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The b -Value Analysis of Aftershocks 170 Days After the 23 October 2011 Van Earthquake (M_w , 7.1) of the Lake Van Basin, Eastern Anatolia: A New Perspective on the Seismic Radiation and Deformation Characteristics

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Additional information is available at the end of the chapter

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Abstract

In this study, we analyzed the seismic radiation and deformation characteristics of the 2011 Van earthquake during aftershock events with the support of estimated dynamic parameters (seismic b -value and radiation efficiency, ηR), 3D crustal cross sections of aftershock hypocenters, and deformation styles of Lake Van basin. The resulted variation in the b -value exhibits two dramatic changes in the b -value: one ($b > 1$) during the first 100 days of the mainshock and the other ($b < 1$) in the last 70 days of the mainshock. The constant b ($b = 1$) indicates a seismically active time interval and transitional variation in the b -value from high to low. The estimated b -value ($b > 1$) reveals that the aftershock sequence comprised a large number of the small and same-sized events of the Van mainshock due to the extreme material heterogeneity within the rupture zone. This indicates a general decrease in shear stress and increasing complexity in the focal area. The small value ($\eta R < 1$) of ηR implies that the amount of energy mechanically dissipated during the Van rupture process is large. This reveals that the microscopic breakdown process dominates the rupture dynamics and the whole Lake Van basin. The 3D crustal images of hypocenters suggest that the Van event originated in a strongly heterogeneous fractured setting with the aseismic sedimentary section of Lake Van. The high b -value combined with the low radiation efficiency (ηR) shows a strongly faulted-fractured sediment-rock formation filled with gas-fluid. This suggests that the seismic energy is intermittently released in the discrete form of aftershock events which is controlled by nonuniform and highly heterogeneous stresses, associated with the deformation style of Lake Van. The frequent redistribution of flickering stresses and nonlinear deformations in the rupture area increase the b -value and decrease the radiation efficiency.

Keywords: eastern Anatolia, Van earthquake, aftershocks, seismic b -value, radiation efficiency, micromechanisms, nonlinear deformations

1. Introduction

Eastern Anatolia is a seismically active accretionary complex region where the Arabian and Anatolian plates collide (**Figure 1a**). The Anatolian-Arabian plate collision takes place along a deformation zone, the Bitlis Thrust Zone (BTZ) (**Figure 1a**) [1–3]. A westward extrusion of the Anatolian plate is along the two major strike-slip faults: the dextral North Anatolian Fault (NAF) and the sinistral East Anatolian Fault (EAF) zones. These faults join each other at the Karliova Triple Junction (KTJ) in eastern Anatolia (**Figure 1a**). The east-west trending Mus-Lake Van (MRB) ramp-shaped lake basin is a conspicuous tectonic feature in the region and roughly reflects the N-S compression and W-E extension (**Figure 1a**) [1].

Figure 1. Major tectonic elements and seismicity of eastern Anatolia. (a) Major tectonic elements of eastern Anatolia with the $M_s \geq 6.0$ earthquakes epicenters (stars) and known focal mechanisms (compiled from [4–8]). KF, Karayazi Fault; TF, Tutak Fault; BTZ, Bitlis Thrust Zone; MRB, Mus Ramp Basin; NAFZ, North Anatolian Fault Zone; PRB, Pasinler Ramp Basin; KTJ, Karliova Triple Junction; EAFZ, East Anatolian Fault Zone; EF, Ercis Fault; HT, Hasan Timur Fault; AV, Ağrı Volcano; NV, Nemrut Volcano; TV, Tendürek Volcano; SV, Süphan Volcano. A large rectangle with large arrows encloses the map shown in **Figures 2** and **3** indicate relative plate motions. Map reprinted from Ref. [9] with kind permission of Springer Science and Business Media. (b) Epicenters determined by the KOERI network (inset map) are the basis of our analysis. The inset map shows seismographic stations used for reexamination of hypocenters in this study. A rectangle indicates the study area of this paper.

Two intraplate (midplate-related) earthquakes took place within an accretionary complex area, near the Lake Van basin (**Figures 1 and 2a**), the former 23 October 2011 Van event (M_w 7.1) occurred to the east of Lake Van and the later 9 November 2011 Edremit event (M_w 5.6) occurred to the south of Lake Van (**Figure 2a**). The preliminary source mechanism solutions of these earthquakes indicate almost pure thrust and oblique-slip faulting, respectively (**Figures 1 and 2a**). The epicenters of the two earthquakes were reported by Kandilli Observatory and Earthquake Research Institute (KOERI, Turkey) and by USGS (**Figure 1b**). The hypocentral and source parameters of these earthquakes estimated by different organizations and seismological institutes are summarized in the map views given in **Figures 2 and 3**.

Figure 2. Aftershock seismicity and faulting of Lake Van basin. Topographic maps of the Lake Van area and vicinity showing the epicenter distribution of aftershock events (5487 events) between 23 October 2011 and 13 April 2012 (173 days) (LE: Lake Erçek). Boundary faults of Lake Van basin are also shown in the maps (see the text for details). The main 14 aftershocks with magnitudes $M_w \geq 5.0$ as a function of time (245 days) are shown in A. The 189 aftershock events with magnitudes $M_w \geq 4.0$ as a function of time (248 days) are shown in B. The locations of the 2011 Van (M_w 7.1) and Edremit (M_w 5.6) earthquakes and their focal mechanisms are indicated in a, by different institutions (KAN, USGS, EMSC, AZUR, GFZ, ERD, HARV, INGV). (KAN: B.U. Kandilli Observatory and Earthquake Research Institute (KOERI); EMSC: European Middle East Seismology Center; AZUR: Nice University, GeoAzur Laboratory, France; GFZ: Geoforschung Zentrum, Potsdam, Germany; ERD: Disaster Management and Emergency Presidency, Ankara, Turkey; HARV: Harvard CMT; INGV: Instituto Nazionale di Geofisica e Vulcanologia, Italy; USGS: United States Geological Survey).

