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Tectonic Activities of the Mid-Atlantic Ridge and Implication of Seismicity in West African Region

Kadiri Umar Afegbua[1,2*], Friday O. Ezomo[2], O. D. Osahon[2], Andrzej Kijko[3], Ansie Smit[3] and Vicki-Ann Dimas[4]

[1]Centre for Geodesy and Geodynamics, P.M.B 11, Toro, Bauchi State, Nigeria.
[2]Department of Physics, University of Benin, Benin City, Nigeria.
[3]University of Pretoria, South Africa.
[4]OzRocks Geoservices Pty Ltd, Australia.

Authors' contributions

This work was carried out in collaboration between all authors. Authors KUA and FOE designed the study, performed the statistical PSHA analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors ODO, AK, AS, and Authors VAD, KUA managed the analyses of the study. Authors KUA, FOE and ODO managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The aim of this research is to contribute to insights on how the tectonic activities in the MAR may have been influencing observed seismic activities in the region of West Africa. The seismic activities in parts of Mid-Atlantic Ridge (MAR) have been investigated with respect to seismicity in the West African region, using Statistical and Probabilistic Seismic Hazard Assessment (PSHA) techniques. Earthquake data were extracted from different catalogues in West Africa and international agencies for the study. The catalogues were declustered to remove foreshocks, aftershocks and repeated earthquakes. The different magnitude scales were also harmonized to moment magnitude (Mw). The statistical technique involved Regression Analysis, Focal Depth and Frequency Distribution analyses of observed events to establish distinct trend, using a decade-long

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**Corresponding author: E-mail: umakad@yahoo.com;*

of earthquake sub-catalogues at different completion levels. The results, especially from the statistical technique, clearly showed a trend of an increasing seismicity along the MAR in the West African region, with respect to number of earthquakes occurrence and magnitudes from 1963 to 2014. This could be as a result of progressively increasing seismic activities in response to tectonic stresses along the ridge. The results from PSHA, the b-values, activity rates and maximum magnitude for the investigated region are 0.82, 168 and 7.1 respectively. The b-value falls well within the acceptable tectonic seismicity of 0.72 to 0.82. The results also show that magnitudes 6.00 and 7.0 earthquakes are likely to occur approximately every 2 and 10 years along MAR; the probability of these events occurring annually is high at 98% and 92%; and the probability of their occurrence once in 50, 100 and 1000 years is 100%, 100%, 100% (for surface waves magnitude, M_s 6.0) and 98%, 99% and 100% (for M_s 7.0) respectively. The increase in seismic activities along the ridge may be responsible for observed increase of seismic activities especially in the West African countries along the coast of the Atlantic Ocean. This calls for further research in future. Although, West Africa is not an active region compared to regions of high seismicity like East African Rift, Japan, etc., a trend that showed an increasing earthquake occurrence and appearance of larger magnitudes has been revealed in this study.

Keywords: Mid-Atlantic ridge; West Africa; tectonic activity; seismic trend; earthquake recurrence parameters; seismicity of West Africa.

ABBREVIATIONS

MAR	*: Mid-Atlantic Ridge*
PSHA	*: Probabilistic Seismic Hazard Assessment*
Mw	*: Moment Magnitude.*
M_s	*: Surface wave magnitude*
NNNSS	*: Nigerian National Network of Seismographic Stations*
USGS	*: United States Geological Survey*
ISC	*: International Seismological Commission*
ANSS	*: Advanced National Seismic Systems*
(PDF)	*: probability density function*
Mmax	*: Maximum magnitude*
Ms	*: Surface wave magnitude*
Mb	*: body wave magnitude*
RP	*: Return Period*
Mag	*: Magnitude*
Prob	*: Probability*

1. INTRODUCTION

In the last few years, seismic activities in parts of the West African region have been on the increase. In 2016 alone, Nigeria, a country in the West African region witnessed more than ten seismic-related activities, for which three were recorded by four seismic stations located in the country. The possible mechanism for the Nigerian earth tremors has been attributed to the locations of Earth movements associated with NE-SW trending fracture and zones of weakness extending from the Mid-Atlantic Ridge into the country [1]. There is a strong suggestion that a possible relationship exists between the epicenters of some of the West African earthquakes and continent-ward extensions of oceanic fracture zones [2]. The tremors could be attributed to partial reactivation of fossil plate boundaries [3]. The tremors have most likely been caused by regional stress and zones of weakness in the crust or transfer of stress from plate boundaries [3].

1.1 Brief Information about Seismicity, Seismotectonic and Seismic Hazard Assessments in West African Region

Unlike the East African Rift System and some parts in the North African Maghreb regions, West Africa is not an active region. However, a couple of historical and instrumental earthquakes have been observed in West Africa from more than 300 years ago till date [3]. Several studies had been carried out on the possible sources of earthquakes in West Africa. They include the fracture zones located at Guinea [4]; Ivory Coast [2]; the Romanche fracture zone [5,2]; Ifewara-Zungeru fault zone in Nigeria which has been shown to be linked with the Atlantic fracture system [6,7,8,9], the Zungeru, Anka and Kalangai faults, all within Nigeria [10].

Remarkable seismic hazard studies have not been done in West Africa because of the hitherto belief the region was free from destructive earthquakes. The average annual frequency of earthquakes in Western Africa had been studied by [11] while areas of West Africa for which there is historical evidence or local traditions relating to earthquakes were mapped and discussed comprehensively in [12]. Studies had been carried out in [13] about the Fossil plate boundaries in West Africa and their bearing on seismotectonics. The Nigerian earthquakes have been discussed in [1,3,14,10] and [15]. In [16] past major earthquakes in Southern Ghana using intensity data have been documented.

Records of most of the seismic hazard studies conducted in Africa are found in Central, East and South Africa, for example, in [17] and [18]. Seismic hazard studies have not been so prominent in West Africa because of dearth of complete earthquake catalogues. Most of earthquakes are either observed or recorded instrumentally with local magnitudes between 2.0 and 5.0 [3]. However, the magnitude 6.5 of June 22, 1939 earthquake with an epicenter in Ghana, was the largest yet. The earthquake occurred along the Akwapin fault in Ghana and its vibrations were felt far away in Lagos, Ibadan, and Ile-Ife, in Nigeria [3]. Table 1 shows some significant tremors observed in parts of West Africa.

The Gutenberg-Ritcher [19,20] is important to describe both tectonic and induced seismicity, and have been applied in different time scales such as in seismicity simulation; earthquake prediction in [21] and seismic hazard and risk assessment in [17]. Studies have been carried out in [22,23] to estimate earthquake hazard parameters from incomplete data files, utilizing extreme and complete catalogs with different threshold magnitudes and incorporated magnitude heterogeneity. Similarly, in [24] and [25], the Aki-Utsu b-value estimator has been extended for Incomplete Catalogs. The works in [22,23] and [25] can be modified to achieve the desired seismic hazard results.

