Original Research Article

Seismotectonic Stress Regime and Airborne-Gravity Lineament Investigation of the Caribbean region and its Kinematic implications

*Ayodeji Adekunle Eluyemi[1,2,3] , Frederick Olusegun Adeoti[4], Augustine Babatunde Arogundade[5], Debasis d. Mohanty[3], Awosika, D.D[6], Musa Olufemi Awoyemi[5], Saurabh Baruah[2,3,]**

1 Division of Environment and Earth Science., Centre For Energy Research and Development (CERD), Obafemi Awolowo University (OAU), Ile-Ife, Nigeria.
2 Academy of Scientific and Innovative Research (AcSIR), CSIR- North East Institute of Science and Technology (CSIR-NEIST) Campus, Jorhat-785006.
3 Geosciences and Technology Division, CSIR. North-East Institute of Science and Technology, Jorhat-785006, Assam India.
4 African Regional Institute for Geospatial Information Science and Technology (AFRIGIST), Ile-Ife, Nigeria
5 Department of Physics and Engineering Physics, Obafemi Awolowo University (OAU), Ile-Ife, Nigeria.
6 Department of Physics Adeyemi Federal University of Education, Ondo, Nigeria

***Corresponding author**: *E-mail: ay_dot2006@yahoo.com*

Abstract: The tectonic stress regime of the Caribbean region has been studied by stress tensor inversion analysis for the area bounded by Latitudes 17.32º to 23.79º N and Longitudes 81.47º to -60.56º E. A total of two hundred and twenty (220) fault plane solutions (FPS), made up of the seismic (earthquake) events that have occurred in the region of the study were found on the data catalog of the project website of the global centroid moment tensor, were employed in this study. To characterize the stress regimes of the region of study, the classification of the region based on the global moment tensor project is as follows: Cuba-zone, Haiti-zone, Dominican-republic, Monapassage, Puerto Rico, Virgin-Island and the Leeward Island. The gravity geophysical method revealed the presence of multiple or swarms of fractured lines within the same geographical range of study which might have developed over the years as a result of the interaction and coupling effect of the plate boundaries that have close proximity to the region of study. The seismicity pattern indicates that none of the provinces or countries located within the Caribbean region is devoid of large-magnitude earthquake occurrences capable of wreaking severe havoc on the immediate environment. Obviously, our stress tensor inversion result indicates two types of stress regimes namely compression and the strike-slip with different orientations. Cuba-zone, Haiti-zone, Dominican Republic, Monapassage, and Leeward Island are governed mainly by compression stress regimes. In contrast, the strike-slip stress regimes mainly govern the Puerto Rico and the Virgin Island.

Keywords: Caribbean region, Stress tensor inversion, Airborne gravity geophysical investigation.

1. Introduction

The region between North and South America is surrounded by the North Atlantic Ocean, most of which is composed of fragments of islands that are regarded as the Caribbean region. This region is one of the most seismically active zones in the world. Evidence of tectonic activities abound on the oceanic and continental floor of this zone, including plate boundaries, submarine volcanic fields, seismicity, and subduction zones. The tectonic activities/seismicity within the plate boundaries has a significant contribution to the seismic activities of the adjoining areas pertinent to the continental crust (Shimazaki, 1976); (Eluyemi et al., 2019a); (Eluyemi et al., 2019b). This has resulted in the accumulation of stress and successive migration/progression of the occurrence of earthquakes toward the continental crust from its inherent secondary faulting. The Caribbean plate

Received: 13 June 2023 Accepted: 1 August 2023 Available online: 21 August 2023

is roughly estimated to be 3500 km in E-W and 1000 km in N-S direction, it lies between the North American, South American, Nazca, and Cocos plates (Molnar and Sykes, 1969). Some interesting features abound around the Caribbean region, the plate borders the subduction zone, Lesser Antilles (LA) in the east, and the westward subduction of the North Atlantic lithosphere in acute shape underneath the Caribbean plate is prominent (van Benthem et al., 2014). Towards the southern boundary, the Caribbean plate is under-thrusted below the South American plate; Trenkamp et al., 2002; van Benthem et al., 2013). Towards the west, the Caribbean Plate borders the Central American subduction zone, at this zone, the Cocos plate subducts in an NNE-ward direction (DeMets, 2001).

Since the plate of the Caribbean is located within and around several plate boundaries, including active volcanism, the region is seismically active and constantly under the influence of tectonic stress. Stress accumulation within the earth is often released in form of earthquakes, which could be inform of foreshocks, main-shocks, aftershock and earthquake swarms (Michael, 1987). These have always been one of the cardinal attributes of active tectonic regions of the world including the Caribbean region.

Stress tensor inversion of fault plane solutions (FPS) of given sets of earthquake events occurring from a particular region could reveal information about the stress regimes governing that particular region. It is usually done through the determination of the stress field orientation (Martinez-Garzon et al., 2014). Conventional methods of stress tensor determination are through the inversion of fault plane solutions. Michael (1987), Kiratzi (1999), Abers and Gephart (2001) Yamaji and Sato (2006), Zalohar and Vrabec (2007), Angelier and Baruah (2009), de Vicente et al. (2008), Delvaux and Barth (2010), Tirifu and Shumila (2011), Baruah et al. (2013), Martinez-Garzon et al. (2014), Eluyemi et al. (2019b) contributed significantly to writing up of codes and developing a more precise and accurate means of evaluating stress tensor inversion. In this study, we have examined earthquakes events from the year 1909 up to 2021 of the Caribbean region, with the sole aim of resolving the complex and the poorly established geologic/seismologic structures and motion/stress orientation within the Caribbean, North America and the South America Plate boundaries. Considering the fact that earthquake distribution could be highly heterogeneous, historically, on several occasions, there have been reports of devastating earthquake occurrences among the member states of the Caribbean region. In this work, we have approached the study in three dimensions; the first one is to analyze the frequent regional distribution of earthquake events within the region as a means of determining the relationships between the geologic features and hypocentral parameters Figure 1. The second approach is to determine the stress orientation and establish the stress regime of the various seismogenic zones within the study region. Finally, we intend to combine the earlier approaches to predict the sub-zones where it is likely to produce the next devastating earthquake event.

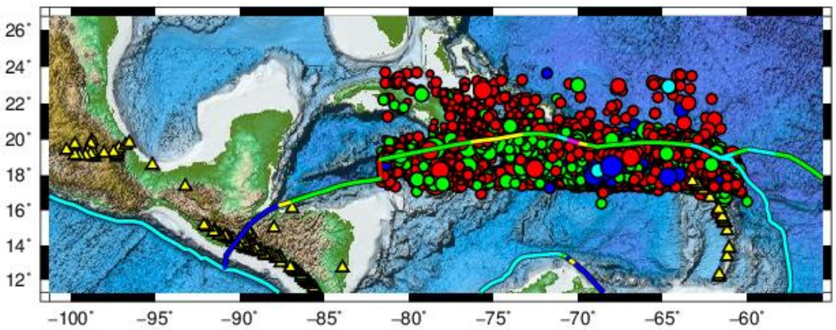

Figure 1 Tectonic setting and epicentres plot of the Caribbean region. In order to depict the seismicity pattern of the region of study, seismic data during the period of 1900-2021 were utilized. The epicentres are shown in red to green circles (the red circles represent events with depth range of 0-33 Km, and the green circles represent events with a depth range of 33-70 Km blue circles represent event with depth range of 70-150 Km, Cyan circle represents event with depth range of 150-300 Km). Blue-yellow-green-red line indicate the plate boundary, the volcanic zones are depicted in yellow triangles.

