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## NEW INSIGHTS INTO THE SEISMIC ACTIVITY OF DAMASCUS FAULT (SYRIA): A QUANTITATIVE ANALYSIS

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### RESUMEN

La falla de Damasco es una estructura tectónica inversa notable que atraviesa la ciudad de Damasco; posiblemente representa un riesgo sísmico significativo para la ciudad. En ese sentido, el presente trabajo examina la actividad sísmica instrumental y establece un catálogo de terremotos que cubre el período de 1995 a 2012 para esta importante falla, lo anterior con el objetivo de identificar su contribución a la amenaza sísmica regional. El análisis cuantitativo revela que la falla de Damasco se caracteriza por sismos de baja magnitud, lo que implica que la falla podría considerarse en estado de reposo. Si se toma en cuenta la literatura publicada, el análisis muestra que el valor “b” de la relación Gutenberg-Richter se estima en 0,90 al utilizar el método de mínimos cuadrados, lo cual podría ser compatible con una falla de cabalgamiento, como la falla de Damasco. Este valor podría ser razonable para futuras interpretaciones. Además, se ha estimado que los periodos de retorno de los grandes terremotos son muy largos por extrapolación de la relación de recurrencia establecida. La magnitud máxima del terremoto regional se ha estimado mediante el procedimiento de Kijko como estimador de máxima verosimilitud. Este procedimiento ha pronosticado que la magnitud máxima posible del terremoto es de 4,2. En consecuencia, la quiescencia sísmica, observada en la actualidad a lo largo de la falla de Damasco, y el largo período de retorno estimado implican que un gran terremoto podría estar aún muy lejos.

**PALABRAS CLAVE:** falla de Damasco, terremoto instrumental, relación Gutenberg-Richter y Siria.

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## ABSTRACT

Damascus fault is a remarkable reverse tectonic structure trending through Damascus city, and may possibly represent a significant seismic hazard to the city. In that respect, the present work examines the instrumental seismic activity and establishes an earthquake catalogue covering the period 1995-2012 for this important fault, aiming to identify its contribution to the regional seismic hazard. The quantitative analysis reveals Damascus fault is characterized by low magnitude earthquakes, which implies that the fault could be considered in quiescence status. The analysis exhibits that the  $b$ -value of Gutenberg-Richter relationship is estimated to be 0.90 using the least-squares method, which could be compatible with a thrust faulting, such as Damascus fault, regarding the published literature. Also, this value could be reasonable for further interpretations. In addition, the return periods of large earthquakes have been estimated to be very long by extrapolation of the established recurrence relationship. Moreover, the maximum regional earthquake magnitude has been estimated by Kijko's procedure as maximum likelihood estimator. This procedure has predicted the maximum possible earthquake magnitude to be 4.2. Consequently, the seismic quiescence, observed at the present along Damascus fault, and the estimated long return period implies that a large earthquake could be still so far away.

**KEY WORDS:** Damascus fault, Instrumental Earthquake, Gutenberg-Richter relationship and Syria.

## INTRODUCTION

Previous studies in Syria have revealed that the crustal deformation is ongoing along four tectonic zones: the Dead Sea Faults System (DSFS), the Abd-el-Aziz-Sinjar, the Euphrates Fault System, and Palmyra Fold Belt (PFB) (Barazangi *et al.*, 1993; Brew *et al.*, 2001) (Fig. 1). Numerous destructive earthquakes have occurred along these zones in the history (Sbeinati *et al.*, 2005). Damascus is the most populated city in Syria with historical and cultural importance. The city has suffered from several destructive earthquakes, such as 1759 earthquake, which caused much casualties and damage. Damascus fault, the SW ending of PFB, is a remarkable reverse tectonic structure trending through the city of Damascus, and covered by thick recent formations. In Damascus area, the model of regional kinematic predicts a crustal shortening rate across the PFB of  $\sim 2 \text{ mm a}^{-1}$  (Abou Romieh *et al.*, 2009). This model suggests the activity of Damascus fault with significant slip rates. Furthermore, the GPS measurements estimated this rate to be about  $\sim 1.5 \pm 1.0 \text{ mm a}^{-1}$  crossing the PFB in Damascus area (Alchalbi *et al.*, 2010). Consequently, Damascus fault could represent a significant seismic hazard to Damascus. The seismic activity of this important fault was for many years a subject of debate during many scientific meetings in Syria, such as ASST, 2004; 2009. In this context, the current research is an attempt to identify the seismic activity of this fault, to estimate its contribution to the regional seismic hazard, and evaluate threat to Damascus the megacity located within its vicinity. This issue could be interesting for the scientific society, especially because of the scarce information available about this important fault. Some preliminary results of this research reveal that Damascus fault is at the present in a quiescence state in contrast with other faults segments of the Dead Sea Faults System such as Yammounah and Aqaba segments (Fig. 1) (Abdul-wahed, 2019). The instrumental seismicity of the eastern Mediterranean region shows that the southern part of DSFS is seismically the most active (Hofstetter *et al.*, 2007; Imprescia, 2010; Imprescia *et al.*, 2012). Since the early 1980s, the Gulf of Aqaba was the most active area, where thousands of small earthquakes clusters have occurred during several months to few years (Baer *et al.*, 1999; Klinger *et al.*,

