The Review of Seismicity of Central Mid-Atlantic Fracture Zones

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Abstract - The seismic activities between 1990 and 2009 in the Mid-Atlantic Fracture Zones (between Latin America and West Africa) have been analysed using 688 sets of seismic parametric data obtained from the International Seismological Centre bulletin. The analysis of the data showed that the epicentral locations of majority of the earthquakes were along, Romanche and Saint Paul Fracture Zones. The focal depth of most of the earthquakes is 10 km and their body wave magnitudes range between 3.5 and 6.3 with magnitude range of 4.0 – 4.4 and 4.5 – 4.9 being dominant having 246 (36%) occurrences each. The surface wave magnitude ranges between 3.0 and 7.0 with magnitude range of 4.0 – 4.4 being dominant with 219 (32%) occurrences and moment magnitude ranges between 4.7 and 7.0 with 5.0 – 5.4 magnitude range having 91 (50%) occurrences. Empirical relationships between correlated magnitudes were mb = 0.701Ms + 1.544, Mw = 1.062 mb - 0.205 and Mw = 0.711Ms– 1.997. The yearly and monthly time occurrences of earthquakes did not show any clear characteristic period. The b-value for the year interval 1990 – 2009 was 0.88. The result of b-values over two decades suggested that there was no likelihood of earthquake with surface wave magnitude > 7.0 before 2019.

Keywords: fracture zone, epicentral location, focal depth, magnitude, empirical relationship, time occurrence, b-value

1 INTRODUCTION

Seismicity is a term used to describe the geographical distribution of earthquake foci, their magnitudes, their occurrences over time, their mechanism and the damage produced by them [1]. Information from seismic catalogs that include parameters such as the dates and times of earthquake occurrence, hypocenter coordinates, magnitudes and focal mechanisms of earthquake can be used for the studies of regional seismicity. Globally, most earthquakes occur under the oceans at the plate boundaries with fewer occurrences within the plates at fault zones. Considering the nature and the distance of the closest plate boundaries to the West African landmass (South American and African plate boundary) where most of the earthquake activities are concentrated, West African countries have not been considered as one of the seismic hazard zones of the world.

However, some West African cities have experienced destructive earthquakes in the past. Accra has three times been damaged by major earthquakes of which the last one in 1939, had surface wave magnitude of 6.5 and the previous ones were at least as great, judging from reports of damage caused [2]. Records have also shown that both the Northern and Southern parts of Nigeria have also experienced some earthquakes of low magnitude, most expecially the southern part [2],[3],[4],[5],[6].

The southern Mid-Atlantic Ocean is characterised by four major seismologically active fracture zones or trenches. According to [7], the most prominent ones are the equatorial fractures – Saint Paul, Romanche Chain and Charcot Fracture Zones (Fig. 1). These fracture zones extend into the landmass of Africa and the epicenters of the West African intraplate earthquakes had been located along their inland extensions. The causes of these intraplate earthquakes had been probably attributed to stresses propagated from the tectonic activities across the Mid-Atlantic Fracture Zones [8]. Seismic parametric data over these Mid-Atlantic Ocean fracture zones and along the plate boundaries between a period of twenty years has been collated and analysed in order to determine the inherent characteristics of these earthquakes and to probably use some of the results to get approximate information for seismic activities of West Africa.

2 GEOLOGY AND GEOLOGIC SETTING

The Mid-Atlantic ridge is the major geologic unit of Mid-Atlantic Ocean. It runs from Iceland to Antarctic and is the longest underwater mountain range on Earth. The ridge was formed by an

