

Spatial Variation of Precursory Seismic Quiescence Observed Before Earthquake from 01.04.2010 in the Region of Crete



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Abstract Statistical analysis was performed, which reveals statistical parameters of the seismic setting before the earthquake in the region of Crete (01.04.2011 with coordinates 26.56° E, 35.64° N; $M_1 = 6.2$, $h = 63$ km and $T_0 = 13: 29: 10.5$). For this purpose, the spatial and temporal changes in the b -value and the value of the Z -seismic lull were estimated. The temporary change in the b -value shows that the average value of b decreased from 1.75 ± 0.02 between 1985 and 2002 to 1.4 ± 0.02 between 2003 and 2011. A significant decrease in the b -value and clear anomalies of calm in the Z -value in early 2011 were also observed in several neighbouring areas. The epicenter of the earthquake falls in an area with a relatively low value of the a -parameter estimated for the entire previous period. In the study area, the abnormal decreasing trend of the b -value may be an indicator of increased stress, and the increasing trend of the Z -value may indicate areas of calm before the studied earthquake.

Keywords Earthquake · Recurrence graph · Seismic hush

1 Introduction

There are a lot of studies on the spatial and temporal phenomenon of precursory seismic quiescence, using different approaches to measure, map and evaluate possible episodes of seismic quiescence (e.g., RTL, PI, RI, ZMAP, etc.). Some of the studies on the precursors of past earthquakes suggest that particular space-time seismicity

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patterns, including the phenomenon of precursory quiescence, can be related to the seismo-tectonic processes that lead to earthquakes.

Wyss and Habermann [1] defined the phenomenon of seismic quiescence formally. Their amended definition states that the quiescence hypothesis assumes that some main shocks are preceded by precursory quiescence, which is a significant decrease of the mean seismicity rate (number of events of magnitude exceeding a given threshold, per unit time), as compared to the preceding declustered background rate in the same crustal volume, judged significant by some clearly defined standard (e.g., [2, 3]). Rate of the decrease may take place within part, or the entire source volume of the subsequent main shock, and it extends up to the time of the main shock, or may be separated from it by a relatively short period of increased seismicity rate. Usually, the rate decrease is larger than 40%, and takes place in all magnitude bands. Also, Wiemer and Wyss [4] defined the precursory quiescence hypothesis as a statistically significant decrease of the seismicity rate that occurs in a restricted segment of a seismogenic zone. The rate decrease is terminated by a main shock and the quiescent volume covers all or a major part of the source volume.

Quiescence hypothesis is based on the assumption that the seismicity rate in large and small seismogenic volumes is constant, unless a change in process takes place [2]. Major earthquakes redistribute stress locally and thus cause aftershock sequences as well as local seismic quiescence. Creep episodes or slow earthquakes on deep extensions also redistribute stress and hence cause local increases and decreases of seismicity rate. To measure quiescence, it must be documented how constant the seismicity rate is in the study area. This is done by classifying all deviations from the average rate by their significance. If it is found that the most significant or one of the most significant deviations from a constant rate occurs near a main shock, in time and space, it may be proposed that a connection exists.

In addition to variations in changes in seismic activity and seismic lull, the values of b can also be indicators of an impending earthquake. The spatial variations in the slope value of the repeatability graph (b -value) characterize the seismicity in a given region [5]. Usually, at a value of $b \geq 1$, heterogeneity of the earth's crust and low voltage are assumed, while at $b < 1.0$, volumes with homogeneity of the earth's crust and high voltage are assumed [6]. Studies have shown that a decrease in the value of b in the studied seismogenic region may be associated with an increase in stress before major earthquakes [7–10].

The present work aims to study the spatial zones around the epicenters of relatively strong earthquakes that occurred on the Balkan Peninsula, for anomalous values of the slope of the recurrence graph and other statistical parameters before the seismic event of 01.04.2011 with epicentral coordinates: 26.56 E, 35.64 N, magnitude $M_l = 6.2$ and depth $h = 63$ km.

