ANNALES GÉOLOGIQUES DES PAYS HELLÉNIQUES

Fondées
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PRELIMINARY RESULTS OF THE ATHENS SEPTEMBER 7, 1999
AFTERSHOCK SEQUENCE.

By

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I. INTRODUCTION

The September 7, 1999 Athens earthquake Mw=5.7 (figure 1), occurred south of the mountain Parnes, at a depth of 8 km, in the northwestern suburbs of the city of Athens (Papadimitriou et al, 2000). The main earthquake was preceded by 4 foreshocks, with magnitudes of 3.7, 3.0, 3.0, 3.7, which occurred within a time span of half an hour before the main shock. Following this foreshock activity the main shock at 11:56:50.5 GMT caused extensive damage in the suburban areas near the epicenter and minor damages in the center of the city of Athens. In total 143 people died and more than 2000 where injured. Over a hundred buildings collapsed or were totally destroyed and thousands sustained considerable damage.

The area of Athens was until now generally considered as an area of low seismic activity with no important earthquake records during the instrumental period since 1900. However, according to Galanopoulos (1967), seismic activity in the area of Athens has been previously observed in the areas of Ekali and Filii to the north and northwest of Athens close to the epicenter of the September 7, 1999 earthquake (figure 1).

II. DATA ACQUISITION AND ANALYSIS

Following the earthquake of September 7, 1999 the Geophysics – Geothermics Department of the University of Athens, deployed a digital network (figure 2) of 6 continuous recording seismographic stations (FILI, STEF, MAGO, PSAR, NEOK and ZOFR) and 2 strong motion instruments (PEFK and COUR), in order to monitor the aftershock activity in the area. The network remained in operation for a period of 3 months and the permanent station of the CORNET network located at the Athens University was also used to obtain additional phase

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readings for aftershock location. During the first week of the network's operation, more than 1300 earthquakes were recorded, while the total number of located aftershocks during the first two weeks following the main shock exceeds 2000.

Figure 1. Geological map of Attiki and the earthquake foci of the area (After Galanopoulos, 1967)

According to standard practice, the HYPO71 algorithm (Lee and Lahr, 1975) was used for epicenter location and focal parameter calculation. However, in order to obtain accurate locations, calculations were based on a detailed 1-D velocity model (figure 3), derived by applying the method introduced by Kissling et al (1994, 1995) on a selected dataset of 500 earthquakes. As proposed by the authors, several trials were made starting from different initial
1-D models and the one, which provided the smaller overall errors, was selected (figure 3). The application of this model in the location of the epicenters of the aftershock sequence yielded satisfactory results reducing RMS, ERH and ERZ errors substantially (figures 4 and 5).

![Map](image)

**Figure 2.** Station locations, main shock and the first two weeks of aftershock activity spatial distribution (2047 events). Mapped geotectonic features of the Thriassio basin are after IGME geological maps.

### III. DATA INTERPRETATION

As it can be seen from figure 6, where the depth distribution of the recorded aftershocks is presented, most of the seismic activity appears to be contained at depths between 3 and 11 km and concentrated at depth of 7 km. Very few aftershocks were located at shallower depths. This observation, coupled with the fact that no surface ruptures were observed during field operations, indicates that the rupture of the September 7 earthquake fault did not reach the surface.

The large number of aftershocks, the high level of accuracy obtained during epicenter location calculations and the effective network geometry, permits the selection of a data subset of 1070 aftershocks (figure 7) using rather strict selection criteria (RMS<0.1 and ERH, ERZ<1.0). Examination of the epicenter spatial distribution of all the aftershocks recorded during the first two weeks (figure 2) and that of selected events (figure 7) reveals a predominant
WNW - ESE trend which is in agreement with the direction obtained by the calculation of the focal mechanism of the main shock (Papadimitriou et al., 2000). In addition, the aftershock depth appears to generally increase towards the SSW, verifying the dipping of the fault plane towards the same direction.

Figure 3. 1-D model used for hypocenter parameter calculation.

Figure 4. RMS error distribution for all hypocenter calculations. Mean ERH and ERZ values are also presented.
A more detailed examination of the spatial distribution of the epicenters reveals an increased aftershock activity to the east, in the Ano Liosia area, where the Parnes and Egeleio mountains converge. In this area, which also represents the easternmost boundary of the aftershock activity, the epicenter distribution is more diffused and characterized by the presence of a larger number of aftershocks at shallower depths and relatively larger magnitudes. A possible interpretation of the overall spatial distribution of epicenters could be based on the assumption that the rupture process was initialized by the main shock on a WNW-ESE main fault (Papadimitriou et al., 2000) and secondary faults along different directions were subsequently activated to the east of the main shock, as a new tectonic equilibrium was being
established. However, it is noticeable, that immediately following the main shock, during the first two days, considerable aftershock activity was also observed to the west of the main shock.

