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An Evaluation of the 11th September, 2009 Earthquake and Its Implication for Understanding the Seismotectonics of South Western Nigeria

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Abstract

The evaluation of an intra-plate earthquake that occurred on Friday, 11th September, 2009 and felt in parts of Abeokuta, Ago-Iwoye, Ajambata, Ajegunle, Imeko, Ijebu-Ode, Ilaro and Ibadan, all in south western Nigeria is presented. This event has been the largest inland earthquake recorded since the inception of digital seismological recording in Nigeria in 2008 was incepted. The event was recorded by three seismological stations operated by Centre for Geodesy and Geodynamics (CGG), Toro. Data obtained from the CGG stations and others distributed around the world were analysed to determine precise earthquake locations and focal mechanism and to assess the regional tectonic stress. The data recorded in MiniSEED format at a sampling rate of 40 samples per second (sps) were analyzed using the SEISAN earthquake analysis software. The result showed an epicentral location situated about 108 km west of Lagos, a focal depth of 10.0 km and an origin time of 03:10:21.60 GMT. The local and moment magnitudes were 4.5 and 4.2 respectively. The P-wave to S-wave velocity ratio was 1.72. The fault plane solutions obtained for the rupture process indicated that a normal dip-slip fault with median solution of strike 325˚, dip 40˚ and rake −90˚ was the probable trigger mechanism for this earthquake. It suggested that the event was a reactivation of a buried high-angle fault in the Precambrian basement represented by the contemporary northeast-southwest trending regional horizontal compressive stress. Generally, the seismotectonics of the region was linked to the fracture zones in the Atlantic Ocean.

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Keywords

Intra-Plate Earthquake, Normal Fault, Epicentre, South Western Nigeria

1. Introduction

The Nigerian landmass is not expected to be affected by naturally occurring earthquakes because it is located far from the major earthquake zones of the world, as the nearest active plate boundary lies far away at the Mid-Atlantic Ridge and therefore considered a stable continental area. However, over time, earth tremors have been felt in the country especially in the south western part [1] [2]. The areas which have experienced the vibrations resulting from past tremors include: Lagos, Ibadan and Ile-Ife in 1939 [3], Ijebu-Ode in 1963 [4], Ibadan, Ijebu-Ode, Shagamu and Abeokuta in 1984 [5], Ibadan and Ijebu-Ode in 1990 [1] [2] [5], Okitipupa in 1997, Okitipupa, Ibadan, Ijebu-Ode, Akure, Shagamu, Abeokuta and Oyo in 2000 [2] [6]. The 1984, 1990 and 2000 events were the only ones that were instrumentally recorded, but epicentres were only determined for the 1984 and 2000 events. The 2000 event was recorded teleseismically by twenty-seven seismological observatories around the world [2]. The National Earthquake Information Centre (NEIC) of the United States Geological Survey (USGS) located the event at 6.224˚N and 5.147˚E, calculated a body wave magnitude (M_B) of 4.5 and a focal depth of 10 km. The International Seismological Centre (ISC), United Kingdom located the same event at 6.290˚N and 5.070˚E, determined the body wave (M_B) and surface wave (M_S) magnitudes of 4.4 and 3.9 respectively as well as focal depth of 10 km. The 1984 event was recorded by five stations (one in Nigeria and four in Cote d'Ivoire) and the epicentre was located somewhere near Ijebu-Ode [4] whereas the 1990 event which was recorded by only one station in Nigeria had its epicentre assumed to be near Ijebu-Ode based on previous occurrences and the areas within which the vibrations were felt [1] [2].

The most recent event occurred on 11th September, 2009 and the vibrations were felt in the south western Nigeria towns of Abeokuta, Ago-Iwoye, Ajambata, Ajegunle, Imeko, Ijebu-Ode, Ilaro and Ibadan. At the time of occurrence of this event, three seismographic stations of the Centre for Geodesy and Geodynamics (CGG), Toro, Nigeria were operational and recorded this event. Since the stations became operational in 2008, this has been the first major local event recorded. This paper therefore discusses: a review of past earthquakes in the study area, brief geology of the study area, data acquisition, analysis of data for epicentral location, determination of local and moment magnitude, determination of focal mechanism and establishing a spatial link between the earthquake and the fracture zones of the Atlantic Ocean to give a better understanding of the seismotectonics pattern of the region.

