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STUDY OF THE 2ND DECEMBER 2002 VARTHOLOMIO EARTHQUAKE (WESTERN PELOPONNESE) M5.5 AFTERSHOCK SEQUENCE

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Abstract

On the 2 December 2002 an earthquake (M_w=5.5) occurred near the city of Vartholomio (western Greece) causing damage in more than 1000 buildings. The University of Patras Seismological Laboratory permanent network stations recorded the mainshock and the aftershocks. Furthermore, twenty-six sites were instrumented to study the aftershock sequence. We identified more than 500 aftershocks with Md ranging from 2.0 to 4.3 during the first 30 days following the mainshock. The spatial and temporal evolution of the aftershock sequence is presented. We use the 370 earthquakes recorded at a minimum of 20 stations, with RMS less than 0.1 s and uncertainties less than 1 km, to infer the precise distribution of the seismicity in the fault region. The mainshock moment tensor inversion results are used in parallel to the aftershock sequence distribution in order to identify the causative fault. The results suggest a strike slip fault with dextral movement, which is trending NNE-SSW and fits the regional tectonics.

Key words: *moment tensor, centroid, waveform inversion, fault plane, Vartholomio.*

1. Introduction

An earthquake of Mw=5.5 occurred on 2 December 2002 at a distance of 10 km from the center of the city of Vartholomio (Fig. 1); The epicenter was located in south western Greece, in the coastal area of western Peloponnese. Although the earthquake magnitude was moderate, the damage reported was serious, since the intensity reached V$^+$. Seventeen people were wounded, eight buildings collapsed and tenths of buildings were seriously damaged, in the city of Vartholomio, while over a thousand were reported with damage in twenty nine nearby settlements (ITSAK, 2003).

The seismogenic area is situated in the external part of the Hellenic Arc, which is characterized by intense neotectonic deformation and high seismicity. More specifically, this area is part of the neotectonic depression (graben) of Pirgos, which is delimited by two faults of NW- SE and NNE-SSW direction and it is characterized by co-sedimentation tectonism (Le Pichon et al., 1995).

Throughout its history, Vartholomio has been severely affected by strong earthquakes. Damaging earthquakes occurred at the area in 1954 and 1988 with magnitudes M=5.8 and M=6.0, respectively. The 16th October 1988 earthquake caused serious damage in the city of Vartholomio reaching a seismic intensity of VII, a value which has been higher than would normally be expected for the particular magnitude and epicentral distance. The focal mechanisms calculated for these events revealed pure strike slip faulting. Kiratzi and Louvari (2003) mention that the sense of motion of the strike-slip faults of the western Peloponnese could not be evidenced from the aftershock distribution of the major events (i.e. Vartholomio in 1988, Pirgos in 1993). The dextral sense of strike slip motion is favoured, parallel to the strike of the Cephalonia strike-slip fault, which would result in clockwise rotations of the NW margin of the Hellenic trench. The absolute peak ground acceleration (PGA) in Zakynthos island (R~20km) measured by ITSAK's strong motion records, was 90.7cm/sec^2. The estimated PGA for Vartholomio by synthetic strong motion calculations (ITSAK, 2003), was 113cm/sec^2. The aftershock activity was mainly concentrated around the coastal area southwest of Vartholomio city.

The PATNET network of Patras Seismological Laboratory (UPSL) operated in the area since 1991 and up to 2000, recorded the mainshock and the aftershock sequence. Stations operated by the National Observatory of Athens (NOA) also recorded the sequence. Furthermore, twenty-six sites in the area were instrumented by UPSL, to study the aftershock sequence. We identified more than 500 aftershocks with Md ranging from 2.0 to 4.3 during the first 30 days following the mainshock. In this paper results obtained by seismological data from PATNET network, NOA network and the temporary seismological network following the 2 December 2002 earthquake are analysed. The mainshock was located using the available records and the source parameters were determined by moment tensor inversion. Aftershock sequence data and source parameters were combined in order to clarify the geometry of the causative fault.

2. Location

The mainshock was located by HYPOINVERSE code (Klein, 2002), using manual P and S readings from short period records of PATNET stations and two broad band stations of NOA (RLS, ITM), in distances up to 140km (Fig. 1). The uncertainty was evaluated by repeating calculations with: a) various starting depths, varying from 10km up to 20km; the 17km depth was favoured by the residuals. b) two Vp/Vs ratios, 1.76 and 1.78; the latest provided the best results and c) three 1D crustal models: Haslinger et al., 1999, Tselentis et al., 1996, and Novotny et al., 2001. The model by Tselentis et al., 1996 provided the least RMS residuals.