Table 1. Some prominent earthquakes observed in the West African region [3,10,1]

Area/Country	Date Tremor Was Felt
Ghana, Accra	1636, 1832, 1906, 22nd June, 1939
Guinea	Dec 22, 1983
Cameroon – near Kribi	1903, 1911, 1987
Cameroon - near Buea	1987, 1989, 1997
Nigeria - Warri and Lagos	22 June 1939
Nigeria - Gembu	1987
Nigeria - Ibadan and Ijebu-Ode	July 28, 1984; Aug. 2, 1984
Nigeria - Asaga, Ohafia near Umuahia	2nd July, 1961

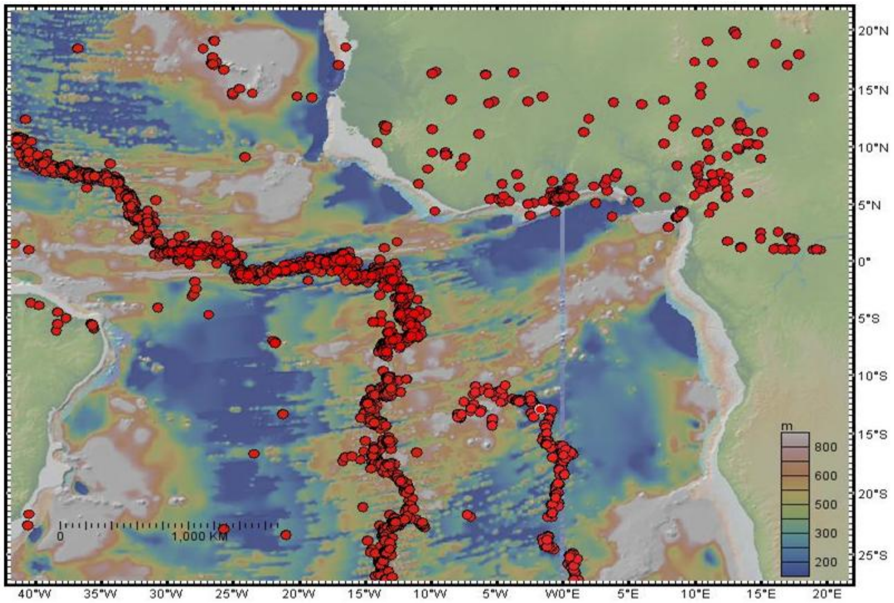

Fig. 1. Plot of events in parts of Mid Atlantic Ridge and West African region using GeomapApp
Data sources: [26,27,28] and [12]

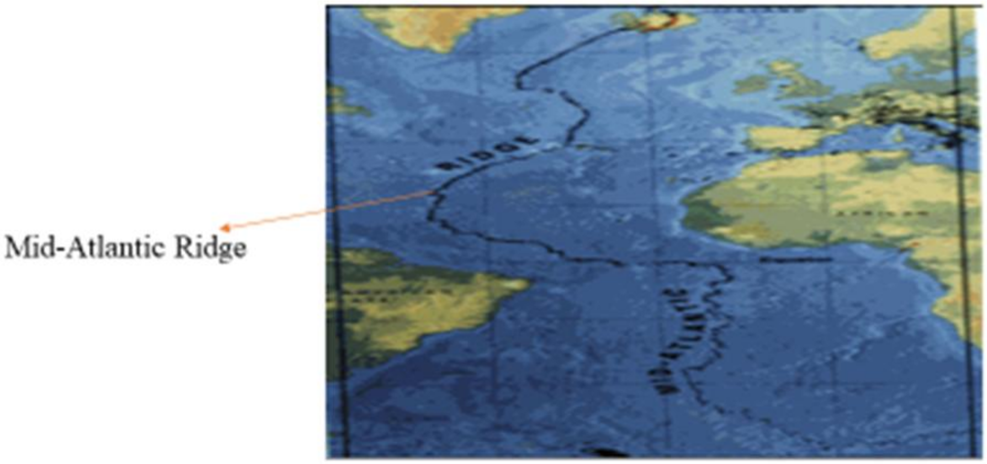

Fig. 2. Location of Mid-Atlantic Ridge (Modified after [35])

1.2 Geology and Tectonic Settings of the Study Area

The geology of West Africa lies mainly in Precambrian Crust [29]. According to [13], the Leo uplift or the Guinea Rise, which is comprised of a deeply eroded granitized root dated over 1,000 million years (My), forms the West African craton. West of the craton is fragments of a Hercynian fold belt which are in a thrust contact with an unfolded Paleozoic cover dated at 570-350 My [13]. A broad fold belt of upper Precambrian sediments dated at 650-550 My (Togo-Dahomey-Nigerian shield), are found to the east of the Leo uplift and also in thrust contact with granitized basement and Paleozoic cover [13]. A correlation of the seismicity map of West Africa with the geological features of different parts of the sub-region in terms of earthquake epicentral locations and fossil plate boundaries has been established in [13]. This correlation was applied to explain the seismicity of southern Ghana and its linkage to movement along the Akwapin fault zone and to the Coastal Boundary fault a few kilometers offshore [2].

Investigations in [30] after the Guinean earthquake in December 1983, revealed among many other things, area where there is large-scale tectonics resulted in the superposition of the Pan-African and Hercynian provinces and the West African craton.

The Mid-Atlantic Ridge (MAR) shown in Fig. 2, is an underwater mountain system (chains), formed by plate tectonics with valley running along its spine [31]. MAR has been identified as responsible for all Global earthquake sources at the divergent boundary of two plates [32]. Majority of earthquakes appearing along the oceanic ridge probably arise from shears across transform faults connecting section of ridges [33]. MAR is the longest mountain range on earth (about 1600 km long and 970 km wide); running from South of the North pole to sub-Antarctic Bouvet Island. The MAR sits above the Mid-Atlantic Rise, which is a progressive bulge that runs the length of the Atlantic Ocean, with the ridge resting on the highest point of this linear bulge [31]. This bulge is thought to be caused by upward convective forces in the asthenosphere pushing the oceanic crust and lithosphere. This divergent boundary first formed in the Triassic period, when a series of three-armed grabens coalesced on the supercontinent Pangaea to form the ridge [34].

2. MATERIALS AND METHODS

The data used in this research are basically the parametric earthquake data and were sourced from Nigerian National Network of Seismographic Stations (NNNSS), international Agencies and [12]. The data covered a period of 1618-2014. Two techniques adopted for analysis of the data are:

1. The Statistical method, and
2. The Probabilistic Seismic Hazard Assessment (PSHA) method.

2.1 Theories

According to the Gutenberg–Richter frequency-magnitude relation [19,20] the number of earthquakes n, having a magnitude equal to or larger than m, can be expressed in equation 1.1, where parameter 'a', is a measure of the level of seismicity and parameter 'b' describes the ratio between the number of small and large events.

$$\log(n) = a - bm \tag{1.1}$$

However, Aki's classic estimator in [24] which considered earthquake magnitude as a continuous random variable, is still the preferred estimator. [24] derived the maximum likelihood estimate of the b-value, equivalent to equation 1.2.

$$\beta = \frac{1}{\bar{m} - m_{min}} \tag{1.2}$$

The parameters $\bar{m}$ and m_{min} are the average magnitude and the level of completeness of a given sample of earthquake magnitudes, respectively. Assume that a given seismic event catalog can be divided into s sub-catalogs, each with known, but different levels of completeness, $m_{min}^{1}, m_{min}^{2}, \ldots\ldots, m_{min}^{s}$. Let each of these sub-catalogs last t_i years and contain a record of n_i (i= 1,2,…, s) number of events with known magnitudes. An overall maximum likelihood estimate of the b-value can be obtained by the application of the additive property of likelihood functions [36]. The joint likelihood function, which utilizes all earthquakes that occurred within the whole span of the catalog, is defined as $L = L_1 L_2 \ldots\ldots\ldots L_s$, where Li represents the i-th likelihood function based on data observed within i-th sub-catalog and i=1, 2,…….s [25].

If magnitudes of seismic events are assumed to be independent, identically distributed random variables following the frequency–magnitude Gutenberg–Richter relation in equation 1.1, the probability density function (PDF) of earthquake magnitude takes the form as in equation 1.3, [24]:

$$f(m;\beta) = \begin{cases} 0 & for\, m \geq m_{min} \\ \beta \exp[-\beta(m - m_{min})] & for\, m \leq m_{min} \end{cases} \tag{1.3}$$

Where magnitude m is considered as a continuous variable that may assume any value equal to or larger than the level of completeness m_{min}. It has been shown in [22], that if the number of seismic events per unit of time is a Poisson random variable, the maximum likelihood estimator of λ(m_{min}) takes the form in equation 1.4.

$$\hat{\lambda}(m_{min}) = \frac{n}{\sum_{i=1}^{s} t_i \exp\left[-\hat{\beta}\left(m_{min}^{i} - m_{min}\right)\right]} \tag{1.4}$$

However, equation 1.4 can also be written as

$$\log\lambda m = a - bm \tag{1.5}$$

where λm is the rate of earthquakes with magnitudes greater than *m*; and *a* and *b* are constants. Equation 1.5 is called the Gutenberg-Richter recurrence law, relevant for the computation of earthquake recurrence parameters.