2. Geology of the Study Area

The study area lies within the Dahomey Basin which is Cretaceous to Recent in age [7] [8] (**Figure 1**). The Dahomey Basin is a combination of inland, coastal and offshore basins that stretches from south eastern Ghana to southern Togo, southern Benin Republic and south western Nigeria [8]. The basin forms the onshore part of the West African Miogeocline in eastern Ghana, Togo, Benin and western Nigeria [7]. The origin of the Dahomey Basin is related to the Mesozoic break-up and dispersal of Gondwana and the subsequent opening of the Atlantic Ocean [9].

Sedimentation in this basin started in the Late Cretaceous [10]. This was initiated in fault-controlled depressions on the crystalline basement complex. The depressions were formed as a result of rift-generated basement subsidence during the Early Cretaceous (Neocomian). The subsidence gave rise to the deposition of a very thick sequence of continental grits and pebbly sands over the entire basin. Over 1400 metres of these sediments is preserved in coastal areas in Nigeria and offshore Benin Republic [11]. During the Late Cretaceous (Santonian), there was another major tectonic activity, probably associated with the closure and folding of the Benue Basin in eastern Nigeria. The basement rocks as well as the sediments in the basin were tilted and block-faulted, forming a series of horsts and grabens [11]. The basin is bounded by faults, and other tectonic horsts and grabens structures like the Benin Hinge Line, Okitipupa Ridge, Romanche Fracture Zone and Chain Fracture Zone [12].

The following stratigraphic units was proposed for the Dahomey Basin of south western Nigeria: the Abeokuta, Araromi, Ewekoro, Oshosun, Ilaro and Benin Formations [10] [13] [14]. The stratigraphy of the Nigerian