Figure 3. Aftershock seismicity, focal mechanisms, and faulting of Lake Van basin. Yellow lines demarcate the margin boundary faults and red dots indicate the aftershock distribution in the major basinal provinces of Lake Van basin. NM-bf, Northern Margin Boundary Fault; WM-bf, Western Margin Boundary Fault; SM-bf, Southern Margin Boundary Fault; ÇM-bf, Çarpanak Margin Boundary Fault; TB, Tatvan Basin; PR, Pressure Ridge; ÇSZ, Çarpanak Spur Zone; ISB, Internal Sub-Basin; F-KF, Fault-Kalecik Fault; LEF, Lake Erçek Fault; LE, Lake Erçek; GF, Gevas Fault; SV, Süphan Volcano; NV, Nemrut Volcano; PVD, Parasitic Volcanic Domes; MS, Mus Suture (black-dashed line) [12, 13]. 3D digital elevation block diagram of Lake Van basin shows relative fault motions and locations of some distinct events with fault focal mechanisms, as shown in **Figure 2**.

The Van earthquake (M_w , 7.1) was the largest thrust earthquake known to have occurred in the Van area (**Figure 2a**) and Turkey since at least the 1976 Çaldıran-Muradiye event of M_s , 7.3 [9–11] (**Figure 1a**). The Van earthquake was related to the oblique “blind” thrust faulting, which is inconsistent with mapped boundary faults in the Lake Van area [12–14]. Multifractal occurrence and distribution of long-period aftershock activity and focal mechanism of this larger event show a NE-SW striking rupture plane dipping toward northwest [15–17]. The rupture gradually expanded near the hypocenter and propagated both northeast and southwest, but mainly to southwest [15]. The 9 November 2011 (M_w , 5.6) Edremit earthquake (5–7 km depths) occurred offshore to the south of Van along the north dipping a normal oblique-strike-slip Edremit fault [9] (**Figure 2a**). The epicenter locations and the fault focal solutions of these earthquakes indicate that they occurred on different faults (**Figures 1b** and **2a**).

Seismic scaling relation shows that the way of quantifying the mechanical efficiency of earthquakes is with the radiation efficiency parameter (η_R) as defined in Ref. [18]. The smaller radiation efficiency ($\eta_R < 1.0$) or higher critical fracture energy [19] has an important implication for the rupture growth of the seismic activity and is easily comparable with the high b -values ($b > 1.0$) and time-dependent variability in the b -value. For the 2011 Van earthquake to determine the seismicity changes and understand the local stress state, the irregular changes in b -value were reported to be extremely localized spatially [20]. This case requires subsurface stress perturbations occurring at similar and smaller spatial scales. The 2011 Van earthquake combined with intense fluid withdrawal and gas migration [14, 21] may cause frequent redistribution of flickering stresses [22]. This leads to nonlinear effects such as the rapid development of an additional fault-fracture complex in Lake Van. This, in turn, facilitates the subsidence process [23, 24], increases the b -value ($b > 1.0$), and decreases the radiation efficiency ($\eta_R < 1.0$) in the mainshock area [24]. This inverse relationship means that the higher b -value causes the lower radiation efficiency and vice versa. Since, the massive fracturing and flickering stresses induce small-scale faulting movements and nonlinear deformations, which produce smaller earthquakes (microseismic activity) in the area of the mainshock and its vicinity. These nonlinear deformations contain elastoplastic and viscoplastic (or hydroelastic) components, which can change with time and depth, and the rate and the total amount of seismic deformation energy [22–24] and thus, control both the b -value and the radiation efficiency (η_R).

The aftershocks shown in **Figures 1b** and **2** associated with the 2011 Van mainshock still continue to occur today and there were several thousands of events from October 2011 to July 2012. In this study, it can be found that the aftershocks of the Van mainshock play a key role in the appearance of strong seismic coupling between basin-bounding faults, faulting style, and active deformation of Lake Van (**Figures 2** and **3**) and upper crustal seismogeneity [12–14, 25, and the references therein]. This allows for a detailed investigation of thousands of events in the focal region and provides an objective path to obtain an improved understanding of the stress state of the 2011 Van earthquake. Aftershock magnitudes of $M \geq 4.0$ observed in the 2011 Van event (**Figure 2**) may suggest that an amount of energy is not radiated and used in the form of fracture and frictional energy near the focal region [19]. Some of the nonradiated energy may also function to significantly increase the temperature in the focal region [16, 19, 26, 27]. The b -values calculated for various sizes of events in the 2011 Van earthquake suggest both high and low b -values. This variability in b -values is considered to support the idea that some part of the volcanic intraplate crust may have increasing mechanical heterogeneity (**Figure 4**). This may decrease the shear stress after the Van event. To test these concepts, imaging time and depth-dependent variability in b -value and correlating aftershock seismicity with b -values seemed to be an appropriate approach. In this study, a first attempt is made to interpret the variations in the b -value combined with the radiation efficiency (η_R) and the cross-sectional profiles of hypocenters of aftershocks. Thus, the current research of the 2011 Van earthquake aims to investigate the time-dependent distribution of seismic b -values of aftershocks in the light of the active tectonic deformation of Lake Van and provide a new view of the seismic deformation characteristics of this larger dip-slip event.

Figure 4. Velocity seismograms of hybrid and long-period (LP) events at the VANB broadband station. Examples of the three-component velocity seismograms of hybrid (A and B), LP events (C and D) recorded at the VANB broadband station and their normalized amplitude velocity spectra. Dashed arrows show the locations of classified earthquakes. (Md: duration magnitude, D: depth (km), X: distance from hypocenter to receiver (km), i: incidence angle measured from downward vertical ($^{\circ}$), Azm: azimuth angle ($^{\circ}$). Earthquake waveforms reprinted from Ref. [28] with kind permission of Springer Science and Business Media.

2. Structural setting and tectonic elements of Lake Van Basin

The Lake Van basin is the eastern continuation of the MRB and was separated from it by the Nemrut Volcano (NV) with parasitic volcanic domes (PVD) [1, 2] (**Figures 1a** and **3**). Deformational patterns of the lake have been formed as a result of the tectonic structure of eastern Anatolia [14, 29]. Lake Van was formed through a combination of normal and strike-slip faulting and thrusting [1, 2, 29]. The strike-oblique-slip deformation in Lake Van caused distinct strike-slip sedimentation, extensional magma propagation through boundary faults (see **Figure 2**), upper crustal seismicity, and hydrothermal activity [12–14, 29–33].

