Geophysical Evaluation of Central Nigeria Earth Tremor Activities Using High Resolution Airborne Magnetic Data

Abstract:

Since 1933 till date (over 88 years), small to moderate magnitude earthquakes have either been observed or instrumentally recorded in Nigeria. However, the specific causes of the intra plate earthquakes in Nigeria is still not well known. In this study therefore, a high-resolution aeromagnetic data analysis was performed to evaluate the various theories proposed as the causes of tremor activity in central Nigeria with a view to ascertaining the actual causes of earthquakes in the West African country that lies on a stable crust. The total magnetic intensity data acquired from the Nigerian Geological Survey Agency (NGSA) in the Central Basement complex of Nigeria, was processed and filtered using the tilt derivative, lineament analysis, and advanced Analytic Signal- Hilbert Solution filter. To define the trends of both major and minor structure, a lineament plot was extracted and plotted. The analysis revealed a dominant NE-SW and NW-SE trending structure that is distributed throughout the study area. The regional North Atlantic Romanche fault system, which extends from the offshore (Niger Delta) into the continental crust, was mapped and is thought to extend from Gwagwalada in the study area's south, through Gwarinpa and Mpape, to Kwoi, and beyond Kafanchan.Findings from our study have indicated that, areas prone to Earth tremors are linked to the Romanche fault by numerous NE-SW and NW-SE faults that act as conduits for seismic energy that causes tremor. Using lineament density analysis, tremor active areas have been interpreted to be highly deformed; thus, seismic energy induced into the environment would result in tremors. This study demonstrates that the regional North Atlantic Romanche fault system is the primary source of seismic energy that causes the earth tremors in central Nigeria.

Keywords: Aeromagnetic, Central Nigeria, First Vertical Derivative, Lineament, Causes of Earth Tremors.

1. Introduction

Earth tremors are minor involuntary seismic movement of the earth crust. They are often described as slight earthquake with lesser magnitude measuring between 1 – 4.5 on Richer scale.An earthquake could be generally defined as a sudden vibration, sometimes violent, of the earth's surface that follows a release of elastic energy in the Earth's crust (Ben, 2012). In areas felt, it is described as a rapid rattling of the earth leading to falling of objects from shelves, breaking of glasses, vibration of the crust and uprooting of trees.

Seismic activities (tremors) have been reported in different parts of Nigeria since 1933 (Adepelumi et al, 2008). Earlier investigation include those ofAdepelumi*et al*. 2008, Olujide and Udo 1989, Afegbua *et al*., 2011, Tsalha*et al*., (2015), Osagie (2008), Ofonime and Yakubu (2010), Eze *et al* (2011), Anifowose 2006, Ajakaiye1984, Ajakaiye*et al* 1987, Odeyemi 1986, Elueze 1990, Ofonime 2010, Madrigal 2008, Onuoha, 1989., Ugodulunwa*et al* 1986., Ajakaiye*et al* 1988., Ananaba 1991., Ojo 1995, Nwankwaoala and Orji 2018andNathaniel *et al* 2020. Most of these works were based on the regional studies of seismic activities in Nigeria except for the work of Nathaniel *et al* 2020, who studied the effect of tremor event in Kwoi area in 2016. The earliest tremor in Nigeria was recorded in 1933 Warri (Delta State) and Ohafia (Abia State) while the most resent was felt within Abia State, Nigeria in 2020. Afegbua *et al* (2011) stated that Nigeria sits on a stable Precambian Basement complex rocks hence, the region is not expected to experience earth tremors;however,the country has experienced tremor with magnitudes ranging from 2.9 to 4.5. Osagie (2008); Ofonime and Yakubu (2010); Eze et al (2011) and Tsalha*et al*., (2015) reported that Nigeria has experienced about 31 earth tremors activities between 1933 and 2015. Nwankwoala and Orji., (2018) stated that ten seismic activities were experienced in 2016, in addition to the earth tremor of Abuja in 2018 and 2019; and AbiaState in 2020; making a total of about 44 notable seismic activities in Nigeria.The Centre of Geodesy and Geodynamics, reports that the average value of intensities for Nigerian Earthquakes ranges from III –VI on the Modified Mercalli Scale, with therecorded Mpape earth tremor a magnitude of 3.1 . The impacts of the earth tremors of 2018 at Mpape, Federal Capital Territory and those of 2016 whose epicenters were located at Kwoi in Kaduna State are shown in figures 1a and 1b respectively.

Figure 1: (a) Field photograph of cracked wall observed at Mpape area **(b)** Field photograph of cracked wall observed at Kwoi area

There are numerous schools of thought on the likely causes of the seismic activities in Nigeria. Ajakaiye et al., (1986), Ajakaiye et al., (1987), Elueze 2003; Anifowose 2006; Ajakaiye1984 accredited the causes of earth tremors in the country to earth movement associated with NE-SW trending fractures and zone of weakness extending from Atlantic Ocean into Nigeria. This Atlantic transform fractures include the St Paul, Romanche, Charcot and Chain fractures zones (figure 2). The presence of these fractures zones which prominently traverse the Western half of Nigeria has been proposed by Ajakaiye*etal.*, (1987); Odeyemi (1989) and Ofonimeand Yakubu (2010) as the source of seismic activities experienced in the western half of Nigeria. The findings of Nathaniel et al., (2020) study on earth tremors that occurred at Kwoi are consistent with the theory of tectonic origin. This is because all of the epicenters plotted along an extrapolated trend coincided with the North Atlantic regional fracture zone.

Another school of thought by Onuoha (1988), attributed the earth tremors to partial reactivation of fossil plate boundaries.Nwankwoala and Orji., (2018) also talked about the theory of stress transfer from plate boundaries. Tsalha (2015) and Eze *et al*., (2011) correspondingly, argued that stresses that build up around plate boundaries could travel towards the center of the plates triggering intraplate tremors especially in pre-existing faults.