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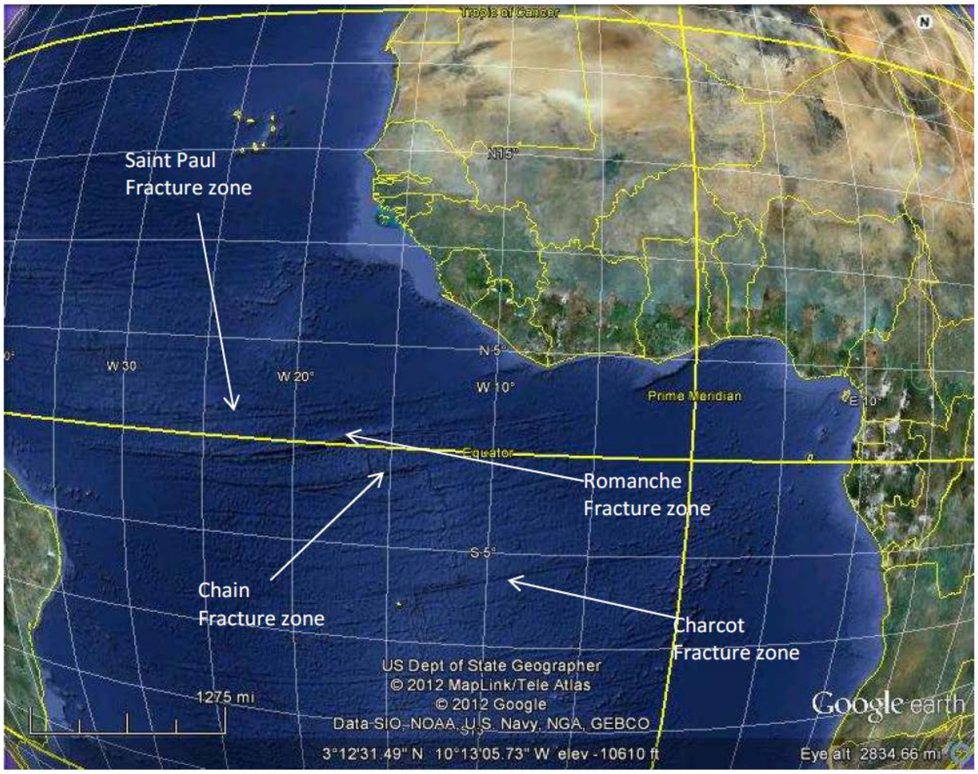

Fig. 1. Google Map Showing the Four Major Mid-Atlantic Fracture Zones.

oceanic rift separating the North American Plate from the Eurasian Plate in the North Atlantic Ocean. In the South Atlantic, the Mid-Atlantic ridge separates the South American Plate from the African Plate. The Mid-Atlantic ridge sits atop of the highest point of the mid-Atlantic rise, a bulge in the ocean floor where upward convective forces in the asthenosphere push up the oceanic crust and lithosphere [9]. The Mid-Atlantic ridge is a divergent boundary first formed in the Triassic period when a series of two arms of three-armed grabens coalesced on the supercontinent Pangea to form the ridge. The ridge is about 2,500 meters (8,200 ft) below sea level, while its flank is about 5,000 meters deeper and has average spreading rate of 2.5 cm per year [9],[10].

3 DATA COLLECTION

The seismic data for this study are parametric data (hypocenters, origin time and magnitudes) acquired from Seismic Catalogue of [11] – a non-governmental scientific organization with the objective of the collection, collation and analysis of terrestrial seismic events for the advancement of scientific knowledge of earthquakes, and the structure of the Earth. A total of 688 sets of seismic parametric data were acquired covering year 1990 to 2009. These sets of data are on earthquakes from the Mid-Atlantic Fracture Zones.

4 EARTHQUAKE SPATIAL DISTRIBUTION

The spatial distribution of the epicenters of earthquakes constitutes a fundamental parameter when studying the seismicity of a particular region and thus, the seismic hazard and risk. The epicenters of 688 earthquakes have been used to produce a seismiciy map (Fig. 2) for the study area.

5 FOCAL DEPTH

Focal depth is a major parameter used for locating earthquakes. The study area is a divergent zone and the earthquakes occur generally at shallow depths. Usually for teleseismic oceanic events focal depths are fixed between 10 and 40 km [12]. Pre-determined depths as reported in ISC bulletin were used for the focal depth distribution analysis (Fig. 3).

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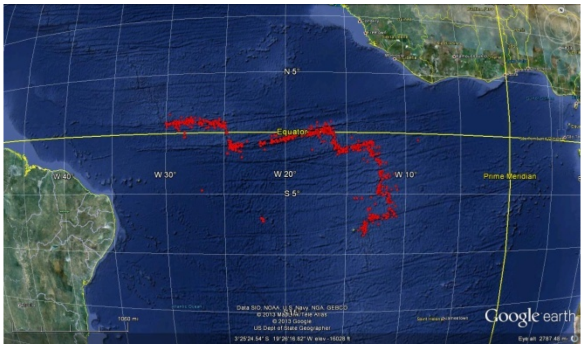

Fig. 2. Map showing the earthquake epicenters in the Mid-Atlantic ridge zone.

