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"RECENT SEISMOTECTONIC STRESS REGIME OF MOST SEISMICALLY ACTIVE ZONES OF GULF OF GUINEA AND ITS KINEMATIC IMPLICATIONS ON THE ADJOINING SUB-SAHARA WEST AFRICAN REGION"

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ABSTRACT

The Tectonic stress regime of Gulf of Guinea region has been studied by stress tensor inversion analysis for the area bounded by latitude –10.0 ^{0} S to 4.0ºN and longitude –25 ^{0} W to –11.0 ^{0} E. A total of one hundred and four focal mechanism solutions, pertaining to the earthquake events which have occurred in this region, were used for this study. In order to decipher the stress pattern of this region, we have divided the region into four fracture zones namely Romanche, Chain–Romanche, Charcot and Ascension fracture–zones based on seismicity clustering, tectonics and available focal mechanism solutions. The seismicity pattern indicates that none of the nearby countries on the border line between the west Africa region and the gulf of Guinea is devoid of seismicity. Simultaneously, the stress tensor inversion in the four subzones of investigation indicates different types of stress orientations. All of these zones are characterized by varying principal axial directions. The orientation of the principal axial direction along Romanche, Chain–Romanche, Charcot and Ascension fracture–zones are along NE–SW, NE–SW, ENE–WSW and ESE–WNW respectively. The stress tensor inversion results indicate that Chain–Romanche, Charcot and Ascension fracture zones are characterized by extensional stress regime while Romanche fracture zone is characterized by strike–slip stress regime respectively. These patterns imply sea floor spreading activities in and around the mid oceanic ridges and the general orientation of the extensional stress regime is found towards the continents, along the line of migration / progression of earthquakes.

1. INTRODUCTION

The South Atlantic Ocean around the equator is known as the Gulf of Guinea. This gigantic water body borders most of the West African nations in the south and few of the central Africa nations in the west. Most of the countries located on the adjoining area of the gulf of Guinea are mega cities / national capitals and are highly populated, having their various boundaries to the south-Atlantic ocean (gulf of Guinea) and are regarded as stable and aseismic in nature (Figure 1). Though, evidence of tectonic activities are numerous on the oceanic floor of this zone including submarine volcanic fields, seismicity and the mid Atlantic ridges, the tectonic activities / seismicity within the Atlantic ocean have a significant contribution to the intraplate seismic activities of the adjoining areas pertinent to the continental crust [Shimazaki, 1976]. This has resulted into accumulation of stress and successive migration / progression of occurrence of earthquakes toward the continental crust from its inherent secondary faulting.

Stress accumulated within the earth is often released in form of earthquakes, which take the form of foreshocks, main-shocks, aftershock and earthquake swarms [Michael, 1987]. This has been reflected in the identified seismically active zones of the gulf of Guinea, extending from the north of Ascension Island to the mid Atlantic ridge province. The seismicity pattern indicates clusters of earthquakes that are well observed within this region (Figure 1). This is substantiated by the evidence of earthquake migrations and successions. On the other hand, it was argued that the intra plate seismic activities on the continental crust of the West Africa is greatly affected by the seismic activities within the oceanic crust which is still very active. In general, stress accumulation in the province of intra plate zones takes a longer period of time to accumulate, hence the recurrence time for intraplate earthquakes is often found to be longer than the inter plate zones Shimazaki [1976] as a result, the continental crust of the west African sub region is seen to be seismically quiet (Figure 1). Consequently, the orientation of its seismotectonic stress regime is poorly known.

Over the years, the information of the stress regime of a particular region could be obtained from stress tensor inversion of focal mechanisms of given sets of earthquake events occurring from a particular region, which is based on determination of stress field orientation [Martinez-Garzon et al., 2014]. However, the conventional methods of stress tensor determination are through inversion of focal mechanisms. Efforts towards writing up of a code and developing a more precise and accurate means of determining stress tensor have been carried out by various authors [Michael, 1987; Kiratzi, 1999; Abers, 2001; Yamaji, 2006; Zalohar and Vrabec, 2007; Angelier, 2008; de Vicente, 2008; Delvaux and Barth, 2010; Tirifu, 2011; Baruah et al., 2013 and Martinez-Garzon et al., 2014].

In recent past, seismotectonics of the intraplate earthquake of the west Africa has been linked to the adjoining area of the gulf of Guinea province [Kutu, 2013 and Akpan et al., 2014]. Attempts to determine the stress tensor and its orientation through in-situ and mechanical methods within this region were made to ascertain the bore-hole lithological-wall stability of the Asahnti deep gold mine in Ghana [Affam and Achibald, 2012]. In-situ stress determination, through ocean drilling project (ODP) integrated with focal mechanism solutions of earthquake events were carried out in order to have an

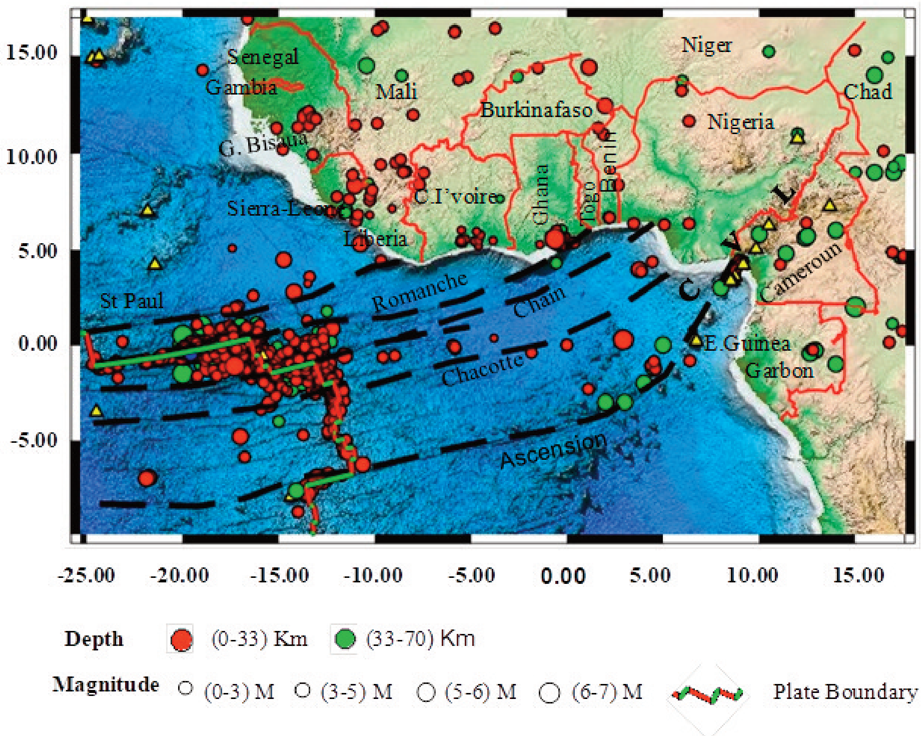

FIGURE 1. Tectonic setting and epicentres plot of the gulf of Guinea and the adjoining continental crust of the countries of sub–Sahara west Africa. In order to depict the seismicity pattern of the region of study, seismic data during the period of 1900–2016 were utilized. The epicentres are shown in red to green circles (the red circles represent events with depth range of 0–33 Km, and the green circles represent events with depth range of 33–70 Km). Dashed lines indicate the fault lines, the volcanic zones are depicted in yellow triangles.

in-depth knowledge of the structural, thermal and sedimentary processes that take place at the transform margine [Mascle et al., 1998]. Since the region around the gulf of Guinea is comprised of numerous geological features with active tectonics: including Cameroun volcanic line (CVL), which is estimated to one thousand and eight hundred kilometers long and made up of continental and oceanic sectors Tokam et al. [2010] and Adams et al. [2015] seismically active mid Atlantic ridge and the array of submarine volcanoes on the oceanic floor of the Gulf of Guinea.

