FOCAL PROPERTIES OF THE OCTOBER 16, 1988 KILLINI EARTHQUAKE (WESTERN GREECE)

Karakostas,B.G.*, Scordilis,E.M.*, Papaioannou,Ch.A.*, Papazachos,B.C* and Mountrakis,D**.

* Geophysical Laboratory, University of Thessaloniki, Thessaloniki GR 540 06, Macedonia, Greece.
** Geological Laboratory, University of Thessaloniki, Thessaloniki GR 540 06, Macedonia, Greece.

A B S T R A C T

Focal properties of the October 16, 1988, M_s=5.9, earthquake which occurred in the sea area between Killini peninsula (NW Peloponnesse) and Zakynthos island have been investigated. The spatial distribution of well located aftershocks, a fault plane solution based on the first onsets of longitudinal waves and synthetic isoseismals show that this earthquake was due to a thrust fault striking almost north-south and dipping to the east. Field observations, which were made after the occurrence of the main shock in the broader epicentral area, are in agreement with such a fault.

ΕΣΤΙΑΚΕΣ ΙΔΙΟΤΗΤΕΣ ΤΟΥ ΣΕΙΣΜΟΥ ΤΗΣ ΚΥΛΛΗΝΗΣ ΤΗΣ 16 ΟΚΤΩΒΡΙΟΥ 1988

Καρακώστας,Β.Γ., Σκορδύλης,Ε.Μ., Παπαϊωάννου,Χ.Α., Παπαζάχος,Β.Κ. και Μουντράκης,Δ.

Π Ε Ρ Ι Λ Η Ψ Η

Μελετώνται οι ιδιότητες της εστίας της σεισμικής ακολουθίας του Σεπτέμβρη - Οκτώβρη 1988 που έγινε στη θαλάσσια περιοχή μεταξύ Κυλλήνης και Ζακύνθου. Η χωρική κατανομή των καλά υπολογισμένων επικέντρων των μετασεισμών που καταγράφηκαν από ένα δίκτυο φορητών σεισμογράφων που λειτούργησε για τέσσερις μέρες καθορίζει ικανοποιητικά το σεισμογενές ρήγμα. Πρόκειται για ένα ανάστροφο ρήγμα με διεύθυνση περίπου Β-Ν που βυθίζεται προς τα ανατολικά (προς τη μεριά της Πελοποννήσου). Σε καλή συμφωνία με αυτά τα στοιχεία βρίσκονται ο μηχανισμός γένεσης και οι ισόσειστες καμπύλες του κύριου σεισμού (16.10.1988, Ms=5.9) καθώς και τα γεωλογικά στοιχεία και οι παρατηρήσεις υπαίθρου στην ευρύτερη περιοχή μετά τη γένεση του κύριου σεισμού.

INTRODUCTION

On October 16,1988 (12:34 GMT) a shallow earthquake with surface wave magnitude M_s=5.9, occurred in the sea area between Killini peninsula and Zakynthos island. Twenty five people were injured and extensive damage was caused in the Killini -

Vartholomio area (I_{max}=VIII). Damage and landslides were caused also in Zakynthos island. The foreshock activity started almost one month before. The largest foreshock occurred on September 22 (12:05, M_s=5.5) and caused slight damage. Numerous aftershocks followed the main shock.

The epicentral area belongs to a seismic zone trending NW-SE with very high seismic activity (Papazachos,1990). This zone occupies the area near the northwestern termination of the Hellenic Arc and its seismicity is due to the convergence of the Mediterranean oceanic lithosphere and the Aegean continental lithosphere. Thus, thrust faulting for strong earthquakes previously occurred in this area has been found. Anderson and Jackson (1987) determined the fault plane solution of an earthquake with M_s=5.9 (March 28,1968) which occurred near the main shock of the present sequence (37.8N-20.9E) and found thrust faulting with a nodal plane trending almost N-S and dipping to E.

During the present century, more than twenty earthquakes with M_s>5.0 occurred in a distance less than 20 Km from the epicenter of the 1988 earthquake. Four of them, with M_s>5.4, caused damage with maximum observed intensity I_{max}=VIII in Killini and Vartholomio area (Comninakis and Papazachos,1986).

