

CHARACTERISTICS OF SEISMIC EXCITATIONS IN CORINTH GULF (GREECE)

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Abstract

Seismic excitations occur as mainshock-aftershock sequences (MS-AS) encompassing a strong event called mainshock with the largest magnitude in the set, or as earthquake swarms (ES) when a distinctive main event is absent. In regions as the gulf of Corinth, where active deformation is manifested with frequent seismicity bursts, it is important to distinguish MS-AS from ES for providing information on the physical process of earthquake generation and contribute to the seismic hazard assessment. For this purpose, a highly accurate local earthquake catalogue was compiled and an effort was made for clusters identification after establishing certain criteria based on spatio-temporal seismicity properties. The skewness and kurtosis of moment release history were calculated considering the normalized time of every event in a cluster since the starting time of the cluster and its seismic moment. For MS-AS we found large positive values for skewness and kurtosis contrary to ES that exhibit negative to low positive values for skewness and even lower values for kurtosis. In order to verify the classification of clusters, the b-value, the spatial size and the number of events of each cluster were examined. Finally, a scaling relation between the length of the rupture zone and magnitude derived for the MS-AS sequences.

Keywords: main shock, swarms, relocation, skewness, b-value, statistical seismology.

Περίληψη

Οι σεισμικές εξάρσεις διακρίνονται σε μετασεισμικές ακολουθίες οι οποίες συνδέονται με τη γένεση ενός κύριου σεισμού μεγαλύτερου σε μέγεθος από τους υπόλοιπους της ακολουθίας και σε σημηνοσεισμούς στους οποίους δεν εμφανίζεται σεισμός με διακριτά μεγαλύτερο μέγεθος από τους υπόλοιπους. Σε περιοχές όπως ο Κορινθιακός κόλπος όπου η ενέργεια παραμόρφωσης εκδηλώνεται υπό τη μορφή συχνών σεισμικών εξάρσεων, είναι σημαντική η διάκρισή τους σε μετασεισμικές ακολουθίες ή σημηνοσεισμούς διότι συμβάλλει στην κατανόηση των φυσικών διεργασιών σεισμογένεσης καθώς και στην εκτίμηση της σεισμικής επικινδυνότητας. Για το λόγο αυτό δημιουργήθηκε ένας κατάλογος σεισμών ακριβής ως προς τις εστιακές παραμέτρους των σεισμών από τον οποίο αναγνωρίστηκαν οι σεισμικές εξάρσεις βάσει χωροχρονικών κριτηρίων που τέθηκαν. Για κάθε αναγνωρισμένη σεισμική εξάρση υπολογίστηκαν η λοξότητα και η κύρτωση της σεισμικής ροπής ως προς το χρόνο. Οι μετασεισμικές ακολουθίες είχαν μεγάλες θετικές τιμές λοξότητας και κύρτωσης σε αντίθεση με τους σημηνοσεισμούς οι οποίοι είχαν αρνητικές έως χαμηλές θετικές τιμές

της λοξότητας και μικρότερες τιμές κέρτωσης. Με σκοπό την επαλήθευση της διάκρισης των σεισμικών εξάρσεων υπολογίστηκαν οι τιμές της παραμέτρου b , το μήκος της σεισμικής ζώνης και ο αριθμός των σεισμών για κάθε σεισμική εξάρση. Τέλος, βρέθηκε σχέση μεταξύ του μήκους της σεισμικής ζώνης και του μέγιστου μεγέθους για τις μετασεισμικές ακολουθίες.

Λέξεις κλειδιά: κύριος σεισμός, σμηνοσεισμοί, επαναπροσδιορισμός εστιών, λοξότητα, b -value, στατιστική σεισμολογία.