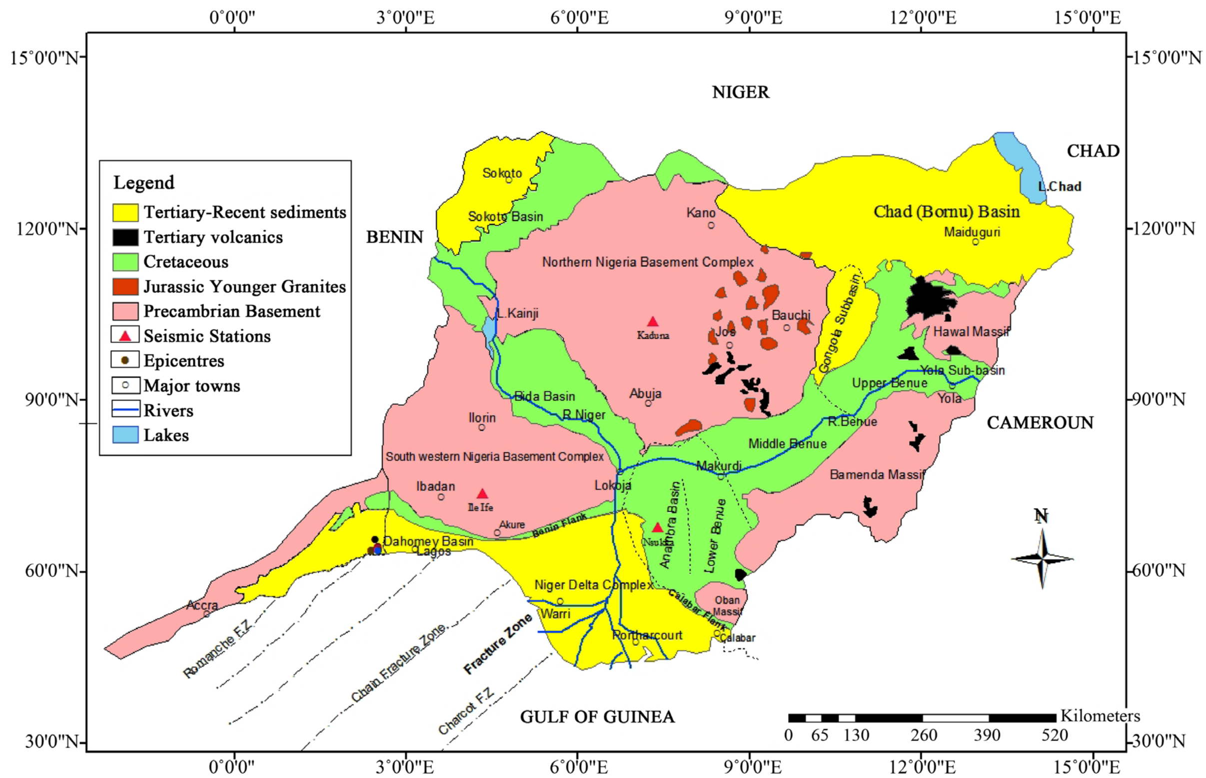

Figure 1. Geological map of Nigeria and coastal parts of the area showing the location of epicentre (west of Lagos) determined for the 11th September, 2009 earthquake (this study-brown circle, IDC-Black circle, USGS-Red circle and NAO-blue circle) (Whiteman, 1982 [7], Obaje, 2009 [8]).

sector of the Dahomey Basin is similar to that of the Republic of Benin [14]. The Abeokuta Formation which conformably overlies the basement complex and is late Albian to Late Senonian in age comprises predominantly of unconsolidated sands with intercalations of grey shale, mudstone, silt and clay [14]. The Araromi Formation which unconformably overlies the Abeokuta Formation is Campanian to Paleocene in age and consists of dark grey and black shales with interbeds of sandstones, limestone, marl, and silty and glauconitic shale [14]. The Ewekoro Formation which conformably overlies the Araromi Formation is dated Paleocene to Early Eocene and comprises of massive fossiliferous limestone, nodular limestone, glauconitic shale bed, grey laminated shale and black shale [10]. The Oshosun Formation comprises of green, greenish-grey or beige clay and laminated, calcerous and glauconitic shale with interbeds of sand, and phosphorites with thin limestone or marl beds. The Oshosun Formation is Early to Middle Eocene. The Ilaro Formation comprising of massive fine to medium grained sandstones with intercalations of clay and phosphate beds is Middle to late Eocene age [10]. The Benin Formation which is Miocene to Recent age uncomformably overlies the Ilaro formation. It consist of continental sands with intercalations of shale [13].

3. Methodology

3.1. Data Acquisition

The three seismological stations operated by the Centre for Geodesy and Geodynamics, Toro, Nigeria that recorded the 11th September, 2009 event are located in Ile-Ife (IFE), Kaduna (KAD) and Nsukka (NSU) (**Figure 1**). These stations are each equipped with Eentec DR 4000 24 bit three-channel data acquisition system (digitizer and data logger), 30 seconds period broadband seismometer (EP-105) and Global Positioning System (GPS) receivers. Each station is powered by 12 V battery which is charged by solar panels to ensure that they operate continuously. The data used for this analysis were recorded in the MiniSEED format at a sampling rate of 40 samples per second (sps).

3.2. Data Analysis

3.2.1. Location of Earthquake Epicentre

The seismic database has been managed using SEISAN earthquake analysis software, version 9.1 [15]. Data from the 3 stations were used for the location of the earthquake. The first arrivals of the P- and the S-waves were picked on each of the vertical components of the 3 stations (**Figure 2**). Although the velocity structure under the crust of Nigeria is not known, for the location of the epicentre of this earthquake, a flat six-layered earth model was adopted (**Table 1**). The thickness of the crust was assumed to be 40 km which is the average value for Proterozoic crust [16]. The upper and lower crust were 23 km and 17 km thick respectively. The program HYPOCENTER 3.2 [17] was used to locate the epicentre of the event.

