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RECENT SEISMIC ACTIVITY IN CENTRAL GREECE REVEALING LOCAL SEISMOTECTONIC PROPERTIES

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Abstract

The December 2008, M=5.2 earthquake occurred in the Voiotikos–Kifissos basin near the town of Amfikleia in Central Greece and was followed by an intense sequence with hundreds of earthquakes. Mainshock source characteristics derived from the recordings of the Greek National Seismological Network are consistent with previous known earthquakes as well as with the current nearly N–S extensional regime. The adequate azimuthal coverage and the calculated time residuals at each seismological station ensure high location accuracy, whereas the stations operated close to the seismic excitations constrained 80% of the focal depths between 8 and 12km. Distances from the mainshock epicenter to the 10 closest seismological stations vary from 15 to 75 km. Hypoinverse and HypoDD were used for locations, and FPFIT was used for fault plane solutions of events with an adequate number of clear first arrivals. The hypocenters and focal mechanisms illuminate a ≈10km–long fault zone striking nearly E–W with oblique normal faulting and a small left lateral component. The Voiotikos–Kifissos basin is bordered in the south by two left–stepping en echelon segments known as the Pavliani fault zone and the Parnassos detachment, which strike NW and dip NE. In our preferred interpretation, the Amfikleia mainshock ruptured a previously recognized south–dipping fault antithetic to the basin border faults. This fault may be associated with the left step on the border fault, which would be releasing if that fault had a sinistral component.

Key words: *Central Greece, microseismicity, relocation, active structures.*

1. Introduction

Small and moderate magnitude earthquakes offer an opportunity to explore the active tectonic regime without causing damage. Earthquakes can 'illuminate' active faults, not only by specifying their location, but also their geometry and kinematics, or the way they move. A powerful way to map active faults is to combine earthquake data with good resolution and structural data from surface investigations. Central Greece is considered an area of high seismicity and has experienced large and damaging earthquakes, both within and before the instrumental era (Table 1 and Figure 1). Central Greece is characterized by extensional normal faulting, which connects strike slip faulting in the North Aegean trough along the continuation of the NAF into the Aegean Sea and in the Ionian Is-

Table 1. Historical data of large events in the broader area of our interest (Papazachos and Papazachou, 2003).

Date	Latitude (ϕ^o_N)	Longitude (λ^o_E)	Magnitude
–426	38.85	22.78	7.0
–226	38.60	22.70	6.4
551	38.80	22.80	6.8
04/10/1740	38.90	22.60	6.6
27/04/1894	38.56	23.24	7.0

lands region. Earthquake data are essential in testing hypotheses in such complex tectonic systems.

The purpose of this study is to examine the 2008 aftershock sequence in the Voiotikos–Kifissos basin and illuminate the active structure in the area. We use the recordings from the 10 closest seismological stations in order to determine the focal parameters with maximum possible accuracy. The spatial distribution of aftershock hypocenters along with the fault plane solutions of the main shock and of the largest aftershocks is combined in order to constrain the geometry and the kinematics in the region.

2. Seismotectonic setting

Central Greece is in the back–arc area of the Hellenic Arc and has experienced extension since the Early Miocene (Le Pichon and Angelier, 1978; Mercier et. al., 1989). This extensional deformation has resulted in many fault–bounded grabens, the most important striking WNW–ESE, such as the Sperchios River graben, the Maliakos Gulf, the Corinthiakos Gulf and the South Evoikos Gulf. These first order morphotectonic features, are emblematic of many other fault controlled basins, including the North Gulf of Evia and the Voiotikos–Kifissos basin in our study area. The WNW–ESE striking Arkitsa–Kammena and Kallidromon fault zone are the main border faults of these basins, respectively, on their SW side (Fig. 1). These fault zones belong to the Sperchios Fault system, which represents an extensional zone between the Cephalonia Transform Fault and the North Anatolian fault (Kilias et al., 2008). Cross–cutting relationships and other geologic data suggest a chronology of fault activity leading to the currently active (late Quaternary) faults. Examples of the latter include the Arkitsa–Kammena and the Hyampholis faults, intersecting and yet active, the later being a WSW–ENE striking fault, which is considered that acted as a barrier in the propagation of the 1894 earthquake rupture of the Atalanti f.z. (Ganas et al., 1998). The Kallidromon fault zone (Fig. 1), however, may be inactive (Palyvos et al., 2006).