The aftershocks occurred during the first week (2 – 10 December 2002), were recorded by the Patras Seismological Network (PATNET) stations; they were located using P and S manual readings and using the parameters that were favoured by the test concerning the mainshock (Fig. 2A). During the following days the aftershocks were recorded both by PATNET and a portable network of 26 stations, which was installed in the area (Fig.1) for a period of one month (9th December 2002 – 10th January 2003).

Each station was equipped with a three-component 4Hz SIG borehole sensor, a 24-bit Earth Data recorder and a GPS unit. The instruments have flat transfer function for velocity in the frequency range from 1Hz to 50Hz. The recording was continuous with a sampling frequency of 100Hz. During the operation of the network hundreds of earthquakes were recorded. The initial hypocentral locations were determined using the program HYPO71 (Lee and Lahr, 1975). The local magnitudes M_D of these events were within 0.5 and 4.5, while their depths varied between 5 and 20km. (Fig. 2B). The magnitudes were computed using the coda duration method (Lee and Lahr, 1972), with the same parameters used in the mainshock processing.

A dataset of 50 events, commonly recorded and located by the permanent network PATNET and the temporary microseismic network of Vartholomio, was created. This group of events is con-

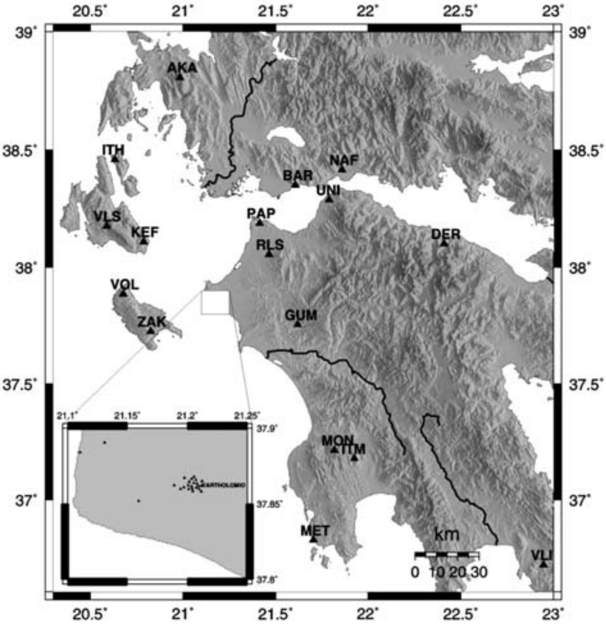

Fig. 1: Distribution of the seismological stations, which recorded the mainshock and the aftershock sequence. White rectangle shows the study area where the microseismic network (inset) was installed.

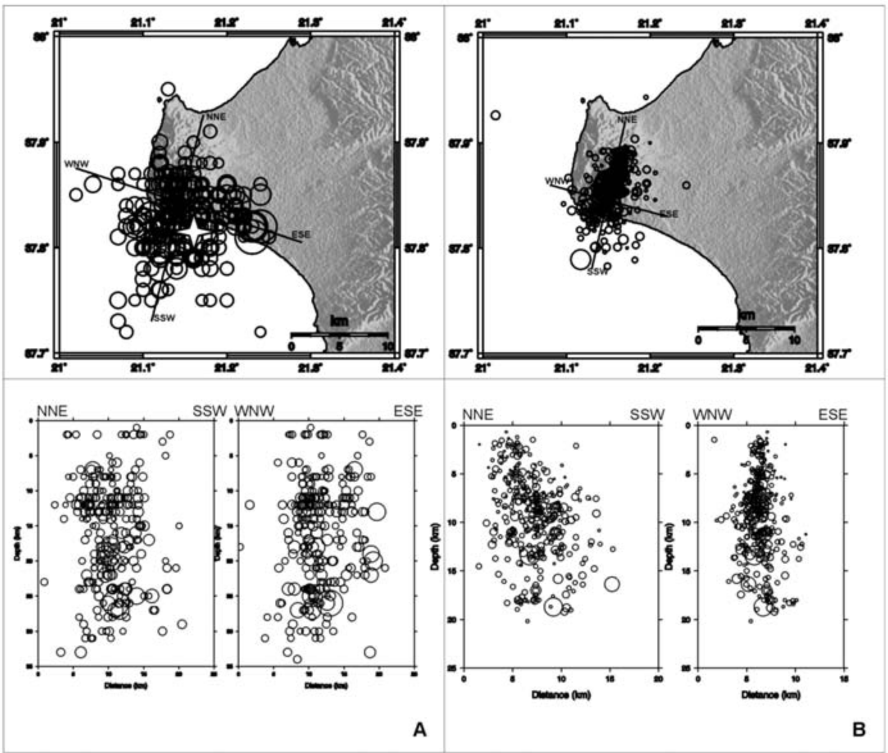

Fig. 2: Aftershock sequence distribution and cross-sections, located by the permanent network PATNET (A) and the temporary network (B).

