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Temporal clustering of the seismicity of the Absheron-Prebalkhan region in the Caspian Sea area

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Abstract. The historical and instrumental catalog of the Absheron-Prebalkhan region in the Caspian Sea area was analyzed in order to reveal the existence of temporal clustering in the time dynamics of the seismicity. The timespan of the catalog is from 1842 to 2012 and the magnitude of the events ranges from 2.5 to 6.8. The Gutenberg-Richter analysis indicates 4.0 as the completeness magnitude of the catalog. The temporal clustering analysis was performed over the sequence of events with magnitude $M \geq 4$ by using the methods of the Allan Factor and the coefficient of variation. Both the methods have revealed the presence of time-clusterized structures in the time dynamics of large events in the Absheron-Prebalkhan region. Such findings, which suggest a non-Poissonian behavior of the seismicity of the investigated area, could contribute to a deeper knowledge of the time dynamics of the seismicity and to a better assessment of the relative seismic hazard.

1 Introduction

Temporal dynamics of a seismic process can assist in time-dependent seismic hazard studies. The knowledge of the statistical distribution of the seismic interevent times is linked with the feasible and reliable estimation of the occurrence time of future earthquakes. Earthquake time occurrence can be statistically distributed like a Poisson or a clusterized process. A Poisson seismic process qualifies earthquakes that seem to occur homogeneously on time, and are characterized by typical properties (memoryless, uncorrelated and independent events). A clusterized process qualifies earthquakes that at both short and long timescales are correlated with each other, and whose density varies over time featuring the whole sequence as an ensemble of clusters (Telesca et al., 2000). Clusterization in seismic sequences was investigated at regional and local levels (Telesca et al., 2001, 2009), and was used to reveal a nontrivial relationship with hypocentral depth (Telesca et al., 2001) and to identify spatial (Telesca et al., 2003) and temporal patterns (Telesca et al., 2007).

The Absheron Peninsula, surrounded by the Caspian Sea, is located in the eastern part of Azerbaijan, which is situated in the active collision zone between Arabian and Eurasian plates, and is considered to be an earthquake-prone region. The Peninsula along with the Azerbaijan sector of the Caspian Sea, lies in the south-eastern of the Greater Caucasus. It was shown that the earthquakes occurred between 1930 and 1990 migrated in the southeast direction along the Alpine-Himalayan seismic belt (Ismail-Zadeh, 1996). The earthquakes are associated with the fault zones located either in the peninsula itself, in the Azerbaijan sector of the Caspian Sea or in the adjacent fold belts of the Greater Caucasus and Kopet-Dag (Fig. 1).

The purpose of the paper is to investigate the temporal clustering properties of the seismicity of the Absheron-Prebalkhan region, located along the western part of the Caspian Sea. The Absheron-Prebalkhan region is located within the Absheron-Balkhan Sill (Fig. 1) and is characterized by a fault structure system which separates the South Caspian Basin, which is a deep structure, from the shallower northern Caspian. The analysis of regional earthquakes reveals that magnitudes of the events range from 2.5 to 6.8 (Guliev, 1999).

Absheron-Prebalkhan is one of the highly seismic areas of the Caspian region. A number of studies were done in previous years which contributed to the analysis of seismicity and geodynamics of the region (Gorshkov, 1984;