The Amfikleia sequence

On the 13th of December 2008 (08:27.19 GMT time) an earthquake of M=5.2 occurred in the Voiotikos–Kifissos Basin near the town of Amfikleia in Central Greece (black triangle in Fig. 2). The Voiotikos–Kifissos is a composite half graben bordered on the SW side by the NE–dipping Pavliani–Parnassos fault (Kranis & Papanikolaou, 2001). This fault comprises three en echelon segments stepping to the left. The longest SE segment has been characterised as a detachment, but its trace is remarkably linear, suggesting a steep dip (Fig. 1). The footwall of this fault rises to the Parnassos Mountains range. On the NE side, the basin is bordered by the Kallidromon Mountains, which are on the footwall side of a set of NE–dipping faults bordering the submerged Evia Basin. The dominant faulting in the study area is clearly NW–SE trending and dipping to the north with normal dis-

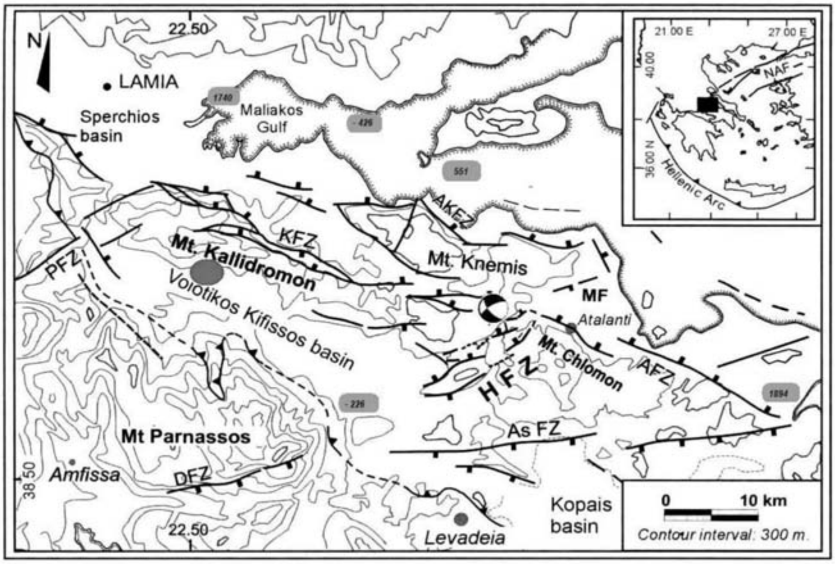

Fig. 1: Regional tectonic setting of Central Greece (modified from Kranis et al., 2001). The area of the seismic sequence occurrence is shown with the red ellipse. Large earthquakes that occurred in the past are shown with the orange rectangles. Thick hachured lines: Normal faults and/or fault zones; thick lines with triangles: alpine thrusts. HFZ: Hyampholis, AFZ: Atalanti, AKFZ: Arkitsa–Kammena Vourla, KFZ: Kallidromon, AsFZ: Aspledon, PFZ: Pavliani, DFZ: Delphi, MF: Megaplatanos fault. Focal mechanism solution from Hatzfeld et al. (1999).

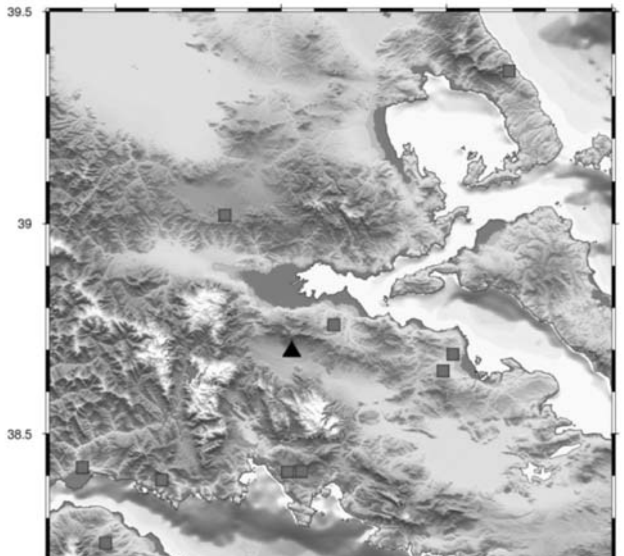

Fig. 2: Mainshock (black triangle) and location of the 10 closest seismological stations (red squares).