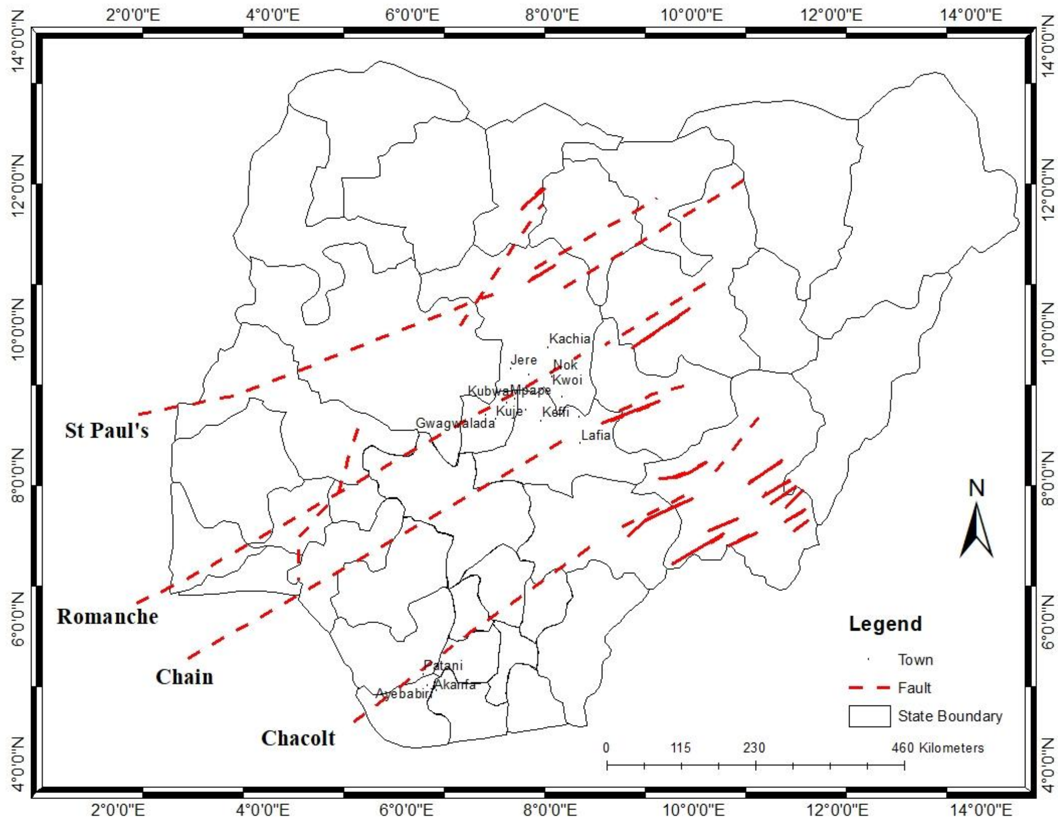

Figure 2: North Atlantic Fault Systems and their Extensions into Nigeria's Landmass

Nwankwoala and Orji., (2018), Adepelumi*et al*., (2008); Eze *et al.,* (2011); Tsalha (2015) and Yusuf, (2016) agreed that tremors activities resulted from regional stresses in the crust since Nigerian Basement Complex rocks occur between the West African Craton and Congo Craton. Murat (1988) inferred a principal stress acting WNW-ESE in the basement rocks and they accredited this stress as the major cause of the tremor. Their thought is in agreement with the regional stress models of Sykes, (1978); Iio and Kobayashi., (2002); Johnston and Kanter, (1990) and Zoback, (1992).Nwankwoala and Orji., (2018), Adepelumi*et al*., (2008). Eze *et al.,* (2011) also proposed the theory of zone of weakness stating that when a magmatic intrusion is present in stable rock, the difference in geophysical properties can cause localized stress concentrations particularly when the intrusion is weaker than the surrounding rock. They stated that Initially, the mafic intrusion is more rigid than the surrounding rock but over time, the intrusion can become much weaker than the surrounding rock, hence leading to breaking that resulting is the release to seismic waves.

Madrigal, (2008) stated that evidence has shown that anthropogenic activities such as oil and gas exploration, could trigger earthquake and Nigeria is among the top oil producing countries. More localized study of the tremor affected areas by Nigerian Geological Survey Agency and Centre of Geodesy and Geodynamics, Nigeria stated that the Mpape and Kwoi tremor activities could have resulted from human activities such as mining (blasting processes) and borehole (water withdrawal) and resettling of geologic formations.

As there is no confirmatory existing study with definite results about the causes of the intraplate earth tremors in the Central part of Nigeria, this study therefore assesses three major schools of thought: the theory that attributes tremor activity to a NE-SW trending fracture extending from the North Atlantic Ocean into Nigeria, the theory of zone of weakness, and the theory of human activities.

2. The Study Area

The study area is located in the North Central part of Nigeria. It is bounded by Latitudes 7.00 °N and 8.30 °N and Longitudes 8.30 °E and 10.00 °E. it covers a total surface area of about 27,225 km^2. Fourmajor states, including Federal Capital Territory, Nassarawa, Kaduna and Niger State (Figure 3) is covered in this study. The two major communities of interest are Mpape (Federal Capital Territory) and Kwoi (Kaduna State).

The study area falls within the Basement complex of Nigeria, it is part of an upper proterozoic to lower phanerozoic mobile belt situated between West African and congo crayon. The belt is believed to have evolved by plate tectonic process resulted from continental collision between the passive continental margin of the Tuaraep Shield (Burke and Deway 1972; Black, 1980; Ajibade et al; 1987). The rocks of the basement complex have been subdivided by Oyawoye (1972), McCurry (1976); Woakes et al; (1987), Rehaman (1981:1988));Geologically, the study area is underlain by metasedimentary rocks (migmatite, gneiss, schist and quartzites) and these metasedimentary rocks have been intruded by granitic rocks (Older and Younger Granite Suite). The rock types constitute the major Basement Complex rocks as defined by Oyawoye (1972), McCurry (1976); Woakes et al; (1987), Rehaman (1976:1988). The granite rocks are well exposed in outcrop, while the metasedimentary rocks are majorly exposed at road cuts and quarries.

