ANNALES GÉOLOGIQUES DES PAYS HELLÉNIQUES

Fondées
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THE SEPTEMBER 7, 1999 ATHENS EARTHQUAKE SEQUENCE
RECORDED BY THE CORNET NETWORK: PRELIMINARY RESULTS
OF SOURCE PARAMETERS DETERMINATION OF THE
MAINSHOCK.

By
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Makropoulos, K.

I. INTRODUCTION

On 7 September 1999, an earthquake of magnitude $M_s = 5.9$ occurred in the
Aspropirgos basin located close to the Saronic Gulf as well as to the city of Athens, the capital
of Greece (Fig. 1). This event was the strongest that happened in a region of low seismic
activity. In this region no evidence of important earthquakes was reported by historical
catalogues or other sources, therefore this area was considered to be of low seismic risk.
Although the earthquake magnitude was moderate the caused damage was very serious. There
were 143 killed people, a great number of wounded and several thousands of people became
homeless. Consequently it may be considered as one of the most disastrous earthquakes that
occurred in Greece during the last centuries.

The seismogenic area is situated next to the eastern edge of the Gulf of Corinth where
important earthquakes occurred during the last 20 years (Papadimitriou et al., 1994; Hatzfeld
et al., 1996; Bernard et al., 1997). The Gulf of Corinth is characterized by E-W trending, north-
dipping normal faulting and by a NNE-SSW direction of extension with a rate of about 1 cm/yr
(Amijo et al., 1996; Rigo et al., 1996). On 1981 three major earthquakes of magnitudes
$M_s = 6.7$, 6.4 and 6.4 occurred in the easternmost part of this Gulf (Jackson et al., 1982; King
et al., 1985). Focal mechanisms of these events revealed normal faulting trending E-W dipping
north for the two first events and south for the last event of 4 March. The constrained focal
depths vary between 8 and 10 km. Surface breaks were observed and were related to the second
and the third event. Coseismic slip reaches 150 cm but the more typical range is 50-70 cm. The
aftershock activity is mainly concentrated at the eastern edge of the Gulf (Fig. 1), close to the
Vill station, and reaches until the village of Plataia (PI).

The Comnet seismological permanent network has been installed since 1995 around the
eastern Gulf of Corinth by the Department of Geophysics of the University of Athens
(Papadimitriou et al., 1996). For the period 1996-1999 approximately 5000 events were
recorded, while more than 2000 were located in the Gulf and the surrounding area. During the

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operation period of the Comet network there was no clear evidence of seismic activity in the Aspropirgos basin, until the earthquake sequence of 7 September. The Comet network has recorded four foreshocks, the main shock of 7 September 1999 and numerous aftershocks. In addition a temporary network of 8 stations was installed one day after, to record the aftershock activity of the mainshock.

In this paper we present seismological data from the local Comet network and from the worldwide network (GDSN) following the September 7, 1999 Athens earthquake. The mainshock was relocated and the source parameters were determined using spectral analysis and body wave modeling. We then combined seismological and tectonic observations to discuss the rupture process of the earthquake.

II. RELOCATION OF THE MAINSHOCK

The mainshock occurred on 7 September 1999 at 11:57 GMT in the Aspropirgos basin and was preceded by four foreshocks during the last 20 minutes before the main event. The location of the mainshock given by different seismological institutes varies significantly (Table 1). Thus, the relocation of the foreshocks and of the mainshock is necessary for the interpretation of the rupture process.

A temporary seismological network was installed by the Department of Geophysics of the University of Athens one day after the mainshock to record the aftershock sequence (Delibasis et al., 2000; Voulgaris et al., 2000). For the relocation of the mainshock and of the foreshocks, an aftershock recorded both by the Comet and the temporary seismological networks is selected as a master event. The hypocenter of this event, that is located using the HYPO71 program and a local velocity model, is very accurate. The master event was used to estimate systematic delays for the first arrivals at the Comet stations. In addition, we used arrival times from two stations of the NOA permanent seismological network (ATH and PTL). We ran several times the HYPO71 program with various weights to the stations and with or without the arrival times of the NOA stations. The obtained hypocenter locations are very stable, clustered within less than 1 km around 38.105°N, 23.565°E with a rms of 0.30s. The relocated epicenter of the mainshock is very close to the original location using data only by the Comet network and to the USGS epicenter but is significantly different from the original epicenters given by NOA and PDE that are shifted about 10 km eastern. The hypocenter of the mainshock is located at the deep western edge of the fault plane and is consistent with the depth distribution of the aftershocks in this part of the fault. The same procedure was followed for the four foreshocks that were relocated very close to the mainshock and the obtained results are presented in Figure 2.
Table 1. Locations and magnitudes of the mainshock by different institutes