2.2 Statistical Analysis

The statistical analysis employed in this study involved the analysis of the frequency distribution of earthquakes occurrence and magnitudes respectively, covering the entire harmonized catalogue. In order to test for variation in earthquake occurrence and magnitude, the entire catalogue was divided into ten-year sub-catalogues; and each sub-catalogue was handled independently.

2.3 Probabilistic Seismic Hazard Assessment (PSHA)

The PSHA method was implemented using the following steps:

(i) Identification of all earthquake sources capable of producing damaging ground motions; These zones are usually associated with active geological or tectonic features, like faults.
(ii) Characterization of the distribution of potential earthquakes into different magnitudes.
(iii) Unification of various magnitudes from different agencies
(iv) Declustering the resulting catalogues of earthquakes to remove foreshocks and aftershocks and earthquake swam, in order to ensure only representative earthquake data were used for the study. Also, to remove duplicated earthquakes.
(v) The final step is the computation of all earthquake recurrence parameters (maximum earthquake magnitude, b-value and activity rate etc.) for the region covered. Fig. 3 further explained the steps.

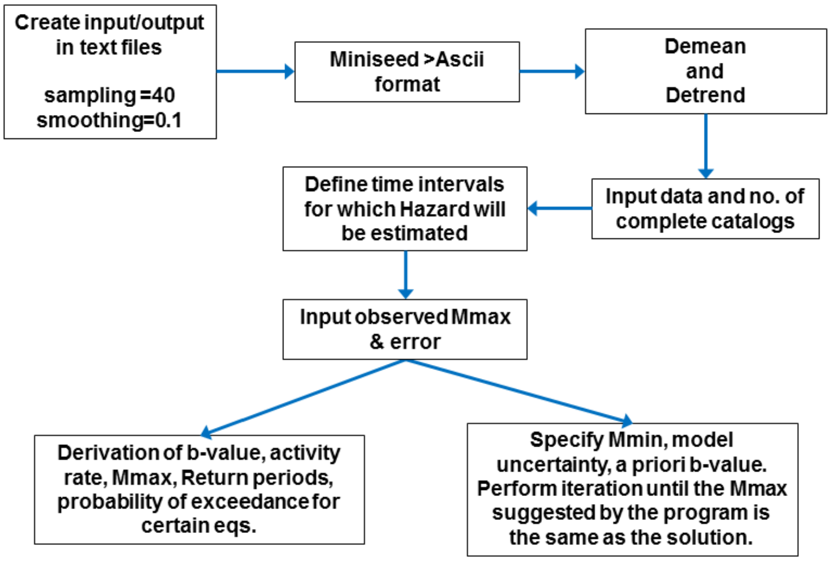

Fig. 3. Flow chart illustrating procedures for PSHA adopted in this study

Fig. 3 summarizes the procedures adopted in performing the PSHA using the model in [25]. At the initial stage, input/output files in text files were created and the region of interest covered by the data was defined. The number of sub-catalogues at different levels of magnitude completeness were extracted from the main catalogue and fed into the hazard program written in matlab programming language. From available geological and tectonics information of the region, the natural seismicity of the area was then specified without the option of considering induced seismicity from oil exploration, mining, fracking, and bodies of water etc.

Progressively, four time (years) intervals for which hazard will be computed were chosen as 1, 50, 100, and 1000 years respectively. Then the maximum ever observed magnitude (Mmax) in the region was imputed and its standard deviation computed. The threshold value of earthquake magnitude (Mmin) and the model uncertainty adopted was specified; then the Kijko-Sellevoll-Bayes model in [37], a model that is based on Bayesian principles, was used to calculate maximum magnitude (Mmax) expected in future.

The apriori information of the parameter b, or the b-value and its standard deviation were also specified, and subsequently, iteration was performed on the data until the maximum magnitude suggested by the Hazard program was the same as the solution obtained in this study. All the earthquake recurrence parameters for the study area were thus generated.

3. PRESENTATION OF RESEARCH RESULTS

3.1 Statistical Analysis

Consider a sample illustrating equation 1.6,

$$(Y)i = a + b(X)i + (error)i \tag{1.6}$$

where:

(Y)i = value of Y for observation i
a = mean value of Y when X is zero (intercept coefficient)
b = average change in Y given a unit change in X, i.e. (slope of X)
(X)i = value of X for observation i

From the linear equation 1.6, a relationship linking Ms (surface wave magnitude) and Mb (body wave magnitude) of earthquakes for instance, can be written as in equation 1.7

$$(Ms)i = a + b(Mb)i + (error)i \tag{1.7}$$

Using the sorted data for the entire study area therefore, models as represented in equations 1.8 and 1.9, were derived.

$$Ms = 5.9 – 0.203Mb \tag{1.8}$$

$$Mw = 0.69Mb + 1.94 \tag{1.9}$$

Equation 1.9 is a model linking the body wave magnitude and a moment magnitude of earthquakes.

In the analysis, the goodness of fit measure (Adjusted R square) is 0.892583; representing 89.3% of Ms determined by Mb in equation 1.8, and 0.894201 representing 89.4% of Mw determined by Mb in equation 1.9 respectively.

Figs. 4 and 5 represent line fit plots for surface wave and body wave magnitudes, and moment wave and body wave magnitudes respectively.

