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Research Article

Potential of Fractal Analysis of Earthquakes through Wavelet Analysis and Determination of *b* Value as an Aftershock Precursor: A Case Study Using Earthquake Data between 2003 and 2011 in Turkey

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The b value of earthquakes is very useful to forecast the occurrence of aftershocks in a given region. The b value characterizes the release of energy due to stress accumulation in the rocks through an earthquake and is a direct indicator for the prediction of aftershocks in the region. Wavelet based fractal analysis is used in this study to determine the b value by calculating the fractal dimension. This method guarantees high accuracy results through a limited dataset. The objective of this work was to demonstrate an elegant method for the determination of the b value after an earthquake and predict the occurrence of aftershocks with high accuracy. Repeated earthquakes were analyzed between 2003 and 2011 in Turkey and the b value was found for these earthquakes. The results gave an indication that the b value of the mainshock and its aftershocks are different and aftershocks occur in the region when the b value of the mainshock deviates significantly from 0.5, and aftershocks keep occurring until the b value of the earthquake approaches close to 0.5 for this region.

1. Introduction

Prediction of earthquakes is an important step in preventing large loss of life and property. Earthquakes mainly occur due to failure of rocks in activated faults. The rocks in the subsurface withstand high amount of stress and their ability to withstand stress depends on the rock type and varies from region. The increase in the stress levels beyond the threshold stress limits leads to failure of rocks. The b value has been calculated in the past from earthquakes [1–3] through many methods. Fractal analysis of earthquakes through wavelet analysis requires a limited number of datasets as compared to other methods.

Fractal analysis of earthquakes has been done in the past [4, 5] and is a measure of the fracture scale in reactivated faults [6, 7] which often causes earthquakes. The fractals are the macrostructure characteristics which are discovered through microstructure studies. The characteristics do not change by changing the scale of observation. The b value of earthquakes has been found to be related to the fractal dimension in the past [8]. The b value is traditionally related to the Gutenberg-Richter Law [9]. The b value is dependent on the heterogeneity, rheology, thermal gradient, and stress conditions [10–12]. The b value has been found to increase with heterogeneity. For seismically active regions the b value is high (typically 1.0 and above), but after an earthquake the b value changes in the region [13] and the chances of aftershocks are related to this change in b value. The b value of an earthquake is typically high (above 1.0), if it is caused due to a heterogeneous and fractured rock matrix and commonly associated with the flow of fluids or other viscous materials into the rock matrix. The low b values of earthquakes are related to the release of energy in highly stressed zones [14].The b value has been found to decrease if the sample size of the events increases. It has been found to be lowered by 0.1 for events larger than 200 [15].The prediction

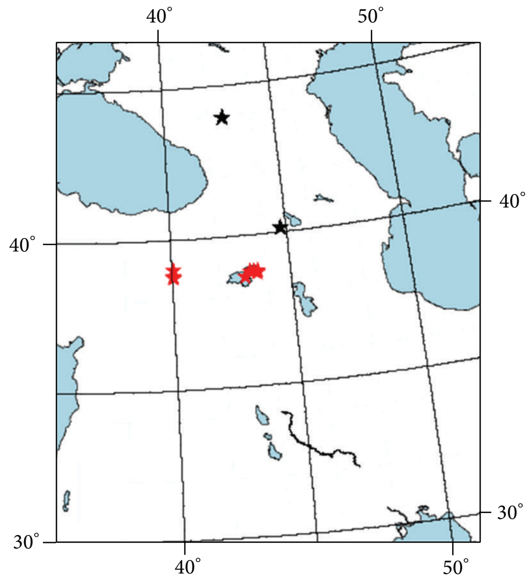

FIGURE 1: The map showing the earthquake locations marked with red stars and the receiver station marked with black stars.

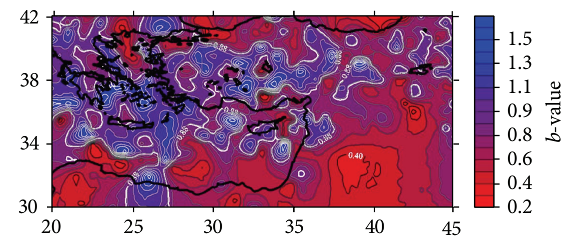

FIGURE 2: b value predicted by the Guttenberg-Richter relation using least-squares algorithm [21].