Since the Caribbean region is tectonically active, it has experienced a devastating earthquake occurrences and Tsunami claiming several lives and damages to properties, notably among them are: the 12 January 2010, a

7.0 magnitude earthquake of Haiti, and the November 18,1867, a magnitude 7.5 earthquake occurred in the Anegada trough, located between the US Virgin Islands of St. Croix, and St. Thomas, This earthquake consists of two shocks which generated two tsunami waves capable of massive destructions.

In this paper, we aim to interpret the active deformation of Caribbean region bound by the Latitudes 23.7° to 17.31° N and Longitudes -81.46° to -60.55° E through estimation of seismotectonic stress regimes based on inversion of earthquake focal mechanism solutions, with an implication to better resolution of the present day geodynamic. This would be a major indicator to identifying an existing major structural domain or seismogenic sources within the study area. Majorly, this study attempts to determine the stress tensor inversion of the Caribbean zones exclusively for the followings: The dimension of azimuthal variation of compressional axis related to existing geodynamics of the study area; the significance of seismotectonic mechanisms related to the interactions of the plate boundaries. These features are connected to stress accumulation and discharge of the Caribbean seismicity. Considering the seismic hazard assessment of the region for a probable future large earthquakes occurrence, finally we intend to characterize the interplate deformation in the Caribbean region and its corresponding kinematic implications on the study region.

2. Tectonic Settings

The Caribbean Plate is an independent lithospheric entity of the un-deformed or less deformed Cretaceous oceanic plateau of Colombia and Venezuela Basins and the Palaeozoic-Mesozoic Chortis continental block of about 700,000 km^2, bounded by deformed marginal belts, resulting from the Mesozoic era to modern day interactions with the adjacent Nazca, Cocos, and American Plates. The Caribbean plate crustal thickness varies from 6-8 km, west of the Beata Ridge and up to 20 km between the Central Venezuelan and the western part of the Beata Ridge and 3-5 km in the southeast of the Venezuela Basin (Diebold and Driscoll, 1999). The crustal variation in thickness is also found in Yucatán Basin around 8-9 km to Colombian and Grenada Basins. The thickness of the marginal belts varies from 10-22 km (Case et al., 1990). The Caribbean lithosphere is deformed and tectonically emplaced over the Pacific and Atlantic Oceanic crusts leading to the formation of the western and eastern arc systems of the Central American Isthmus and Lesser Antilles. The lithosphere got squeezed against the North and South American continental crusts, with effect to the formation of suture zones in the Cordilleras of Guatemala, Greater Antilles and Venezuela. Several internal Caribbean marginal areas in Colombia, Venezuela, Panama and Hispaniola are shortened forming accretionary prisms with a centripetal convergence (Stephan et al., 1986). The existence of Divergent flower structures is found along the northern and southern Caribbean margins where diachronous oblique movements have occurred from the Cretaceous until present day. The active northern Guatemala and Greater Antilles and southern (northern Venezuela) plate margins are majorly formed by deformed terrenes in shear zones bounded by east-west trending sinistral and dextral strike-slip faults respectively. The western (Central America Isthmus) and eastern (Lesser Antilles) are represented by convergent systems and related magmatic arcs. The Caribbean marginal belts are the product of complex interaction between several first-order geotectonic elements, made of different tectonic-magmatic features and originated in different paleo-domains, presently lies fragmented and dispersed along the margins. The paleo-domains consist of continental margins, rifted continental margins, thin oceanic crust, oceanic plateau, intra-oceanic and sub-continental subduction zones and fore-deep basins. The interaction between portions of these domains brought about the present-day settlement of the Caribbean plate, recording some important compressional episodes, starting from the Cretaceous, followed by tensional and/or strike-slip tectonics. Attempt to reconstruct the evolution the plate encounters several problems mainly related to unresolved facts (Giunta and Oliveri, 2009).

3. Data used

The Caribbean region is one of the most active seismogenic zones in the world. In this study, in order to understand the spatial distribution of the hypocentral parameters of the region, we found over seventy five thousand (75,000) data set on the event catalogue project of the International Seismological Centre (ISC) covering the time period of 1900 up to 2021 and for the stress tensor inversion study, we obtained the fault plane solutions (FSP) pertaining to the region of study on the global centroid moment tensor (GCMT) known as Harvard CMT (Dziewonski et al., 1981; Ekström et al., 2012). The seismicity of this region is characterized in linear pattern, it is found to be concentrated along the plate boundaries. The global centroid moment tensor (GCMT) categorized the fault plane solutions of the study area into Nine zones: Bahama-Island, Caribbean sea, Cuba region, Dominican republic, Haiti, Jamaica, Leeward-Island, Monapassage, Naicaragua, North of Honduras, North Atlantic region, Puertorico-region and the Virgin-Island.

4. Methodology

4.1 Seismicity

To achieve the aim and objectives of this study, over seventy-five thousand (75,000) earthquake data sets were downloaded from the International Seismological Centre (ISC), with varying magnitudes. The data is for the period of 1909-2021, comprised of historical and recent seismicity. In line with Eluyemi et al. (2022a), such large data could help us to characterize the spatial distribution of the hypocentral parameters of the events emanating from the seismogrnic sources of the Caribbean region. These correspond to the geographical coordinates of 17.32º to 23.79º N in latitude and -81.47º to -60.56 º E in longitude. Earthquake events magnitude M_w ranges from 1 - 7.7. Figure 1 revealed the seismicity pattern of the studied region. Figure 1 depicts the spatial distribution of the earthquake events as a function of magnitude and depth.

4.2 Quality assessment of the employed focal mechanism solutions

The quality assessments of the employed Fault Plane Solutions (FPS) in the stress tensor inversion analysis normally considers the following parameters: the $fCLVD$, which is defined as the sign ratio of the amplitudes of the intermediate and largest principal moments, it is an indicator used to determine the similarity of a particular focal mechanism solution (FMS) to a compensated linear vector dipole (CLVD), similar to the emergence of earthquake by slip on a planar surface. Sanchez and Nuuez-Cornu (2009) define $fCLVD$ statistic as : $fCLVD = \frac{-\lambda_B}{\max(|\lambda_T|.|\lambda_P|)}$ Whenever a compensated linear vector dipole ($CLVD$) nears ±0.5 the extreme value of $fCLVD$, this implies that the orientation of the T, B and P axes are not conclusive. The next parameter is the relative error (E_{rel}) of the utilized FPS and the E_{rel} compares the relative size of moment tensor M and its standard error tensor U (Davis and Frohlich, 1995; Frohlich et al., 1997 and Sanchez and Nuuez-Cornu, 2009). The mathematical expression for E_{rel} is given as: $(E_{rel}) = \sqrt{\frac{U:U}{M:M}} = \sqrt{\frac{u_{11}^2+u_{22}^2+u_{33}^2+2u_{12}^2+2u_{13}^2+2u_{23}^2}{m_{11}^2+m_{22}^2+m_{33}^2+2m_{12}^2+2m_{13}^2+2m_{23}^2}}$. The colon denotes the tensor scalar product. If A and B are tensors, their respective elements are a_{ij} and b_{ij}, then $A:B = \sum i.ja_{ij}b_{ij}$. Therefore, ($E_{rel}$) as the norm of U divided by the norm of M. $1 \le E_{rel} \le 1$. In practice, it is usually advisable to seek for values of $Erel$ as low or small as possible. The last parameter is the n_{free}. This is the numbers of moment tensor components of an earthquake source that is not equal to zero. All of the three aforementioned above parameters were not manually computed but have been well treated in the inversion algorithm of Michael (1984, 1987), known as Michael's method.

