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THE AFTERSHOCK SEQUENCE AND FOCAL PROPERTIES OF THE JULY 14, 1993 (M_S=5.4) PATRAS EARTHQUAKE

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ABSTRACT

An earthquake with Ms=5.4 occurred on July 14, 1993 (12:32 GMT) in the city of Patras (NW Peloponnese) and caused considerable damage in the epicentral area. A network of 10 portable stations (MEQ800 and MARS88) was installed two days after the occurrence of the mainshock, to monitoring the aftershock sequence. The spatial distribution of the epicenters of the numerous aftershocks recorded define well the active area which trends NW-SE. The observed macroseismic effects support this direction of the active zone, which crosses the city of Patras. The focal depths are distributed from 14 to 22 km, and the length of the active area was found equal to 14 km. The fault plane solution of the main shock shows a thrust fault with a considerable strike-slip component. The one nodal plane trending NW-SE and dipping to NE, is considered as the fault plane, in good agreement with the distribution of the aftershocks epicentres. Geological data and historical seismicity support the idea that this is a part of a major fault broken during the occurrence of the 1785 and 1804 (Ms=6.6) earthquakes, constituting a severe threat for the city of Patras.

ΣΥΝΟΨΗ

Ένας σεισμός με μέγεθος Ms=5.4 έγινε στις 14 Ιουλίου 1993 (12:32 GMT) στην πόλη της Πάτρας και προκάλεσε σοβαρές βλάβες στην επικεντρική περιοχή. Ενα πυκνό δίκτυο 10 φορητών σεισμογράφων (MEQ800 και MARS88) εγκαταστάθηκε στην περιοχή, για την παρακολούθηση της σεισμικής δράσης. Από τη χωρική κατανομή των επικέντρων των μετασεισμών που καταγράφηκαν, φαίνεται ότι η περιοχή που ενεργοποιήθηκε είχε διεύθυνση ΒΔ-ΝΑ και μήκος 14 km, ενώ τα εστιακά βάθη των μετασεισμών κυμαίνονται από 14 έως 22 km. Την ίδια διεύθυνση ακολουθούν και τα μακροσεισμικά αποτελέσματα του κύριου σεισμού που παρατηρήθηκαν στην περιοχή. Από τη λύση του μηχανισμού γένεσης του κύριου σεισμού προκύπτει ότι πρόκειται για ανάστροφη διάρρηξη με σημαντική συνιστώσα οριζόντιας μετατόπισης. Το επίπεδο του ρήγματος έχει διεύθυνση ΒΔ-ΝΑ και κλίνει προς ΒΑ και βρίσκεται σε καλή συμφωνία με την κατανομή των επικέντρων των μετασεισμών. Γεωλογικές πληροφορίες καθώς και πληροφορίες από ισχυρούς

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σεισμούς που έγιναν στην περιοχή κατά τους προηγούμενους αιώνες, δείχνουν ότι πρόκειται για τμήμα μεγαλύτερου ρήγματος το οποίο έδωσε τους σεισμούς του 1785 και 1804 (Ms=6.6) και το οποίο αποτελεί απειλή για την πόλη της Πάτρας.

INTRODUCTION

The July 14, 1993 Patras, NW Peloponnese, earthquake sequence yielded instrumental recordings for a noteworthy earthquake sequence. The main shock occurred on a shallow fault near the city of Patras at 15:32 p.m. local time and was assigned a surface-wave magnitude (Ms) of 5.4, causing considerable damage in the epicentral area. This event was not preceded by recorded foreshocks, but numerous aftershocks were followed, the largest of them having local magnitude equal to 4.1.

The epicentral area belongs to a seismic zone with very high seismic activity (Papazachos, 1990), although during the present century the seismic activity in this part of the Patras-Corinth seismic zone is relatively low, the maximum earthquake magnitude beeing equal to 5.2 (in a distance less than 10km from the city of Patras). From historical seismicity there is evidence that in the same area very strong earthquakes have occurred (Papazachos and Papazachou, 1989). In January 31, 1785 an earthquake with magnitude Ms=6.6 destroyed a large part of the city of Patras, that is, many churches, part of the fortification, as well as a large number of buildings, causing the death in several people (more than 50). In June 8, 1804 an earthquake with Ms=6.6, which caused considerable damage in the island of Zakynthos as well, destroyed almost all the buildings along the coast of the city of Patras and the neighbouring villages, resulting in several deaths (unknown number). Two years later (1806, Jan. 23) an earthquake with Ms=6.3 had also affected the city of Patras with severe damage reported.