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Depth (km)</th>
<th>Ms</th>
<th>Mw</th>
<th>Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>99-09-07</td>
<td>11:56:50</td>
<td>38.105</td>
<td>23.565</td>
<td>8</td>
<td>5.9</td>
<td>5.7</td>
<td>ATHU</td>
</tr>
<tr>
<td>99-09-07</td>
<td>11:56:50</td>
<td>38.15</td>
<td>23.62</td>
<td>30</td>
<td>5.9</td>
<td>5.7</td>
<td>NOA</td>
</tr>
<tr>
<td>99-09-07</td>
<td>11:56:50</td>
<td>38.132</td>
<td>23.545</td>
<td>10</td>
<td>5.6</td>
<td>5.9</td>
<td>USGS</td>
</tr>
<tr>
<td>99-09-07</td>
<td>11:56:49.3</td>
<td>38.119</td>
<td>23.605</td>
<td>10</td>
<td>5.8</td>
<td>6.0</td>
<td>PDE</td>
</tr>
<tr>
<td>99-09-07</td>
<td>11:56:56.5</td>
<td>37.87</td>
<td>23.64</td>
<td>15</td>
<td>5.8</td>
<td>6.0</td>
<td>HRV</td>
</tr>
</tbody>
</table>

III. SPECTRAL ANALYSIS AND TELESEISMIC BODY-WAVE MODELING

The Comets network consists of five digital telemetric Lennartz stations equipped with Le-3D (5 sec) seismometers, recording in triggering mode with a sampling rate of 125 samples/s. The spectral analysis of the mainshock is performed using recordings of the Desf (local) and the MAJO (teleseismic) stations. Deconvolution of the instrument response was performed in order to calculate the displacement spectrum. Figure 3a shows the displacement spectrum for the Desf station, where the vertical axis is converted to seismic moment units (dyn·cm). The estimated corner frequency is 0.2 Hz and the seismic moment is equal to \(4 \times 10^{24} \text{dyn·cm}\). Concerning the spectral response of the Desf station, we observe that for the frequency range between 0.2 and 3 Hz the slope doesn’t follow the same decay observed at higher frequencies. This observation may be related to the complexity of the medium or to the rupture process (Herrero and Bernard, 1994; Bernard et al., 1996) and provokes further investigation. These results were compared with those obtained for MAJO teleseismic station (Fig. 3b). The estimated seismic moment is \(8 \times 10^{24} \text{dyn·cm}\) and the corner frequency is 0.2 Hz. The comparison between the local and the teleseismic recordings shows similar results: the length of the source time function is 5s and the seismic moment is approximately \(8 \times 10^{24} \text{dyn·cm}\).

The determination of the source parameters of the mainshock was performed using teleseismic recordings (IRIS network) at epicentral distances between 30° and 90° and the trial and error technique. The anelastic attenuation along the path is applied with a ratio of travel time to average quality factor of 1s and 4s for P and SH waves respectively. We assumed a simple point source and the final best-fit solution is: \(\delta=105°\), \(\phi=55°\), \(\lambda=-80°\), depth H=8.0 km, trapezoid source time function of 5s duration and seismic moment \(M_o=1.7 \times 10^{25} \text{dyn·cm}\) (Fig. 4). In Table 2 the source parameters determined in this study and those proposed by USGS and Harvard are presented. The results are comparable indicating normal faulting striking approximately E-W. The main differences concern the strike and the dip of the fault. The azimuth calculated in the present study is closer to E-W, while the value of the dip given by HRV is underestimated. The values of azimuth and dip were calculated mainly using the recording from BGCA teleseismic station, since this is the only available recording very close to the fault plane dipping south.
Table 2. Source parameters determination by different institutes

