SEISMICITY PATTERNS BEFORE THE OCCURRENCE OF THE 13 MAY 1995, M6.6 KOZANI-GREVENA EARTHQUAKE

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Abstract

The 13 May 1995, M6.6, earthquake that occurred in the area between Grevena and Kozani (Northern Greece), and seriously affected these two prefectures, was one of the largest in Greece during the decade of nineties. The available information on the historical seismicity shows that the study area is characterized by low seismic activity. During the last four hundred years four earthquakes with magnitude M^{3}6.0 occurred in the broader area with intervening times of the order of 100 years. Their epicenter's distribution appears to follow the valley of the Aliakmon river. Taking into account the seismic activity around the mainshock before its occurrence and applying the "negative earthquake" model (Bowman and King, 2001; King and Bowman, 2003) the calculated 'pre-stress' field revealed that the earthquakes with epicenters located in areas with positive stress changes have higher occurrence rate for the last 17 years in comparison with the earthquakes located in areas of negative stress changes. This observation, combined with other premonitory patterns, supports the idea that seismic activity in a broad area around the epicenter of a future earthquake is associated with the preparation of the future main event.

Introduction

The 13 May 1995 Kozani Grevena earthquake struck an area of northern Greece with low historical and instrumental seismicity. The epicentral area is located at the western margin of internal Hellenides, mainly consisting from geological structures trending NW-SE. At the southern part of the artificial lake Polyfytos (fig. 1) there is one of the most prominent active structures in western Greece, the ENE-WSW striking Servia fault. The best evidence for tectonic surface ruptures after the earthquake was observed south of the Vourinos ophiolite massif, on the Paleochori fault, which crosses the sediments of the Mesohellenic Trough, in the WSW prolongation of the Servia fault (Hatzfeld et al., 1995; Pavlides et al., 1995; Meyer et al., 1996). The accurate location of several hundred aftershocks using the recordings of a dense seismological network that installed in the area after the mainshock occurrence (Hatzfeld et al., 1995, 1997) and the Harvard CMT solution show normal faulting (rake=-97°) on a 243° trending fault, dipping 43° to NNW. Seismicity is restricted between 5 and 15 km.

It is well known that large earthquakes are in many cases preceded by variations in regional seismicity. Additionally, it is broadly accepted that seismicity is strongly influenced even by small changes in the static stress field due to the coseismic slip of previously occurred earthquakes and the long-term tectonic loading. The aim of the present work is to study the spatial and temporal variation of the moderate size seismicity in association with static stress changes before the 1995 mainshock, going back in time as long as the data permit.

Seismic activity

Information on historical seismicity in western Macedonia is available since the end of the 17th century (Papazachos and Papazachou, 2002 and references therein). The epicenters of all the known earthquakes with M^{3}6.0 are shown on the map of figure (2). The first known earthquake occurred in 1695 (M=6.5) and the macroseismic

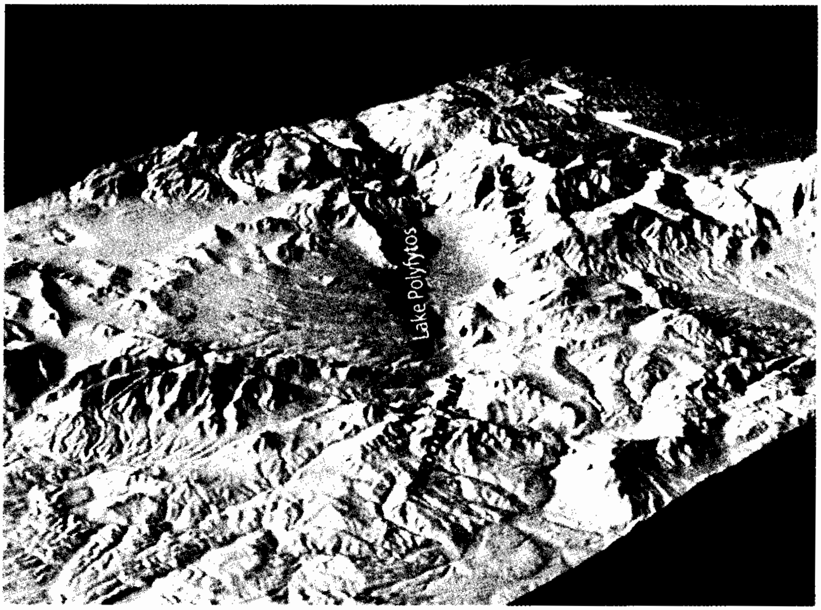

Fig. 1. Geomorphological map of western Macedonia. Servia fault, the most prominent tectonic feature in the area, bounds the southern part of lake Polyfytos. The Paleochori fault, which is the WSW prolongation of the Servia fault, is associated with the aftershock activity of the 13 May 1995 mainshock.