The multichannel seismic reflection profiles collected from Lake Van basin [12–14, 21, 25, 34, 35] and bathymetry data [36–38] revealed that the lake basin is dominated by a deep Tatvan basin (TB), north-eastern delta (NE-delta), and a south-eastern delta (SE-delta) (**Figure 3**). The lake is completely bounded by steep, oblique boundary faults, namely the northern boundary fault (NM-bf, transpressive), southern margin boundary fault (SM-bf, transtensive), western margin boundary fault (WM-bf, transtensive), and Çarpanak margin boundary fault (ÇM-bf, transpressive) (see **Figure 3** for the sense of shear). In the current study, ÇM-bf is currently named because of its prominent location close to Fault-Kalecik Fault (F-KF) or Van Fault [39]. These marginal faults have a basinward, downthrown side (TB in **Figure 3**), and gently folded

sedimentary sections on the downthrown side of these faults together with some small splay faults (**Figure 3**).

The location of the 2011 Van mainshock and epicentral distribution of its aftershocks (**Figures 1 and 2**) occurred in a wedged-shape area (**Figure 3**) that is transpressively uplifted by major boundary faults, namely ÇM-bf (F-KF) in south and NM-bf in north (**Figures 2 and 3**). These faults are prominent structural elements, controlling the dextral faulting regime in the east of the lake and also the 2011 Van mainshock. Ref. [40] gave field evidence for possible dextral faulting, extending roughly in the E-W direction, east of the eastern shore of the Lake Van basin (**Figure 3**). These faults have been mapped by several studies such as Lake Erçek Fault (LEF), Kalecik fault [40, 41], inferred Edremit fault (EF) [40, 42], Gevas fault (GF) [43, 44] (**Figure 3**). These faults are dextral oblique-slip faults lying east and south-east of the Lake Van basin [9, 45, 46].

High heat flows, hydrothermal discharges, and CO₂-emissions in Lake Van may give some evidence of seismic ductile events (high *b*-value) in the upper crust beneath the lake. Ref. [28] observed three types of seismic events (≤ 10 km) on the spectral band of earthquake waveforms in and around the Lake Van area: hybrid events, long-period (LP) events (see **Figure 4**), and a kind of tremor. In the study, Ref. [28] revealed the presence of upward rising of magmas and the instability of high viscous lava domes [47] in and around the Lake Van basin. The calculated high *b*-values in this study were associated with an increase in material heterogeneity [48] and thermal gradient [28, 49] near the Lake Van area.

3. Data and methodology

3.1. Used data

The earthquake catalog published by Kandilli Observatory and Earthquake Research Institute [50] of Turkey was used to determine the seismicity pattern of aftershock events as a function of time and develop the clean images of the seismic *b*-values. Fifteen permanent broadband seismic stations with high-gain seismometers provided real-time data (**Figure 1b**). After the Van event, eight temporal seismic stations were operated by KOERI around the Lake Van area. The location errors in the focal depths of the aftershocks are about 2–3 km [17, 20, 27, 51]. We did not relocate the focal depths of aftershocks and only precisely located focal depths of aftershocks were used in our study (see Refs. [17, 20] for the criteria used to select high-quality events and the focal depths). The uncertainties in the focal depths are considered not to affect the *b*-value estimates and the main results in this study. The earthquake catalog of the study area includes Lake Van basin, spanning the period 23 November 2011 to 5 July 2012 and contains 6005 events over 255 days. The depth and magnitude of the earthquakes range from 5 to 30 km and 1.5–7.1 M_w , respectively. To establish cross-sectional images of the hypocentral depths and epicenter distribution of the aftershocks, we selected 5304 event epicenter distributions for a time period from 23 November 2011 to 28 March 2012 (**Figures 1b and 3**).

3.2. Frequency-magnitude relationship

The frequency-magnitude distribution (Eq. (1)) defines the relationship between the frequency of occurrence (N) and the magnitude of earthquakes. The size distribution of earthquakes is adequately described by the G-R relation [52]:

$$\log_{10} N(\geq M) = a - bM \quad (1)$$

where $N(M)$ is the frequency of earthquakes with magnitudes higher than or equal to M , and the parameter a is a real constant that characterizes the seismic activity. The b -value varies regionally, both spatially and with depth and describes the relative size distribution of events.

The frequency-magnitude distribution (Eq. (1)) and the variation in the b -value depend on the tectonic and rheological conditions such as material heterogeneity, crack density, thermal gradient, creep, applied stress, and asperities [48, 53, 54]. The analyses of laboratory data and observed seismicity suggest that the b -values are related to strength heterogeneities and the state of stress on a fault [48, 53, 55, 56]. The estimated b -values of regional and global seismicity also exhibit systematic dependencies on depth, focal mechanisms, and other statistical variables [16, 27, 57–61].

Although the b -values equal 1 over long-timescales and large spatial scales, significant variations occur on smaller scales. A b -value greater than 1.0 is related to the areas of crustal heterogeneity and low applied stress [61–63]. However, the b -value lower than 1.0 indicates high differential stress [61–63] and volumes with crustal homogeneity [64–66].

In this study, the b -value was estimated by the maximum-likelihood (ML) method [67] and calculated using ZMAP software [68]:

$$\log_{10} e = b (M_{mean} - M_C) \quad (2)$$

where M_C is the minimum (cutoff) magnitude of the given sample [69], M_{mean} is the mean magnitude, and the variable “ e ” is the Napier's number (base of the natural logarithm), which is approximately 2.7183. This formulation is described by a linear relationship with the constants a and b . It is generally about 1 depending on the number of aftershocks in the time and region sample (a) and the slope (b). The shorter the time and/or the smaller the area, the more the fit is degraded by the statistics of small numbers [70]. In a statistical study conducted by Ref. [27], about 5454 aftershock events were obtained by sampling longer intervals (256 days) in a large epicentral area (the Lake Van) and this produced better fits (see Ref. [27]). Although the aftershock data in that study were generally well described by the linear relationship, some deviations were observed. The data deviated from the $b = 1$ line for very small ($M_C < 2.5$) magnitudes and the aftershock events with $M_C > 2.5$ closely followed the G-R relation with $b = 1$. This result suggests that the G-R relation and Omori-Utsu law provide good overall descriptions and estimations of aftershock seismicity [27].