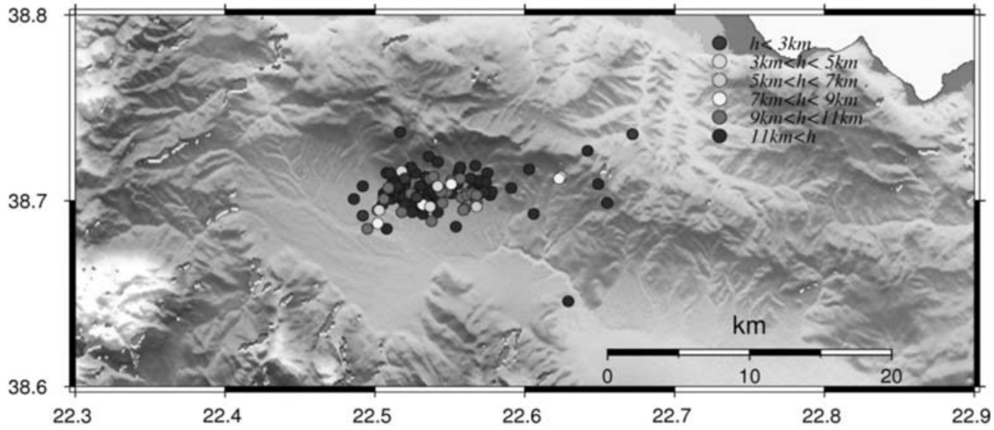

Fig. 3a: Spatial distribution of the epicenters according to their focal depths using Hypoinverse.

placement. Secondary features particularly important to this study include a systematic left–lateral component on many of these faults (REF) and secondary south–dipping faults at the northern end of the Voiotikos–Kifissos Basin.

2.1 Focal parameters determination

The 2008 Amfikleia mainshock was followed by an intense aftershock sequence. This study analyzes all the aftershocks of the first two days (13th and 14th of December) as recorded by the 10 closest seismological stations of the Greek National Seismological Network (red squares in Fig. 2). The 1d velocity model used was derived from an earlier study in the same area using the travel–times curves from a temporary seismological network that was operating for a six months period in 2005 (Karakostas et al., 2006). A V_p/V_s = 1.76 was calculated with the Wadati method, as well as time delays (station corrections) for each of the ten seismic stations the recordings of which were used in the analysis. With the term 'time delay' we mean the difference between the theoretical and observed travel time from the hypocenter of the earthquakes until the seismological station. A total of 116 earthquakes were processed by the Hypoinverse (Klein,2002) computer program, resulting in the epicentral distribution in Fig. 3a, and then they have been relocated with HypoDD (Waldhauser, 2001) (Fig. 3b).

The improvement in resolution can be appreciated by comparing statistical parameters of the hypocenters obtained by these procedures. Histograms in Figure 4 compare the root mean square error between observed and predicted arrival time (RMS), the calculated error in epicentral coordinates (ERH) and the error in focal depth (ERZ). After the location process with Hypoinverse, all RMS values are smaller than 0.36 sec, while 75% of them are smaller than 0.2 sec. When the same dataset was relocated with HypoDD, the RMS values are concentrating in the 0.1–0.26 sec range. The epicentral errors that derived from Hypoinverse have values smaller than 0.8 km. More than 70% of these values are even smaller than 0.4 km. After the relocation process with HypoDD these errors have values smaller than 0.7 km, with 90% of the events having values under 0.4 km. The maximum in this distribution is appearing between the values 0.2–0.4 (Hypoinverse) and 0.1–0.2 (HypoDD). As for the errors in focal depths, all the earthquakes have errors less than 5.5 km, with 80% of them having values even less than 2km with HYPOINVERSE. After the relocation with HypoDD, 90% of the events have erz smaller than 1km.