1. Introduction

Corinth Gulf (Fig.1) is one of the most seismically active regions in Greece, with several destructive earthquakes both in historical and instrumental eras, and seismicity manifestation with the occurrence of numerous small earthquakes forming sequences of Mainshock - Aftershock (MS-AS) type or earthquake swarms (ES). Spatial and temporal discrimination of these sequences and study of their properties could contribute to understanding of the seismogenesis in the area.

Previous research in the area was conducted by Mesimeri *et al.* (2015) aiming to classify earthquake clusters to MS - AS and ES for the west part of Corinth Gulf (subregion A on the present study, Fig. 1) and for the period 2011-2014. In this study the seismicity clusters were identified for the entire Corinth Gulf and their classification as MS-AS and ES was attempted. For that purpose statistical parameters as skewness and kurtosis of moment release history were calculated (Mesimeri *et al.*, 2013; 2014; 2015) The difference in magnitude (ΔM) of the two largest events in each cluster was taken into account as an additional criterion along with the values of skewness and kurtosis. In order to verify the classification of each cluster, other parameters such as b -value, spatial size and the number of events in each cluster were identified.

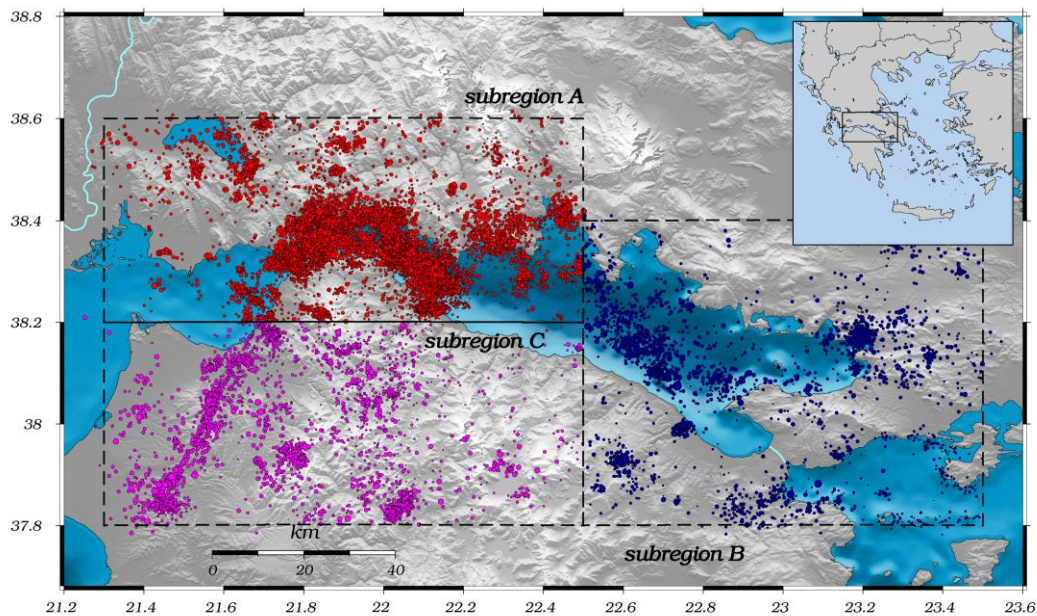


Figure 1 - Seismicity map of Corinth Gulf.

2. Data and Methods

2.1. Relocation

In order to investigate spatio-temporal characteristics of the study area it is necessary to compile an earthquake catalogue with as much as possible accurate locations. For that purpose, the recordings of approximately 50 stations of the Hellenic Unified Seismological Network (HUSN) operating during 2011-2014 and located in epicentral distances less than 160 km from the study area were used. P and S phases were mainly gathered from the monthly bulletins of the Geophysics Department of Aristotle University of Thessaloniki (<http://geophysics.geo.auth.gr/ss>) and the National Observatory of Athens (<http://bbnet.gein.noa.gr/HL/>) for approximately 24,000 events. Earthquake location was performed after dividing the region into 3 sub-regions, as shown in Figure 1, in order to calculate station delays for smaller areas, a procedure that improves location accuracy. The regional crustal model proposed by Rigo *et al.* (1996) was used and a new velocity ratio was estimated for each sub-region using the Wadati method. For further improving location accuracy, time corrections for each station were calculated and taken into account in the location procedure. Then, for each sub-region the focal coordinates were re-estimated using the double difference technique (Waldhauser, 2001).

