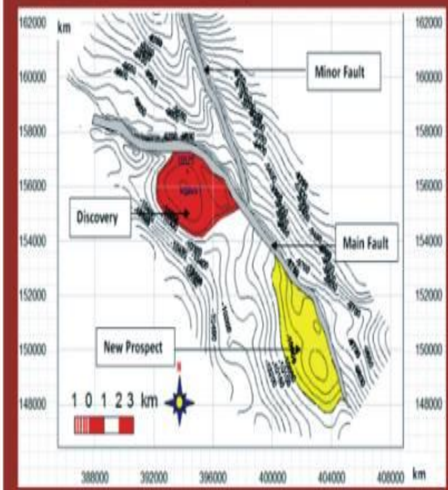

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INAUGURAL LECTURE SERIES 25

LADOKE AKINTOLA UNIVERSITY OF TECHNOLOGY (LAUTECH)
OGBOMOSO, NIGERIA

THE GOOD AND THE BAD OF FAULTS: A GEOPHYSICAL PERSPECTIVE

PROF. LUKMAN AYOBAMI SUNMONU
B.Sc, M.Sc, Ph.D (Ibadan), MGAN, MAAAS, FNIP
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Faculty of Pure and Applied Sciences.

Delivered at the

LADOKE AKINTOLA UNIVERSITY OF TECHNOLOGY

OGBOMOSO, NIGERIA

On

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LADOKE AKINTOLA UNIVERSITY OF TECHNOLOGY

OGBOMOSO, NIGERIA

25th INAUGURAL LECTURE

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Faculty of Pure and Applied Sciences.

Dedication

This lecture is dedicated to the Almighty God.

Protocol

The Vice Chancellor,

The Registrar,

The Ag. Bursar,

The University Librarian,

Provost College of Health Sciences,

Dean of the Postgraduate School,

Dean of the Faculty of Pure and Applied Sciences,

Deans of other Faculties,

Gentlemen of the Press,

Distinguished Guest and Friends,

Greatest Nigerian Students.

1.0 PREAMBLE

I feel honoured and highly privileged to present to you today, the first inaugural lecture of its kind in the Department of Pure and Applied Physics of this great institution. I thank the Almighty Allah who has led me this far in my career as an academic. My pursuit as a scholar in Solid Earth Physics/Geophysics paved the way for me in deciphering the uppermost part of the Earth-the treasure house of the resources that serve as pillar of global economy.

Mr. Vice Chancellor Sir, I consider this presentation a rare opportunity in my life-time.

Basis of the earth

And the earth: He has put down (laid) for the creatures.

(Quran 55 verse 10).

“The Earth is the Lord’s, and the fullness thereof; the world and they that dwell there-in”. (Psalm 24 verse 1)

However, this God given knowledge to mankind has made it possible to interact with His work. My venture into the field of geophysics has made it possible for me to see more into the earth’s interior (in particular, the upper 200 m - the continental crust) while standing on the surface. Please sit back and enjoy the account of my career experience in the field of geophysics over the years.

INTRODUCTION

All activities of man occur on the earth. There is atmosphere above the surface of the earth, while the strata below the surface are called the earth structure. The atmosphere comprises of layers based on temperature. These layers are the troposphere, stratosphere, mesosphere and thermosphere. A further region at about 500 km above the earth's surface is called the exosphere (Figure 1). The basic earth structure is composed of crust, upper mantle, lower mantle, outer core and inner core (Figure 2). Crust is the outermost part of the earth. It is rigid and brittle. Its depth ranges from 38 – 40 km on the continent and from 6-8 km under the ocean. Upper mantle is partly solid and partly semi-solid. The solid part with the crust is referred to as the lithosphere. The lithosphere has a depth of 100 -150 km under the continent and 70-100 km under the ocean. The semi-solid part is referred to as the asthenosphere. Lower mantle is under the upper mantle and it is semi-solid (plastic form). Outer core is in fluid form (liquid form) and it lies under the lower mantle. It is from a depth of about 2,891 km to 5,150 km. Inner core is solid and it is of a depth of about 5,150 km to the centre of the earth. The beauty of Geophysics is that these subsurface structures can be delineated without disturbing the subsurface via geophysical approach.

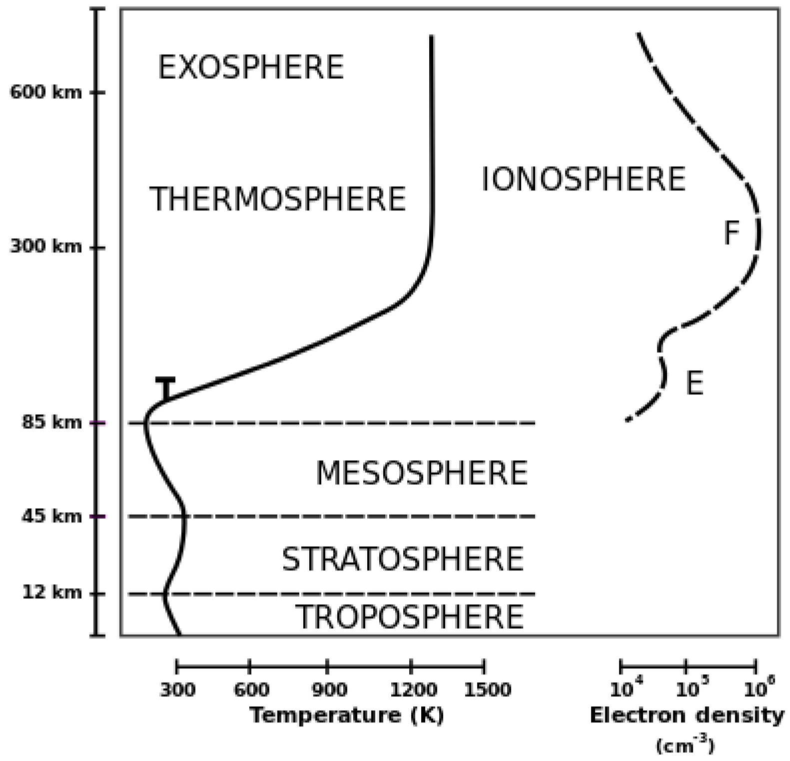


Figure 1: Layers in the atmosphere

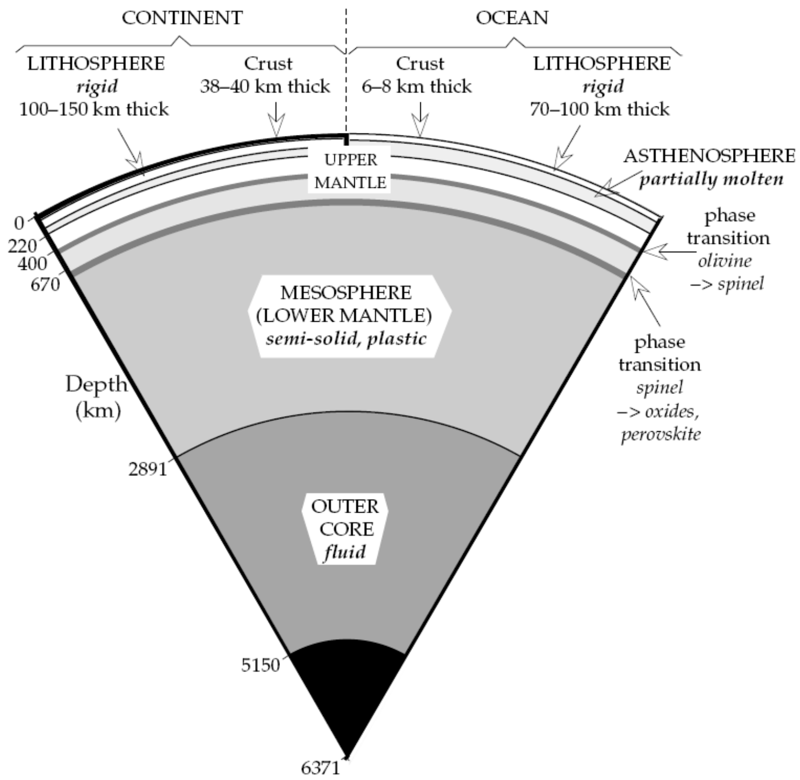


Figure 2: Simplified structure of the earth.

Faults and Joints

In geophysics, a fault is a planar fracture or discontinuity in a volume of rock, across which there has been significant displacement along the fractures as a result of earth movement. In short, it is a fracturing and displacement of rock strata (Figure 3). Fracture in which no displacement has occurred along the rock strata is known as joint (Figure 4). Large faults within the earth's crust result from the action of plate tectonic forces, with the largest forming the boundaries between the plates, such as subduction zones or transform faults. Energy release associated with rapid movement on active faults is the cause of most earthquakes (Adagunodo and **Sunmonu**, 2015).

Types of Faults

There are three (3) types of faults. These are dip-slip faults, strike-slip faults and thrust faults. The dip-slip come from the concept of dipped bed. Suppose we have a dipped bed going through the subsurface as shown in Figure 5, the angle between the topmost stratum and the horizontal line is called dip, while the perpendicular one to it is called strike.

i. Dip-slip faults: are faults in which movement is primarily parallel to the inclination.

ii. Strike-slip faults: are faults in which movement is perpendicular to the inclination. That is, a fault in which the dominant displacement is horizontal. An example of a strike-slip fault is shown in Figure 6.

iii. Oblique-slip faults: are faults which exhibit the properties of both strike-slip and dip-slip faults.

Dip-slip faults are further divided into normal faults, reverse faults, and thrust faults. These three types of dip-slip faults have been discussed extensively in Adagunodo and **Sunmonu** (2015). In a dip-slip fault, the ‘upper part’ is the hanging wall, while

Figure 3: Representation of fault

Figure 4: Joints within a volume of rock

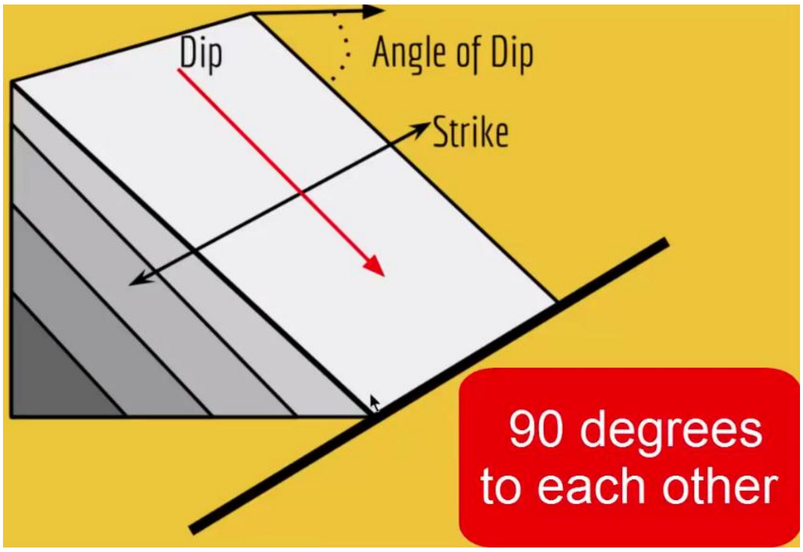


Figure 5: Representation of dip and strike faults

Figure 6: Representation of strike-slip fault

the ‘lower part’ is the foot wall as revealed in Figure 7. The two sides of a non-vertical fault are known as the hanging wall and footwall. By definition, the hanging wall occurs above the fault plane and the footwall occurs below the fault. This terminology derives from mining. When working a tabular ore body, the miner stands with the footwall under his feet while the hanging wall hangs above him. The movement of either the foot wall or the hanging wall determines the types of dip-slip fault that we have.

There are three (3) types of dip-slip faults. These are normal faults, reverse faults and thrust faults.

i. Normal fault: is the fault where the hanging wall moves down relative to the foot wall (Figure 8).

ii. Reverse fault: is the fault where the hanging wall moves up relative to the foot wall (Figure 9).

iii. Thrust fault: is a type of reverse fault having dips less than 45° as shown in Figure 10.