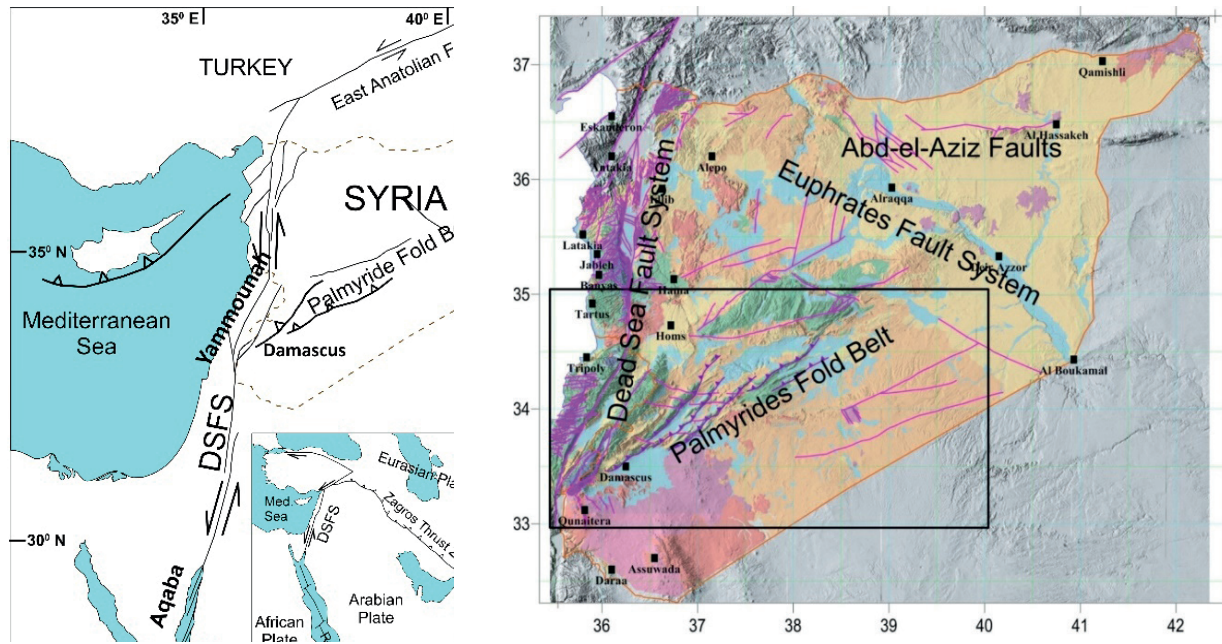


Figure 1. Regional setting (left) and major tectonic zones in Syria (Right). The rectangle indicates the location of Figs 3 and 5 (modified from Brew *et al.*, 2001).

1999). By comparison to Abdul-wahed (2019), the current paper presents more details and results of additional procedures to identify the seismic activity of Damascus fault. Details are provided to justify determining the Gutenberg-Richter relation assuming a fixed  $b$  value. Additionally, the maximum possible magnitude  $M_{\max}$  of an earthquake on the Damascus fault is calculated using Kijko's maximum likelihood method (Kijko and Sellevoll 1989; Kijko, 2004; Kijko *et al.*, 2021).