3.2.2. Determination of Magnitude

Two magnitude scales were computed in this study, the local magnitude scale and the moment magnitude. The

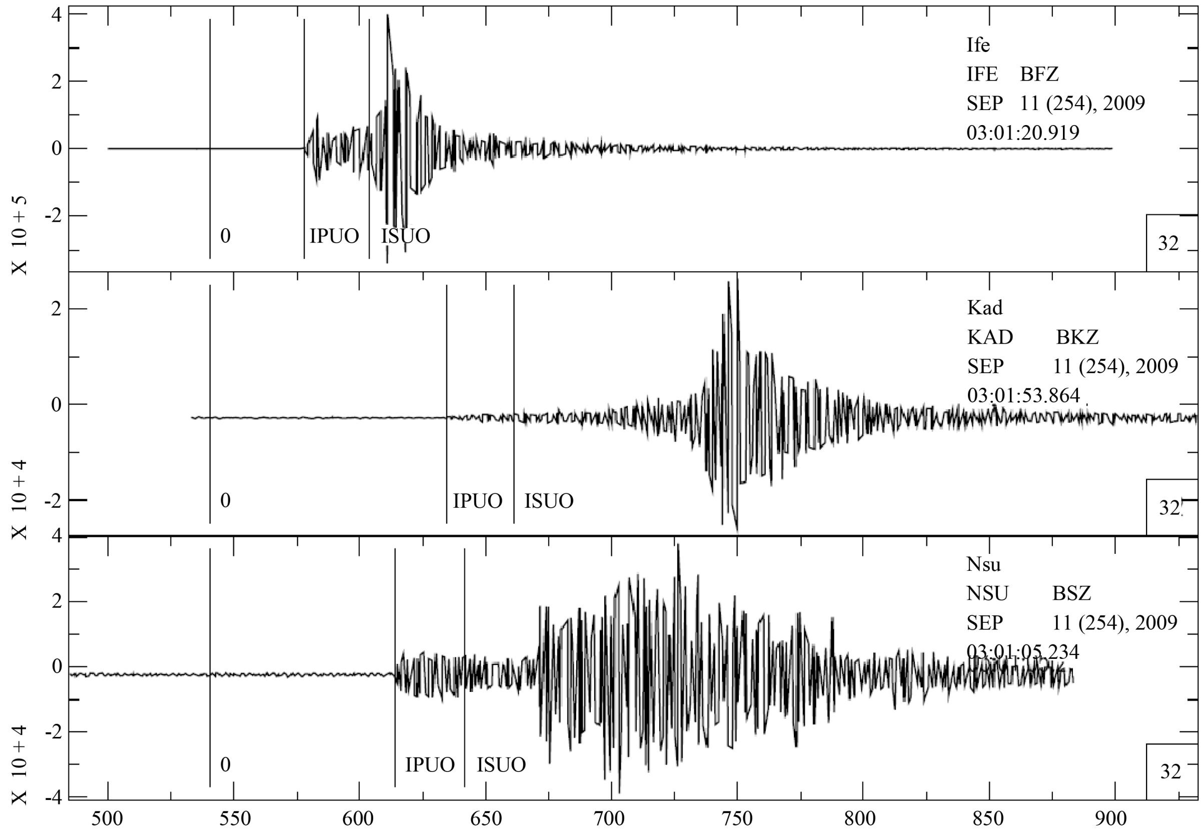

Figure 2. Vertical component of the seismogram of the 3 stations that recorded the event. O represents the origin time, IPUO is the time of arrival of the first P-wave and ISUO is the time of arrival of first S-wave.

Table 1. Earth model used for the location of the epicentre of the earthquake.