information revealed that it was located near the 1995 mainshock. The next strong earthquake occurred fourteen years later (1709, M=6.0) at the northwestern part of the area and caused damage to the fortification of Kastoria (Ambraseys and Finkel, 1999). This was the first one of four earthquakes that occurred from NW to SE along the banks of the Aliakmon river, which in the area follows generally NW-SE direction. The second one in this series (1812, M=6.5) also affected the city of Kastoria. The third one (1894, M=6.1) occurred near Siatista, more southwesterly while the last one is the earthquake of 1995. These four earthquakes cover a period of about four centuries with time interval between their occurrences almost equal to one hundred years. From the area where the 1695 and 1995 earthquakes occurred, the river changes direction from NW-SE to SW-NE and the seismicity seems to follow this change with two earthquakes in Veria (900, M=6.0 and 1211, M=6.5). Karakaisis et al. (1998) studied the seismicity of western Macedonia and found that during the 20th century it is mainly concentrated along the Aliakmon river as well as in clusters close to the margins of some minor grabens. They also observed that in a rectangular area in the vicinity of Polyfytos artificial lake, no earthquake occurred for the period 1910-1980, while several moderate magnitude ($M^{3}4.0$) earthquakes occurred since 1981. They attribute this change of the seismic activity to the filling of the Polyfytos artificial lake, which completed in 1974.

Seismicity Patterns

A number of publications have suggested that seismicity over a wide region appears to be modified before a major event (Bowman et al., 1998; Jaume and Sykes, 1999; Papazachos and Papazachos, 2000). In recent years there is an increased interest in observations of accelerating moment release before large earthquakes. Bowman and King (2001) linked two previously unre-

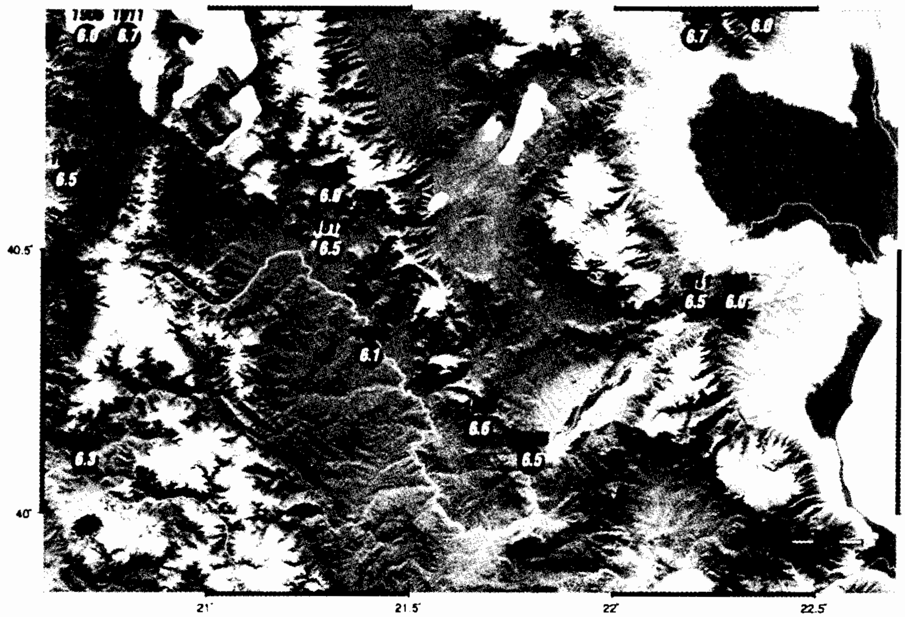

Fig. 2. Epicenters of all the known historical and instrumental earthquakes of $M^3$6.0 in western Macedonia (from Papazachos and Papazachou, (2002).

lated subjects: Coulomb stress interactions and accelerating seismicity before large earthquakes. They illustrated their model using seismicity in California, however, as they pointed out the technique can be applied to any tectonically active region.