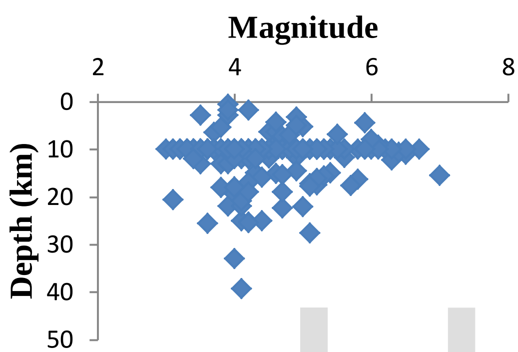

Fig. 3. Depth versus Magnitude obtained for the investigated area

6 EARTHQUAKE MAGNITUDES

Earthquake magnitudes are quantitative measures of the size of earthquakes and the basic idea behind any magnitude scale is to classify earthquakes objectively and independently of local ground conditions and environment. Three types of earthquake magnitude (m_b, M_s and M_w) were analysed using pie chart to evaluate the relative proportions of these magnitudes (Figs. 4.1 – 4.3).

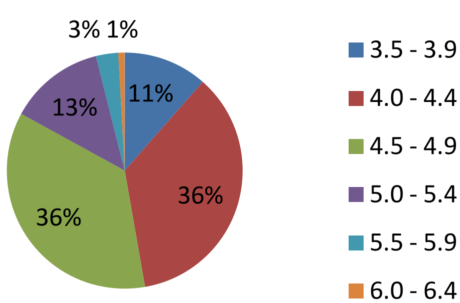

Fig. 4.1. Pie Chart for m_b

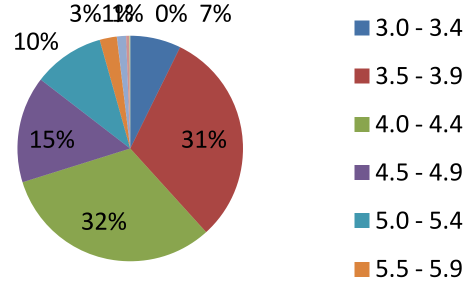

Fig. 4.2. Pie Chart for Ms

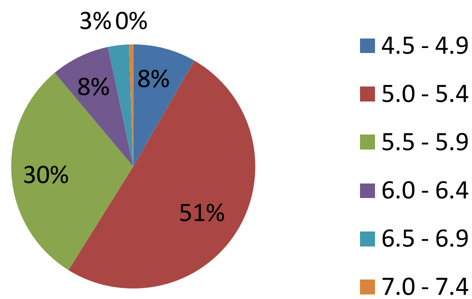

Fig. 4.3. Pie Chart for Mw

7 SEMI-EMPIRICAL ESTIMATION OF MAGNITUDE

There are different magnitude scales with different valid ranges. Some of these magnitudes have a reasonably good agreement within some magnitude ranges while some are not [13],[14]. Body wave and surface wave magnitudes which are the most common magnitudes are distance dependant and these magnitudes can therefore not be calculated for some events using some seismic networks. Because of the disparities between earthquake magnitudes and the inability to derive some magnitudes for some earthquakes, there is often a need to derive empirical relations between different magnitude scales in order to convert one magnitude to another. This relation will also help to determine magnitudes for some past earthquakes whose seismograms are not available but with some information on some of the magnitude types. Different methods for deriving an empirical relation between different magnitudes which is of the form $y = a + bx$ (a and b are constants and y and x are magnitudes) are in use. *Mag* program within SEISAN environment was used to determine the regression between correlated magnitudes using maximum likelihood estimation method of linear fitting. In all, the three magnitude types were correllated with one another (Figs 5.1 – 5.3). Some other studies have derived empirical relation for m_b and M_s for other regions such as [15],[16],[17].