The specific objectives of this study are to determine reliable hypocentral locations, based on local seismic network observations and an appropriate region-specific velocity model, and to determine the focal mechanism of the main shock. From these analyses more accurate assessments are made regarding the style and orientation of seismogenic faulting, contributing to a comprehensive analysis of the contemporary seismicity and active faulting in this area. Based on this evaluation, an improved understanding of the level of seismic hazard in the region has resulted and is discussed below.

LOCATION OF THE MAIN SHOCK

The arrival time of P and S seismic waves at the stations of the Greek seismological network, as well as at the seismological networks of the neighboring countries were used to locate the main shock of this sequence. The program HYPO71 (revised) (Lee and Lahr, 1975) was used with velocity ratio vp/vs=1.78 (Panagiotopoulos and Papazachos, 1985). Karakostas et al. (1993) proposed a crustal model which is valid for the broader area of NW Peoloponnese. This is a modified model of those proposed for the broader Aegean area by Panagiotopoulos and Papazachos (1985) and consists of two layers above a half space. The velocities of P waves and the thicknesses of the layers are:

$u_1 = 6.0\ Km.sec^{-1}\quad d_1 = 29\ Km$

$u_2 = 6.6\ Km.sec^{-1}\quad d_2 = 19\ Km$

$u_3 = 7.9\ Km.sec^{-1}\quad d_3 = \infty$

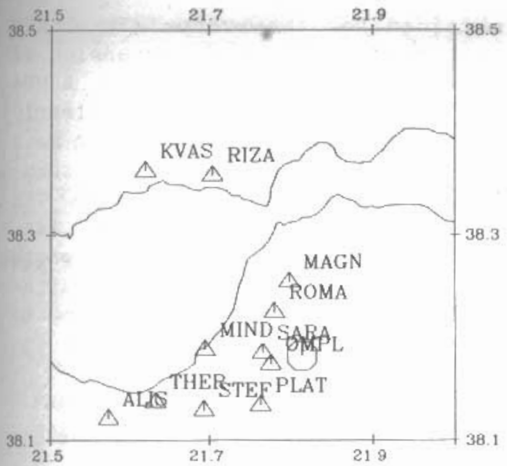

Fig. 1: The sites of the stations of the local seismological network (triangles) and the epicenter of the main shock (circle).

The epicentre that was found by this way is 38.18°N, 21.81°E and the focal depth h=21.3 km.

LOCATION OF THE AFTERSHOCKS

The sites of the portable seismological stations installed in the area are marked by triangles in Fig. 1, while the epicenter of the main shock is denoted by a circle. From this figure it is seen that the stations distribution is adequate for accurate hypocentral locations of the aftershocks. During the operation of the network (July 16 - July 23, 1993) 237 aftershocks were recorded by all the stations. The arrival times of all these events, and the program HYPO71 (revised) (Lee and Lahr, 1975), were used for the estimation of the most appropriate crustal model.

Reliable Vp/Vs ratio is an important parameter for the depth control of the earthquakes. The velocity ratio used in the present study is Vp/Vs=1.82 which was estimated by Rigo et al. (1993), by using data of more than 1000 microearthquakes. Fig. 2 shows the frequency diagrams of ERH, ERZ and RMS values for the 122 best located earthquakes of the sequence.

Several local crustal models have been proposed for the broader epicentral area (Makris, 1978; Melis et al., 1989; Rigo et al., 1993). In the present work these, as well as various other models were tested in order to obtain the best results. It was observed that the focal coordinates of the aftershocks were not changed significantly for the different models, that is, the location is rather independent of the model used. This is attributed to the dense local seismological network installed in the epicentral area. The crustal model that gives the minimum errors was finally adopted. It consists of one layer with thickness d1=6.0 km and vp=4.8 km sec-1, above a half space with velocity of P-waves vp=6.0 km sec-1. This model is similar with those proposed by Rigo et al. (1993), but it consists with less layers.

In order to improve the accuracy of the results, only the aftershocks located by using 10 or more P- and S- wave arrivals were used. Fig. 2 shows the frequency diagrams of RMS, ERH and ERZ values of these aftershocks.

The magnitudes (ML) of the aftershocks were estimated by using the signal duration at each station, calibrated with the magnitudes of seven aftershocks that were recorded by the permanent network as well, while the magnitude (Ms) of the main shock was estimated by the permanent seismological networks of Greece.