However, the Adjoining region of the gulf of Guinea (sub Shara West Africa) is far away from the plate boundaries but it has experienced devastating earthquakes on five occasions, thrice in Ghana, once in Togo and Guinea. During the period of 18th December, 1636 (Ms = 5.7), 1862 (M_L ~ 6.5 and Ms ≥ 6.5), 11th February, 1907, on 22nd of June, 1939 (Ms ~ 6.5 and Mb ~ 6.4) Accra earthquake in Ghana killed sixteen (16) people and one hundred and thirty three (133) others were severely injured. On 22nd December, 1983 in Conakry-Guinea (Mw ~ 6.3) caused the death of three hundred (300) people and several others were severely injured including loss of properties [Juner, 1941; Blundell, 1976; Bacon and Quah, 1980; Yarwood and Doser, 1990; Amponsah, 2004 and Ramdani et al., 1984]. Similarly, in recent years, the region has also suffered from devastating volcanic eruption with estimated death of one thousand and seven hundred (1,700) people, only on 21st of August 1986 [Fomine, 2011]. Other similar volcanic eruptions took place in the year 1999 and 2000 [Such et al., 2003] respectively.

In this paper, we aim to interpret the active deformation of Gulf of Guinea bound by the latitude -10.0^o to 4.0^{o}N and longitude -25^o to -11.0^{o}E through estimation of seismotectonic stress based on inversion of earthquake focal mechanism solutions, with emphasis on reconstruction of the consistent seismotectonic stress state. In fact, prior to stress estimation, we required delineating the major structural domain through an in-depth understanding of present geodynamics. Thus, this study attempts to determine the stress tensor inversion of the investigated zones exclusively for: (1) the dimension of azimuthal variation of compressional axis related to existing geodynamics of the region and (2) the significance of seismotectonic mechanisms related to four major fracture lines. The aforementioned features are directly or indirectly connected to stress accumulation and discharge of the intra-plate earthquake on the adjoining areas of the gulf of Guinea (continental crust of West Africa), with the scope of seismic hazard assessment and its mitigation pertaining to the occurrence of future large earthquakes. We finally intend to better characterize the interplate deformation in gulf of Guinea and its kinematic implications on the sub-Sahara West African region, with emphasis on the west African rift system along the Cameroun volcanic line (CVL).

2. TECTONIC SETTINGS

Freeth [1977] described the regional tectonics of the west Africa and the gulf of Guinea from a "membrane tectonics" perspective: The West Africa and the Gulf of Guinea with peripheral "compression" was transformed into peripheral "tension", as African plate moved across the equator having Africa and south America split apart, where a major rift opened up into west Africa rift system during Hauterivian to Turonian times [Burke et al., 1971; Burke and Whiteman, 1973]. The rifts are the lower Benue-rift and the Yola rift [Burke et al., 1972]. This involved the separation of continents and zones of major weaknesses in between the eastern ends of the Yola rift and the Red sea rift which is termed as the effective centre of the African plate known as "Jebel Marra" which is a major geographical feature. This "effective centre" moves towards the equator, as the portion of the plate on the same side of the equator known as the "effective centre" experiences peripheral compression, towards south of the equator during early Cretaceous to Eocene times [Freeth, 1977].

Post early Cretaceous, to Eocene times, "Jebel Marra" moved away from equator, therefore, peripheral extension was experienced, north of the equator. Having acted upon the west African rifts are evidences of peripheral extension or compression, in which resulting membrane effects were therefore completely swamped by the stresses, which opened the Atlantic and the west African rift systems. During the last 30 m.y. "Jebel Marra" has been moving northwards, away from the equator. This is the period of the formation of rifts opening up in west Africa and the Gulf of Guinea, with major rift formation known as the Cameroun volcanic line (CVL) extending up to one thousand and eight hundred kilometers (1,800 Km), from the offshore (gulf of Guinea) up to the central African republic [Tokam et al., 2010 and Adams et al., 2015].

Cameroun volcanic line (CVL) is further explained as a subset of the Pan African belt formed by the collision of Sao Francisco, Congo and west African cratons during Neoproterozoic formation of Gondwana that lies within the Obanguides belt, with multiple shear zones, consisting of central African shear zones, in close association with Pernambuco lineament in Brazil [Brown and Fairhead, 1983; Dorbath et al., 1986 and Adams et al., 2015]. CVL comprises of a chain of Tertiary to recent alkaline volcanoes, which split into two arms. One running northward into the northeast of Nigeria, forming Biu plateau, while the other arm of CVL runs eastwards through Nagoundere plateau of eastern Cameroun [Fitton, 1980] thereby forming a "Y" shaped volcanic feature.

Based on long-baseline geodetic GPS data from Africa to Eurasia Kreemer et al. [2014] there is indication that within the framework of northerly extension of gulf of Guinea (25 mm/yr), the present day deformation is statistically significant, relative to mainland Africa which comprises of Guinea, Liberia, Ivory-coast, Ghana, Togo, Benin, Nigeria and Cameroun.

3. DATA USED

The global centroid moment tensor (GCMT) and the International seismological centre (ISC) data catalogue revealed the presence of four types of available focal mechanism solutions (strike- slip, normal, thrust and oblique) that are Present along the existing fracture zones of the gulf of Guinea region. Altogether 104 FMS data used were obtained from global centriod moment tensor (GCMT) known as Harvard CMT Dziewonski et al. [1981]; Ekström et al. [2012] and International seismological centre (ISC) catalogue project where magnitude (M_w) ranges from 4.8-7.1 and depth range (Km) varies from 3.0-33.2 Km. From the time period of 1977-2016. Since different types of focal mechanism solutions are available for the study region, specific types of focal mechanism solutions are more prevalent than the others. Therefore, the focal mechanism solutions are not uniform and neither are these focal mechanism solutions are likely to be controlled by a single fault system with similar orientations.

The epicentral pattern of the studied region can be broadly divided into three, namely: area around the Cameroun volcanic line (CVL), with moderate to active seismicity, the rest of the adjoining area of the gulf of Guinea (west Africa sub-continent) with less seismicity and the gulf of Guinea region, which its earthquake sources has been categorized by the ISC and the GCMT as well as other seismological organizations into: The north of Ascension island, Ascension island and central mid Atlantic ridge with active seismicity. However, due to non availability of FMS data, stress tensor inversion could only be carried out on the gulf of Guinea region alone. The FMS data of the studied zone is mainly characterized by normal, strike-slip, oblique and very few thrust fault mechanism.