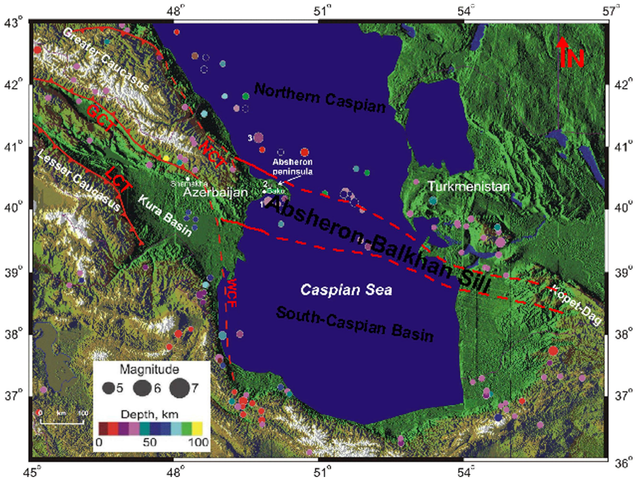

Fig. 1. Topography, simplified tectonics and seismicity of Caucasus to Kopet-Dag (by Babayev et al., 2010) with overview of Azerbaijan and Absheron-Balkhan Sill. Earthquake epicentres are marked by circles, and the colors of the circles provide information on the depth of the earthquake hypocenters (earthquakes of magnitude 5 and greater for the period of 1950–2006 are plotted here). Numbers mark the important earthquakes affected Absheron peninsula: (1), the 2000 $M = 6.3$ Caspian earthquake; (2), the 1935 Surakhani earthquake; (3), the 1963 $M = 6.5$ Caspian earthquake. Abbreviations: NCT, North Caucasus thrust fault; GCT, Greater Caucasus thrust fault; LCT, Lesser Caucasus thrust fault; WCF, West Caspian fault and NCF, North Caspian fault. Faults are positioned according to the researches done in previous years (Borisov, 1967; Gadjiyev, 1965; Kadirov, 2000, 2004).

Zonenshaine and Le Pichon, 1986; Agamirzoyev, 1987; Ivanov and Guliev, 1988; Guliev, 1999; Allen et al., 2002; Jackson et al., 2002; Ulomov, 2003; Ritz et al., 2006).

From the seismicity viewpoint, it represents a seismic threat to the Absheron peninsula which is part of the whole elongated geological structure named the Absheron-Balkhan Sill, despite the fact that earthquakes of the study area occurred at a distance from the peninsula. The Absheron peninsula is a fast growing megaregion with capital city of Azerbaijan – Baku – that influences the economic and industrial developments of much of the country. A rapid growth of population, increasing migration from rural areas into the urban areas, and lack of public awareness regarding the earthquake hazard significantly contributes to the seismic vulnerability of the Absheron peninsula and the city of Baku.

At the longitude of the Caspian Sea, previous studies (e.g. Jackson et al., 2002) have noted that the majority of deformation occurs within three broad but distinct zones of high seismicity: from south to north, the Bitlis-Zagros Fold and ThrustBelt, the Alborz-Kopet Dag, and the Greater Caucasus Mountains and the Central Caspian Seismic Zone (CCSZ) (Kadirov et al., 2012). The shortening rate along the Absheron Peninsula is about 15 mm yr^{-1} (Kadirov et al., 2012). Kadirov et al. (2012) suggested that the western part of the south Caspian Sea is moving northwards relative to Eurasia. Model results in Kadirov et al. (2012) imply that the strain rate anomaly is located near the junction between continental thrusting along the Main Caucasus Thrust Fault (MCTF) and the early stages of subduction along the CCSZ (Jackson et al., 2002), where a complexity in the accommodating structures, such as the existence of an active West Caspian Fault, may exist (Kadirov et al., 2012).

Studying the temporal fluctuations of the occurrence time series of earthquakes can contribute to gaining insight into the dynamical properties of the seismic process. This, in turn, will contribute to seismic hazard assessment of the Absheron peninsula and the city of Baku.

2 Geological and tectonic settings

The Absheron-Balkhan Sill coincides with an anticline in the sediments of late Miocene–early Pliocene age. "At the top of the Productive Series are sediment thicknesses affected by the folding, suggesting that the anticline development is late Pliocene in age" (Jackson et al., 2002). The band of earthquakes crossing the central Caspian within this area is very anomalous. Tectonically, the area is complicated by a number of active faults, such as the North-Absheron seismogenic zone, which is the southeastern continuation of the Main Caucasus Fault system, and the South-Absheron seismic fault which is the continuation of the Vandam Deep Fault system, Eastern Caspian Sea (Fig. 1). There are some substantial earthquakes with a moment magnitude of $M_\mathrm{w} > 6$, which indicate normal faulting parallel to the strike of the belt, which is unexpected in a collision zone setting as well as thrust-faulting earthquakes with the same strike (Jackson et al., 2002). The pattern of depths is relatively simple: only in the Absheron–Balkhan sill zone is there unequivocal evidence for earthquakes deeper than 30 km, and in this place they extend at least as deep as 75 km. Furthermore, there is very little evidence for any earthquakes shallower than 30 km in the offshore part of this trans-Caspian sill zone (Jackson et al., 2002). The pattern of focal mechanisms on this structure indicates a normal faulting parallel to the strike of the trans-Caspian sill zone at depths of 30–50 km, with two thrust events, also parallel to the same structure, that are deeper and further to the NE (Jackson et al., 2002). The occurrence of seismic events with intermediate-depth hypocenters most clearly reflects the development of seismogeodynamic processes (Jackson et al., 2002). The earthquakes with subcrustal sources are directly related to the geodynamics of the Absheron-Cheleken deep structure, which is a subduction zone (Ulomov, 2003). According to Jackson (2002), because of the clear pattern of focal mechanisms, these earthquakes are suspected to be related to the NE subduction of the South Caspian basement beneath the Absheron–Balkhan sill.

