

THE SPATIAL DISTRIBUTION OF THE AFTERSHOCKS
AND THE FOCAL MECHANISM OF THE GALAXIDI EARTHQUAKE
(CENTRAL GREECE) OF NOVEMBER 18, 1992

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A B S T R A C T

Data from 15 portable seismographs deployed immediately after the occurrence of the November 18, 1992 ($M_s=5.9$) earthquake near Galaxidi, in the Gulf of Corinth, are used to retrieve information on the fault parameters. The spatial distribution of the aftershocks revealed a delineation of the shocks in a NNE-SSW trend. Vertical cross sections of the best located aftershocks indicate the existence of a NNW dipping fault. The location of the main shock was determined using the arrival times at all stations of the Greek network and of the neighbouring countries. The fault plane solution of the main shock has the following parameters: strike= 68° , dip= 59° , rake= -95° and source depth of 10 Km, as it was determined by the inversion of long and short period body waves recorded at teleseismic distances, and constrained by the first motion polarities at closer stations. The waveforms were typical of a shallow normal fault. The fault plane that dips to the NNW is considered to be the fault which produced the main shock, since it fits the distribution of the aftershocks . The results are in accordance with previous work concerning the deformation pattern of the area under study.

ΧΩΡΙΚΗ ΚΑΤΑΝΟΜΗ ΤΩΝ ΜΕΤΑΣΕΙΣΜΩΝ ΚΑΙ ΜΗΧΑΝΙΣΜΟΣ ΓΕΝΕΣΗΣ
ΤΟΥ ΣΕΙΣΜΟΥ ΤΟΥ ΓΑΛΑΞΕΙΔΙΟΥ (ΚΟΡΙΝΘΙΑΚΟΣ ΚΟΛΠΟΣ)
ΤΗΣ 18ης ΝΟΕΜΒΡΗ 1992

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Π Ε Ρ Ι Λ Η Ψ Η

Δεδομένα απο 15 φορητούς σειсмоγράφους που εγκαταστάθηκαν στην επικεντρική περιοχή του σεισμού της 18ης Νοεμβρίου 1992 στο Γαλαξείδι (Κορινθιακός Κόλπος), χρησιμοποιούνται για να μελετηθούν οι παράμετροι της σεισμικής ακολουθίας. Η χωρική κατανομή των μετασεισμών έδειξε ότι αυτοί κατανέμονται σε μια διεύθυνση ΒΒΑ-ΝΝΔ. Προβολές των εστιών των σεισμών σε κατακόρυφο

επίπεδο έδειξαν την ύπαρξη ενός ρήγματος που κλίνει προς τα ΒΒΔ. Το επίκεντρο του κύριου σεισμού προσδιορίσθηκε με τους χρόνους άφιξης των σεισμικών κυμάτων στους σεισμολογικούς σταθμούς των δικτύων της Ελλάδας και των γειτονικών χωρών. Ο μηχανισμός γένεσης του κύριου σεισμού προσδιορίσθηκε με την αντιστροφή των κυμάτων χώρου. Οι κυματομορφές ήταν τυπικές ενός κανονικού ρήγματος με μικρό εστιακό βάθος. Το ρήγμα που κλίνει προς τα ΒΒΔ θεωρείται ότι είναι το ρήγμα που προκάλεσε το σεισμό, με βάση την κατανομή των μετασεισμών. Τα αποτελέσματα είναι σε καλή συμφωνία με προηγούμενη γνώση σε σχέση με το πεδίο παραμόρφωσης στην περιοχή που μελετάται.

INTRODUCTION

On November 18, 1992 (21h 10m 42s) an earthquake of $M_s=5.9$ occurred in the Gulf of Corinth, near the town of Galaxidi in central Greece. This area is considered one of the most active of the entire Greece and there is a long record of seismicity since historical times (Papazachos and Papazachou, 1989; Papazachos, 1990). Table 1 lists the most important events that occurred in this region:

Table 1. Largest historical and present century earthquakes that occurred in the central part of the Corinth gulf