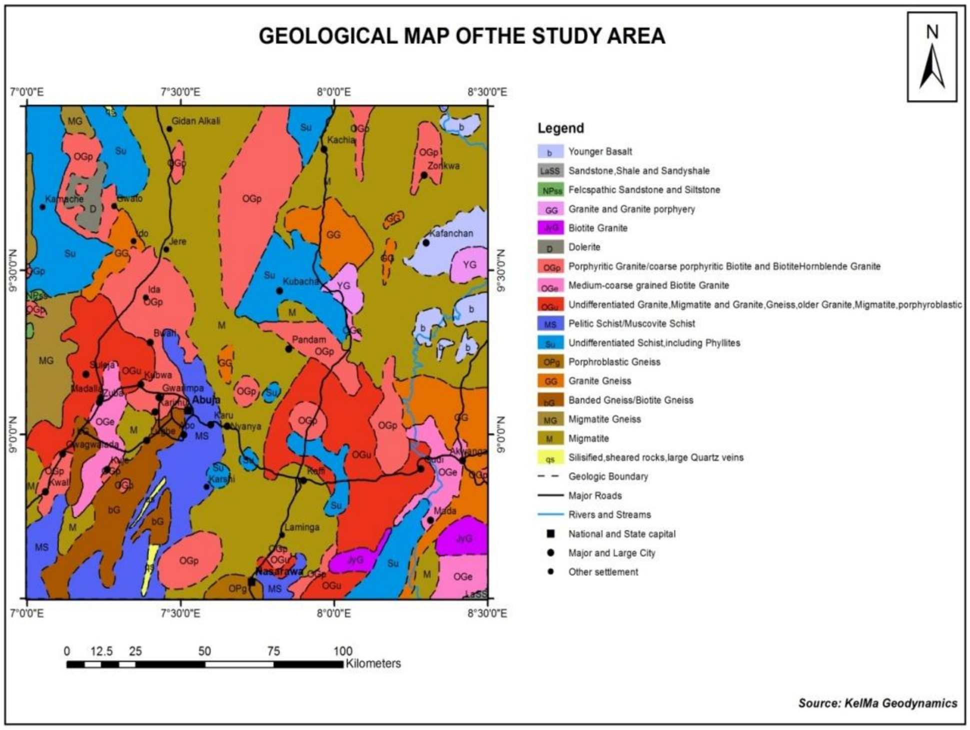

Fig 3: Geology Map of the Study Area

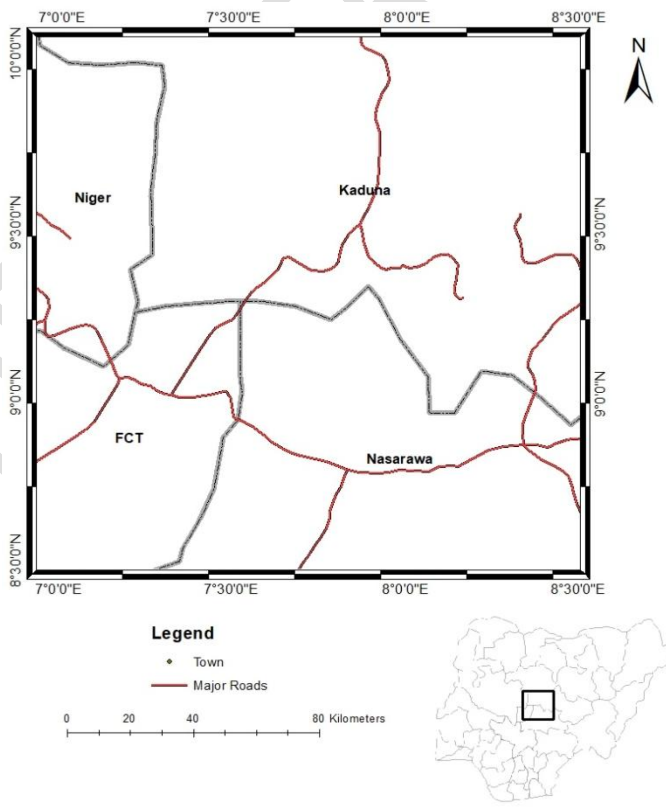

Figure 4: Accessibility map of the Study Area

3. Materials, Method and Data Processing

The airborne magnetic dataset used for this study was acquired by Fugro Airborne Survey and Nigerian Geological Survey Agency. The data was acquired along a NW – SE flight lines at 500 m line spacing and 80 m terrain clearance. The airborne magnetic dataset consists of nine (9) index sheets including Bisnini-165, Kachia-166, Kafanchan-167, Abuja-186, Gitata-187, Jemaa-188, Kuje-207, Keffi-208 and Akwanga-209. Each data sheet covers an estimated 3,025-kilometer square. The total magnetic intensity grid was developed by employing a minimum curvature algorithm at 100 m grid cell size. The digitized data were filtered by utilising a low pass Fourier domain sub-routine filter to exterminate undesired wavelengths and to pass longer wavelengths. The aeromagnetic dataset was subjected to Reduction-To-Pole (RTP) transformation to reduce appreciably the polarity effects. A computer program, Geosoft (Oasis Montaj, version 8.4), was utilised to generate the residual magnetic anomaly values.This was achieved by subtracting regional fields values, from the measured intensity of the total field, at the grid cross point.

`Tilt derivatives was applied to enhance structural interpretation. Itis extremely useful in mapping out shallow basement structures. Tilt derivative was introduced by Miller and Singh (1994) and later modified by Verduzco et al., (2004), its defined as:

$$TDR = \tan^{-1} \frac{\frac{\partial T}{\partial z}}{\sqrt{\left[\frac{\partial T}{\partial x}\right]^2 + \left[\frac{\partial T}{\partial y}\right]^2}} \qquad (1)$$

Where;T is the observed magnetic anomaly at (x, y).

Qualitative interpretation of magnetic anomaly attempts to give a reliable estimate of the direction, size, shape and depth of magnetic sources. It is a complementary to qualitative interpretation. This technique is broadly characterized as curve matching, forward or inverse modeling (Telford et al., 1990). In 1982, Thompson developed a technique known as Euler deconvolution method, to process magnetic data and to convolve them to a point source at depth. Equation 2 is known as Euler deconvolution equation. For an arbitrary specific structural index the depth and location for various targets can be resolved from these first order derivatives (x,y and z).

$$(x - x_0)\frac{dT}{dx} + (y - y_0)\frac{dT}{dy} + (z - z_0)\frac{dT}{dz} = N(B - T) \qquad (2)$$

Where;(x_0, y_0, z_0) is the source of magnetic anomaly (x,y,z) is the total magnetic field detection points,**B** is the regional magnetic field. **N** is the fall-off rate magnetic field measurement else known as the structural index (**SI**).

4. Results and Discussion

Theories related to NE-SW Atlantic faults and Human Activities

The residual magnetic intensity map (figure 5) reflects the local magnetic anomaly within the study area. The residual magnetic anomaly map was computed by applyingIGRFto the acquired total magnetic intensity dataset and polynomial fitting applied to the IGRF result. The residual magnetic intensity has a range of -54.7 nT to >104.9 nT,, the high magnetic intensity is observed at the southeastern part of the study area (Akwanga, Kwakwasa, Masaka and Keffi). The northern and central part of the study area is characterized by intermediate to low magnetic intensity (around Kwoi, Nok, Kafanchan, Kachia, Jere, Bwari, Mpape, Gwarinpa). The northwestern part of the study area (around Jere, Bwari, Kubwa area) is characterized by bipolar magnetic bodies, indicative of intrusive rocks (granites).

Numerous extensive faults are observed within the study area. The regional Romanche fault is interpreted within the study area; it cuts into the study area at Gwagwalada, passing through Gwarinpa, Mpape, Kwoi, Nok and exist the study area through Kafanchan. The Romanche fault has a NE-SW trend and extends from the North Atlantic Ocean.Minor faults are also observed at the southeastern part of the study area (Akwanga, Kwakwasa, Masaka and Keffi), with a dominant NE-SW trendand minor NW-SE trends. Numerous low magnitude faults are also observed around Kachia. The intensity of the bipolar structures within Jere, Bwari, Mpape, Kubwa and Kagarko is indicative of intense deformation and probable weakness of subsurface geology.