4.3 FMS data preparation and Stress Tensor Inversion (STI)

A total of two hundred and twenty (220) FPS data pertaining to the site of study, within the geographical coordinates of 17.32º to 23.79º N in latitude and -81.47º to -60.56º E was downloaded on global centroid moment tensor (GCMT) catalogue Dziewonski et al. (1981) and Ekström et al. (2012) and utilized for the Stress tensor inversion analysis, as compiled in Table 1. Figures 2 and 3 represent the beach ball presentation of the fault plane solutions associated with the earthquake events in respective tectonic domain of the investigated zone of the Caribbean region. The corresponding beach balls were constructed with the aid of Rake software Louvari and

Kiratzi (1997).

The constructed beach balls were positioned into their respective tectonic domain on the image map of the investigated zone. The orientation of the stress tensor were evaluated and determined using the inversion algorithm of Michael (1984, 1987) known as Michael's method, and Zalohar and Vrabec (2007) known as Gauss method, in order to constrain the consistency of inferred results, the inversion results of the 220 fault plane solutions are tabulated according to their tectonic domain in Table 2. Gauss method is based on the concept of best fit of stress tensor, with consideration for angular misfit between resolved shear stress and actual direction of movement of fault plane. It takes into account the ratio between the normal and shear stress on fault plane. Optimal stress tensors of each homogeneous sub-system of faults are found by maximizing the object function, which is defined through a summation of the compatibility function for all the fault plane solutions. Michael's principle takes into consideration the condition that must be satisfied by the input data and during the observed time interval, stress is assumed to be uniform in respective domains of investigation. Earthquakes are assumed to be shear-dislocated on pre-existing faults and slips occur in the direction of resolved shear stress on fault plane.

Table 1 Shows the distribution of fault plane solutions (FPS) utilized for the stress tensor inversion study of the Caribbean region.

Zone	Number of Events	Depth (Km)			Magnitude (Mw)			FPS Type			
		Min	Max	Avge	Min	Max	Avge	NF	SS	TF	OB
Cuba- zone	31	10.0	33.2	21.6	4.7	7.7	6.2	-	-	24	7
Haiti-Zone	21	12	34.0	23	4.7	7.1	5.9	-	-	17	4
Dominican-Republic	30	12.1	106.4	59.05	4.7	6.7	5.7	-	7	18	5
Monapassa-ge	29	12.1	159.6	85.85	4.8	6.1	5.45	-	-	25	4
Puertorico	36	12.0	92.6	52.3	4.5	6.4	5.45	-	33		3
Virgin-Island	33	12.0	106.7	59.35	4.8	6.1	5.45	-	32	--	1
Leeward-Island	40	12.0	168.0	90	4.8	6.0	5.4	-	3	32	5

The acronyms contained in the table are explained as follows: NF indicates normal fault, SS indicates strike-slip fault, TF indicates thrust fault and OB indicates oblique fault mechanism respectively.

Three principal stresses: maximum stress, intermediate stress and minimum stress, from statistical technique of bootstrapping re-sampling are accounted for in Michael's method. The orientations of the principal stresses σ_1 and σ_3 of the stress tensor inversion results derived from Gauss and Michael's methods are illustrated in Figure 4. The inferred lineament map derived from the airborne gravity geophysical investigation of the Caribbean region Figure 5.

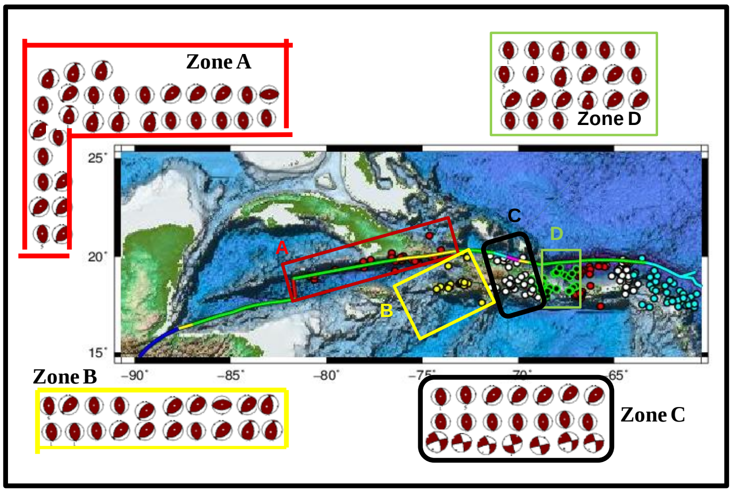

Figure 2 Shows the beach ball presentation of the fault plane solutions associated with the earthquake events in respective tectonic domain: Zone A (Cuba-zone), Zone B (Haiti-zone), Zone C (Dominican republic) and Zone D (Monapassage-zone).

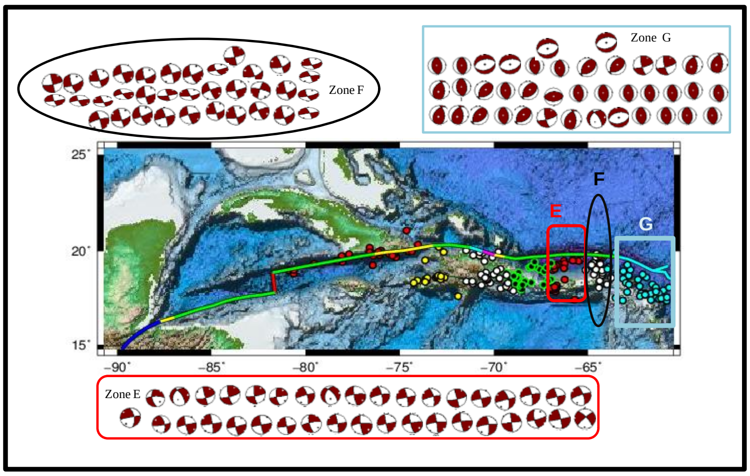

Figure 3 represent the beach ball presentation of the fault plane solutions associated with the earthquake events in respective tectonic domain: Zone E (Puertorico-zone), Zone F (Virgin-Island) and Zone F (Leeward Island).

Table 2 The stress tensor inversion results for the Caribbean region

Zone	(σ_1)		(σ_2)		(σ_3)		ϕ	Variance	Std Dev.
	Azim (°)	Pln (°)	Azim(°)	Pln (°)	Azim (°)	Pln (°)			
Dominican Republic	112.5	1.2	-157.2	7.1	13.3	82.8	0.65	0.17	0.412
Leeward Island	-35.2	25.8	-129.5	8.9	122.8	62.4	0.43	0.17	0.412
Cuba region	124	15.5	-136.9	29.1	9.5	56.2	0.46	0.17	0.412
Virgin Island	-49.1	27.5	163.7	58.1	48.7	14.7	0.066	0.053	0.230
Mona-passage	-75.8	34.8	28.9	20.2	143.2	48.1	0.35	0.19	0.436
Puerto Rico	-33.7	7.5	167.1	81.9	56.6	2.8	0.67	0.13	0.361
Haiti	-57.7	1.9	-147.7	3.6	60.3	85.8	0.49	0.05	0.224