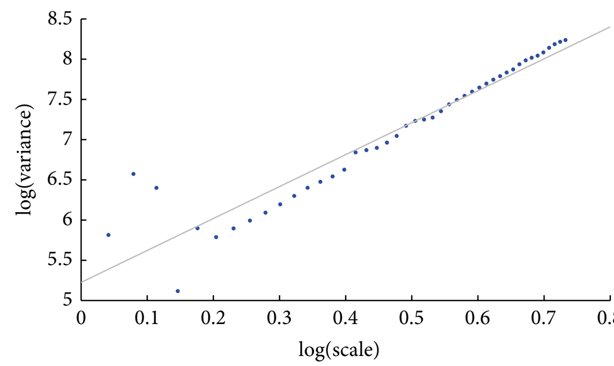

FIGURE 3: Holder exponent calculated for the mainshock occurring on May 1st 2003.

of aftershocks was commonly done by the power law, Omori's Law which states that the chances of aftershocks decrease with increasing time. If the b value increases drastically after an earthquake, the chances of an aftershock are remote, but if the increase is not substantial, then the chances of aftershocks increase. Similarly if the b value decreases in a region after an earthquake then there is a very high chance that an aftershock will occur, but if this decrease is not substantial then the occurrence of an aftershock decreases. This increase or decrease in b value is with respect to the typical b value of the region under consideration.

2. Geology and Seismicity of the Area

The area under consideration extends from the Van region near Lake Van to the northern most margin of the Tauride-Anatolide Platform, characterized by the Izmir-Ankara suture belt [16], where there is a high degree of metamorphism observed in the continental and oceanic assemblages. The Van region is a seismically active region due to the movement of the Arabian plate towards the Eurasian plate with a North-South convergence occurring at a rate of 18 mm/yr [17]. The Lake Van basin is located between the Zagros fault zone in the east and the Karliova junction in the west and is composed of many strike slip faults [18]. The region is primarily composed of two types of rock units, Pre-Late Pliocene paleotectonic units and Plio-Quaternary neotectonic units [19]. The former units are highly deformed, folded, and reverse faulted, while the latter units are composed of fluviolacustrine sedimentary facies with volcanic intercalations. There are also many active volcanoes seen in the region [20].

A series of earthquakes (magnitude greater than 5.0) was observed in these regions between 2003 and 2011 (Figure 1). The b values for these earthquakes were found and the criteria for the occurrence of an aftershock after the mainshock were arrived upon for this region through wavelet based fractal analysis of these earthquakes.

3. Theory and Methodology

The determination of b value from aftershocks has been done previously [22] through wavelet based fractal analysis of aftershocks. In this method the wavelet transform is applied to the seismic data and the wavelet coefficients are calculated. Wavelet transform of the time series is represented as

$$W(x, y) = \frac{1}{\sqrt{|x|}} \int_{-\infty}^{\infty} f(t)\, \varphi\left(\frac{(t-y)}{x}\right) dt. \tag{1}$$

Here $\varphi((t-y)/x)$ is called the mother wavelet and is chosen from the family of wavelets, $f(t)$ is the time series, and $W(x, y)$ are the wavelet coefficients. The mother wavelet is defined as a function of scale factor x, and translation y. The scale factor can be seen to be inversely proportional to the frequency of the signal and in the application of the mother wavelet to a time signal with a high scale factor; it can be seen as a way of analyzing the lower frequency spectrum of the time series. The translation factor controls the shifting of the mother wavelet window function. In fractal analysis of earthquakes, wavelet transform is applied to the given time series by varying the scale factor in small steps.

The variance in the wavelet coefficients for the variation in the scale factor is then calculated.

Table 1: Summarization of the results.

Date	Type of earthquake	Latitude	Longitude	H	D	b
October 23rd 2011	Mainshock	38.72°	43.51°	2.56	1.21	1.21
October 23rd 2011	Aftershock	38.75°	43.59°	3.85	0.57	0.57
October 23rd 2011	Aftershock	38.81°	43.45°	4.21	0.39	0.39
October 23rd 2011	Aftershock	38.81°	43.30°	4.16	0.42	0.42
October 23rd 2011	Aftershock	38.63°	43.08°	4.08	0.45	0.45
October 23rd 2011	Aftershock	38.81°	43.62°	4.01	0.49	0.49
March 8th 2010	Mainshock	38.79°	40.04°	4.00	0.45	0.45
March 8th 2010	Aftershock	38.75°	40.06°	4.04	0.48	0.48
May 1st 2003	Mainshock	39.00°	40.50°	3.97	0.51	0.51