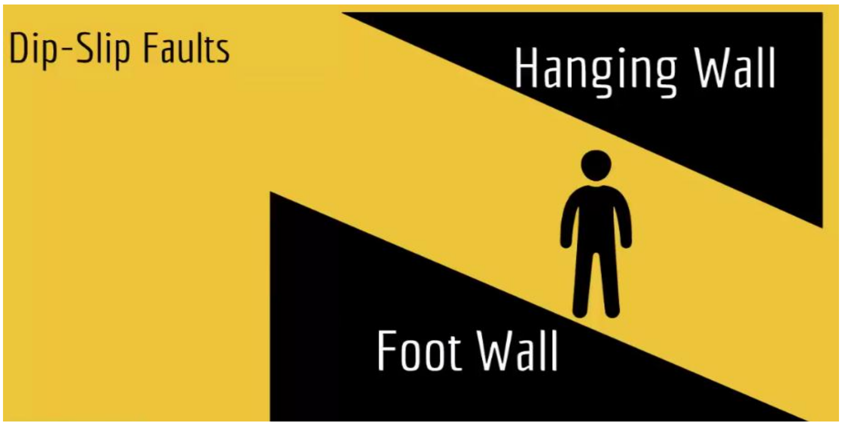


Figure 7: Representation of dip-slip faults

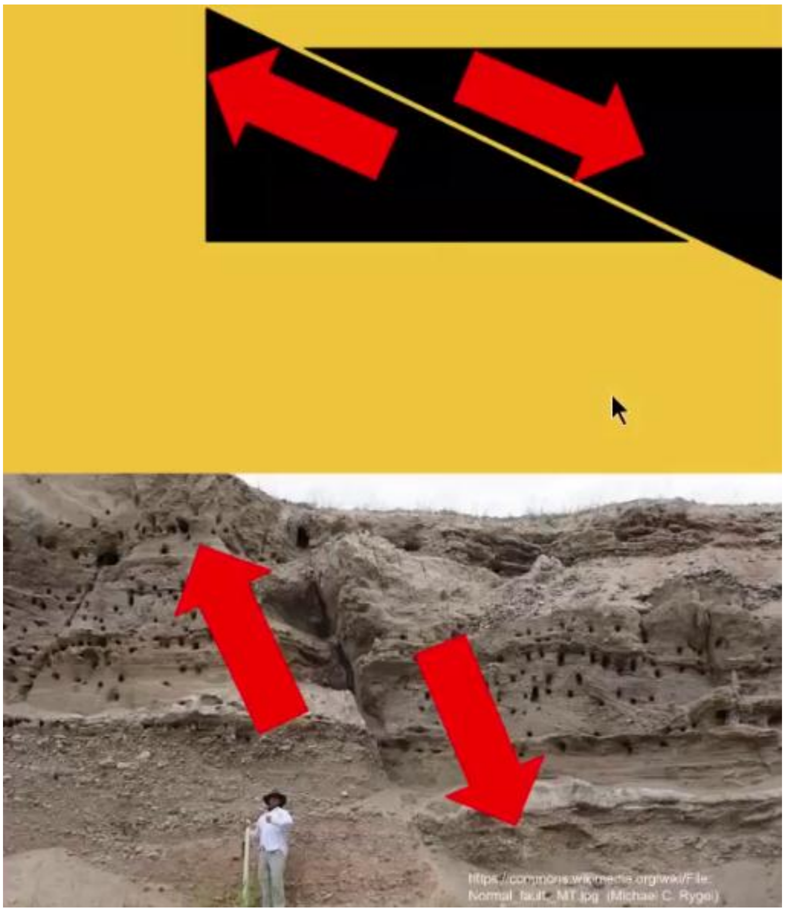


Figure 8: Representation of a normal fault

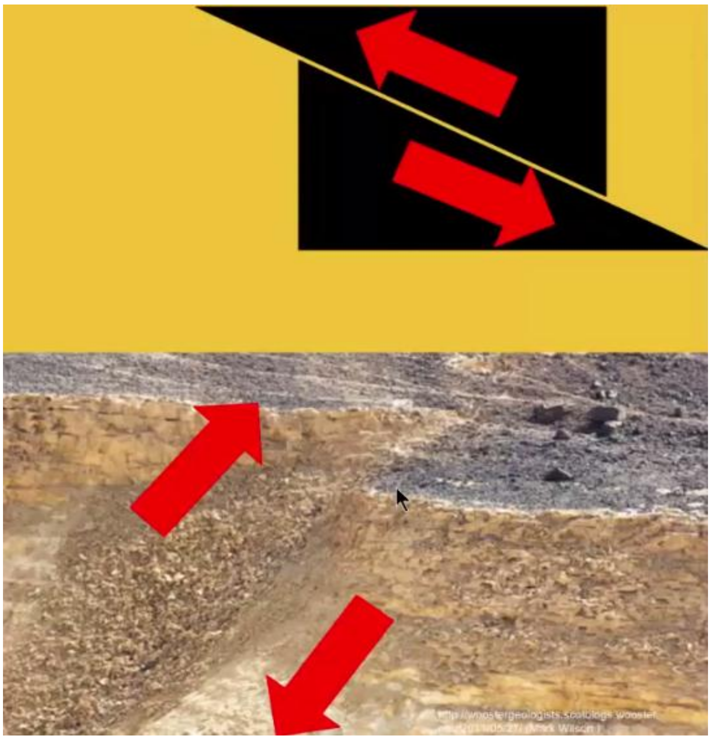


Figure 9: Representation of a reverse fault

Figure 10: Representation of a thrust fault

The Beauty of Geologic Fault

The Vice-Chancellor Sir, it is important to note that in real life experiences, there are at times good things in every bad situation. Occurrence of faults/joints has brought solution to so many challenges of humans on earth. Some of the beauties of faults/joints include access to sustainable water supply where there is insufficient water supply, accumulation of mineral resources, trapping mechanisms in hydrocarbon system and so on.

The Ugliness of Geologic Fault

In another words, ugliness of faults/joints include structural failures (such as bridges, houses and roads) and occurrence of natural disasters such as tsunamis, earthquakes, and tremors.

Geophysical approach to solving human problems

Geophysical methods (such as electrical resistivity, electromagnetic, magnetic, gravity, seismic, radiometrics and so on) are the scientific methods used to probe into the subsurface (beneath the earth). These geophysical methods are used either singly or integratedly in order to provide solutions to the problems encountered by humans in relation to her environment/subsurface.

The problems addressed via geophysical approach

In the last two decades of my career studying the Solid Earth/Geophysics, we have been able to delineate the subsurface for the good of humanity, exploring the good and the bad of geologic faults/joints. For ease of explanation and understanding the essence of this lecture, the problems addressed are categorized into seven major areas. These are:

1. ***Fractal Analysis and Seismicity***
2. ***Fault Pattern and Earth Tremor***
3. ***Subsurface Integrity***
4. ***Environmental Geophysics***
5. ***Groundwater Exploration***

6. ***Solid Mineral Exploration***
7. ***Hydrocarbon Reservoir***

1. Fractal Analysis and Seismicity

The fundamental concept of fractals is the property of self-similarity which was introduced by Mandebrot, 1983. A self-figure appears similar at all scales of observation which is known as scale invariance. Mandebrot, (1983), showed that some geographic lines such as coastline are described in terms of a statistical property, which he termed the fractal dimension (D) of the line. Similarly, surfaces can also have properties of self-similarity or self-affinity or self-similarity with vertical exaggeration. The two aspects which are important from the point of view of fractal analysis are the range of variations in a particular property of the signal observed and the fractal dimension. So, these fundamental concepts of fractal analysis may also be applicable to any observed geophysical signal (**Sunmonu** and Dimri, 1999).

Furthermore, on fractal analysis, **Sunmonu** (2002), made an attempt to derive a relationship between the depth to the subsurface geological structure and fractal dimension. For this purpose, a thin sheet model equation has been considered and theoretical magnetic anomaly at four different depths from the surface was computed. The fractal dimension (D) was computed using the fundamental relationship between the Mandbrot fractal function and the Fourier power spectrum and derived a linear relationship between the depth to the subsurface structure and fractal dimension. This methodology was tested and applied to the total magnetic field data of Bida sedimentary basin, Nigeria. A profile was constructed across the basin for which the profile fractal dimension was computed and depth to the basement fault was estimated using the derived linear relationship.

Sunmonu and Dimri (1999), reported that India experienced compressive forces from the Himalayan Arc in the North and the Burnese Arc in the East, which led to the development of a number of seismogenic faults, fractures and lineaments. This region is seismically one of the most active regions of the world. Tectonically, the region is bounded by Himalayan Arc in the north and Burmese Arc in the east shown in Figure 11. The former was involved in a continent-continent collision, whereas the later was involved in a subduction process.

The fractal analysis and seismic data results suggest that the faults were spatially distributed in the whole area. Also, the block B (Tripura fold belt) with higher fractal dimension of fault system obtained by box counting method indicates that the Tripura fold belt is an active fault area, and produces more earthquakes compared to the block A, Bengal basin (Figure 12).

It was also observed that the characteristics of earthquakes occurring on an active fault were closely related to the irregularity of the fault geometry of the Fractal analysis and seismicity of Bengal Basin and Tripura fold Belt, Northeast India. The lineaments are rough over many length scales, thus the faults can be conveniently regarded as fractal sets, and their geometrical irregularity can be quantified using fractal dimension. We calculated fractal dimension (D) of the distribution of faults in the two tectonic blocks, Bengal basin and Tripura fold belt of the area and found that in the spatial sense, the fractal dimension (D) of the fault and the seismicity are positively correlated.

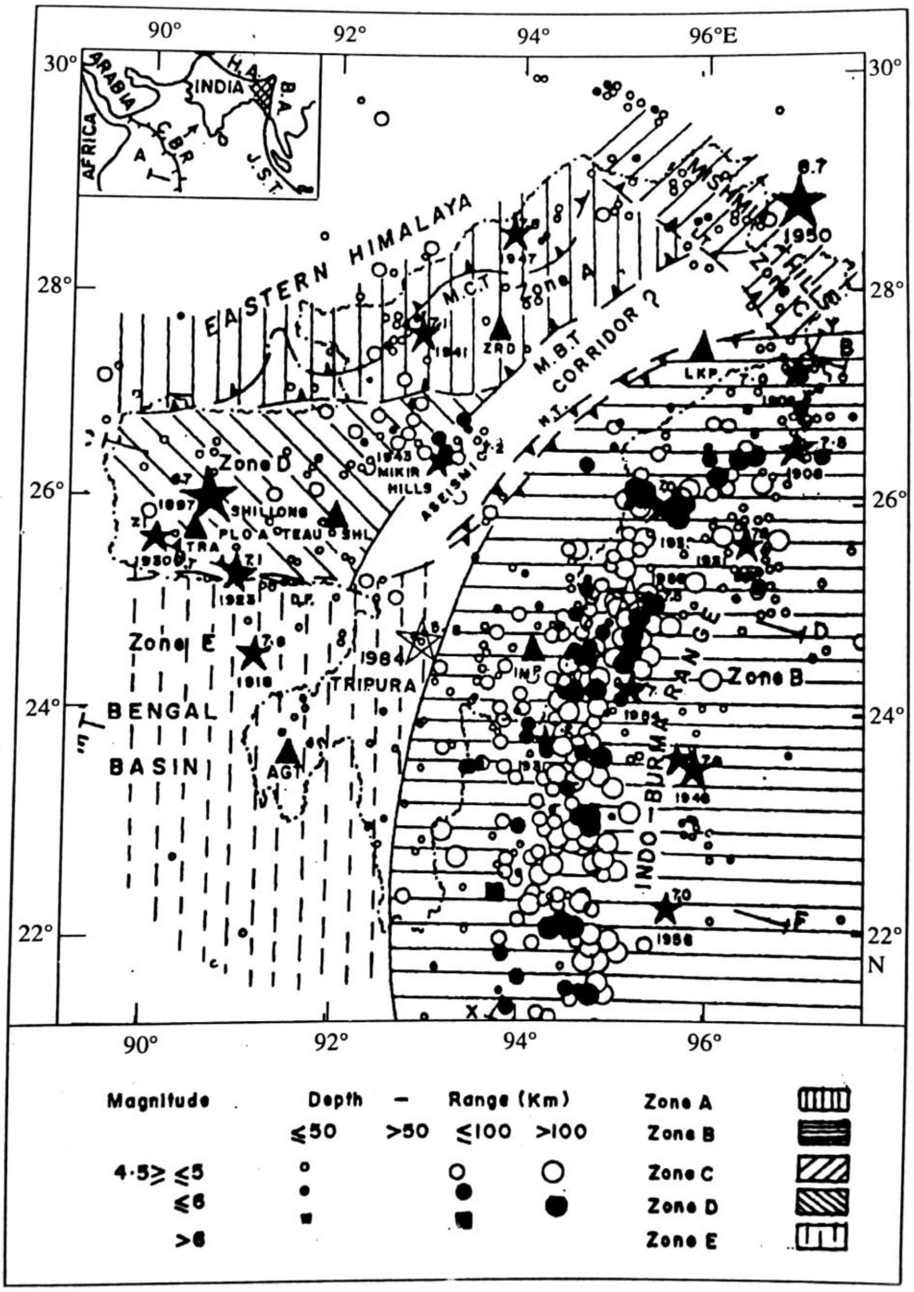


Figure 11: Seismicity in the Northeastern India. Zone E is the study area. Tectonically zone and major thrusts are indicated as MCT: Main Central Thrust, MBT: Main Boundary Thrust, D.F Dauki Fault, D.T: Dapsi Thrust. Great and large earthquakes are shown by solid stars. Two open stars indicate the damaging earthquakes. Year of occurrence and magnitude of these earthquakes are annotated (Kayal, 1996).

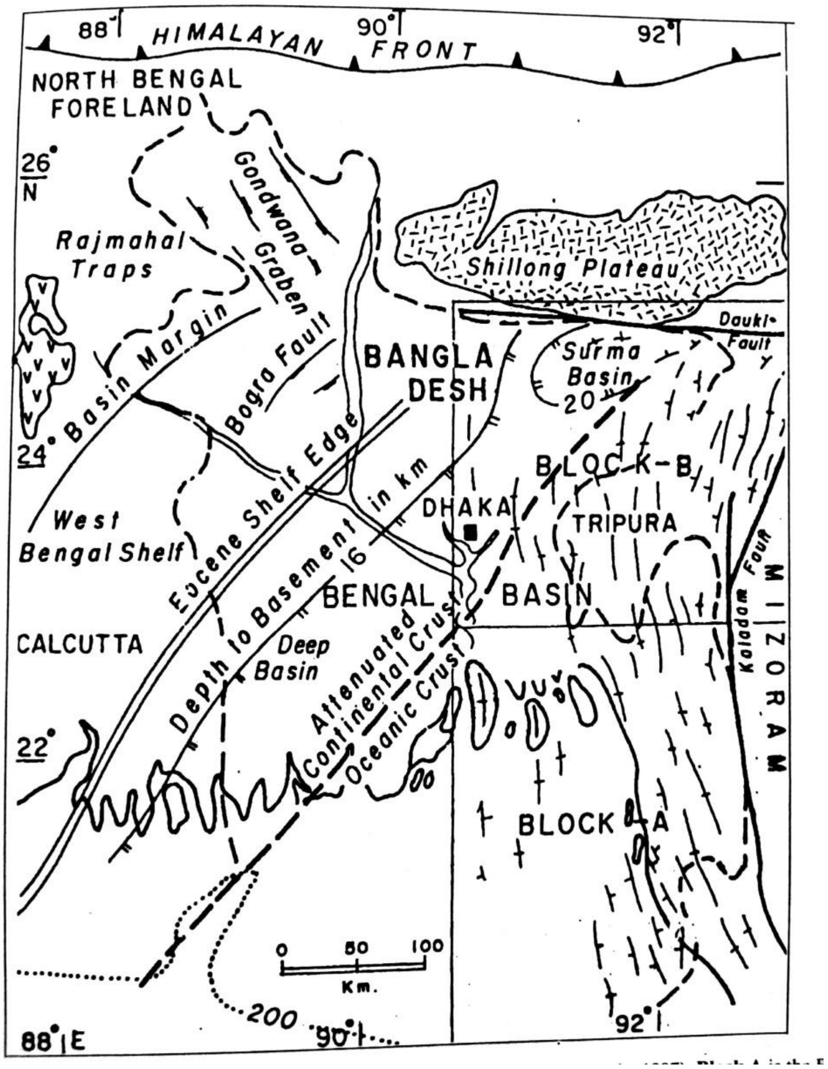


Figure 12: Tectonic framework of the Bengal basin and the Tripura fold belt (Ganguly, 1997). Block A is the Bengal basin, and Block B is the Tripura fold basin.

Sunmonu and Dimri (2000), worked on the Fractal geometry and Seismicity of Koyna-Warna Region West India, using LANDSAT images. These images showed that, the Koyna-Warna region has been shaken by several earthquakes greater than magnitude 4. Four of them in 1967, 1973, 1980 and 1993 were potentially very destructive with magnitudes exceeding 5.0 (Figure 13). The majority of the seismic event recorded to date has been induced from Konyna-Warna areas. The region is divided into six blocks and the fractal dimension of each block is calculated using a box-counting technique. A plot of a three-dimensional map of the fractal dimension was prepared (Figure 14). It shows that the value of the fractal dimension is gently dipping from NE–SW, the fractal dimension was used to estimate the b-value in the frequency-magnitude relation of earthquakes in the region which was in agreement with earlier studies. Therefore, we reported that the external forces that acted in the zone more than once influence the sequence of earthquake in Koyna-Warna reservoir area. These external forces were attributed to the activities around the Arabian sea coast and the continuing northward push of the Indian plate in conjunction with the induced forces from the reservoir filling, which at times led to the re-activation or growth of fault accounting for seismicity in the region. In order to understand the seismotechtonics of the region, low activity with fractal dimension (D_w) of 1.45 obtained for the whole region, suggests that there were fractal discontinuities in the region which may be attributed to a break in the activities of the external forces. Therefore, this may be one of the causes of the greater proportion of large to small faults with a relative gap in the area. Nevertheless, if the sea bottom deformation was traced, we believe that a submarine fault extending with pre-existing fault may underlie the reservoir during the monsoon period and also through the river's channel, coupled with the distribution of near field effects may break these detachment faults and may even cause a sequence of minor earthquakes in the area.