3 Methods

The coefficient of variation (CV) is a quantity used to evaluate the temporal clustering behavior of a seismic sequence (Kagan and Jackson, 1991) and is given $\mathrm{CV} = \sigma_\tau / < \tau >$, where $< \tau >$ is the mean interevent time (time between two successive events) and σ_τ is the standard deviation: CV assumes characteristic values in three different cases: (i) for a periodic sequence $\mathrm{CV} = 0$; (ii) for a Poissonian process $\mathrm{CV} = 1$; and (iii) for a time-clusterized process $\mathrm{CV} > 1$. From the definition, CV can be used as a discriminator among different time dynamics and in particular to discriminate between phases with Poissonian dynamics from those with clusterized dynamics ($\mathrm{CV} > 1$).

The CV is based on a representation of the seismic sequence by means of the interevent times. An alternative representation of the seismic sequence is obtained dividing the time axis into equally spaced contiguous counting windows of duration T and producing a sequence of counts $\{N_k(T)\}$, where $N_k(T)$ represents the number of events falling into the k-th window of duration T. The duration T of the window is called timescale. With this representation, the Allan Factor (AF) (Allan, 1966) is the variance of successive counts for a specified counting time T divided by twice the mean number of events in that counting time $\mathrm{AF}(T) = \frac{<(N_{k+1}(T) - N_k(T))^2>}{2<N_k(T)>}$. This measure reduces the effect of possible nonstationarities in the process, because it involves the difference of successive counts (Viswanathan et al., 1997). Varying the timescale T, a relationship $\mathrm{AF}(T) \sim T$ is obtained that is useful to identify time-clustered sequences. For these sequences, the AF behaves as a power-law $\mathrm{AF}(T) = 1 + \left(\frac{T}{T_1}\right)^\alpha$, where α is the fractal exponent quantifying the strength of the clusterization in the process; for $\alpha \sim 0$, the process is Poissonian and $\mathrm{AF} \sim 1$.

4 Seismicity analysis

The historical and instrumental catalog was compiled by Kondorskaya and Shebalin (1982), Sultanova (1986) and Gasanov (2003), and used in Babayev (2005, 2010) and Babayev et al. (2010). The catalog contains earthquakes from 1842 to 2012 with event moment magnitude ranging from 2.5 to 6.8.

The magnitude-frequency distribution (MFD) is given by the cumulative number of events with magnitude $M \geq M_{\mathrm{th}}$, where M_{th} represents the threshold magnitude. For a complete catalog, the Gutenberg-Richter law (Gutenberg and Richter, 1944) (GR) predicts a power-law behavior of the MFD: $\log_{10}(N) = a - bM_{\mathrm{th}}$, where N indicates the number of events with magnitude $M \geq M_{\mathrm{th}}$. In real cases, such a relation does not hold for all the measurable magnitude M; in fact, due to the incompleteness of the catalog at the lowest magnitudes, the power-law behavior of the GR law only exists for a certain range of magnitude $M \geq M_{\mathrm{c}}$, where M_{c} is the completeness magnitude that is the lowest magnitude of the catalog above which all the earthquakes with magnitude larger than M_{c} are reliably detected (Rydelek and Sacks, 1989). Therefore, the analysis of the completeness of the catalog implies the estimation of M_{c}. To this aim we carried out two methods in our study: (i) the maximum curvature (MAXC) method (Wiemer and Wyss, 2000), in which the threshold magnitude corresponding to the maximum of the non-cumulative frequency-magnitude distribution is defined as M_{c}; and (ii) the entire-magnitude-range (EMR) method, first developed by Ogata and Katsura (1993) and then modified by Woessner and Wiemer (2005). In the EMR method, a model for the MFD given by the combination of a power-law distribution (for the complete part of the catalog) and a normal distribution (for that incomplete part) are estimated by means of the maximum-likelihood estimation. The complete part is characterized by the parameters a and b, while the incomplete part is characterized by the parameters μ (the magnitude at which 50 % of the earthquakes are detected) and σ (the standard deviation describing the width of the range where earthquakes are partially detected). All the described methods are implemented in the Matlab software ZMAP (Wiemer, 2001). The completeness magnitude is 4, with the MAXC method, and 3.8 with the EMR method, with $b = 0.843 \pm 0.06$ (MAXC) and $b = 0.733 \pm 0.04$ (EMR). Both methods furnish quite consistent values for M_{c} and b. However, in order to guarantee a larger completeness of the catalog, hereafter we will consider in our study only the set of events with magnitude $M \geq 4$.