Many studies have demonstrated that the history of seismicity in a region strongly influences the location of subsequent strong events. Such works include the observation of Coulomb stress interactions and stress shadows following great earthquakes. According to these studies, stress must accumulate not only on the fault itself, but also in a large region surrounding the fault prior to a large earthquake. One method to define the stressed volume is to combine historical seismological data with the long-term stress buildup due to the slow movement of the tectonic plates. An alternative way to approach the problem is to calculate the stress field required to move the fault with the orientation, displacement, and rake observed for the main shock (Bowman and King, 2001). The stress existing before rupture on a fault of finite length can be determined by calculating the stress that results from slipping the fault backwards by the amount that it moved in the earthquake (Savage, 1983; Matsuura et al., 1986). Bowman and King (2001) observed that the radius of the critical region found using this method scales with the magnitude of the associated large event.

In the present work static stress changes due to a "negative earthquake" were calculated. Thus, it was considered that before the occurrence of the 13 May 1995 mainshock, the stress distribution was this one that is produced by a coseimic slip of the opposite sense. The Harvard CMT solution is considered here (strike=243°, dip=43°, rake=97°) and for the model, thrust faulting with slight sinistral horizontal component (rake=83°), is considered on a 243°-striking fault dipping 43° to the NNW. Additionally, the aftershock distribution of the period 19-25 May 1995, based on the recordings of a dense portable local seismological network (Hatzfeld et al., 1997), was taking into account to define the dislocation plane. This plane was considered to be rectangular with a length equal to 26 km. It is extended from 5km – 14 km

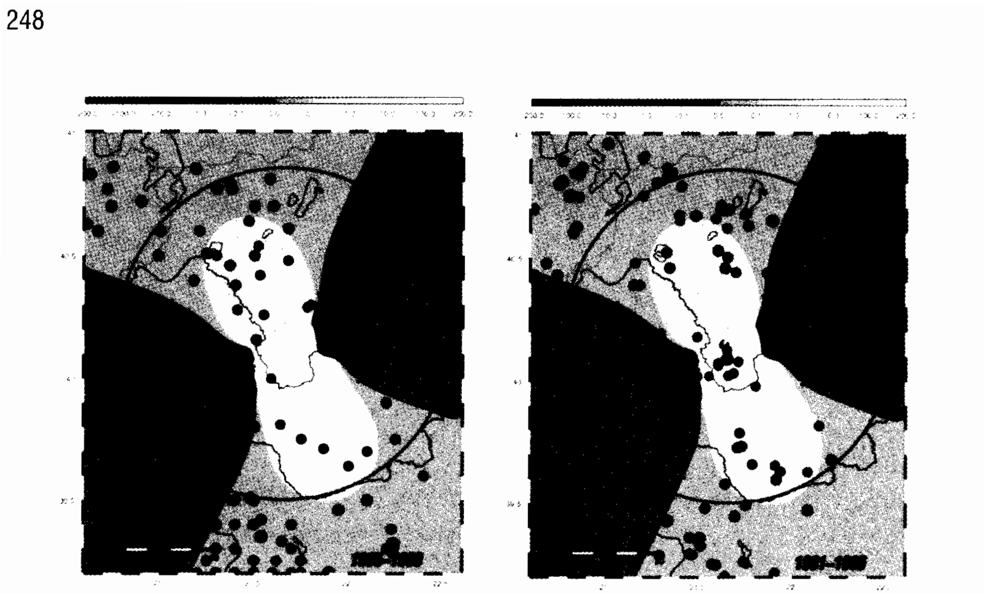

Fig. 3. Stress changes calculated according to the "negative earthquake" model along with the epicenters of the magnitude M^{3}4.0 earthquakes for two different periods: (a) 1965–1980, (b) 1981–1995. Inside the area with radius 75 km around the mainshock epicenter, the random distribution of the epicenters in the first period is followed by an increase in the seismicity rate in "positive" areas and a respective decrease in the "negative" areas, during the second period.

beneath the earth's surface, having downdip width equal to 14 km.

One more parameter necessary for the stress calculations is the slip on the dislocation plane. The slip distribution on a fault of a main rupture is complicated and not well known. The knowledge of the detailed slip distribution is necessary to define the stress changes on the fault and very close to it. Nevertheless, the shape of this distribution in the broader area around the fault is not changed if an average slip is taking into account. Since the aim of the present work is the study of the distribution of the seismicity before the main shock in a broad area around the fault, an average slip value is adequate. Using the fault dimensions (26 x 14 km^2), the Harvard CMT seismic moment (M_0=7.64*10^{25} dyn*cm), and considering the rigidity m=3.3*10^{11} dyn/cm^2, a slip equal to u= 50 cm was estimated. Stress field calculated on a horizontal planar surface at the depth of 9 km, which is the mid of the seismogenic layer. The apparent coefficient of friction was considered equal to 0.4 and the Poisson ratio equal to 0.25.