373 BC	(38.2°N, 22.2°E, M=7.0, IX Eliki)
551 AD	(July 7,	38.4°N, 22.4°E, M=7.2, X Haeronia)
996	(38.3°N, 22.4°E, M=6.8, IX Galaxidi)
1402	(June	38.1°N, 22.4°E, M=7.0, X Diakofto)
1580	(38.4°N, 22.3°E, M=6.7, X Mynia)
1660	(38.3°N, 22.5°E, M=6.4, IX Galaxidi)
1742	(Febr.21,	38.1°N, 22.5°E, M=6.0, VII, Zacholi)
1753	(March 6,	38.1°N, 22.6°E, M=6.2, VII, Zacholi)
1861	(Dec.26,	38.2°N, 22.3°E, M=6.7, X, Valimitica)
1887	(Sept.9,	38.1°N, 22.1°E, M=6.2, IX, Aegio)
1909	(May 30,	38.4°N, 22.2°E, M=6.2, VIII, Daphnohori)
1965	(July 6,	38.4°N, 22.3°E, M=6.3, VII, Eratini)
1970	(April 8,	38.3°N, 22.6°E, M=6.2, VII, Antikyra)

In the beginning of 1981 the Alkyonides Gulf sequence occurred and its study revealed many details about the style of deformation of the Gulf of Corinth (Jackson et al., 1982; Papazachos et al., 1984; King et al., 1985). The Corinth Gulf represents a graben formation, with an asymmetric structure, where the main active normal faults are considered to be those of the southern part, dipping to the north.

The last event, of November 18, 1992, was mainly felt in the northern part of the Corinth Gulf, particularly in the towns of Galaxidi and Itea. Although the events that have occurred in this region are known to produce tsunamis (373 B.C., 551 A.D., 1402, 1861), there were no reports for such a wave for this particular last event.

After the occurrence of the main shock a network of 33 portable stations (of analog and digital recording) was deployed in the epicentral area, in order to study the aftershock

sequence. The network was installed by with the Universities of Thessaloniki, Athens, Grenoble, Paris and Cambridge. The present paper represents the results of a preliminary analysis of the earthquakes recorded by the stations operated by the teams of the Geophysical Laboratory of the University of Thessaloniki and of the Dept. of Geophysics and Geothermy of the University of Athens.

LOCATION OF THE MAIN SHOCK AND SPATIAL DISTRIBUTION OF THE AFTERSHOCKS

In order to constrain the location of the main shocks all the arrivals at the national seismological network and at the stations of the neighbouring countries were collected and analysed adopting HYPO 71 (revised) (Lee and Lahr, 1975), using as a velocity model the one suggested by Rigo et al. (1993), for this particular area. After many trial runs the best constrained solution for the parameters of the main shock is: $\varphi=38.30^{\circ}\text{N}$, $\lambda=22.41^{\circ}\text{E}$, $h=9.4\text{Km}$. This solution places the epicenter about 6 Km SSE from the town of Galaxidi.

The analog and digital records of the aftershocks were analysed and the P and S wave arrivals were read. The HYPO 71 (revised) program was used again with the above mentioned velocity model in order to define the parameters of each aftershock.

In order to use the best of the available information concerning the location of the earthquake foci of the sequence, we finally used the focal parameters of the events for which the standard error in the estimation of the epicenter (ERH), the standard error in the estimation of the focal depth (ERZ), the root mean square of the time residuals (RMS) and the number of station readings (N.O.) satisfied the following conditions: $\text{ERH} \leq 3 \text{ Km}$, $\text{ERZ} \leq 3 \text{ Km}$, $\text{RMS} \leq 0.6 \text{ sec}$ and $\text{N.O.} \geq 10$.

Table 2 gives information on the aftershock parameters that occurred between November 22 and December 2, 1992 and satisfy the above mentioned conditions. This table includes the date of occurrence, the origin time, the epicentral coordinates, the focal depth and the quality of the solution, represented by GAP (the largest angle, in degrees, between two successive stations), DMIN (the distance of the closest station to the epicenter), RMS, ERH, ERZ and N.O.

Figure 1 shows the distribution of all the earthquakes which were recorded by the seismological stations of the mobile networks during November 22 - December 2, 1992 in the broader area of the Corinth Gulf (solid circles). Circles with triangles denote the sites of the stations, while solid squares indicate the epicenters of the historical earthquakes listed in table 1.

Figure 2 shows the distribution of the aftershocks listed in table 2, which occurred within the area defined by the square in figure 1. It is observed that the epicentres tend to delineate in a NE-SW line. This is in fairly good agreement with the fault plane solution of the main shock. The proposed formula between the length of the fault and the magnitude (Papazachos and Papazachou, 1989) predicts for an earthquake of $M_s=5.9$ a fault length equal to 15Km. This length is in accordance with the one

Table 2. Information on the parameters of the main shock and the aftershocks of the period Nov.22 - Dec. 2, 1992, recorded by the local mobile networks.