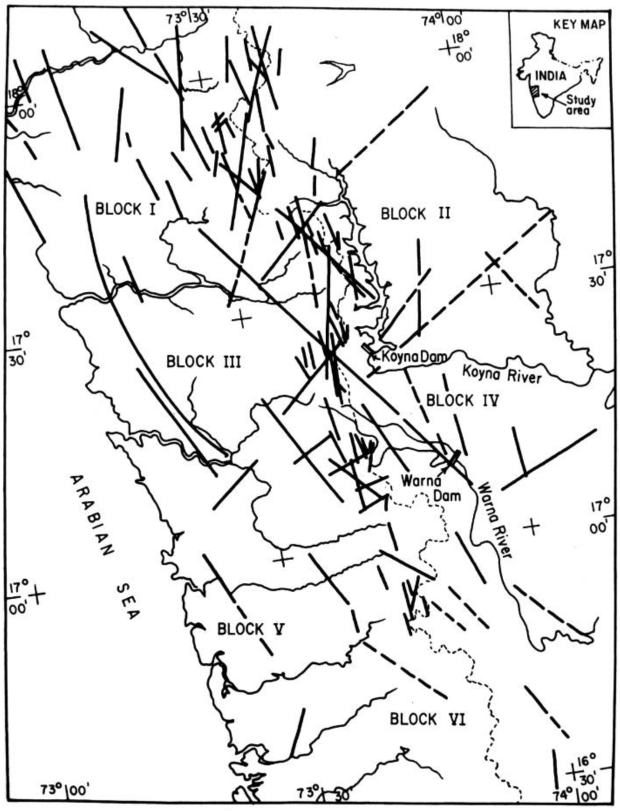


Figure 13: Fault map for the Koyna-Warna region interpreted from LANDSAT images (Langston, 1981)

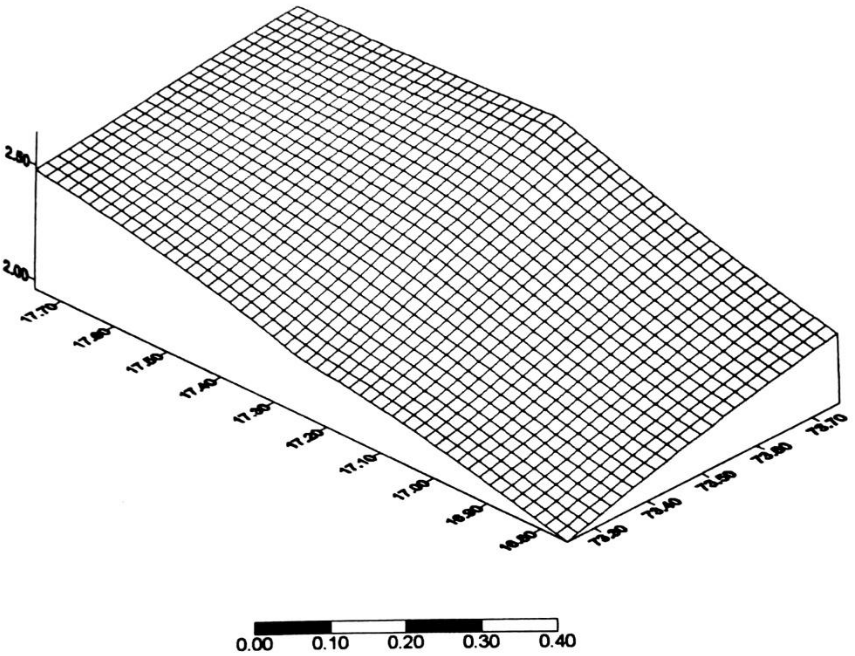


Figure 14: A 3D dimensional map of volume fractal dimension distribution of the area

Also**, Sunmonu,** Dimri, Prakash, and Bansal (2001), worked on the multifractal approach of time series of magnitude greater than or equal to 7.0 earthquakes in Himalayan region and its vicinity during 1895-1995 as shown in Figure 15. The region is one of the world's highest earthquake prone regions where several large earthquakes had occurred. The occurrence of the earthquake is attributed to the collision between the Indian and Eurasian plates. We used a technique called time series analysis of multifractal properties of $M \geq 7.0$ earthquake to explain in a better way the scale related complexity observed in the spatial and time distribution of earthquakes, rather than the mono-fractal one.

Our findings revealed the distribution of earthquakes of $M \geq 7.0$ in the time axis had a multifractal set and well distributed, steep type decreasing function of D_q with increasing q indicated high rate of accumulation and release leading to adjustment of a large scale stress field in the area and value of $D_2 = 0.95 > D_3 > D_\infty \geq 0.80$. Also, it can be seen from Figure 16, which the seismicity of the region throws light on the geodynamic processes of plate collision that had been attributed to the movement along either the Main Boundary Thrust (MBT) or to the Main Central Thrust (MCT). Furthermore, the area can be divided into the Eastern Himalaya, Central Himalaya, and Western Himalaya. The earthquake activities in the Central Himalaya are not intense as compared to Eastern and Western Himalaya. Most earthquakes occurring within Central Himalaya were characterized by horizontal compression. Faults near the two ends of the Himalaya arc have been shown to have features of compression-torsion tectonics with obvious horizontal dislocation.

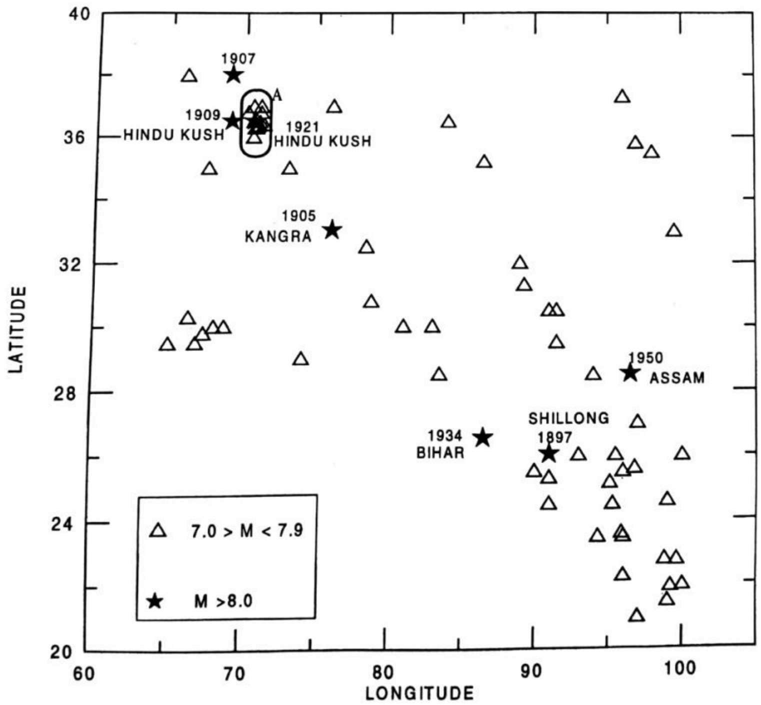


Figure 15: The Spatial distribution of M ≥ 7.0 earthquakes in Himalaya and Vicinity for the period 1895-1995 (Data Source: NOAA Earthquakes file). There are 22 events marked by A.

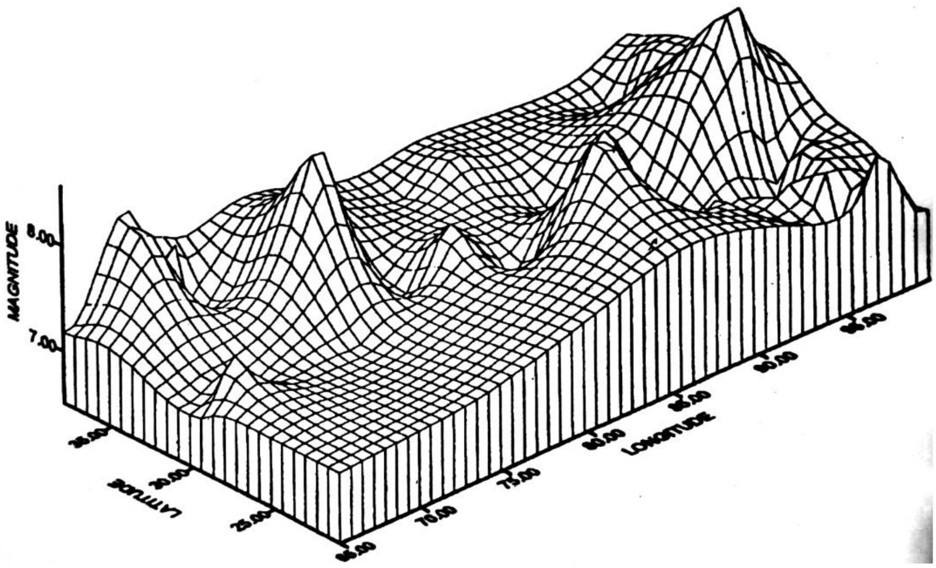


Figure 16: Three dimensional plot M ≥ 7.0 earthquakes in Himalaya region and vicinity for the period 1895-1995

2. Fault Pattern and Earth Tremor

Earthquake is the shaking of the surface of the earth, resulting from the sudden release of energy in the earth's crust that creates seismic waves. Despite the volume of information gathered by Geoscientists about the cause of earthquakes; scientists have not been able to predict when exactly one will occur because before it strikes, little or no warning is given and when it begins nothing can be done to stop it. The recent increase in the occurrence of this phenomenon especially along the equatorial region of the earth could be as a result of the earth's periodic slowdown which began five years ago because of geological activities deep in the core. Although, Nigeria is not located within the major seismic zones of the world, but over the years, between 1933 till date several minor earthquakes have been experienced in some parts of the country. Locations that have experienced tremors in Nigeria in the recent past are summarized in Table 1.

In the course of our studies, we have been able to provide scientific explanations to this natural hazard since the possibility of stopping it is in doubt.

Table 1: History of Earth Tremor in Nigeria (Sunmonu *et al*., 2018)

S/N	Year	Felt Area
1	1933	Warri
2	1939	Lagos,Ibadan and Ile-Ife
3	1948	Ibadan
4	1961	Ohaifa
5	1963	Ijebu-Ode
6	1981	Kundunu
7	1982	Jalingo and Gembu
8	1984	Ijebu-Ode, Ibadan, Shagamu, Abeokuta, Ijebu Remo and Yola
9	1985	Kombani Yaya
10	1986	Obi
11	1987	Gembu, Akko and Kurba
12	1988	Lagos
13	1990	Ibadan and Jere
14	1994	Ijebu-Ode
15	1997	Okiti-Pupa
16	2000	Jushi-Kwari, Benin, Ibadan, Akure, Abeokuta, Ijebu-Ode and Oyo
17	2001	Lagos
18	2002	Lagos
19	2005	Yola
20	2006	Lupma
21	2009	Abomey-Calavi
22	2011	Abeokuta
23	2017	Shaki
24	2018	Iseyin, Ado-awaye, Lanlate, Okeho, , Oyo and Ibadan

Sunmonu, Adabanija and Oladejo (2018), shared the view in spite of the fact that Nigeria is located on tectonically stable African plates; it has continued to experience series of tremors in the last few decades. Hence, the need to examine the fault pattern of some parts of Southwestern, Nigeria with a view to investigating the tectonic stability of the area. In the research, high resolution aeromagnetic data of Lagos-Ore (sheets 268 and 269), Ibadan (sheet 261) and Ilesha (sheet 243) were processed, enhanced and interpreted in Figure 17.

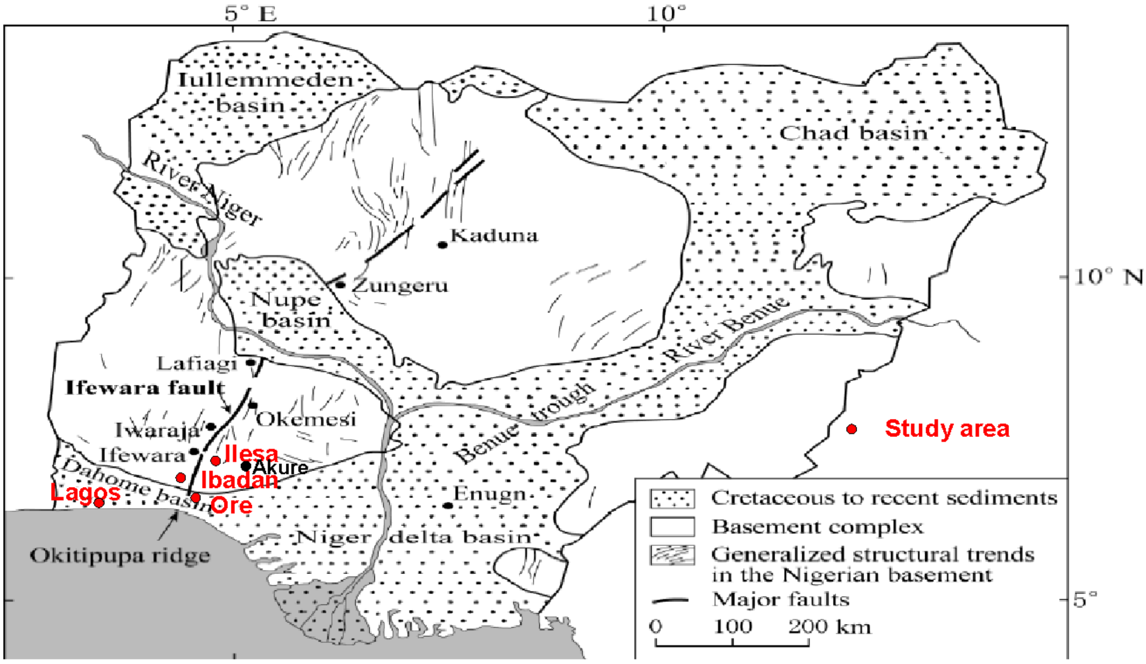


Figure 17: The investigated area in SW Nigeria for stability against occurrence of earthquakes (Kadiri *et al*., 2011)

The results of our findings revealed depths to basement estimates which ranged from 573.73-6212.12 m beneath Lagos-Ore, around 300 m beneath Ibadan and Ilesha at various structural index which suggest contacts, sill/dyke and horizontal cylinder geologic models. The alarming depth range otherwise known as overburden thickness beneath Lagos-Ore axis of our investigated area establishes the reason for incessant building collapse experienced in the area.

The orientations of the lineaments obtained from Total Horizontal Derivatives maps of these locations indicated the dominance of Pan African and Liberian Orogeny at Ibadan/Ilesha and Lagos-Ore axis respectively. Ductile deformations were found around Idiroko, Iwopin, North of Ijebu-Ode and most of the southeastern edge of Lagos-Ore axis (Figure 18); around Mehinsin and Olowo/Olode in Ibadan (Figure 19); as well as NE-SW trending central portion of Ilesha (Figure 20). However; the deformations around Atan, Ewekoro, Sagamu, Ijebu-Ode, Ore area of Lagos-Ore; the remaining parts of Ibadan apart from southwestern part; and southwestern/southeastern and southcentral areas of Ilesha are brittle.