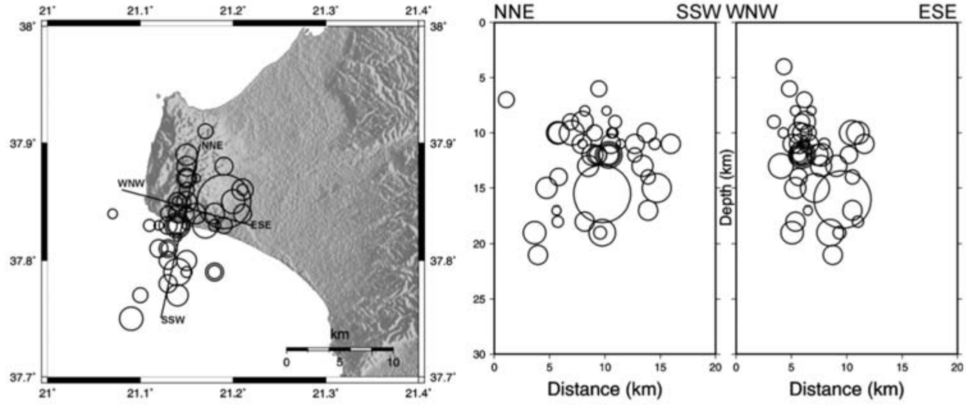

Fig. 3: Thirty-eight relocated hypocenters distributed in map and cross-sections.

sidered as the most accurately located, since the hypocenter locations were provided by local and regional station records. This indicates a complete azimuthal coverage but also a large number of P and S readings. The mainshock and the 50 most accurately located aftershocks were relocated by HYPODD (double difference) software Waldhauser (2001). Catalog P- and S-wave data were used in the procedure derived from stations within 140 km from the centre of the epicentral area. Fifty initial sources and 35 stations were combined in the procedure, and parameters were set, following Waldhauser (2001) suggestions for datasets containing a small number of events. The maximum number of neighbour events was set to the number of the initial sources. The double-difference residuals for the pairs of earthquakes at each station were minimized by weighted least squares using the method of singular value decomposition. The 1D-velocity model to calculate the theoretical travel-times was the Tselentis et al. (1996) model.

The HYPODD final results include 38 relocated events, which form a single cluster (Fig. 3). Most of the events are located in the sea area SSW of the Vartholomio city and the large percentage of the hypocenters is located in depths between 9 and 16km. The mainshock relocated hypocenter was at 20km.

The distribution of the epicentres, in all the cases, suggest a fault plane striking NNE-SSW and according to the cross-sections is almost vertical, slightly dipping to the east (Fig. 2 and Fig. 3).

3. Moment Tensor

The moment tensor inversion is performed by the so-called iterative deconvolution of Kikuchi and Kanamori (1991), modified for regional distances by Zahradnik et al., 2005. Complete waveforms are used, without separation of individual phases; full wave Green functions are calculated by the discrete wavenumber method in a 1D velocity model. Easy processing of many events is possible due to a user-friendly Fortran-Matlab program package called ISOLA (Sokos and Zahradnik, 2008). The present work focuses on the case of the single-source and deviatoric inversion (no volume change). The results are presented in terms of the double-couple component of the deviatoric solution, represented by the scalar moment, strike, dip and rake.

We used the mainshock records from four broadband stations of NOA; ITM, VLI, VLS and RLS. In some cases broadband records of moderate near earthquakes at stations of NOA network

Table 1. Moment tensor solution.