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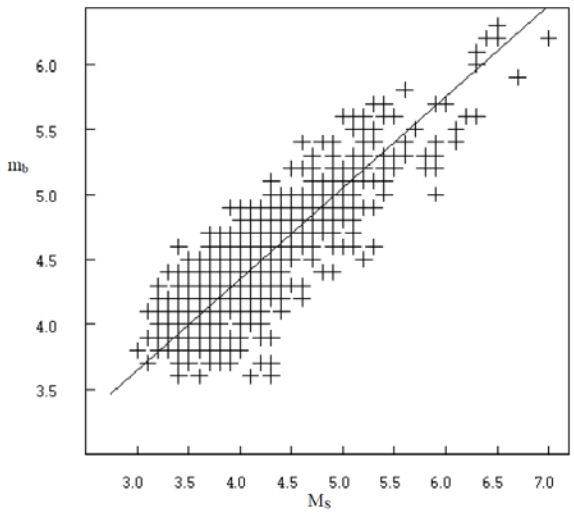

Fig. 5.1. Body Wave Magnitude m_b Versus Surface Wave Magnitude M_s Between Year 1990 – 2009 for Shallow Earthquakes. The regression equation is $m_b = 0.703M_s + 1.534$

8 EARTHQUAKE TIME OCCURRENCE

The time occurrence of earthquakes is an important aspect in the probabilistic prediction of earthquakes in any region. This helps to determine the possible periods of earthquake and to classify a given time on the basis of seismic activities. The analysis of the yearly and monthly time occurrence distributions of examined earthquakes were carried out (Figs. 6.1 and 6.2).

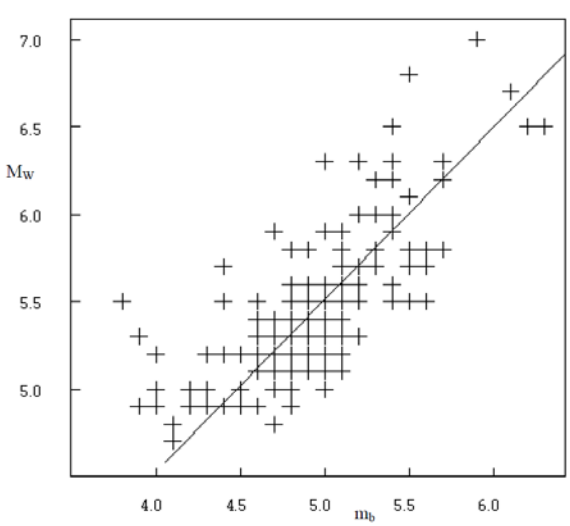

Fig. 5.2. Moment Magnitude M_w Versus Body Wave Magnitude m_b Between Year 1990 – 2009 for Shallow Earthquakes. The regression equation is $M_w = 0.962m_b + 0.601$.

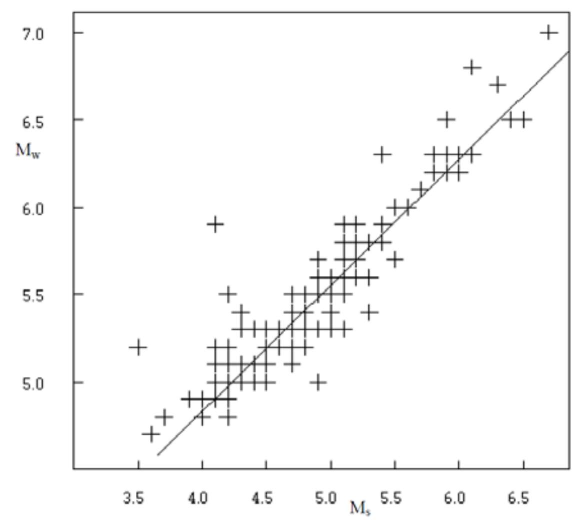

Fig. 5.3. Moment Magnitude M_w Versus Surface Wave Magnitude M_s Between Year 1990 – 2009. The regression equation is $M_w = 0.719M_s - 1.96$.

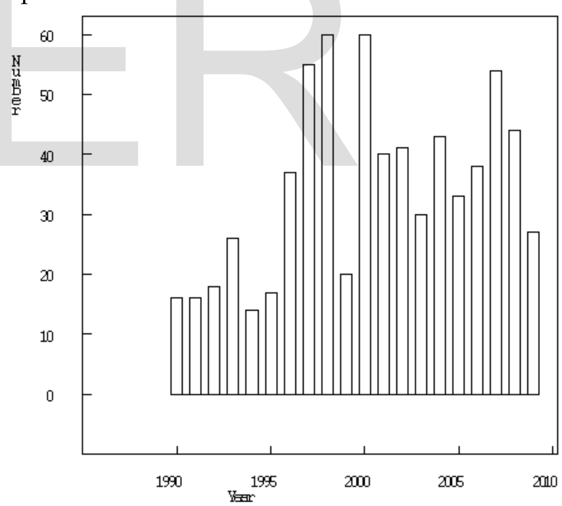

Fig. 6.1. Histograms of Earthquake Yearly Time Occurrence Distribution of Events Between 1990 and 2009 for the Study Area.