<table>
<thead>
<tr>
<th>Azimuth (°)</th>
<th>Dip (°)</th>
<th>Rake (°)</th>
<th>Scalar Moment (dyn·cm)</th>
<th>Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>105</td>
<td>55</td>
<td>-80</td>
<td>1.7·10^8</td>
<td>ATHU</td>
</tr>
<tr>
<td>123</td>
<td>55</td>
<td>-84</td>
<td>7.8·10^8</td>
<td>USGS</td>
</tr>
<tr>
<td>116</td>
<td>39</td>
<td>-81</td>
<td>1.1·10^8</td>
<td>HRV</td>
</tr>
</tbody>
</table>

Using the source parameters calculated in the present study, we performed an inversion to determine the complexity of the source time function (Fig. 5). The shape is similar for all the stations, showing that the source time function can be decomposed in three elementary sources. Comparing the duration of the source time function in the FFC and the MAJO stations, we observe that its duration is shorter in the MAJO station. This difference could be attributed to the directivity of the source propagation.

The recordings of the mainshock for the Sofi and Desf Comet stations are presented in Figure 6. In both stations an important phase is observed approximately 5s after the first P-arrival time. This phase was not observed in any foreshock or aftershock and consequently it can not be attributed to the local structure of the seismogenic area. On the other hand, this phase can be considered as a source propagation effect. Taking into account the comparison between the individual source time functions and the phase that was recorded by the local stations, we assume that this phase could be a stop phase caused by a barrier.

The Aspropirgos basin is bordered on the north by the southern slopes of the Parnitha Mountain characterized by normal faulting striking E-W and dipping south. The length of this fault, visible in aerial photographs and satellite images, is of the order of 15 km. Eastern it is bordered by the Aegaleo Mountain characterized by transverse limestone ridges striking N-S. No surface breaks were found during the field reconnaissance after the occurrence of the mainshock, although the Parnitha normal fault clearly appears on satellite images. Only some small fissures striking N110° were observed at the Agios Kyprianos monastery and at the Fili castle. These observations are in agreement with the results obtained by body wave modeling that revealed normal faulting striking E-W, parallel to the topography of the Parnitha Mountain, and dipping south. The estimated fault dimensions are length 15 km and width 10 km.

The duration of the source time function is approximately 5s. In most cases, the slip diminishes progressively during the rupture propagation until it stops. This does not seem to be the case for the Athens earthquake, since the rupture propagation stops abruptly. Taking into account the above mentioned observations we propose the following rupture process model: the rupture nucleated at the deep western edge of the fault plane and propagated eastwards for a time period equal to the duration of the source time function. Assuming a rupture velocity u_r=3km/s and the above-mentioned duration, the rupture propagated for 15 km, until it stopped abruptly. Once the rupture front met the Aegaleo Mountain it stopped, since it could not
propagate through it. This means that the Aegaleo Mountain acted as a barrier (Fig. 7) that caused interference phenomenon and diffracted waves. This abrupt stopping can explain the big damage observed close to the eastern edge of the fault plane as well as the concentration of the aftershocks in this area.

CONCLUSIONS

We presented preliminary results of the September 7, 1999 Athens earthquake to determine the rupture geometry and kinematics. The mainshock was relocated at the western deep edge of the fault plane. The rupture nucleated at 38.105°N, 23.565°E at a focal depth equal to 8 km, approximately 20 km NW of the city of Athens. The source parameters were calculated using body wave modeling. The fault plane is striking in E-W direction dipping south and revealing an approximately N-S direction of extension, while the estimated fault dimensions are 15 x 10 km². These results are in good agreement with the tectonic observations. The remarkable phase that was observed at the local stations was interpreted as a stop phase caused by the Aegaleo Mountain that acted as a barrier.

ABSTRACT

We present preliminary results of the September 7, 1999 Athens earthquake (M,=5.9). Seismological data from the Comet local permanent network and GDSN recordings are presented and analyzed to discuss the rupture process. We relocated the mainshock at 38.105°N, 23.565°E, about 20 km northwest of Athens, as well as four foreshocks close to the located mainshock. The focal mechanism of the main shock obtained from body wave modeling (strike=105°, dip=55° and rake=-80°) represents almost pure north-south extension, the depth is constrained to 8 km and the seismic moment to M,=1.7 \times 10^{25} \text{ dyn cm}. No surface breaks were observed but the fault plane solution is in agreement with the tectonics of the area and with the focal mechanisms constrained by aftershocks. The estimated dimensions of the fault are 15 km length and 10 km width. The relocated hypocenter of the mainshock lies on the deep western edge of the fault plane. The rupture lasted 4 to 5 sec, propagating eastward on the fault, towards the city of Athens. An evident stop phase was observed that was interpreted as a barrier caused by the Aegaleo Mountain.