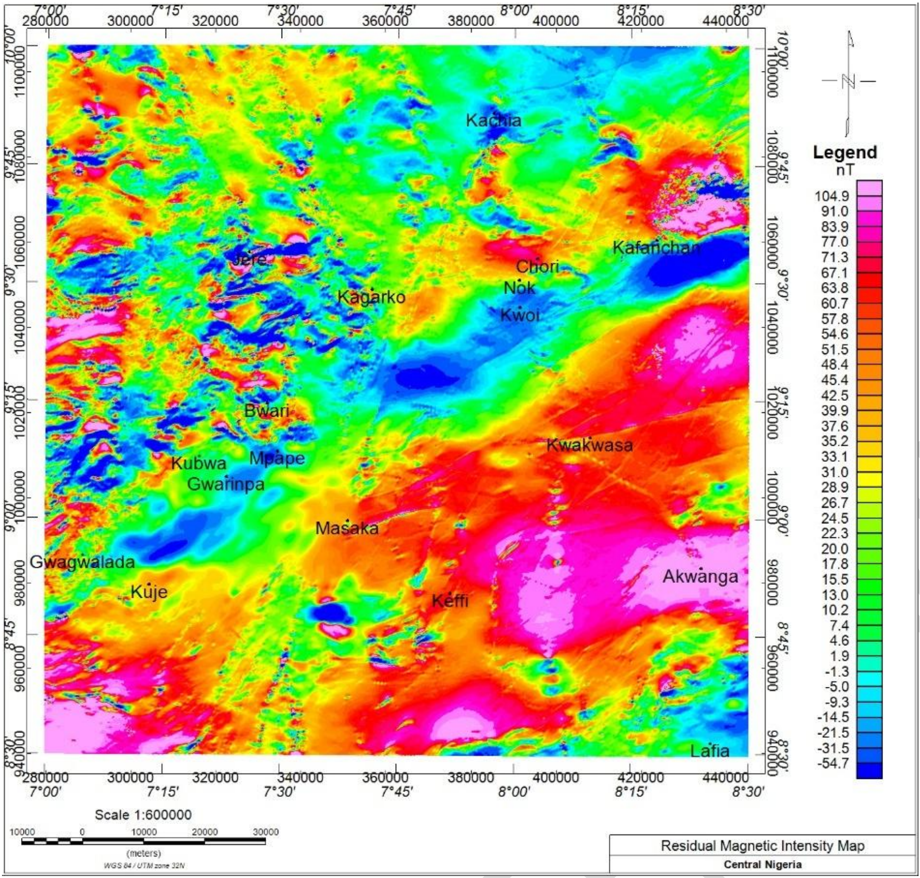

Figure 5: Residual Magnetic Map of the Study Area Showing Interpreted Fault

Tilt derivative (TDR)enhance and sharpen up anomalies over causative bodies and tend to reduce complexity, allowing a clearer imaging of the causative structures. The TDR map (Figure 6) shows inferred faults, fractures, folds, contacts and to some extent the shape of some lithologic contacts which indicate structural features. The tilt derivative map better enhances the faults within the study area, the fault has a regional dominant NE-SW, with minor NW-SE trend. The NE-SW trending structures is interpreted as the older structural trends while the NW-SE is the younger; this is based on theircross-cutting relationship as observed around Kwoi, Nok, Chori, Kafanchan, Kwakwasa, Keffi, Masaka and Akwanga.

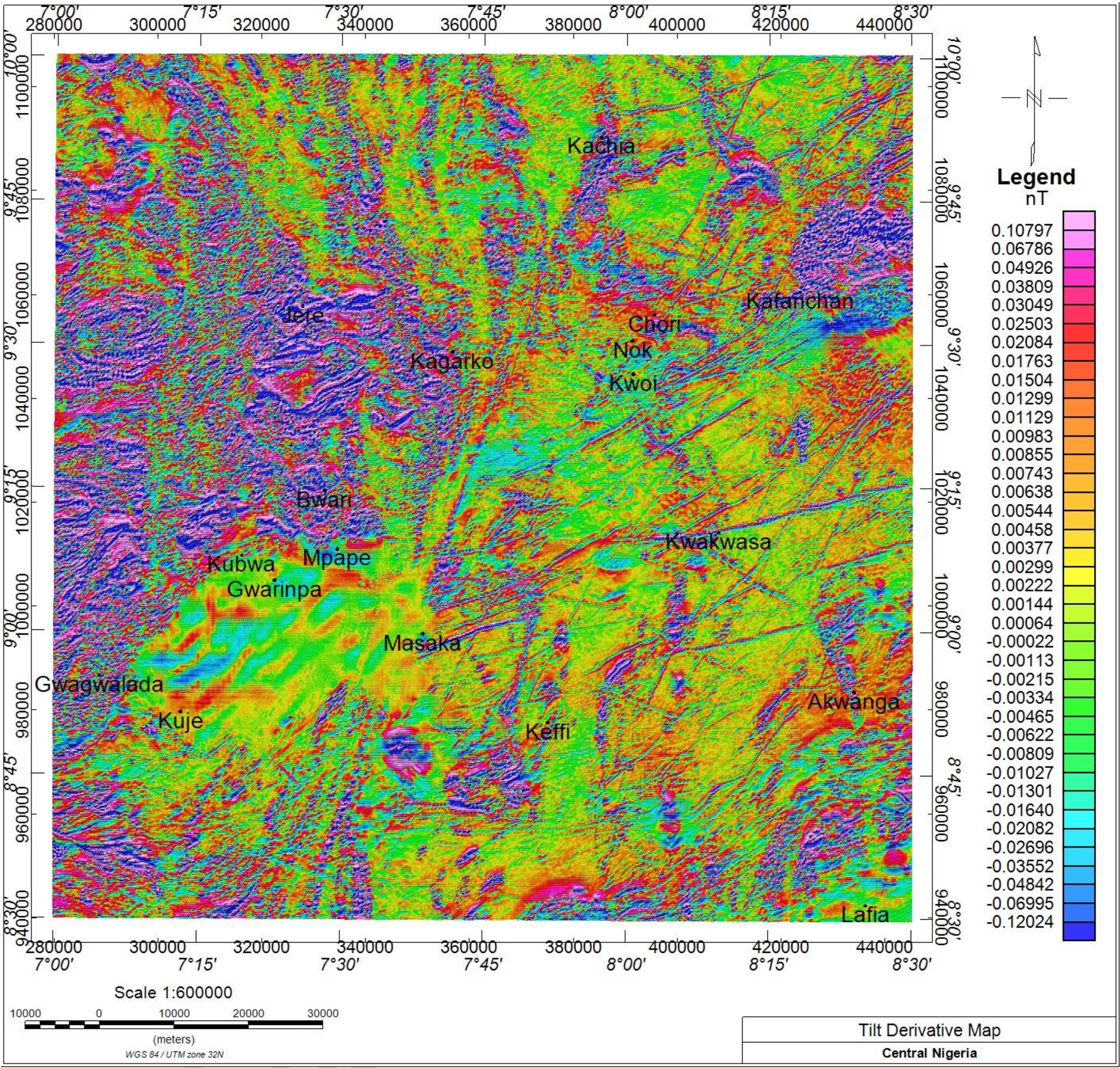

Figure 6: Tilt derivative (TDR)Map of the Study Area Showing Interpreted Fault

Qualitative interpretation of both the residual and tilt derivative map defied numerous major faults within the study area, although the tilt derivative map better enhanced the structures. The regional *F1* fault is interpreted to have demarcated the study area into two different structural complexes with the eastern structural complex is characterized by extensive faults lines, while the western portion is characterized by bipolar structures separated by NNW-SSE faults. The regional fault *F1* is interpreted is better visualized in the tilt derivative map than the residual magnetic map, the fault extends from the south of Masaka, through Kagarko to Kachia. Parallel faults trending NE-SW is observed at the eastern part of the study area, extending from Kwoi, Nok, Chori to Kafanchan, these faults looks to be terminated by the regional *F1* at the central part of the study area. The study area is also divided into the northern structural complex and the southern structural complex by the Romanche Fault system. The northern structural complex is characterized by high occurrence of bipolar structures while the southern part is characterized by low occurrence of bipolar structures, this is indicative of different tectonic regimes and high intensity of tectonic activities in the past.

The qualitative interpreted structures where used to produce a structural map of the study area (Figure 7). From the interpreted structural map, the oldest structure Romanche Fault, and thethree deformation events were identified based on their structural relationship. The early deformation event (D1) is defined to be a ductile deformation producing folds whose axial planes trends NNE-SSW, the second deformation event resulted in the reactivation of the D2 structures particularly the folds in the NE-SW direction. The third deformation event produced a transgressive deformation starting with ductile deformation resulting in the development of NE-SW to EW oriented structures, brittle deformation occurring at later stages of the D3 event producing fractures oriented in the NW-SE and EW direction which are more associated with the reactivation of D1 and D2 faults and fractures.

