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B-value examination of the nubia-eurasia plate boundaries- appraisal for coulomb stress investigation of the september 8, 2023, Morocco

Ayodeji Adekunle Eluyemi[1*], Michael Ayuk Ayuk[2], Imuetinyan Aigbogun[3], Peter Adetokunbo[4], Mako Sitali[5]
[1] Division of Environmental and Earth Sciences, Centre for Energy Research and Development (CERD), Obafemi Awolowo University (OAU), Ile Ife, Osun State, Nigeria
[2] Department of Applied Geophysics, Federal University of Technology, Akure, Nigeria
[3] Department of Biological Science and Applied Chemistry, Seneca Polytechnic, Toronto, Ontario, Canada
[4] Boone Pickens School of Geology, Oklahoma State University, Stillwater, USA
[5] Ministry of Mines and Energy, Geological Survey of Namibia, Namibia

Abstract
This study investigates the seismic evolution of the Nubia-Eurasia plate boundaries using time-lapse seismicity analysis and Gutenberg-Richter recurrence parameters to understand the seismo-dynamics, stress distribution patterns, and earthquake hazard potential of the region. We analyzed 171,824 hypocentral data points from the International Seismological Centre (ISC) catalog spanning 45 years (1978-2024) within the geographical bounds of 19.0000°W to 7.0000°E and 27.0000°N to 40.0000°N. The dataset was segmented into eight five-year intervals (1978-1983, 1984-1989, 1989-1994, 1995-2000, 2001-2006, 2007-2012, 2013-2018, and 2019-2024) to examine temporal seismicity evolution. Time-lapse seismicity maps reveal an increasing trend in both earthquake frequency and magnitude over the study period, with pronounced clustering along the northern coastal regions near the African-Eurasian plate convergence zone and within the Rif Mountains. Gutenberg-Richter analysis using maximum likelihood solutions demonstrates a significant correlation between elevated b-values (>1.0) and the occurrence of major earthquakes exceeding magnitude 6.0 Mw. This relationship is evident in two recent seismic windows: the 2013-2018 interval (b-value = 1.04 ± 0.01) corresponding to the January 25, 2016, Al Hoceima earthquake (6.3 Mw), and the 2019-2024 interval (b-value = 1.08 ± 0.009) encompassing the devastating September 8, 2023, Marrakesh-Safi earthquake (6.8 Mw) that resulted in over 2,000 fatalities. These findings provide crucial insights for seismic hazard assessment and underscore the urgent need for enhanced building code enforcement, early warning systems, and comprehensive earthquake preparedness programs in this tectonically active region.

Keywords: Gutenberg-richter relation, A- and B-value, nubia-eurasia plate boundary, time-lapse seismicity, earthquake hazard assessment

Introduction

The September 8, 2023, earthquake in Morocco represents one of the most devastating seismic events in the Nubia-Eurasia plate boundary region in recent decades. This shallow earthquake, occurring at a depth of 18.5 km with a moment magnitude of 6.8 Mw and Mercalli intensity IX (Violent), resulted in more than 2,900 fatalities and 5,500 injuries, accompanied by numerous aftershocks (Huang *et al*., 2024) [8]. The event caused extensive damage to the ancient sections of Marrakech-Safi and devastated several remote areas, with ground motion felt across Spain, Portugal, and Algeria.

The Nubia-Eurasia plate boundary zone encompasses several seismotectonic regions, including the Strait of Gibraltar, Morocco, Azores-Cape St. Vincent, Algeria, and Northern Algeria. This tectonically complex region experiences active seismicity under varying stress regimes (Stitch *et al*., 2006; Medina and Cherkaoui, 1991; Eluyemi *et al*., 2025; Grevemeyer *et al*., 2015) [3, 4, 9]. The area has a long history of destructive earthquakes, most notably the devastating Lisbon earthquake of November 1, 1755, which was felt across the Iberian Peninsula, North West Africa, France, Italy, and Germany. This historical event caused severe damage to Lisbon, with an estimated 60,000 fatalities and widespread destruction of public buildings including churches, mosques, and hospitals due to violent ground shaking (Reid, 1914) [10].