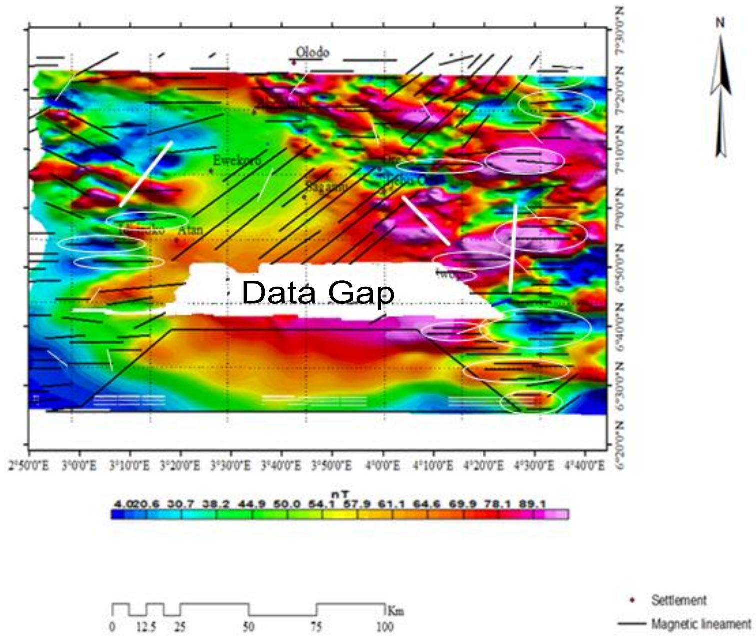


Figure 18: Magnetic fault and structural deformation of Lagos-Ore

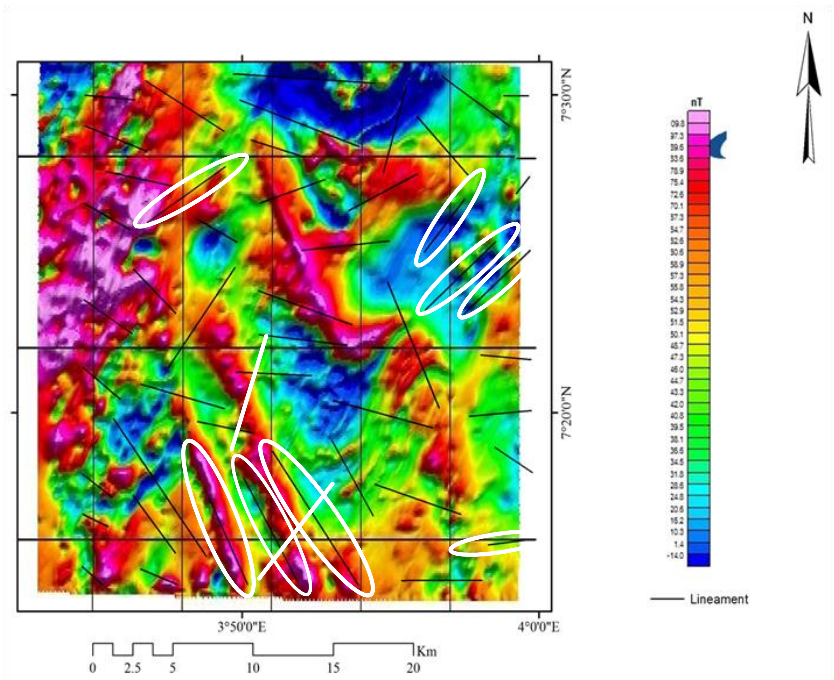


Figure 19: Magnetic fault and structural deformation of Ibadan

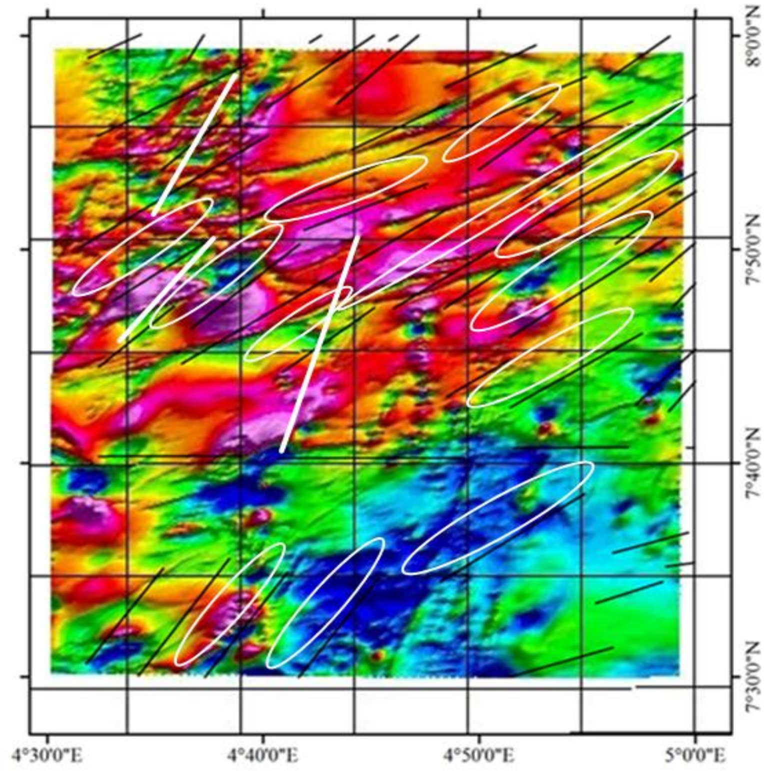


Figure 20: Magnetic fault and structural deformation of Ilesha

The depth continued maps obtained from upward and downward continuation process of the areas suggest the presence of deep faults at depths range of 0.50-2.75 km, 1.25-1.75 km and 0.15-0.25 km beneath Lagos-Ore, Ibadan and Ilesha respectively.

Mr. Vice Chancellor Sir, based on orientations of faults on magnetic fault maps obtained from the superposition of the lineaments extracted on the respective geological maps of the study areas as depicted in Figures 21 and 22. Seven distinct sets of sinistral/dextral faults were recognized trending NE-SW, NNW-SSE, ENE-WSW, NNE-SSW, NW-SE, E-W and WNW-ESE. While the NE-SW and ENE-WSW trending faults sets are common to Lagos-Ore and Ibadan; the E-W, NNW-SSE trending fault set was found both in Lagos-Ore and Ilesha. The fault sets are as shown in Table 2.

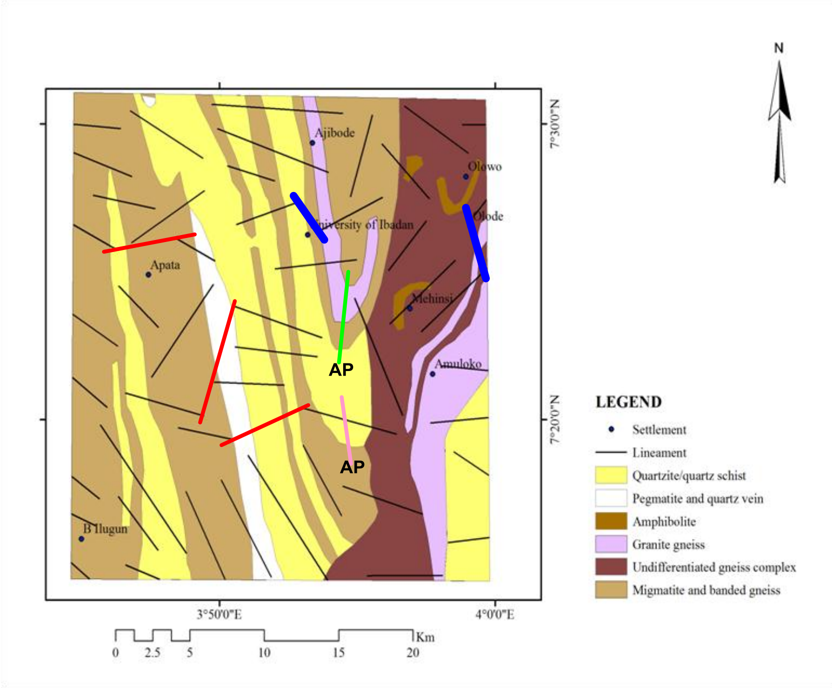


Figure 21: Lineament fault patterns of Ibadan

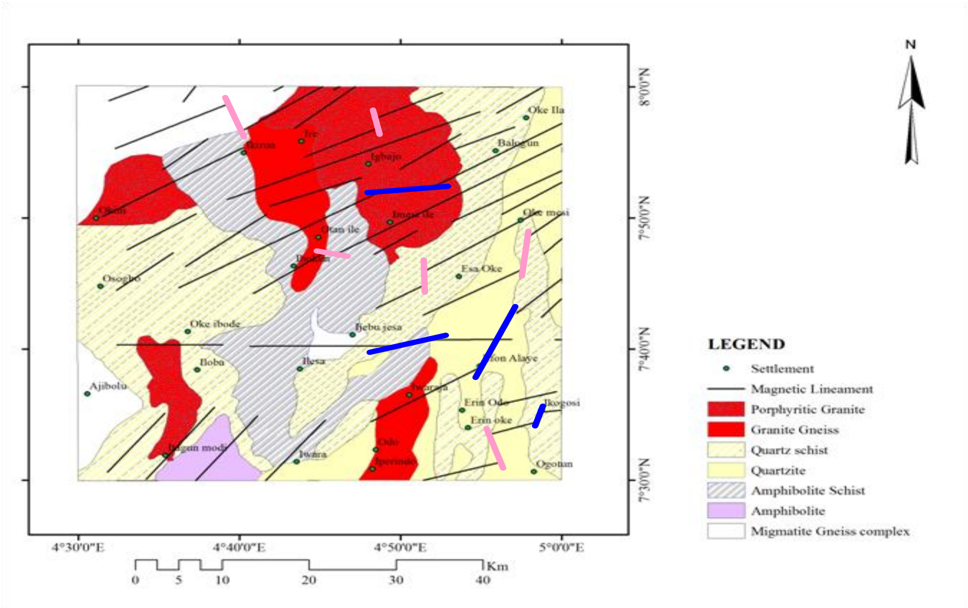


Figure 22: Lineament fault patterns of Ilesha

Table 2: Distribution of Sinistral and dextral faults of the Areas

Location	Faults		Percentages		Orientations
	Sinistral	Dextral	Sinistral	Dextral	
Lagos – Ore	17	5	77.3	22.7	NE-SW, NNW-SSE, ENE-WSW, E-W
Ibadan	4	3	57.1	42.9	NE-SW, NW-SE, ENE-WSW
Ilesha	6	3	66.7	33.3	NNW-SSE, NNE-SSW, WNW-ESE, E-W

This suggests that the NE-SW and ENE-WSW fault sets could be responsible for the tremor experienced in 1939 felt in Lagos, Ibadan and Ile-Ife, 1948 felt in Ibadan, 1963 felt in Ijebu-Ode, 1984 felt in Ijebu-Ode, Ibadan, Shagamu, Abeokuta, with aftershock experienced in Ijebu-Remo, and the following month of the same year in Ijebu-Ode, Ibadan, Shagamu and Abeokuta, 1988 felt in Lagos, 1990 felt in Ibadan, 1994 felt in Ijebu-Ode, 1997 felt in Okiti-Pupa, 2000 felt in Ibadan, Akure, Abeokuta, Ijebu-Ode and Oyo, 2009 felt in Abeokuta, Ago-Iwoye, Ajambata, Ajegunle, Imeko, Ijebu-Ode, Ilaro and Ibadan, 2011 felt in Abeokuta, 2017 felt in Shaki and 2018 felt in Iseyin, Ado-Awaye, Lanlate and Okeho. The NE-SW trending fault set obtained in Lagos-Ore and Ibadan is probably an extension of the NE-SW trending fracture, considered as synthetic with or part of NE-SW trending Zungeru-Ifewara fault from the Atlantic Ocean to which Nigeria Earth tremors have been attributed. All these faults are depicted in Figure 23.

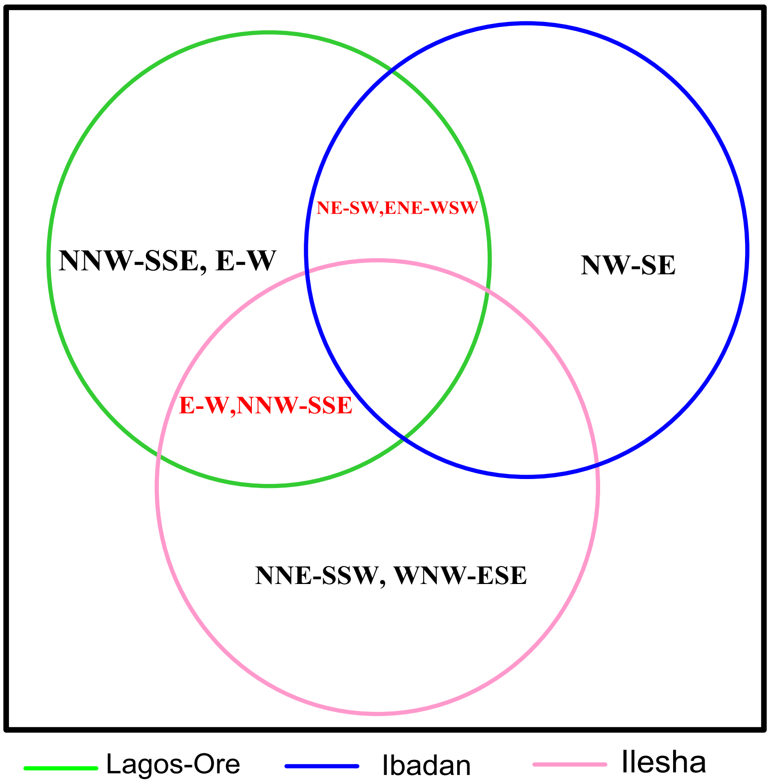


Figure 23: Venn diagram of fault distribution in the study areas

The identified synthetic magnetic faults we observed at NW of Idiroko, SE of Ijebu-Ode, south and southwest of University of Ibadan, central portion of Ilesha, could be synthetic to the Ifewara-Zungeru fault when tectonically activated.

This suggests that some of areas in southwestern Nigeria are not immune from experiencing at least earth tremors because the fault pattern established are the conduit pipes for the tectonic energy.

Sunmonu, Ayantunji and Adabanija (2005), investigated the fault pattern of Odokoto, Ogbomoso, located between latitude 8^0 5’ and 8^0 11’ and longitude 4^0 12’ and 4^0 19’ using the integration of electrical resistivity survey and electromagnetic survey (VLF) methods. The study covers an area of about 46, 550 m^2 within the premise of Nigeria Baptist Theological seminary, Odokoto, Ogbomoso. The area covered was chosen in such a way that it enclosed the main area where the reported tremor was pronounced 4th of May, 2004. When integrating our result with information gathered from analyses of the questionnaires, it was revealed that tremor occurred along SW-NE direction. This is a line joining the two boreholes being sunk during the time of occurrence of the tremor. Therefore, there is probably a major fault in the SW-NE direction, in form of a deeply concealed dyke-like formation. Hence, the drilling of the boreholes triggered the tremor.

Adetoyinbo, Popooola, Hammed, and **Sunmonu** (2009), investigated the detection of seismic ultra-low frequency (ULF) geo-electrical potential variations as tremor precursors prior to quarry blasts. We embarked on this study to detect geo-seismic electrical signals produced from the brittle upper crust during rock loading and fracture as a simulated earthquake precursor. This was done by setting up seismic ULF geo-electrical signal recording instrument in three different quarry sites in the south-western part of Nigeria.

Our findings showed that the geo-electrical potential signals associated with the ULF waves were varying anomalously during the deformation stages of crustal layers of rocks. These signals were recorded a few seconds before and after fracture of the rocks as systemic precursors to the main tremor observed in each of the stations and 5 km away. This implies that the rock fracture associated with each of these recording stations is a gradual process formed through the initial formation of micro fracture which leads to the sudden formation of some macro-fractures and to final collapse of the loaded or stressed rocks.