The epicenters of the earth tremors as located bythe local seismic stationsoperated by the Centre for Geodesy and Geodynamics, Toro, Bauchi State, Nigeria, where plotted on the interpreted structural map so as to understand the structural relationship to the seismic activities. It was observed that all the earth tremor epicenters are located around the regional NW-SW structural joints which in turn are all connected to the continental Romanche Fault line. These therefore, indicate that, the transfer of energy from the continental Romanche Fault line into localized regional fault lines could be a major cause of the tremor activities. This is evident around Mpape, Kwoi and Kachia areas, where the epicenters sit close to structural joints of faults which are all connected to the continental Romanche Fault line (Figure 7). Gwagwalada and Jere areas were earth tremors have also been felt, are seen to be located around a regional fault joint that is also connected to the continental Romanche Fault line. It was also observed that seismic activities are concentrated at the northern part of the Romanche fault line, with no record of these activities in the south. This can simply be explained by employing the angular relationships between the continental Romanche Fault line, the localized regional faults and,the direction of the transferred seismic energy. When the continental Romanche Fault line comes into contact with regional low angular NE-SW trending fault lines at its structural joints, the energy is transferred to a smaller fault line in the NE direction based on the angular relationship of the faults. Also, small seismic energy transmitted through the continental Romanche Fault line would be larger when transmitted through the localized regional fault lines; hence, resulting in seismic activities when it collides with the structural joints during the transfer of seismic energy.

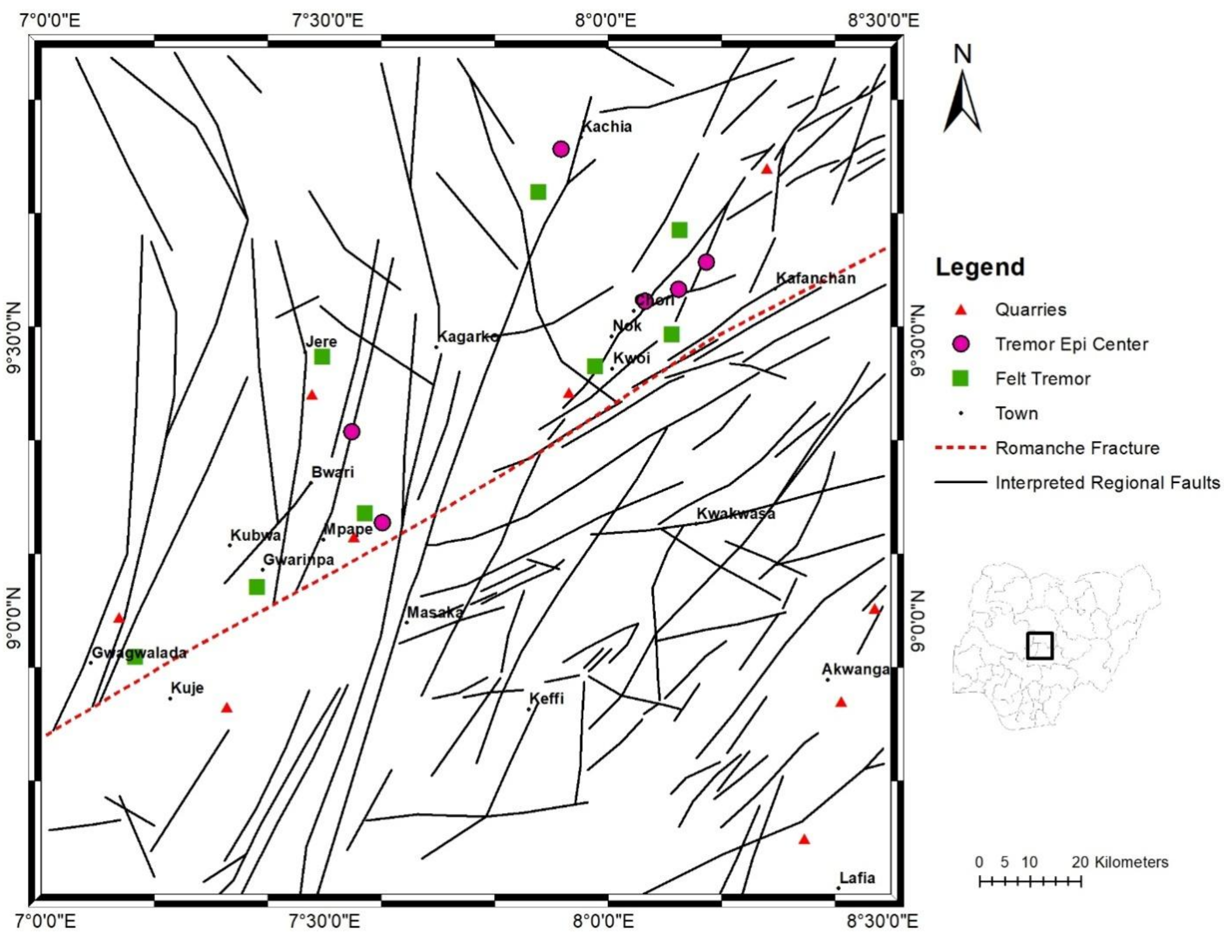

Figure 7: Interpreted Structural Map of the Study Area

Quarry locations where also plotted on the structural map, to analyze the relationship between blasting activities during mining and the tremors experienced within Central Nigeria. Numerous quarries were located around the epicenters where earth tremors were felt as well as at the southern part of Romanche fault. Some of these quarries are located close to regional fault lines, as observed around Jere, Mpape, Kwoi and Gwagwalada; therefore, blasting activities could lead to the accumulation of stress within these faults, which could eventually lead to seismic activities. This theory anyway does not explain why earth tremors are not felt in the southern part of the study area which also has numerous quarries located around regional fault lines.Therefore, the theory of mining/quarries activities as being the major cause of seismic activities in the study is unlikely.

4.1 Theories related to zone of weakness

Lineaments were extracted from the tilt derivative map to aid structural intensity to evaluate the deformation/stability of the local geology. Lineaments are linear features on a landscape which expresses the underlying geological structures such as faults, joints, and arched zones or even geological contacts and could be of regional extent, usually in linear or curvilinear continuous or discontinuous over an entire length (Megwara and Udensi 2014). The lineament map shows a dominate NE-SW and NW-SE structural trend, with minor E-W trends. The extracted lineaments (figure 8) was used to compute the lineament density map (figure 9) of the study area, which generally indicates the density of lineaments/structure at a particular location. The lineament density is directly related to the structural complexity of an area, which is also directly proportional to the stability of geologic structures.Areaswith high lineament density indicate high deformation and low structural stability, while in areas with less lineament density indicate low deformation and high structural stability (Chukwu *et al*., 2013).

