το χρόνο και το βάθος. Η διεύθυνση και η φορά του ανύσματος αντιστοιχούν στην κλίση του επιπέδου ενώ το μήκος του ανύσματος είναι ανάλογο του αριθμού των επιπέδων ανά λύση.

Fig.6.: Time-depth plot of different fault type solutions. Vector direction corresponds to the dip of every solution. Vector length corresponds to the number of planes per solution.

This is verified in figure 7 where it is obvious that all calculated solutions can be combined in to one, with an average strike of N45°W ±2° and an average dip of 52°±6°. For the same area, similar solutions were estimated by Lyon-Caen et al., 1987.

In conclusion, the results of the procedure followed in this study, show that the area is tectonically complex. This is suggested by the variety of orientations and dips calculated for the subfaults activated during the aftershock sequence. Thus, the analysis of the northern cluster, indicates the existance of 2 types of orientation, which are dipping in in 4 different angles, while the southern cluster is characterised by a rather uniform behaviour, activated later in the sequence.

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