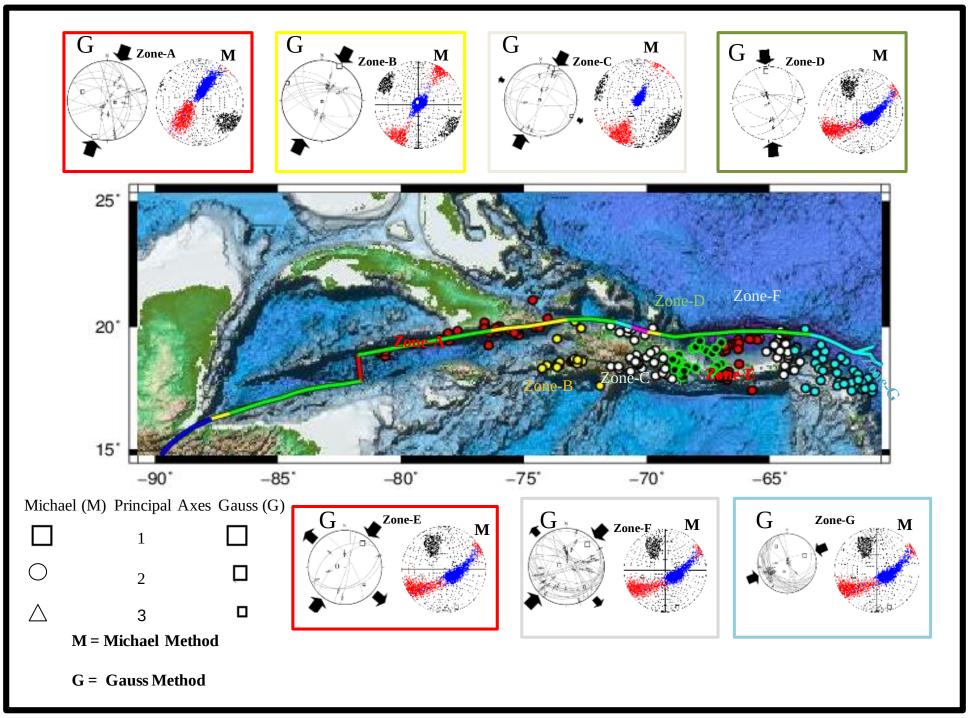

Figure 4 Stress tension inversion results of the Caribbean region, using Michael and Gauss methods as categorized by the Global Centroid Moment tensor project: Cuba-zone, Haiti-zone, Dominican-republic, Monapassage, Puertorico, Virgin Island and Leeward Island. The black convergent and divergent arrows indicate compression and extensional stress regimes respectively.

4.4 Airborne gravity geophysical data

The Earth Gravitational Model (EGM 2008) Bouguer anomaly data was downloaded from the Bureau Gravimetrique International website in XYZ format. The regional gravity anomaly grid with spatial resolution of 2.5 arc-minute by 2.5 arc-minute was computed from the EGM 2008 spherical harmonic coefficients (Palvis et al., 2008) and the Bouguer anomaly corrections were done at regional scale using FA2BOUG code (Fullea et al., 2008) for a reduction density of 2670 kg/m3. The topographic corrections were made with the ETOPO1 1 arc-minute by 1 arc-minute digital elevation model.

The gravity data set in XYZ format was gridded using the minimum curvature gridding method (Briggs, 1974) at a grid cell spacing of 3000 m to produce the Bouguer anomaly (BA) grid. The first order of the polynomial surface fitting method was used to isolate the residual fields of the BA by removing the regional field components (Radhakrishna and Krishnamacharyulu, 1990; Ajama et al., 2021). A low pass filter with cut-off wavenumber of 0.733 (wavelength of~1.364 km) was applied to the BA spectrum to accentuate the deep seated features and focus on mapping deep-seated regional-scale lineaments. The horizontal gradient magnitude (HGM) grid which provides a good estimation to enhance and delineate the signature of the geologic structures and lithologic boundaries (Nabighian, 1972; Blakely and Simpson, 1986; Awoyemi et al., 2017; Arogundade et al., 2022) was applied to the filtered residual field of the BA grid to delineate the deep-seated lineaments. Figure 5 illustrates the inferred tectonic lines of the Caribbean region.

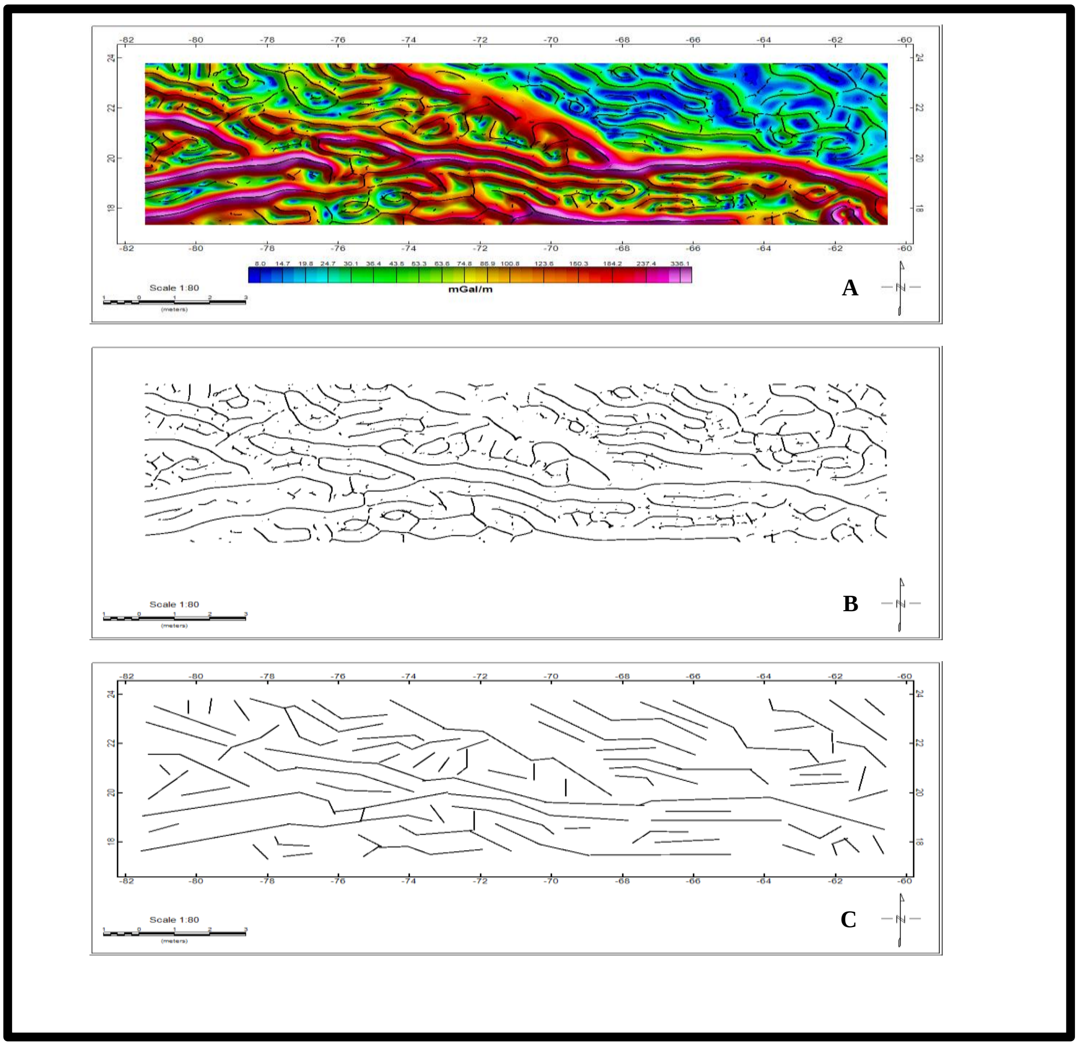

Figure 5 Gravity geophysical investigation of the Caribbean region: Fracture lines (Tectonic) associated with the investigated region: (A) Horizontal Gradient Magnitude map with peaks (B) Horizontal Gradient Magnitude map with peaks without the spectral band. (C) Inferred tectonic/fractured lines from the Horizontal Gradient Magnitude map.