4. METHODOLOGY

4.1 SEISMICITY

In order to completely understand the seismicity pattern of the Gulf of Guinea and its implications on the sub Sahara west African region, a total of one thousand and one hundred (1,100) numbers of earthquake events were collected from International seismological centre (ISC), which comprised of historical and recent seismic data from the period of 1900-2016 and magnitude (M_w) range of 3.0-7.1. Figure 1 presents the seismicity pattern of the studied area. The corresponding epicenters are located inside a quadrangle from -10.0 ^{0} N to 17.0 ^{0} N in latitude and -25.0 ^{0} E to 17.0 ^{0} E in longitude, which represent a total area of nearly 14,193,792 Km^2. Figure 1 summarizes the distribution of the earthquake data as a function of magnitude and depth. The epicentral map, indicate clusters of earthquakes in the gulf of Guinea, within the area of longitude -25 ^{0} E to -11.0 ^{0} E and latitude -9.0 ^{0} N to 4.0 ^{0} N. The overall seismicity pattern shows a progression / migration of earthquakes from clustered zone in the gulf of Guinea to the adjoining sub-Sahara West African region.

4.2 QUALITY ASSESSMENT OF THE EMPLOYED FOCAL MECHANISM SOLUTIONS

The earthquake events of which the fault plane solutions were used in our stress tensor inversion (STI) analysis were recorded teleseismically around the world. The global centriod moment tensor (GCMT) catalogue contains two descriptions of moment tensor for every earthquake source. The first one contains the azimuths (φ_T, φ_B, φ_P) and plunges (α_T, α_B, α_P) of the T, B and P axes respectively. Their associated eigenvalues is represented as (λ_T, λ_B, λ_P). The second description is in form of the six independent components of the matrix (m_{11},m_{22},m_{33},m_{12},m_{13}, and m_{23}) which represent the moment tensor (M) and their respective standard error estimate as follows: u_{11},u_{22},u_{33},u_{12},u_{13} and u_{23} the standard error estimates is made up of the standard error tensor denoted by U. In this study, we employed various statistical approaches that are useful tools in measuring the quality of the focal mechanism solutions employed. The first parameter we considered is the f_{CLVD}. This is the sign ratio of the amplitudes of the intermediate and largest principal moments, an indicator used to determine the similarity of a particular focal mechanism solution (FMS) to a compensated linear vector dipole (CLVD), which is same as earthquake produced by faulting occurring simultaneously along series of properly oriented non parallel surfaces or more similar to a double-couple solution (emergence of earthquake by slip on a planar surface). Sanchez and Nuuez [2009] define f_{CLVD} statistic as:

$$f_{\text{CLVD}} = \frac{-\lambda_B}{\max(|\lambda_T|.|\lambda_P|} \quad (1)$$

Whenever a compensated linear vector dipole (CLVD) nears ±0.5 the extreme value of f_{CLVD}, this implies that the orientation of the *T*, *B* and *P* axes are not conclusive.

Simultaneously, we also consider evaluating a relative error (E_{rel}) for the respective focal mechanism solutions employed in the stress tensor inversion analysis. 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, 2009]. Mathematical expression for E_{rel} is given below as:

$$(E_{\text{rel}}) = \sqrt{\frac{U:U}{M:M}} = \sqrt{\frac{u_{11}^2 + u_{22}^2 + u_{33}^2 + 2u_{12}^2 + 2u_{13}^2 + 2u_{23}^2}{m_{11}^2 + m_{22}^2 + m_{33}^2 + 2m_{12}^2 + 2m_{13}^2 + 2m_{23}^2}} \quad (2)$$

The use of colon denotes the tensor scalar product, if A snd B are tensors, their respective elements are a_{ij} and b_{ij}, then A:B = $\sum_{i.j} a_{ij} b_{ij}$. We therefore consider (E_{rel}) as the norm of U divided by the norm of M. $0 \leq E_{rel} \leq 1$. In practice, it is usually advisable to seek for values of E_{rel} as low or small as possible.

The next parameter that we examined for the quality assessment of the employed FMS is the n_{free}. This takes into consideration the numbers of moment tensor components of an earthquake source that is not equal to zero. For an instance, if a particular element m_{ij} of the moment tensor is equal to zero, the associated standard error u_{ij} is also equal to zero. Hence, n_{free} is determined by counting the number of elements of U that satisfy the condition $u_{ij} \neq 0$. This is an important factor for shallow earthquake sources, whereby the CMT constrains the m_{12} and m_{13} elements of the moment tensor to be exactly zero. The geometrical effect of restricting one of the *P*, *T* or *B* axes to the vertical and the two others are confined to the horizontal plane. However, constraining the *P*, *T* or *B* axes to the vertical in the case of pure double couples for shallow earthquakes is equivalent to having a perfect strike-slip, normal or thrust fault.

Out of the 463 FMS reported by the ISC and GCMT for the gulf of Guinea region, only 104 satisfy the three aforementioned conditions. Our computed values for f_{CLVD} for the gulf of Guinea region range between -0.007-0.275; (E_{rel}), varies between 0.096-1.00 and earthquake events that are made up of moment tensor component of n_{free} = 6 was also considered for the STI analysis. These are the criteria upon which the selected 104 FMS data for this study were based upon.

4.3 FMS DATA PREPARATION AND STRESS TENSOR INVERSION (STI)

Stress tensor inversion analysis was done by selection of one hundred and four (104) FMS data on global centroid moment tensor (GCMT) catalogue Dziewonski et al. [1981] and Ekström et al. [2012] as compiled in Table 1. Statistical analyses of these data were prepared for: depth, magnitude and time which are depicted through histogram (Figure 2). Figure 3 represents the beach ball presentation of the focal mechanism solutions associated with the earthquake events in respective tectonic zones of the investigated region. Respective beach balls were generated using Rake software Louvari and Kiratzi [1997].

Zone	Number of Events	Depth (Km)			Magnitude (Mw)			FMS Type			
		Min	Max	Avge	Min	Max	Avge	NF	SS	TF	OB
Romanche	36	4.0	33.2	18.6	6.1	7.1	5.2	-	27	-	9
Chain / Romanche	34	3.0	25.0	14.0	4.8	6.8	5.8	3	17	-	14
Chacotte	10	10.0	23.2	16.6	4.9	5.6	5.25	5	-	-	5
Ascension	24	08.0	33.0	20.5	4.8	6.5	5.65	9	6	1	8

TABLE 1. Shows distribution of earthquake focal mechanism solutions (FMS) within subzones of the investigated zones of the gulf of Guinea. The following acronyms are contained in the above table and are explained as follows: NF indicates normal fault, SS indicates strike–slip fault, TF indicates thrust fault and OB indicates oblique fault mechanism respectively.