2.2. Declustering

Initially for each sub-region the magnitude of completeness (M_c) was sought using the maximum curvature method (Wiemer and Wyss, 2000). For each of the sub-regions A, B, C the threshold magnitude was found to be equal to $M_c=1.1$, $M_c=1.5$ and $M_c=1.4$ respectively. Earthquake clusters were identified after declustering the complete catalogues applying Reasenbergs's algorithm (1985) as it has been written in Zmap software (Wiemer, 2001), for MATLAB platform.

The algorithm requires as input the minimum (T_{min}) and maximum (T_{max}) duration of the earthquake sequence in days, the interaction zone in km (R_{fact}), the probability of an earthquake (P_1) being part of a seismic excitation and the magnitude of completeness. Different sets of parameters were examined concerning the interaction zone and the duration. For the interaction zone a value of 1 km was chosen after the examination of values between 1 and 5 km, and for the duration one day. Clusters with more than 10 events were kept according to the criterion of Mogi (1963). For the sake of comparison the CURATE (Cumulative RATE) method (Jacobs *et al.*, 2013), which uses seismicity rate as the main link between earthquakes, was applied. The obtained results by both the algorithms were quite similar and for the purposes of the current study Reasenbergs's algorithm was used.

2.3. Skewness – kurtosis

One simple way to quantitatively identify earthquake clusters with swarm-like properties is through characterizing the timing of the largest event relative to the rest of the seismicity (Roland and McGuire, 2009; Chen and Shearer, 2011). To accomplish this task, the skewness (S) of moment release history and the kurtosis (K) for each cluster were calculated. Initially for each cluster we normalize the time for each event since the beginning of the sequence

Equation 1- Mean time delay

$$t_i = \frac{(T_i - T_o)}{\text{mean}(T_i - T_o)}, i = 1, N. \quad t_i = \frac{(T_i - T_o)}{\text{mean}(T_i - T_o)} i = 1, N$$

Then, for each event in a cluster, the moment is estimated from the catalogue magnitude (Hanks and Kanamori, 1979)

Equation 2

$$M_o(i) = 10^{1.5M_w(i)+16.1}$$

where M_w is the moment magnitude for each earthquake. The centroid time of moment release is obtained from the weighted mean time

Equation 3 - Centroid time

$$\bar{t} = \frac{\sum_1^N t_i \cdot M_o(i)}{\sum_1^N M_o(i)} .$$

Individual moments (M_o) are normalized by

Equation 4

$$m_o(i) = \frac{M_o(i)}{\sum_1^N M_o(i)} .$$

The third (μ_3) and the fourth (μ_4) central moment of this sequence are given by

Equation 5 - Third central moment

$$\mu_3 = \sum_1^N (t_i - \bar{t})^3 m_o(i) \quad \mu_4 = \sum_1^N (t_i - \bar{t})^4 m_o(i)$$

Equation 6 – Fourth central moment

$$\sum_1^N (t_i - \bar{t})^4 m_o(i)$$

and the standard deviation:

Equation 7 – Standard deviation

$$\sigma = \sqrt{\sum_1^N (t_i - \bar{t})^2 m_o(i)} . \sqrt{\sum_1^N (t_i - \bar{t})^2 m_o(i)}$$