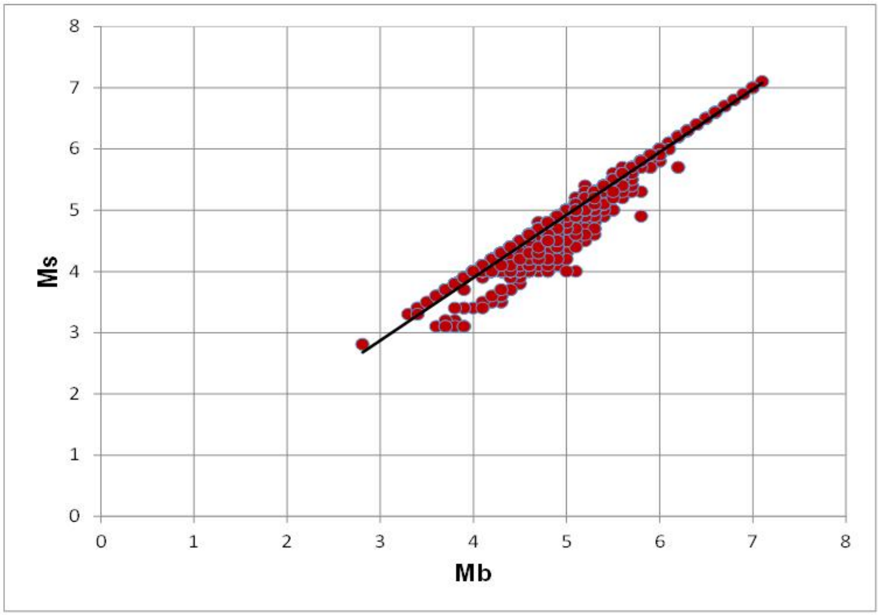

Fig. 4. Line of Fit Plot between Ms and Mb

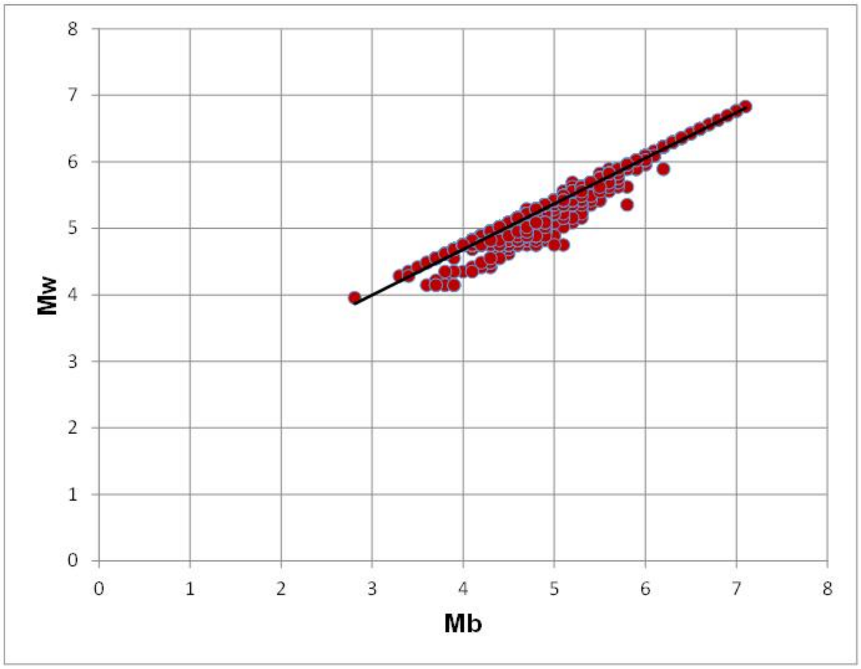

Fig. 5. Line of Fit Plot between Ms and Mb

Table 2 shows the results of the statistical analysis of focal depth distribution (decade) of earthquakes along the Mid-Atlantic Ridge (MAR), using magnitudes from 3.1 – 7.1, and at different hypocentral depths. The focal depth of an earthquake is the vertical depth above the earth surface from the point of rupture. The purpose for the statistical study under this section was to investigate the trend of earthquake occurrence along the mega divergent ridge, the Mid-Atlantic Ridge, and critically assess its tectonic activities and their implications to West African region. Although earthquake occurrence along the ridge was not captured for a whole decade, but a progressive increase of occurrence is already obvious between the two years (2013-2014) captured in the last part of Table 2. From the Table 2, it could be affirmed that earthquakes occurrence has progressively increased from 1963 to 2014.

Figs. 6 to 11 are earthquake Frequency-Magnitude distribution per decade along the Mid Atlantic Ridge.

Figs. 12 and 13 present the results of total earthquakes per decade for the entire period, using bar and pie charts respectively. The trend clearly showed that earthquake occurrence along the Mid-Atlantic Ridge has increased progressively from 1963 to 2012. Using this trend, it is obvious earthquake occurrence from 2013 to 2022, (another decade), would be significantly high, if more than 200 events were recorded from 2013 to 2014 alone.

Table 2. Focal depth distribution of earthquakes along the Mid Atlantic Ridge in West African region (MAR) for the period (1963-2014)

Year interval	Magnitude range	Hypocentral depth	Cumulative number of earthquakes per decade
1963-1972	2.1 - 3.0	0	463
	3.1 - 4.0	0	
	4.1 - 5.0	366	
	5.1 - 6.0	95	
	6.1 - 7.0	2	
	7.1 - 8.0	0	
	8.1 - 9.0	0	
	9.1 - 10.0	0	
1973-1982	2.1 - 3.0	0	626
	3.1 - 4.0	0	
	4.1 - 5.0	476	
	5.1 - 6.0	144	
	6.1 - 7.0	6	
	7.1 - 8.0	0	
	8.1 - 9.0	0	
	9.1 - 10.0	0	
1983-1992	2.1 - 3.0	0	782
	3.1 - 4.0	0	
	4.1 - 5.0	613	
	5.1 - 6.0	163	
	6.1 - 7.0	6	
	7.1 - 8.0	0	
	8.1 - 9.0	0	
	9.1 - 10.0	0	
1993-2002	2.1 - 3.0	0	782
	3.1 - 4.0	51	
	4.1 - 5.0	940	
	5.1 - 6.0	165	
	6.1 - 7.0	6	
	7.1 - 8.0	0	
	8.1 - 9.0	0	
	9.1 - 10.0	0	

Year interval	Magnitude range	Hypocentral depth	Cumulative number of earthquakes per decade
2003-2012	2.1 - 3.0	0	1162
	3.1 - 4.0	21	
	4.1 - 5.0	1140	
	5.1 - 6.0	260	
	6.1 - 7.0	19	
	7.1 - 8.0	0	
	8.1 - 9.0	0	
	9.1 - 10.0	0	
2013-2014	2.1 - 3.0	0	289
	3.1 - 4.0	1	
	4.1 - 5.0	245	
	5.1 - 6.0	42	
	6.1 - 7.0	1	
	7.1 - 8.0	0	
	8.1 - 9.0	0	
	9.1 - 10.0	0	

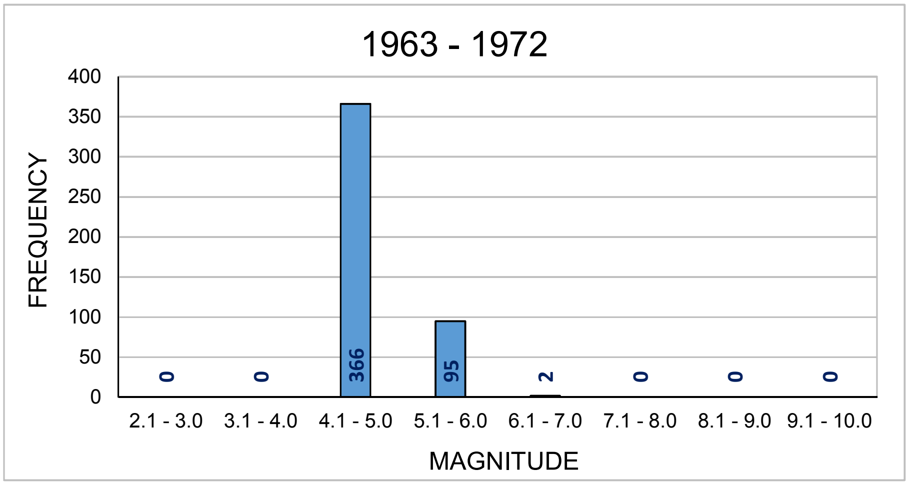

Fig. 6. Frequency-Magnitude distribution along MAR (1963-1972)

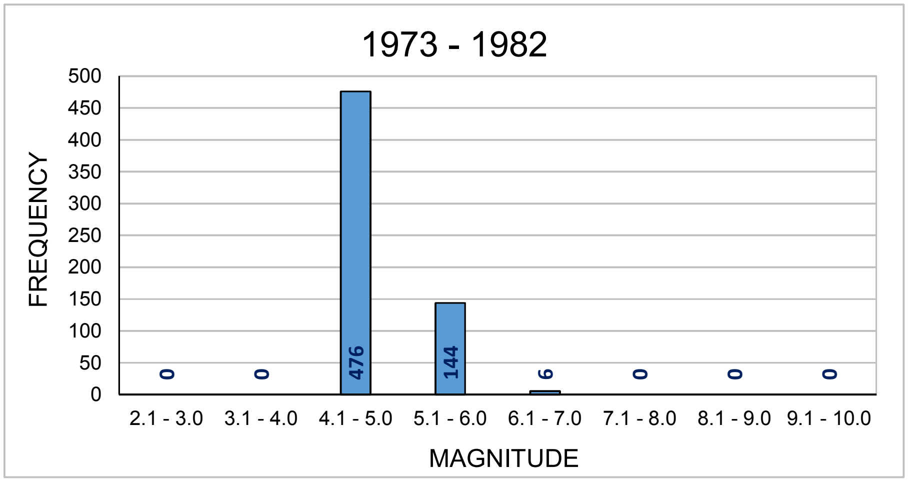

Fig. 7. Frequency-Magnitude distribution along MAR (1973-1982)