The radio seismic emission of large volume of geo-electrical potential signals recorded during the rock extraction or mining, though on a microscopic scale, prior to the rock fracture serves as a systemic precursor that precedes a tremor or simulated earthquake of low magnitude associated with seismic activities in the quarries. On a macroscopic scale, in the active fault zones, this can be a way towards the earthquake prediction. The Geo-Electrical Potential Signals Recorded for each station during rock loadings and fractures are shown in Figures 24, 25 and 26.

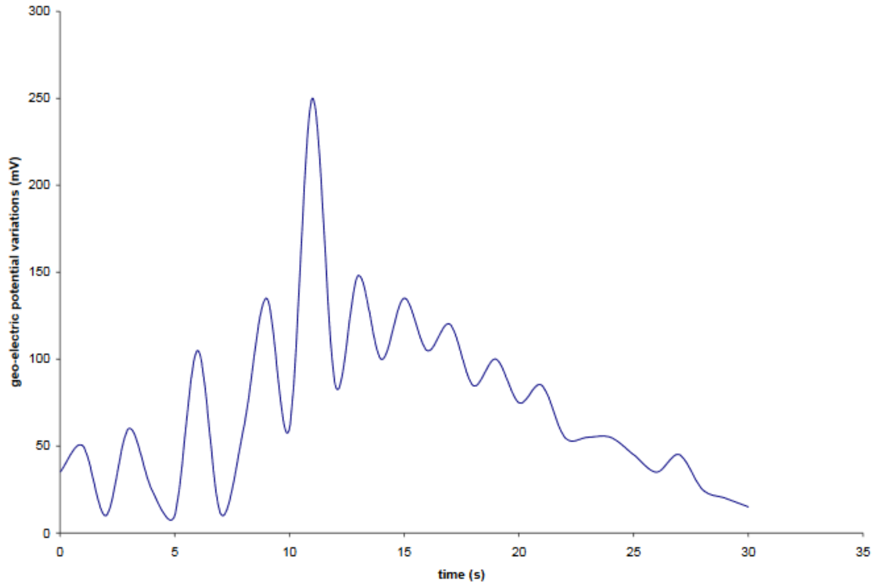


Figure 24: Geo-Electrical Potential Signals Recorded during rock loading and fracture in station A.

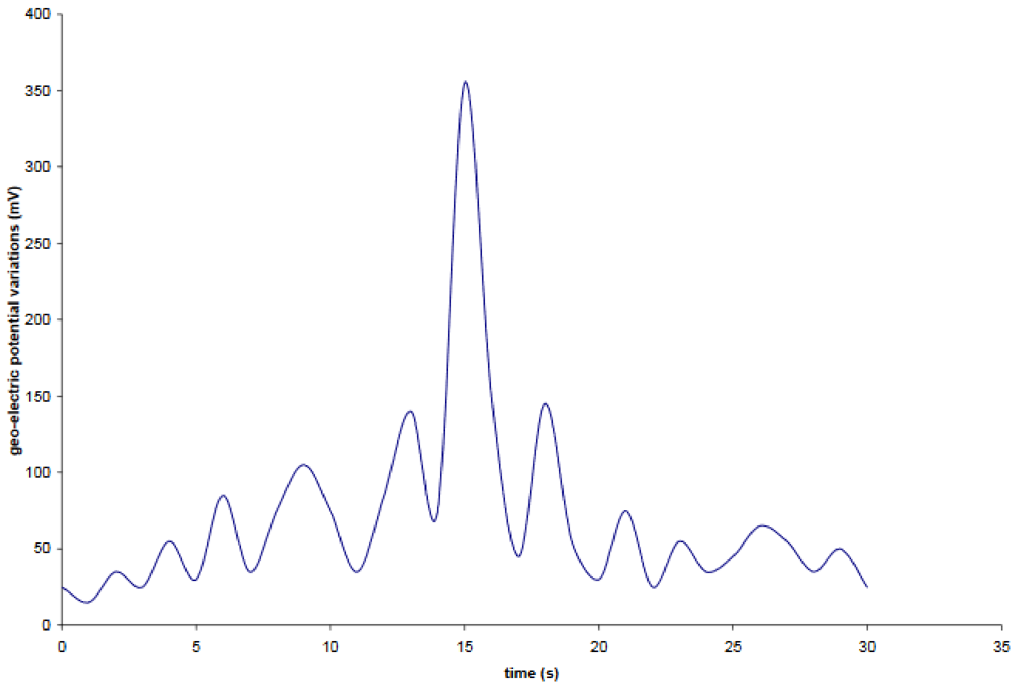


Figure 25: Geo-Electrical Potential Signals Recorded during rock loading and fracture in station B.

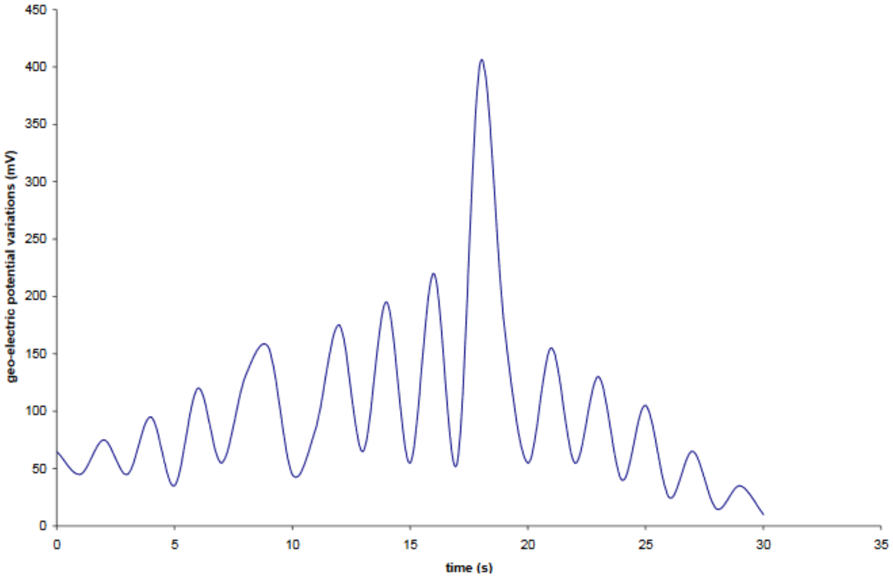


Figure 26: Geo-Electrical Potential Signals Recorded during rock loading and fracture in station C.

3. Subsurface Integrity

There is a proverb in the Holy Bible that was summarized as 'a fool built on sandy foundation while a wise built on solid rock' (Matthew 7: 24-27). A sandy foundation is likened to constructing civil engineering structures on incompetent zones, while solid rock is likened to construction of civil engineering structures on competent zones. Understanding the subsurface properties and geologic signatures and making use of the knowledge will distinguish the wise from the fool. However, having this understanding will bail us out of situating infrastructure on planes that are good for other purposes, such as building on fractures/faults/void planes that are rather good for other facilities like borehole water developments. As a result of this, we have been able to investigate some areas across Nigeria solving problems of subsurface characterization and integrity.

The knowledge of fault was also applied on infrastructures such as buildings, roads, bridges and so on. We are of the opinion that buildings are expected to have certain characteristics that make them attractive for many uses which may be residential, commercial, institutional, educational, and industrial to meet people's daily needs. Characteristics of a good building include provision of security, safety to lives and properties, convenience, in addition to social, psychological and economic satisfactions derived by occupiers.

In some cases, buildings that are expected to meet the people's daily needs have become source of great concerns to occupiers, owners, developers, governments, and physical development planning authorities, consequent upon their incessant failure and collapses. Causes of foundation failure include: faulty or no subsurface investigation, wrong choice or wrong design of suitable foundation, and sinking of column footings. The frequency of collapse of building structures in Nigeria in the past few years had become very alarming and worrisome. Many lives and properties have been lost in the collapse of buildings mostly in Port Harcourt, Abuja and Lagos. Many property owners have developed high blood pressure and some have been sent to early grave. Figures 27 and 28 depict the effect of geologic fault on buildings. Furthermore, Figure 29, reveals the deteriorated portion of road as a result of geologic structure. Road failure is common in Nigeria such that there is no way someone would travel a 100 km journey without encountering this disaster on the road.

Figure 27: Building collapse in Lagos as a result of subsurface incompetency

Figure 28: Differential settlement in wall column as a result of subsurface structures (faults)

Figure 29: Road failure as a result of geologic fault

One of the fundamental principles of building design is that a building should be designed and constructed to meet its owner's requirements and also satisfy public health, welfare and safety requirement. No part of such building should pose a hazard to its occupants (Adagunodo *et al*., 2014).

Substandard material, especially reinforcement rods, steel sections and cement, can contribute immensely to failure of buildings. Some of these contractors are faithful to their clients but at the end of the day, the fact that they (contractors) have neglected the geophysical survey in order to understand the subsurface features, their effort went uncrowned with series of complains that arise after the construction of the building which finally leads to the collapse of the constructed building.

Subsidence and building collapse has become immense globally and Nigeria is not exempted. Due to increase in the number of people living in urban area and increase in the value of land, high-rise buildings have become preferred choice for people. Some of the high-rise buildings in urban areas have become death traps for the people living within because of cracks, subsidence, transport of water from subsurface to the supporting walls of the building, and finally sudden collapse.

An example of this is the research we carried out in Akure, to settle the dispute between a house owner along Oda Road, Akure, Ondo State, Nigeria and his contractor **(**Adagunodo, **Sunmonu** and Oladejo, 2017). Vivid cracks were seen from a high-rise building after the construction works had finished. This made the owner to believe that the contractor had used inferior building materials for the job. The building and the noticed cracks were revealed in Figures 30 and 31 respectively.

Figure 30: Location of the VES stations and the patched cracks in the building.

Figure 31: The cracks noticed at the Eastern fence that separates the building from another house.

The overburden thickness information of the study area varied between 14.9 and 39.6 m with an average value of 28.3 m as shown in Figure 32. This overburden is relatively thick for a high-rise building without an artificial basement before the foundation is laid. Besides, the surface looks good but the subsurface structure looks tilted at the spot where these cracks were observed (Figure 30).

The above investigation was embarked on to determine the characteristics of weathered layers in the study area, and to detect whether it will permit the transport of water from subsurface to the supporting walls of the building or not. The result showed that the apparent resistivities of the weathered layer's value constitute little and medium weathering processes with poor potential for groundwater. The weathered layer isoresistivity varied between 102.8 and 258 ∧m with an average value of 160.4125 ∧m. Therefore, water cannot be transported from the subsurface to the supporting walls of the building. The contractor has his blame because a geophysicist should have been invited for geophysical survey before the construction works started.

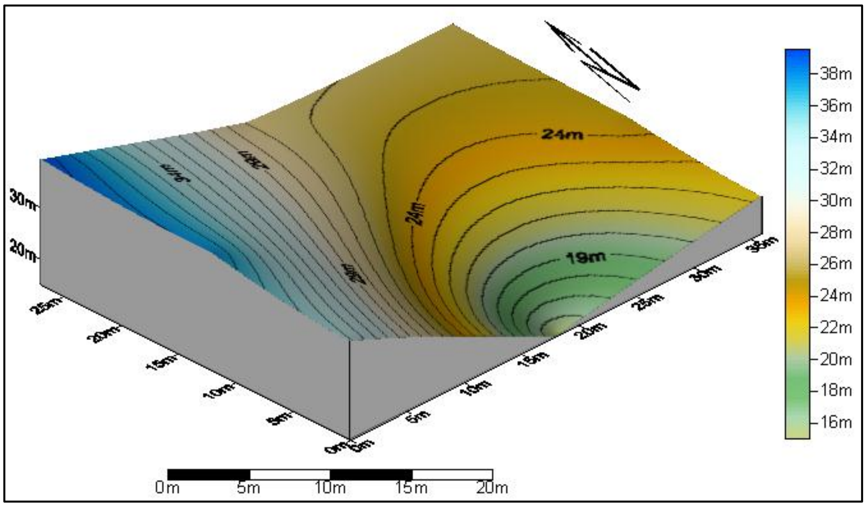


Figure 32: Three-Dimensional plot of overburden thickness in the area.

As if that was not enough, Adagunodo, **Sunmonu,** Oladejo and Olafisoye (2013), investigated into the cause of the subsidence at an abandoned Local Government Secretariat, Ogbomoso, South-western Nigeria, which was constructed in the regime of the old Oyo State. The coordinates of the building fall within latitude 8° 9′ 50.6″ to 8° 9′ 55.9″ and longitude 4° 15′ 36.1″ to 4° 15′ 42.3″ respectively. Ground magnetic method was employed with a view to determining whether the sinking and cracks in the plasterworks experienced at the eastern side of the area is due to subsurface features or insufficient use of building materials. Areas with high magnetic values are the competent zones for construction while areas with low magnetic values are the weak zones. The quantitative interpretation gave the overburden thickness to the top of the magnetic basement rock as varied between 7.0 to 13.0 m. Interpretation of ground magnetic data revealed that the weak zones present at the Southeastern, Eastern and North-eastern part of the area are the cause for the subsidence that occurred towards the eastern side of the building (Figure 33). Contrary to the opinion of people that the building contractor used inferior building materials for the construction, it was found out that half of the building was erected on collapsed tunnel, fault or fracture which resulted into the sinking and new cracks in plasterworks experienced at the eastern part of the abandoned Local Government Secretariat. Mr. Vice Chancellor Sir, the identified fault in the area extends through the roundabout to Kinnira area of Ogbomoso North Local Government Area.

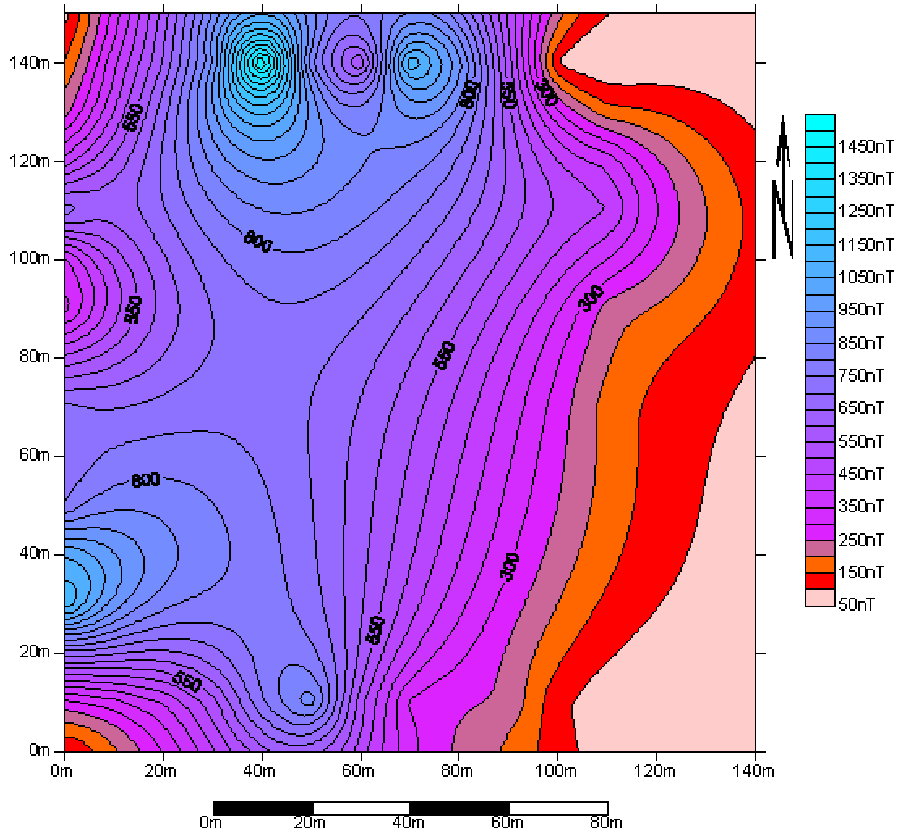


Figure 33: 2-D Plot of geomagnetic structures beneath the abandoned Local Government Secretariat, Ogbomoso, Nigeria

We also researched on estimation of overburden thickness of Industrial Estate, Ogbomoso, South-western Nigeria. Adagunodo and **Sunmonu** (2012**)**, using Vertical Electrical Sounding (VES) geophysical method to delineate the area which is bounded by latitude 08° 6′ 07.4″ to 8° 6′ 25.4″ and longitude 4° 15′ 03.3″ to 4° 15′ 49.0″. The focus of the study was to estimate the overburden thickness and to characterize the competent zones with respect to engineering purpose in the area. The geoelectric sections obtained from the sounding curves revealed 3-layer and 4-layer earth models (Figure 34). The models showed that the subsurface layers were categorized into the topsoil/first layer, second layer, third layer (which only revealed beneath one VES station), and the last layer (which is either fractured basement or fresh bedrock) (Figure 35). Areas with thick overburden and those with fractured basement were the ones we recommend that factories making use of heavy machines should not be built on because the continual vibration of the heavy machines might cause subsidence in the factories which might lead to loss of lives and properties. This result was in consonant with Adagunodo *et al*. (2012), using magnetic method.