Earth layer	P-wave velocity (km/s)	Layer thickness (km)
Upper crust	6.2	12
	6.6	11
Lower crust	7.0	17
Upper mantle	8.0	10
	8.15	30
	8.5	

local magnitude scale (M_l) is an important parameter in earthquake hazard assessments both in terms of quantifying the rate and amount of seismicity and in understanding the attenuation of ground motion with distance. M_L scales are typically based on amplitude measurements of high-frequency S waves [18]. Lg is commonly the largest amplitude S phase seen in high-frequency local and regional seismograms, and it can travel great distances in the crustal waveguide. Due to the absence of a local magnitude scale for Nigeria, the scale obtained by [19] for Tanzania region was used for this study. The expression is given as:

$$M_l = \log A + a\log(r) + br + c \tag{1}$$

where M_l is the local magnitude, A the maximum ground displacement (nm) measured in the frequency band 1.25 - 20 Hz, a the geometric spreading (0.776), r the hypocentral distance, b the attenuation (0.000902), and c the base level (−1.66).

The moment magnitude, M_w, of the earthquake was computed using the expression of [20] given as follows:

$$M_w = \frac{2}{3}\log M_0 - 10.73 \tag{2}$$

where M_w is the Moment magnitude, and M_0 the seismic moment measured in dynes-cm.

Equation (2) is equivalent to:

$$M_w = \frac{2}{3}\log M_0 - 6.06 \tag{3}$$

where M_0 is measured in Nm.

The seismic moment was calculated from the spectral analysis of the 3 seismograms using the model proposed by [21]. For the spectral analysis, the following parameters were used: P-wave velocity = 6.2 km/s, bulk density = 3.0 g/cm^3, Q_0 = 440, Qalpa = 0.7 and kappa = 0.

3.2.3. Determination of Focal Mechanism

The orientation of a fault is an important information for understanding the nature of the earthquake rupture [22]. The fault plane solution or focal mechanism is defined by 3 parameters: strike, slip and dip of the fault. The first two parameters are related to the physical orientation of the fault in space while the last parameter, slip, is the direction of movement in the fault plane. P-wave polarities were used to determine the focal mechanism of the earthquake using FOCMEC routine [23]. The FOCMEC routine computes all possible double-couple solutions given the sense of the polarities.

4. Results and Discussion

The result of the location program gave an epicentral latitude of 6.611˚ and longitude 2.433˚, focal depth was 10.0 km and origin time was 3:10:21.60 GMT with a rms error of 0.4 (**Table 2**). The errors in origin time, latitude and longitude were given as 0.8 s, 8.4 km and 7.8 km respectively. The Vp/Vs ratio computed from the Wadati diagram was 1.72 (**Figure 3**). The local magnitude (M_L) was 4.5 while the moment magnitude (M_w) was 4.1. Summarised in **Table 2** are results of epicentral parameters from the analysis of the earthquake done in this work compared with published solutions from international seismological centres like the International Data Centre (IDC), Laboratoire de detection et de geophysique (LDG), NORSAR (NAO) and United States Geological Survey (USGS). The result compared favourably with those published by these agencies. For instance, the epicentral location determined in this study and those of the other seismological centres were within 100 km of each other which is acceptable for local earthquakes [22]. Arrival times of the P-wave and S-waves are given in **Table 3**. The spectral analysis of the event showed that the fault ruptured at about 10 km within the upper crust with a stress drop of about 384.8 bar, a source radius of 0.313 km, corner frequency of 4.09 Hz and seismic moment of $10^{15.3}$ Nm. The focal mechanism had a median solution of strike 325˚, dip 40˚ and rake −90˚. **Figure 4(a)** displays the first 6 solutions which are in agreement with all the polarities and the prime fault plane solution. Most of the fault plane solutions for the rupture process suggested a normal dip-slip fault mechanism (**Figure 4(b)**). The normal dip-slip fault could possibly be an after effect of the strike slip fault. This solution is similar to what was obtained for earthquakes that occurred in southern Ghana where majority of the epicentres were concentrated around the intersection of the coastal boundary faults and the Akwapim faults [24]-[26]. Considering

Table 2. Source parameters and magnitudes of the earthquake obtained from different agencies.