The calculated stress field (fig. 3a,b) is not permanent but holds only during the preparation stage of the ensuing earthquake. King and Bowman (2003) have shown that during the seismic cycle the distribution of seismicity in the vicinity of the main fault depends on the stress distribution and differs in different periods. Immediately after the main shock the seismicity should be located in completely different areas than in the prior to the earthquake stage. On maps including the calculated stress field, the epicenters of the earthquakes with magnitude M^{3}4.0, which occurred in a distance of 75 km around the epicenter of the main shock, were plotted for different time periods starting from 1965. The radius of this circular area is almost three times the fault length. It was found (fig. 3a) that until 1980, the epicenter distribution is rather random and there is no tendency of the earthquakes to prefer the stress enhanced, according to the model, areas. A possible explanation is that until 1980, was not yet formed as the model shows. Since 1981, until the occurrence of the main shock in 1995 (fig. 3b) the epicenter dis-

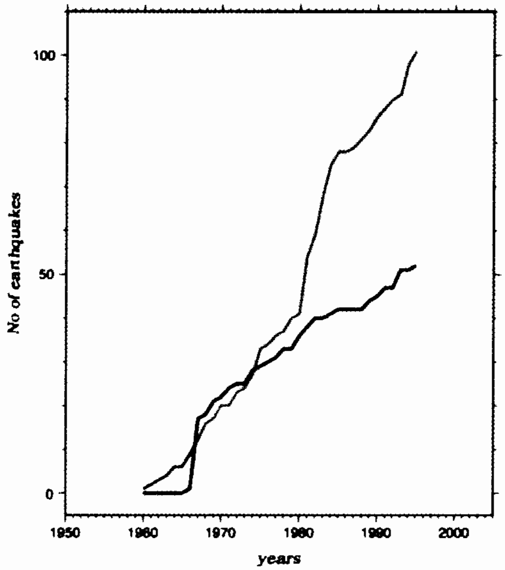

Fig. 4. Seismicity rates of the earthquakes with M^{3}4.0, which occurred in a distance of 75 km from the mainshock epicenter. Red line represents earthquakes in "positive" areas while the blue one represents earthquakes in "negative" areas.

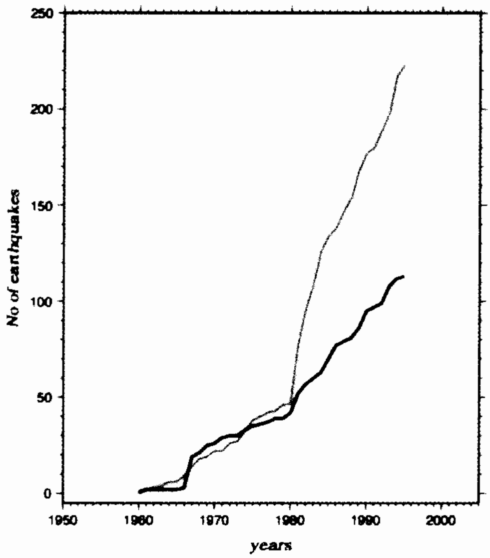

Fig. 5. Seismicity rates as in fig. 4, for the earthquakes of magnitude M^{3}3.5.

tribution shows that they almost exclusively occurred in the areas characterized by positive values of the stress changes. A similar behavior is observed for the epicenters of the lower magnitude (M^{3}3.5) earthquakes, although not shown here.

Another way to present the seismicity pattern described above is to plot the cumulative annual number of the earthquakes, which are inside the circle of 75 km radius for both areas of positive and negative stress changes (fig. 4). For this reason the static stress change due to the "negative earthquake" model at the focus of each earthquake was calculated. Gray line represents the cumulative number of the earthquakes with magnitudes M^{3}4.0, which have their epicenters in areas of enhanced stresses, while black line was used for the earthquakes of the same magnitude, which occurred in areas with negative stress changes. It is clearly observed that for the period 1965-1980, the rate of seismicity is similar in the two regions, while since 1981 the seismicity rate increases in the 'positive' areas. In the areas of negative stress changes the slope of the curve is rather decreased since 1981 in comparison with the previous period. The same results are obtained using the earthquakes of magnitude M^{3}3.5 (fig. 5). The two areas have the same level of seismic activity during the first stage (1965-1980). The slope of the positive (gray) curve is considerably higher than the slope of the negative (black) curve since 1981. It is likely that the increasing rate observed for both curves in this last case, is due to the lower level of the completeness threshold. However, it should be noted that what is compared here, is the rate of seismicity in two regions for the same time period. The curves clearly show that during the first period the rates of seismicity are similar, while in the second period the seismicity is much higher in the area of the positive stress changes according to the model.