Understanding the seismicity patterns and stress distribution in this region is crucial for earthquake hazard assessment and risk mitigation. The Gutenberg-Richter relation, first established by Gutenberg (1945) [5], provides fundamental insights into seismic behavior through its key parameters: the b-value, a-value, and magnitude of completeness (Mc). Variations in b-values across a region serve as indicators of tectonic stress conditions, where low b-values may indicate higher likelihood of larger magnitude earthquakes, while high b-values suggest increased frequency of smaller magnitude events. Recent studies by Adetokunbo *et al*. (2025) [1] have demonstrated the importance of geostatistical analysis for Gutenberg-Richter parameter estimation in the Nubian-Eurasian plate boundary region, highlighting the significance of comprehensive seismic analysis in this tectonically active zone.

The practical applications of Gutenberg-Richter analysis extend far beyond theoretical understanding (Gutenberg and Richter, 1956a) [6, 7]. These parameters are essential for evaluating recurrence cycles, seismicity rates, and predicting aftershock magnitudes following major seismic events (Gutenberg and Richter, 1956b; Eluyemi *et al*., 2019) [2]. In modern engineering seismology, b-value evaluation has become a critical tool for designing earthquake-resistant structures and assessing large magnitude earthquake potential. Francisco *et al*. (2018) have even suggested modifications to Gutenberg-Richter parameters for evaluating local damage in reinforced concrete structures through acoustic emission methods.

This study aims to investigate the spatial and temporal variations of seismicity in the Nubia-Eurasia plate boundary region through comprehensive time-lapse seismicity analysis and Gutenberg-Richter parameter evaluation. By examining the tectonic domains and stress distribution patterns across different temporal windows, we seek to enhance understanding of the seismodynamics controlling earthquake occurrence in this critical region and provide insights for improved seismic hazard assessment.

Methodology

We queried the International Seismological Centre (ISC) event catalog to obtain historical and recent instrumentally recorded earthquake events near the Nubia-Eurasia plate boundaries. The search covered the last 45 years within the geographical quadrangle bounded by 19.0000°W to 7.0000°E longitude and 27.0000°N to 40.0000°N latitude. This query yielded 171,824 hypocentral data points, including the notable September 8, 2023, Marrakesh-Safi earthquake (Mw 6.8).

To analyze the seismicity behavior and stress distribution patterns for hazard assessment, we divided the dataset into eight five-year intervals: 1978-1983, 1984-1989, 1989-1994, 1995-2000, 2001-2006, 2007-2012, 2013-2018, and 2019-2024. This temporal segmentation allows for examination of seismic activity evolution and identification of periods with heightened earthquake occurrence potential.

The earthquake data were processed and formatted for spatial analysis using Mirone software. For each five-year window, we generated epicentral distribution maps to visualize seismic patterns across the study region. Additionally, we constructed Gutenberg-Richter plots for each temporal window using maximum likelihood solutions within Mirone software. These analyses provide insights into the seismogenic sources of the region and their temporal distribution characteristics, enabling assessment of the Gutenberg-Richter relation parameters for the investigated area.

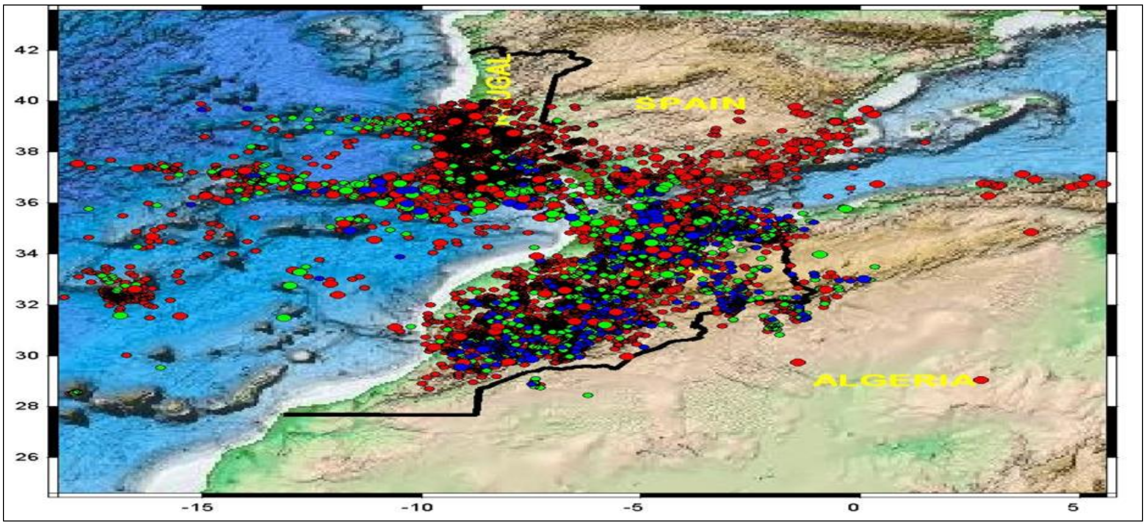

Fig 1: Illustrates the epicentral map of the study region, utilizing the hypocentral data from 1979 up to 2024.