## DAMASCUS FAULT

Damascus city is bounded by Qassioun mountain which extends from the South West to North East, where Paleogene (Middle Eocene) and Cretaceous (Turonian) outcrop (Fig. 2). This folded mountain, which rises ~400 m above the city, constitutes the SW ending of the PFB. The tectonic evolution of this folded mountain system started in Mesozoic period. The PFB represents a major tectonic feature in central Syria that extends SW-NE for about 400 km, from the Damascus area to the Euphrates River (Figs. 1 and 3). Damascus fault is the SW end of the PFB. It is a NW-dipping thrust fault, where the Qassioun mountain is forming its hanging wall and Damascus city is in its footwall (e.g., Sharkov *et al.*, 1994) (Fig. 4). The ~600 m thickness of Pliocene/Pleistocene alluvium in the Damascus basin, which has been dated using interbedded basalt, according to Mouty *et al.* (1992) and Sharkov *et al.* (1994) indicates that this fault has developed a throw of at least ~1000 m on an estimated timescale of 3.6 Ma (neglecting any loss of the hanging-wall escarpment to erosion). This implies a vertical slip rate of at least ~0.3 mm a<sup>-1</sup> (Westaway *et al.*, 2009). Damascus fault and other reverse faults near the city of Damascus, which adjoins the southwestern trend of the PFB, have been regarded as inactive (e.g. Rukieh *et al.*, 2005). However, Abou Romieh *et al.*, (2009) suggests otherwise and its regional kinematic model proposes a rate of ~2 mm a<sup>-1</sup> for the crustal shortening across the PFB. Additionally, Abou Romieh *et al.*, (2009) indicated that some historical earthquakes, which previously attributed to the DSFS in western Syria, could be occurred on the faults of PFB, and thereby these faults may possibly represent a significant seismic hazard to Damascus.

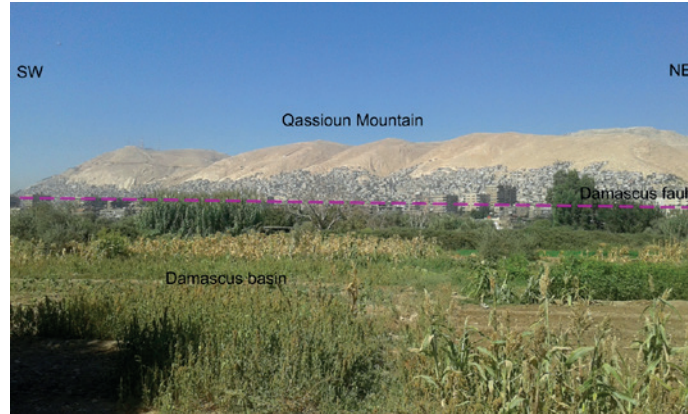


Figure 2. General view of Damascus city and Qassioun Mountain. The photo is taken from the SE direction.

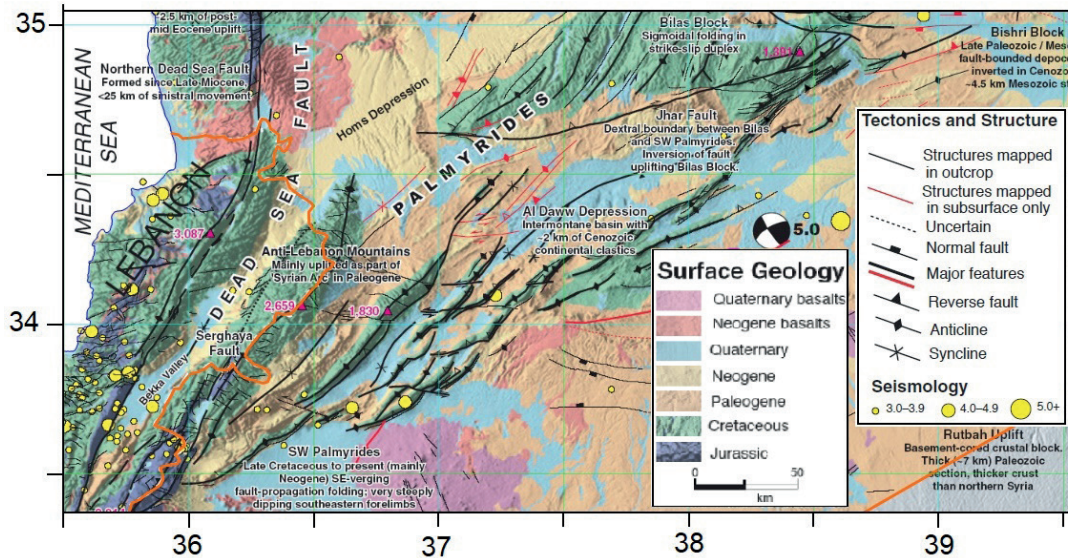


Figure 3. Seismo-tectonic and geological map of Damascus region showing the main reverse faults and structures (modified from Brew *et al.*, 2001).