2 Methodology

Considering the exponential distribution of earthquakes by magnitude [11], the value of the slope of the recurrence graph is estimated by the method of maximum likelihood [12].

$$b = \frac{\log e}{M_{mean} - M_{min}}, \quad (1)$$

where M_{mean} —average value of magnitude in the sample, M_{min} —is the minimum magnitude of the sample and is calculated as: $M_{min} = M_c - \Delta M/2$, where ΔM —takes into account the rounding of magnitude and here is selected $\Delta M = 0.1$ [13], and M_c —the magnitude of the completeness of the sample. The root mean square error of the estimate is:

$$\sigma_b = \frac{b}{\sqrt{|N|}} \quad (2)$$

In this study, the spatial distribution of the b-value was calculated using the ZMAP software [4, 14], using the maximum likelihood methods and the least squared regression method. According to Aki [15], the maximum likelihood method gives a more solid estimate than the least squared regression method. The first step in analyzing b-values is to determine the magnitude of M_c 's completeness and its error. M_c is defined as the lowest magnitude at which 100% of events in a given space and time are detected [16, 17]. Values lower than M_c are considered heterogeneous and incomplete.

The Z-test method is based on the research of Wyss and Habermann [17, 18], and is focused on the determination of spatiotemporal blocks in the seismically active zone with a significant change in the intensity of the seismic flow of events in the selected energy range. The analysis is based on the statistical function of the Z-test. To determine the seismic calm, the study area is covered with a grid with a fixed pitch. For each network node at a given point in time, the function is calculated

$$Z(t) = \frac{R_1 - R_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}, \quad (3)$$

where R_1 and R_2 are the mean values of the earthquake flow velocity, respectively (number of earthquakes in a time window of 30 days) for two time intervals (one lasting at least a year and tied to the test date, the other including all other time); σ_1 and σ_2 —standard deviations of R_1 and R_2 respectively for the first and second time interval, and n_1 and n_2 —number of earthquakes for the respective period. For each node of the network, earthquakes with a depth of the hypocenter up to 70 km are considered. The high ones (positive) values of Z indicate a decrease in the velocity of the earthquake flow and low values indicate an increase [19]. For all nodes of the

network with a value of $Z > 3$ corresponds to 99% reliability of seismic attenuation determination [4, 14]. The calculated values in the nodes of the network are combined on the principle of spatio-temporal neighbourhood and determine the areas with seismic lull.

In this study, an alternative method for calculating the statistical parameters of seismicity was applied, using an extended software package widely adopted by geophysicists—ZMAP [14]. ZMAP is open source software used to assess seismic hazards [1, 14, 16]. ZMAP contains many advanced seismological functions for earthquake catalog analysis, measurement of variations in b , a , z -values, time series analysis. Damanik [20] uses ZMAP with a completion magnitude of about 4.7 for the larger region of the island of Java (106–115.50 N, -0.7 to -11.50 E), using data from the Geological Earthquake Catalog. US Office (USGS) and Engdahl catalogs.

3 Data

The spatiotemporal change in seismicity is an important contribution to the understanding of the seismic-tectonic environment and the seismic analysis of the hazard. To study the change in seismicity in a region, information in the form of an earthquake catalog is needed.

The present study analyses a catalog of earthquakes for the period 1964–2020.05.18, 21. The catalog covers data in a spatial window 320–4400 N and 100–3000 E with a total number of earthquakes 295,029, with depths $0 \leq h \leq 70$ km (Fig. 2b) and with a magnitude M_I . The catalog is declustered using the Zmap program (selected parameters: min for Unclustered events [day] = 1; max for clustered events [day] = 10; confidence level = 0.95; XK factor = 0.5; effective min mag cutoff = 1.5; interaction radius factor = 10; epicenter error = 5 km; Depth error = 10 km). The minimum magnitude of complete recording, M_c , is an important parameter for many studies related to seismicity (e.g., Taylor et al. [22]). It is well known that it changes with time in most catalogues, usually decreasing, because the number of seismographs increases and the methods of analysis improve. In seismicity studies, it is frequently necessary to use the maximum number of events available for high-quality results. In order to examine the seismic quiescence and the frequency-magnitude relationship, the change of M_c as a function of time is determined using a moving window approach with maximum curvature method (MAXC) in Woessner and Wiemer [23]. Also, M_c is calculated with entire-magnitude-range method (EMR) as stated in Woessner and Wiemer [23]. Since the result is not changed, we used MAXC method (one can find many details on the methods, in order to estimate the magnitude of completeness of earthquake catalogues, in Woessner and Wiemer [23], Schorlemmer and Woessner [24]). The minimum magnitude of complete recording, was rated on $M_c \geq 3.5$ (Fig. 2a), after which the catalog is considered complete. The events below this magnitude threshold are removed, after which 24,750 earthquakes remain (Fig. 1).