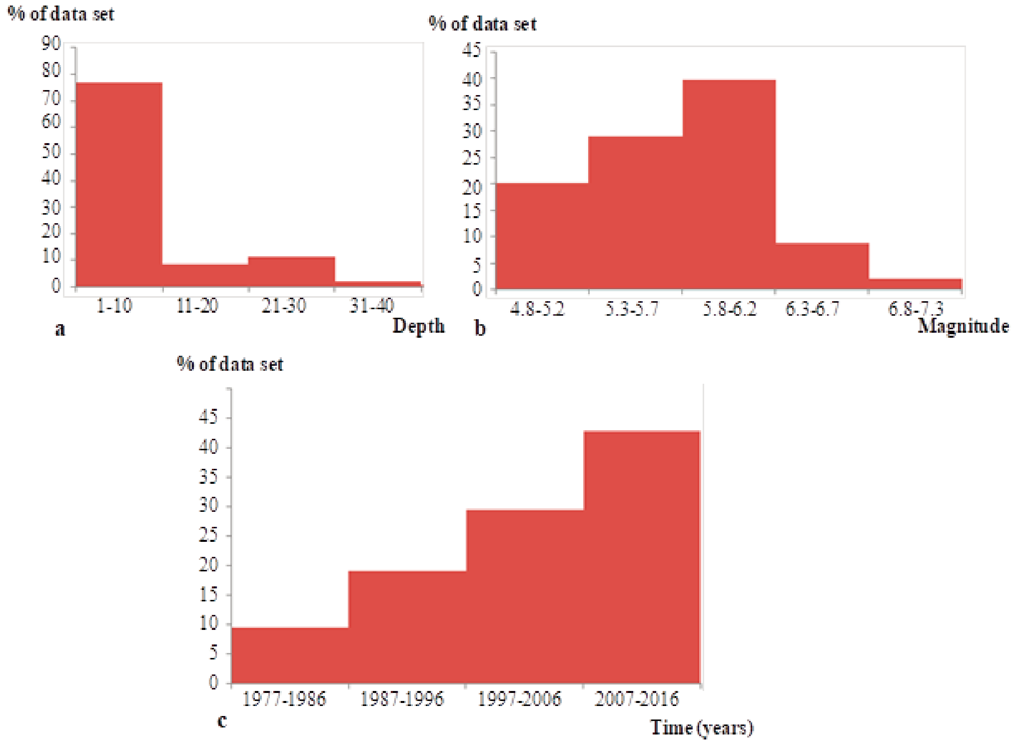

FIGURE 2. Shows the statistical analysis of 104 focal mechanism solutions selected for STI analysis for the clustered zone of the gulf of Guinea. The following histograms are presented: (a) depth (b) magnitude and (c) time. Database of the focal mecha– nism solutions for the period of 1977–2016 used for the stress tensor inversion analysis.

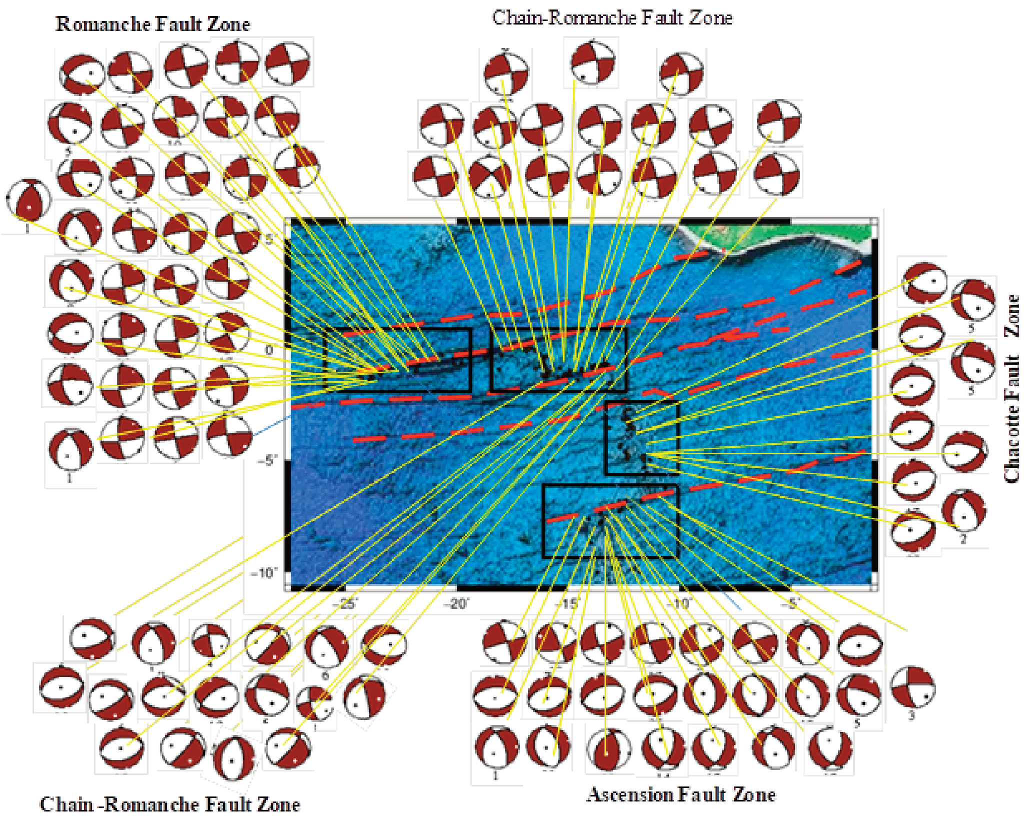

FIGURE 3. Map showing the selected 104 focal mechanism solutions in the study region. All focal mechanism solutions are shown by conventional beach–ball illustrations of global CMT solutions.

The beach balls were divided into four subzones, associated to four fracture zones, based on the corresponding tectonic domain. The focal parameters of the fault plane solutions utilized in this study (supplementary) and the direction of the stress tensor were calculated and determined using the inversion algorithm of Michael [1984, 1987] also known as Michael's method and Zalohar & Vrabec [2007] known as Gauss method, simultaneously, in order to constrain the consistency of inferred results. Inversion results of the 104 fault plane solutions are zone-wise tabulated in Table 2. The operational principles of the Gauss method is based upon 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. Secondly, it also takes into account the ratio between the normal and shear stress on fault plane. The optimal stress tensors for 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 focal mechanism solutions. Michael's principle works upon a condition that must be satisfied by the input data. During the observed time interval, stress is assumed to be uniform in respective zones 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. Michael method accounts for determination of three principal stresses: maximum stress, intermediate stress and minimum stress, from statistical technique of bootstrapping re-sampling. Orientations of the principal stresses σ_1 and σ_3 of the stress tensor inversion results derived from Gauss and Michael methods are illustrated in Figure 4. The world stress map of the study region (gulf of Guinea) Heidbach et al. [2016] is presented

In figure 5 and the geodetic GPS data from Africa to Eurasia Kreemer et al. [2014] movement of African plate towards the Eurasia plate is indicated with dashed arrow line, in Figure 6.