In this study, the standard deviation (δb) in the b -value was estimated using Eq. (3) devised by Ref. [69] and modified by Ref. [71]:

$$\delta b = 2.3b^2 \sqrt{\frac{\sum (M_i - \{M\})^2}{n(n-1)}} \quad (3)$$

where n is the sample size.

Detectable minimum magnitude (M_C) is a necessary parameter using with the maximum number of aftershock events over a long period of time to achieve a more accurate analysis [72, 73]. The variation in M_C as a function of time during the period 23 October 2011 to 1 August 2012 was shown in Ref. [27]. M_C irregularly fluctuated due to the large number of aftershock events, and the strong changes in seismicity.

The depth-dependent variations of the b -value were imaged using the focal depths of events (5 days $\times$ 5 km), which were densely clustered from 5 to 15 km. The depth cutoff technique is not used; however, focal depths more than 15–25 km are not taken into account in this study. We chose to use a time interval approach to image the b -value. The variation in the b -value as a function of time and focal depth is imaged for sampled time interval (170 days) including 5454 aftershock events (**Figure 5**). To perform high-resolution images of b -values, we tried different time intervals of 70 days and increased the window to 1930 events for the interval between the 20th and 90th days (**Figure 6a**) and to 855 events for the interval between the 100th and 170th days (**Figure 6b**). This was required due to the distinct variation in the foo of the observed events as a function of time (cumulative number of events/per days).

3.3. Seismic scaling relations

Static stress drop $\Delta\sigma_s$ is roughly constant over a range of M_0 from 10^{18} to 10^{23} N m [19]. Ref. [17] estimated that in the 2011 Van earthquake with its 18 km focal depth, the $\Delta\sigma_s$ is, on average, approximately 10–15 MPa. This range is roughly consistent with the assumption that the rupture-front velocity (V_r , 3.2 km/s) is, on average, similar to the S-wave velocity (V_s , 3.9 km/s) of the Van earthquake (see Ref. [17] for the velocity model). The scaled energy, $\tilde{e}$, is a dynamic parameter that can be determined by the ratio of the radiated seismic energy to seismic moment;

$$\tilde{e} = E_R / M_O \quad (4)$$

This ratio can be interpreted as proportional to the energy radiated per unit fault area and per unit slip [74, 75]. In this study, following the approach of Ref. [19], $\tilde{e}$ is taken as a constant, because the static stress drop, $\Delta\sigma_s$, is constant. E_R is difficult to determine accurately due to the complex wave propagation and scattering effects of the 2011 Van earthquake. It is estimated

that $\tilde{\epsilon}$ is, on average, approximately 5×10^{-5} with a range 10^{-4} – 10^{-6} for large earthquakes ($M_w \approx 7.0$) [19, 76, 77].

Figure 5. Time and depth-dependent variation in the b -value and aftershock seismicity pattern. Time and depth-dependent variation in the b -value is correlated with aftershock seismicity that indicates the time-dependent variation in magnitude and focal depths of 5454 events for 170 days. Standard deviation (SD) in the b -value falls in the range of 0.05–0.09. Dots show the distinct events with magnitudes ($M_w \geq 4.0$). Note the time-dependent relation and compatibility between variation in the b -value and magnitudes of events. This indicates that a relative increase in the number of the events ($M_w \geq 4.0$) is compatible with the decrease in the b -value (see the first days).

Figure 6. High-resolution images of time and depth-dependent variation in the b -value. High resolution images of time and depth-dependent variation in the b -value given in A for the calculated 1930 events between the 20th and 90th days ($b > 1$) and in B for the calculated 855 events between the 100th and 170th days ($b < 1$).

The radiation efficiency, η_R , determines the dynamic character of an earthquake [18, 19, 77]. A relation between η_R and observable seismological parameters was obtained, thus:

$$\eta_R = 2\mu \tilde{\epsilon} / \Delta\sigma_s \quad (5)$$

where, $\tilde{\epsilon}$ is 5×10^{-5} ($\tilde{\epsilon}$ is always less than 10^{-4}) [19, 78], $\Delta\sigma_s$ represents the static stress drops with a range 10–15 MPa, and μ is a shear modulus, 3×10^4 MPa for the 2011 Van earthquake. The seismic moment M_0 5.37×10^{19} N m (M_w , 7.1 and the centroid focal depth 18 ± 2 km) in the waveform fit using a shear modulus μ of 30 GPa (the rigidity of the top 15 km) is given by the velocity model proposed by Ref. [17] for the Van earthquake (see [17]). Using the estimates of these parameters, the radiation efficiency, η_R , is determined for the 2011 Van earthquake using Eq. (5).

The computed η_R values of the 2011 Van earthquake typically fall in the range of 0.2–0.3 within a range of 10–15 MPa ($\Delta\sigma_s$). It is also estimated that the η_R value is 0.6 for a value of 5 MPa ($\Delta\sigma_s$) (data from Ref. [17]). The radiation efficiency of most earthquakes lies between 0.25 and 1. Ref. [19] classified the radiation efficiency for the rupture zone interpretation as follows:

If $\eta_R = 1$, the breakdown zone is unimportant and failure occurs primarily in the steady-state regime. No energy is mechanically dissipated and the potential energy is radiated as seismic waves, after the heat loss has been subtracted, and the earthquake is considered to be a very brittle event. If $\eta_R = 0$, no energy is radiated, the event is quasi-static and even if the static stress drop is very large as in the range of 10–15 MPa estimated in this study. If $\eta_R \ll 1$, the microscopic breakdown process dominates the dynamics.