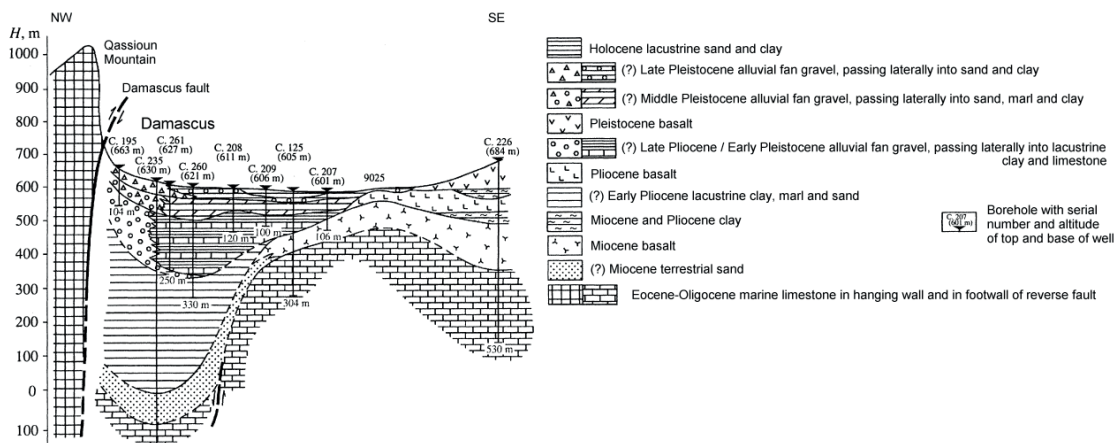


Figure 4. Simplified geological section across Damascus fault (modified from Sharkov *et al.*, 1994).

Given the age of Damascus fault to be  $\sim 0.9$  Ma, and a revision of its throw to  $\sim 2500$  m, considering the hanging wall erosion, (Abou Romieh *et al.*, 2012) estimated the vertical slip rates on this reverse fault of  $\sim 2.8$  mm  $a^{-1}$ . Abou Romieh *et al.* (2012) has explained the low slip rate, recently measured on the northern DSFS in western Syria, by absorbance of the northward motion of the Arabian plate, relative to the African plate, by crustal shortening within the PFB. A soil-gas radon survey has been performed across the expected westward ending of Damascus fault, in order to trace the location of the concerned fault where it is covered by unconsolidated formations (Al-Hilal and Abdul-wahed, 2016). The relative abnormal radon values, (2-3 times higher than the background level), has been found to vary in accordance with the expected orientation of the buried fault axis in the bedrock.

## REGIONAL SEISMICITY

Syria has suffered from many large historical earthquakes (Sbeinati *et al.*, 2005). However, the present instrumental seismic activity is passing in quiescent status, which is supported by the low-level magnitude of recorded events during the period 1995-2012 (Abdul-Wahed and Al-Tahan, 2010; Abdul-Wahed *et al.*, 2011; Abdul-Wahed and Asfahani, 2018). The Syrian National Seismological Network (SNSN), operated since 1995, allows recording about 1600 local events during the period (1995-2012) along and around Damascus fault (Fig. 5). These events have been located with errors less than 10 km (Abdul-Wahed and Asfahani, 2018). A noteworthy seismic activity has been observed along the north-eastern of Damascus fault, thus, the South West Palmyra Fold Belt (SWPFB) can be considered as a potential seismic source area. In the SWPFB, 3 seismic swarms of events were observed in 2004 in the west of Jayrud town. The first swarm occurred on 8 February 2004 including 6 events. The second occurred in the same site on 16 and 17 May 2004 including 22 events. Although these events were of low magnitude ( $M_c=2.6-3.3$ ), they were widely felt in the region of Ma'alula. The third swarm, including 8 events, occurred on 7 June 2004, where the strongest event attends the