Origin (GMT)	Lat (N) (deg.)	Lon (E) (deg.)	Depth (km)	Scalar moment (Nm)	Mw
04:58:56	37,8557	21,1793	20	2.173e+17	5,5
Strike I	**Dip I**	**Rake I**	**Strike II**	**Dip II**	**Rake II**
209°	83°	178°	299°	88°	7°

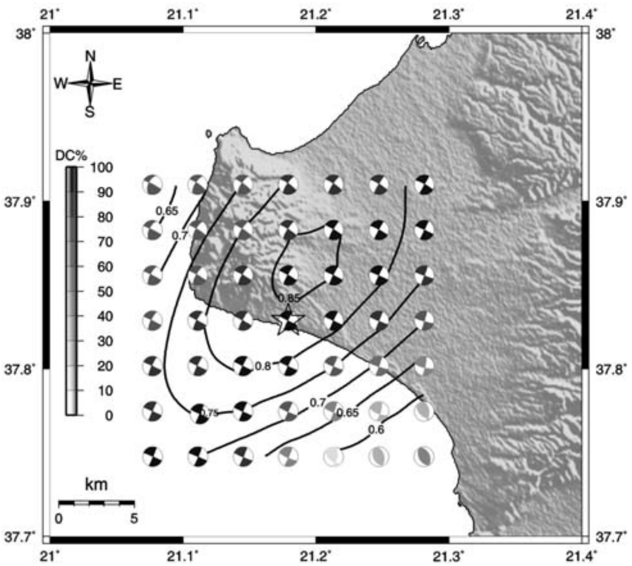

Fig. 4: Moment tensor inversion and source grid search. The star represents the initial epicenter position.

equipped with Lennartz Le-3D/20s (20-sec) sensors exhibit long period, pulse like signals; Numerical simulation of the pulses allows their removal, thus making the records fully utilizable for waveform inversion in seismic source studies (Zahradnik and Plesinger, 2005). The RLS station records were corrected for such disturbances according to Zahradnik and Plesinger, 2005.

The MT calculation was performed in crustal model provided by Tselentis et al., 1996 and at the 0.020 - 0.10 Hz frequency range. The centroid was determined by repeated calculations of the MT in a volume grid of trial source positions not far from the hypocenter, aiming at optimizing the fit between the observed and synthetic waveforms. Next, the so-called hierarchic grid search was applied (Zahradnik et al., 2008), using a progressively finer grid (1km) while approaching towards the likely centroid position.

The optimum source position (C) was identified at the location shown in Fig.4, a few kilometers northeast of the epicenter at depth of 20km. The moment tensor inversion revealed a strike – slip fault (Table 1); nodal plane I is trending NNE – SSW and nodal plane II is trending WNW – ESE while, both are steeply dipping. The variance reduction per component varied from 62% up to 97%, indicating an excellent fit between observed and synthetic waveforms, while the DC percentage was 90.5% (CLVD 9.5%). The activated fault produced an Mw5.5 earthquake. Ap-

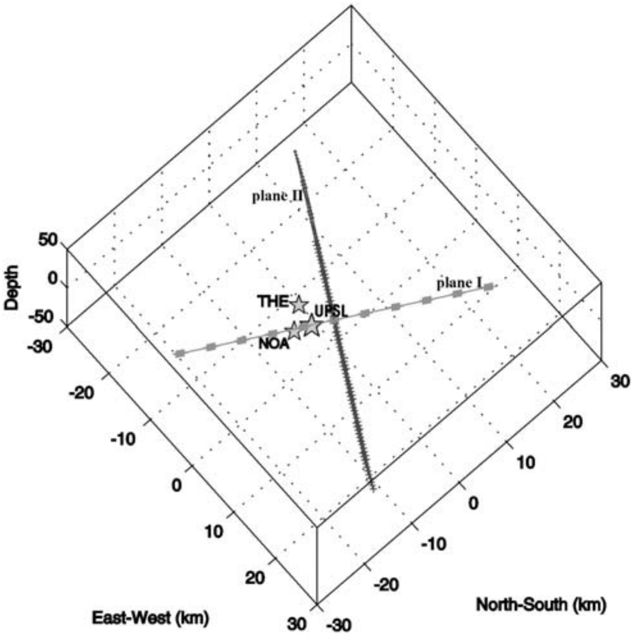

Fig. 5: Two nodal planes passing through the centroid, both according to the MT solution of this paper and the hypocenters: the one calculated in this paper - UPSL, National Observatory of Athens – NOA and Thessaloniki University – THE. Nodal plane I appears in gray line while nodal plane II, in black line.

plication of empirical relationship, according to Papazachos and Papazachou (1997), indicates a 10km fault length and 8km fault width.

The application of the moment tensor inversion method produced results slightly different than the previously published by Roumelioti et al. (2004) for the same event (strike:50^o, dip: 68^o, rake: -166^o).