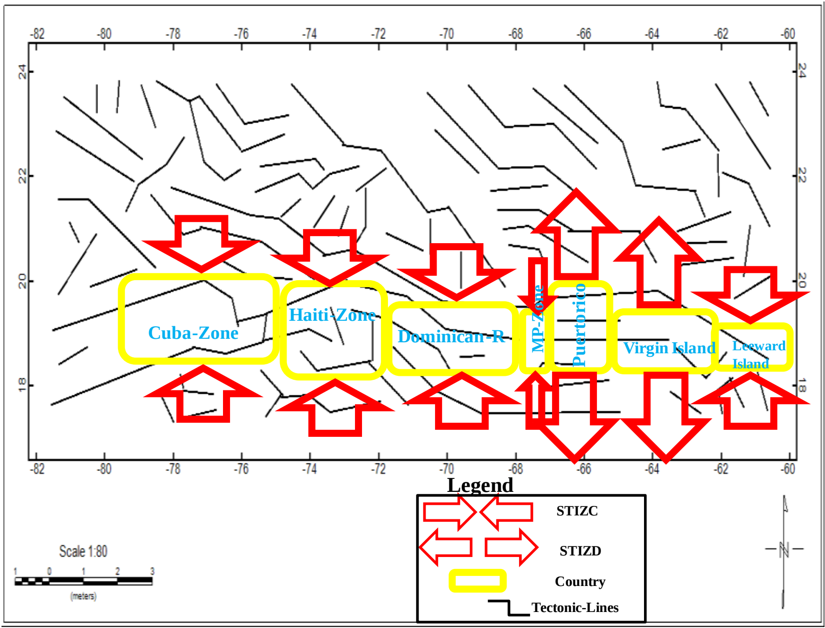

Figure 6 Tectonic-Map depicting the synthesis of main stress regime derived from stress tensor inversion associated with fracture zones. The symbols in the legend are explained in details in the text. Pairs of convergent arrows denoted by STIZC stands for compression stress regime and divergent arrows denoted by STIZD stands for extensional stress regimes.

5. Result

5.1 Stress inversion and earthquake mechanisms: seismotectonic consideration

To characterize the tectonics of the Caribbean region, we have examined the homogeneity or variations in stress regime of the region, using the Methods of Michael (1984, 1987) and Gauss by Zalohar and Vrabec (2007). The results of stress tensor inversion for each of the investigated zones are shown in Table 2. The principal stresses and obtained orientations from Michael and Gauss methods are illustrated in Figure 4. Cuba-zone comprised of stress tensor inversion of 31 focal mechanism solutions which shows that the principal compression axis σ_1 is along NE-SW direction. Michael's method revealed azimuthal, plunge and phi measurement of this zone, for principal compression axis (σ_1) as follows: 124°, 15.5° and $\phi = 0.46$. The direction of orientation of the dominant compression axis σ_1 is illustrated using the Gauss method.

Haiti-zone is made up of stress tensor inversion of 21 focal mechanisms solutions (FMS). The zone is characterized by compression regime, the compression axis (σ_1) using Michael's method shows the azimuthal, plunge and phi as follows: -57.7°, 1.9° and 0.49°, the Gauss method indicated the orientation of the existing principal stress regime along NE-SW.

Dominican republic-zone is made up of stress tensor inversion of 30 focal mechanism solutions, Michael's method shows (σ_1) with an azimuth of 112.5°; Plunge of 1.2° and ϕ = 0.65°; while Gauss method shows the orientation of principal compression axis (σ_1) which is towards NE-SW.

Monapassage-zone comprised of stress tensor inversion of 29 focal mechanism solutions which revealed that the zone is governed by NE-SW compression (σ_1). The dominant principal compression axis (σ_1) measured in this zone using Michael's method is as follows: azimuthal value = -75.8°, plunge = 34.8° and phi = 0.35°, while Gauss method shows the orientation of the principal compression axis in near vertical direction NNW-SSE.

Puertorico-zone is characterized with strike-slip regimes, it is made up of stress tensor inversion of 36 focal mechanism solutions, Michael's method estimates (σ_1) with azimuth of -33.7°; plunge of 7.5° and $\phi = 0.67$°, while σ_3 shows azimuth of 56.6°; plunge of 2.8° and $\phi = 0.67$. The orientations of the principal axial directions of the σ_1 and σ_3 are indicated with the Gauss method.

Virgin Island-zone comprised of stress tensor inversion of 33 focal mechanism solutions which revealed that the zone is governed by strike slip stress regimes. The compression axis (σ_1) shows the azimuthal, plunge and phi values of -49.1°, 27.5° and 0.07°; while the extensional axis σ_3 shows the azimuthal, plunge and phi values of 48.7°, 14.7° and 0.07°, respectively. The orientation of the prevailing principal compression axis (σ_1) and extensional axis σ_3 is indicated by Gauss method.

Leeward Island-zone comprised of stress tensor inversion of 40 focal mechanism solutions. This zone is majorly governed by compression stress regime, Michael's method revealed the azimuthal, plunge and the phi values of this zone as follows: -35.2°, 25.8° and 0.43°, respectively. Gauss method indicated the orientation of the compression axis (σ_1) in NEE-SWW direction.

Out of the seven (7) investigated zones, two of the zones, namely the Puertorico and the Virgin Island are governed by strike-slip regimes. The Dominican Republic shows slightly the presence of strike-slip but the dominant axis is compression stress regime.

5.2. Synthesis of stress tensor inversion result and tectonic/lineament map

To practically explain the kinematic of the investigated region, we have supported the obtained stress tensor Inversion results of this study with the tectonic/lineaments map derived from the gravity geophysical investigation Figure 5. The obtained stress map from the result of the present study as it is, in Figure 4 was synthesized with the tectonic map of the studied region Figure 5. On a broader scale, the region is characterized mainly by two tectonic stress regimes (Compression and strike-slip stress regimes). These regimes are found to be primarily associated with seismic activities in the Caribbean region. However, the synthesis of the stress tensor inversion result and the tectonic/lineaments map derived from the gravity investigation of the study region revealed swarms of fractures which could also be responsible for seismic activities in the region.

Cuba-zone, Dominican republic, Haiti, Monapassage, and the Leeward Island are characterized with compression stress regime and their stress orientation are well indicated on the tectonic-map, while Puertorico and Virgin Island are majorly characterized with the strike-slip stress regimes and their respective orientation are well indicated on the tectonic map.

The outcome of our stress tensor inversion result and the gravity derived lineament/ tectonic map of the Caribbean region have been synthesized together to generate a detailed and current seismotectonic map of the investigated region. A detailed explanation of the present day seismotectonic stress regimes of the Caribbean region and its kinematic implications is presented in Figure 6.

6. Discussion

The Caribbean marginal belts are the product of complex interaction between several first-order geotectonic elements, made of different tectono-magmatic features and originated in different paleo-domains, presently lies fragmented and dispersed along the margins. This consist of continental margins, rifted continental margins, thin oceanic crust, oceanic plateau, intra-oceanic and sub-continental subduction zones and fore deep basins. The interaction between portions of these domains brought about the present-day settlement of the Caribbean plate, which is dominated by compression episodes from the Cretaceous and the strike-slip tectonics. Hence the region remains one of the most active seismogenic zones in the world with the history of devastating seismic hazard and array of active volcanos.

The investigated region is large and has significant implications for seismic hazard assessment of the Caribbean region because of the presence of multiple plate boundaries. The employed stress tensor inversion methods of Michael and Gauss in this study provide reliable and stable results. The results of the two methods are complimentary to each other. The Michael's method is very versatile and has no limitation in its application to focal mechanism solutions (FMS) as such, it has been applied in this study to determine the values of the azimuth, plunge and phi of the stress regimes while the Gauss method has been utilized to determine the orientation of the stress regimes which gives a better insight to the kinematic and ultimately, the seismic hazard assessment of the Caribbean region.