SPATIAL, TIME AND MAGNITUDE DISTRIBUTION OF THE AFTERSHOCKS

In the map of Fig. 3 the epicentres of 122 events estimated with more than 10 arrivals were plotted, with the main shock represented by a big circle. The mean RMS value was less than 0.3, and ERH and ERZ values less than 3.0km. These events occurred between 16 and 19 July, that is from the second till the fourth day of the sequence. Reliable epicentre estimation

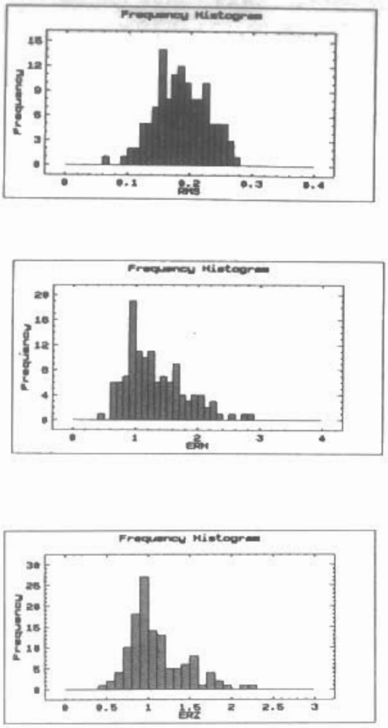

Fig. 2: Frequency diagrams of RMS, ERH and ERZ values for the best located aftershocks.

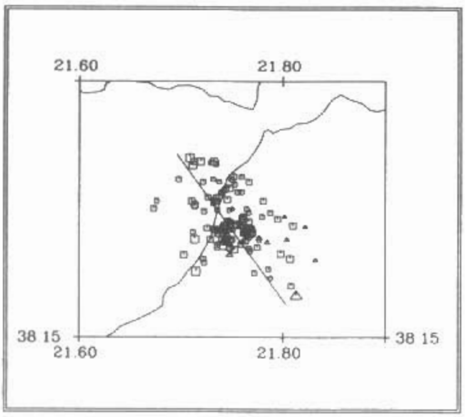

Fig. 3: *Distribution of the epicentres of the aftershocks occurred between 16 and 19 July 1994. The epicenter of the main shock is denoted by a triangle.*

was obtained for the events after this time interval, but a small expansion of the aftershock area was observed. A NW-SE trending of the active area is clearly observed while the epicenter of the main shock is located in the southeastern-most edge of the aftershock area. The length of the epicentral area is 14km which is slightly larger than the length of a fault capable to generate an earthquake of magnitude Ms=5.4 according to the formula:

$$\log L - 0.51\, M_S - 1.85 \quad (1)$$

proposed by Papazachos (1989) for the broader Aegean area.

A cross section perpendicular to the trend of the aftershock area is shown in Fig. 4. The focal depths of the shocks vary from 14 to 22 km and the aftershock zone is dipping to NE with an angle of 65o. It is also evident that the epicenter of the main shock lies in the lower part of the aftershock zone.

It has been shown (Mogi, 1962) that the number of aftershocks per day, n, decreases with the time, t, according to a relation:

$$n = n_1 . t^{-p} \quad (2)$$

The parameter p has physical significance because it depends on the properties of the material in the focal region. Fig. 5 shows the time variation of the frequency of aftershocks studied in the present paper. The data are fitted by relation (2) with p=1.03 and n1=144.2. This value of p is almost equal to the mean value of 1.13 for the area of Greece (Papazachos, 1974).

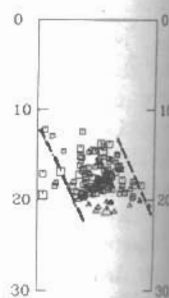

Fig. 4: A cross section on a vertical plane perpendicular to the trend of the distribution of the aftershock epicentres.

It is well known that the Gutenberg-Richter relation between the cumulative number of shocks, N, and their magnitudes

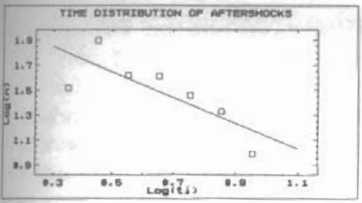

Fig. 5: The logarithm of the aftershock frequency as a function of the logarithm of time.

holds also for aftershocks. Fig. 6 shows the cumulative frequency distribution for 95 aftershocks with ML≥1.6, which is the cut off magnitude for the data completeness. The data are fitted by the relation:

$$\log N = 3.70 - 0.99\ M \quad (3)$$

This value of b (=0.99) is in good agreement with the mean b-value (=1.08) calculated for aftershock sequences of the area of Greece (Karakaisis, 1984).