The skewness and the kurtosis of moment release of each sequence are

Equation 8 - Skewness

$$\text{skewness} = \mu_3 / \sigma^3 ,$$

Equation 9 - Kurtosis

$$\text{kurtosis} = \mu_4 / \sigma^4 .$$

As described by Roland and McGuire (2009) a larger positive value of skewness is expected for MS-AS sequences (approximately 30) and negative or low positive values for ES (between -2 to 2). Chen and Shearer (2011) classified clusters with $t_{\max} \leq 0.4$ as early M_{\max} (more similar to MS-AS) and clusters with $t_{\max} \geq 0.4$ as late M_{\max} (more swarm like), where t_{\max} is the normalized timing of the largest event in the cluster. In addition to these criteria, values of kurtosis of the seismic moment release history were calculated for each cluster, where larger and lower values of kurtosis characterize the MS-AS and swarm-like sequences (Mesimeri *et al.*, 2013), respectively. Finally, the parabolic relationship between these parameters was tested.

2.4. b-value

The slope of the magnitude frequency distribution (b-value) describes the relative distribution of small and large earthquakes (Gutenberg and Richter, 1944; Ishimoto and Iida, 1939). Its value spans

from 0.5 to 2.5 and depends on material heterogeneity, fluid intrusion and applied stress (e.g. Scholz, 1968). For the estimation of b-value we used the maximum likelihood method was used (Aki, 1965):

Equation 10- b value calculation

$$b = \frac{1}{\bar{M} - M_{\min}} \log e$$

where \bar{M} is the mean and M_{\min} the minimum magnitude of the given sample. The uncertainty in the estimation of b-value is calculated using equation 11:

Equation 11 - error of b value calculation

$$S = \frac{b}{\sqrt{N}}$$

where N is the number of events in each cluster.

2.5. Spatial size of earthquake clusters

The spatial extent of each earthquake cluster was estimated by calculating the radius of gyration. This approach was proposed by Potanina *et al.* (2011) according to equation 12:

Equation 12 - Radius of gyration

$$R_g = \sqrt{\frac{1}{N} \sum_{i=1}^N [(x_i - X_o)^2 + (y_i - Y_o)^2 + (z_i - Z_o)^2]}$$

where X_o , Y_o and Z_o are the average coordinates of the events in each cluster that determine the coordinates of barycenter.

2.6. Classification of earthquake clusters

Classification of earthquake clusters as MS-AS and ES was based on several criteria. Firstly the difference in magnitude of the two largest shocks in the sequence (ΔM) was taken into consideration. According to Båth (1965) the difference in magnitude of the two largest events for a MS-AS sequence is approximately 1.2. Hence, we seek for low values for ES and larger for MS-AS sequences. The obtained values were compared to skewness and kurtosis for each cluster and then the clusters are characterized as MS-AS and ES. Finally, the value of t_{\max} is examined as an applicability criterion for the discrimination of clusters.

3. Results

Calculations were conducted for each sub-region separately due to their differences in M_c . In particular, for sub-region A, 83 clusters were identified with $N \geq 10$ out of a complete data set containing 10,859 events. Regarding their classification, 31 clusters were characterized as MS-AS and 52 as ES. This classification was based on the difference of the two largest earthquakes in each cluster and the values of skewness and kurtosis. A mean value of $\Delta M=0.3$ was found for ES and 0.8 for MS-AS. ES present low values of skewness ($S < 2$) and kurtosis ($K < 10$) contrary to MS-AS which present higher values ($S > 25$ and $K > 700$). However, there are clusters with $2 < S < 25$ and $10 < K < 700$ that could not be categorized clearly. Some of these are characterized as MS-AS but there are also others with very low ΔM (eg. 0.1). In order to properly characterize these clusters a more detailed study is necessary concerning their duration. Finally, 79% of ES have $t_{\max} \geq 0.4$ with a total mean value of 0.83 and 65% of the MS-AS have $t_{\max} < 0.4$ with a total mean value of 0.28.

For sub-region B, seven clusters were identified with $N \geq 10$ out of a complete catalog containing 1,574 events. Six of the clusters are characterized as ES with $S < 2$, $K < 10$ and a mean $\Delta M=0.2$.