7. Conclusion

We have determined the regional stress regime and its orientation in the Caribbean region as well as its kinematic implications. This would serve as a significant input toward further studies of the seismic hazard assessment of the region, which might be required for the infrastructural developmental program Eluyemi et al. (2020a); Eluyemi et al. (2020b); Eluyemi et al. (2022b). The obtained result from this study gives a better understanding to the tectonics stress regime of the Caribbean Island province: Cuba, Haiti, Dominican Republic, Monapassage, Puertorico, Virgin Island and Leeward Island. The investigated region lies within the multiple lithospheric plate boundaries in between the Zazca Cocos and the American plates, as such, there exists plate boundary forces as well as potential energy and the ridge-push forces estimated to around 2-3×1012 N per metre of the ridge length (Lister, 1975; Parson and Ritcher, 1980 and Coblentz et al., 1994). Consequently, stress is being generated, which is characterized mainly with compression and strike-slip regimes. Both the compression and the strike-slip stress regimes have a significant impact on the lithology of the Caribbean plate: The portion of the plate characterized with the compression stress regime will experience collision of two plates moving towards each other, when this happened, its resultant effect is a major earthquakes and development of a subduction zones, hence Haiti and Puertorico are identified for an historically devastating earthquake disaster. Similarly, portion of the plate characterized with strike-slip stress regime became zones of weakness and tends to fracture as a result of action of forces per unit area (stress = F/A).

The presence of the multiple plate boundaries and their interactions with the existing tectonic stress regimes explains the origin of the swarms and regional fracture lines revealed or inferred from the gravity geophysical investigation of the Caribbean plate. Interestingly, of all the investigated sub- zones, only Puertorico and Virgin Island are characterized with strike slip, which is as a result of simultaneous effect of the ridge push and a plate boundary forces The rest of the sub-zones are majorly compression stress regimes which can also be explained in terms of relative motion of two or more tectonic plates towards each other or one another.

Since the Caribbean tectonic plate is located within and closer to multiple plate boundaries, the plate will be seismological active with the ability to wreck seismic havoc on its habitats and destruction of properties and loss of lives. Several new tectonic lines are expected to be propagated due to the coupling effect and the interaction of the prevailing plate boundaries. The result of this study is one of the vital information needed for the seismic hazard assessment of any of the member nations of the Caribbean island for vulnerable constructions study.

Conflict of interest

The authors declare no conflict of interest.

Data and Resources

The Global Centroid Moment Tensor Project database was searched using http://www.globalcmt.org/CMTsearch.html (last accessed on March 18th, 2022).

The International Seismological Centre catalogue was searched using http://www.isc.ac.uk/iscbulletin/search/catalogue/ (last accessed was on April 2nd, 2022).

Acknowledgements

The authors hereby acknowledge the International Seismological Centre, On-line Bulletin, http://www.isc.ac.uk, Internatl. Seismol. Cent., Thatcham, United Kingdom, 2014 for enabling us access to recent and historic seismic data and global centroid moment tensor (GCMT) catalogue Dziewonski et al. (1981) and Ekström et al. (2012).

The Authors hereby acknowledge the criticisms and loopholes identified and presented by the anonymous reviewer in contribution to the quality of this manuscript. The comments have sincerely improved the quality of this manuscript. Much profound appreciation is hereby extended.

References

1. Abers, G. A. and J. W. Gephart (2001). Direct Inversion of Earthquake First Motions for Both The Stress Tensor and Focal Mechanisms and Application to Southern California. Journal of Geophysical Research, 106 (B11), 26,523-26,540.
2. Adams, A. N., D. A. Wiens, A. A. Nyblade, G. G. Euler, P. J. Shore, and R. Tibi (2015). Lihosphereic Instability and the Source of the Cameroun Volcanic Line: Evidence from Rayleigh Wave Velocity Tomography. Journal of Geophysical Research: Solid Earth, 120 (3), 1708-1727.
3. Affam, M. and J. Achibald (2012). In-Situ Stress Determination at the Ashanti Mine. IJMMP, 3 (1), 1-12.
4. Ajama, O.D., M.O. Awoyemi, A.B. Arogundade, O.A. Dasho, S.C. Falade, O.S. Hammed, O.H. Shode (2021). Deep crustal network of the equatorial Atlantic fracture zones in southern Nigeria. Results Geophys. Sci. 8, 100027.
5. Akpan, O. U., M. A. Isogun, T. A. Yakubu, A. A. Adepelumi, C. S. Okereke, A. S. Oniku, and M. I. Oden (2014). An Evaluation of The 11th September, 2009 Earthquake and Its Implication For Understanding The Seismotectonics of South Western Nigeria. Open Journal of Geology, 4, 542-550. doi:10.4236/ojg.2014.410040
6. Amponsah, P. E. (2004). Seismic Activity In Ghana: Past, Present and Future. Annals of Geophysics, 47 (2 / 3), 539-543.
7. Angelier, J. and S. Baruah (2009). Seismotectonics In Northeast India : A Stress Analysis of Focal Mechanism Solutions of Earthquakes and Its Kinematic Implications. Geophysical Journal International, 178 (1), 303–326,https://doi.org/10.1111/j.1365-246X.2009.04107.x
8. Arogundade A.B., M.O. Awoyemi, O.S. Hammed, S.C. Falade, O.D. Ajama (2022). Structural investigation of Zungeru-Kalangai fault zone and its environ, Nigeria using aeromagnetic and remote sensing data, Heliyon, 8(3), e09055.
9. Awoyemi, M.O., O.D. Ajama, O.S. Hammed, A.B. Arogundade, S.C. Falade, (2017). Geophysical mapping of buried faults in parts of Bida Basin, North Central Nigeria. Geophys. Prospect. 66, 40–54.
10. Bacon, M. and A. O. Quaah (1981). Earthquake Activity in Southeastern Ghana (1977-1980). Bulletin of the Seismological Society of America, 71 (3), 771-785.
11. Baruah, S., S. Baruah and J. R. Kayal (2013). State of Tectonic Stress In Northeast India and Adjoining South Asia Region: An Appraisal. Bulletin of Seismological Society of America, 103 (2A), 894-910. https://doi.org/10.1785/0120110354
12. Blakely, R.J. and R.W. Simpson (1986). Approximating edges of source bodies from magnetic or gravity anomalies. Geophysics 51 (7), 1494–1498.
13. Blundell, D. J. (1976). Active Faults Iin West Africa. Earth and Planetary Science, 31, 287-290.
14. Briggs, I.C. (1974). Machine contouring using minimum curvature. Geophysics 39, 39–48.
15. Brown, J. and J. Fairhead (1983). Gravity study of the Central African Rift System: A model of continental disruption, In tThe Ngaoundere and Abu Gabra Rifts. Tectonophysics, 94, 187–203.
16. Burke, K .C. and A. J Whiteman (1973). Uplift, Rifting and The Break-up of Africa. In Tarling, D.H and Runcorn, S. K. (Eds.), Implications of Continental Drift to the Earth Sciences, 735-755.
17. Burke, K. C., T. F. J. Dessauvagie and A. J. Whiteman (1971). Opening of the Gulf of Guinea and geological history of the Benue Depression and Niger Delta. Nature, Physical Science, 233, 51-55.
18. Burke, K. C., T. F. J. Dessauvagie and A. J. Whiteman (1972). Geological history of the Benue Valley and adjacent Areas. African Geology, 187.
19. Case, J. E., MacDonald. W. D., and Fox, P. J. (1990). Caribbean crustal provinces; seismic and gravity

evidence. In: The Caribbean Region. The Geology of North America, Boulder, Colorado, Dengo, G., Case, J.E. (eds.), Geological Society of America, Vol. H, 1536 .