Figure 34: Acquisition of ground magnetic data in Oyo State Industrial Estate, Ogbomoso (Adagunodo and Sunmonu, 2012).

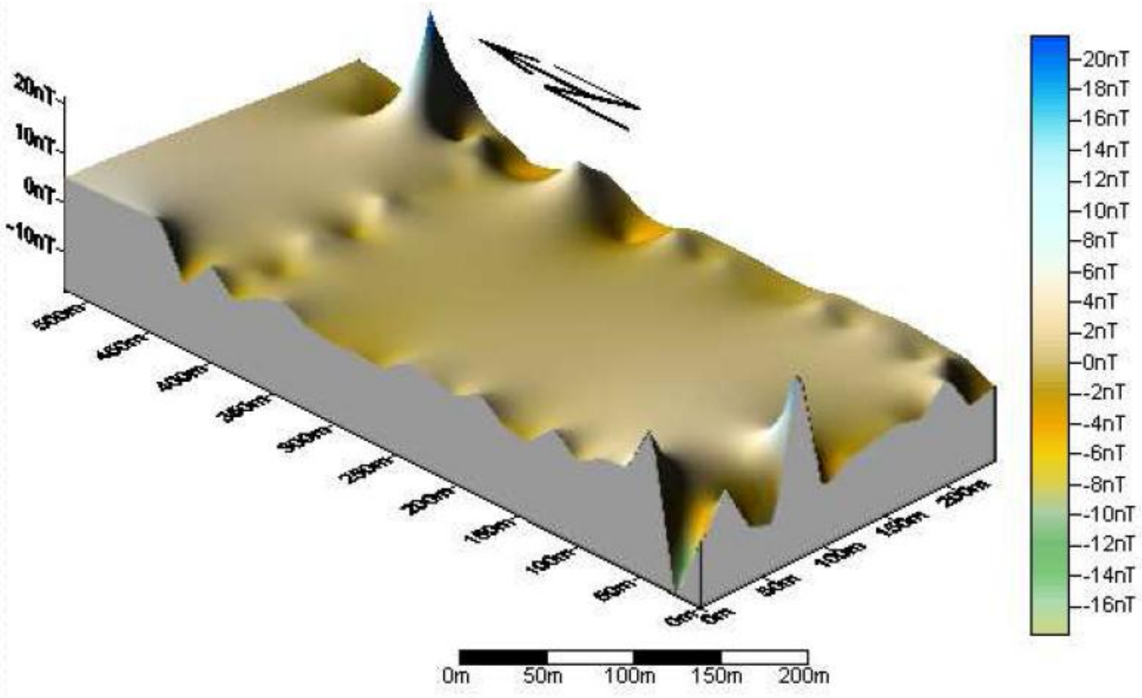


Figure 35: The 3-D Plot generated from geomagnetic signatures in Oyo State Industrial Estate, Ogbomoso

Another infrastructure which we worked on was a road which is a wide one leading from one place to another, especially one with a specially prepared surface that vehicles can use. Major roads in Nigeria are known to fail shortly after construction and well before their designed age. Poor construction materials, bad design, usage factor, poor drainage network, are some of the factors responsible for these failures. Subsurface structures are rarely considered as precipitators of road failures in Figures 36 and 37.

Figure 36: Loss of goods as a result of road failure

Figure 37: Accident on the highway as a result of road failure

Studies of past road failures showed some major causes as usage, poor design and construction problems (Levik, 2002), use of substandard materials for road construction (Momoh *et al*., 2008), bedrock depressions (Adeyemo and Omosuyi, 2012), presence of undetected linear features such as fractures and rock boundaries (Akintorinwa *et al*., 2010), and construction of roads on weathered layer (Ibitomi *et al*., 2014).

Geophysical survey was also carried out to unravel the cause of road failure along Takie-Ikoyi road, Ogbomoso, South-western Nigeria. The road which was constructed less than two years ago (as at the time of carrying out this research) has been abandoned due to its deterioration (Figure 38). Very low frequency-electromagnetic method (Figure 39) was used to carry out the research by Adagunodo, **Sunmonu** and Oladejo (2014). Conducting bodies which indicated clayey materials or linear geologic features such as faults, fractures, joints, and contact between two rocks were inferred from the interpretation in Figure 40. It was concluded that the road was constructed on clayey materials which was supposed to be excavated and refilled with artificial basements.

Figure 38: Snapshot of some stable and deteriorated portion of the area

Figure 39: The VLF-EM equipment

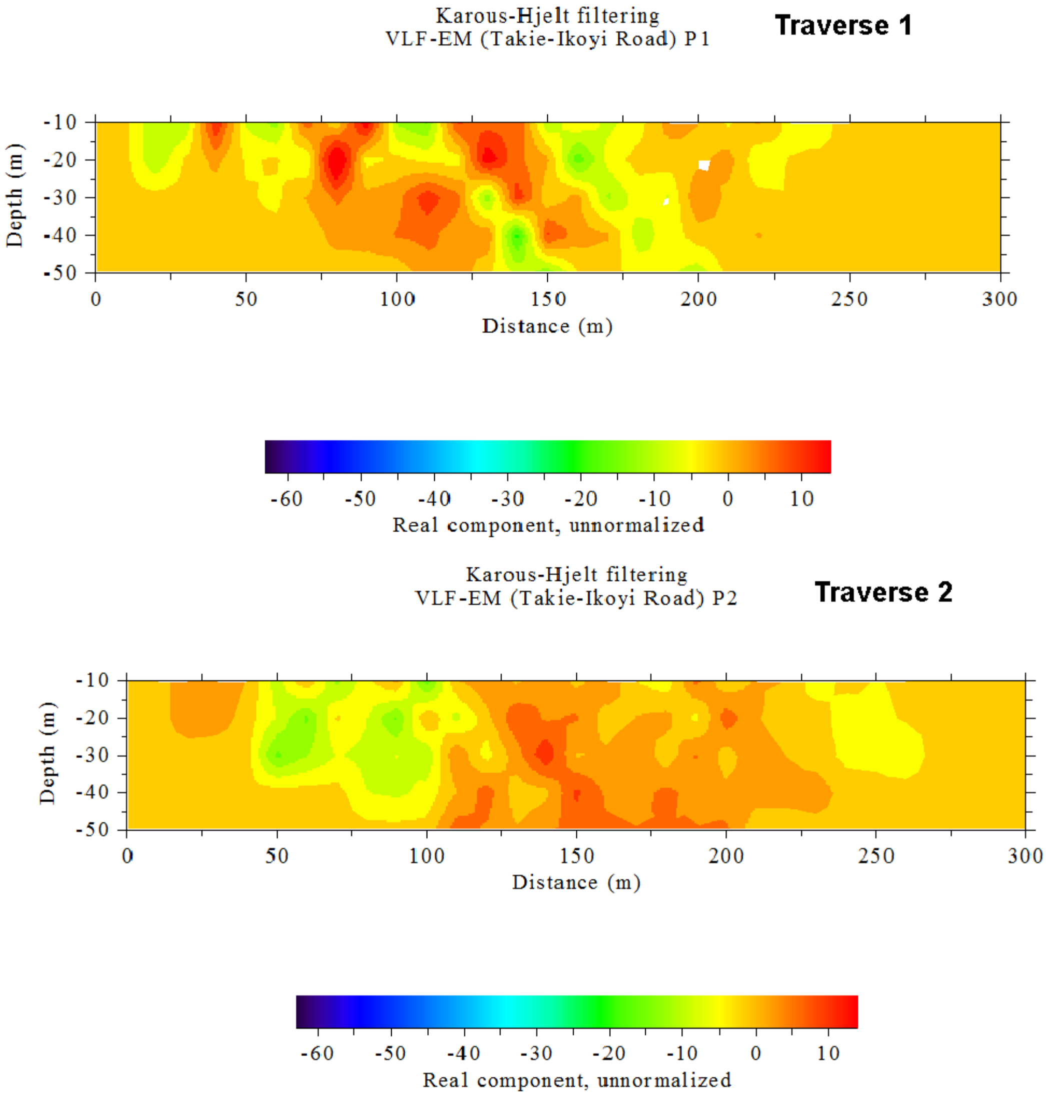


Figure 40: 2-D imaging of subsurface structure along Takie-Ikoyi road

Sunmonu, Alagbe, Mabunmi, Adeniji, and Olasunkanmi (2013), investigated the cause(s) of structural failure within BACOSA and the Faculty of Science Buildings, Bowen University Temporary site, Iwo. The geophysical methods used for the investigation were the Very Low Frequency Electromagnetic (VLF-EM) and the Electrical Resistivity (ER) methods. The results showed that the structural failure in the area were due to the presence of subsurface features mapped as fractures, faults, contacts and clayey formations present in the area. Therefore, in order to avert future geotechnical problems and to minimize resources used in repairing or total reconstruction of failed and distressed structures, the services of the geophysicist should be engaged for pre-foundation studies, which will act as a guide for the civil engineers before and during construction.

Adagunodo, **Sunmonu,** Oladejo, and Ojoawo (2013), has been able to highlight the importance of vertical electrical sounding in determining fractured distribution in the basement and to determine the overburden thickness of Adumasun Area, Oniye, South-western Nigeria, using electrical resistivity method. The result revealed that the overburden thickness of the area ranges from 3.1 to 20.1 m with an average of 10.63 m. From Figures 41 and 42, areas underlying with fresh bedrock and thin overburden thickness were recommended for the construction of high-rise buildings while areas with fractured basement and thick overburden thickness were recommended for the construction of low-rise buildings. It is recommended that other relevant geophysical methods be used in the study area so as to confirm the fractures pattern predicted in our study.

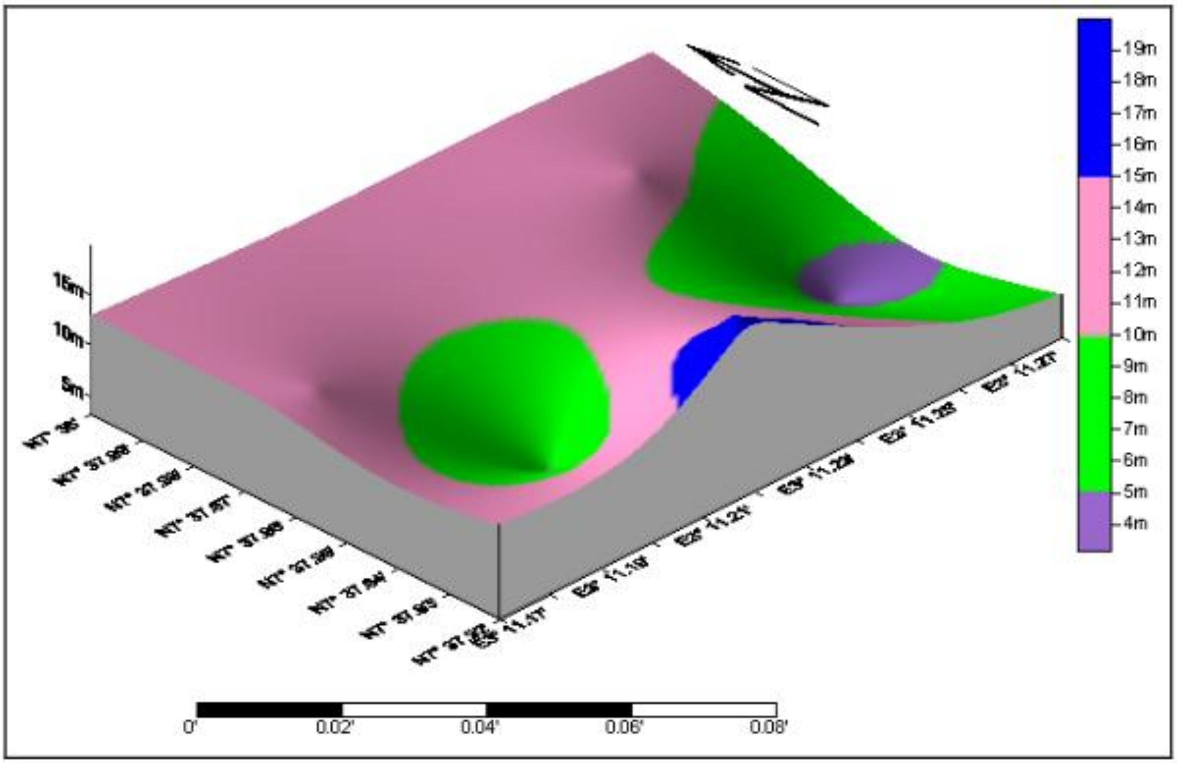


Figure 41: Surface (3-D) Plot of overburden thickness at Adumasun.