Results

The spatial evolution of seismicity in the Nubia-Eurasia plate boundaries and adjoining regions is illustrated in Figures 2, 3, 4, and 5. These time-lapse seismicity maps reveal distinct patterns of earthquake distribution across the eight five-year intervals from 1978 to 2024. The Gutenberg-Richter relation parameters for each temporal window were calculated and corresponding a-value,

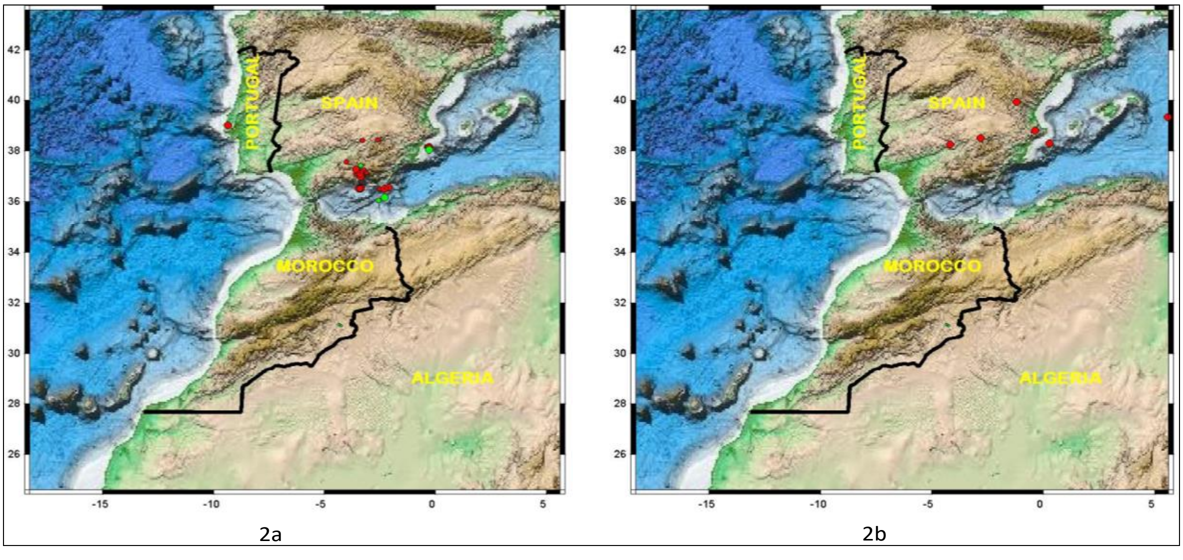

Fig 2: Illustrates the time lapse seismicity windows of the year (a) 1979-1983 and (b) 1984-1989 respectively.