4. Results

4.1. The variation in the *b*-value as a function of time

In this study, the estimated *b*-value varies from 0.93 to 1.07 for 5454 events (**Figure 5**), 1.06 to 1.15 for 1930 events, and 0.85 to 0.99 for 855 events (**Figure 6**). The estimated *b*-values generally fall in the range 0.85–1.15 with standard deviations (δb) in the range of 0.05–0.09 (**Figure 5**). The range of the standard deviation (δb) is relatively low.

The resulted variation in the *b*-value clearly exhibits two dramatic changes in the *b*-value, one ($b > 1$) during the first 100 days of the mainshock and the other ($b < 1$) in the last 70 days of the mainshock (**Figure 5**). **Figure 5** shows that the event magnitude begins to drop considerably, corresponding to the time interval of the high *b*-value, and after that it continues to drop, corresponding to the time interval of the low *b*-value and it decreases significantly. These remarkable changes can be seen to coincide with the 23 October 2011 (M_w , 7.1), Van and 9 November 2011 (M_w , 5.6), and Edremit events (**Figure 2a**).

The variation in the *b*-value after the mainshock ranges from 0.93 to 1.06 for 5454 events over 170 days, suggesting a relatively small change in *b*-value (**Figure 5**). After a large number of aftershocks, the *b*-value began to drop slightly, reaching a normalized constant value. The constant *b* is typically equal to 1.0, indicating a seismically active time interval (**Figure 5**). This interval may indicate a transitional variation in the *b*-value. Then, the *b*-value continued to

drop, reaching its lowest value ($b < 1$ in **Figure 5**). **Figure 5** shows the b -value ranging from 1.06 to 1.0 over the first 100 days and from 1.0 to 0.93 over the last 70 days. High b -values suggest that a large number of small or same-sized aftershocks of the Van and Edremit events are dominant. However, low b -values suggest a relative decrease in the smaller magnitudes of events and an increase in the medium magnitudes of events (**Figure 5**). This reveals that the time-dependent variation of individual events with magnitudes ($M_w \geq 4.0$) dominantly resulted in low b -values.

Time and depth-dependent differences in b -values illustrate significant seismic variability (**Figure 6**) for different intervals. We clearly observed a sharp decrease in the b -value, from 300 to 100 events, between the 20th and 25th days, typically giving a “sharp stress drop pattern” of intraplate seismicity [27, 79, 80]. We selected the 20th day as a starting point, extending to the 90th day (**Figure 6a**). After the sharp pattern of stress drop, the selected interval between the 20th and 90th days (**Figure 6a**) seems to be well suited to reveal and understand the superimposed effects of the first (Van) and the second (Edremit) mainshocks on the variation in the b -value. From the 90th day, the relative number of individual events with magnitudes of $M_w \geq 4.0$ considerably increases toward 170th day (**Figure 6b**). The Van mainshock was followed by a b -value increase near the source area during approximately 100 days after the mainshock (**Figure 6a**). The variability in the b -value for time interval between the 20th and 90th days was between 1.06 and 1.14 (**Figure 6a**) for 1930 events, which suggests $b > 1$, while the variability ranges from 0.85 to 0.98 for 855 events suggesting $b < 1$, and for the time interval between the 100th and 170th days it was between 0.85 and 0.98 (**Figure 6b**). **Figure 6a** shows the increase in the b -value for the period between the 20th and 90th days and it is followed by a slight decrease in the b -value, to 0.85 minimum (**Figure 6b**). The zone of the low b -value (0.85–0.98) anomaly (**Figure 6b**) was found in the vicinity of the epicenter of the mainshock (**Figure 2a**). This low b -value in the focal area indicates that medium-sized events are likely to take place (**Figure 2b**).

As shown schematically in **Figure 7**, the high and low b -values illustrated for the 5454 events over 170 days (**Figure 5**) correlated with high-resolution images of variation in the b -value for 1930 events and 855 events (**Figure 6a** and **b**, respectively). The schematic illustration of the variation in the b -value shows that the b -values are consistent with basin-bounding faults, fault focal mechanisms, and the magnitudes of the events (**Figure 3**). In **Figure 7**, the observable increase in the b -value is correlated with lowering the effective stress level. This indicates increased material heterogeneity and reduced shear stress [81]; however, the dramatic decrease in the b -value is correlated with rising effective stress level prior to major medium-sized earthquakes [82], indicating high stress accumulation and an increase in shear stress [81].

4.2. The frequency-magnitude statistics of the aftershocks

We estimated the b -values for various sizes of aftershocks and then showed the obvious anomaly of aftershock seismicity pattern. Our results mainly relate the variations in the b -value to the stress state and temporal stress transfer in and around the focal area.

The variation in the magnitude of completeness (M_c) (23 October 2011 to 1 August 2012) irregularly fluctuated due to the large number of aftershocks, and the rapid changes in seis-

micity (see data in Ref. [27]). A moving window approach was chosen to create a temporary change in M_c with a window size of 5454 events to observe the M_c for the sequence (256 days), using the maximum curvature [27]. The variations in the minimum magnitude (M_c) for the entire catalog ranged from 1.4 to 2.3. The M_c for the aftershock sequence was estimated to be equal to 2.5 with a 95% goodness-of-fit level [27].

Figure 7. Correlation of the variation in the b -value with aftershock seismicity. Correlation of the time and depth-dependent variation in the b -value with aftershock seismicity given in **Figure 5** and the high-resolution images of variation in the b -value given in **Figure 6**. White-dashed lines show time intervals for b -values.

Ref. [27] calculated the exponential and linear plots of the b -value for events larger than M_c with one population; the G-R distribution of events smaller than 7.1. The G-R statistics ranged over the magnitude interval $M_c < M < M_{\text{mean}}$. For the 5454 aftershock events, there was a variation in the b -value ranged between magnitudes 2.5 (M_c) and 7.1 (M_{mean}). The b -value for this sequence was estimated to be equal to 1.9 ± 0.05 with a 95% goodness-of-fit level [27]. This supports the idea that the aftershock events follow the G-R frequency-magnitude statistics of events [52].