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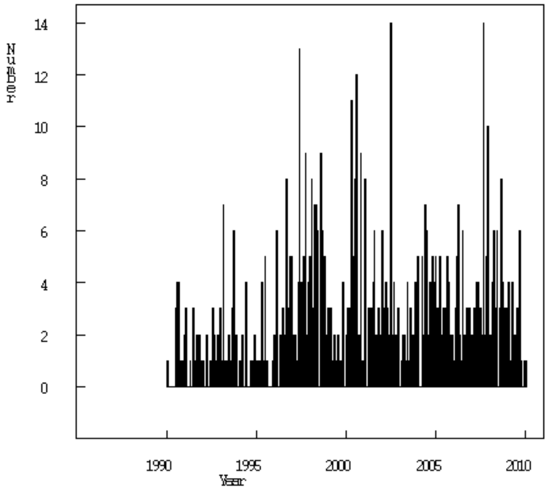

Fig. 6.2. Histograms of Earthquake Monthly Time Occurrence Distribution of Events Between 1990 and 2009 for the Study Area.

9. FREQUENCY-MAGNITUDE RELATIONSHIP

Smaller earthquakes occur much more frequently than large earthquakes. This trend is expressed in the empirical relationship proposed by [18] in logarithmic form:

$$Log\ N(M) = a - bM \quad (1)$$

where N is the number of earthquakes with magnitudes greater than or equal to M. a and b are constants whose values are seismic region dependent. Parameter a is the quantitative measure of the level of seismic activity of a region and it represents the number of earthquakes with magnitude higher than 0 and parameter b, called the b-value, describes the relative number of small and large events in a given time interval and is indicative of the seismotectonics of a region. Theoretically b-value over different regions ranges from 0.6 – 1.4, and in most cases, its value is very close to unity [1],[19]. A high value of b indicates a high number of small earthquakes and low stress condition while a low value indicates a high number of large earthquakes and high stress condition [20],[21],[22]. a- and b- values are also very useful in seismic hazard assessment [23]

Determining a and b-values requires the determination of the regression line of plot of Log N versus M. Different methods for calculating the regression line have been proposed of which the simplest is the eye fitting method. For this study, these two constants have been calculated using the Least Square Estimation method:

$$b = -\frac{\sum_{i=1}^{n}(m_i - \overline{m})(\log N_i - \overline{\log N})}{\sum_{i=1}^{n}(m_i - \overline{m})^2} \quad (2)$$

$$a = \overline{\log N} + b\overline{m}, \quad (3)$$

where $\overline{m}$ is the mean magnitude and $\overline{\log N}$ is mean of log N. The b-value and a-value for the period of twenty years (1990 – 2009) for the study area were determined for earthquakes that have surface wave magnitude ≥ 3.0. Six hundred and eighty seven events were used to produce a plot for investigating frequency-magnitude relationship of earthquakes within the study area and 530 events were used for regression with M_s = 3.8 as threshold magnitude (Fig. 7.1). Also, the b-values for the periods of 1990 to 1999 and 2010 to 2009 were calculated in order to determine the variation between the b-values over the two decades. A program *bvalue* within SEISAN environment was employed to determine the regression equation (Figs. 7.2 – 7.3)

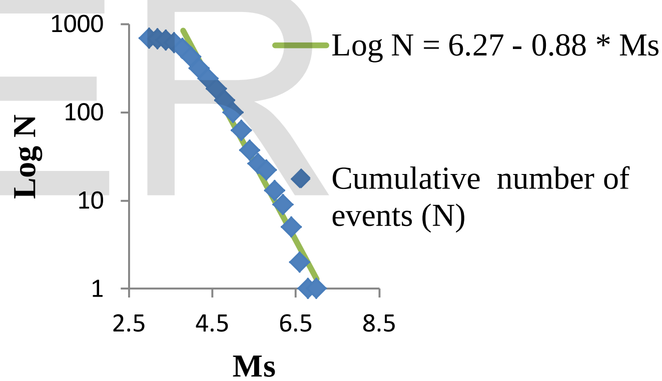

Fig. 7.1. The Number of Earthquakes Together with their Surface Wave Magnitude (M_S ≥ 3) Between 1990 – 2011. Magnitude interval is 0.2. The line is the least square line for the magnitude interval 3.8 – 7.0. a and b-values are respectively 6.27 and 0.88.