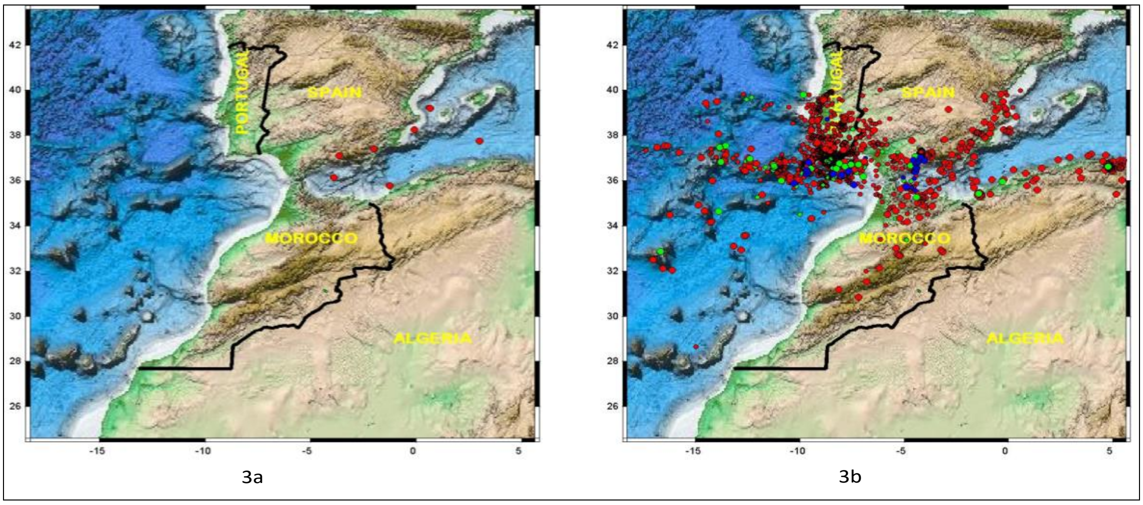

Fig 3: Illustrates the time lapse seismicity windows of the year (a) 1989-1994 and (b) 1995-2000 respectively.

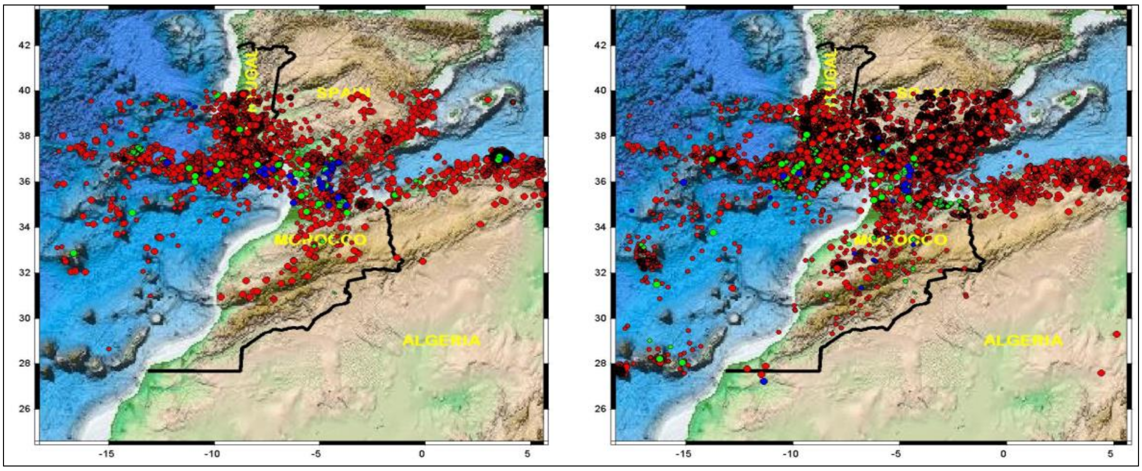

Fig 4: Illustrates the time lapse seismicity windows of the year (a) 2001-2006 and (b) 2007-2012 respectively.

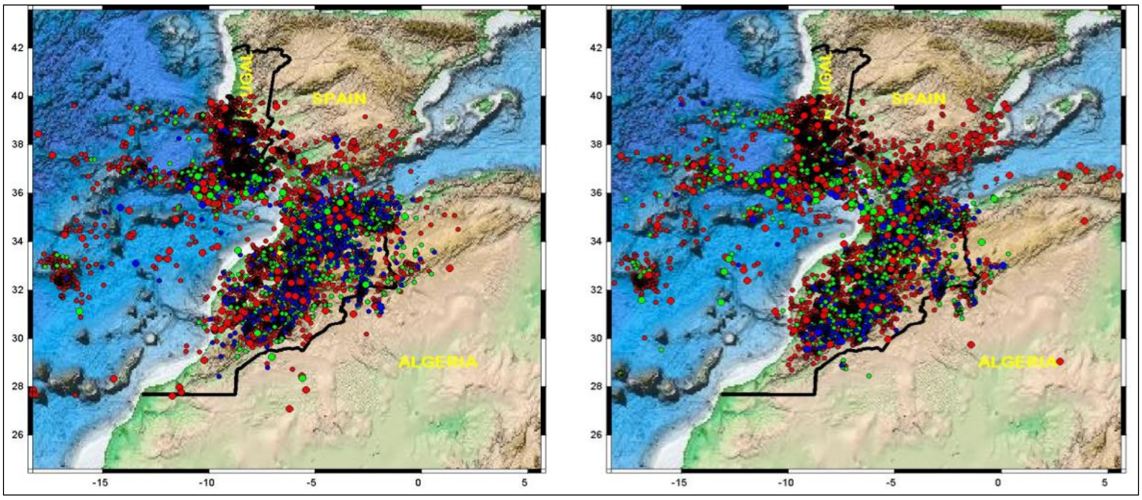

Fig 5: Illustrates the time lapse seismicity windows of the year (a) 2013-2018 and (b) 2019-2024 respectively.