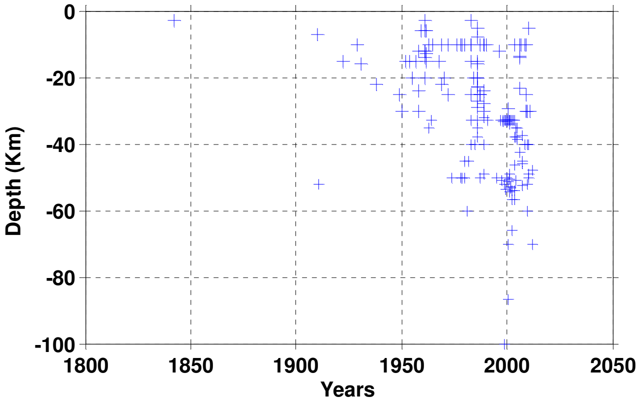

Fig. 2. Time-depth distribution of the events in the investigated area with $M \geq 4$.

The depth-time plot is shown in Fig. 2. The Absheron-Prebalkhan area exhibits a seismicity pattern with remarkable differences in various tectonic units. Hypocenters are mostly restricted to the crust in the region being distributed extremely heterogenic at the depth of 0–40. Such heterogeneity of distribution of seismicity is associated with the faults of various activity levels on all extent of their tracing. Strong earthquakes here occur rarely and not everywhere; plenty of

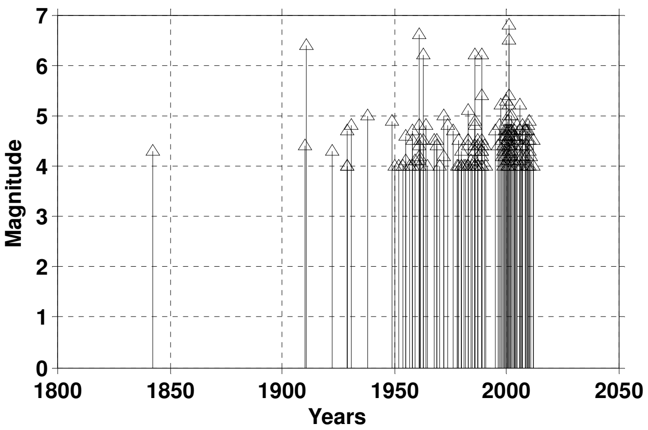

Fig. 3. Time-magnitude distribution of the events in the investigated area with magnitude $M \geq 4$. Approximately three sub-sequences can be identified: (i) from 1910 to 1938, (ii) from 1949 to 1991 and (iii) from 1995 to 2012. In the period (i) only 9 events occurred, in the period (ii) 83 events, while in the period (iii) 96 events were detected. The lack of earthquakes with magnitude $M \geq 4$ between 1842 and 1910 is very probably due to the incompleteness of the catalogue even for rather high magnitudes rather than to a real aseismic gap.

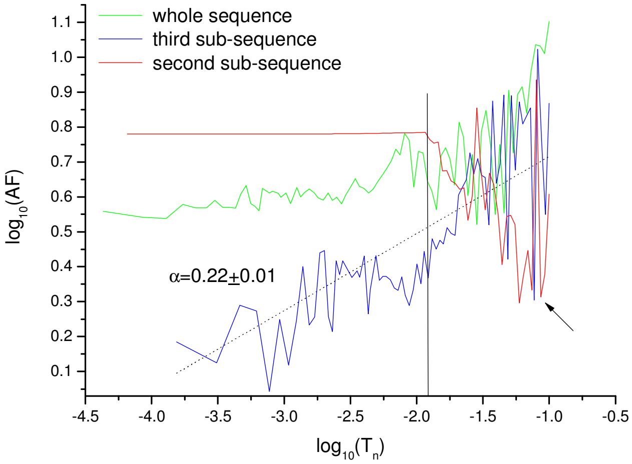

Fig. 4. Allan Factor analysis for the three sub-sequences as indicated in Fig. 3.

earthquakes of weak and average intensity are concentrated in one area, whereas their small quantity is observed in other areas. A medium- to high-level of activity is characteristic for both the crustal and mantle part of the lithosphere, between the depths of 40 and 60 km since 1975, while single events are still observed at the depth level of 60–100 km, within the period 1975–2012. The reason is likely to be associated with the use of the Harvard CMT earthquake catalogue, where the depths are reliably determined for $M > 5$ events. Regarding the earthquakes' depth determination before 1975, we refer to the work done by Kondorskaya and Shebalin (1982).