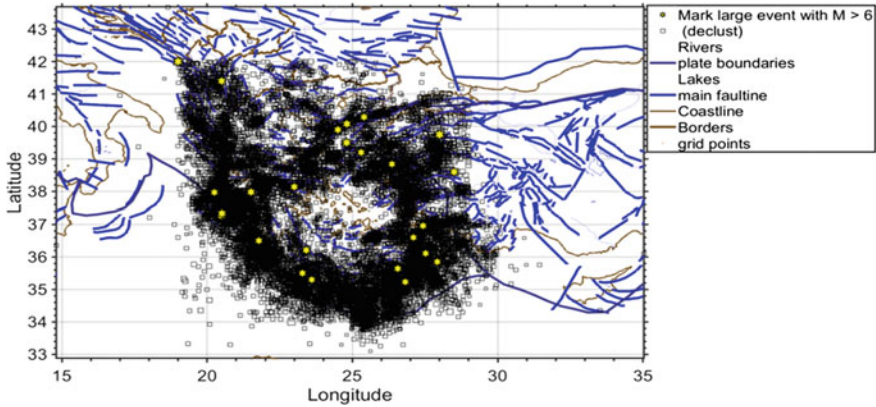


Fig. 1 Map of earthquake epicenters with $M_c \geq 3.5$ after declustering of the catalog

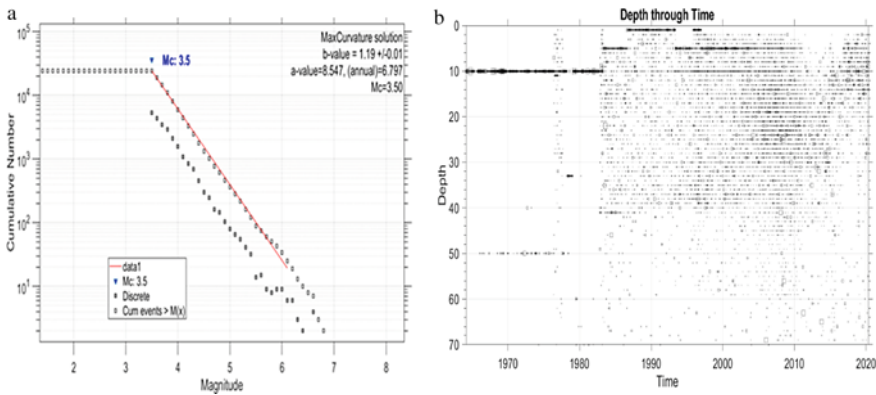


Fig. 2 **a** graph of the magnitude-frequency distribution $M_c > 3.5$; **b** distribution of the hypocenters of the earthquakes in depth through time

Furthermore, the spatial distribution of b-value is presented (declustered catalog with $M \geq 3.5$) for the southern part of the Balkan Peninsula, for the period from 01.01.2005 to 01.01.2011 in Fig. 3. As in the magnitude completeness map, we considered spatial

grid of points with a grid of 30 km. The spatial variations in b-value change between 1 and 1.8. The highest b-values (>1.7) are located between 33–36° N and 22–26° E. The lowest b-values (~ 1) are found in a large area in the SW part between 33–38° N, 17–23° E and in the SE part (where the epicentre of the studied earthquake falls) between 33–37° N, 26–30° E. The low value of b ($b \sim 1.0$) and in the SE part in the studied seismogenic region may be associated with an increase in stress before the studied earthquake from 01.04.2011, with coordinates 26.56° E, 35.64° N; $M_1 = 6.2$, $H = 63$ km and $T_0 = 13: 29: 10.5$.