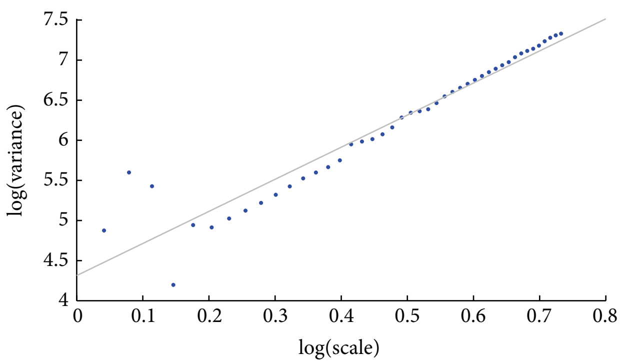

Figure 4: Holder exponent calculated for the mainshock occurring on March 8th 2010.

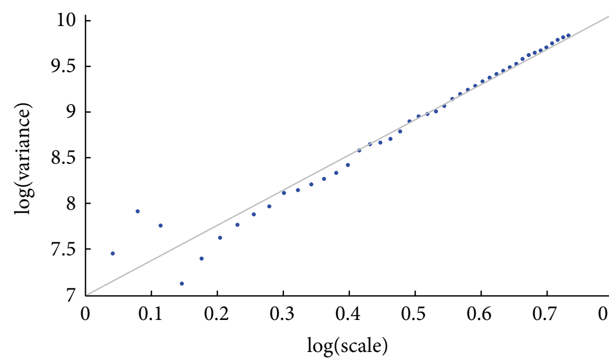

Figure 6: Holder exponent calculated for the mainshock occurring on October 23rd 2011.

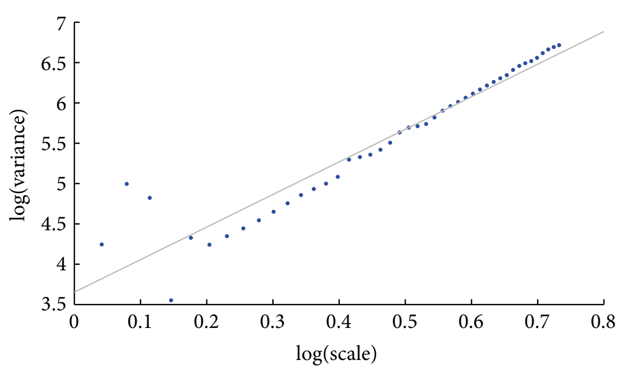

Figure 5: Holder exponent calculated for the aftershock occurring on March 8th 2010.

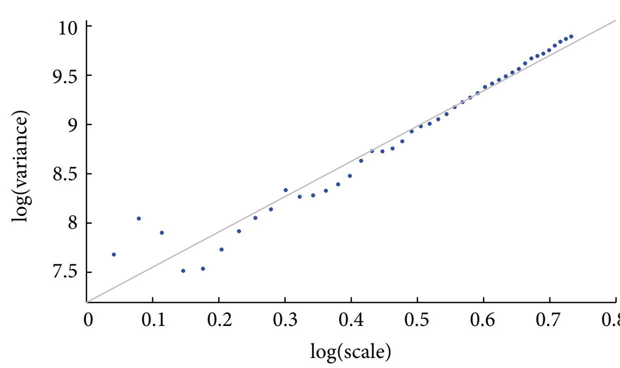

Figure 7: Holder exponent calculated for the first aftershock occurring on October 23rd 2011.

The given area under consideration has crystalline rocks and so the value of c given in (2) below is taken as 3.0 [23] though it is typically taken as 1.5 [21]:

$$b = c * \left(\frac{D}{3}\right). \quad (2)$$

In the above equation D is the fractal dimension and c is a constant depending on the lithology of the area. In analyzing the time series the Symlet and Daubechies family of wavelets gave very good results on account of their smoothness and their symmetric nature. In particular, the Symlet-2 and the Daubechies-2 family gave almost similar results. The variation of the scale factor for the analysis was done from 1.0 to 4.0 in increasing steps of 0.1. Large scales were not taken as there was significant deviation observed from the power law. The wavelet coefficients are obtained and the variance of these coefficients is found. A plot of scale versus variance on a log-log plot after linear regression analysis gives a straight line whose slope gives the value of the Holder exponent (H). The range of this exponent must be typically between −3 and 5 for good estimates of the fractal dimension, which can be found from the following:

$$2D = 5 - H. \quad (3)$$

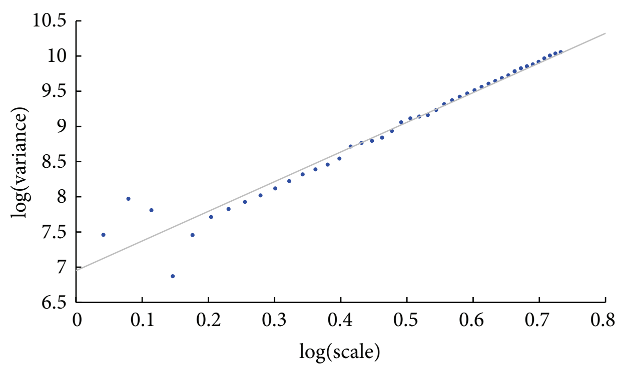

Figure 8: Holder exponent calculated for the second aftershock occurring on October 23rd 2011.

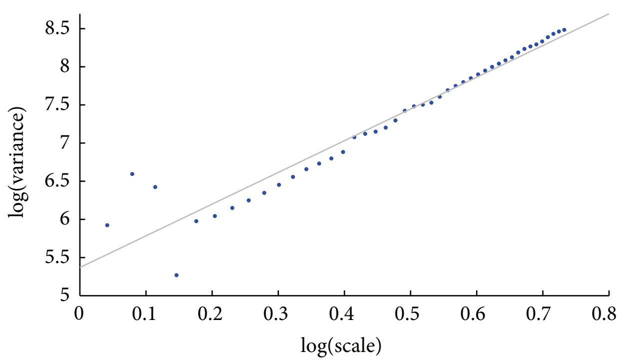

Figure 9: Holder exponent calculated for the third aftershock occurring on October 23rd 2011.

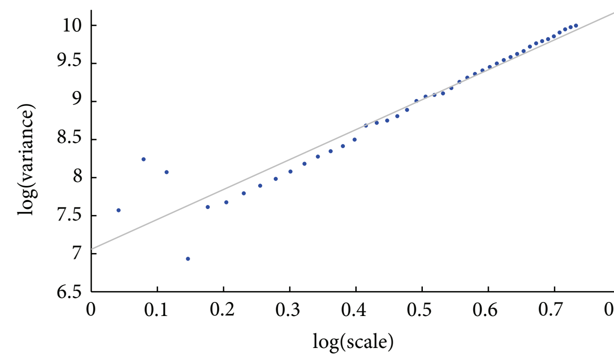

Figure 10: Holder exponent calculated for the fourth aftershock occurring on October 23rd 2011.

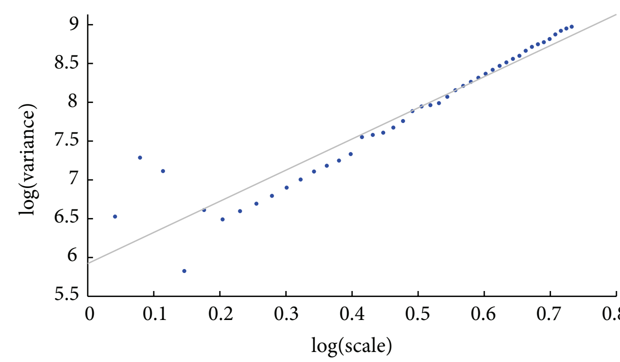

Figure 11: Holder exponent calculated for the fifth aftershock occurring on October 23rd 2011.

This was obtained only for the Symlet and Daubechies family of wavelets, though other wavelets like Morlet, Haar, family of Coiflets, Meyer, and Mexican hat have been proposed. For the given region the b value has been found previously using the Gutenberg-Richter relation [24] as shown in Figure 2. But this is the general b value of the region and this changes if there is a premonition of an earthquake. Earthquakes and aftershocks keep occurring until the b value approaches or exceeds the typical b value of the region and then they stop occurring.

4. Observations

The earthquake data of Turkey was taken from 2003 to 2011 and fractal analysis was performed on the mainshock and aftershock data to obtain the fractal dimension. From this the b value of the region after the earthquake occurrence was determined using (2) and (3). Figures 3, 4, 5, 6, 7, 8, 9, 10, and 11 show the results of the wavelet analysis. It was also observed that the time series analysis of the stations nearest to the epicenter gave the best results for the calculation of the fractal dimension. Stations situated nearby to the epicenter gave almost similar results. The results of the analysis are presented in Table 1.