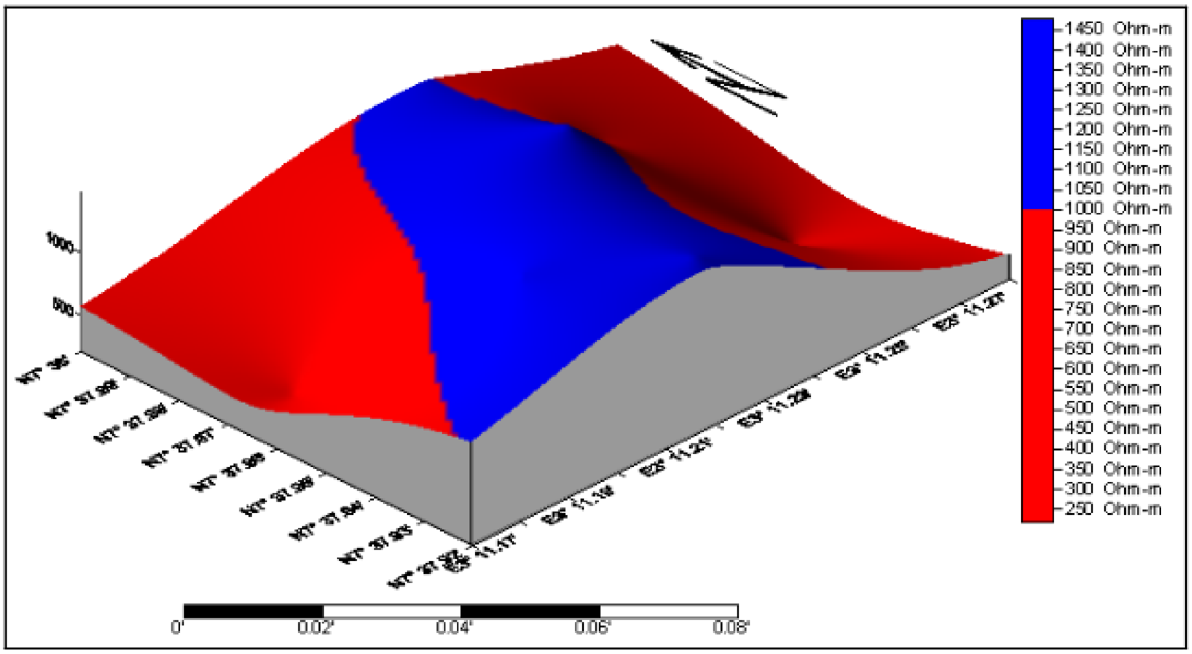


Figure 42: Surface (3-D) plot of bedrock resistivity at Adumasun.

Sunmonu, Alagbe, and Adeniji (2014), investigated the Ogbagba near Iwo South-western Nigeria, located between latitude 7˚500 to 8˚000 N and longitude 4˚000 to 5˚000 E in South-western, Nigeria (Figure 43). The need for foundation studies is highly significant since the alarming rate of structural failure in Nigeria has become more intense, as it may constitute a significant potential hazard to the downstream of people such as loss of valuable lives and properties that always accompany such failures. Therefore, there is the need for thorough mapping of bedrock configuration which is very important for both civil engineering and hydrogeological purposes. The groundmagnetic data acquired from the study area was analyzed using second vertical derivative. The study revealed a network of geologic features which are the reflections of the basement pattern within the study area. The major parts of the area is generally considered good for engineering purposes with the exception of some parts of the south-western portion where a deep fault is suspected. However, this part could be a better site for groundwater development.

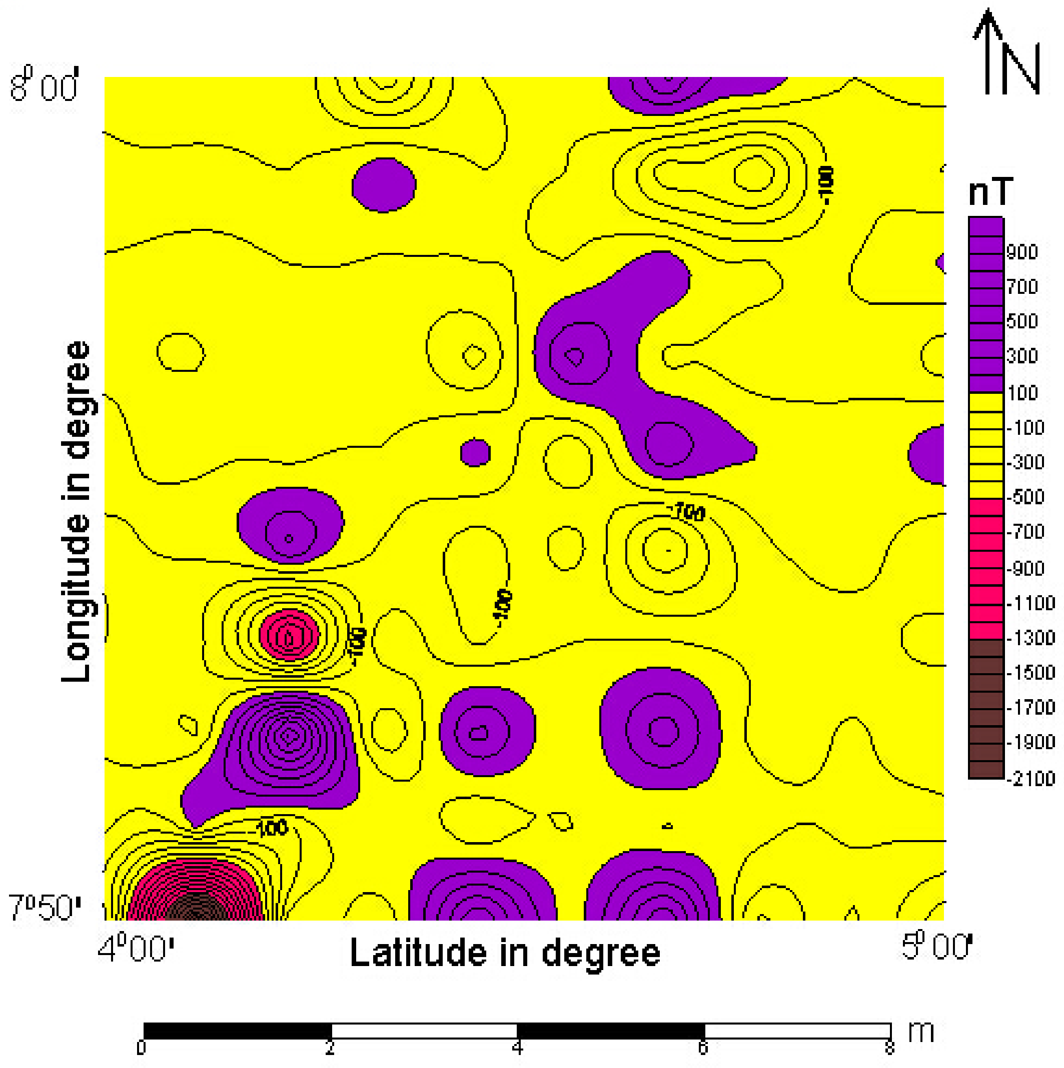


Figure 43: Residual map of the area

4. Environmental Geophysics

As the product of weathering from the parent rock, soil is not only a medium for plants growth or waste disposal but also a transmitter of many pollutants to surface water, groundwater, atmosphere and food. Soil pollution may threaten human health not only through its effect on hygiene quality of food and drinking water, but also through its effect on air quality (Odukoya, 2015). Little attention has been paid to food and water related diseases as a result of environmental hazards. One of the identities of any developing nation like

Nigeria is disease epidemic which has claimed lives more than war, and have impoverished and made most of the African Countries still on their knees.

Mr. Vice-Chancellor Sir, in my quest to proffer solutions to mass challenges on Environmental Impact Assessment (EIA), I have been able to assess the quality of drinking water and the extent of contaminant plume around dumpsite, assess the impacts of heavy metals on agricultural soils for sustainable food security, and apply radiometric survey to analyze the radiological hazards associated with over exposure to radionuclides in contaminated areas.

Groundwater is very essential for domestic, industrial and agricultural applications. The health and productive life of the people in any society depend solely on potable and safe drinking water. However, maintaining a good quality groundwater supply free from microbial and chemical pollution is far from reality in most of our cities and towns due to poor waste disposal and management practices. The major causes of waste generation are industrial development and increased urbanization in the municipality. The problem of inadequate trained waste disposal personnel and equipment, poor waste collection, inadequate solid waste disposing method, improper functioning septic tank systems, and indiscriminate location of disposal sites without regard to the local geology and hydrogeology of the area, contribute significantly to the contamination of soil and groundwater. Polluted groundwater has elevated microbial, ionic and volatile organic content, resulting to hazardous effects on public health and poor groundwater quality. As a result of the imminent dangerous impact of solid waste disposal site, it has become necessary to investigate the subsurface contaminant level of soil and groundwater around a municipal solid waste dumping site. The waste disposal site receives municipal wastes, mainly domestic garbage, with hazardous and non-hazardous constituents. These release large amount of leachate into the surrounding soil and groundwater.

Generally, electrical resistivity method provides economical and reliable means to identify and delineate leachate contaminant plumes from waste disposal site because there is elevation in the electrical conductivity of leachate to that of natural groundwater.

Sunmonu, Olafisoye, Adagunodo, Ojoawo and Oladejo (2012), conducted an investigation on the impact of waste disposal site on groundwater resources around Aarada area, Ogbomoso, Oyo State, Nigeria, using electrical resistivity (vertical electrical sounding) and hydro-physicochemical methods as revealed in Figure 44.

The research was carried out to map out the contamination patches at the subsurface and investigate the contamination level of the various hand dug wells situated in the area. The hydro-physicochemical analysis was conducted both at the peak of the wet and dry seasons on nine (9) water samples taken from nine different hand-dug wells in Aarada area, Ogbomoso, Southwestern Nigeria. The result obtained from the interpreted vertical electrical sounding (VES) data revealed leachate plumes at the subsurface in the study area. The outcome of the hydro-physicochemical method revealed hazardously high values of Fe^{2+}, Pb^{2+}, Zn^{2+}, Cu^{2+} and NO_3^- to further support the findings from the VES survey.

Figure 44: Geophysical survey in Aarada area showing the electrical resistivity survey gadgets

In another study, the nitrate concentration of the groundwater in some parts of Ogbomoso, Southwestern Nigeria, was investigated by **Sunmonu,** Adabanija, Ayantunji, and Awodele (2005), from hand-dug wells scattered over the locality between latitude $8^0$5'N and $8^0$11'N and longitude $4^0$12' and $4^0$19'.

The study revealed that concentrations of nitrate ranged from 5.64 mg/l to 15.63mg/l in water; and 35.35 mg/l to 168.07 mg/l in soil. The high concentrations are due to the shallow depth of well, proximity to dump site, high hydraulic conductivity of the soil media, and high clay mineral content of the vadose zone. Other non-point sources also contribute infinitesimally to the nitrate contamination. It is suggested that hand dug wells that are meant for consumption should be very deep and sited far away from dump sites and other potential non-point sources. Furthermore, there is need to control or prevent indiscriminate waste disposal by locating land fill or waste dump areas far away from residential areas.

Adegoke, **Sunmonu** and Lateef (2010), researched on the effect of water pollution in selected water dams in Osun State, Southwestern Nigeria. The level of water pollution by heavy metals (Cu, Zn, Co, Ni, As, Mn, Cd, Cr, Pb) in twelve selected dams in Osun State were determined in order to know their distribution and possible source into the dams. Their bottom sediments were collected for analysis. The result showed that concentration of manganese was high in all the dams with values ranging from 21.27 to 775.99 mg/kg and it spreads across all locations. Cobalt was detected only at one location with concentration of 3.01 mg/kg. The result in water analysis showed that the concentration of zinc was more than that of manganese, almost in all the dams. The values detected were between 0.0618 and 0.5068 mg/kg, while that of manganese was between 0.0112 and 0.1887 mg/kg. Cobalt and cadmium were not detected in all the dams. The variation in the concentration of these metals in sediment and water may be due to chemical factors such as solubility, ion exchange ratio, and electrochemical deposition. The concentrations of all metals detected were below the standard limit for the heavy metals in surface water according to World Health Organization. Meanwhile, bioaccumulation of these metals in the body tissue may be toxic to human health. Adegoke, **Sunmonu** and Ojeniyi (2010), also conducted similar research in selected functional dams in Oyo State, Southwestern, Nigeria. The result of the research showed that the concentrations of Manganese (Mn) varied from 14.18 to 332.96 mg/kg, Zinc (Zn) varied from 6.18-52.53 mg/kg, while lead (Pb) was not detected in virtually all the locations except in Ilora which had a concentration of 0.87 mg/kg. The presence of lead in Ilora was attributed to the activities of automobile mechanics around the dam. In the water samples, the result showed that the concentration of heavy metals is very low and is far below the limit specified by World Health Organization (WHO). Zinc (Zn) had the highest concentration ranging from 0.049 to 0.729 mg/kg while manganese (Mn) varied between 0.011 and 0.344 mg/kg. Lead (Pb), Cadmium (Cd) and Cobalt (Co) were not detected at all in all the water samples. The variation in the concentrations may be due to geological nature of the ground, solubility, ion exchange, and human activities.

Adabanija, **Sunmonu** and Olayinka (2002), used integrated geochemical and electrical resistivity techniques in the investigation of corrosive characteristics of groundwater in low latitude crystalline basement, Ogbomoso. The method used involved elemental analysis of water samples collected from boreholes and open wells scattered over the locality for major anions namely chloride (Cl^-), sulphate (SO_4^{2-}), carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-); and vertical electrical sounding (VES) survey over the areas in the vicinity of the sampled wells and boreholes. The resultant apparent resistivity curves obtained from VES data were interpreted using conventional and computer-assisted techniques to obtain the layer model/parameters. The resistivity of the saprolitic zones, the corrosivity ratio computed using Ryzner expression and physicochemical parameters were then contoured. The overlaying and correlation of the corrosivity ratio and saprolite zone resistivity maps indicate that low corrosive factor regions are characterized by low resistive (< 3.0 Ωm) saprolitic zones. Therefore, the corrosive transition resistivity value of the groundwater in the study area was 3.0 Ωm. Consequently, regression analysis of the anion concentration and pH as well as the overlaying of contour maps of pH-values and corrosive ratio revealed that the limiting corrosivity factor is 0.46 corresponding to a pH value of 6.95.

Adagunodo, **Sunmonu** and Emetere (2018), used Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to analyze ten (10) basic heavy metals namely: copper (Cu), lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), cadmium (Cd), nickel (Ni), antimony (Sb), cobalt (Co) and vanadium (V) from soil samples in a farmland at Odo Oba, Ogbomoso, Nigeria. The results were compared with the International Standard (UNEP, 2013) in order to check the risk(s) of crops grown on these farm lands if contaminated. It was revealed that none of the heavy metals in the study area exceeded the threshold limit as presented in Table 3. However, the maximum range of the samples showed that Cr and V exceeded the permissible limit which could be associated with ecological risk.

In our upcoming findings from the Bulletin of the Mineral Research and Exploration, Adagunodo, **Sunmonu**, Adabanija, Omeje, Odetunmibi and Ijeh (2018), assessed the radiation exposure risks of farmers on agricultural farm settings at Odo Oba, Ogbomoso, Oyo State as we all know that Odo Oba is significant in this environment in terms of food security. The concentrations of thorium, uranium and potassium in the randomly selected topsoil samples from Odo Oba were determined using ICP-MS. The risks; namely: Dose Rates (DR), Annual Effective Doses (AED), Annual Gonadal Equivalent Dose (AGED), Excess Life Cancer Risk (ELCR), External Radiation Hazard Index (H_{Ext}) and Gamma Radiation Hazard Index ($I_{\gamma r}$) as well as the radioelements' ratios were estimated from the naturally occurring radionuclides in the study area.

Table 3: Threshold and permissible limits for heavy metals in soils.