Joint knowledge of centroid, MT solution (nodal planes) and hypocenter position is a key to identify the causative fault plane. This is the nodal plane that passes through centroid (C) and includes the hypocenter (H) (Zahradnik et al., 2008). The mainshock was investigated for the mutual position of the hypocenter (H) and the centroid (C).

4. H-C Method

The method is based on relative position of hypocenter (H), centroid (C) and nodal planes. Hypocenter (nucleation point) is determined by kinematic location. Centroid (the point approximating the dominant slip region) is determined as a part of the moment tensor (MT) retrieval, C is the position of the best match between observed and synthetic seismograms. The nodal planes I and II, passing through the centroid C, are determined by the strike, dip and rake of the optimum moment tensor. Then the fault plane can be identified as the nodal plane encompassing the hypocenter (Zahradnik et al., 2008).

The H-C method was applied for the mainshock using the hypocenter, which was proposed in this paper (UPSL) but also the ones by the Greek institutes (National Observatory of Athens – NOA and University of Thessaloniki – THE). The distribution (Fig. 5) shows consistency of the hypocenters with the nodal plane I (strike:209^o and dip:83^o). The UPSL hypocenter and NOA hypocenter both lay in the nodal plane I, while the THE hypocenter is located closer to nodal plane I also.

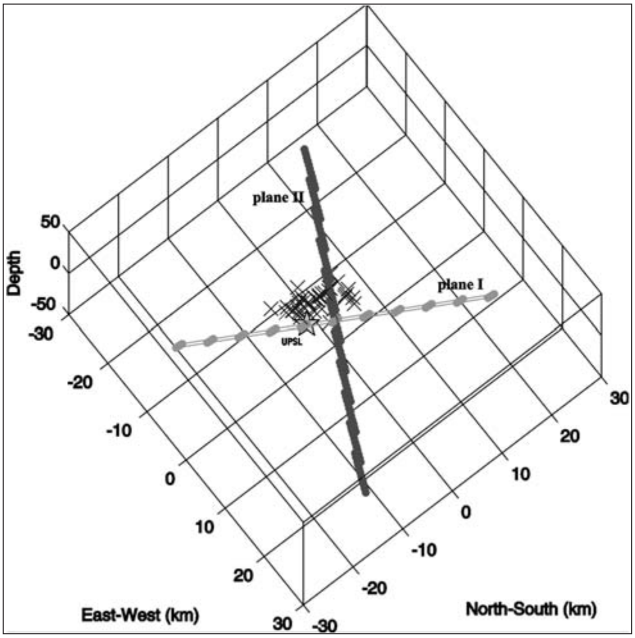

Fig. 6: Two nodal planes passing through the centroid, both according to the MT solution of this paper and the thirty eight relocated hypocenters.

Finally, the method was applied for the hypocenters produced by relocation of the combined data, from PATNET and microseismic network. Fig. 6 shows that the hypocenters distribution is consistent with nodal plane I. Furthermore, the best-fit plane for the relocated hypocenters was calculated which, pointed out a plane with strike=198^o and dip=87^o. This plane is in good agreement with nodal plane I.

5. Conclusions

A moderate magnitude earthquake occurred on 2 December 2002 close to the city of Vartholomio (Western Peloponnese). We located the mainshock using the available short period and broad band records. Several tests were carried out in order to decide the most appropriate crustal model and location parameters (starting depth, ratio Vp/Vs). The aftershock sequence was recorded by the permanent network PATNET and partially by a temporary microseismic network, which was installed in Vartholomio and surroundings. The aftershocks were located using the available records and a dataset of the most accurate hypocenters was relocated by double-difference method. The epicenters spatial distribution suggests a NNE-SSW trending fault of about 10km long. The cross- sections show that the hypocenters are distributed in an almost vertical plane of 8km width.

The moment tensor inversion was applied for the mainshock. The focal mechanism reveals a strike – slip fault; nodal plane I trending NNE – SSW and nodal plane II trending WNW – ESE, both dipping almost vertical. The aftershock sequence epicenters distribution favors the nodal plane I.

The H – C plot method was applied for the mainshock; the hypocenter calculated in this work as well as the hypocenters published by the Greek institutes NOA and THE favor nodal plane I. Finally, the H - C plot also indicates that the 38 events lie closer to the nodal plane I while, the distribution of the relocated hypocenters dataset fits a plane which also approximates nodal plane I.

The results of the analysis suggest that the activated fault was a nearly vertical strike - slip fault with dextral movement, trending NNE – SSW, which is in consistence with the evidence from tectonic studies in the area. The fault length was estimated to be 10km and the width up to 8km.

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