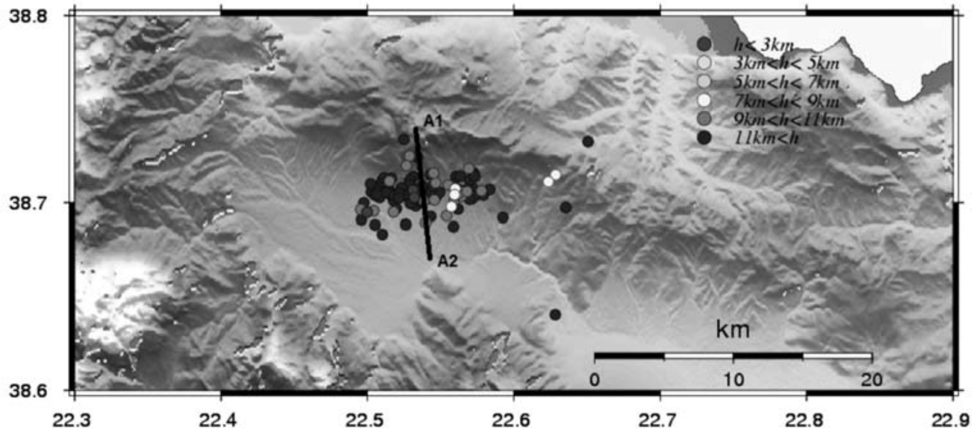

Fig. 3b: Spatial distribution of the epicenters according to their focal depths using HypoDD.

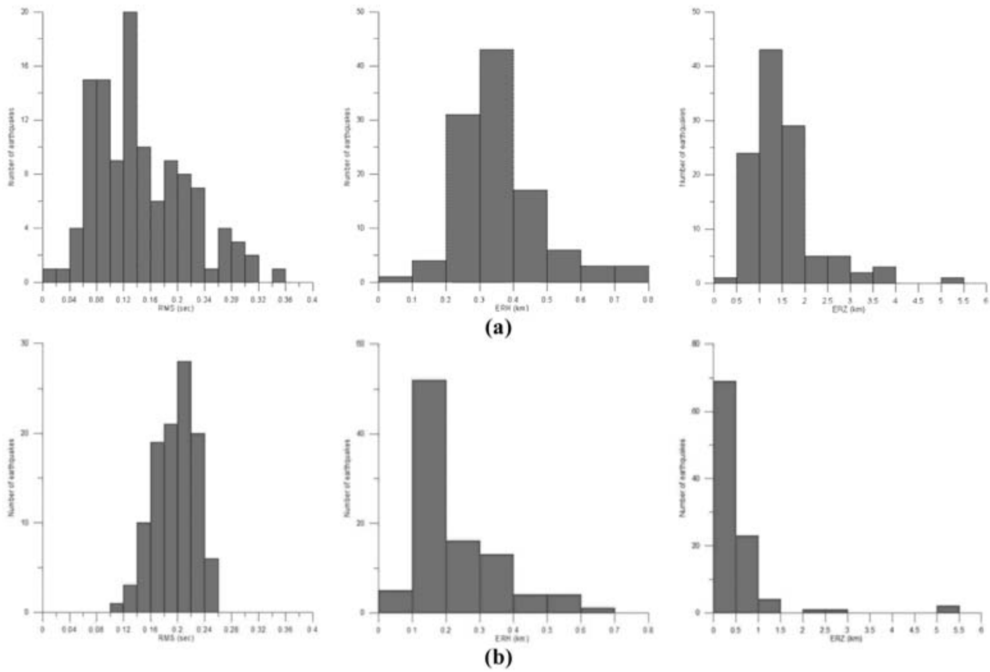

Fig. 4: Histograms of the root mean square error in the occurrence time (rms), epicentral determination error (erh) and depth determination error (erz), of hypocenters in this study. (a) Hypoinverse results, (b) HypoDD results.

2.2 Focal depths

The distribution of the hypocenters relocated by HypoDD is more concentrated than the distribution of hypocenter from HYPOINVERSE which is symptomatic of greater relative location accuracy. The epicentral distribution is tighter in Fig. 3b than Fig. 3a. and clearly shows a WSW–ENE striking source zone, in agreement with the focal mechanisms. The focal depths calculated using Hypoinverse