A few days after the main shock, a network of portable seismographs installed in the epicentral area by the Geophysical Laboratory of Thessaloniki University. Five short period instruments, Spregnether MEQ-800, were operated there for four days (October 25-28,1988). At the same time surface expressions caused by the main shock in the epicentral area were studied.

Some studies concerning this seismic sequence have been focused to macroseismic effects and surface expressions (Papadopoulos and Profis, 1990; Lekkas et al., 1991; Theodulidis et al., 1992). Preliminary results of the fault properties have been presented also by Papanastasiou et al. (1989).

The purpose of the present paper is to deduce some basic fault properties for this seismic sequence on the basis of well located aftershocks recorded by the local portable seismic network in conjuction with the fault plane solution, the macroseismic effects of the main shock and the available information on the surface faulting in the epicentral area.

LOCATION OF THE AFTERSHOCKS

The sites of the portable seismological stations installed in the area are marked by triangles in Figure (1), while the epicenter of the main shock is denoted by a circle. It is shown that the azimuthal coverage of the epicentral area is satisfactory. Two of the seismological stations, KLG at the northern part and KAT at the southern part of the area, are rather far from the epicenter of the main shock but it was impossible to install them in a better site because the area is covered by alluvial deposits.

During the four days operation of this seismological network, more than 100 aftershocks were recorded. Almost all of them had their first arrival at KAS station, that is, the seismic activity was concentrated in a restricted area near to this station.

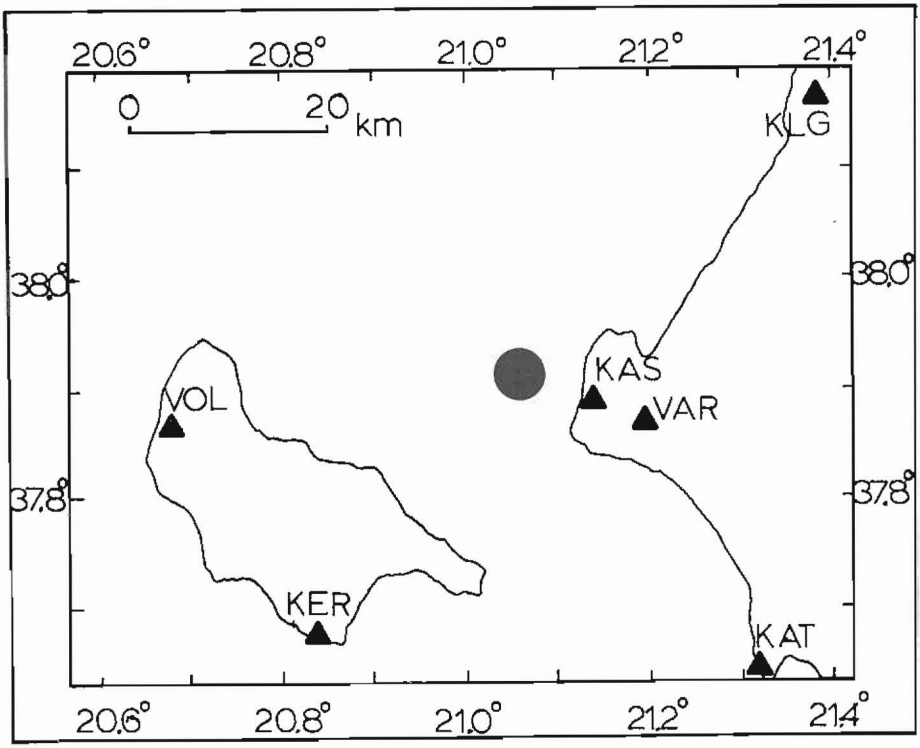

Fig.1. The sites of the stations of the local seismological network (triangles) and the epicenter of the mainshock of the sequence.

Reliable V_p/V_s ratio and local velocity structure are necessary for the accurate location of the aftershocks. The V_p/V_s ratio is an important parameter for the depth control of the earthquakes. Individual Wadatti plots were constructed to determine this parameter. By this way, a mean value V_p/V_s=1.96 was found.