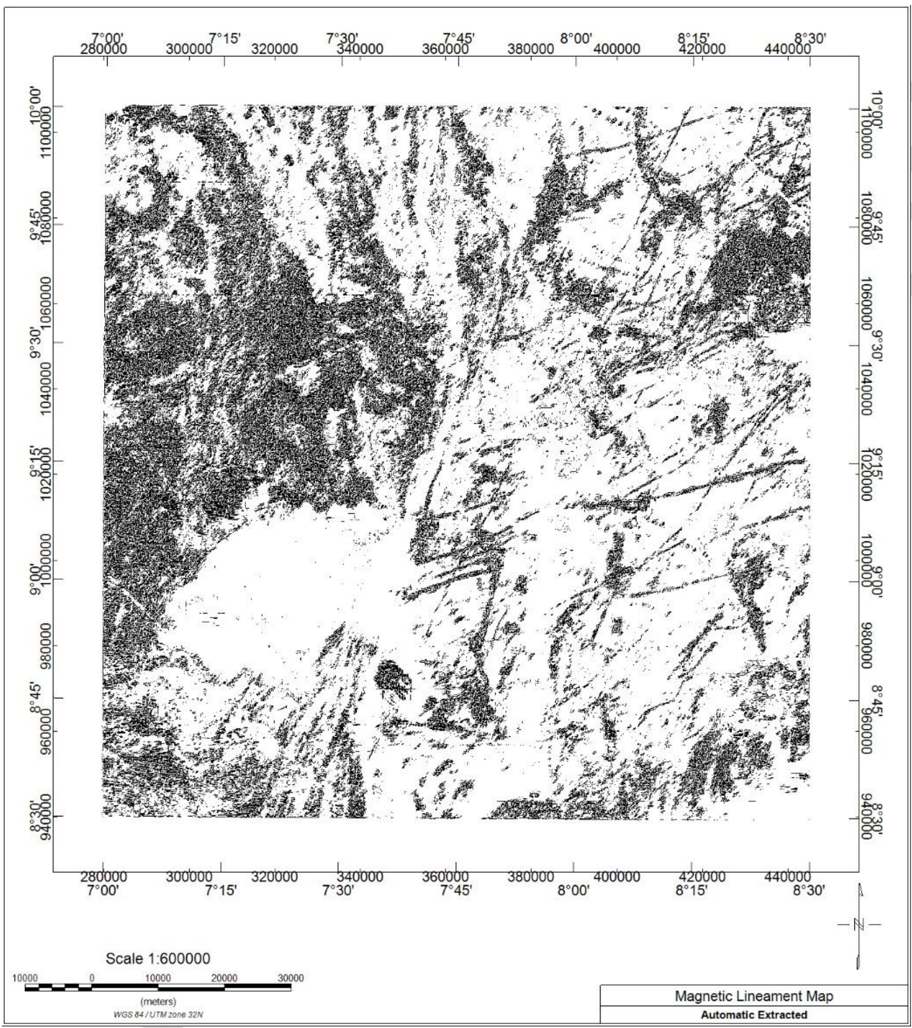

Figure 8: Lineament Map of the Study Area

Using figures 8 and 9, Jere, Bwari, Kubwa, Gwarinpa, Kagarko, Kwoi, Chori, Kafanchan, Gwagwalada and Kachiaareasshow high lineament density. Therefore, these areas are defined as low structural stability/ high zone of weakness regions. This is important because, based on their intense deformation, any seismic stress induced into the environment could result into earth tremors. Source of this seismic stress could be the continental Romanche Fault line or cumulative effect of blasting within the weakness zones.

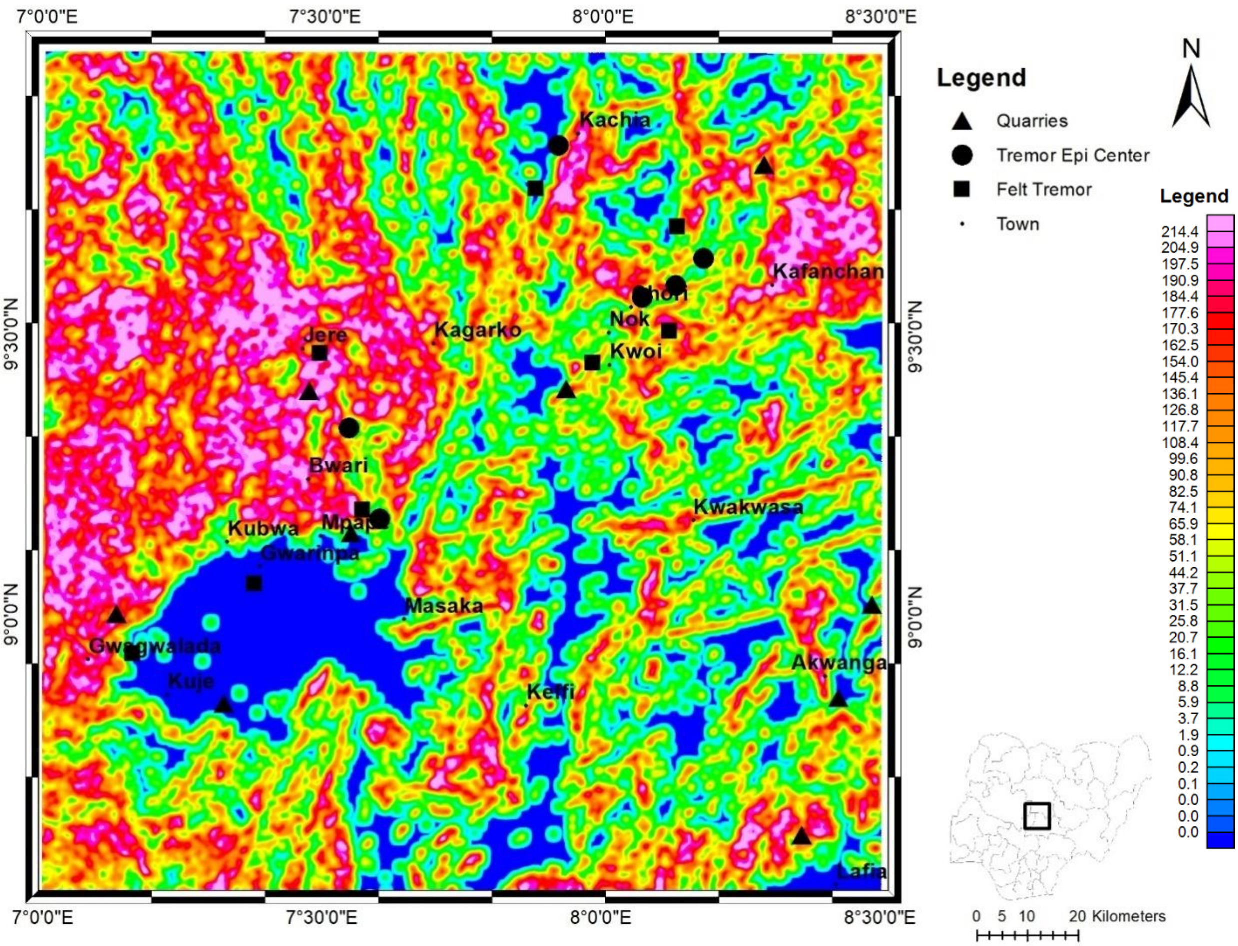

Figure 9: Lineament Density Map of the Study Area

Areas around Akwanga, Masaka, Kwakwasa, Kuje, and Keffi also have notable zones of weakness (high lineament density regions), but not as much as the northern part of the study area; however, numerous blasting activities dating back to the mid-1990s have still not resulted in any tremor activities within these areas; thus, it is safe to conclude that blasting activities during the mining process is an unlikely source of seismic stress that lead to the earth tremors in Central Nigeria. These findings also suggest that the zone of weakness within the local geology of the tremor active areas plays an important role in the earth tremor activities, and that the continental Romanche Fault line could be a major source of seismic energy, with localized regional fault lines serving as the primary conduit for this energy.