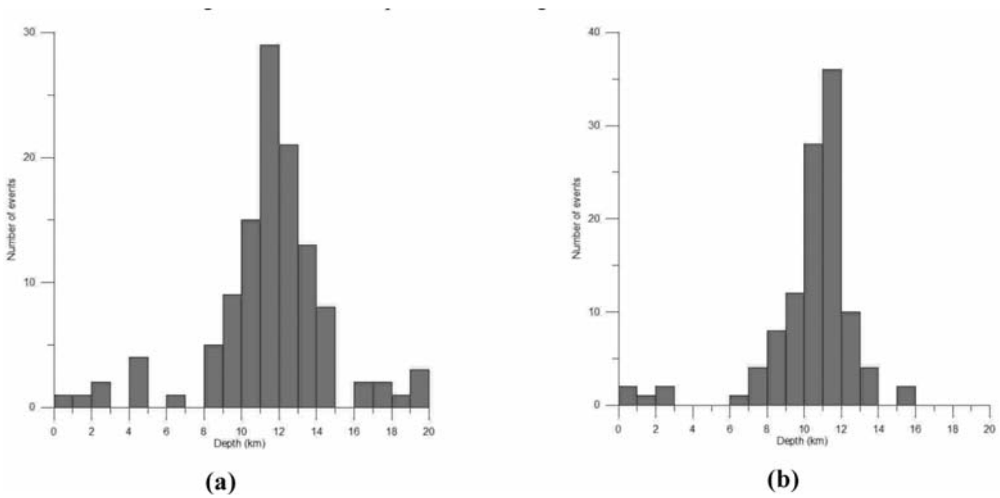

Fig. 5: Focal depths distribution of (a) Relocated events using Hypoinverse, and (b) Relocated events using HypoDD algorithm.

were found between 0 and 24 km, with most of them between 8 and 15 km (Fig. 5a). The same data processed with HypoDD yielded a seismogenic layer significantly thinner, with the majority of the events occurring between 9 and 12 km (Fig. 5b).

The magnitudes of the earthquakes in this study were calculated from the maximum amplitudes in the two horizontal components of each station of the regional network. Waveforms from these stations were converted to Wood–Anderson recordings using simulation filters. The maximum amplitudes in these simulated recordings weighted for distance yielded local magnitudes for each recording. The mean value of these magnitudes was adopted as the magnitude for each event.

2.3 Fault plane solutions determination

Fault plane solutions were determined with the FPFIT algorithm (Reasenberg & Oppenheimer, 1985). This program requires at least six first arrivals of the P waves, and the mainshock and 5 aftershocks fit this criterion (Table 2 and Figure 7). The steeper nodal planes in these solutions are very similar, striking nearly E–W and dipping to the south steeply, also including a small sinistral component. We consider this result quite robust. Collectively, our results indicate normal faulting with a small sinistral strike–slip component. The focal mechanism we obtain for of the mainshock is in good agreement with the focal mechanisms for the same event proposed by AUTH (94/77/-76), by NOA (92/69/-64) and Global CMT Solution (94/67/-85).

2.4 Spatial distribution

Figure 7 (a–c) exhibit cross sections perpendicular (A1–A2) to the almost E–W striking spatial distribution of the sequence (as shown in Fig 3b). The distribution of hypocenters is narrow in both depth and N–S direction. This distribution is consistent with the focal mechanism, but cannot readily discriminate whether the source fault is represented by the north or south dipping nodal planes. We propose the mainshock rupture to be on the steep south–dipping plane for a number of reasons listed below, which are based primarily on the relationship of the earthquake parameters and the pattern of faulting around the Voiotikos–Kifissos Basin.

Table 2. Strike, dip and rake of the steeper nodal planes for the mainshock and 5 aftershocks obtained with FPFIT. The first four rows show the parameters for the mainshock from all available sources (As mentioned in the text).

Date/Time	Magnitude	Strike	Dip	Rake
13/12/2008 08:27:19 (FPFIT)	5.2	92	70	-70
13/12/2008 08:27:19 (AUTH)	5.2	94	77	-76
13/12/2008 08:27:19 (NOA)	5.2	92	69	-64
13/12/2008 08:27:19 (Global CMT)	5.2	94	67	-85
13/12/2008 10:36:46	2.8	97	68	-75
13/12/2008 11:40:33	3.0	92	67	-81
13/12/2008 11:52:52	4.0	94	60	-82
13/12/2008 14:01:20	3.0	94	57	-63
13/12/2008 16:24:32	2.6	91	54	-80