S/N	Date (Yr/Mo/Da)	Origin Time (Hr:Mi:Se)	RMS	Latitude (Deg.)	Longitude (Deg.)	Depth (km)	No. of Stations	Magnitude M_l	M_w	M_B	M_s	Agency
1	2009/09/11	03:10:21.60	0.40	6.611	2.433	10.0	3	4.5	4.2	-	-	This study
2	2009/09/11	03:10:17.80	0.80	6.681	2.422	-	55	4.2	-	4.3	-	IDC
3	2009/09/11	03:10:17.90	0.50	6.614	2.393	10.0	55	-	-	-	2.9	LDG
4	2009/09/11	03:10:23.40	0.10	7.086	2.443	25.0	40	-	-	-	-	NAO
5	2009/09/11	03:10:18.80	-	6.558	2.412	10.0	-	-	-	4.4	-	USGS

RMS: Root Mean Square. M_l: Local magnitude scale. M_w: Moment magnitude. M_B: Body wave magnitude scale. M_S: Surface wave magnitude scale. IDC: International Data Centre. LDG: Laboratoire de detection et de geophysique. NAO: NORSAR. USGS: United States Geological Survey.

Table 3. Earthquake parameters obtained at the different stations.

S/N	Station code	Time of arrival of P-wave (Hr:Mi:Se)	Time of arrival of S-wave (Hr:Mi:Se)	Angle of incidence (Deg.)	Azimuth (Deg.)	Back azimuth (Deg.)	Epicentral distance (km)
1	IFE	03:10:58.92	03:11:26.83	51	66.14	246.40	253.49
2	KAD	03:11:55.12	03:13:03.21	47	53.19	233.96	711.62
3	NSU	03:11:35.45	03:12:30.51	50	86.77	267.35	551.69

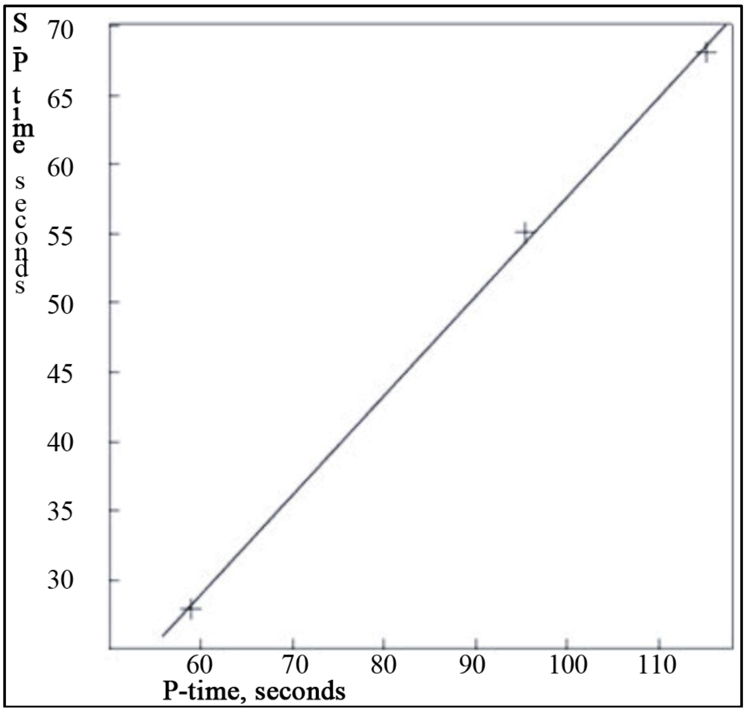

Figure 3. Wadati diagram of the three seismological stations.

the areas where the vibration of the recent earthquake was felt, the rupture process must have propagated up to north-east and down to south-west.