It is not so clear if the data used here are complete for the whole time period. The cumulative number of earthquakes for different periods does not give clear results. Probably this is due to

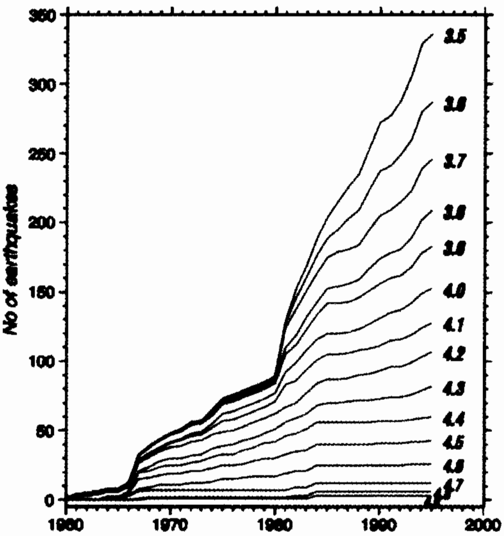

Fig. 6. The annual rate of the earthquakes for different magnitudes from 3.5 to 4.9 for the period 1960–1995 in the area of 75 km around the mainshock.

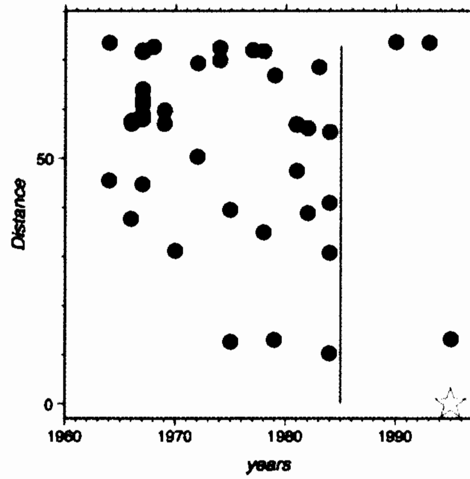

Fig. 7. Space–time plot of the epicenters of the earthquakes with M³4.5 according to their distance from the epicenter of the mainshock.

the low level of seismicity in association with the small size of the area and the short time span and magnitude range. The annual rate of the earthquakes for different magnitudes from 3.5 to 4.9 (fig. 6) shows that there is an abrupt increase in the number of earthquakes since 1981 for the earthquakes of magnitudes 3.5 to 3.9. This is obviously due to the operation in Northern Greece of the telemetry seismological network of the Department of Geophysics of the Aristotle University of Thessaloniki, which decreased considerably the level of detectability in Northern Greece. For earthquakes of larger magnitudes, especially for magnitudes M³4.2, the rate seems to be stable since 1967. Although the seismicity is low in the area, it is remarkable that no earthquakes with M³4.7 occurred in the area for the period 1985-1995, that is, ten years before the mainshock.

Finally, the behavior of the stronger earthquakes, which occurred in the same area as before, was studied. Fig. 7 is a space-time plot of the epicenters of the earthquakes with M³4.5, according to their distance from the epicenter of the mainshock. Until 1984, when an earthquake of magnitude M=5.5 occurred, seismicity is continuous and then it stops abruptly for ten years. This observation is in agreement with the results of Papazachos et al. (2004), who recognized a decelerating seismic deformation in the close vicinity of the mainshock. In 1964, the closer epicenter to the mainshock, is in a distance of about 50 km. The distances of the closer to the mainshock epicenters become shorter with time. The epicenter of the 1984 earthquake, the last one before the ten years quiescence, is located only 10 km far from the mainshock. A similar observation was made before the occurrence of the Sumatra M=9.3 earthquake on Dec. 26, 2004 (Karakostas, 2005). In this latter case a shift of the epicenters of the magnitude M³7.0 earthquakes towards the mainshock was observed during the 20th century. This progressive approaching of the preearthquake activity to the future mainshock epicenter is considered as a consequence of the stress reestablishment during the earthquake cycle (King and Bowman, 2003).