Date	Origin Time	Lat N	Lon E	Depth	GAP	DMIN	RMS	ERH	ERZ	N.O	
Y M D	H M S			(Km)	Deg.	Km	sec	Km	Km		
921118	2110	42.6	38.301	22.410	9.4	100	80.	0.50	1.8	2.4	37
921122	1515	26.0	38.353	22.410	11.3	221	3.	0.13	1.7	1.2	8
921122	1849	53.9	38.362	22.402	11.9	210	1.	0.03	0.5	0.3	8
921123	010	12.5	38.263	22.414	5.4	286	12.	0.09	0.9	3.0	8
921123	654	25.3	38.318	22.369	9.1	254	7.	0.04	0.5	0.4	8
921123	1019	39.2	38.364	22.469	13.0	230	7.	0.06	0.9	0.6	8
921123	1453	59.9	38.286	22.358	9.0	280	10.	0.05	0.7	0.9	8
921123	1859	44.6	38.307	22.415	5.3	250	8.	0.12	1.1	0.9	10
921123	20 2	51.9	38.311	22.369	10.2	255	7.	0.09	1.1	0.7	10
921123	2044	57.6	38.275	22.389	9.1	270	11.	0.16	1.8	3.0	10
921124	14 8	49.6	38.311	22.360	9.9	227	8.	0.18	1.2	1.2	11
921125	114	17.2	38.307	22.449	8.5	238	9.	0.22	2.1	4.6	11
921125	2 7	5.8	38.312	22.376	6.6	244	7.	0.11	1.3	1.0	9
921125	218	14.8	38.332	22.557	9.7	278	10.	0.04	0.5	0.6	8
921125	410	45.5	38.333	22.348	11.0	234	6.	0.10	1.6	1.1	9
921125	1643	42.1	38.241	22.367	7.9	97	11.	0.15	0.5	0.8	18
921125	1758	36.6	38.245	22.370	3.5	158	12.	0.12	0.8	0.9	10
921125	1939	44.9	38.288	22.387	6.8	112	9.	0.18	0.5	0.5	19
921126	351	53.5	38.356	22.515	13.3	269	3.	0.17	2.2	1.2	9
921126	834	43.6	38.301	22.413	10.3	96	8.	0.17	0.7	0.9	18
921126	1037	34.2	38.297	22.421	8.9	246	9.	0.13	0.8	1.5	15
921126	1313	30.5	38.246	22.350	7.2	143	11.	0.16	0.9	1.3	19
921126	1328	37.1	38.264	22.359	8.3	134	13.	0.13	0.6	3.5	17
921126	1442	18.3	38.293	22.422	6.8	227	9.	0.16	0.8	0.6	11
921126	1518	7.7	38.340	22.498	13.1	234	6.	0.20	4.2	2.5	8
921126	1849	17.0	38.250	22.349	5.8	143	12.	0.23	0.8	1.5	14
921126	1940	56.4	38.336	22.487	11.7	64	6.	0.18	0.9	1.2	15
921127	0 4	55.1	38.348	22.415	11.6	109	3.	0.16	0.5	0.7	24
921127	035	30.6	38.292	22.372	7.9	137	9.	0.16	0.7	0.9	15
921127	118	18.0	38.332	22.511	11.8	299	6.	0.03	0.4	0.3	8
921127	258	4.3	38.341	22.489	13.3	201	6.	0.15	1.1	0.9	14
921128	517	43.0	38.262	22.443	5.5	119	13.	0.23	1.3	1.9	9
921128	652	20.3	38.366	22.509	12.9	184	6.	0.21	2.5	1.5	9
921129	21 4	48.2	38.355	22.432	11.8	215	4.	0.09	0.9	0.6	11
921130	251	20.1	38.327	22.417	11.4	145	11.	0.13	0.9	1.6	9
921130	630	52.4	38.263	22.409	2.9	176	12.	0.20	1.2	2.7	7
921130	10 6	18.5	38.330	22.441	9.7	147	6.	0.17	0.8	1.2	12
921130	1336	6.6	38.361	22.417	11.4	216	2.	0.18	1.8	1.1	11
921130	1714	38.3	38.347	22.414	10.5	118	3.	0.16	0.5	0.9	19
921130	2333	15.5	38.340	22.413	10.3	135	4.	0.12	0.7	0.7	13
921201	156	33.8	38.286	22.345	10.3	98	15.	0.16	0.5	0.8	21
921201	2 0	9.0	38.311	22.422	9.1	134	7.	0.18	0.6	1.4	21
921201	9 9	48.2	38.353	22.505	9.2	201	4.	0.27	3.3	2.2	10
921201	2347	38.6	38.373	22.513	12.7	175	2.	0.20	1.1	0.9	17
921202	619	38.3	38.368	22.509	12.7	182	2.	0.24	2.2	1.2	13
921202	924	23.3	38.303	22.420	7.0	286	8.	0.13	1.3	0.7	7