The velocity structure in this area is not known in detail. According to a cross section from Zakynthos to NW Peloponnesse based on seismic exploration data (Monopolis and Bruneton,1982), the seismic rays of the aftershocks, recorded by the portable seismological network, pass through a "seismic unit" with internal velocity 5.0 km/sec or higher. Taking into consideration these data, and by using the program HYPO71 (revised) (Lee and Lahr,1975), different half space models with velocities 4.0 km/sec - 6.0 km/sec by step 0.1 km/sec were tested. The best results, that is, minimum RMS, ERH, and ERZ values, were obtained for the half space model with velocity of P waves V_p=5.3 km/sec. Several other models were tested but with no better results. Thus, the above mentioned half space model was adopted to locate the aftershocks recorded by the local seismological network.

The magnitudes of the aftershocks were estimated by using the signal duration at each station, in relation to the magnitude of the aftershock of October 28, 05:49 GMT, which was determined from the records at the permanent seismological network of Greece.

The spatial distribution of all the located aftershocks was rather complicated. This is attributed to observational errors. For this reason, an effort was made to use data with higher accuracy. Several plots were made by using different set of data on the basis of different criteria, such as RMS, ERH and ERZ values and the number of the phases used. It was found that the fault plane is better described by the aftershocks with seven or more P and S arrivals. Information on the dates, origin times, geographical coordinates of the epicenters (latitude and longitude), focal depths, magnitudes, number of phase arrivals, and the values of RMS, ERH, and ERZ, are given in the ten columns of Table I . The first two raws of Table I, include information on the two major shocks of the sequence which were relocated in the present study.

Table 1. Information on the focal parameters of the events of the sequence.

Date	Or. time	Lat. φ°N	Lon. λ°E	Depth km	Mag. M_s	No	RMS	ERH km	ERZ km
88 09 22	12:05:38.3	37.94	21.08	14.5	5.5	60	0.70	2.2	2.0
88 10 16	12:34:03.7	37.91	21.06	13.0	5.9	54	0.20	0.9	0.8
88 10 26	15:06:07.6	37.88	21.05	5.4	2.7	7	0.20	1.8	2.5
88 10 26	19:30:10.6	37.92	21.10	7.9	1.7	7	0.18	2.7	2.5
88 10 26	19:45:48.1	37.89	21.04	7.5	2.7	7	0.13	1.1	2.2
88 10 27	01:10:29.1	37.86	21.07	3.6	2.9	7	0.12	1.0	2.7
88 10 27	03:25:00.4	37.85	21.07	4.0	3.4	7	0.15	1.1	3.0
88 10 27	14:47:26.3	37.89	21.05	7.8	2.6	7	0.19	1.4	3.2
88 10 27	18:40:39.8	37.89	21.10	9.3	2.4	7	0.06	0.5	0.7
88 10 27	18:45:57.3	37.97	21.05	7.0	3.0	7	0.12	1.0	3.7
88 10 27	19:26:56.0	37.99	21.04	9.0	3.4	8	0.15	1.1	3.0
88 10 27	19:28:50.5	37.98	21.05	4.6	2.9	8	0.06	0.4	2.0
88 10 27	19:29:31.3	38.00	21.05	9.8	3.2	9	0.14	0.8	2.0
88 10 27	20:13:15.5	37.88	21.10	10.8	3.7	9	0.15	0.9	1.2
88 10 27	20:55:43.4	37.95	21.08	10.1	2.1	8	0.25	1.9	2.5
88 10 27	21:15:40.3	37.89	21.05	7.8	2.7	9	0.12	0.6	1.0
88 10 27	21:32:48.8	37.90	21.09	10.4	2.8	9	0.16	1.0	1.6
88 10 27	22:10:24.3	37.93	21.05	11.9	2.0	7	0.06	0.5	1.0
88 10 27	22:30:45.2	37.92	21.07	4.6	2.2	9	0.22	1.1	2.5
88 10 27	23:44:34.9	37.92	21.07	3.0	1.3	7	0.11	1.1	2.5
88 10 28	01:15:34.8	37.92	21.02	6.4	2.3	8	0.06	0.3	1.2
88 10 28	01:58:07.0	37.91	21.01	5.4	3.1	8	0.20	1.3	4.5
88 10 28	04:58:12.2	37.87	21.05	6.4	2.7	7	0.10	0.8	1.3
88 10 28	05:49:09.5	37.87	21.10	14.6	4.4	8	0.16	1.2	1.4
88 10 28	05:53:25.9	37.86	21.09	8.7	2.6	8	0.17	1.1	1.3
88 10 28	06:17:31.3	37.91	21.07	7.9	1.7	7	0.12	1.1	1.5
88 10 28	08:16:20.3	37.89	21.09	16.4	2.4	7	0.15	2.0	1.8
88 10 28	10:29:26.2	37.92	21.08	11.0	2.4	7	0.15	1.8	2.6