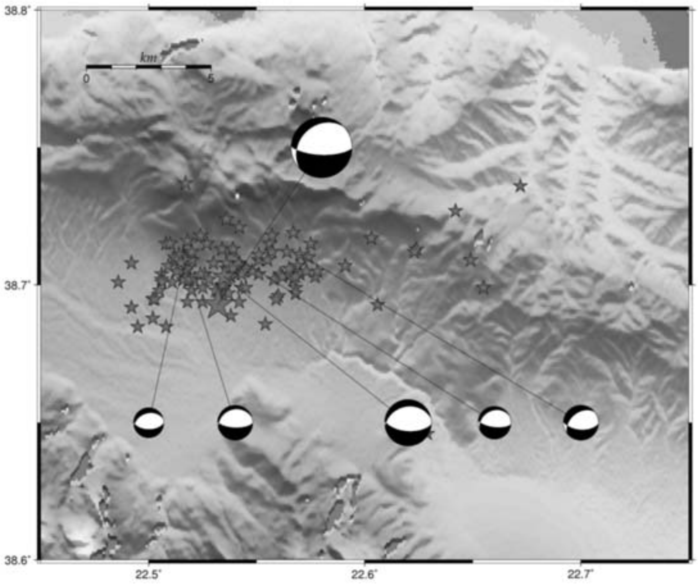

Fig. 6: Focal mechanisms of the main event and the 5 largest aftershocks as they were derived from the use of FPFIT.

A fault striking E–W and dipping south is mapped on the NW end of the Kallidromon Range (as described by Kranis, 2002). This fault would intersect the hypocenters if the dip was ≈60°, which is within the uncertainty of the focal mechanism for the mainshock.

The main border fault of the basin could also intersect the hypocenters, but the strike of the fault is clearly inconsistent with both the hypocenter distribution and with the north–dipping nodal planes of the focal mechanisms (Fig. 6).

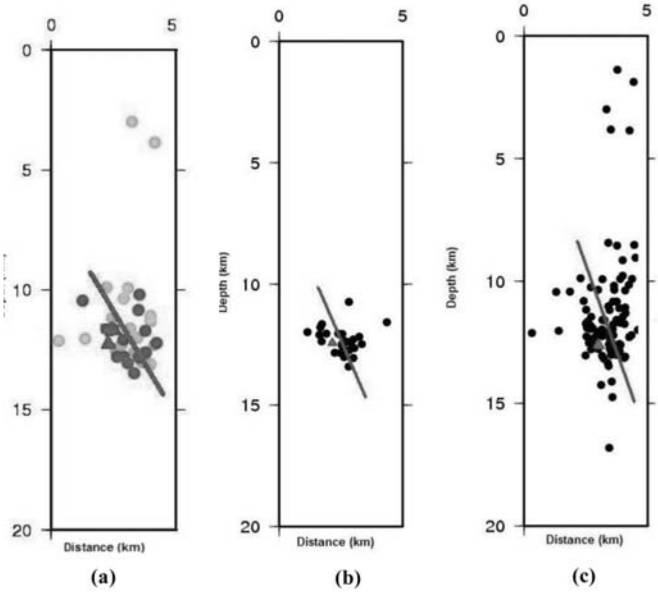

Fig. 7: Cross sections perpendicular to the strike of the spatial distribution of the earthquakes. (a) green hypocenters are earthquakes that occurred in the first two hours of the excitation while red ones indicate the hypocenters in the next six hours, (b) hypocenters of the largest events (min magnitude M=2.0) and (c) hypocenters of all the events. The red triangle in all three cross sections shows the hypocenter of the mainshock.

3. Conclusions

The distribution of faults around the Voiotikos–Kifissos basin, the southwestward dip of syntectonic strata in the basin, and the morphology of the uplifted blocks suggest that the Parnassos fault on the SW side of the basin is the main border fault. This implies that the south–dipping fault at the north end of the basin is a secondary antithetic fault cut by the border fault. The earthquake sequence could therefore have occurred near the intersection between these faults. While the mainshock was probably on the south–dipping antithetic fault, as we propose, some of the aftershocks may have originated on the main NE–dipping border fault. This may account for a hypocenter distribution that does not clearly outline a single fault plane. The antithetic fault proposed to be the source of the mainshock faces a major left step on the main border fault of the basin. This left step could be associated with localized extension additional to the regional pattern of extension, if the border fault includes a sinistral component. This is likely, based on sinistral components on other faults in the region, and on the general pattern of N–S extensional tectonics in central Greece applied to the NW strike of this fault.

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The GMT system (Wessel and Smith, 1998) was used to plot the figures. Geophysics Department contribution 755.

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