b-values, and magnitude of completeness (Mc) presented in Table 1. The analysis shows variable seismicity characteristics across different time periods, with complete data available for six of the eight intervals studied. The magnitude-frequency relationships for the study region are presented through Gutenberg-Richter plots in Figures 6, 7, and 8. Figure 6 displays the plots for the earlier seismic windows of 1978-1983, 1984-1988, and 1989-1994, while Figure 7 presents the plots for the intermediate periods of 1995-2000, 2001-2006, and 2007-2012. Figure 8 illustrates the most recent seismic windows of 2013-2018 and 2019-2024. These plots, generated using maximum likelihood solutions, provide statistical insights into the seismicity patterns and hazard assessment for each temporal period.

Analysis of the dataset identified two significant recent earthquakes exceeding magnitude 6.0 Mw within the study region. Table 2 summarizes these events along with their associated hazard impacts and social consequences, demonstrating the substantial risk posed by major seismic events in this tectonically active zone.

Table 1: Shows the tabular arrangement of A value, b-value, and Magnitude of Completeness for all year intervals of study.

Year	A-Value	b-Value	Magnitude of Completeness
1978-1983	5.02	1.36 +/- 0.3	2.8
1984-1988	-	-	-
1989-1994	-	-	-
1995-2000	3.8	0.493 +/- 0.01	1.6
2001-2006	4.8	0.605 +/- 0.01	2.2
2007-2012	4.58	0.606 +/- 0.006	1.4
2013-2018	5.58	1.04 +/- 0.01	1.6
2019-2024	5.8	1.08 +/- 0.009	1.6

Table 2: Shows Recent Earthquakes with Magnitudes above 6.0 Mw and the death count

Date	Region	MMI	Magnitude (Mw)	Deaths	Injuries	Note
2023-09-08	Marrakesh-Safi	IX	6.8	2960	5674	Extreme damage
2016-01-25	Al Hoceima	V	6.3	1	15	Moderate damage

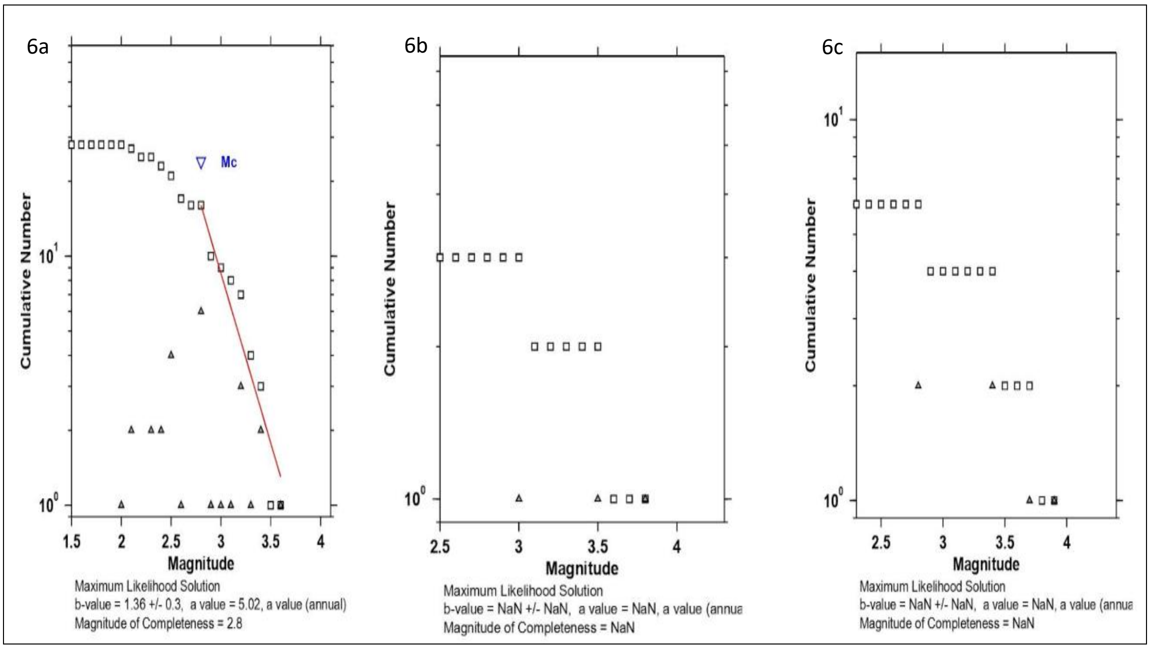

Fig 6: Illustrates the Gutenberg-Richter plot for the seismic windows of 1978-1983 (left panel), 1984-1988 (middle), and 1989-1994 (right), respectively, utilizing Maximum likelihood solutions.