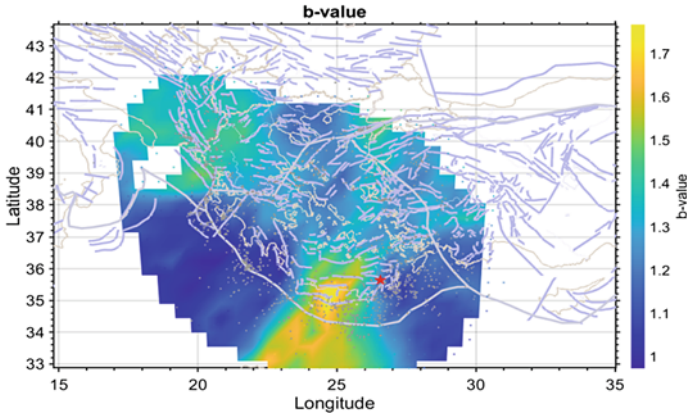


Fig. 3 Spatial distribution of the b-value for the study area for the period from 01.01.2005 to 01.01.2011. The epicenter of the studied earthquake with coordinates 26.56° E, 35.64° N is marked with a red dot

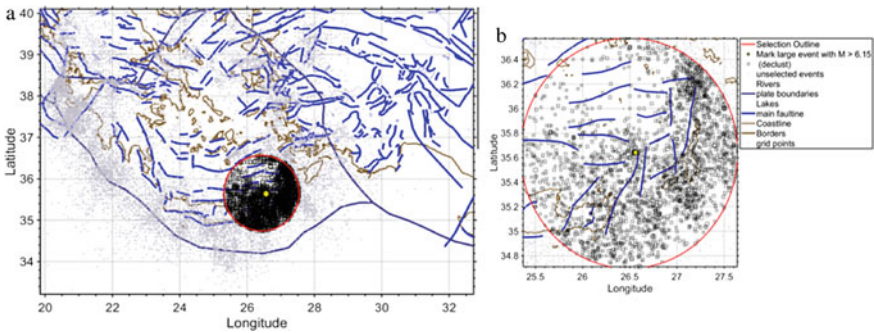


Fig. 4 **a** Map of the selected spatial circle of research; **b** test polygon

To establish a statistically significant decrease of the seismicity rate that occurs in a restricted segment of a seismogenic zone, we selected a circle centered in the epicenter of the studied event (26.56° E, 35.64° N) with 100 km radius. It contains 702 events with $M_c > 4$ (Fig. 5, a) which are presented in Figs. 4a, b. The plots of cumulative number of events versus time for test polygon for $M_c > 4$ is present in Fig. 5b.

4 Results

Figure 6 shows the graph of the time change of the b-value in the studied spatial window. The following parameters are set for the construction in the Zmap program:

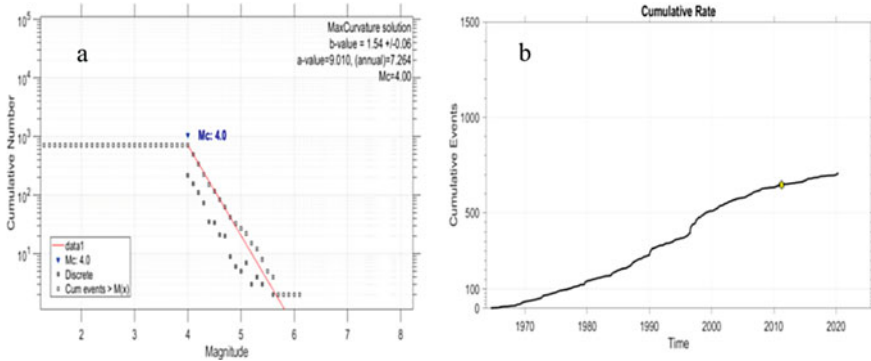


Fig. 5 **a** Graph of the magnitude-frequency distribution $M_c > 4$ for the selected landfill; **b** plots of cumulative number of events versus time for test polygon