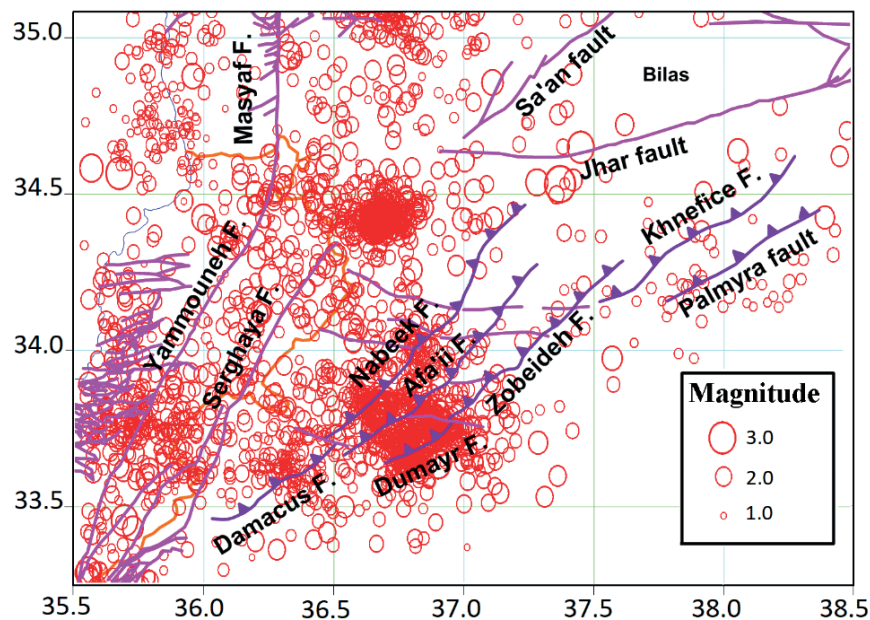


Figure 5. Epicenters map showing the instrumental seismic activity recorded in Damascus region during the period 1995-2012 (F.: fault).

magnitude of 3.7. Another swarm of 8 events was observed on 21 April 2011 in Jayrud region. These swarms can be related to SWPFB reverse faults such as the extension of Damascus fault.

## DATA AND METHODS

Special catalogue of earthquakes for Damascus fault covering the period from 1995 to 2012 has been compiled by using essentially the data of the published SNSN bulletins. A total of 1600 earthquake events have been recorded in Damascus region. About 1007 events, that occurred within 25 km around SWPFB during the period of 17 years, are included in this catalogue. The annual average of the recorded events is about 60 events, which could be considered very low in comparing with other parts of DSFS, such as Yammounah or Aqaba Gulf, which consequently indicates that SWPFB is actually passing with a relative quiescence. For comparison, 2414 events were recorded in Aqaba Gulf in 1995 (Jordan Seismological Observatory, 1995) and 948 events in 1997 (Jordan Seismological Observatory, 1997).

Magnitudes are calculated from the coda wave duration via the following formula (SNSN bulletins, 1995-2012):

$$MC = -3.0 + 2.6 * \log (T) + 0.001 * D \quad (1)$$

Where MC is the coda magnitude, D is the epicentral distance (in km) and T is the coda duration (in sec). Most of these events are micro-earthquakes ( $MC < 3.0$ ) and their magnitude varies between 1.0 and 3.7, where the average magnitude is approximately 1.6 (Fig. 6). The largest observed earthquake magnitude in the area is 3.7. A quantitative idea about the seismic activity produced by a fault could be obtained by examining the frequency-magnitude distribution and adopting the empirical relation of Gutenberg and Richter (G-R relation) (Gutenberg and Richter, 1944; 1954). This empirical relation is extensively used in the studies of active faults and their earthquake activity. The G-R relation is given as:

$$\log N = a - bM \quad (2)$$

In this relation,  $N$  is the number of events with magnitude larger or equal to  $M$ , and  $a$  and  $b$  are empirical constants, where  $a$ -value indicates the level of seismic activity and  $b$ -value is the slope of G-R relation and indicates the rate of occurrence within a given magnitude range. “ $b$ -value” describes the relative abundance of large to small earthquakes. G-R relation could be applied to cumulative number “ $N$ ” as well as to incremental numbers “ $n$ ”. In the first case,  $N$  is the cumulative number of earthquakes with magnitude larger than  $M$ . However,  $n$  is the number of events within an interval of magnitudes:  $M \pm \Delta M$  in the second case, where  $\Delta M$  should be carefully chosen for any incremental  $b$ -value evaluation. The magnitude data are usually discrete quantities and calculated with a precision of 0.1 magnitude unit in approximately all global catalogs. Thus, a proper choice of  $\Delta M$  will be a compromise between the magnitude sampling as close to 0.1 as possible and statistically large numbers of events in each magnitude group. Further, the cumulative distribution of magnitudes is preferable; it provides better linear fit since large numbers are less degraded by statistics of small numbers.