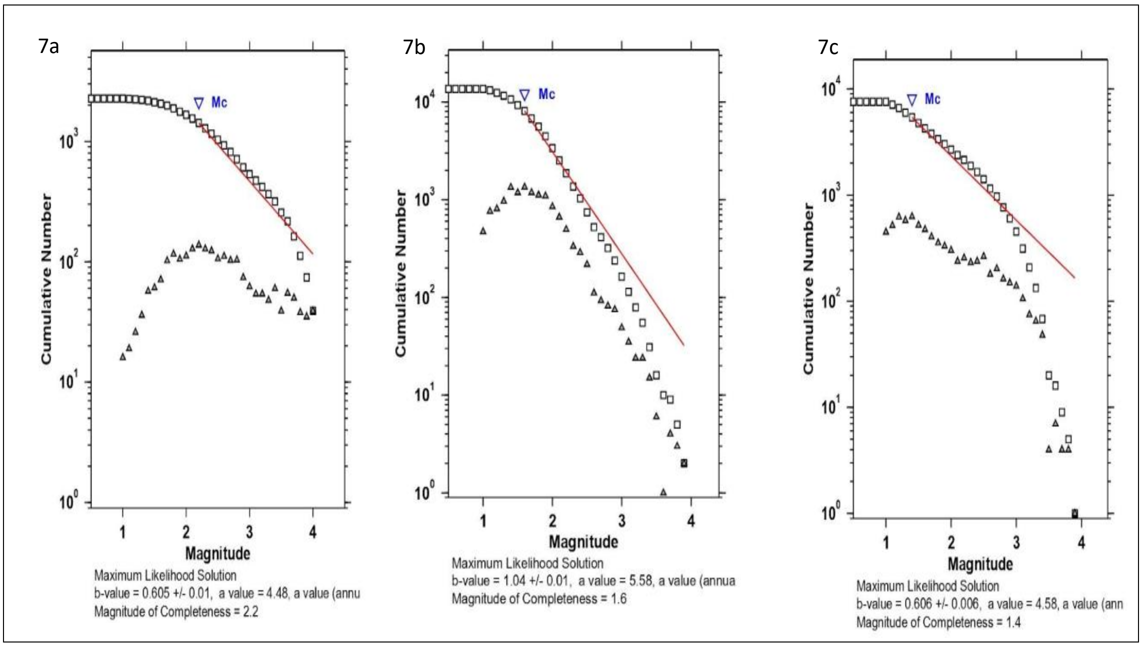

Fig 7: Illustrates the Gutenberg-Richter plot for the seismic windows of 1995-2000 (left panel), 2001-2006 (middle), and 2007-2012 (right), respectively, utilizing Maximum likelihood solutions.