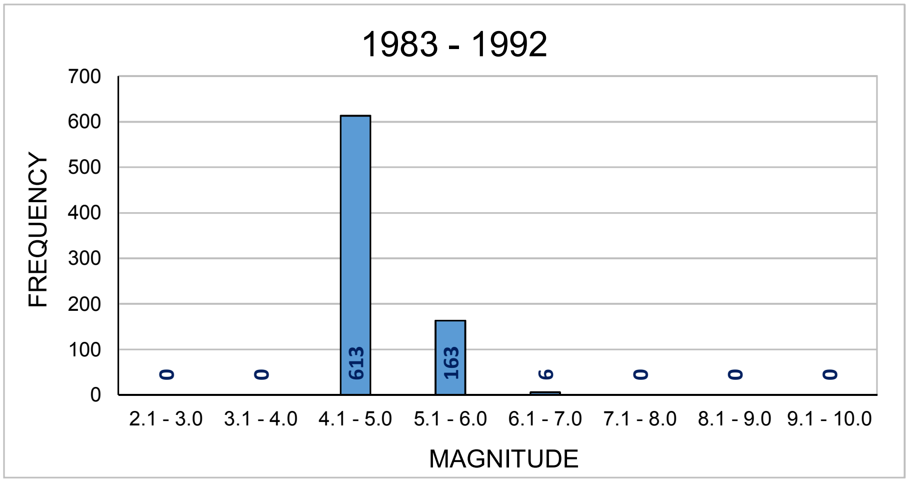

Fig. 8. Frequency-Magnitude distribution along MAR (1983-1992)

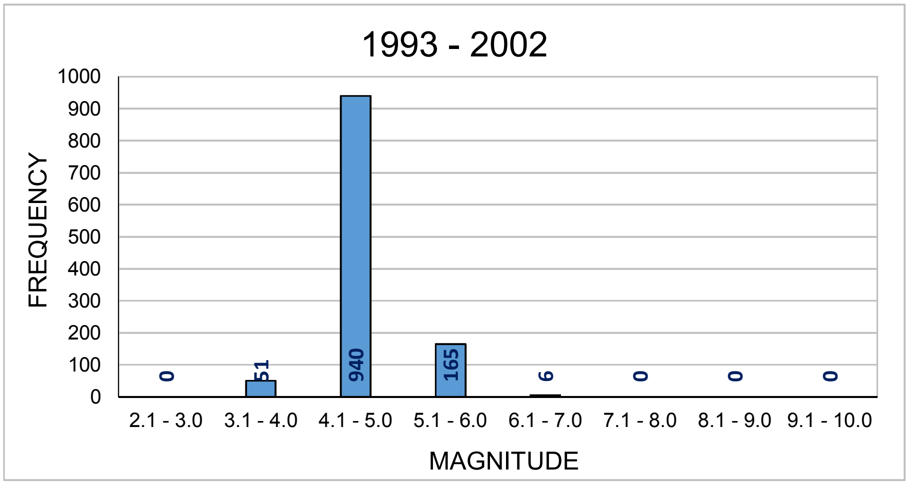

Fig. 9. Frequency-Magnitude distribution along MAR (1993-2002)

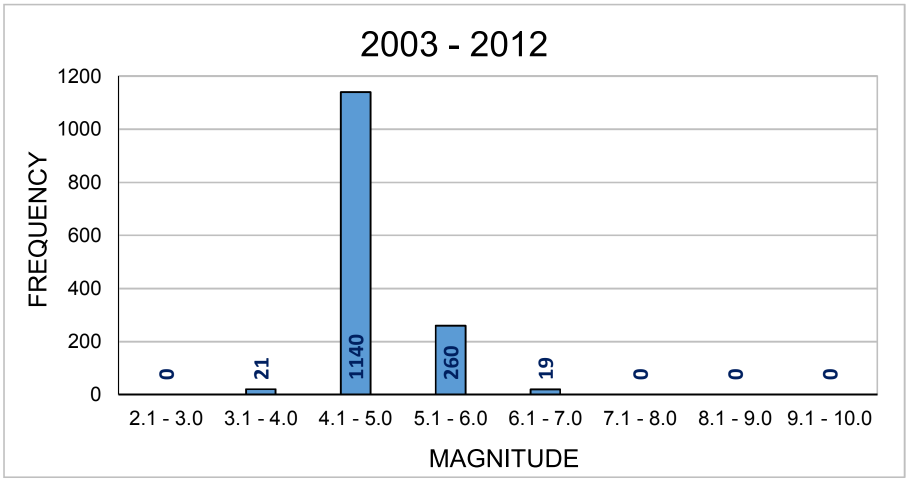

Fig. 10. Frequency-Magnitude distribution along MAR (2003-2012)

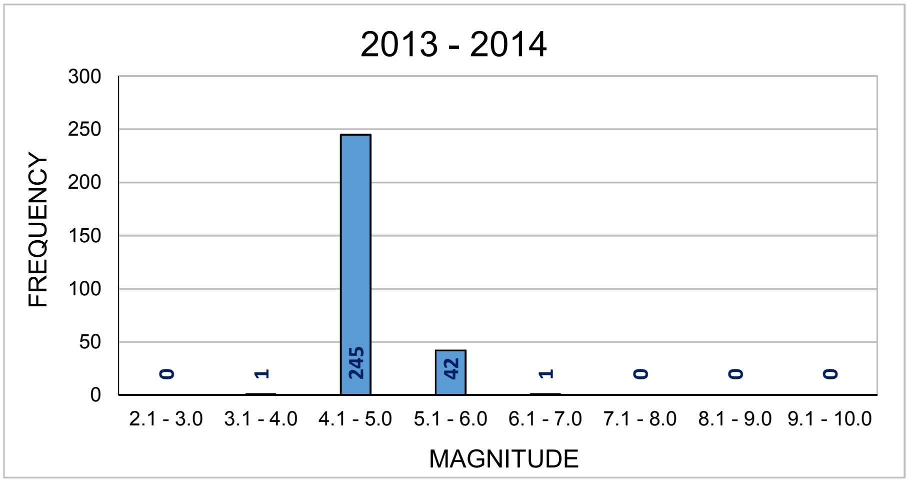

Fig. 11. Frequency-Magnitude distribution along MAR (2013-2014)