The epicentral location of this event lies close to Allada in southern Benin Republic and is about 108 km west of Lagos, Nigeria. The geology of the study area is made up of rocks of the Dahomey Basin [7] [8]. In **Figure 1**, it can be seen that in between the Romanche and Chain fracture zones, there are two smaller un-named fracture zones. Odeyemi (personal communication) named one of them the Olokun fracture zone. The extension of the Atlantic fracture zones into the continent and the two smaller fracture zones lying between the Romanche and Chain fracture zones has been shown [7]. Thus, it is then deduced that the epicenter of this earthquake lies along

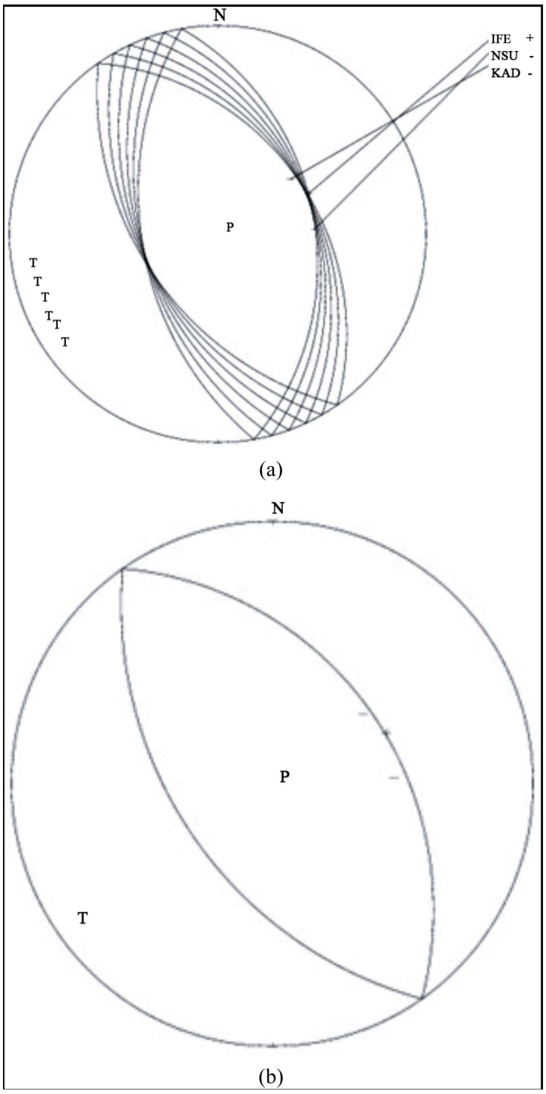

Figure 4. Lower-hemisphere projections of the focal sphere for fault planes of all the first 6 solutions with zero polarity errors. (a) The median solution fault plane superimposed on the polarity data and showing the stations and (b) The median solution fault plane (strike = 325˚, dip = 40˚ and rake = −90˚) superimposed on the polarity data (a). For polarities, + represents emergent compressions and-represents emergent dilatation.

this fault zone which is assumed to be an extension of one of the Atlantic fracture zone into the continent.

Studies have shown that in west Africa, some oceanic fracture zones have been found to extend inward into the continental landmass after offsetting the Mid-Atlantic Ridge and manifest as fault zones [7] [27] [28]. Most of the earthquakes that have occurred in this region have their epicentres near these faults and have been attributed to instability along these ancient suture zones [25]-[27] [29]-[31]. The close link between these earthquake epicentres and ancient suture zones in West Africa has also been shown [32]. There has also been suggestion of the Atlantic fracture zones projecting into the Nigerian continental landmass [4] [12] [33]. Recent research has also shown the extension of one of the Atlantic fractures into the continental landmass as zones of weaknesses within the Nigeria Precambrian basement [34] [35]. The fault was named the Ifewara-Zungeru fault and the characteristics of the southern part of the fault zone were given [35]. Therefore, the sources of the past earthquakes experienced in south western Nigeria and southern Benin Republic is related to movement along these fault zones [1] [2] [4] [6].

5. Conclusion

The results of the analysis of the September 11, 2009 earthquake that was felt in parts of south western Nigeria showed that the fault that triggered the tremor ruptured at about 10 km within the upper crust. The fault plane solutions for the rupture process suggested a normal dip-slip fault for the event. It was deduced that the epicentre of the earthquake lies very close to one of the un-named fracture zones situated between the Romanche and Chain fracture zones where studies have shown to be an extension of the Atlantic fracture zone into the continent. Furthermore, we observed that most of the historical earthquakes in this region also have their epicentres concentrated around this area. Thus, for the first time, a good understanding of the seismotectonics signature obtained from the recorded seismological in south-western Nigeria is reported.