Ref. [20] reported that M_c for the Van sequence was estimated to be equal to 2.6 with 90% goodness-of-fit level and that the b -value for this sequence was estimated to be equal to 0.89 ± 0.02 with a 90% goodness-of-fit level (see Ref. [20] for the spatial variations of M_c). Because the b -value is lower than the global mean value of 1.0, Ref. [20] reported that the Van sequence consisted of larger magnitude aftershocks and high differential crustal stress in the regime. However, this result is considerably different from the result from the current study due to the higher b -value ($b > 1.0$). The higher b -value indicates that the Van aftershock sequence consists of smaller and/or medium-sized magnitude aftershocks and relatively low differential crustal stress in the focal area [61, 83].

In the previous studies, the observed b -values of regional seismicity fall in the range 0.7–1.3 [57–59] and in the range 0.7–1.2 [20] for the Van sequence. The cross-sectional maps of depth distribution of the b -value performed by Ref. [20] fall in the range 0.8–1.65. The b -values vary from 0.9 to 1.5 along the Van rupture fault zone computed by Ref. [84]. These results clearly indicate that the estimated b -values with the low (δb) in this study are statistically significant. The estimated b -values in this study are also correlated with the slip distribution models of the 2011 Van mainshock obtained through the inversion of seismological and geodetic data from Ref. [84]. Thus, we can explain a possible physical process over the source fault or surrounding crustal volume that may control the b -value as a function of time.

4.3. The hypocentral cross sections

A prominent aseismic zone can be observed in the deep central basin of Lake Van (TB), where no remarkable events are recorded (**Figure 3**). Aseismicity suggests that there is clear evidence of seismic quiescence (SQ) in this area (TB) (**Figure 3**). This may imply a strong structural asymmetry between the seismic (ÇSZ-LEF-LE) and aseismic zones (TB) in Lake Van (**Figure 3**). This asymmetry is also illustrated by the depth distribution of the epicenters at upper crustal depths (**Figure 8**). In the hypocentral cross sections in **Figure 8**, aseismic (TB) and seismic zones (ÇSZ-LEF-LE) with strong crustal asymmetry are referred to as seismic quiescence and uplifting (U) zones, respectively (which can be seen by comparing **Figure 3** with **Figure 8**). The aseismic (TB) or seismic quiescence zones are distressed and declustered, while seismic zone (ÇSZ-LEF-LE) or the uplifted (U) area are highly stressed and clustered. The SQ zone extends over a thick sedimentary volume of TB surrounding the focal zone, while the U zone is rooted in a fault-bounded block basement (ÇSZ). Previous seismic reflection studies reported that the deep central basin (TB) of Lake Van is thick depositional province (600 m), onlapping onto the shallowing delta settings (NE-delta), toward ÇSZ where the deposition is sharply terminated, reaching a thickness of sediments of 150–250 m. Sediment termination is occurred due to the fault-bounded block uplift (ÇSZ) [12–14]. This finding reflects a typical pattern of strike-/oblique-slip deformation and sedimentation [1, 2, 85] and is in good agreement with the high and low b -values (**Figure 7**) and the seismic asymmetry (**Figure 8**).

Time-dependent variability in the b -value from high to low (**Figure 7**) and the aseismic TB (**Figure 3**) may suggest a low b -value with the occurrence of medium-sized events near to the focal area in future (events with $M \geq 4.0$ in **Figure 5**). This assumes a basinal stress transfer [79] from TB through the boundary faults toward ÇSZ and the focal area (**Figure 3**). The low b -value is interpreted as there being a complex fault network area, highly strained (or locked) and a stress condensation zone nearby the focal area (**Figures 2 and 3**). This zone may indicate asperities on the complex faults prior to a large dip-slip earthquake [79]. This complex zone seems to be an isolated fragmentation barrier [86], implying a strong seismic coupling between the Lake Van basin and the focal area (**Figures 2 and 3**). This barrier is the probable zone for future medium-sized earthquakes (**Figures 2a and 5**). This suggests that high stresses are being accumulated and condensed, causing a potentially locked zone near the focal area.

These results indicate that the variation in the b -value for 170 days implies a highly fractured and heterogeneous earthquake setting. The 2011 Van earthquake and its aftershock distribution

were controlled by irregular stress and strain patterns in and around the focal zone, associated with the present-day deformation style of Lake Van basin (**Figure 3**). This suggests that remarkable physical and mechanical changes occurred in the seismic deformation potential of the crust beneath the Lake Van basin.

Figure 8. Hypocentral profiles of aftershock events. Low-resolution cross-sectional images of the hypocenter distribution of 5304 events indicate radiated patterns of seismic density of events at crustal depths shown by sections projected on the shaded relief map. W-E projections are shown by A and C and N-S projections are shown by B and D. W-E and N-S cross-sections seen in C and D are the sections toward the south. Directions are indicated by black-dashed arrows to show seismic density changes in different projections. Note that the deep central basin of Lake Van is aseismic, indicating seismic quiescence (SQ) zone and the focal area is seismic with high event density, indicating the uplifted (U) zone (see **Figure 3**) (depths in km $\times$ 100).

5. Interpretation and discussion

The time-dependent variability of the b -values (**Figure 7**) of the 2011 Van earthquake provided useful and significant information about the seismic deformation characteristics of the Van mainshock. The computed b -value distribution as a function of time over the Van focal area underwent significant variation throughout the aftershock sequence. The Van event was followed by aftershocks of variable medium magnitudes. The data given in **Figures 2** and **3** show that aftershock seismicity is concentrated in time and space in relation to the principal mainshock event, growing nonlinearly and widely varying in space and time.

The resulting variation in b -value can be seen to coincide with the two mainshocks of the Van (23 October 2011) and Edremit (9 November 2011) events (**Figure 2a**). In this study, the variability in the b -value is correlated with decreasing and increasing effective stress levels. The basinal distribution of events, hypocentral cross sections, active tectonics, and deformation style of the Lake Van basin suggest that differing amounts of rapid stress changes over 170 days or the type of driven mechanism at crustal depths caused the variations in the b -value (**Figure 7**).