RELOCATION OF THE TWO MAJOR SHOCKS OF THE SEQUENCE

The accurately located aftershock of October 28, 05:49, M_s=4.4, by the local seismological network, which was also recorded by the permanent seismological stations in Greece and the surrounding countries, gave us the opportunity to define a reliable regional crustal model, which was necessary for the relocation of the two major shocks of the sequence,that is the foreshock of September 22,1988 (M_s=5.5) and the main shock. The above mentioned aftershock was considered as an explosion in running the HYPO71 program and the effort was to determine a model that minimize the RMS, ERH, and ERZ values, as well as, the travel time residuals of the seismic waves at each permanent seismological station. As initial crustal model, the one suggested by Panagiotopoulos (1984) was used. This is a two layers model above a half space, that is, a granitic and a basaltic layer above the mantle. The velocities of P waves and the thicknesses of the layers of this model are: V_g=6.0 km/sec, d_g=19 km, V_b=6.6 km/sec, d_b=12 km, V_n=7.9 km/sec. This model is valid for the broader Aegean area, but beneath the western Greece a crustal thickness of 45 km has been proposed by Makris (1978) and Panagiotopoulos and Papazachos (1985), by using seismic refraction profiles and travel times of P_n waves, respectively. Thus, keeping constant the velocities of P waves of the model mentioned above, different thicknesses of the crust were tested. The minimum errors for the fixed solution were obtained for a crustal thickness of 48 km. The thicknesses of the granitic and the basaltic layers of this model are d_g=29 km and d_b=19 km.

The two major shocks of the sequence were relocated by using this model, and the travel time residuals of the fixed solution as time delays at each seismological station. An accelerogram recorded near the epicenter, in Zakynthos island, was very useful for the accurate determination of the focal parameters of the main shock.

SPATIAL DISTRIBUTION OF SHOCKS

The epicenters of all shocks, listed in Table I, have been plotted in the map of Figure (2).

The aftershocks located by the local network have been represented by small black circles, while the main shock by a circle inclunding a triangle and the foreshock by an open circle. An almost NS trending of the plotted epicenters is clearly observed while the epicenter of the main shock is located in the middle of the epicentral area. The length of the epicentral area is 17 km which is in good agreement with the length of a fault capable to generate an earthquake of magnitude M_s=5.9 according to the formula:

$$logL = 0.51M_s - 1.85 \quad (1)$$

proposed by Papazachos (1989).

A cross section perpendicular to the trend of the epicenters is shown in Figure 3. The focal depths of the shocks vary from 3 km to 16 km. A plane with clear lower boundary, dipping 59°E is

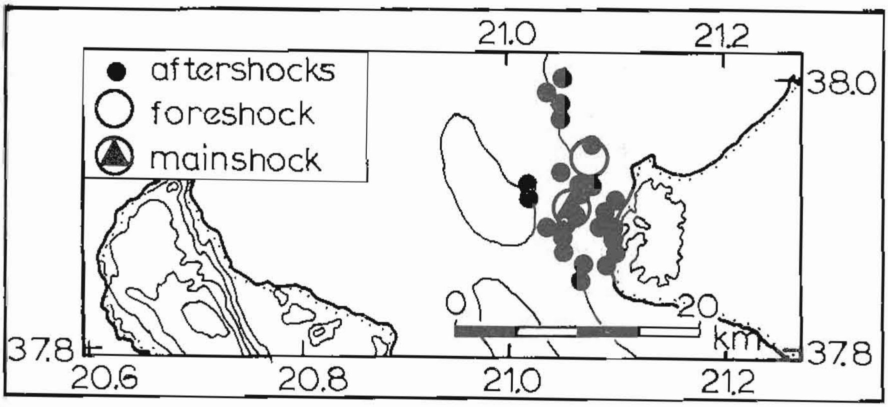

Fig.2. Distribution of the epicenters of aftershocks located by using the data of the local network (small circles) and the epicenters of a strong foreshock (large circle) and of the mainshock (circle with a triangle).