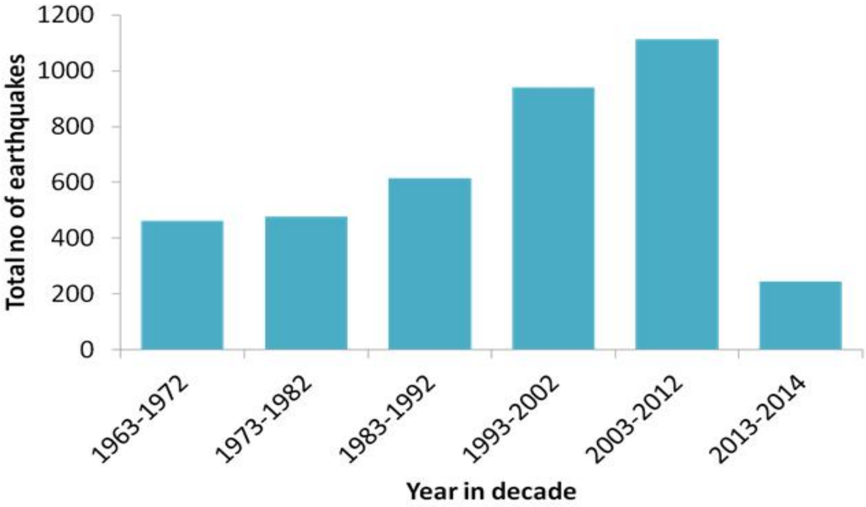

Fig. 12. Bar chart of earthquake distribution per decade

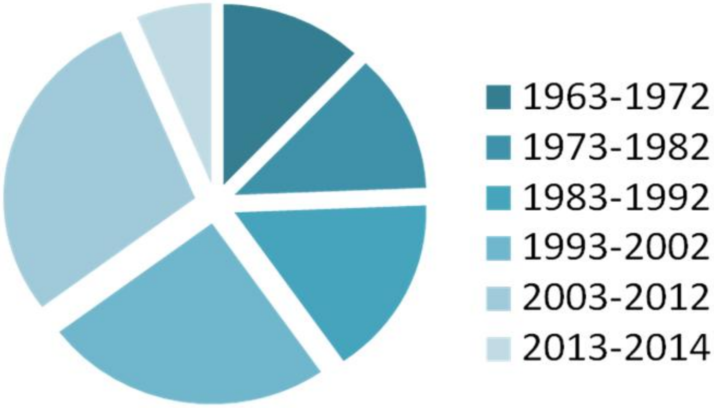

Fig. 13. Pie chart of earthquake distribution per decade

3.2 Probabilistic Seismic Hazard Assessment (PSHA) for the Mid-Atlantic Ridge (MAR)

Fig. 14 represents the magnitude-hypocentral depth of earthquakes in the MAR, with a minimum of 0 km to a maximum of 48 km depth. Table 3 and Figs. 15 to 17 are the earthquake occurrence forecasts along the MAR region. Earthquake prediction and recurrence probability in table 3 covered the entire period (1963-2014). It could be deduced from table 3 that small magnitude earthquakes (less than 5.0) have high probability of occurrence and recurrence within 1, 50, 100 and 1000 years respectively; while the probability of earthquakes occurrence and recurrence of the magnitude above 6.0 diminish within the same year intervals.

The results for beta (β), b-value, lambda (λ) or the earthquakes activity rate, and maximum expected earthquake magnitude (Mmax) for MAR region in the period are: β = 1.93± 0.05; b = 0.82 ± 0.02; λ = 168.122 ± 24.270 (for Mmin = 4.00) and Mmax = 7.06 ± 0.06 (for Mmax obs. = 7.00 ± 0.02). These are the earthquake recurrence parameters computed for the MAR region.

The value of beta is used to estimate the reliability of the b-value. The b-value is the ratio of small earthquakes to big ones; lambda is the activity rate of earthquakes; Mmin is the threshold earthquake magnitude used for the seismic hazard analysis; and Mmax is the expected maximum earthquake magnitude forecast from the hazard analysis. The parameters could be utilized to predict future occurrence of earthquakes, even though it is still not possible to exactly predict when, where and how earthquakes will occur in future.

Table 3. Earthquake recurrence parameters for MAR region for the entire period (1963-2014)

Mag	Lambda	RP	Prob (T = 1 yr)	Prob (T = 50 yrs)	Prob (T = 100 yrs)	Prob (T = 1000 yrs)
4.0	1.6812E+02	5.95E-03	1.00000	1.00000	1.00000	1.00000
4.1	1.3853E+02	7.22E-03	1.00000	1.00000	1.00000	1.00000
4.2	1.1437E+02	8.74E-03	1.00000	1.00000	1.00000	1.00000
4.3	9.4610E+01	1.06E-02	1.00000	1.00000	1.00000	1.00000
4.4	7.8402E+01	1.28E-02	1.00000	1.00000	1.00000	1.00000
4.5	6.5079E+01	1.54E-02	1.00000	1.00000	1.00000	1.00000
4.6	5.4104E+01	1.85E-02	1.00000	1.00000	1.00000	1.00000
4.7	4.5042E+01	2.22E-02	1.00000	1.00000	1.00000	1.00000
4.8	3.7545E+01	2.66E-02	1.00000	1.00000	1.00000	1.00000
4.9	3.1328E+01	3.19E-02	1.00000	1.00000	1.00000	1.00000
5.0	2.6164E+01	3.82E-02	1.00000	1.00000	1.00000	1.00000
5.1	2.1864E+01	4.57E-02	1.00000	1.00000	1.00000	1.00000
5.2	1.8278E+01	5.47E-02	0.99999	1.00000	1.00000	1.00000
5.3	1.5281E+01	6.54E-02	0.99998	1.00000	1.00000	1.00000
5.4	1.2772E+01	7.83E-02	0.99992	1.00000	1.00000	1.00000
5.5	1.0667E+01	9.37E-02	0.99972	1.00000	1.00000	1.00000
5.6	8.8984E+00	1.12E-01	0.99915	1.00000	1.00000	1.00000
5.7	7.4094E+00	1.35E-01	0.99773	1.00000	1.00000	1.00000
5.8	6.1539E+00	1.62E-01	0.99452	1.00000	1.00000	1.00000
5.9	5.0933E+00	1.96E-01	0.98799	1.00000	1.00000	1.00000
6.0	4.1960E+00	2.38E-01	0.97592	1.00000	1.00000	1.00000
6.1	3.4355E+00	2.91E-01	0.9555	1.00000	1.00000	1.00000
6.2	2.7900E+00	3.58E-01	0.9236	1.00000	1.00000	1.00000
6.3	2.2412E+00	4.46E-01	0.87724	1.00000	1.00000	1.00000
6.4	1.7740E+00	5.64E-01	0.81406	1.00000	1.00000	1.00000
6.5	1.3755E+00	7.27E-01	0.73275	1.00000	1.00000	1.00000
6.6	1.0352E+00	9.66E-01	0.63327	1.00000	1.00000	1.00000
6.7	7.4421E-01	1.34E+00	0.51685	1.00000	1.00000	1.00000
6.8	4.9495E-01	2.02E+00	0.38581	1.00000	1.00000	1.00000
6.9	2.8117E-01	3.56E+00	0.24326	0.99996	1.00000	1.00000
7.0	9.7569E-02	1.02E+01	0.09269	0.98585	0.99951	1.00000