5. RESULT

5.1 STRESS INVERSION AND EARTHQUAKE MECHANISMS: SEISMOTECTONIC CONSIDERATION

In order to examine the homogeneity or variations in stress regime within the identified active seismicity zone (clusters of earthquake events) in the Gulf of Guinea (Figure 1). Methods of Michael [1984, 1987] and Gauss by Zalohar and Vrabec [2007] have been implemented. The results of stress tensor inversion for each of the mentioned four fracture zones are shown in Table 2. The principal stresses and obtained orientations from Michael and Gauss methods are illustrated in Figure 4. Romanche fracture zone comprised of stress tensor inversion of 36 focal mechanism solutions which shows that the principal ex-

Zone	Method Used	(σ1)		(σ2)		(σ3)		ϕ	ϕ Avg	Variance	Std Dev.
		Azim (°)	Pln (°)	Azim(°)	Pln (°)	Azim (°)	Pln (°)				
Romanche Fault zone	Michael	135.9	11.3	-52.7	78.6	45.7	1.2	0.75	0.63	0.019	0.138
	Gauss	127.0	7.0	272.0	81.0	37.0	5.0	0.5		-	-
Chain/Romanche Fault Zone	Michael	159.9	87.8	-39.8	2.1	50.2	0.7	0.8	0.70	0.089	0.293
	Gauss	305	65.0	145.0	24.0	51.0	8.0	0.6		-	-
Chacotte Fault Zone	Michael	-71.8	66.5	137.8	20.6	43.8	10.6	0.44	0.52	0.084	0.289
	Gauss	226.0	76.0	339.0	6.0	71.0	13.0	0.6		-	-
Ascension Fault Zone	Michael	-172.6	19.6	0.1	70.0	96.4	2.3	0.82	0.76	0.100	0.316
	Gauss	2.0	86.0	189.0	4.0	98.0	0.0	0.7		-	-

TABLE 2. Result of stress tensor inversion for the four subzones of the studied region of the gulf of Guinea using Michael and Gauss methods.

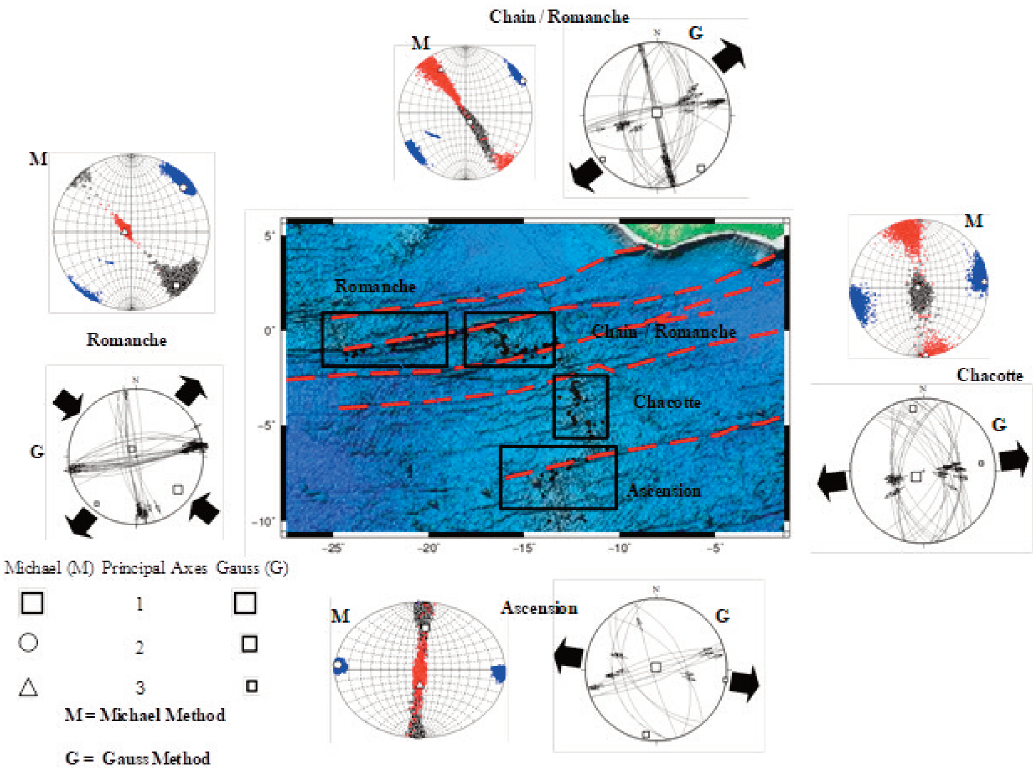

FIGURE 4. Stress tension inversion results of the four fault zones for the cluster of events therein using Michael and Gauss meth–ods. Syntheses of stress pattern at the associated fault zones / clusters are depicted with symbols. The black convergent and divergent arrows indicate compression and extensional stress regimes.

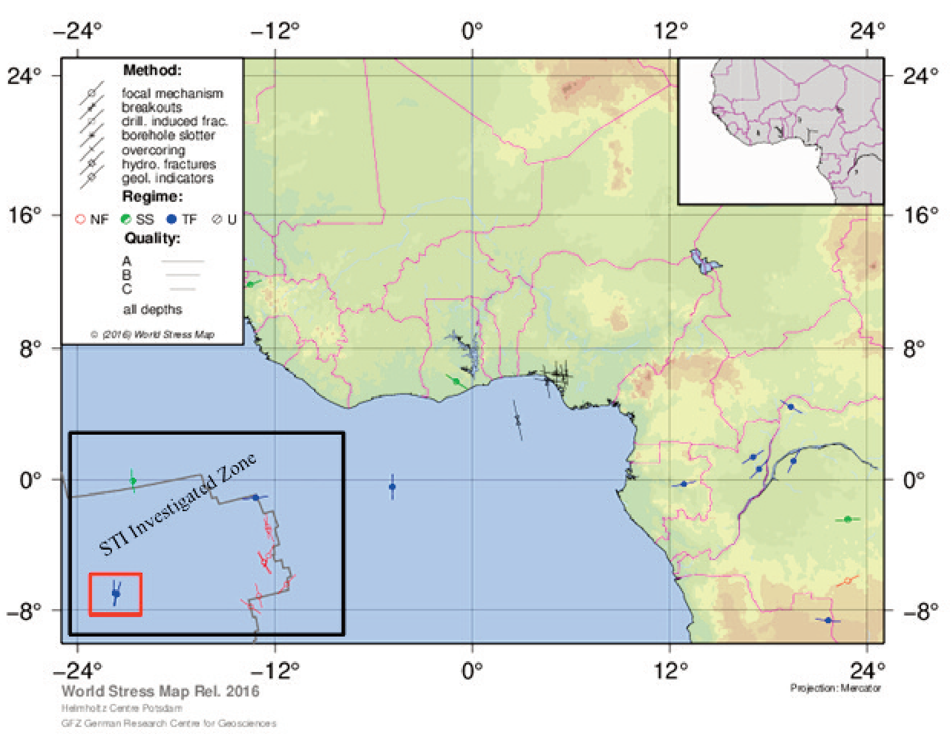

FIGURE 5. World stress map release, 2016 edition showing the tectonic of the studied region in rectangular box. 3 types of tecton–ics have been identified within the studied region by WSM project: strike–slip (SS), normal (NF) and thrust (TF) [Heid–bach et al., 2016]. The small red box indicated a thrust fault but with only two FMS data, which were found on ISC and GCMT data catalogues for the period of 1977–2016. Perhaps an indicator to the development of a new tectonic domain, these were synthesized with the result of our study in figure 6.

tensional axis σ_3 is along N-E direction. Michael method revealed azimuthal, plunge and phi measurement of this zone, for principal extensional axis (σ_3) as follows: 45.7 ^{0}, 1.7 ^{0} and ϕ = 0.75. The dominant extensional axis (σ_3) measurement, using Gauss method is as follows: azimuthal value of 37.0 ^{0}, plunge of 5.0 ^{0} and ϕ = 0.5 respectively, while the dominant compression axis σ_1 is along NW-SE direction. Michael method shows azimuth and plunge measurement for σ_1 as follows: 135.9 ^{0}, 11.3 ^{0} while Gauss method revealed azimuth and plunge for σ_1 as 127.0 ^{0} and 17.0 ^{0} respectively.