20. Coblentz, D. D., R. M. Richardson and M. Sandiford (1994). On the Potential energy of the Earth's Lithosphere, Tectonophysics, 13 (4), 929-945. https://doi.org/10.1029/94TC01033
21. Davis, S. D. and C. Frohlich (1995). A Comparison of Moment Tensor Solutions in the Harvard CMT and USGS Catalogs. EOS Trans. American Geophysical Monographs 76, F381.
22. Delvaux, D. and A. Barth (2010). African Stress Pattern from Formal Inversion of Focal Mechanism Data. Tectonophysics 482, 105-128. doi: 10.1016/j.tecto.2009.05.009.
23. DeMets, C., (2001). A new estimate for present-day Cocos-Caribbean plate motion: implications for slip along the Central American volcanic arc. Geophys. Res. Lett. 28 (21), 4043–4046.
24. de-Vicente, G., S. Cloetingh, A. Munoz-Martin, A. Olaiz, D. Stitch, R. Vegas, J. Galindo-Zaldivar and J. Fernandez-Lozano (2008). Inversion of Moment Tensor Focal Mechanism for Active Stresses around the Micro continent Iberia: Tectonic Implications. Tectonics, 27, 1-22. Doi:10.1029/2006TC002093
25. Diebold, J. and l. P. Driscol, (1999). New insights on the formation of the Caribbean basalt province revealed by multichannel seismic images of volcanic structures in the Venezuelan Basin: In: Caribbean Sedimentary Basins, Sedimentary Basins of the World, Mann, P. (ed.), Elsevier, 561589 https://doi.org/10.1785/0220130189
26. Dorbath, C., L. Dorbath, J. D. Fairhead and G. W. Stuart (1986). A Teleseismic Delay Time Study Across The Central African Shear Zone In The Adamawa Region of Cameroon, West Africa. Geophysical Journal International. 86 (3), 751-760.
27. Dziewonski, A. M., T. A. Chou and J. H. Woodhouse (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. J. Geophys. Res., 86, 2825-2852. doi: 10.1029/JB086Ib04p02825.
28. Ekström, G., M. Nettles and A. M. Dziewonski (2012). The global CMT project 2004-2010: Centroid-moment tensors for 13,017 earthquakes, Phys. Earth Planet. Inter., 200-201, 1-9. doi:10.1016/j.pepi.2012.04.002.
29. Eluyemi, A. A., Baruah, S., Sharma, S., and Baruah, S. (2019a). Recent Seismotectonic Stress regime of most seismically active zones of the Gulf of Guinea and its kinematic implications on the adjoining region of the sub-Sahara West African region. Annals of Geophysics, Vol. 62. pp. 1-13. Doi: 10.4401ag-7877.
30. Eluyemi, A. A., Baruah, S., and Baruah, S. (2019b). Empirical relationships of earthquake magnitude scales and estimation of Guttenberg–Richter parameters in gulf of Guinea region, Scientific African, Elsevier Publishers, Vol. 6, pp. 1-8. https://doi.org/10.1016/j.sciaf.2019.e00161
31. Eluyemi, A.A., Sharma, S., Olotu, S.J., Falebita, D.E., Adepelumi, A.A., Tubosun, I.A., Ibitoye, F.I., and Baruah, S. (2020a). A GIS-based site investigation for Nuclear Power Plants (NPPs) in Nigeria, Scientific Africans, Elsevier Publishers, Vol. 7, pp 1-15.https://doi.org/10.1016/j.sciaf.2019.e00240
32. Eluyemi, A. A., Ibitoye, F.I., and Baruah, S. (2020b) Preliminary analysis of probabilistic seismic hazard assessment for nuclear power plant site in nigeria. Scientific Africans, Elsevier Publishers, Vol. 8, pp. 1-12.https://doi.org/10.1016/j.sciaf.2020.e00409.
33. Eluyemi, A. A., Awosika, D. D., Adebisi, O. D. and Baruah, S. (2022a). Time-lapse Seismicity Study of the sub-Sahara West Africa and the Gulf of Guinea region. In P. Elangovan (Ed). Research Developments in Science and Technology (pp. 65-72). BP International: doi.org/10.9734/bpi/rdst/v1/2741c
34. Eluyemi, A. A., Awosika, D. D., Adebisi, O. D., Isreal O. O. and Ibitoye, F.I., Baruah, S. (2022b). Alternative Method of Seismic Hazard Assessment of Moderate to Aseismic Region with interest to Nuclear Power Plant Siting. In Jelena Purenovic (Ed). Research Developments in Science and Technology Vol. 8, Page 177-181 https://doi.org/10.9734/bpi/rdst/v8/2742C
35. Fittion, J. G. (1980). The Benue Trough and Cameroun Line - A Migrating Rift System In West Africa.

Earth and Planetary Science Letters, 51, 132-138. https://doi.org/10.1016/0012-821X(80)90261-7

36. Fomine, F. L. M. (2011). The Strange Lake Nyos Co2 Gas Disaster: Impact and The Displacement and Return of the Affected Communities. The Australasian Journal of Disaster and Trauma Studies. ISSN: 1174 – 4707.
37. Freeth, S. J. (1978). Tectonic Activity In West Africa and The Gulf of Guinea Since Jurassic Times-An Explanation Based On Membrane Tectonics. Earth and Planetary Sciences, Letter, 298-300. https://doi.org/10.1016/0012-821X(78)90103-6
38. Frohlich, C., M. F. Coffin, C. Massell, P. Mann, C. L. Schuur, S. D. Davis, T. Jones and G. Karner (1997). Constraints on Macquarie Ridge tectonics provided By Harvard focal mechanisms and telesiesmic earthquake locations. J. Geophys. Res. 102 (B3), 5029-5041.
39. Fullea, J., M. Fern´andez and H. Zeyen (2008). FA2BOUG-A FORTRAN 90 code to compute Bouguer gravity anomalies from gridded free-air anomalies, application to the Atlantic-Mediterranean transition zone. Comput. Geosci. 34 (12), 1665–1681.
40. Giunta, G. and E. Oliveri (2009). Some remarks on the Caribbean Plate kinematics: facts and remaining problems. In: The Origin and Evolution of the Caribbean Plate, James, K. H., Lorente, M. A. & Pindell, J. L. (eds). Geological Society, London, Special Publications, 328 5
41. Grant, N. K. (1971). South Atlantic, Benue Trough, and Gulf of Guinea Cretaceous Triple Junction. Bulletin of Geological Society of America, 82 (8), 2295-2298. https://doi.org/10.1130/0016-7606(1971)82[2295:SABTAG]2.0.CO;2
42. Gubin, I. E. (1960). Regularities In Seismic Manifestations of Tajikistan. Academy of Science, Moscow, 464.
43. .Heidbach, O., M. Rajabi, K. Reiter, M. Ziegler and WSM Team (2016). World Stress Map Database Release 2016. GFZ Data Services. doi: 10.5880/WSM. 2016.001.
44. Isacks, B., J. Oliver and L. R. Skyes (1968). Seismology and The New Global Tectonics. Journal of Geophysical Research, 73, 5855-5899.
45. Juner, N. R. (1941). The Accra Earthquake of 22nd June, 1939. Gold Coast Geological Survey Bulletin, 13.
46. Kiratzi, A. A. (1999). Stress Tensor Inversion In Western Greece Using Earthquake Focal Mechanisms From The Kozani-Grevena, 1995 Seismic Sequence. Annal Di Geofisica, 42,(4).
47. Kreemer, C., G. Blewitt and E. C. Klein (2014) A Geodetic Plate Motion and Global Strain Rate Model. Geochemistry, Geophysics, Geosystems, 15, 3849-3889. doi: 10.1002/2014GC005407.
48. Kutu, J. M. (2013). Seismic and Tectonic Correspondence of Major Earthquake Region In Southern Ghana With Mid-Atlantic Transform-Fractured Zones. International Journal of Geosciences, 1326-1332.
49. Lister, C. R. (1975). Gravitational Drive on Oceanic Plates Caused by Thermal Contraction: Nature, 257, 663-665.
50. Louvari, E. K. and A. A. Kiratzi (1997). Rake: A Windows Program To Plot Earthquake Focal Mechanisms and The Orientation of Principal Stresses. Computer and Geo-science, 2 (8), 851-857. https://doi.org/10.1016/S0098-3004(97)00070-8
51. Martinez-Garzon, P., G. Kwiatek, M. Ickrath and M. Bohnoff (2014). A Matlab Package For Stress Inversion Combining Solid Classic Methodology, A New Simplifies User Handling and A Visualization Tool. Seismological Research Letter, 85 (4), 896-904.
52. Mascle, J., G. P. Lohmann and M. Moullade (Eds.) (1998). In-Situ Stress at the Cote D'Ivoire-Ghana Marginal Ridge from FMS Logging In Hole 959D1. Proceedings of the Ocean Drilling Program Scientific Results, 159.
53. Mckenzie, D. P. (1969). Speculations on The Consequences and Causes of Plate Motions. Geophys. J. R. astr. Soc. (18), 1-32. doi: 10.1111/j.1365-246X.1969.tb00259.x.
54. Michael, A. J. (1984). Determination of Stress From Slip Data: Faults and Folds. Journal of Geophysical