5.1. Stress state as a function of time

The magnitude characteristics of the aftershocks, including the low b -values (**Figure 7**), are strong evidence of the cause resulting from high stress accumulation. The individual events with magnitudes of $M_w \geq 4.0$ as shown in **Figure 5** can be interpreted as indicating the potential zones of locked faults and reducing the b -value. However, the magnitude characteristics of the aftershocks, including the high b -values (**Figure 7**), are being caused by extreme crustal heterogeneity. The large number of smaller events with magnitudes of $2.0 \leq M_w \leq 4.0$ can be interpreted as indicating a decrease in shear stress and increasing the b -value. The strong clustering of aftershocks with time and variable b -values over 170 days fits with an inhomogeneously stressed crust with high fracture energy. The high amount of fractured energy reduces the strength, causes low shear stress (high b -value), and allows the stress to be released [19], but the fracture energy can also create locked seismic zones (low b -value) (see events $M_w \geq 4.0$ in **Figure 5**).

High-resolution images of the b -values for time intervals from the 20th to the 90th day (**Figure 6a**) and the 100th to the 170th day (**Figure 6b**) are shown in **Figure 7**. The high b -value over 70 days may have some similarities to the swarms [87]. However, the low b -value indicates locked fault zones. As shown in **Figure 7**, the Van and Edremit events considerably lowered the general stress in the area (see Ref. [79] for the amount of stress drop). The smaller magnitudes are dominant until the stress builds up again (**Figures 5** and **6a**). Then, the medium magnitudes are dominant, reducing the b -value (**Figures 5** and **6b**). In **Figure 7**, the difference in b -values from the 20th day to the 90th day and the 100th day to 170th day period may be an indicator of a situation where there is stress transfer from a lower to a higher stress. This difference can be interpreted as the stress redistribution of the Van aftershock sequence [27]. This stress pattern indicates that the aftershock events (the October 2011) may have promoted and triggered the events (the November–December 2011 and the January 2012). This result is consistent with the Coulomb stress variation in the entire region of Lake Van [20, 88] and temporal and spatial distribution of the b -values [84].

5.2. The variability in the b -value and the radiation efficiency (η_R)

As stated above, the high b -values in **Figure 7** indicate a general decrease in shear stress and increasing complexity in and around the focal zone. There is a slight variability in the b -value from high to low (**Figure 7**). This suggests an increase in the stress level, from low shear to high effective stress. The stress is transferred from the interval dominated by high material heterogeneity and fracture energy to the interval dominated by high stress accumulation and strain condensation.

Previous studies have stated that a large number of smaller and/or same-sized aftershock events with a long-time duration can represent the small values of the radiation efficiency parameter (η_R) [19]. This suggests that the fracture energy of seismic deformation is much greater than the radiated energy. This simple relation can determine the dynamic character of the 2011 Van earthquake [27]. This study has shown that for the 2011 Van earthquake, the radiation efficiency, which is given by $\eta_R = 2\mu\tilde{e}/\Delta\sigma_s$, is smaller than 1. This value implies that

the microscopic breakdown process dominates the dynamics of faulting and the fracture energy [19]. The amount of energy mechanically dissipated during rupture is relatively larger than that of the energy radiated as seismic waves. Time period between the 20th and 90th days (high b -value in **Figure 7**) can be interpreted as a fault or fracture density-dominated period. This period implies a maximum fracture energy and related breakdown micromechanisms occurring during the Van mainshock.

5.3. The shallow gas and microseismicity

Various shallow gas indicators have been observed from multichannel seismic reflection and chirp data from Lake Van [21]. Strong evidence of the shallow gas accumulations in Lake Van includes acoustic blanking, pockmarks, seismic chimneys, bright spots, mound-like features, and enhanced reflections (**Figures 9b** and **c**).

Figure 9. 3D-faulting and deformation map of Lake Van basin with aftershock seismicity. 3D-digital elevation block diagram of Lake Van basin with its boundary faults and epicentral distribution of the Van aftershock sequence show deformational relations between faults, deep Tatvan basin (TB), and aftershocks in A (see **Figure 3**). Inferred transpressional faults (dextral) at crustal depths compiled from previous studies [10, 29, 40] are hypothetically shown in this diagram. Numbers (1–5) represent faults. Number 1 is MS Mus Suture, 2 is GF Gevas Fault, 3 is EF Edremit Fault, 4 is F-KF Fault-Kalecik Fault, and 5 is eastern segment of NM-bf, Northern Margin Boundary Fault (see **Figure 3** for these faults). Distribution maps show seismic chimneys in B, acoustic blanking, pockmarks, bright spots, and mound-like features in C (data obtained from Ref. [21]). The wide area shown by black-dashed line indicates the epicentral image of aftershock hypocenters at focal depths between 5 and 25 km. The inverse relationship between the radiation efficiency and the b -value is compatible with depths at 5–25 km shown in B and C (see b -value depth profiles in Ref. [20]). TB-S, Tatvan Basin-Subsidence; ÇSZ-LEF-LE, Çarpanak Spur Zone-Lake Erçek Fault-Lake Erçek; and ISB, Internal Sub-Basin.

The enhanced reflections observed at more than 200 locations suggest the presence of free gas in Lake Van with seismic chimneys, suggesting the emission of gases (**Figure 9b**). Some of these chimneys have pockmarks (**Figure 9c**), which may be vertical vents or conduits for active fluid emission. Faults, fractures, and fissures may provide migration pathways for deep gas in TB. The acoustic blanking (**Figure 9c**) indicates that changes in the hydrostatic pressure may control the formation and preservation of the gas-charged zones. The mound-like features

(mud volcanoes) (**Figure 9c**) suggest active gas emission and venting activity. Bright spots, which are a characteristic of gas accumulations, indicate gas-charged zones (**Figure 9c**). These pockmarks are only seen in the northeastern part of the lake. The absence of pockmarks in other parts of the lake (**Figure 9c**) can be due to a higher permeability of the lake sediments [14, 21].