FAULT PLANE SOLUTION OF THE MAIN SHOCK

First onsets of long period instrumentation were used to determine the fault plane solution of the main shock of this sequence. The data were taken from a questionnaire that was answered by seismologists at the seismological stations all over the world. The data were plotted on an equal area projection of the lower hemisphere of the focal sphere, and a velocity equal to 6.8 km/sec was assumed for the compressional waves at the focus of the earthquake (Fig. 7). Triangles and circles represent dilatations and compressions, respectively.

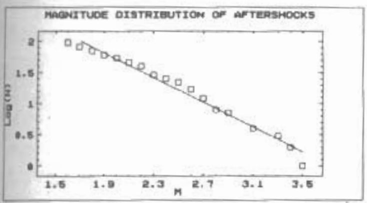

Fig. 6: The cumulative frequency-magnitude relation for the aftershocks with ML^{3}1.6.

It is seen that the proposed fault plane solution shows thrust faulting with a considerable strike-slip component. The one of the nodal

Table 1: The parameters of the fault plane solution of the main shock.

Plane A			Plane B			P		T	
φ°	δ°	λ°	φ°	δ°	λ°	φ°	δ°	φ°	δ°
331°	73°	35°	229°	57°	158°	97°	10°	95°	37°

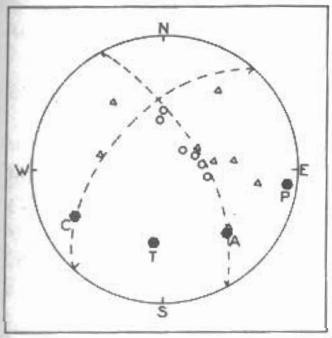

Fig. 7: The fault plane solution of the July 14, 1994 Ms=5.4 main shock.

planes strikes in an about NW-SE direction and dips to NE. It is reasonable to assume that this is the fault plane, because its strike and its dip are in agreement with the distribution of the aftershocks (Fig. 3 and 4). Table 1 gives information on the focal mechanism and the trend and plunge of the axis P (maximum compression) and axis T (maximum tension).

This type of faulting, (thrust with considerable strike slip component), seems to be the same with other known reliable fault plane solutions of recent earthquakes along the western part of the Greek mainland, that is, 1988 Killini earthquake (Karakostas et al., 1993a) and the 1993 Pyrgos earthquake (Karakostas et al., 1993b).

Hatzfeld et al. (1990), computed fault plane solutions of microearthquakes from this area and

Fig. 8: Damage on reinforced concrete construction.

found strike-slip motion for events with depths larger than 11km, occurred around the Rio and in the northern and central Peloponnese. They noted that all the strike-slip mechanisms were located between reverse faulting and normal faulting and generally showed **P**-axes trending E-W and **T**-axes trending N-S. These results support our solution as far as the orientation of **P** and **T** axes concern.

MACROSEISMIC OBSERVATIONS

According to our field investigations, serious macroseismic effects were observed mainly in the SSE suburbs of the city of Patras and in the nearby villages.

The meizoseismal area (with intensity VII in MM scale) has a NW-SE trend with a length of about 8km. It starts from the suburb Ities (near the coast south of the city of Patras) and goes SE to Ovria, Demenika up to Saravali village. This is the only area where serious damage on reinforced concrete constructions was observed (Fig. 8).

Fig. 9: Cracks on brittle structures in the city of Patras.

In the city of Patras damage was observed mainly on brittle constructions (mean intensity equal to VI in MM scale). The macroseismic effects were more intensive at the central and the southern part of the city where fall of the upper parts of walls on brittle structures, as well as severe cracks were observed (Fig. 9).

At the northern part of the city, only light cracks and fall of plaster pieces were observed mainly on brittle houses and less damage in reinforced concrete buildings.

DISCUSSION AND CONCLUSIONS

The analysis of the data concerning the main shock of 14 July 1993 and its aftershock sequence showed that it is connected with an active fault almost beneath the city of Patras. This is the fault that generated very strong earthquakes in this site, three of which producing severe damage in Patras, as it is known by historical seismicity and geological information. Assuming that the "characteristic" earthquake in this area is an Ms=6.6 event, corresponding to a fault length equal to 33km, it is then evident that a part of this fault was activated. Thus, the dominant fault within the study region has been essentially aseismic along the half of its length. On the other hand, the distribution of the foci of the reliably located aftershocks, in depths between 14 and 22 km, suggest that the segment of the fault that was activated, is located in the lower part of the known active fault.

The fault plane solution of the main shock of the sequence shows thrust faulting with a considerable strike-slip component.

The axis of maximum compression is almost horizontal and trend in about E-W direction. These results are in good agreement with the regional stress pattern (Papazachos et al., 1991), as well as with fault plane solutions of recent strong earthquakes occurring in the area of NW Peloponnese.

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