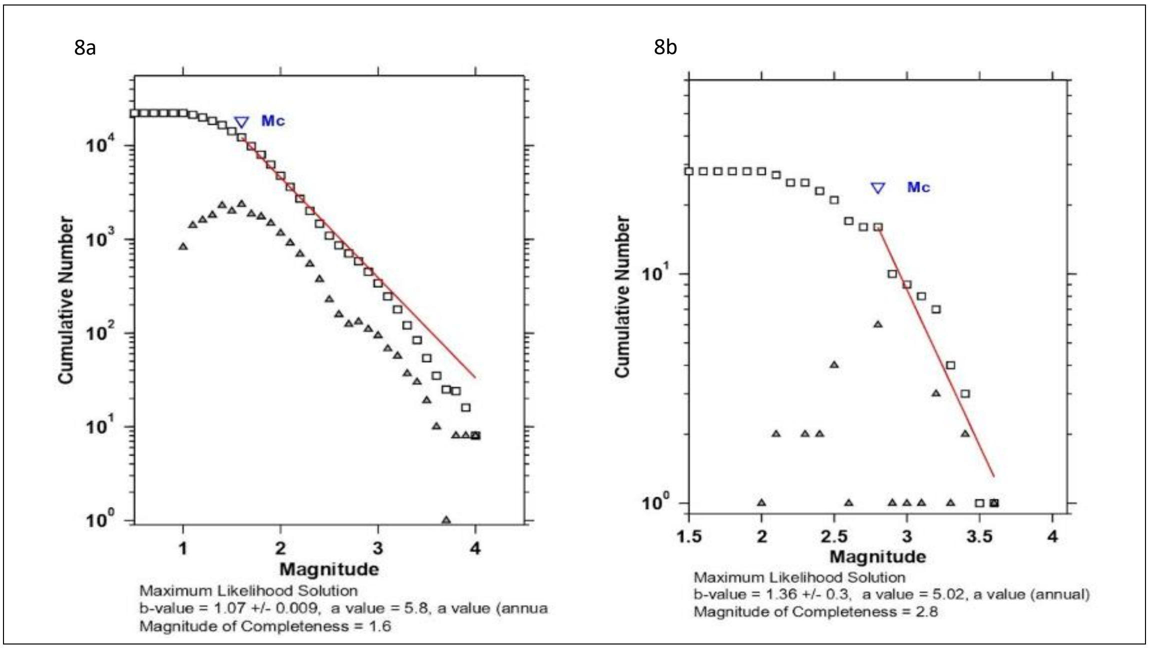

Fig 8: illustrate the Gutenberg-Richter plot for the seismic windows of (a) 2013-2018 and (b) 2019-2024 respectively, utilizing Maximum likelihood solutions.

Discussion

The magnitude of completeness (Mc) represents the threshold magnitude above which 100% of earthquakes in a given space-time volume are reliably detected. Accurate Mc determination is crucial as it directly influences b-value calculations, which subsequently affect a-value assessments. The a-value quantifies overall seismicity rates, while the b-value characterizes the relative proportion of small to large earthquakes. Together with Mc, these parameters ensure reliable statistical analysis of seismic catalogs.

The time-lapse seismicity maps demonstrate a notable increase in both earthquake frequency and magnitude over the 45-year study period. This apparent trend likely reflects improvements in seismic monitoring infrastructure, including expanded station networks and enhanced instrument sensitivity, rather than solely representing increased tectonic activity. Earthquake clustering is particularly pronounced along the northern coastal regions, especially near the African-Eurasian plate convergence zone and within the Rif Mountains. This spatial distribution reflects the ongoing collision between the African and Eurasian plates, which generates significant tectonic stress and drives frequent seismic activity. Major fault systems, including the Rif fault, play a crucial role in accommodating this stress and controlling regional seismicity patterns.

Our investigation reveals a significant relationship between elevated b-values and the occurrence of major earthquakes. Time intervals with b-values exceeding 1.0 correspond to periods when magnitude 6+ earthquakes occurred, resulting in moderate to severe damage and casualties. This pattern is evident in the 2013-2018 and 2019-2024 intervals, both showing b-values greater than 1.0. During 2013-2018 (b-value = 1.04 ± 0.01), the Al Hoceima region experienced a magnitude 6.3 Mw earthquake on January 25, 2016, causing one fatality and fifteen injuries. Similarly, the 2019-2024 interval (b-value = 1.08 ± 0.009) encompasses the devastating September 8, 2023, Marrakesh-Safi earthquake (magnitude 6.8 Mw), which resulted in over 2,000 deaths, thousands of injuries, and property damage exceeding millions of dollars.

Conclusion

This comprehensive analysis of 45 years of seismicity data along the Nubia-Eurasia plate boundaries reveals important patterns in earthquake occurrence and hazard potential. The study demonstrates a clear correlation between elevated b-values (>1.0) and the occurrence of major earthquakes exceeding magnitude 6.0 Mw, providing valuable insights for seismic hazard assessment. The increasing seismicity rates observed in the region, combined with the identification of high-risk temporal windows, underscore the critical need for enhanced earthquake preparedness measures.

Based on these findings, the enforcement of stringent building codes adapted to local seismic conditions, development and enhancement of early warning systems to provide timely alerts, and implementation of comprehensive seismic hazard preparedness programs for at-risk communities are strongly recommended. The continued monitoring of b-value trends, combined with improved understanding of the magnitude of completeness variations, will be essential for future seismic hazard assessment and risk mitigation strategies in this tectonically active region.

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