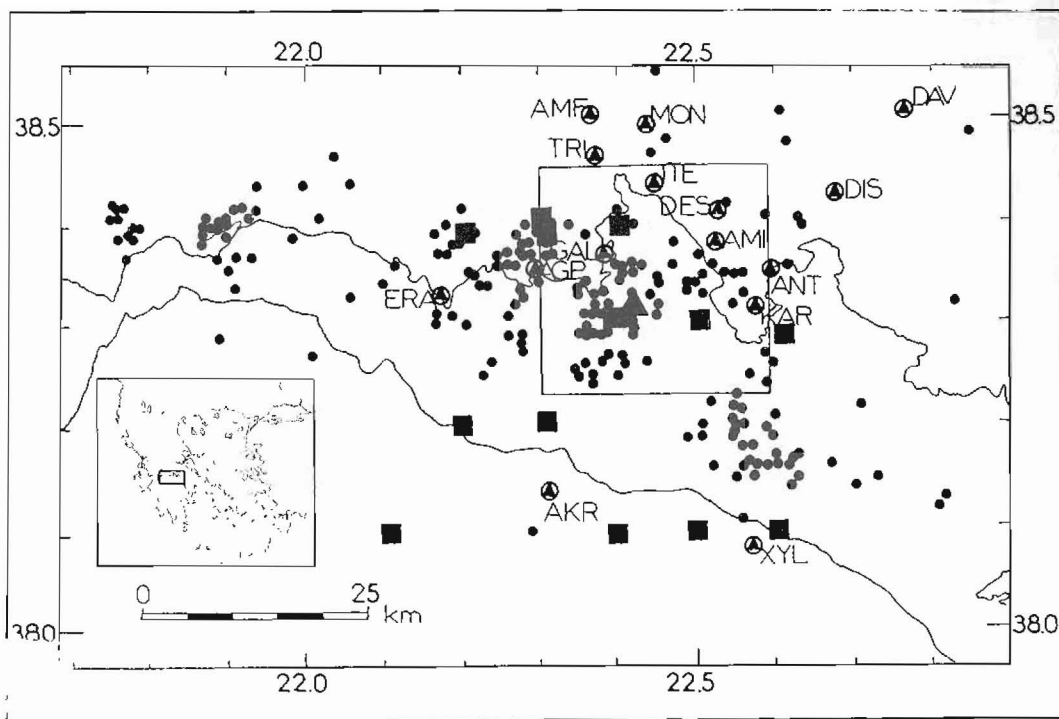


Fig.1. Distribution of the epicenters of the earthquakes that occurred in the broader area of the Corinth Gulf during the period Nov. 22 - Dec. 2, 1992 (solid circles). The epicenter of the main shock is shown with the black triangle, whereas the epicenters of the major historical and present century events, are shown with solid squares. Circles with triangles indicate the sites of the seismological stations used.

measured from the distribution of the aftershocks.

Figure 3 represents a cross section normal to the line AB (shown in Fig. 2). It is seen that the foci follow a well outlined dipping fault towards NNW with a mean dip of about 34° . The focus of the main shock is situated at a depth of about 9 Km at the center of the aftershock distribution. There are no earthquakes at depths shallower than 5 Km.