Chain-Romanche fault zone is made up of stress tensor inversion of 34 focal mechanism solutions, Michael method shows σ_3 with an azimuth of 50.2 ^{0}; Plunge of 0.7 ^{0} and ϕ = 0.8 while Gauss method shows, σ_3 with an azimuth of 51 ^{0}; plunge of 8.0 ^{0} and ϕ = 0.6. σ_3 tends towards north-east direction, Charcot fault zone comprised of stress tensor inversion of 10 focal mechanism solutions which revealed that the zone is governed by nearly east-west extension σ_3. The dominant principal extensional axis (σ_3) measured in this zone using Michael method is as follows: azimuthal value = 43.8 ^{0}, plunge = 10.6 ^{0} and phi = 0.44. While Gauss method showed azimuthal value of 71.0 ^{0}, plunge = 13.0 ^{0} and phi = 0.6. Ascension fracture zone is made up of stress tensor inversion of 24 focal mechanism solutions, Michael method estimates σ_3 with azimuth of 96.4 ^{0}; plunge of 2.3 ^{0} and ϕ=0.82 ^{0} while Gauss method shows σ_3, with an azimuth of 98.0 ^{0}; plunge of 0.0 ^{0} and ϕ = 0.7. Out of the four fracture zones, only Romanche fracture zones is characterized by strike-slip (SS) stress regime while the rest of the fracture zones are characterized by extensional stress regimes only.

5.2 SYNTHESIS OF STRESS TENSOR INVERSION RESULT AND WORLD STRESS MAP PROJECT

The obtained stress tensor Inversion results of the present investigation have been supported by data of world stress map (WSM) project Heidbach et al. [2016] (Figure 5). The derived stress map from the result of the present study as it is, in Figure 4 was synthesized with the existing global stress map of the studied region (Figure 5). On a broader scale, two main tectonic stress regimes [strike-slip and extensional stress regime] have been identified that are primarily associated with seismic activities in the Gulf of Guinea. However, two of the existing stress regimes have been well indicated in this study. There is possibility of development of a new stress regime perhaps in its initial stage (Figure 5). The red small rectangular box, contains just two focal mechanism (FMS)

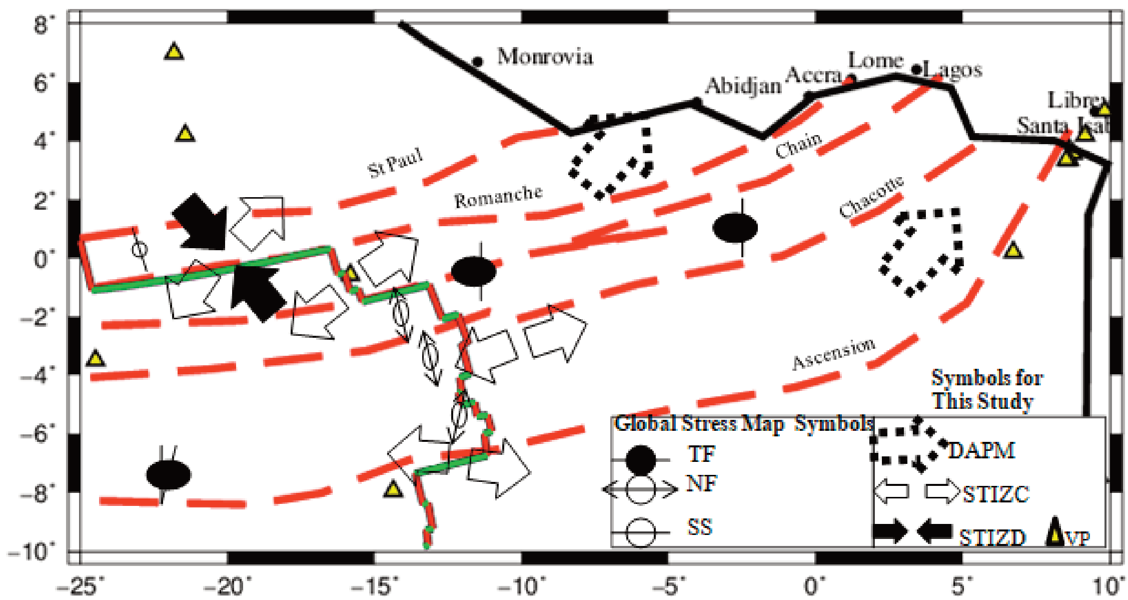

FIGURE 6. VMap depicting the synthesis of main stress regime derived from stress tensor inversion associated with four fracture zones. The inputs from global stress map are included as indicated in legend. The symbols are explained in details in the text. Yellow triangle denoted with VP represent the volcanic points; Pairs of convergent arrows denoted by STIZD stands for compression stress regime and divergent arrows denoted by STIZC stands for extensional stress regimes are shown as in Figure 9 are the final determination. Extensional stress regime accounts for 72 per cent of the events out of the total data set. Compiled GPS observation in adjoining region (see text), the large dotted arrow marks on the right top corner of the figure indicate the velocity vector of the African plate with respect to the Arabian and Eurasian plate at the same scale.

data belonging to Thrust fault. As such, no stress tensor inversion could be done, due to limited availability of FMS data.

Romanche fracture zone is characterized with strike slip stress regime and its stress orientation is well located, while Chain-Romanche, Charcot and Ascension fracture zones are characterized by extensional stress regimes respectively, each with different degrees of orientation. The outcome of our stress tensor inversion result and the WSM data map project of the same region have been synthesized together to generate a detailed and current seismotectonic map of the investigated region. A comprehensive explanation of the present day seismotectonic stress regimes of the gulf of Guinea and its kinematic implication on its adjoining region is presented in Figure 6.

6. DISCUSSION

The study region is quite large enough and has significant implications for seismic hazard assessment of the adjoining continental region of sub-Sahara West Africa because of the presence of five regional fracture zones that are oceanic and continental by extension. The Michael and Gauss methods of stress tensor inversion analysis employed in this work provide reliable and stable results. The results of the two methods are relatively comparable in terms of stress axes orientation and stress regimes determination (Table 2).

The synthesized stress pattern from focal parameters and associated earthquake events of the seismogenic zones could be inferred. These seismogenic zones can be categorized into three major zones, namely: area around and along the Cameroun volcanic line (CVL) or the west African rift zone, the rest of the adjoining region (West African continental crust) and the gulf of Guinea region, (involving the central mid Atlantic ridge, mid Atlantic ridge, north of Ascension Island and the Ascension Island).

Seismicity around the CVL region is directly connected to the Gulf of Guinea region, since the region is the zone of weakness arising from the rifting and the separation of the south American plate from the African plate, therefore, build up of stresses from the Gulf of guinea region are easily released along the CVL zone in form of earthquakes more than the adjoining areas. Migration and succession of seismic events in linear pattern are evident towards the CVL and the adjoining area, around the west African continental crust, in conformity with Gubin [1960] and Nikonov [1976] from the clusters of the earthquake events within the gulf of Guinea. It is obvious that tectonic stresses are being released on a regular basis within the studied zone (gulf of Guinea). However, amidst and closer to the clusters of the seismic events, lies an array of submarine volcanic field, within the oceanic segment, which is obvious on the continental segment extending up to Cameroun, Sudan Chad and Algeria. Historically, volcanic eruption along the CVL, on mount Cameroun a subset of the continental segment of CVL took place in 1986, 1999 and 2000 [Fomine, 2011; Suh et al., 2003].