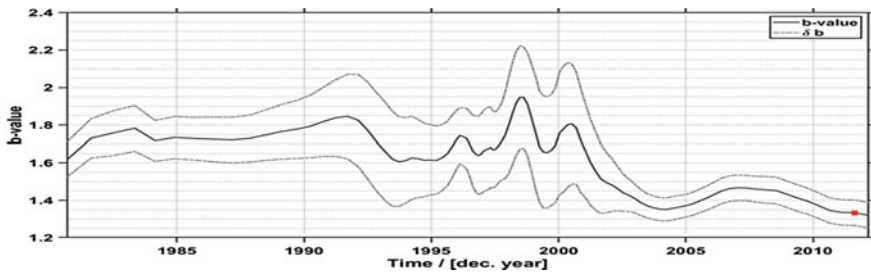


Fig. 6 Time change of the b -value of earthquakes with $M > 3.5$ within the studied area; - moment of occurrence of the investigated event

method—Max Curvature; sample window size = 500 number of events; min of events = 50; window overlap (%) = 4; bootstraps = 200; smot plot = 5.

The graph of the value of b (Fig. 6) shows a maximum ($b = 1.95$) around 1998, which suggests increased heterogeneity and reduced voltages [25]. Since 2000 the b -value decreases continuously and in 2003 reaches its minimum $b = 1.35$. The studied earthquake occurs in a period of decreasing value of b . A significant decrease in the value of b may be associated with an increasing effective level of stress before major earthquakes [10, 13]. In addition to the change in time, the spatial changes in a spatial circle of the parameter b are analyzed.

The results are presented in Fig. 7, (a) maximum likelihood estimations and (b) least squares estimations. The spatial fluctuations of b for the studied area were estimated for the period from 1964 to 30.03.2011. Spatial differences in the value of b illustrate variability in plan, and relatively low values can determine the places where an earthquake would most likely occur [26, 27]. The zones with relatively low values of b (0.9–1.2) are clearly delineated and the epicenter of the earthquake falls into them. According to [13] and [28] low values of b indicate that fault stresses accumulate in these zones until the main event is activated. Note that the least squares

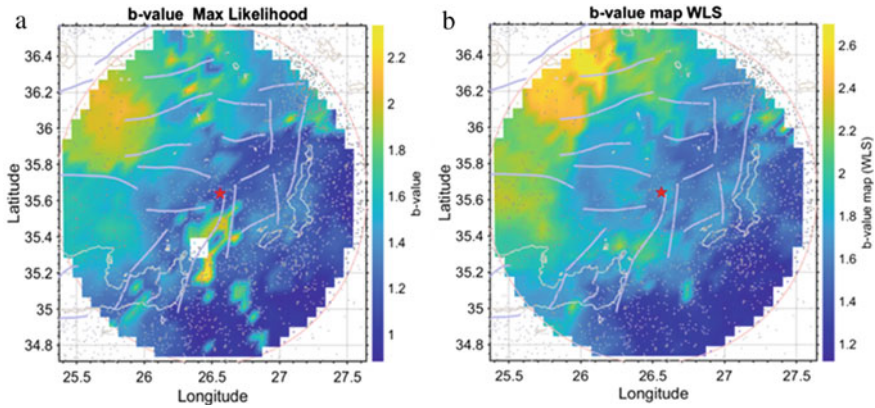


Fig. 7 Spatial distribution of the b-parameter, calculated by the methods: **a** maximum likelihood; **b** least squares; ★—epicentre of the earthquake from 01.04.2011

method gives better results. In order to confirm the result and get a better idea of the area of seismic calm, the radius of the studied area was increased to $r = 200$ km. A period of reduction from 01.01.2000 to 28.02.2011 of the value of b (Fig. 6) was selected, after which the spatial distribution of b (Fig. 8a) was built again. This result confirms the decrease of the value of b around the epicenter of the studied earthquake for the determined period. The spatial distribution of the a -parameter characterizing the seismic activity before the earthquake showed (estimated for the period from 2000 to 28.02.2011) that the epicenter falls in an area with relatively low seismic activity ($a = 7-7.5$), but which is close to the zone with relatively high activity (west of the epicenter, $a = 8-9$) (Fig. 8b).