Furthermore, Five of the ES have $t_{\max} \geq 0.4$ and the MS-AS have $t_{\max} < 0.40$. For sub-region C, 8 clusters were identified with $N \geq 10$ out of a complete catalog containing 1,987 events. Five of the clusters are characterized as ES and three as MS-AS. ES have values of $S < 2$, $K < 10$, a mean $\Delta M = 0.4$ with three of them having $t_{\max} \geq 0.4$. The MS-AS sets have $S > 2$, $K > 10$, a mean $\Delta M = 1.3$ and all of them have $t_{\max} < 0.40$.

Combining all the calculated values of skewness and kurtosis a parabolic relation (Eq. 4, Fig. 2) was derived:

Equation 13 - Parabolic relation between skewness (S) and kurtosis (K)

$$K = 0.96S^2 + 7.13S - 0.42.$$

ES have low values of skewness and kurtosis and are placed on the low left part of the parabola whereas the MS-AS type sequences are on the right part.

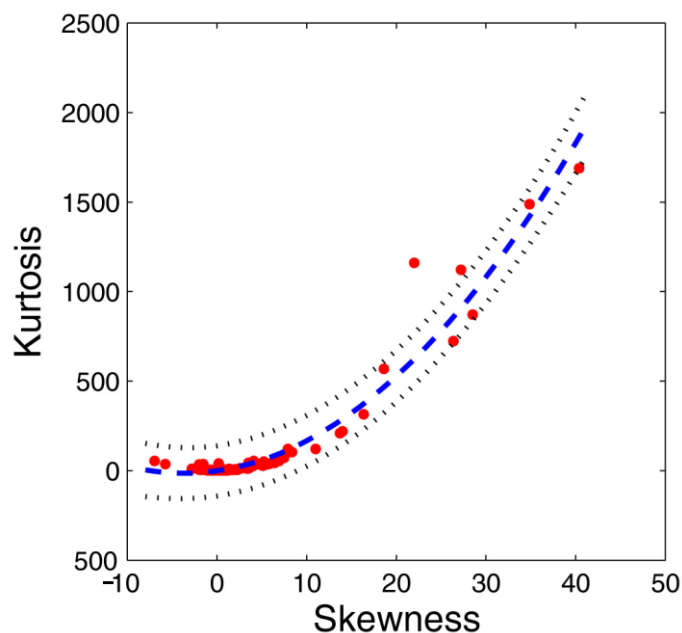


Figure 2 - Parabolic relationship between skewness and kurtosis for the identified clusters.

The b -value for each cluster was calculated along with its uncertainty. The clusters classified as ES have higher b values in comparison to MS-AS clusters (Fig. 3). MS-AS have a mean b value equal to 0.72 whereas the mean value of b for ES equal to 0.93. The results of b -values are in good agreement with the earlier discrimination of earthquake cluster. There are few cases that exhibit large errors in both ES and MS-AS sequences or the b value is extremely high or low. Large dispersion of the data is most probably due to the small number of events in each cluster, which increases the uncertainty in the estimation as well as the small magnitude range in each cluster.

Scaling relations between geometrical properties of the causative fault and magnitude for a typical MS-AS sequence are well known in literature (e.g. Wells and Coppersmith, 1994; Papazachos *et al.*, 2004). Similar relations are not valid for ES as their spatial size is not depending on the maximum magnitude in the sequence. In Figure 4 the length of each cluster (R_g) against the maximum magnitude in it (M_{\max}) was plotted keeping the previous classification. Apparently ES form a cloud and a linear regression is not applicable to the data. The values of the spatial size are between 2 and 8.6 km with magnitudes from 1.7 to 4.3 with most of the swarms having $M_{\max} < 3.2$. On the other

hand, MS-AS sequences could be well described by a linear relationship (Eq.14) for magnitudes spanning from 3.1 to 4.8.