4.2 Depth to Epicenter of the tremors

The focal depths of the 2016 Kwoi and 2018 Mpapeearth tremorthat were recorded by five seismic stations operated by the Centre for Geodesy and Geodynamics (CGG), Nigeria, range from 10-15km.The average macroseismic intensity value of III on the Modified Mercalli Scale was estimated from field work. The processed seismograms of the events by the staff of CGG, Toro, are shown in figures 9 and 10. The 2018 Mpape events' parameters are presented in table 1.

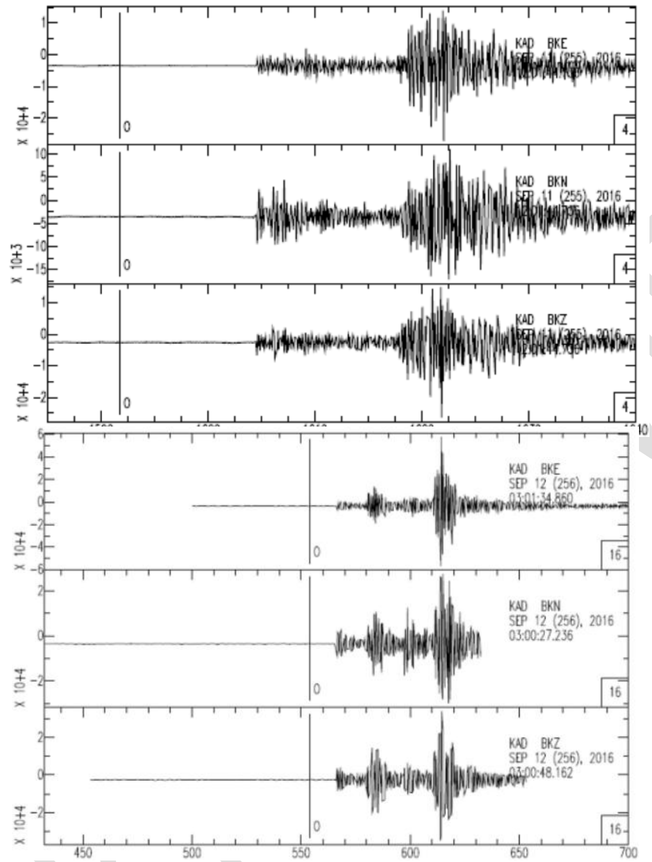

Figure 10:September 11 and 12, 2016 Kwoi tremor recorded in Nigeria (Source: Centre for Geodesy and Geodynamics, Toro)

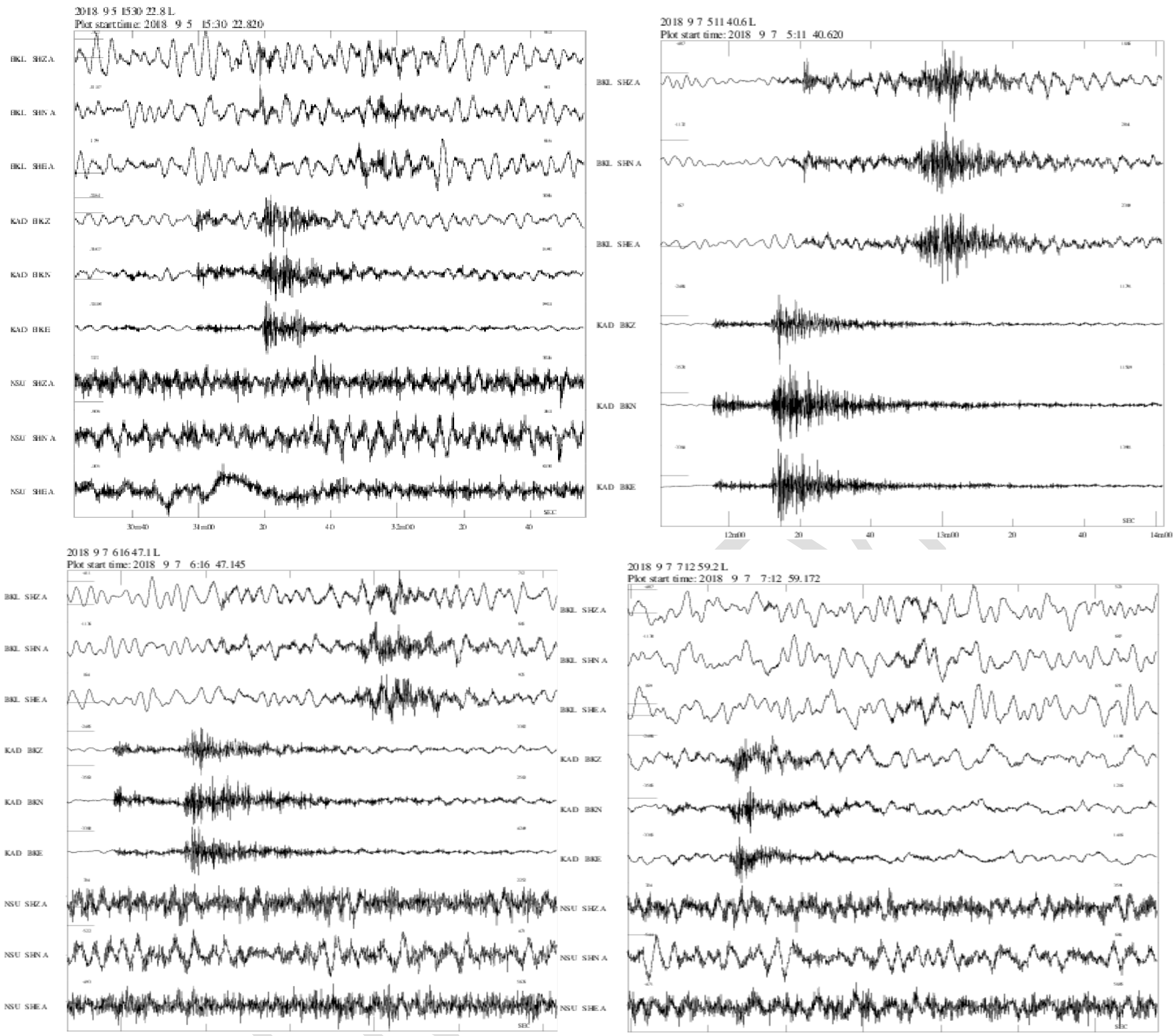

Figure 11:(a) Seismogram of recorded foreshocks in Abuja on the 5th September, 2018**(b)** Seismogram of Abuja Earthquake (main shock) on the 7th September, 2018 **(c)** Seismogram of Abuja Earthquake (first aftershock) on the7th September, 2018 **(d)** Seismogram of Abuja Earthquake (second aftershock) on the7th September, 2018(Source: Centre for Geodesy and Geodynamics, Toro)