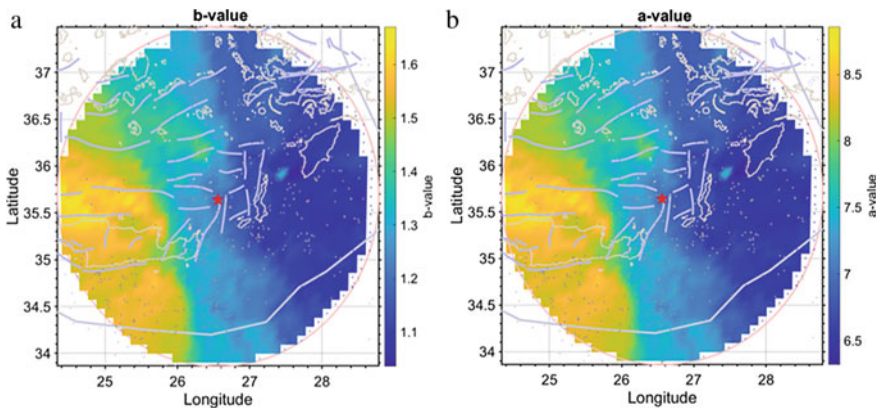
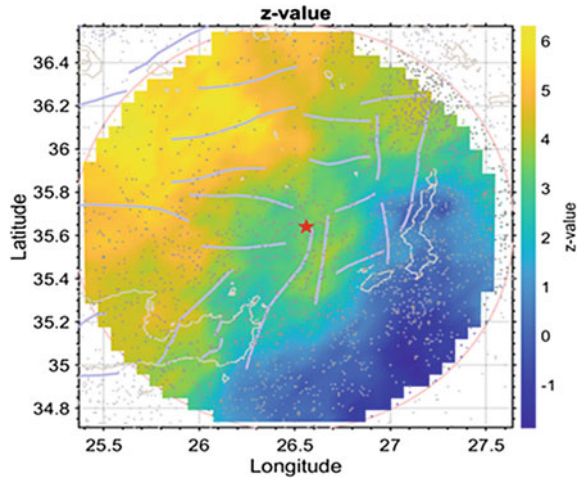


Fig. 8 **a** Spatial distribution of the b-parameter, calculated by the methods maximum likelihood for the selected polygon with radius $R = 200$ km; **b** Spatial distribution of the a-parameter; ★—epicenter of the earthquake from 01.04.2011

Fig. 9 Z-statistics for the studied area in a circle with radius $R = 100$ km, around the epicenter of the earthquake from 01.04.2011;
 ★—epicenter of the earthquake



The spatial distribution of the Z-parameter before the earthquake of 01.04.2011 (Fig. 9) is calculated for the same area ($R = 100$ km), comparing two time periods: 1st period from 30.03.1997 to 30.03.2005 and 2nd period from 30.03.2005 until 30.03.2011.

The high (positive) Z-values of the maps can be interpreted as a decrease in the flow rate of seismic events (seismic lull) compared to the first period, and the low (negative) Z-values represent an increase in velocity. Earthquake density and distribution is a critical factor in interpreting Z-value variations. Large areas of constant value could show the same density of earthquakes for different periods of time, may show a homogeneous degree of seismicity in this area.

In the Fig. 9 the epicenter falls in an area with relatively high values of ($Z = 4-5$), which means that the selected period (30.03.2005 to 30.03.2011) before the earthquake is a period of relative seismic lull. These relatively high values of $Z = 4-5$ show 99% reliability of the result. High values of $Z = 5-6$ are also observed in the northwestern part of the landfill, which may be due to the low density of earthquakes in this part of the area. To check, the Z-value was calculated in a polygon excluding the northwestern part. In this case, the epicenter falls exactly in the zone of relative seismic lull (Fig. 9, $Z \approx 4$).

For the verification of the result, the Z-value was calculated in a circle with radius $R = 200$ km for first period from 01.01.2005 to 01.01.2008 and second period from 01.01.2008 to 01.01.2011. In this case, the epicenter falls exactly in the zone of relative seismic lull (Fig. 10a; $Z \approx 4$).