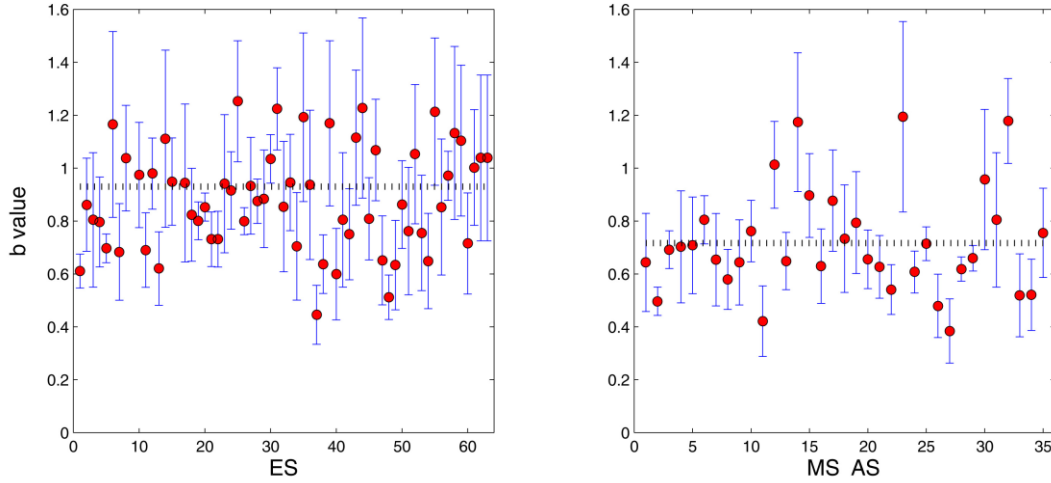


Figure 3 - b-values along with their errors for the ES (left) and MS-AS (right). The mean value of b in each dataset is shown with dashed line.

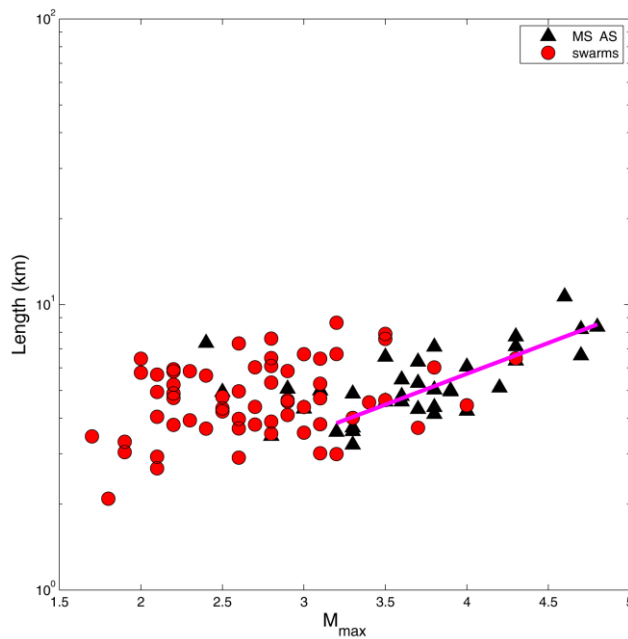


Figure 4 – Length of the activated area against maximum magnitude in each cluster. With circles and triangles are shown the clusters classified as ES and MS-AS, respectively.

Equation 14 - Scaling relation Magnitude Length

$$\log L = 0.21M - 0.10 \quad 3.1 < M \leq 4.8$$

Figure 5 shows that for $M_{\max} \leq 2.6$ the number of events occurring in an ES is not depending on the largest event in the swarm. For $M_{\max} > 2.6$ the number of events is increasing considerably, showing

a dependence on the M_{\max} , although there is a big scattering of the data. For equal M_{\max} , the number of events in the MS-AS clusters is less than the number of events in ES with the same M_{\max} .