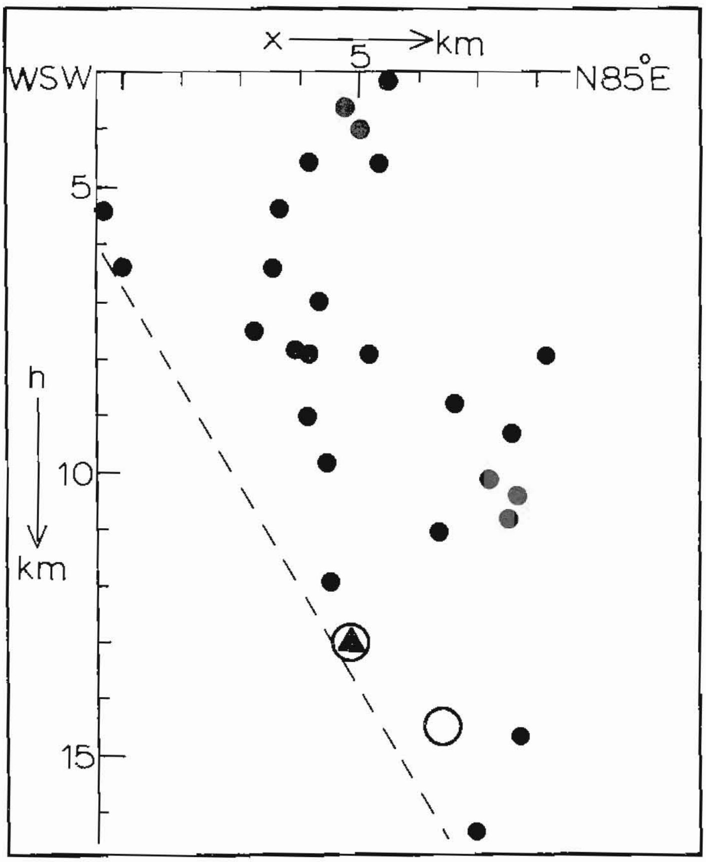

Fig.3. A cross section on a vertical plane perpendicular to the trend of the distribution of the epicenters of the aftershocks.

defined by the foci of the shocks. The main shock and the largest foreshock are located in the lower part of the plane.

FAULT PLANE SOLUTION OF THE MAIN SHOCK

The first onsets of long period instruments were used to determine the fault plane solution of the main shock. Figure (4) is an equal area projection of the lower hemisphere of the focal sphere. A value equal to 6.8 km/sec was assumed for the longitudinal waves at the focus of the earthquake. Dilatations and compressions have been represented by triangles and circles, respectively. The number of the observations is not very adequate but the one of the nodal planes is rather well constrained. This focal mechanism indicates a 338° NNW-SSE striking plane dipping to the ENE at an angle of 48°. This is considered as the fault plane since its direction coincides with the direction of the epicenters (Fig. 2) and the dip of the plane obtained by the cross section (Fig. 3). This solution shows that the main shock