Table 1: Parameters for locating the 2018 Mpape tremor events (Source: Centre for Geodesy and Geodynamics, Toro)

Event	**Date**	**Time**	**Magnitude**	**Focal Depth (km)**	**Epicenter**	
					Latitude (◦N)	**Longitude (◦N)**
Foreshock	05-09-2018	3:30	<2.5	-	-	-
Foreshock	05-09-2018	3:34	<2.5	-	-	-
Foreshock	05-09-2018	3:39	<2.5	-	-	-
Foreshock	05-09-2018	3:42	<2.5	-	-	-
Foreshock	05-09-2018	7:47	<2.5	-	-	-

Foreshock	05-09-2018	8:57	<2.5	-	-	-
Main Shock	07-09-2018	5:11	3.0	15	9.14	7.59
Aftershock	07-09-2018	6:16	2.6	12	9.03	7.50
Aftershock	07-09-2018	7:12	2.5	10	9.16	7.40
Main Shock	11-09-2016	2:28	2.8	10	9.57	9.64
Aftershock	12-09-2016	3:10	2.7	10	9.64	8.18
Aftershock	12-09-2016	3:11	2.9	10	9.59	8.13

The focal depths of the epicenters of the 2018 Mpape earth tremors range from 10 km to 15km. Depth analysis was carried out using the magnetic dataset, by implementingthe advanced Analytic Signal- Hilbert Solution depth analysis to project the depth of interpreted regional fault structures around the epicenters. This was done in order to evaluate the potential of the source of the seismic energy being responsible for the observed earth tremors in the study area. The regional fault joint around Mpape area was interpreted to have depths ranging from 8 km to 9 km (figure 12); these values are very close to the values of the focal depthswhich range from 10 km to 12 km as estimated from the seismograms(table 1). The faults joints around Kwoi,andChori areas have a depth range of 7 km to 8 km, while the estimated focal depth using the seismograms was 10km. It is therefore safe to conclude that, the relationship between the North Atlantic Romanche Fault and the continental regional faults system plays a key role in the source of seismic energy that resulted in the earth tremors in the central Nigeria.

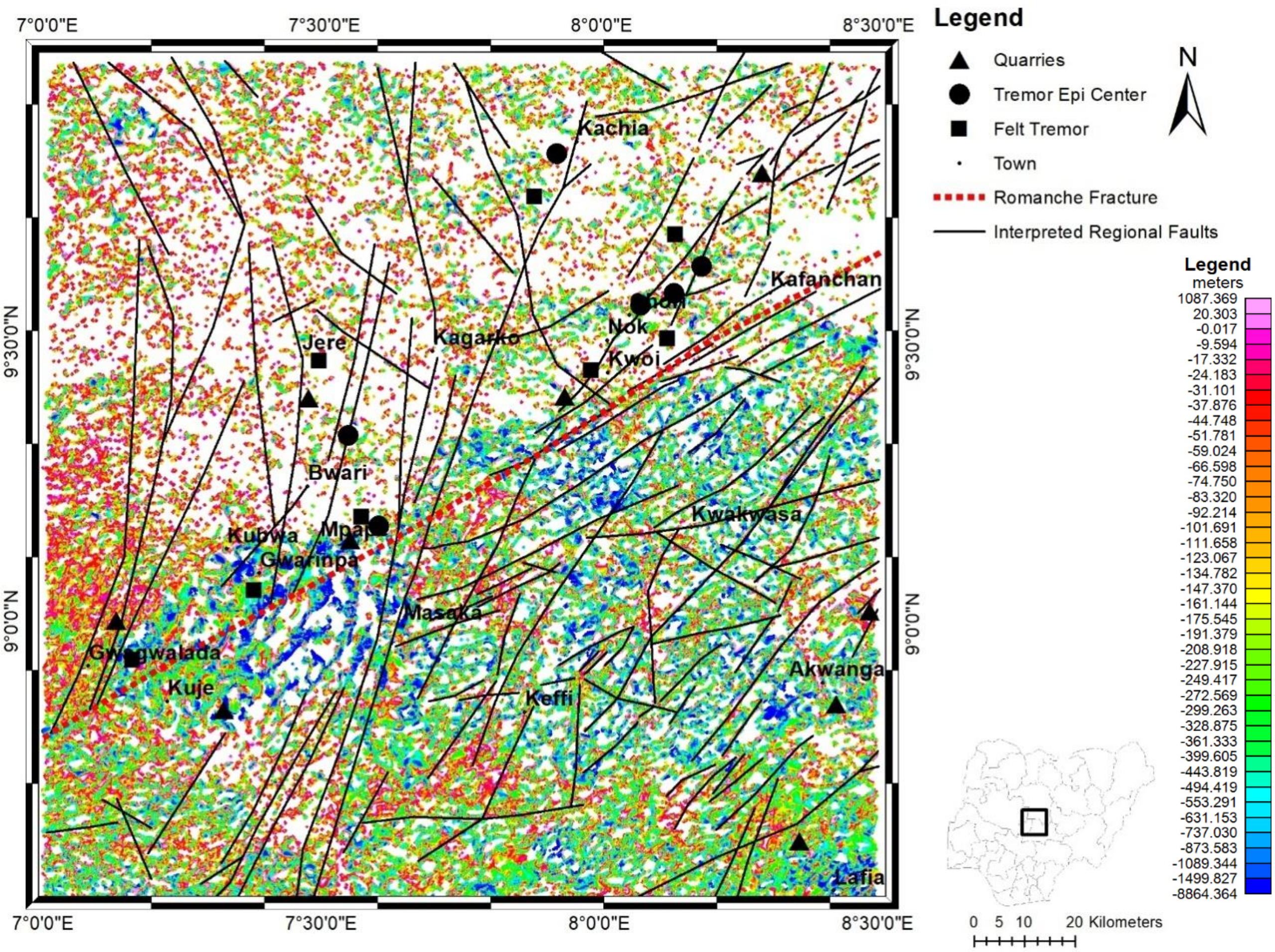

Figure 12: Depth to source map of the study area

5. Conclusion

From the perspective of global seismicity scenario, Nigeria is located on a stable crust; however, from 2016 to 2021, multiple earth tremors have been witnessed within the Central Nigerian region. The averagemoment magnitude of the recorded and analyzed events is 3.0 with average macroseismic intensity value of III on the Modified Mercalli Scale. In an effort to ascertain the actual reason for the occurrence of the increasing seismic activities in the region of interest, several theoretical schools of thought have proposed different probable causes of these tremors. In our study, we evaluated these theories using qualitative and quantitative interpretation of airborne magnetic dataset implemented in the advanced Analytic Signal- Hilbert Solution filter to respectively map out structures and depth of interest for the first time in the Central Nigerian region. Findings from in-depth analysis in our study shows that, ,theNE-SW trending fractures extending from the North Atlantic Ocean into Nigeria's landmass, and the zones of weakness, are the most likely sources of the seismic energy that resulted in the observed earth tremors in the central Nigeria. It is therefore recommended that, relevant authorities take decisive measures to establish a robust and integrated monitoring scheme in the central Nigerian region, to help in better monitoring of seismic activities and their attendant seismic hazards.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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