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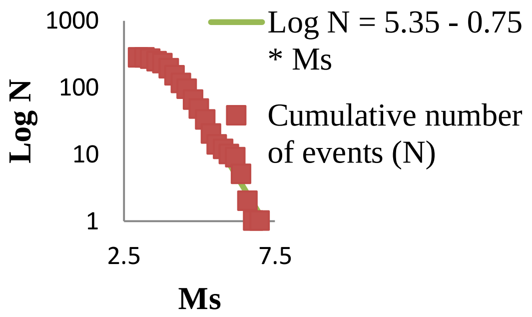

Fig. 7.2. The number of Earthquakes Together with their Surface Wave Magnitude ($M_S \geq 3$) Between 1990 – 1999. Magnitude interval is 0.2. The line is the least square line for the magnitude interval 3.8 – 7.0. *a* and *b*-values are respectively 5.35 and 0.75.

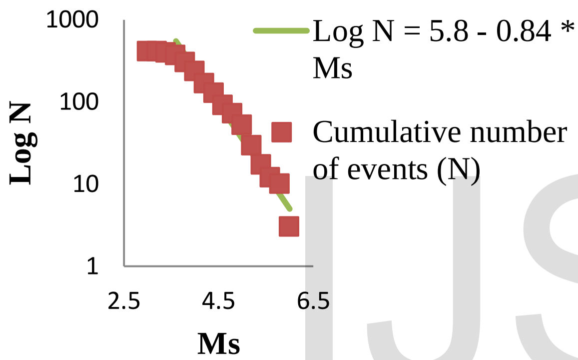

Fig. 7.3. The Number of Earthquakes Together with their Surface Wave Magnitude ($M_S \geq 3$) Between 2000 – 2009. Magnitude interval is 0.2. The line is the least square line for the magnitude interval 3.8 – 6.0. a and *b*-values are respectively 5.8 and 0.84.

10 DISCUSSION OF RESULTS

The epicenters on the map show that most of the earthquakes occur along the Saint Paul, Romanche, Chain and Charcot Fracture zones. Romanche Fracture zone is the most seismically active zone followed by St. Paul Fracture zone, Chain and Charcot Fracture zones (Fig. 2). The focal depths of these earthquakes range between 1.5 and 40 km. Most of the earthquakes have their focal depth at 10 km while few others have their focal depths between 2 and 10 km, and 22 and 40 km. Altogether majority of the focal depths are less than 30 km. The yearly time occurrence distribution shows that 1997, 1998, 2000, 2007 and 2008 have been most active with a total of 55, 60, 60, 54 and 44 earthquakes respectively followed by 2004, 2002, 2001, 2006, 1996 and 2005 with 43, 41, 40, 38, 37 and 33 earthquakes respectively. 1996 and 2005 have 37 events each followed by 2009 with 27 events. 1990, 1993, 1995 and 1999 have 16, 26, 17 and 20 events respectively. The other years: 1991,1992 and 1994 show relatively low seismic activities with 16, 18 and 14 events respectively. Monthly time occurrence (Fig. 5.4) shows that most of the months for the period of study have events less than 8. August, 2007 and June 2002 recorded the highest number of events with 14 earthquakes each followed by May 1997 with 13 events. July 2000, April 2000 and November 2007 recorded 12, 11 and 10 events respectively. Nine events were recorded each in July 1997, September 1997, July 1998 and October 2000 while August 1996, June 2000, January 2001 and August 2008 had 8 events each. Although the years and the different months have varying number of earthquakes, but the earthquake time occurrence distributions did not show any clear characteristic period within the period of study.