These observations show that the thicker and unconsolidated soft sedimentary section, and the deformation style of Lake Van (turbiditic wedges, debris flows, tephra deposits, and progradational clinoform packages and the steep oblique-slip boundary faults) [12–14, 21]) have the potential to provide ideal conditions that allow the sediments in TB (**Figure 9a**) to act as a gas and/fluid reservoir (**Figures 9b** and **c**). This suggests that a gas-soft sediment mixture modulates the preferential emission of deep-sourced fluids through the faults, fractures, and/or fissures in Lake Van and in particular aseismic TB (**Figure 9a**). The abrupt changes in the sedimentary section hamper the fluid transport in the sediments of TB. This process of the gas-sediment-fluid mixture in Lake Van has the potential of many smaller and same-sized magnitude aftershocks (microseismicity) that increases b -value ($b > 1.0$) and dramatically decreases the rate of seismic radiation ($\eta_R \ll 1$) (**Figures 9b, c**, and **10**). Since, the gas accumulations with the local release of deep and/or shallow fluids, soft sediment deformations, and fractures in Lake Van can amplify each other [24] and control the asymmetric distribution and localization of aftershock events as a function of depth (**Figure 10**).

Figure 10. Cluster patterns of seismic density of aftershock events. High-resolution cross-sectional images of the hypocenter distribution of 5753 events indicate the localized cluster patterns of seismic density of events at crustal depths shown by sections projected on the shaded relief map. NE-SW projections are shown by A and B and W-E and N-S projections are shown by C and D, respectively. NE-SW cross section seen in A is the section toward the east to show event clusters (B) in different projections. Note that the deep Tatvan basin (TB) of Lake Van is aseismic, indicating no events recorded and the focal area is highly seismic with event clusters seen in B, C, and D, indicating the uplifted (ÇSZ-LEF-LE) zone (see **Figure 3**) (focal depths of 5753 events in $\text{km} \times 100$ and given by colored scale in A).

The epicenters of aftershock events are densely clustered in a wedge-shaped narrow area, bounded by the west-east extending ÇM-bf, F-KF and NM-bf. This narrow area is a fault-bounded, uplifted block by ÇM-bf and NM-bf (ÇSZ-LEF-LE) (**Figures 3, 9a, and 10**). ÇSZ is interpreted to have been cut by an inferred LEF extending from LE in the east to Lake Van in the west (**Figures 3 and 9a**). The deformational features of Lake Van, especially ÇSZ, ÇM-bf, and NM-bf, are structurally related to the two mainshocks of the Van and Edremit events (**Figure 2a**) and the variability in the b -value. In this study, a concept of seismically active (ÇSZ-LEF-LE) and passive (TB) zones is proposed for the whole Lake Van region (**Figures 3, 9a, and 10**) and it is argued that the results in this study may indicate TB as a relaxation barrier and ÇSZ-LEF-LE as a fragmentation barrier [86] (**Figures 9b, c, and 10**).

This study for the first time takes into account the low seismic radiation (high seismic deformation), considering the b -value combined with the radiation efficiency (η_R) that also represents microprocesses and differential stress in the rupture area.

6. Conclusions

In this study, the time and depth-dependent variability in the b -value of the G-R relation, the radiation efficiency (η_R), and related aftershock seismicity patterns were investigated for the Van earthquake of 23 October 2011. The main conclusions are summarized as follows:

The variation in b -value is associated with the two mainshocks in Van (23 October 2011) (M_w 7.1) and Edremit (9 November 2011) (M_w 5.6) earthquakes. We assume a possibility that the changes in b -value reflect changes in the local stress state in the vicinity of the aftershocks. The variability in the b -values may be correlated with decreasing and increasing effective stress levels near the focal area. The increase of b -value implies that there was an increase in material heterogeneity and a decrease in shear stress. The b -value drop is likely to infer an increase of effective stress and continuous stress accumulation. This indicates that there are potentially locked zones in and around the focal area (seismic ÇSZ-LEF-LE area as a fragmentation barrier).

The main result of the 2011 Van and Edremit earthquakes is that they considerably lowered the general shear stress in the area (high b -value) and increased complexity in and around the focal zone. The epicentral distribution of aftershock seismicity reveals a chaotic picture of clustering of events and irregular variation in magnitude as a function of time. The anomalous occurrence and distribution of aftershock seismicity with variable b -values over 170 days fits an inhomogeneously stressed crust with high fracture energy, causing low (high b -value) and high shear stress (low b -value). Differing amounts of rapid stress changes over 170 days or the type of driven mechanism could have caused the variation in the b -values. The high and low b -values over 170 days suggest that remarkable physical and mechanical changes occurred in the seismic deformation potential of the crust. The time-dependent seismic variability of the events with varying b -values for different time intervals is an indicator of a situation of stress transfer from a lower to a higher stress, associated with active tectonic deformation and the faulting style of the Lake Van basin.

The small radiation efficiency (η_R) (low seismic radiation/high seismic deformation), considering the high b -value combined with gas-fluid-fracture-sediment mixture in aseismic TB (relaxation barrier) represents high fracture energy and differential stress in the rupture area. The complexity of the Van earthquake rupture pattern suggests that the microscopic processes (high b -value) on the fault planes seem to have played very important role in controlling the rupture dynamics and deep basinal section (TB) of Lake Van. This indicates that more than a single process controlled local stress state and the rupture process in the 2011 Van earthquake. The slip zone was governed by the complex processes and this caused the occurrence of a significant rise (low b -value from the distinct slip localization of locked or strained faults) and drop (high b -value) in the friction near the focal area. This assumes that an amount of energy was not radiated and deposited near the focal region in the form of fracture and frictional energy in the 2011 Van event.

Finally, the seismic uniqueness of the 2011 Van earthquake must be considered. This research is the first to take into account the low seismic radiation (high seismic deformation) and examine the b -values associated with active tectonic deformation and faulting style of the epicentral region following the Van earthquake. In this study, as different from the previous studies, a first attempt has been made to interpret the variations in the b -value combined with the radiation efficiency (η_R) and the cross-sectional profiles of hypocenters of aftershocks as most essential seismic parameters of possible increases in the nonlinear stresses. This research has significant implications for the 2011 Van mainshock as an intraplate seismogenic paradigm and the thin-skinned seismic deformation of the Lake Van area during the post-collisional period.

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