RP=Return Period; Prob.=Probability; Mag=magnitude; T=Time in years

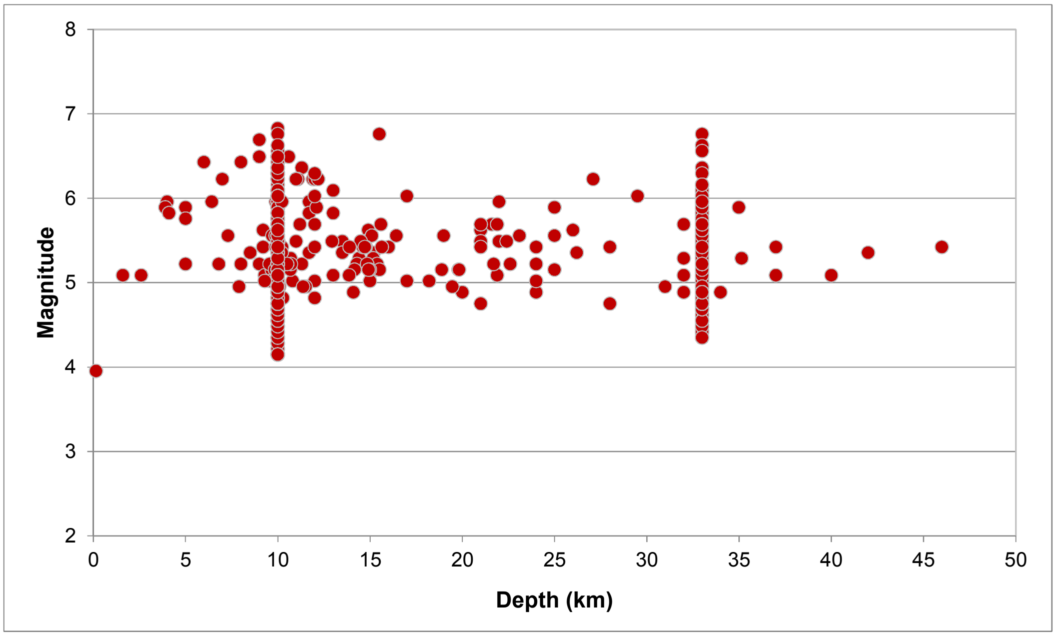

Fig. 14. Magnitude-hypocentral depth of earthquakes in the MAR region

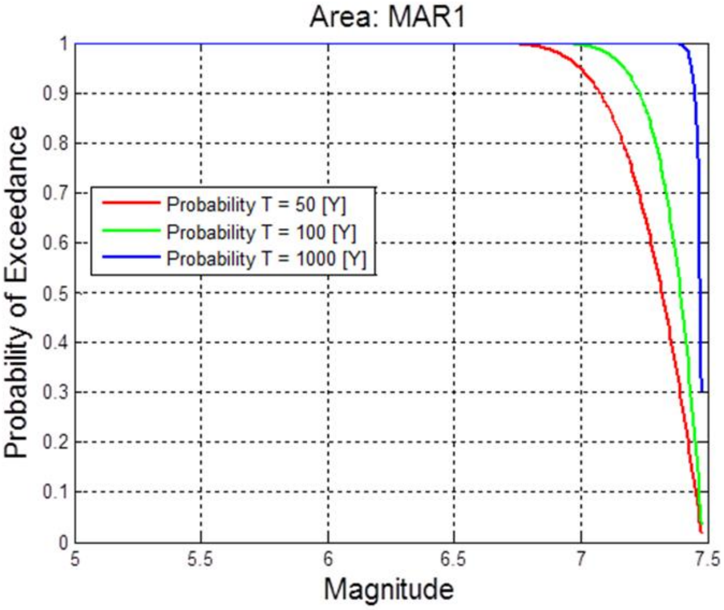

Fig. 15. Magnitudes and probability of Exceedance for MAR region (1963-2014), given 50, 100, and 1000 years' projection

4. DISCUSSION

4.1 Statistical and Probabilistic Seismic Hazard Assessment

The results are presented in two parts: results from statistical analysis and the Probabilistic Seismic Hazard Assessment along the Ridge and environs.

From the point of view of the statistical analysis, the models linking surface wave, body wave and moment magnitudes were established and presented in equations 1.8 and 1.9. These models are useful for magnitude scale conversions.

The statistical study was carried out to investigate the trend of earthquake occurrence along the Mid-Atlantic Ridge, in order to critically assess tectonic activities associated with MAR and their likely implications on West African countries. It can be seen the results, therefore, that the tectonic stresses and the seismic activities are progressively increasing along the area of study. Although further studies are recommended, it is likely the crust-upper mantle layer that surrounded the oceanic ridge, is becoming more unstable and the tectonic stress accumulation may be increasing along the ridge. Therefore, this development may have contributed to recently increased seismicity in the West African region.

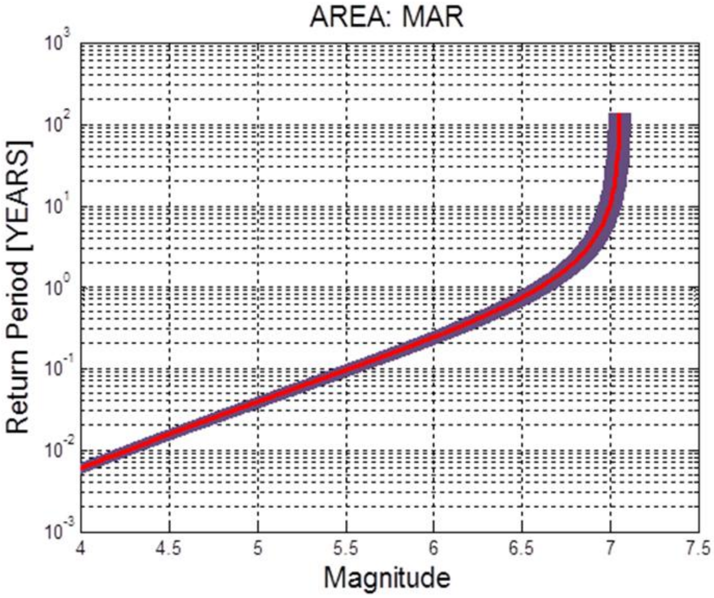

Fig. 16. Magnitudes and Return Periods (years) for MAR region (1963-2014) projection

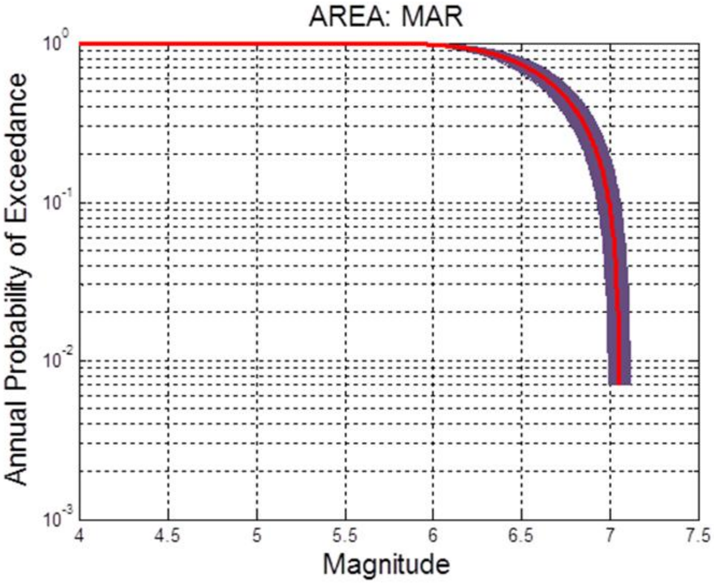

Fig. 17. Magnitudes and annual probability of Exceedance for MAR region (1963-2014) projection

The analysis from PSHA along MAR and immediate environs, showed that small magnitude earthquakes (less than 6.0) have high probability of occurrence and recurrence within 1, 50, 100 and 1000 years respectively; while the probability of earthquakes occurrence and recurrence of the magnitude above 6.0 diminishes in the same year intervals along the MAR region.

The knowledge of mean seismic activity rate λ, the Gutenberg-Richter b-value, and the area-characteristic (seismogenic source) maximum possible earthquake magnitude $\mathrm{m}_{\max}$, are required for most probabilistic seismic hazard analysis procedures. Utilizing these parameters, therefore, it is usually explicitly to assume the parameters remain constant over a specified time and space. However, there may be significant spatial and temporal variations in the seismic activity rate λ as well as the Gutenberg-Richter b-value. In estimating the maximum likelihood of these earthquake hazard parameters, therefore, the incompleteness of catalogues, uncertainty in the earthquake magnitude determination as well as the uncertainty associated with the applied earthquake occurrence models was taken into account. The uncertainty in the earthquake occurrence models is introduced by assuming that, both the mean, seismic activity rate λ and the b-value of Gutenberg-Richter are random variables, each described by the Gamma distribution [38].

The b-value computed from table 3 falls within [0.72 - 0.82] accepted range for tectonic seismicity. That is, the seismic activities along the MAR are tectonic in nature. From table 3, magnitudes M_s 6.00 and 7.0 could be expected to occur approximately every 2 and 10 years; the probability of these events occurring annually is 98% and 92%; and the probability of their occurrences once in 50, 100 and 1000 years is 100%, 100%, 100% (for M_s 6.0) and 98%, 99% and 100% (M_s 7.0) respectively.

5. REMARKS AND CONCLUSION

Statistical and probabilistic seismic hazard assessment has been used to investigate the trend of earthquake occurrence and earthquake recurrence parameters along the Mid-Atlantic Ridge in the West African region. The statistical analysis revealed an increasing trend of earthquakes occurrence along the Ridge and environs that are gradually tending towards the West African region, which may due to increasing in tectonic stress accumulation.

Analysis of the probabilistic seismic hazard assessment revealed that the seismic activities along the MAR are tectonic in nature, and occurrence of large magnitude earthquakes are likely going to be on the increase in future. The increase in seismic activities along the ridge maybe responsible for the observed increase of earthquake occurrence in the West African countries along the coast of the Atlantic Ocean, other factors which include deployment of more sophisticated seismic infrastructure in the region etc., may also be a reason for this development.