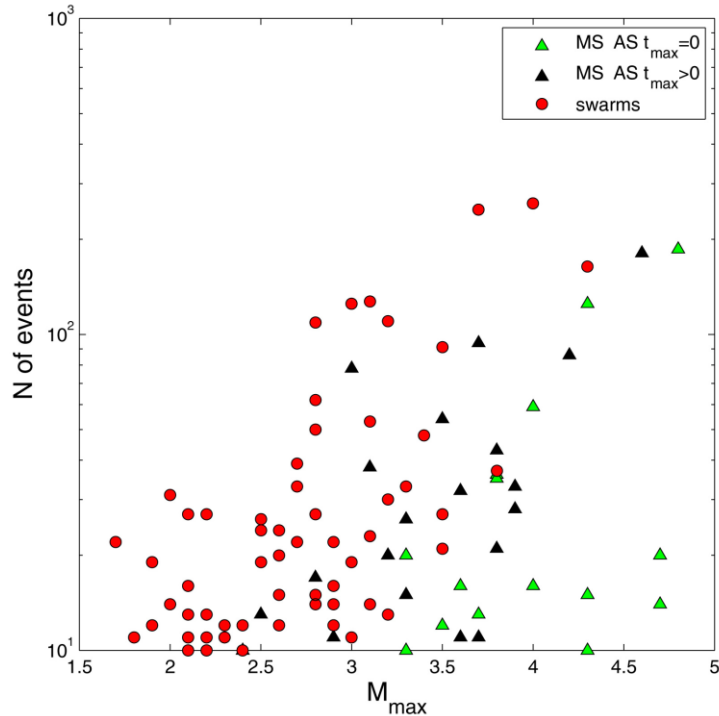


Figure 5 – Number of events in each cluster against maximum magnitude in the cluster. With circles are shown the clusters classified as ES, green triangles represent MS-AS with the mainshock to be the first in the sequence ($t_{\max}=0$) and black triangles represent MS-AS with the mainshock occurred later in the sequence ($t_{\max}>0$).

4. Discussion – Conclusions

The west part of Corinth Gulf (sub-region A) is complex, with highly clustered seismicity in space and time. Distinction of earthquake clusters into MS-AS and ES was attempted. Generally, ES are presenting low values of skewness and kurtosis contrary to MS-AS which exhibit higher values. For sub-regions B and C fewer clusters were identified and their classification into MS-AS and ES is clear. ES in these sub-regions show low values of skewness and kurtosis, and MS-AS have higher ones. In addition, t_{\max} tends to be a valuable parameter which could be used carefully for the classification of earthquake clusters. The parabolic relationship between skewness and kurtosis along with their values could be applied as a criterion for distinguishing MS-AS sequences from ES. This procedure could be used as a preliminary estimation when a seismic excitation is in progress, investigating its evolution in time by re-evaluating the values as a function of time.

The above results were also verified with the values of b and the spatial size of each cluster. The spatial size of ES seems to be magnitude independent with high b -values to be estimated. A scaling relation between magnitude and length of the rupture area was found for MS-AS sequences, where the b values were lower or equal to 1, as expected from already known published work.

The combined results for all sub-regions show that the classification of earthquake clusters is possible by applying the same criteria in the entire region of Corinth Gulf. Characteristics of ES and MS-AS are the same for all sub-regions even though the clusters in sub-regions B and C are fewer. The highly clustered seismicity in sub-region A is probably due to tectonic properties of the area.

Few cases which cannot be categorized into a certain type of sequence may be the consequences of wrong discrimination of clusters. Future work will use more precise locations after the application of relocation with waveform cross correlation data for better spatial distribution of earthquake clusters. In addition more effort is needed to define accurately the beginning and the end of seismic excitations with more strict temporal criteria. All of these will strengthen our findings and the two types of seismic excitations will be related to tectonic features of the area.

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