From Table 1 it can be inferred that when the b value of an earthquake becomes close to 0.50 for this region, then there are no future earthquakes in that region. For the series of earthquakes that occurred on 23rd October 2011, it can be seen that the b value swings from a maximum to a minimum. But it tends to approach 0.5. For the earthquake that occurred on 1st May 2003; there was no aftershock after the mainshock as the b value of that earthquake was very close to 0.5. In the case of the earthquake that occurred on 8th March 2010, the mainshock had a b value lower than 0.5 and as a result there was an aftershock whose b value was much closer to 0.5 and there were no future aftershocks in the region.

5. Conclusion

The b value of a region is a very good indicator to predict the occurrences of aftershocks in a given region. The b value is related to the stability of the crust and when it is perturbed from its state of equilibrium it tends to go back to its original state by oscillating back and forth in terms of its b value. These oscillations are manifested as earthquakes.

Every region is characterized by a crust in a stable state of equilibrium and the crust tries to resist going away from this state of equilibrium and has a tolerance level to it. These levels can be obtained from the classic b value maps of every region. Earthquakes represent this change in state of equilibrium which are commonly perceived to occur due to the sudden release of energy in highly stressed zones and they repeatedly occur until the system is once again back to its equilibrium state. The b value of earthquakes can therefore be used to deduce the arrival of this state of equilibrium in a given region after a mainshock, and by our analysis in the region defined, this value was 0.5.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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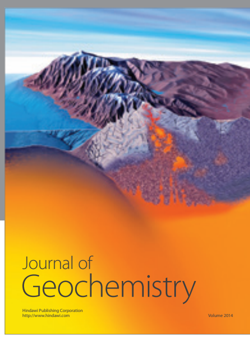
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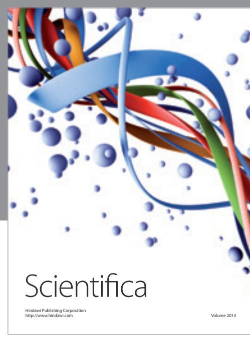
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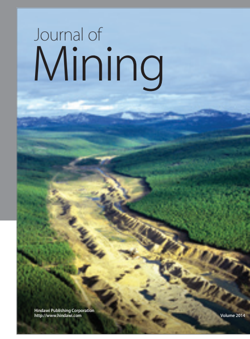
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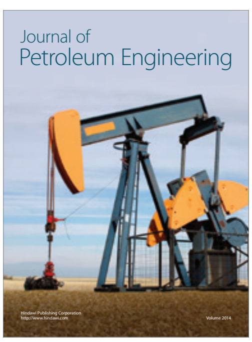
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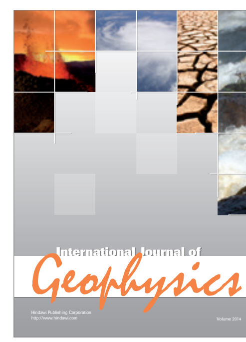
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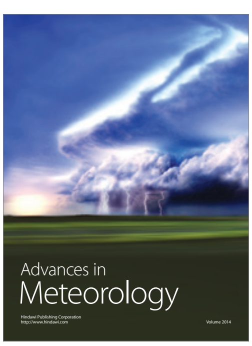
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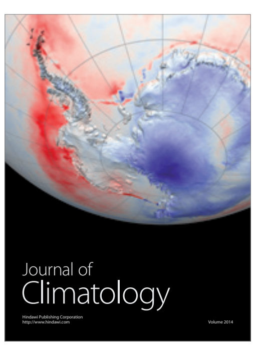
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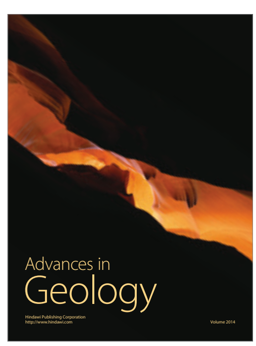
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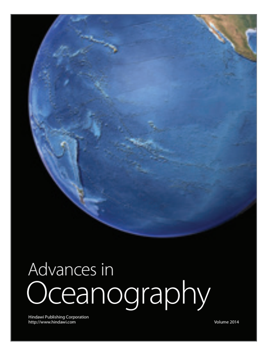
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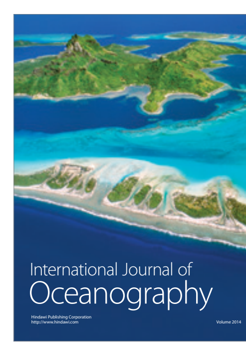
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