Discussion and Conclusions

The general features of the spatial distribution of seismicity in a broad area around the epicenter of the magnitude M=6.6 earthquake of the May 13, 1995 are studied in this paper. The available historical and instrumental earthquakes show a region of low seismicity. All the known strong ($M^{3}6.0$) earthquakes are located along the Aliakmon river, showing its strong relationship with the active tectonics in the area.

Application of the "negative earthquake" model revealed that during the last stage of the preparation of the mainshock, seismicity strongly prefers areas of positive stress changes. This pattern observed in a broad area with radius 75 km around the epicenter, which is almost three times the fault length. A similar behavior of seimicity has also been revealed before the occurrence of the large (M=7.7) Chi-Chi earthquake in 1999 (Karakostas et al., 2004) in a region with radius 210 km around the epicenter, which also is almost three times larger than the 78 km fault length.

For purposes of seismic hazard assessment, it is important to define the time of the ensuing earthquake. In this paper, no effort was made and probably the study of several earthquakes is needed to find such relationship. Nevertheless, taking into account the Kozani and the Chi-Chi earthquakes, it seems, that the preparation stage is proportional to the magnitude of the mainshock. In particular, for the magnitude M=6.6 earthquake, the characteristic pattern lasted for about 15 years, while for the magnitude M=7.7 earthquake, this pattern appeared about 50 years before the mainshock.

The obtained results are a combined application of the two fields of study, which have been gaining increasing attention from the seismological community. Static stress interaction between earthquakes and accelerating or decelerating moment release before large earthquakes. Stress interaction helps to discriminate the areas of different behavior of seismicity and gives a physical explanation to the observed pattern. Using this model the preerthquake activity is determined as the consequence of the processes that lead to the mainshock occurrence.

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ΕΞΕΛΙΞΗ ΤΗΣ ΣΕΙΣΜΙΚΟΤΗΤΑΣ ΠΡΙΝ ΤΗ ΓΕΝΕΣΗ ΤΟΥ ΣΕΙΣΜΟΥ ΤΗΣ 13ΗΣ ΜΑΪΟΥ 1995, M=6.6 ΣΤΗΝ ΠΕΡΙΟΧΗ ΚΟΖΑΝΗΣ – ΓΡΕΒΕΝΩΝ

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Περίληψη

Ο σεισμός με μέγεθος M=6.6, που έγινε στις 13 Μαίου 1995 στην περιοχή Γρεβενών και Κοζάνης και έπληξε σημαντικά τους δύο νομούς ήταν ένας από τους ισχυρότερους στον ελληνικό χώρο στη διάρκεια της δεκαετίας του 1990. Οι διαθέσιμες πληροφορίες της ιστορικής σεισμικότητας δείχνουν ότι ο σεισμός αυτός έγινε σε ένα χώρο χαμηλής σεισμικής δραστηριότητας. Κατά τα τελευταία τετρακόσια χρόνια έγιναν στην ευρύτερη περιοχή τέσσερις ισχυροί σεισμοί με μέγεθος M³6.0, με περίοδο επανάληψης περίπου 100 έτη. Η χωρική τους κατανομή φαίνεται να ακολουθεί την πορεία του Αλιάκμονα ποταμού. Λαμβάνοντας υπόψη τη σεισμική δραστηριότητα η οποία προηγήθηκε του κύριου σεισμού

στην ευρύτερη περιοχή και υπολογίζοντας το πεδίο τον τάσεων πριν τη γένεση του κύριου σεισμού, με εφαρμογή του μοντέλου του «αρνητικού σεισμού» (Bowman and King, 2001; King and Bowman, 2003), αποκαλύφθηκε ότι στη διάρκεια των τελευταίων 17 ετών, ο ρυθμός γένεσης των σεισμών με επίκεντρα σε περιοχές θετικών μεταβολών της τάσης, είναι μεγαλύτερος σε σύγκριση με τους σεισμούς που γίνονται σε περιοχές αρνητικών μεταβολών της τάσης. Η παρατήρηση αυτή, συνδυασμένη με άλλα πρόδρομα φαινόμενα, ενισχύει την άποψη ότι η σεισμική δραστηριότητα σε μια ευρεία περιοχή γύρω από το επίκεντρο ενός ισχυρού μελλοντικού σεισμού συνδέεται με την προετοιμασία γένεσης του σεισμού αυτού.