![Map showing aftershock locations and cross-section orientations](image)

**Figure 7.** 1070 selected aftershock locations (ERH, ERZ < 1.0 km, RMS < 0.1) and cross-sections orientations

This interpretation can be confirmed by looking at a series of cross-sections (figure 8, sections 1-5), aligned along a NNE-SSW direction and the four three-dimensional presented in figure 9. The depth distribution of epicenters in the first cross-section (figure 8, cross-section 1) located to the west of the main shock clearly indicates a southwards dipping plane. This observation is confirmed in figure 9a,b,c and in the next cross-section to the east (figure 8, cross-section 2), which passes through the epicenter of the main shock. Extrapolation of the linear trend defined by the distribution of aftershocks indicates that the actual fault scarp is located well within mount Parnes. A relative absence of aftershocks at a depth of about 8 km were the earthquake of September 7, 1999 was located is observed (figure 9d). This could be attributed to the extensive deformation caused by the main shock at this depth. A similar distribution pattern is observed in cross-section 3 of figure 8. The depth distribution of aftershocks is diversified in the next cross section (figure 8 cross-section 4), to the west of the town of Fili, where two southward dipping planes are defined, interconnected at a depth of 4 to 5 km.
Figure 8. Hypocenters distribution along 6 selected cross-sections (see figure 7).
Figure 9. 3-D hypocenter distribution diagrams viewed from four different angles. (a) NW, (b) ESE, (c) SE, (d) S. Vertical exaggeration 2:1.

This diversification of aftershock distribution could be attributed to an optical effect created by a slight change of the fault plane direction and dip in the areas west and east of the main shock, which is mirrored by a similar variation of the direction of the main morphological axes of Mount Parnes in the same area (figure 9d). The same effect can be also observed in cross-section 6 of figure 8, which is located at the same area but along a slightly different orientation (N-S). In this section the existence of an antithetic fault dipping to the north is indicated by the distribution of aftershocks (figure 9a,d). Additionally, in the same cross-section the activation of several minor faults, related to the boundaries of the sub-basin of Fili, is inferred. Finally, in the last cross-section (figure 8, cross-section 5) located at the easternmost boundary of the aftershock sequence the epicenters appear to be clustered around a depth of 5 km and significant activity along the antithetic fault is evident.
IV. FAULT PLANE SOLUTIONS

The efficient azimuthal coverage and the small epicentral distances implemented by the geometry of the network, allowed the precise determination of a great number of fault plane solutions, using the method of the P-wave first motion radiation pattern. After the completion of the network's installation and for the first 2 ½ days (10-12 September, 1999), more than 400 focal mechanisms were determined. In figure 9, 260 selected focal mechanisms are presented. For these mechanisms the number of observations exceeded 6 and the azimuthal coverage and epicentral distances of the emerging rays, constrained the azimuth and dip determination of the nodal planes within the accuracy range of ±10°. In figure 10, we can observe mainly 3 focal mechanism patterns, all of which indicate normal dip-slip faulting. The first one displays characteristics similar to those defined for the mechanism of the main shock (110, 55, -80) by Papadimitriou et al, 2000, indicating a NNE-SSW tensional stress field orientation. Focal mechanisms of this type are mainly observed in the center of the aftershock area, near the epicenter of the main shock.

Figure 10. Map of 260 selected fault plane solutions, calculated for events recorded during the first 4 days of the aftershock sequence.
A slightly different pattern is observed in the area to the west of the September 7, 1999 earthquake, which as mentioned before, was activated after the nucleation of the main shock. The stress field (T-axis) of this group appears to be oriented along a NNW-SSE to N-S direction. This slight variation of the stress field orientation, is consistent with the previous observations on the aftershock distribution cross-sections verifying the slight change of fault zone orientation in the area west of Fili, from E-W to west to WNW-ENE eastwards.

The third pattern appears to the eastern aftershock area, namely the area of Ano Liosia, Fili, Zofria, where focal mechanisms with a low-angle south dipping nodal plane are located. It is suggested that this nodal plane, is unlikely to be related to the main fault and that the north dipping high-angle nodal plane is probably associated with the Ano Liosia antithetic fault, mentioned before.

The seismic deformation pattern includes also a few strike-slip and reverse focal mechanisms, especially within a diffuse zone located at the eastern boundary of the activated area. The strike-slip and reverse faulting can be attributed to the stress relaxation produced by the footwall-hanging wall interaction of the main fault (Lyon Caen et al., 1988). The diffuse zone to the east, commonly observed within the seismic deformation cycle, could be associated with the interaction between the main fault, its antithetic and the marginal faults of the Fili and Ano Liosia basins, as a barrier is formed in the area were the Parnes and Egaleo mountains converge.