Research. 89 (B13), 11,517-11,526.
55. Michael, A. J. (1987). Stress Rotation During The Coalinga After Shock Sequence. Journal of Geophysical Research. 92 (B8), 7963-7979.
56. Mogi, K. (1974). Active Periods in the World's Chief Seismic Belts. Tectonophysics, 22, 265-282. https://doi.org/10.1016/0040-1951(74)90086-9
57. Molnar, P., and L.R. Sykes (1969). Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. Geol. Soc. Am. Bull. 80, 1639–1684.
58. Nabighian, M.N. (1972). The analytic signal of two-dimensional magnetic bodies with polygonal cross-section: its properties and use for automated anomaly interpretation. Geophysics 507–517.
59. Nikonov, A. A. (1976). Migration of Large Earthquakes Along The Great Fault Zones In Middle Asia. Tectonophysics, 31, 55-60. https://doi.org/10.1016/0040-1951(76)90113-X
60. Palvis, N.K., S.A. Holmes, S.C. Kenyon, J.K. Factor (2008). An earth gravitational model (EGM 2008) to degree 2160. In: Presented at the EGU General Assembly. Vienna, Austria, April 13-18.\
61. Parsons, B. and F. M. Richter (1980). A Relation between Driving Force and Geoid Anomaly Associated with mid-ocean ridges. Earth and Planetary Science Letters, 51, 445-450.
62. Radhakrishna, I.V. and S.K.G., Krishnamacharyulu (1990). Polyfit: a Fortran 77 program to fit a polynomial of any order to potential field anomalies. J. Assoc. Explor. Geophys. 11, 99–105.
63. Ramdani, M., B. Tadili and S. D. Ben (1984). A Strong Earthquake Strikes Guinea (22nd DECEMBER 1983). Bulletin of the Seismological Society of America, 74 (5), 2045-2047.
64. Rhodes, R. C. (1971). Structural Geometry of Subvolcanic Ring Complexes As Related To Pre-Cenozoic Motions of Continental Plates. Tectonophysics, 12, 111-117. https://doi.org/10.1016/0040-1951(71)90012-6
65. Sanchez, J. J. and F. J. Nuuez-Cornu (2009). Sesmicity and Stress in a Tectonically Complex Region: The Rivera Fracture Zone, the Rivera-Cocos Boundary, and the Southwestern Jalisco Block, Mexico. Bulletin Seismological Society of America, 99 (5), 2771-2783. doi:10.1785/0120080350
66. Shimazaki, K. (1976). Intra-plate Seismicity and Intra-plate Earthquake. Historical Activity In South Western Japan. Tectonophysics, 33, 33-42. https://doi.org/10.1016/0040-1951(76)90050-0
67. Stephan, J. F., R. Blanchet, B. Mercier De Lepinay (1986). Northern and southern Caribbean festoons (Panama, Colombia, Venezuela, Hispaniola, Puerto Rico) interpreted as subductions induced by the east west shortening of the Pericaribbean continental frame. In: The Origin of Arcs, Wezel, F. C. (ed.). Development in Geotectonics, 21. Elsevier, New York, 3551.
68. Suh, C. E., R. S. J. Sparks, J. G. Fitton, S. N. Ayonghe, C. Annen, R. Nana and A. Luckman (2003). The 1999 and 2000 Eruptions of Mount Cameroon: eruption behavior and petrochemistry of lava. Bull Volcanol, 65, 267-281. doi. 10.1007/s 00445-002-0257-7.
69. Tirifu, C. I. and V. Shumila (2011). The Analysis of Stress Tensor Determined From Seismic Moment Tensor Solutions At Goldex Mine Quebec. American Rock Mechanics Association, 11-584.
70. Tokam, K. A. P., C. T. Tabod, A. A. Nyblade, J. Julia, D. A. Wiens and M. E. Pasyanos (2010). Structure of The Crust Beneath Cameroon, West Africa, From The Joint Inversion of Rayleigh Wave Group Velocities and Receiver Functions. Geophysical Journal 183 (2), 106-1076. https://doi.org/10.1111/j.1365-246X.2010.04776.x
71. Trenkamp, R., J.N. Kellogg, J.T. Freymueller, H.P. Mora (2002). Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. J. S. Am. Earth Sci. 15, 157–171
72. Turcotte, D. L and E. R. Oxburgh (1976). Stress Accumulation In The Lithosphere. Tectonophysic. 35 (1–3), 183-199.https://doi.org/10.1016/0040-1951(76)90037-8
73. van Benthem, S., R. Govers, W. Spakman, and R. Wortel (2013). Tectonic evolution and mantle structure

of the Caribbean. J. Geophys. Res. Solid Earth 118 (6), 3019–3036.
74. van Benthem, S., Govers, R., Wortel, R., 2014. What drives microplate motion and deformation in the northeastern Caribbean plate boundary region? Tectonics 33, 1–24.
75. Wright, J. B. (1968). South Atlantic Continental Drift and the Benue Trough. Tectonophysics, 6 (4), 273-352. https://doi.org/10.1016/0040-1951(68)90046-2
76. Yamaji, A. and K. Sato (2006). Distance For The Solution of Stress Tensor Invasion In Relation to Misfit Angles That Accompany The Solutions. Geophysical Journal International, 167(2), 933-942. doi:10.1111/j.1365-246X.2006.03188.x
77. Yarwood, D. R. and D. I. Doser (1990). Deflection of Oceanic Transform Motion at a Continental Margin as deduced from Waveform inversion of the 1939 Accra, Ghana earthquake. Tectonophysics, 172 (3-4), 341-349. https://doi.org/10.1016/0040-1951(90)90040-F
78. Zalohar, J. and M. Vrabec (2007). Paleostress Analysis of heterogeneous Fault-Slip Data: The Gauss Method. Journal of Structural Geology. 29, 1798-1810. doi:10.1016/j.jsg.2007.06.00