ΠΕΡΙΛΗΨΗ

Στην παρούσα μελέτη παρουσιάζονται προκαταρκτικά αποτελέσματα του σεισμού της 7ης Σεπτεμβρίου 1999 (M,=5.9). Αναλύονται σεισμολογικά δεδομένα του έχον καταγραφεί από το μόνιμο τηλεμετρικό δίκτυο CORNET, καθώς και καταγραφές από το παγκόσμιο δίκτυο GDSN
προκειμένου να μελετηθεί η διαδικασία της σεισμικής διάρρηξης. Επιπεδοποιηθηκαν τα επίκεντρα του κύριου σεισμού σε γεωγραφικό μήκος και πλάτος 38.105°Β και 23.565°Α αντίστοιχα, 20 περίπου χιλιόμετρα βορειοδυτικά από την Αθήνα, όπως επίσης και των τεσσάρων προσαντιμών. Ο μηχανισμός γένεσης του κύριου σεισμού προσδιορίσθηκε με τη μέθοδο προσομοίωσης συνθετικών χαρακτηριστικών κυμάτων (αξίωμα θ = 105°, κλίση φ = 55° και οριζόντια διέλευση λ = 80°). Πρόκειται για ένα κανονικό ρήγμα με ευθειακή διεύθυνση Β-Ν, το βάθος του κύριου σεισμού προσδιορίσθηκε στα 8 χλμ. και η σεισμική ροπή υπολογίσθηκε ίση με Μw = 1.7 1025 dyn·cm. Μετά την εκδήλωση του κύριου σεισμού δεν παρατηρήθηκαν επιπεδεικτικές διαρρήξεις. Ο μηχανισμός γένεσης συμφωνεί με την τεκτονική της περιοχής και με τους μηχανισμούς γένεσης που προσδιορίσθηκαν από τους μετασεισμούς.

Η συνάρτηση της σεισμικής πηγής που υπολογίσθηκε με τη μέθοδο αντισυνθέσεων των χαρακτηριστικών κυμάτων έχει διάρκεια 5 δευτερόλεπτων. Το μήκος του ρήγματος της Πάρνηθας εκτιμήθηκε ίσως με 15 χλμ. και το πλάτος του με 10 χλμ. Το επίκεντρο του κύριου σεισμού εντοπίσθηκε σε κατάλληλο δυτικό άκρο του ρήγματος της Πάρνηθας και η διάδοση της διάρρηξης έγινε προς τα ανατολικά κατά μήκος του ρήγματος, με κατεύθυνση προς την Αθήνα. Τέλος, παρατηρήθηκε μια εμφανής φάση τερματισμού η οποία ερμηνεύθηκε ως φρέχια του προκλήθηκε από το όρος Αιγάλεω.

REFERENCES


Figure 1: Best located events by Cornet network for 1996-1998 (circles) and aftershock activity of the September 7, 1999 Athens earthquake (triangles). The star represents the epicenter of the mainshock. The squares represent the stations of the Cornet network. Active faults around the Gulf of Corinth are plotted and the arrows present the extension of the Gulf of Corinth.

Figure 2: The initial (big triangle) and relocated epicenter (star) of the mainshock are shown. Small triangles represent the relocated foreshocks and the circle the epicenter of the master aftershock. Small squares represent the location of the stations of the local temporary network.
Figure 3: P-wave displacement spectrum of the earthquake for the (a) local Desf station and (b) teleseismic MAJO station.
Figure 4: Body-wave modeling for a single point source.

Figure 5: Source time functions from P-wave inversion for each teleseismic station.
Figure 6: Recordings of the mainshock for the Soli and Desf Cornet stations, where an important phase is observed in both stations 5s after the first P-wave arrival time.

Figure 7: The fault plane, the initiation and the propagation of the rupture front are presented. The arrow indicates the direction of the rupture propagation.