## RESULTS AND DISCUSSION

The empirical G-R relation has been evaluated using Seisan software (Seisan 10.3, 2015; Havskov

and Ottemoller, 2020). The empirical constants of G-R relation,  $a$ -value and  $b$ -value, are evaluated from the available recorded events using two techniques: the least square and supposing a fixed  $b$ -value, and two incremental distributions of magnitudes ( $\Delta M$ ): 0.1 and 0.5. Since some authors, such as Wesnousky (1999) and Kagan (1999), urge that  $b$ -value must be fixed to 1 as a universal constant for earthquakes; the  $b$ -value has been fixed to 1 in the second technique. However, other authors (e.g., Frohlich and Davis, 1993; Schorlemmer *et al.* 2005; Madahizadeh *et al.* 2016) reveal that  $b$ -value is systematically affected by different styles of faulting. Figure 7 shows the obtained forms of G-R relation; also, the results are shown in table 1, where  $SD$  is the standard deviation of estimator,  $COR$  is the regression coefficient, and  $RMS$  is the root-mean-square error of estimate. The obtained results show  $b$ -value to be 0.93 and 0.90 according to 0.1 and 0.5 incremental distributions of magnitudes, respectively. According to the published literature (e.g., Frohlich and Davis, 1993), the  $b$ -value commonly ranges from 0.60 to 1.30 depending on the different tectonic regimes. Schorlemmer *et al.* 2005 found the thrust zones are associated with small  $b$ -value ( $\approx 0.90$ ), which corresponds to Damascus fault and indicates that the calculated  $b$ -value is compatible. Therefore, this  $b$ -value can be accepted regarding the reported values in the literature and valid for further interpretations. The low standard deviation ( $SD = 0.12$ ), the high regression coefficient ( $Cor=0.99$ ), and the very low residual ( $RMS=0.09$ ) indicate that the return periods can be calculated by extrapolating the obtained G-R relation to larger earthquakes. The return periods for higher magnitude events than those included in the catalogue are deduced by extrapolating of curves fit to the log-linear distribution. The extrapolated return periods are shown in Fig. 8. A return period for an event of magnitude 7.0 is extrapolated to be 2860 years according to the least square method and 0.5 incremental distributions of magnitudes, which can be qualified as very long return period.

Table 1.  $a$ -value and  $b$ -value calculated by using two techniques and two steps of magnitudes.

Technique	$\Delta M_c$	$a$ -value	$b$ -value	accuracy	
Least-squares	0.1	4.17	0.93	$COR=0.99$	$RMS=0.09$
Least-squares	0.5	4.07	0.90	$COR=0.99$	$RMS=0.09$
Fixed b	0.1	4.33	1.0	$SD=0.12$	
Fixed b	0.5	4.29	1.0	$SD=0.15$	

The fitting of G-R relation to the observed frequency-magnitude distribution has shown a magnitude completeness down to  $M_{completeness} = 1.5$  (Fig. 6). This indicates that not all micro-earthquakes ( $M_c < 1.5$ ) have been detected by the SNSN. Some too small events were not recorded on a sufficiently large number of stations to trigger the recording system in the SNSN and to initiate the location procedure, thus these events have not been reported. It might also that the network operators decided that some micro-earthquakes below a certain threshold ( $M_c < 1.5$ ) are not of interest.

The earthquake catalogue, established in this research for the period of 1995-2012, could be considered as incomplete because the magnitude of the biggest recorded event does not exceed 3.7. Therefore, it was essential to look for an appropriate interpretative procedure to process such an incomplete catalogue. Referring to the related literature, Kijko's procedure (Kijko, 1983) seems to be an adequate technique for processing such catalogue. This procedure (Kijko and Sellevoll 1989; Kijko,

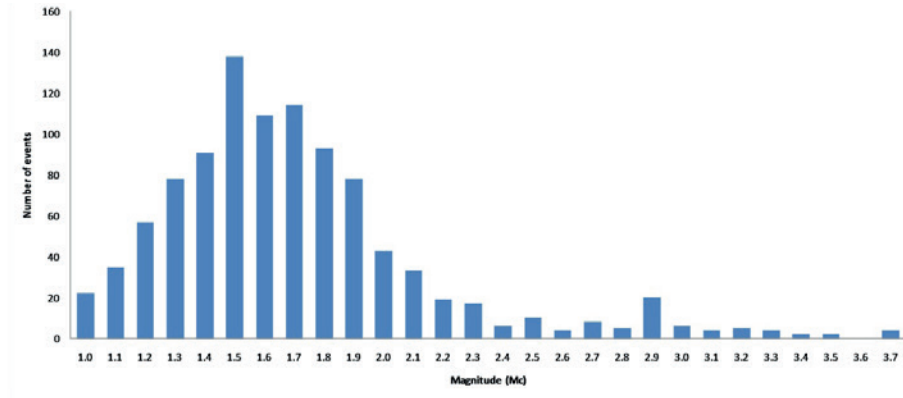


Figure 6. Distribution of the recorded events according to their magnitudes during the period of 1995-2012. The incremental distribution ( $\Delta M$ ) is 0.1.