The magnitude-time plot is shown in Fig. 3. From visual inspection it is possible to see approximately three time regions with different features: (i) from 1910 to 1938, (ii) from 1949 to 1991 and (iii) from 1995 to 2012. In the period (i) only 9 events were recorded, in the period (ii) 83 events, while in the period (iii) 96 events were detected. The seismic rate in the three periods changes significantly, going from about 0.3 events/year in first sub-sequence to about 2 events/year in the second sub-sequence and 5.6 events/year in the third. The lack of earthquakes with magnitude $M \geq 4$ between 1842 and 1910 is very probably due to the incompleteness of the catalog even for rather high magnitudes rather than to a real aseismic gap.

In order to investigate the temporal clustering behavior of the seismicity under study, we applied the Allan Factor (AF) method and the coefficient of variation (CV) to the sequence. We have only analyzed the second and third sub-sequences (as separate sub-sequences and as a whole sequence), since the first sub-sequence could be very probably incomplete. Figure 4 shows the results of the AF analysis. In order to compare the three curves, we normalized the timescale to the period of each sequence: $T_\mathrm{n} = T/P$, where T is the effective timescale, P is the period of the sub-sequence and T_n is the normalized timescale. For the second sub-sequence the period is 15 340 days; for the third sub-sequence it is 6480 days; for the whole sequence the period is 23 281 days. The comparison among the three curves allows deducing the following observations: the AF of the second sub-sequence is mainly characterized by random behavior for normalized timescale $T_\mathrm{n} < 10^{-1.96}$ (indicated by the vertical bar in Fig. 4 and by a flat shape of the AF curve), while for higher timescales the behavior becomes more regular with a signature of periodicity at around $T_\mathrm{n} \sim 10^{1.1}$ (indicated by the drop in the AF). The AF of the third sub-sequence shows a clustering behavior for about all the available normalized timescales, suggested by the power-law form of the curve with exponent $\alpha \sim 0.22$; however, the third sub-sequence is also characterized by an apparent periodicity at the same timescale as the second one (indicated by the arrow in Fig. 4). The AF of the whole sequence is characterized by two different time regimes separated by the normalized timescale $T_\mathrm{n} \sim 10^{-1.96}$ (which represents the crossover normalized timescale in the second sub-sequence from a random regime to a more regular regime); the first regime for $T_\mathrm{n} < 10^{-1.96}$ seems to be more dominated by the randomness of the second sub-sequence, because the AF shares the characteristics of flatness in this timescale range; the second regime for $T_\mathrm{n} > 10^{-1.96}$ seems to be more dominated by the clustering dynamics of the third sub-sequence, because of the presence of the power-law increase in the form of the AF curve, even if an exact determination of the scaling exponent cannot be performed due to the rather rough behavior of the AF curve at those timescales.

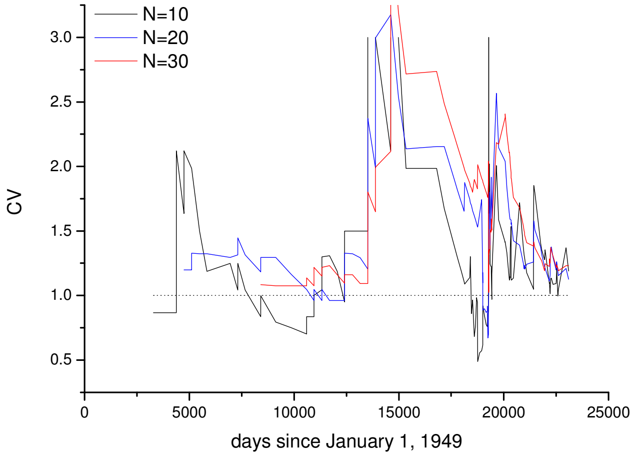

Fig. 5. Time variation of CV for the whole sequence.