FOCAL MECHANISM OF THE MAIN SHOCK

Long period P and SH waves recorded at teleseismic distances by the World Wide Standard Seismograph Network (WWSSN) were inverted simultaneously in order to determine the centroid depth, the far-field source time function, the seismic moment and the source mechanism (strike, dip and rake) using the inversion procedure of Nabelek (1984). To avoid strong mantle and core

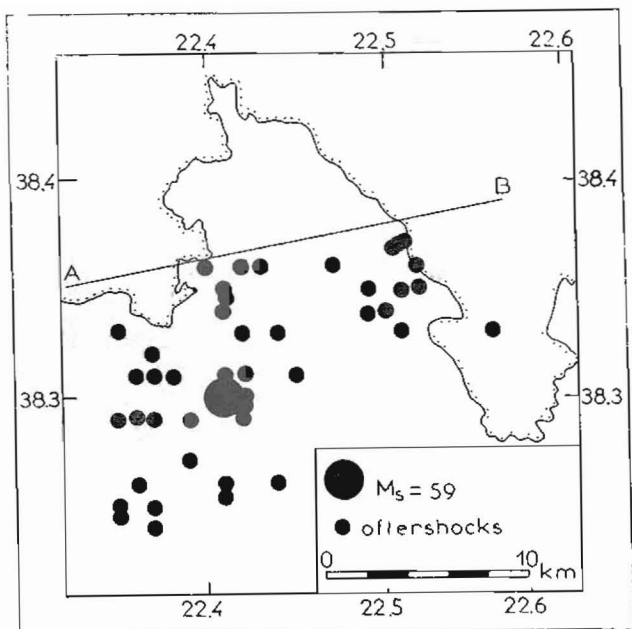


Fig.2. Distribution of aftershocks during Nov. 22- Dec. 2, 1992, as these are listed in table 2.

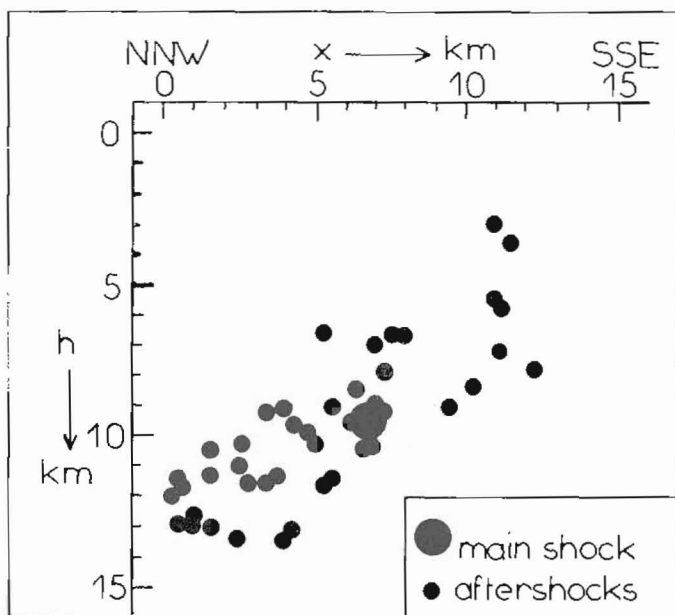


Fig.3. Vertical cross section of the depth of the aftershocks versus the distance from the line AB (shown in Fig.2).

interference we only used records from stations at distances between 30° - 90° for P waves and 40° - 70° for SH waves. At these distances body waves travel mostly in the lower mantle and the computation of synthetic seismograms is simpler. The magnitude of the earthquake was not large enough to produce good records at many stations resulting in a rather poor azimuthal coverage. The records were digitized and interpolated at 4 and 2 samples per second for P and S waves, respectively. The seismograms are equalised to a common instrument magnification and epicentral distance. The crustal structure at the source is assumed to be the following, based on microseismicity studies at the area (Rigo et al., 1993): 0.5 Km thickness of a water layer, 4.5 Km thickness layer with $V_p=4.9$, $V_s=2.8$ and the density=2.7 and the half space with $V_p=5.4$, $V_s=3.1$ and the density = 2.8 gr/cm³.

The earthquake source parameters are estimated by matching the observed seismograms with the synthetic ones in a least square's sense. The final solution is presented in figure (4a). The centroid depth is well constrained (10 ± 1 Km) and is in agreement with the estimation of the depth using the HYPO 71 program. The fault parameters however, are less well constrained especially the rake. At any rate, the obtained solution (strike = $68^{\circ} \pm 10$, dip = $59^{\circ} \pm 5$ and rake = $-95^{\circ} \pm 10$), moment $2.3 \cdot 10^{17}$ N.m, represents a normal fault on ENE striking plane. This solution is similar to the one determined by Briole et al. (1993). Figure (4b) shows the focal mechanism of the main shock based on first motion readings at long and short period instruments. The similarity of both solutions determined by the inversion and by the classical method is evident.