7. CONCLUSION

We have determined the regional stress regime and its orientation in the Gulf of Guinea as well as its kinematic implications on the adjoining sub-Sahara West Africa region, which was not previously known. The result obtained from our investigation gives a better understanding to the tectonics stress regime of the Gulf of Guinea and a better insight to the work of the earlier researchers.

Since the adjoining region of the Gulf of Guinea (the West African sub region) is characterized by regional fracture/fault zones that originated from the Gulf of Guinea. The resultant effects from the Gulf of Guinea are easily propagated through these medium to manifest themselves in various ways, which can be described as follows:

First of all, the investigated region lies on the lithospheric plate boundaries in between the south America and the African plates, there exists a plate boundary forces as well as potential energy and the ridge-push forces estimated around 2-3×10^{12} N per metre of the ridge length [Lister, 1975; Parson and Ritcher, 1980 and Coblentz et al., 1994]. As a result of this, stresses are being generated. The orientation of the generated stress on the Gulf of Guinea, which are mainly extensional stress regime became zones of weakness and tends to fracture as a result of action of forces per unit area (stress = F/A). These explain the origin of the multiple and regional fracture zones in the gulf of Guinea (St Paul, Romanche, Chain, Charcot and Ascension). Interestingly, of all the investigated sub-fracture zones, only Romanche fracture zone is made up of the strike slip regime, which can be explained in terms of plate boundary forces. The rest of the sub fracture zones are made up of extensional stress regime, which is as a result of simultaneous effect of ridge push and a plate boundary forces.

For as long as the stress orientation remains in the same direction, as it is, in this study. It is expected that the processes of the fracturing continue, hence the aforementioned fracture zones traversed several thousand kilometers from mid Atlantic ridge in the Gulf of Guinea onshore through west Africa into the African plate.

The current seismicity being experienced on the continental crust of the West African region could be explained not solely because of transmission of motion from either Romanche or Chain fracture zones in the gulf of Guinea to the continental faults or an early stage in the development of plate boundary on the continent or deflection of motion from Romanche or Chain fractures to coastal boundary fault as theorized by earlier researchers Burke [1971], Blundel [1976] and Yarwood and Doser [1990] but also the seismicity of the West African region can be further explained as a result of release of built up stress in the Gulf of Guinea along the axial orientation of extensional stress regimes, which are towards and along the existing fracture zones in the gulf of Guinea, up to the African continent. This is evident in the progression/migration of earthquake events from the gulf of Guinea to the West African sub region (Figure 1).

The West African rift system, along the Cameroun volcanic line (CVL) is mainly a result of ridge push forces exerted on the CVL from the mid Atlantic ridge in the Gulf of Guinea and gravitational potential energy along the mountainous region on the continent in Cameroun. We also observed a direct connection of the CVL to the mid Atlantic ridge system through Charcot and Ascension fracture zones. The present extensional stress regime within the Charcot subzones is oriented towards and along the West African rift system or the CVL. This implies that the West African rift system is still in its active stage of rifting. Hence a linear progression and migration of earthquakes are observed from the mid Atlantic ridge in Gulf of Guinea through the CVL up to Chad region in (Figure 1).

Results obtained from our work also suggest that the incessant eruptions of the CVL could be due to mechanical coupling between the Gulf of Guinea fracture zones (Chain, Charcot and Ascension) and magmatic systems, due to stress release from large earthquakes on to the magmatic body, thereby perturbing the system and triggering volcanic eruptions. For as long as the orientation of stress from the gulf of Guinea is towards the CVL, the CVL will remain an active volcano for years to come, unless the stress regime axial direction is rotated away from the CVL.

All in all, this work also corroborates the hypothesis of Blundell [1976], which suggested an early stage of development of a new plate boundary, possibly through fault propagation but not rifting processes, along the Akwaipim fault zone (Ghana) into the continent, as a result of active tectonism from Romanche fracture zone to Akwaipim fault zone.

Our work concludes that similar activities could be true of Kandi regional fault line, on the shore of West Africa, in between Benin republic and Nigeria up to Hogga, a volcanic zone in Algeria North Africa.

DATA AND RESOURCES

The Global Centroid Moment Tensor Project database was searched using http://www.globalcmt.org/CMTsearch.html (last accessed on November 18th, 2016).

The International Seismological Centre catalogue was searched using http://www.isc.ac.uk/iscbulletin/search/catalogue/ (last accessed was on October, 2nd, 2016).

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REFERENCES

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, J. Geophys. Res. 106 (B11), 26523-26540.

Adams A.N., D.A. Wiens, A.A. Nyblade, G.G. Euler, P.J. Shore, R. Tibi (2015). Lihosphereic Instability and The Source of The Cameroun Volcanic Line: Evidence From Rayleigh Wave Velocity Tomography. J. Geophys. Res.: Solid Earth 120 (3), 1708-1727.

Afam M., J. Achibald (2012). In-Situ Stress Determination at the Ashanti Mine, IJMMP 3 (1), 1-12.

Akpan O.U., M.A. Isogun, T.A. Yakubu, A.A. Adepelumi, C.S. Okereke, A.S. Oniku, M.I. Oden (2014). An Evaluation of The 11th September, 2009 Earthquake and Its Implication For Understanding The Seismotectonics of South Western Nigeria, Open J. Geol. 4, 542-550, doi: 10.4236/ojg.2014.410040

Amponsah P.E. (2004). Seismic Activity In Ghana: Past, Present and Future, Ann. Geophys. 47 (2/3), 539-543.

Angelier J., S. Baruah (2009). Seismotectonics In Northeast India: A Stress Analysis of Focal Mechanism Solutions of Earthquakes and Its Kinematic Implications, Geophys. J. Int. 178 (1), 303-326, https://doi.org/10.1111/j.1365-246X.2009.04107.x

Bacon M., A.O. Quaah (1981). Earthquake Activity in Southeastern Ghana (1977-1980), Bull. Seismol. Soc. Am. 71 (3), 771-785.

Baruah S., S. Baruah, J.R. Kayal (2013). State of Tectonic Stress In Northeast India and Adjoining South Asia Region: An Appraisal, Bull. Seismol. Soc. Am. 103 (2A), 894-910. https://doi.org/10.1785/0120110354

Blundell D.J. (1976). Active Faults In: West Africa. Earth Plan. Sci. 31, 287-290.

Brown J., J. Fairhead (1983). Gravity study of the Central African Rift System: A model of continental disruption, In: The Ngaoundere and Abu Gabra Rifts. Tectonophysics, 94, 187–203.

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.

Burke K.C., T.F.J. Dessauvagie and A.J. Whiteman (1972). Geological history of the Benue Valley and adjacent Areas, African Geology 187.

Burke K.C., 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.