The percentage comparison simply calculates the changes between the rates of the second and first periods. The range of this function is from -100% (no earthquakes in second period) to infinity (no earthquakes in first period). The percentage change in the area around the epicenter of the event is $-51\sim-52\%$, which clearly shows that around the epicenter of the earthquake during the second period a zone of relative seismic calm is formed. As long as this percentage change is greater than 30%, a

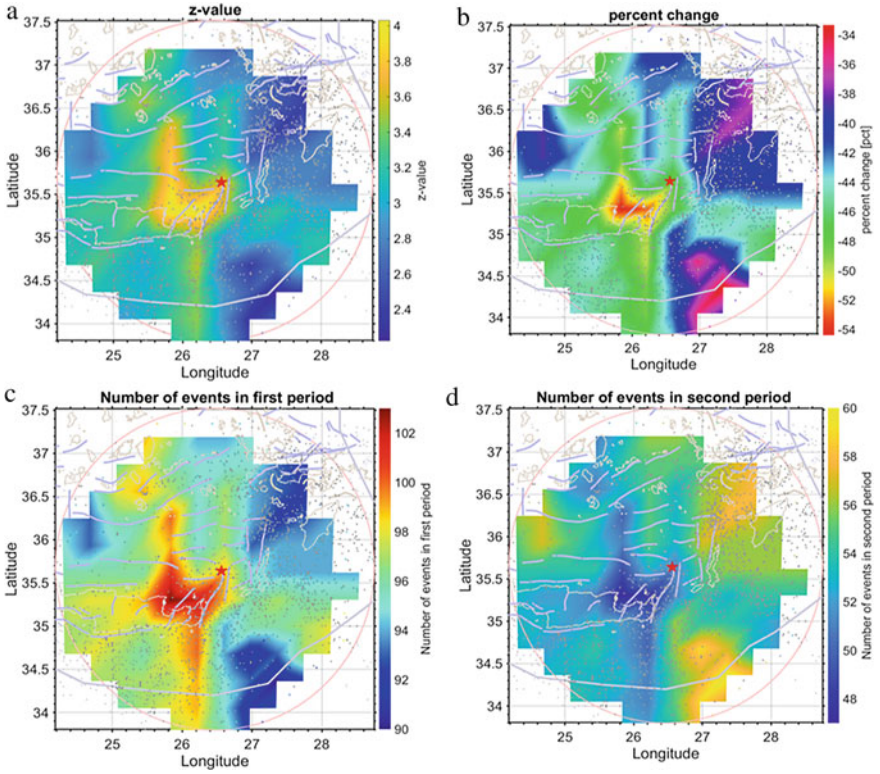


Fig. 10 **a** z -statistics for the studied area in a circle with radius $r = 200$ km, around the epicentre of the earthquake from 01.04.2011; **b** percent change of second to first period; **c** number of events in first period; **d** number of events in second period; ★—epicentre of the earthquake

significant reduction in the number of events is in force, which makes it statistically significant. This can also be seen when comparing the spatial distribution of the number of seismic events for the first (Fig. 10c) and the second (Fig. 10d) period. For the first period (01.01.2005–01.01.2008) the epicenter is in an area with 100–102 earthquakes and in the second period (01.01.2008–01.01.2011) the epicenter is in an area with 48–50 earthquakes.

5 Conclusions

The temporary change in the b -value for the period 1964–2020 shows a minimum in the value of b ($b = 1.35$), preceding the earthquake of April 1, 2011 ($M_I = 6.2$) by about 7 years.

Large decreases in the value of b possibly associated with increasing effective levels of stress before major earthquakes. These significant decreases in the value of b can lead to an increase in effective stress before major events. An increase in the b -value after these earthquakes may mean an increase in the heterogeneity of the earth's crust and a decrease in shear stress.

The change in the spatial distribution of the b value before the earthquake shows that the area with an abnormally low value of b covers the epicenter of the studied earthquake. These low values of b can be interpreted as a potentially locked or high-stress zone before major earthquakes.

The epicenters of the earthquakes are located in areas of relatively high value of the parameter $Z \approx 4.2$, which indicates a statistically reliable determination of an area with relatively seismic "calm" before the earthquake.

Moreover, detecting these two precursory anomalies in relatively large regions might be in relevant to the preparation zone of the 2011 Crete event.

Therefore, a decrease in the value of b and seismic attenuation anomalies can be an indicator of strong stress release and these changes can be interpreted as predictors of strong seismic events in studied region.

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