Body wave magnitude, m_b, ranges between 3.5 and 6.3. The magnitude range of 4.0 – 4.4 and 4.5 – 4.9 are the dominant body wave magnitude with 246 (36%) occurrences each followed by 5.0 – 5.4 and 3.4 – 3.9 which occured 90 (13) and 79 (11%) times respectively. The magnitude ranges of 5.5 – 5.9 and 6.0 – 6.4 magnitude ranges had the least occurrence of twenty one (3%) and six (1%) respectively. M_s ranges between 3.0 to 7.0. The magnitude ranges of 3.5 – 3.9 and 4.0 – 4.4 are the dominant surface wave magnitude with two hundred and twelve (31%) and two hundred and nienteen (32%) occurrences respectively. The magnitude ranges of 3.0 – 3.4, 4.4 – 4.9 and 5.0 – 5.4 ocuured 50 (7%), 105 (15%) and 70 (10%) times respectively. Magnitude ranges of 5.5 – 5.9 occurred 19 (3%) times while 6.0 – 6.4 occurred 97 (2%) times. The least magnitude range is 7.0 – 7.4 with 1 occurrence followed by 6.4 – 6.9 with 3 occurrences both having 0% approximatetly. Moment magnitude ranges between 4.7 and 7.0. The magnitude range of 5.0 – 5.4 is the dominant moment magnitude with ninety one (50%) occurrences followed by 5.5 – 5.9 with fifty four (30%) occurrences. The magnitude ranges of 4.4 – 4.9 and 6.0 – 6.4 occurred fifteen (8%) and forteen (8) times respectively. The least magnitude range is 7.0 – 7.4 with 1 (0%) occurrence followed by 6.4 – 6.9 with 5 (3%) occurrences.

For the relationships existing between reported magnitudes, the following relationships were derived:

$$m_b = 0.703M_s + 1.534. \quad (2)$$

$$M_w = 0.982\, m_b - 0.601. \quad (3)$$

$$M_w = 0.719M_s - 1.96. \quad (4)$$

For the relation between m_b and M_s, the correlation coefficient between the two magnitudes is 0.85. m_b has a mean value of 4.51 and M_s has a mean value of 4.23 while for M_w and m_b, the correlation coefficient between the two magnitudes is 0.74, m_b has a mean value of 4.91 and M_w has a mean value of 5.43. Also M_w and M_s, the correlation coefficient between M_w and M_s is 0.91, M_s has a mean value of 4.83 and M_w has a mean value of 5.43. Applying these relationships to some of the earthquake that occured in and around Nigeria landmass, surface and body wave magnitudes that can not be calculated from seismograms of Nigeria National Network of Seismological Stations (NNNSS) can be now be derived. For example ISC calculated only m_b for September 11 earthquake that was felt in some western parts of Nigeria and gave the value as 4.4. Using equation 1.1, its M_s = 4.1 and using equation 4.2, its M_w = 4.9. So also for the earthquake that was felt in Okitipupa and environs on 7th March, 2000, ISC reported m_b for the event to be 4.4. Therefore its moment magnitude is 4.9. Although the area investigated is a little far away from Nigerian Landmass but the fact that many authors have attributed the quakes in Nigeria and coastal parts of West Africa to tectonic activities of Mid-Atlantic Fracture zones has made us to use these relationships to get at least approximate magnitude values for these earthquakes.

The *b*-value for the period of study was estimated to be 0.88, constant *a* = 6.27 and the rms error of fit of the regression line is 0.11. A *b*-value of 0.88 is relatively low and this suggests that the stress condition is a little high. Using equation 4.2 and considering M_s = 6 and 7, *N* = 9.8 and 1.3 respectively. These imply that two earthquake of M_s = 6 are expected in every 2 years while 1 earthquake of M_s = 7 is expected in every fifteen years. If M_s = 8 is considered, *N* = 0.17 and this implies that in every 118 years one earthquake of M_s = 8 is expected. The *b*-value for the earthquakes that occured between 1990 and 1999 is 0.75 and the one between 2000 and 2009 is 0.84. Comparing these two results, *b*-value has increased from 0.75 to 0.85 and using the findings of [24], which concluded that *b*-value decreases before some large earthquakes occur, it therefore can be said that a large earthquake of $M_s \geq 7$ is not expected between 2010 and 2019 in Mid-Atlantic Fracture Zones.

11 CONCLUSSION

The seismic characteristics of the earthquakes of Mid-Atlantic fracture zones over two decades – between 1990 and 2009 showed that:

1. The Romanche Fracture Zone is the most seimically active followed by St. Paul Fracture Zone.
2. The yearly and monthly time occurence distributions did not show any ovious chacteristic period.
3. The focal depths are dominantly 10 km
4. The *b*-value is 0.88
5. The derived empirical relationships between the three magnitude types examined are $m_b = 0.703M_s + 1.534$, $M_w = 0.982\ m_b - 0.60$ and $M_w = 0.719M_s – 1.96$.

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