Coblentz D.D., R.M. Richardson, M. Sandiford (1994). On the Potential energy of the Earth's Lithosphere, Tectonophysics 13 (4), 929-945. https://doi.org/10.1029/94TC01033

Davis S.D., C. Frohlich (1995). A Comparison of Moment Tensor Solutions in the Harvard CMT and USGS Catalogs, EOS Trans. American Geophysical Monographs 76, F381.

Delvaux D., 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.

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

Dorbath C., L. Dorbath, J.D. Fairhead, G.W. Stuart (1986). A Teleseismic Delay Time Study Across The Central African Shear Zone In The Adamawa Region of Cameroon, West Africa, Geophys. J. Int. 86 (3), 751-760.

Dziewonski A.M., T.A. Chou, 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.

Ekström, G., M. Nettles, 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.

Fittion J. G. (1980). The Benue Trough and Cameroun Line - A Migrating Rift System In West Africa. Earth Plan. Sci. Lett. 51, 132-138. https://doi.org/10.1016/0012-821X(80)90261-7

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.

Freeth S.J. (1978). Tectonic Activity In: West Africa and The Gulf of Guinea Since Jurassic Times-An Explanation Based On Membrane Tectonics, Earth Plan. Sci. Lett. 38 (2), 298-300. https://doi.org/10.1016/0012-821X(78)90103-6

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.

Gubin I.E. (1960). Regularities In: Seismic Manifestations of Tajikistan, Academy of Science, Moscow, 464.

Heidbach O., M. Rajabi, K. Reiter, M. Ziegler, W.S.M. Team (2016). World Stress Map Database Release 2016, GFZ Data Services. doi: 10.5880/WSM. 2016.001.

Isacks B., J. Oliver, L.R. Skyes (1968). Seismology and The New Global Tectonics, J. Geophys. Res. 73, 5855-5899.

Juner N.R. (1941). The Accra Earthquake of 22nd June, 1939, Gold Coast Geological Survey Bulletin, 13.

Kiratzi A.A. (1999). Stress Tensor Inversion In Western Greece Using Earthquake Focal Mechanisms From The Kozani-Grevena, 1995 Seismic Sequence, Ann. Geophys. 42 (4).

Kutu J.M. (2013). Seismic and Tectonic Correspondence of Major Earthquake Region In Southern Ghana With Mid-Atlantic Transform-Fractured Zones, Int. J. Geosci. 1326-1332.

Kreemer C., G. Blewitt, E.C. Klein (2014). A Geodetic Plate Motion and Global Strain Rate Model, Geochem. Geophys. Geosys. 15, 3849-3889. doi: 10.1002/2014GC005407.

Lister C.R. (1975). Gravitational Drive on Oceanic Plates Caused by Thermal Contraction, Nature 257, 663-665.

Louvari E.K., A.A. Kiratzi (1997). Rake: A Windows Program To Plot Earthquake Focal Mechanisms and The Orientation of Principal Stresses, Comput. Geosci. (8), 851-857, doi: https://doi.org/10.1016/S0098-3004(97)00070-8

Martinez-Garzon P., G. Kwiatek, M. Ickrath, M. Bohnoff (2014). A Matlab Package For Stress Inversion Combining Solid Classic Methodology, A New Simplifies User Handling and A Visualization Tool, Seismol. Res. Lett. 85 (4), 896-904, doi: https://doi.org/10.1785/0220130189

Mascle J., G.P. Lohmann, M. Moullade (Eds.) (1998). In-Situ Stress at the Cote D'Ivoire-Ghana Marginal Ridge from FMS Logging In Hole 959D[1], Proceedings of the Ocean Drilling Program Scientific Results, 159.

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.

Michael A.J. (1984). Determination of Stress From Slip Data: Faults and Folds. J. Geophys. Res. 89 (B13), 11517-11526.

Michael A.J. (1987). Stress Rotation During The Coalinga After Shock Sequence. J. Geophys. Res. 92 (B8), 7963-7979.

Mogi K. (1974). Active Periods in the World's Chief Seismic Belts, Tectonophysics 22, 265-282, doi: https://doi.org/10.1016/0040-1951(74)90086-9

Grant N.K. (1971). South Atlantic, Benue Trough, and Gulf of Guinea Cretaceous Triple Junction, Bull. Geol. Soc. Am. 82 (8), 2295-2298, doi: https://doi.org/10.1130/0016-7606(1971)82[2295:SABTAG]2.0.CO;2

Nikonov A.A. (1976). Migration of Large Earthquakes Along The Great Fault Zones In Middle Asia, Tectonophysics 31, 55-60, doi: https://doi.org/10.1016/0040-1951(76)90113-X

Parsons B., F.M. Richter (1980). A Relation between Driving Force and Geoid Anomaly Associated with mid-ocean ridges, Earth Plan. Sci. Lett. 51, 445-450.

Ramdani M., B. Tadili, S.D. Ben (1984). A Strong Earthquake Strikes Guinea (22nd DECEMBER 1983), Bull. Seismol. Soc. Am. 74 (5), 2045-2047.

Rhodes R.C. (1971). Structural Geometry of Subvolcanic Ring Complexes As Related To Pre-Cenozoic Motions of Continental Plates, Tectonophysics 12, 111-117, doi: https://doi.org/10.1016/0040-1951(71)90012-6

Sanchez J.J., 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, Bull. Seismol. Soc. Am. 99 (5), 2771-2783, doi:10.1785/0120080350

Shimazaki K. (1976). Intra-plate Seismicity and Intra-plate Earthquake. Historical Activity In South Western Japan, Tectonophysics 33, 33-42, doi: https://doi.org/10.1016/0040-1951(76)90050-0

Suh C.E., R.S.J. Sparks, J.G. Fitton, S.N. Ayonghe, C. Annen, R. Nana, 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

Tirifu C.I., V. Shumila (2011). The Analysis of Stress Tensor Determined From Seismic Moment Tensor Solutions At Goldex Mine Quebec, American Rock Mechanics Association, 11-584.

Tokam K.A.P., C.T. Tabod, A.A. Nyblade, J. Julia, D.A. Wiens, M.E. Pasyanos (2010). Structure of The Crust Beneath Cameroon, West Africa, From The Joint Inversion of Rayleigh Wave Group Velocities and Receiver Functions, Geophys. J. Int. 183 (2), 106-1076, doi: https://doi.org/10.1111/j.1365-246X.2010.04776.x

Turcotte D.L., E.R. Oxburgh (1976). Stress Accumulation In The Lithosphere, Tectonophysic 35 (1-3), 183-199, doi: https://doi.org/10.1016/0040-1951(76)90037-8

Wright J.B. (1968). South Atlantic Continental Drift and the Benue Trough, Tectonophysics 6 (4), 273-352. doi: https://doi.org/10.1016/0040-1951(68)90046-2

Yamaji, A., K. Sato (2006). Distance For The Solution of Stress Tensor Invasion In Relation to Misfit Angles That Accompany The Solutions, Geophys. J. Int. 167(2), 933-942, doi:10.1111/j.1365-246X.2006.03188.x

Yarwood D.R., 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, doi: https://doi.org/10.1016/0040-1951(90)90040-F

Zalohar J., M. Vrabec (2007). Paleostress Analysis of heterogeneous Fault-Slip Data: The Gauss Method. J. Struct. Geol. 29, 1798-1810, doi: 10.1016/j.jsg.2007.06.009

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