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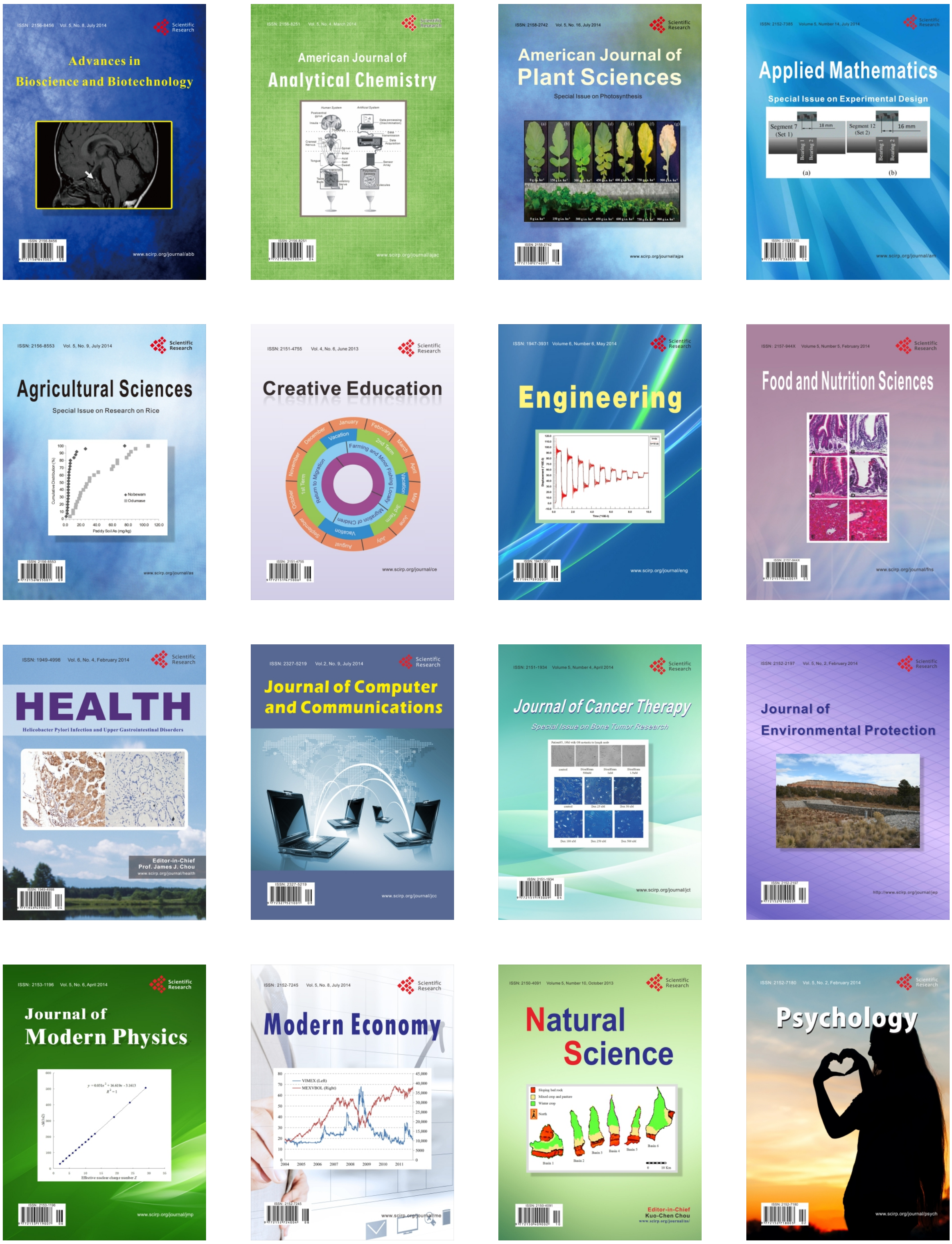
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