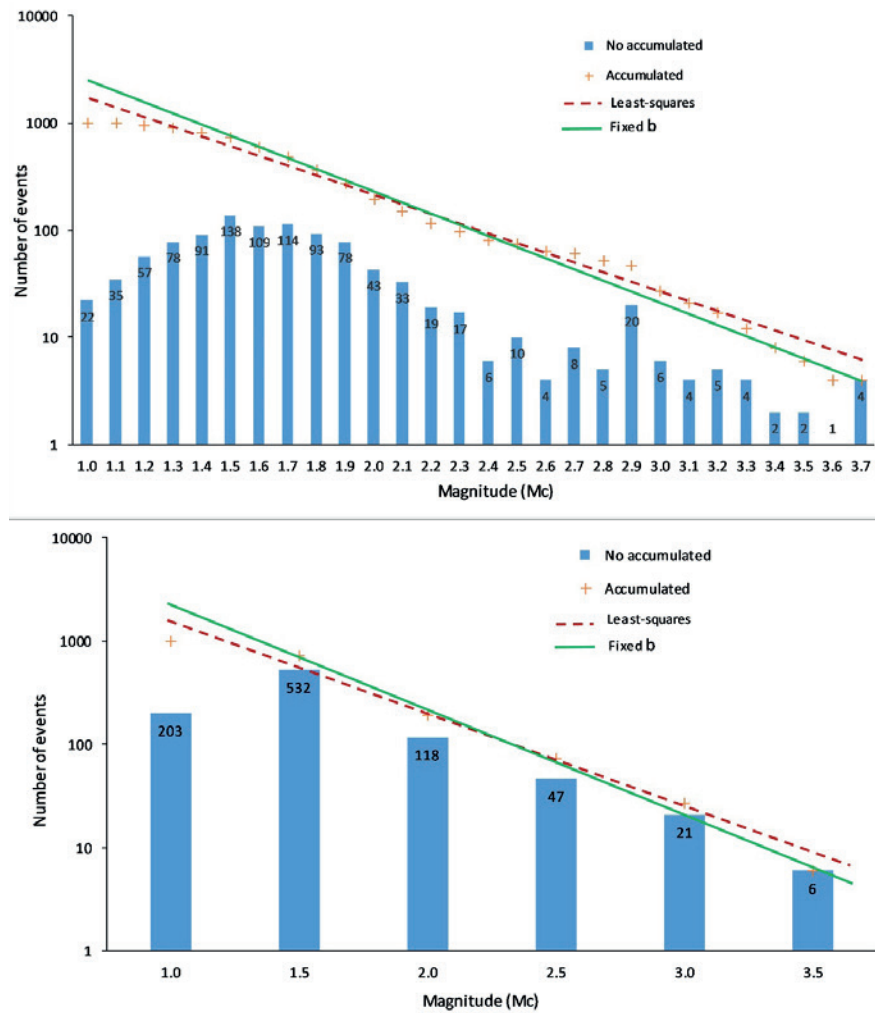


Figure 7. Comparison between the two techniques: least-squares in dashed line and fixed b in continuous line, using two magnitude intervals:  $\Delta M=0.1$  in the top and  $\Delta M=0.5$  in the bottom. Histograms are showing the number of events in selected magnitude intervals and crosses are showing the accumulated number of events.

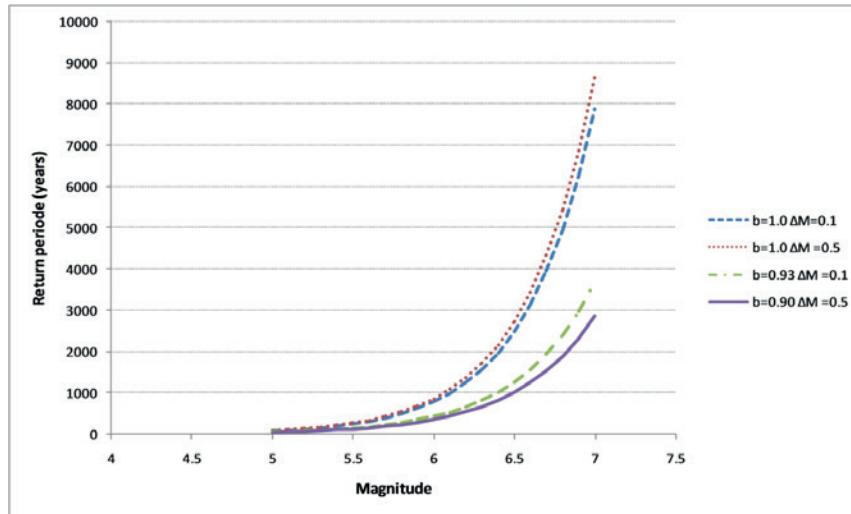


Figure 8. Predicted return periods by the two techniques using two magnitude intervals ( $\Delta M$ ).