CONCLUSIONS

This paper represents a preliminary analysis of part of the data collected by the mobile network installed after the occurrence of the Galaxidi earthquake of November 18, 1992 of magnitude $M_s=5.9$. The distribution of the best located aftershocks clearly shows that the main shock occurred in a fault that has a total length of about 17 Km dipping to NNW. Most of the earthquake foci have focal depths that range from 5-13 Km. It seems that the main shock occurred at a depth of about 10 Km (determined from the inversion of body waves) and then the rupture propagated downwards, towards NNW. The fact that most of the damage was reported to occur in the northern side of the Gulf of Corinth intensifies this observation.

The best double couple mechanism calculated for the main shock, from the inversion of long and short period P and SH waves corresponds to a fault with strike= 68° , dip= 59° , rake= -95° and centroid focal depth $h=10$ Km. The solution is in very good agreement with the general pattern of previously determined focal mechanisms (Liotier, 1989; Papazachos et al., 1991; 1992a) and of the deformation style of the Gulf of Corinth (Ambraseys and Jackson, 1990; Papazachos et al., 1992b).

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November 18, 1992 GALAXIDI EARTHQUAKE

80/59/265/10/2.302E17

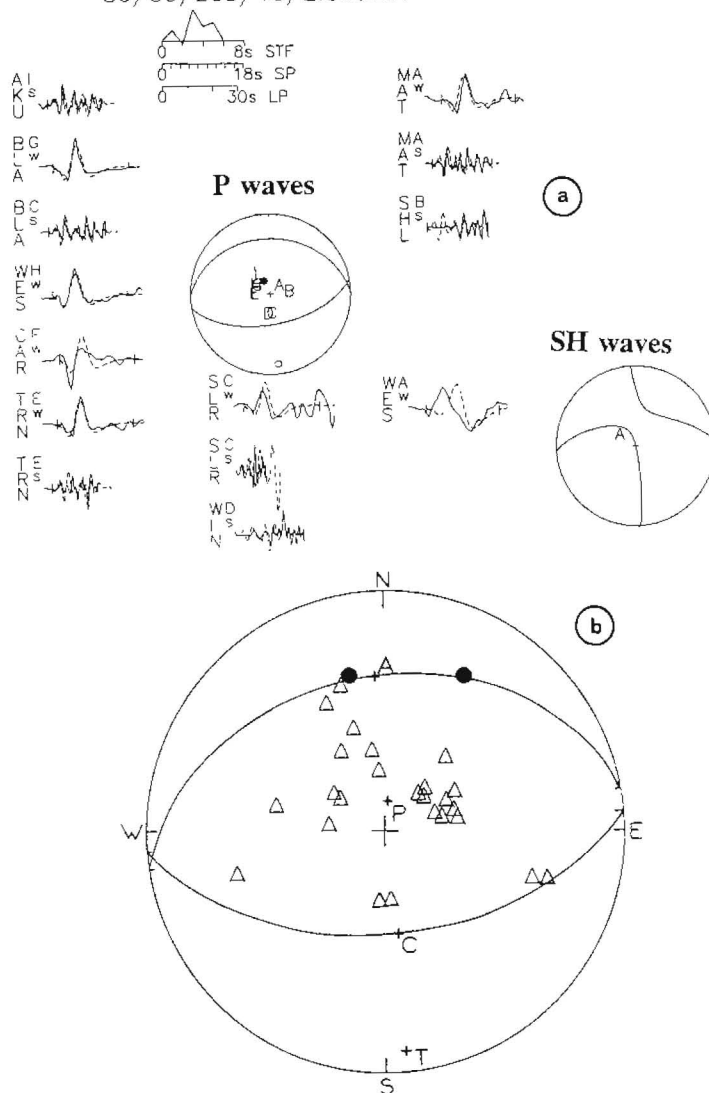


Fig.4. a) Long period and short period observed (straight lines) and synthetic (dashed lines) P and SH waveforms recorded at teleseismic distances of the main shock of Nov. 18, 1992. The synthetics were calculated for a fault plane with strike=68°, dip=59°, rake= -95° and focal depth h=10 Km. All amplitudes are normalized to a common magnification. The source time function shows the double pulse observed in most of the waveforms. b) Focal mechanism based on first motion readings at long and short period instruments.

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