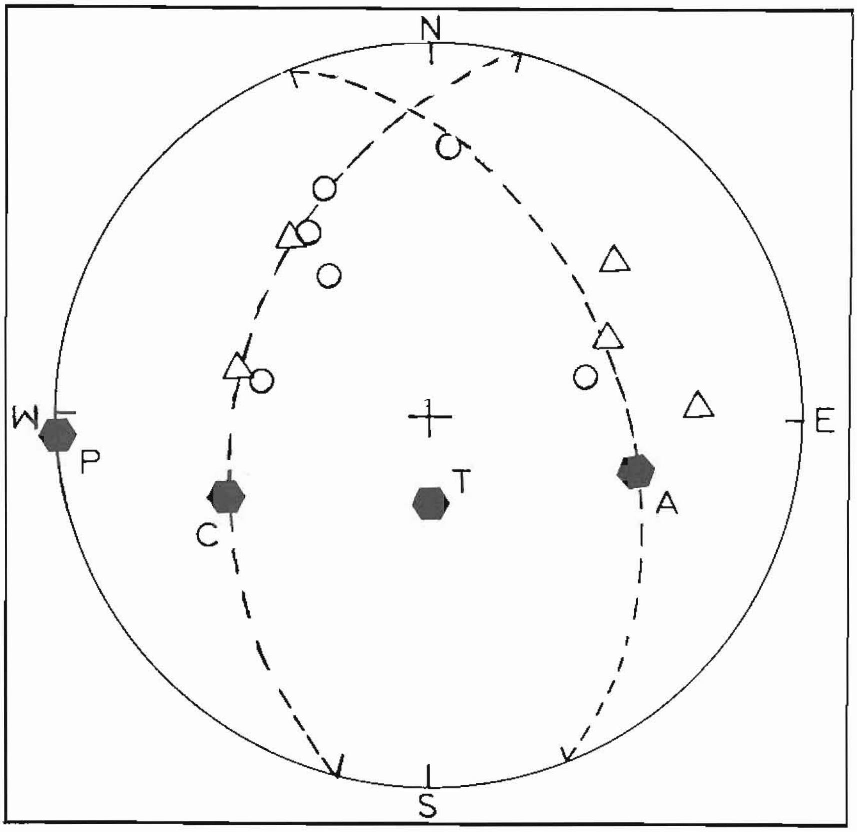

Fig.4. The fault plane solution of the October 16, 1988 M_s=5.9 mainshock.

was caused by a thrust faulting with a slight left lateral component. Table II summarizes the parameters of the fault plane solution of the main shock.

Table 2. 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°
338	48	64	194	48	116	268	01	178	71

ISOSEISMAL MAP

Macroseismic information concerning the main shock of this sequence have been collected at the Seismological Institute of National Observatory of Athens and have been used to determine the intensities in MM scale. These data have been published in the October 1988 bulletin of the Seismological Institute and were used to draw the theoretical isoseismals shown in Figure 5. These isoseismals are based on a modelling of the macroseismic intensities which takes into account the source properties (radiation pattern, size, focal depth), geometric spreading and anelastic attenuation (Papazachos, 1992). It is observed that the maximum axis has an almost north-south direction which is in agreement with a fault of about the same strike.

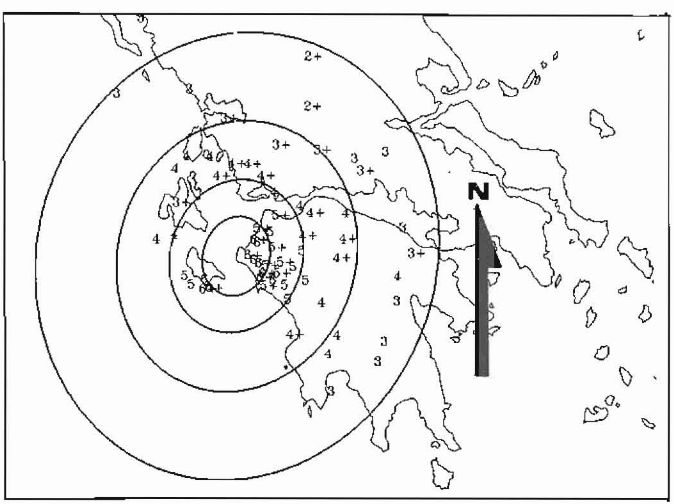

Fig.5. Synthetic isoseismals and macroseismic intensities of the October 16, 1988, M_s=5.9, mainshock.

FIELD OBSERVATIONS

Several tension cracks were observed in the Killini Peninsula, that is, at the hanging-wall block of the fault according to our interpretation. These fissures had an almost N-S trending. In some cases graben formations with the same trend were observed. No obvious relation of these fissures with any known main geological fault exists.

Similar phenomena, that is, extensional cracks on the hanging-wall blocks of thrust faults have been also observed in the past by several scientists (Wise, 1963; King and Vita-Finzi, 1981; Yearts, 1986; Hart et al., 1990; Ponti and Wells, 1991). According to these scientists, this phenomenon is attributed to second order tectonic extension or bending-moment faulting across the crest of the uplifted hanging-wall block or to tectonic and gravity driven processes or even to changes in the dip of the main thrust fault plane with depth. In almost all cases the extensional fissures are subparallel to the main fault and have been formated on the uplifted hanging-wall block.

Vertical movements were observed by Lekkas and his colleagues (1991) in a few sites along the coast lines of the Kilinni Peninsula. The observations were made at beach-rock formations and have been interpreted as uplifting movements of the order of 15-20cm. The beach rocks formations, which are formated under the sea level, have now a total height at least 2m above the sea level. This indicates a general uplifting movement in the area, part of which is the uplift caused by the October 16, 1988 earthquake. This uplifting is in agreement with the thrust faulting suggested in the present paper.