Although, this study was concluded with challenges which include, lack of comprehensive knowledge of suture zones linking the oceanic ridge to suture on land in the West African region, complete earthquake catalogues, uncertainties associated in magnitude determination etc., the study has been able to address some critical questions bothering on recently observed increasing seismic activities in parts of West African region and the likely connection to progressively increasing tectonic activities along the oceanic ridge.

As more data and relevant information on the seismotectonic nature of the region become available in future, it is believed that the knowledge of possible link of recent earthquakes in parts of West Africa and the Oceanic ridge would be improved.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Ajakaiye DE, Daniyan MA, Ojo SB, Onuoha KM. Southwestern Nigeria earthquake and its implications for tectonics and evolution of Nigeria. Journal of Geodynamics. 1984;7:205-214.
2. Burke K. Seismic areas of the Guinea coast where Atlantic fracture zones reach Africa. Nature. 1969;222(5194):655–657.
3. Onuoha KM. Earthquake hazard prevention and mitigation in the West African region. In: Natural and Man-Made

Hazards. (ed) El-Sabh MI, TS, D. Reidel Pub. Co. Dordrecht. 1988;787-797.

4. Kogbe CA, Delbos L. The recent Guinea earthquake: Probable origin and geographic implications. Pangea. 1984;2: 17–19.
5. Junner NR, Bates DA, Tillotson E, Deakin CS. The accra earthquake of 22nd June, 1939, Gold Coast Geological Survey Bulletin. 1941;13:1-57.
6. Anifowose AYB, Oladapo MI, Akpan OU, Ologun CO, Adeoye-Oladapo OO, Tsebeje SY, Yabuku TA. Systematic multi-technique mapping of the southern flank of Iwaraja fault, Nigeria. Jour of Applied Sci & Tech. 2010;15(1-2):70–76.
7. Adepelumi AA, Ako BD, Ajayi TR, Olorunfemi AO, Awoyemi MO, Falebita DE. Integrated geophysical studies of the Ifewara transcurrent fault system, Nigeria. Jr. Afr. Earth Sc. 2008;52:161-166.
8. Olujide PO, Udoh AN. Preliminary comments on the fracture systems of Nigeria. In Proceedings of the National Seminar on earthquakes in Nigeria (Ed.) Ajakaiye DE, Ojo SB, Daniyan MA. 1989;97-109.
9. Olorunfemi MO, Olarewaju VO, Avci M. Geophysical investigation of a fault zone-Case history from Ile-Ife, southwest Nigeria. Geophysical Prospecting. 1986; 34(8):1277-1284.
10. Eze CL, Sunday VN, Ugwu SA, Uko ED, Ngah SA. Mechanical model for Nigerian intraplate Earth Tremors. Disaster Management, Earth Observation. 2011;17.
11. Krenkel E. Die seismizat afrikas. Zentralbl. Mineral Geol. Paleontol. 1923;6:173-183.
12. Ambraseys NN, Adams RD. Seismicity of West Africa. Annales Geophysicae. 1986; 4:679-702.
13. Freeth S, Charles J, Ofoegbu O, Onuoha KM. Natural Hazards in West and Central Africa. Springer Berlin Heidelberg.1992;13-26.
    DOI: 10.1007/978-3-663-05239-5.
14. Akpan OU, Yakubu TA. A review of earthquake occurrences and observations in Nigeria. Earthq. Sc. 2010;23(3):289-294.
15. Afegbua KU, Yakubu TA, Akpan UO, Duncan D, Usifoh SE. Towards an integrated seismic hazard monitoring in Nigeria using geodetic and geophysical techniques. International Journal of the Physical Sciences. 2011;6(28):6385-6393.
16. Quaah A. A study of past minor earthquakes in Southern Ghana using intensity data. Tectonophysics. 1982;88: 175-188.
17. Midzi V, Hlatywayo DJ, Chapola LS, Kebede F, Atakan K, Lambe DK, Turyomurugyendo G, Tugume FA. Seismic hazard assessment in Eastern and Southern Africa. Annali Di Geofisica. 1999;42:6.
18. Mavonga T, Durrheim RJ. Probability seismic hazard assessment for the democratic republic of Congo and Surrounding Areas. Geological Society of South Africa. South African Journal of Geology. 2009;112:329-342.
    Available:https:// doi:10.2113/gssajg".
19. Gutenberg B, Richter CF. Frequency of earthquakes in California. Bulletin of the Seismological Society of America. 1944; 34(4):185-188.
20. Gutenberg B, Richter CF. Seismicity of the Earth, Second Ed., Princeton University Press, Princeton, New Jersey. 1954;310.
21. "Kagan YY, Knopoff L (1987). Statistical short-term earthquake prediction, Science; 236 (4808): 1563–1567".
22. Kijko A, Sellevoll MA. Estimation of earthquake hazard parameters from incomplete data files, Part I, Utilization of extreme and complete catalogues with different threshold magnitudes, Bull. Seismol. Soc. Am. 1989;79:645–654.
23. Kijko A, Sellevoll MA. Estimation of earthquake hazard parameters from incomplete data files, Part II, Incorporation of magnitude heterogeneity, Bull. Seismol. Soc. Am. 1992;82:120–134.
24. Aki K. Maximum likelihood estimate of b in the formula logN _ a _ bM and its confidence limits, Bull. Earthq. Res. Inst. Tokyo Univ. 1965;43:237–239.
25. Kijko A, Smit A. Extension of the Aki-Utsu b-Value Estimator for Incomplete Catalogs. Bulletin of the Seismological Society of America. 2012;102(3):1283–1287.
    Available:https://doi: 10.1785/0120110226"
26. USGS. Department of the Interior, U.S. Geological Survey; 2015.
    (Accessed 25.11.2017.)
    Available:http://www.usgs.gov/datamanagement/share/.
27. ISC. International Seismological Centre, On-line Bulletin. Internatl. Seis. Cent., Thatcham, United Kingdom; 2014.
    (Accessed 25.11.2017.)
    Available:http://www.isc.ac.uk,

28. ANSS. Northern california earthquake data center. UC Berkeley Seismological Laboratory. Dataset; 2014.
    Available:https://doi:10.7932/NCEDC.;
    (Accessed 27.10.2017).
29. Fatoye FB, Gideon YB. Geology and mineral resources of the Lower Benue Trough, Nigeria. Advances in Applied Science Research. 2013;4(6):21-28.
30. Dorbath C, Dotbath L, Caulon R, George T, Mourge P, Randani M, Robineau B, Tadidi B. Seismotectonics of the Guinea earthquake of December 22, 1983. Geophys. Res. Lett. 1984;11:971-974.
31. Ewing WM, Dorman HJ, Ericson JN, Heezen BC. Exploration of the northwest Atlantic mid-ocean canyon, Bulletin of the Geological Society of America.1953;64: 865-868".
32. Jacoby WR. Modern concepts of earth dynamics anticipated by Alfred Wegener in 1912. Geology. 1981;9:25–27.
    Available:https://doi.org/10.1130/0091-7613".
33. Sykes L. Mechanism of earthquakes and nature of faulting on the mid-oceanic ridges. Journal of Geophysical Research. 1967;72(8).
34. Edgar WS. Introduction to the Structure of the Earth, 2nd edition, McGraw-Hill, Tokyo.1977;77.
35. USGS. Understanding plate motions;1999.
    Available:https://pubs.usgs.gov/publications/text/understanding.html.
    (Accessed 13.08.2017.)
36. Rao CR. Linear statistical inference and its application second Ed. John Wiley and Sons, New York. 1973;625.
37. Kijko A. Estimation of the maximum Earthquake Magnitude mmax. Pure Appl. Geophys. 2004;161:1-27.
38. Campbell KW. Bayesian analysis of extreme earthquake occurrences. Part I. Probabilistic hazard model, Bull. Seismol. Soc. Am. 1982;72:1689–1705.

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