2004; Kijko *et al.*, 2021) is based on the estimation of maximum likelihood of the seismic activity rate ( $\lambda$ ),  $b$ -value in the G-R relation, and the maximum possible magnitude  $M_{\max}$ . It is applicable in the extreme case when no information about the nature of the earthquake magnitude distribution is available. The procedure can also be used in the case of an incomplete earthquake catalogue, which is the case of the earthquake catalogue for Damascus fault.

The Kijko's procedure has been applied in this research on the instrumental earthquake catalogue of the Damascus fault using the Fortran code: hn2.exe: Release: 2.10, 24 June 2005. (The code availability is on request from his author Andrzej Kijko, University of Pretoria, Pretoria, South Africa, andrzej.kijko@up.ac.za). The obtained results are:

$$\beta = 2.75 \pm 0.06 \text{ (} b\text{-value} = 1.19 \pm 0.03, \text{ where } \beta = b\text{-value} \cdot \ln(10) \text{)}$$

$$\lambda = 234.15 \pm 8.65$$

$$M_{\max} = 4.20 \pm 0.71$$

The Kijko's procedure predicts the maximum possible earthquake magnitude ( $M_{\max}$ ) to be 4.2 and expects a return period ( $\lambda$ ) of 234 years for this earthquake. Furthermore, this procedure estimates the probabilities of occurrence of large earthquakes within a given interval of time. Figure 9 shows the probabilities of occurrence of earthquakes during the time intervals 1, 50, 100 and 1000 years. The magnitude of the strongest earthquake in these time intervals could attain 2.5, 4.2, 4.5 and 5.3, respectively.

## CONCLUSIONS

The established catalogue for Damascus fault, covering the period 1995-2012, reveals the earthquake activity produces low magnitude events and passes through a relative status of quiescence in contrast with other adjacent faults segments of DSFS. The empirical G-R relation shows a  $b$ -value of 0.90 according to the least square technique, which could be compatible with a thrust faulting, such as Damascus fault, regarding the published literature. Also, this value could be reasonable for further

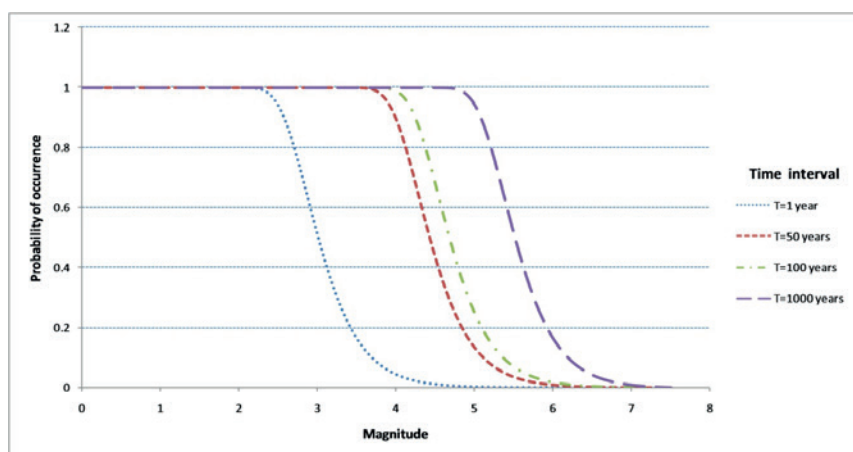


Figure 9. Probabilities of occurrence of earthquakes during the time intervals 1, 50, 100 and 1000 years..

interpretations. Extrapolation of this relation reveals very long return periods of large earthquakes. The seismic hazard parameters, maximum possible magnitude  $M_{max}$ , earthquake activity rate  $\lambda$ , and the Gutenberg-Richter  $b$ -value, have been estimated using the maximum likelihood Kijko's procedure. The Kijko's procedure has predicted the maximum possible magnitude to be 4.2. The seismic quiescence, observed along Damascus fault, and the very long return period implies that a large earthquake is still unlikely. This result needs to be confirmed by additional evidences such as palaeoseismological investigation. Some trenches across the Damascus fault could provide reliable information about the slip rate for this fault and its past seismic activity. Based on possible palaeoseismological evidence, it is suggested to evaluate the recurrence interval for surface faulting events.

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