REFERENCES

Anderson,H. and Jackson,J., (1987). Active tectonics of the Adriatic region. "Geophys. J. R. astron. Soc.", 91, 937-983.

Comninakis,P.E. and Papazachos,B.C., (1986). A catalogue of earthquakes in Greece and surrounding area for the period 1901-1985. "Publ. Geophys. Lab., Univ. Thessal.", 1, pp. 167.

Hart,E.W., Bryant,W.A., Wills,C.J., and Treiman,J.A., (1990). The search for fault rupture and significance of ridgetop fissures, Santa Cruz Mountains, California, "The Loma Prieta (Santa Cruz Mountains), California Earthquake of 17 October, 1989, S.R. Mc Nutt and R.H. Sydnor (Editors), Cal. Mines Geol. Spec.", 104, 83-94.

King,G.C.P. and Vita-Finzi,C., (1981). Active folding in the Al gerian earthquake of 10 October 1980. "Nature" 292, 22-26.

Lee,W.H.K. and Lahr,J.C., (1975). HYPO71 (revised): a computer program for determining hypocenter, magnitude and first motion pattern of local earthquakes. "U.S.G.S. Open File Rep.", 75-311.

Lekkas,E., Logos,E., Danamos,G., Fountoulis,I., Adamopoulou,E., (1991). Macroseismic observations after the earthquake of October 16th, 1988 in Killini peninsula (NW Peloponnesus, Greece). "Proceed. of the 5th Congress of the Geol. Soc. of

Greece, Thessaloniki 24-27 May 1990, Bull. of the Geol. Soc. of Greece," XXV, 3, 313-328.
Makris,J., (1978). The crust and upper mantle of the Aegean region from deep seismic soundings. "Tectonophysics", 46, 269-284.
Monopolis,D. and Bruneton,A., (1982). Ionian sea (Western Greece): its structural outline deduced from drilling and geophysical data. "Tectonophysics", 83, 227-242.
Panagiotopoulos,D.G. (1984). Travel time curves and crustal structure in the southern Balkan region. "Ph. D. Thesis, University of Thessaloniki", 1-173.
Panagiotopoulos,D.G. and Papazachos,B.C., (1985). Travel times of Pn waves in the Aegean and surrounding area. "Geophys. J. R. astron. Soc.", 80, 165-176.
Papadopoulos,G.A., Profis,Th., (1990). Macroseismic observations related with the strong shock of October 16th, 1988, in NW Peloponnesus, Greece: The important role of the microzonation conditions. "Journal of Geodynamics", 12, 217-231.
Papanastasiou,D., Drakatos,G., Latousakis,I., Stavrakakis,G., and Drakopoulos,I., (1989). Preliminary results of the earthquake of 16th October 1988, in Killini. "Proceed. of the 1st Hellenic Geophysical Congress, 19-21 April 1989, Athens", 496-502.
Papazachos,B.C., (1989). Measures of earthquake size in Greece and surrounding areas. "1st Congr. Hellenic Geophys. Union", 438-437.
Papazachos,B.C., (1990). Seismicity of the Aegean and surrounding area. "Tectonophysics", 178, 287-308.
Papazachos,C.B., (1992). Anisotropic radiation modelling of macroseismic intensities for estimation of the attenuation structure of the upper crust in Greece. "Pure Appl. Geophys.", 138, 445-469.
Ponti,D.J. and Wells,R.E., (1991). Off-fault ground ruptures in the Santa Cruz Mountains, California: Ridge-top spreading versus tectonic extension during the 1989 Loma Prieta earthquke. "Bull. Seism. Soc. of Am.", 81, 1480-1510.
Theodulidis,N., Margaris,B., Papastamatiou,D., and Kalogeras,I., (1992). Accelerograms and macroseismic measurements of the October 1988, Killini earthquake. "1st Hellenic Conf. AMTS TEE 6-8 May, 1992, Athens", II, 13-24.
Wise,D.U., (1963). Keystone faulting and sliding driven by basement uplift of Owel Creek Mountains, Wyoming, "Am. Assoc. Pet. Geol. Bull.", 47, 586-598.
Yearts,R.S., (1986). Active faults related to folding. "Active Tectonics, National Academy Press, Washington, D.C.", 63-79.