CONCLUSIONS

The Athens earthquake of September 7, 1999, has confirmed the suggestion of Galanopoulos (1967), that the area of Attiki should not be considered as an area of low seismic activity.

The detailed analysis of the first two weeks of the aftershock sequence indicates that the seismic activity extends along the southern foothills of mount Parnes, which forms the northern boundary of the Thrassion plain and appears to be limited in the northern part. The depth distribution of the well-located aftershocks ranges between 3 and 10 km, indicating a shallow focal depth for the main shock (8km), as reported also by Papadimitriou et al., 2000. At the central part of the fault zone, where the main shock was located, low aftershock activity is observed. Significant activity was triggered to the west, mostly within the first days of the aftershock sequence. The highest level of seismic energy was released at the eastern part of the Thrassion plain, especially in the area where the mounts of Parnes and Egaleo converge. In this area the existence of an antithetic fault is evident and several minor marginal faults were activated during the course of the aftershock activity. Finally, the aftershock activity appears to terminate west of the geotectonic boundary along Kifissos river, where aftershocks with relatively larger magnitudes are observed. This pattern of energy release, also observed at the
aftershock sequence of the Kozani 1995 earthquake (Papazachos et al., 1998), could be explained by the barrier model of Aki (1979), suggesting that the main shock produced a “weak zone” and the area of Kifissos river represents a “strong barrier”.

The spatial distribution of aftershocks and the focal mechanisms, suggest a main southwards dipping fault zone (figure 10a,b) extending along the whole area of the Thrissio plain. Extrapolation of the fault zone, defined by the aftershock distribution, indicates that the actual fault trace is located well within mountain Parnes. This zone, initially oriented along a E-W direction to the west, a direction similar to that of the eastern Corinthian gulf major faults (Deliannis et al., 2000), slightly changes west of Fili to a WNW-ENE direction. This variation of orientation is consistent with direction of the morphological axis of the mount Parnes. Subsequently, the stress field tensional axis (σ3), rotates from N-S to the west, to NNE-SSW to the east, parallel to the main morphological axis of the Egaleo mountain and the geotectonic boundary inferred by Kifissos river, according to the orientation determined by the focal mechanism of the main shock.

ABSTRACT

A dense digital seismological network, deployed one day after the 7th of September earthquake over the area of the Thrassio plain, by the Geophysics-Geothermics Department of the Athens University, monitored the aftershock activity for a time span of three months. The prompt installation and efficient geometry of the array, as well as the high quality of the collected seismograms, enabled the elaboration of a detailed study of the aftershock activity. Preliminary results, deduced from the analysis of the first 2 weeks of the seismic sequence allowed the determination of the characteristics and the geometry of the main fault zone as well as the identification of an antithetic fault and several minor marginal faults in the area. The defined geometry of the main fault zone and the calculated focal mechanisms indicate a slight clockwise rotation of the local stress field orientation in the area west of Fili town.

ΠΕΡΙΛΗΨΗ

Ο Τομέας Επιστήμης-Γεωργερμίας του Πανεπιστημίου Αθηνών, μαίρα μέρα μετά το σεισμό της Πάρνηθας της 7ης Σεπτεμβρίου 1999, εγκατέστησε ένα τοπικό γηφυσικό σεισμολογικό δίκτυο συνεχούς εγγραφής στην ευρύτερη περιοχή του Θρασίου πεδίου, με στόχο την παρακολούθηση της μετασεισμικής δραστηριότητας. Το δίκτυο παρέμενε στην περιοχή για τρεις μήνες και κατέγραψε περισσότερους από 5000 μετασεισμούς. Η άμεση χρονική εγκατάσταση του δικτύου, η καλή γεωμετρική κάλυψη της περιοχής και η υψηλή ποιότητα των σεισμογραφικών, επέτρεπε την εκτύπωση λεπτομερώς μελέτης της μετασεισμικής δραστηριότητας. Η προκαταρκτική ανάλυση 2050 μετασεισμών που
καταγράφηκαν στις πρώτες δύο εβδομάδες μετά τον κύριο σεισμό, υπέδειξε τα γεωμετρικά
χαρακτηριστικά της κύριας ρηξιγονών ζώνης, την ενεργοποίηση ενός αντιθετικού καθώς και
αρκετών μικρών περιθωριακών ρημιάτων στην περιοχή. Όσον αφορά στην κύρια ρηξιγονή
ζώνη, η χαρτική κατανομή των μετασεισμών και τα στοιχεία των προσδιορισθέντων
μηχανισμών γέννησης, υποδηλώνουν μια μικρή διεξάγωση περιστροφή στον προσανατολισμό
tου τοπικού πεδίου τάσεων, που λαμβάνει χώρα δυνατά του δήμου Φυλής.

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