The CV method for the whole sequence is ∼ 1.75, while that of the second and third sub-sequences is ∼ 1.45 and ∼ 1.43, respectively. Such values indicate a quite clusterized behavior of all the sequences under study. However, it is more important to analyse the time variation of the CV, because in this manner we can identify phases in which the sequence can be modelled with a Poissonian distribution and phases in which the sequence can be considered as clusterized. To this aim, we consider a moving window of N events, shifting through the sequence by 1 event; the value of CV for one window is associated to the time of occurrence of the last event in the window. The time variation of the CV was recently used by Bottiglieri et al. (2009) to identify temporal phases of clusterization of seismic sequences. We applied the time variation of the CV to the whole sequence and varied the length of the moving window, selecting $N = 10$, 20 and 30 events. The results are shown in Fig. 5. First of all we can observe that the time variation of the CV does not depend of the length of the time window, indicating the robustness of the results. The time variation of CV suggests the presence of temporal phases in which the whole sequence is Poissonian, but others in which the sequence is clusterized. This is an interesting result, because it shows that for sufficiently long sequences, the clustering behavior is a property that involves also earthquakes with relatively large magnitudes, and not only seismic sequences with low threshold.

5 Discussion

The knowledge of the temporal properties of an earthquake sequence can be considered one of the fundamental steps to be carried out in order to properly model the earthquake interevent time distribution, which is, indeed, one of the main goals of the studies devoted to seismic analysis. The study of temporal clustering of seismic sequences was also performed using statistical approaches different from the AF method. Mega et al. (2003) performed the diffusion entropy method to investigate the interevent time distribution of the seismicity in California, revealing that the time intervals between two successive large earthquakes are not Poissonianly distributed: such a finding was in opposition to the generalized Poisson model, in which earthquakes are grouped into temporal clusters of events, featured by intra-cluster correlations (due to the presence of aftershocks within a cluster following the Omori's law) and inter-cluster uncorrelation (due to the random distribution of the mainshocks in time). The long range model proposed by Mega et al. (2003) and then discussed by Helmstetter and Sornette (2004) and by Mega et al. (2004), reproduced the power-law of the intra-cluster swarms and inter-cluster distances.

The analysis performed in the present paper was aimed at revealing statistical features in the time dynamics of the seismicity observed in the Absheron-Prebalkhan area. The method of the Allan Factor reveals that the time dynamics of the events with magnitude greater than or equal to 4.0 is more compatible with a non-Poissonian distribution. This result seems to reinforce the results obtained by Mega et al. (2003), in which non-Poissonian features were revealed in mainshock sequences that are not characterized by the Omori's effect, indicating the presence of a correlation mechanism, which is beyond the Omori's law (Utsu et al., 1995).

It should be observed that seismic hazard assessments have been generally based on the hypothesis of a Poissoian distribution ruling the largest events of an investigated area (https://geohazards.usgs.gov/eqprob/2009/documentation.php), and the finding that departures from Poissonianity can be observed not only in sequences of small magnitudes but also in sequences of large events could contribute to develop a model of occurrence of mainshocks different from the Poissonian model, but more suited to the real observations. Although the finding of the most suitable model of the Absheron-Prebalkhan earthquake time occurrence (which is the basis of any seismic hazard analysis) is beyond the scope of the present paper, our results suggest how crucial the deep understanding of the time dynamics and the timescale regimes of a seismic sequence are for an efficient seismic hazard assessment.

6 Conclusions

In the present paper we analyzed the time dynamics of both the historical and instrumental seismicity that occur in the Absheron-Prebalkhan area in the Caspian Sea region. The statistical analysis of the catalog has indicated that the completeness magnitude is 3.8–4.0 with b-value around 0.7–0.8. The sequence of the events with magnitude $M \geq 4.0$ appeared to be composed by three sub-sequences with different seismic rate. Time-clusterization is revealed in the third sub-sequence, lasting from 1995 to 2012, with exponent $\alpha \sim 0.22$. A periodical behavior is mainly revealed in the second sub-sequence, lasting from 1949 to 1991. The time variation of the clustering behavior was analyzed by using the CV, which shows Poissonian alternated with clusterized phases. The obtained results are particularly interesting because the temporal clustering was detected in the seismic sequence analyzed in this paper with a relatively high threshold magnitude, while, to our knowledge, such a property has mainly characterized seismic sequences with low threshold magnitude (Telesca et al., 2004). The results obtained in the present paper can contribute to model the time dynamics of the sequence of medium to large events in the Absheron-Prebalkhan area as non random point process characterized by clustering behavior, this implying correlation and dependence among the events.

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