Variables	Threshold limit (mg kg^{-1}) [1, 2]	Permissible limit (mg kg^{-1}) [1, 2]	Present Study (mg kg^{-1})	
			Range	Mean
Cu	100.0	50.0 (er)	3.91 – 20.69	9.14
Pb	60.0	200.0 (hr)	18.99 – 43.89	28.37
Cr	100.0	200.0 (er)	23.00 – 341.00	81.20
As	5.0	50.0 (er)	1.60 – 3.70	2.40
Zn	200.0	250.0 (er)	22.80 – 61.30	31.17
Cd	1.0	10.0 (er)	0.02 – 0.06	0.03
Ni	50.0	100.0 (er)	7.90 – 31.80	15.24
Sb	2.0	10.0 (hr)	0.06 – 0.27	0.13
Co	20.0	100.0 (er)	6.30 – 19.10	10.59
V	100.0	150.0 (er)	22.00 – 124.00	47.70

Note: The risk associated with higher concentrations greater than the permissible limits are grouped into ecological risk (er) and health risk (hr).

The mean concentrations of thorium and potassium were greater than the global average of 30 and 400 Bq kg^{-1}, while uranium fall below the global average of 35 Bq kg^{-1}. In comparison with the results of other studies from Nigeria and other parts of the world (as presented in Table 4), it was revealed that this present study is in agreement with their outcome, except for few cases where the results were below the global average (such as Akinloye *et al*., 2012 and Avwiri *et al*., 2012). The high concentrations of thorium in the study area were associated with the nature of the terrain, as the thorium enriched materials carried from afar are deposited around Odo Oba over the years. Farmers working on Odo Oba can be exposed to thorium by inhaling contaminated dust. The crops grown on the farm land can be contaminated and be transferred to humans by consumption. The estimation of radioactivity ratios showed that depletion of uranium and enrichment of thorium occur in the study area. The estimated radiological risks showed that the mean values of DR, AED, AGED, ELCR and $I_{\gamma r}$ were greater than the global average by the factors of 1.42, 1.43, 2.04, 1.24 and 1.36 respectively. However, the mean of H_{Ext} fall below the global average. The farmers were advised to take safety measures whenever they are on the farm land in order to prevent them from being overexposed to natural radionuclides.

Table 4: Comparison of the results of radioactivity concentrations in this study with other works

Authority	^{238}U (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	Location
Present study	29.40	44.25	1072.07	SW, Nigeria
Akinloye *et al*., (2012)	25.55	11.60	191.78	SW, Nigeria
Adagunodo *et al*., (2018a)	38.17	65.11	93.90	SW, Nigeria
Adagunodo *et al*., (2018b)	46.67	71.76	108.73	SW, Nigeria
Avwiri *et al*., (2012) site 1	13.71	10.45	57.17	SE, Nigeria
Avwiri *et al*., (2012) site 2	11.49	8.83	59.77	SE, Nigeria
Ravisankar *et al*., (2016)	9.19	45.60	295.11	India
Turhan (2009) site 1	39.30	49.60	569.50	Turkey
Turhan (2009) site 2	82.00	94.80	463.60	Turkey

5. Groundwater Exploration

Groundwater has been in existence since ancient days as a God's gift to human and plant's for survivals. This evidence can be found in the Holy Scriptures:

> ''So We open the gates of heaven, with water pouring forth. And We caused springs to gush forth from the earth……''
>
> (Quran: Chapter 54 verse 11-12).

Also, from the biblical view:

‘‘…….the same day were all the fountains of the great deep broken up and the windows of heaven were opened’’.

(Genesis 7:11).

Another instance that talks about groundwater is the sojourn of Prophet Musa (Moses) through the Arabian Desert,

‘‘And remember Musa prayed for water for his people; We said ‘‘Strike the rock with thy staff’’ then gushed forth therefrom twelve springs….’’

(Quran Chapter 2 verse 60)

‘‘Thou shalt smite the rock and there shall come water out of it that the people may drink’’

(Exodus 17 verse 6).

All these narrations are confirming the occurrence of subsurface groundwater.

Water is described as the most indispensable natural resource which life depends on (Oladejo *et al*., 2013; Adagunodo *et al*., 2018). It can be obtained from the troposphere as rain, surface flow as rivers and streams, and subsurface flow as groundwater. Rain and surface water are easily contaminated by human activities and at times, insufficiently distributed for human use. Access to safe water for diverse usage in both urban and rural settings of Nigeria has been the major challenge to the masses (Figure 45). Though the State Water Corporations make use of some minor rivers for the municipal water supply, the truth is that their distributions are insufficient for domestic uses let alone its availability for agricultural and industrial uses. In the present state of Nigeria, groundwater has been the only source of water for all activities.

In Sub-Saharan Africa (SSA), four hydrogeological provinces, which control the occurrences of groundwater in different domains are present. These provinces are: PreCambrian basement, consolidated sedimentary rocks, unconsolidated sediments, and volcanic rocks.

The land areas of the provinces in SSA are 40, 32, 22 and 6% respectively. The weathered rocks or fractured bedrocks are the prospects for groundwater in the PreCambrian basement while limestones and sandstones are the aquifers in the consolidated sedimentary environment. The aquifers in the unconsolidated sediments are composed of gravels and sands, while the fracture zones with the lava flow and palaeosoils are the major housing for groundwater in the volcanic rock settings (Adagunodo *et al*., 2018). Groundwater exploration involves the use of scientific methods to locate and extract groundwater. It helps to understand the aquifer's nature; type and quality, as well as its groundwater quality.

Figure 45: Basic ways of sourcing for domestic water in Nigerian villages

The urge for groundwater exploitation is very high in Oyo State Housing Estate, Ogbomoso, South-western Nigeria. As a result of this, Oladejo, **Sunmonu,** Ojoawo, Adagunodo and Olafisoye (2013), carried out a research to delineate for groundwater potential zones to ease the problem of water scarcity in the study area, because the site is experiencing structural developments and there is no other source of portable water nearby. Geophysical investigation was carried out in the study area using Very Low Frequency (VLF) method. The findings revealed a number of conductive zones for groundwater development for both domestic and commercial purposes. Certain distances showed to be promising area for groundwater development across the profiles. The distances include 160 m at profile 1, Figure 46, 15 and 130 m at profile 2, Figure 47, 0, 100, 125 and 225 m at profile 3 Figure 48, 240 m at profile 4, Figure 49, 150 m at profile 5, Figure 50, 100 and 165 m at profile 6, Figure 51, respectively.

The zones that have been delineated for high groundwater yields should not be designated for any other purpose but for the good of individuals and the community at large.

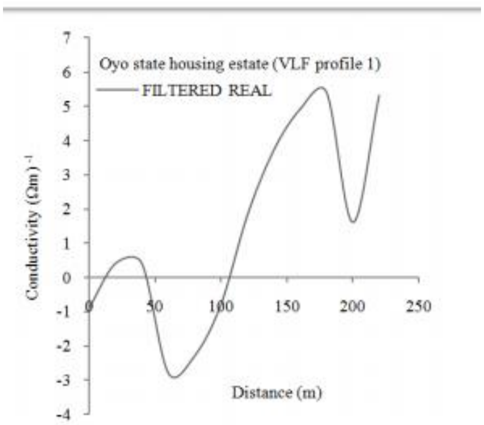


Figure 46: VLF-EM plot of profile 1

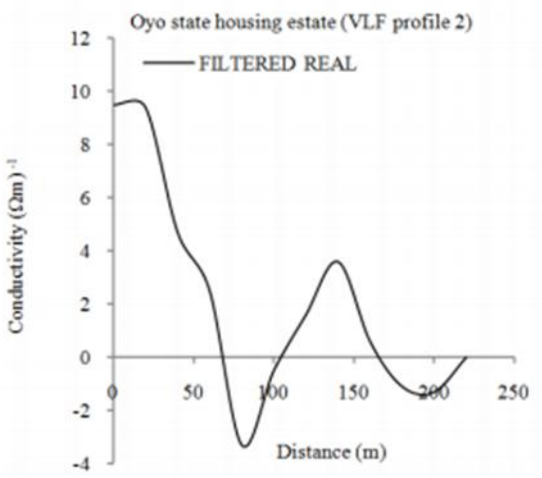


Figure 47: VLF-EM plot of profile 2

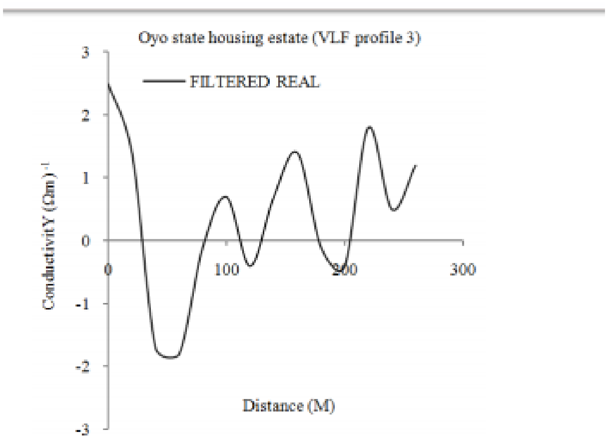


Figure 48: VLF-EM plot of profile 3

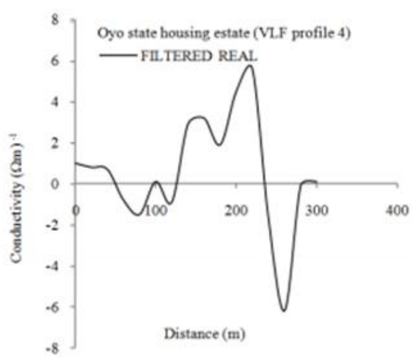
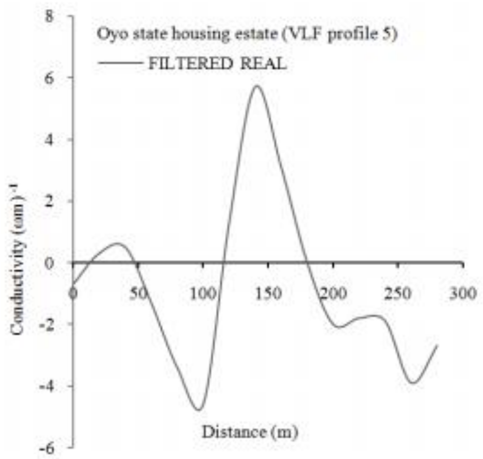


Figure 49: VLF-EM plot of profile 4



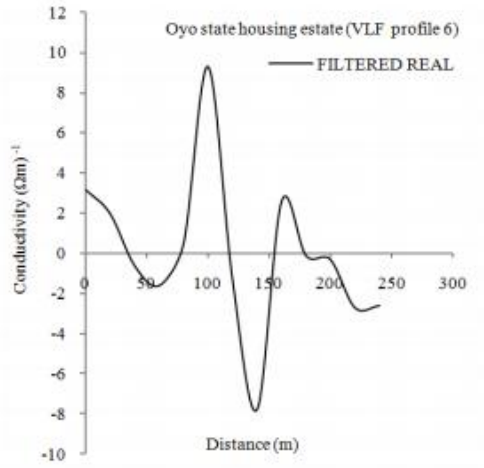


Figure 50: VLF-EM plot of profile 5 **Figure 51: VLF-EM plot of profile 6**

The groundwater exploration of Oyo State Industrial Estate, Ogbomoso for prolific zone(s) of groundwater was also investigated by Adagunodo, **Sunmonu,** Ojoawo, Oladejo and Olafisoye (2013), using the Schlumberger electrode array configuration with current electrode separation (AB) varying from 130 to 200 m. The geoelectric sections obtained from the sounding curves revealed 3-layer and 4-layer earth models respectively. The models showed that the subsurface layers were categorized into the topsoil, weathered/clay, fractured layers and the fresh bedrock. The weathered basement and fractured basement are the aquifer types delineated in Industrial Estate, Ogbomoso. Flow net and bedrock relief maps showed that the Southern, North-eastern and towards the base of North-western direction of the area are good for borehole development.

Oladejo, **Sunmonu,** and Adagunodo (2015), carried out another research on ground water investigation using electromagnetic method at Ibodi village, Ilesha, in Atakunmosa West Local Government Area of Osun State. Ibodi falls within latitude $7^{0}35'35.21'$ North and longitude $4^{0}40'48.28''$ East. The development and increase in immigrants at Ibodi has necessitated this study. It was discovered that distances (100.0-140.0) m, 40.0 m, 80.0 m and 35.0 m on profiles 1, 3, 4 and 5 respectively (Figures 52-55), revealed fractured zones which are suspected to be the best locations for groundwater prospects in the area.

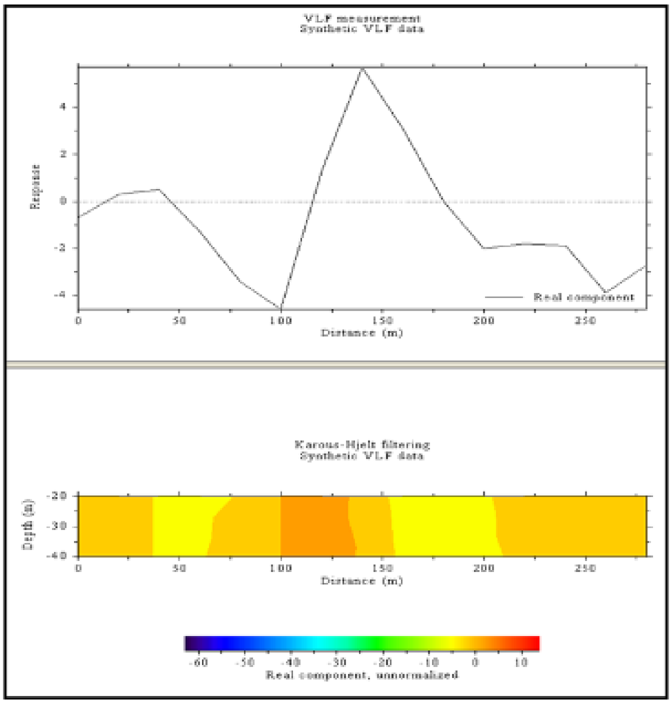


Figure 52: Karous-Hjelt representation of profile 1

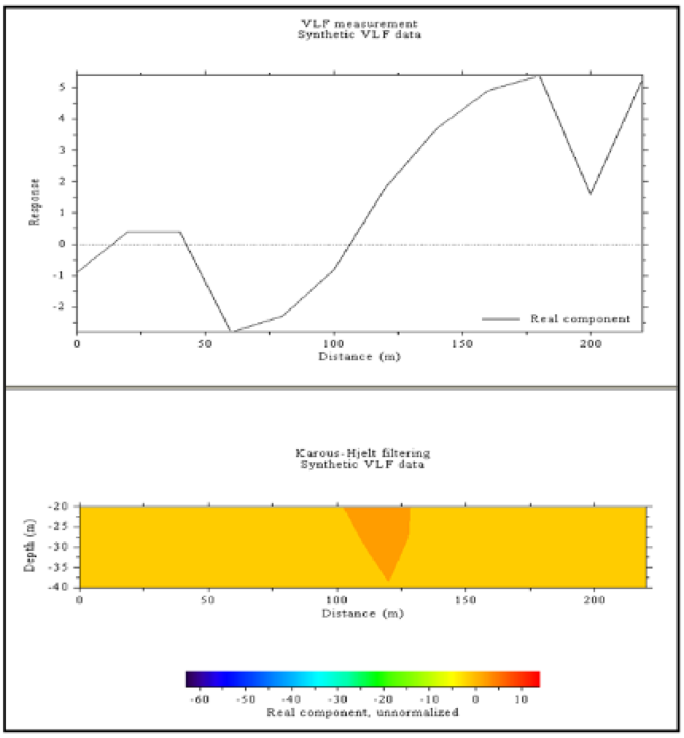


Figure 53: Karous-Hjelt representation of profile 3

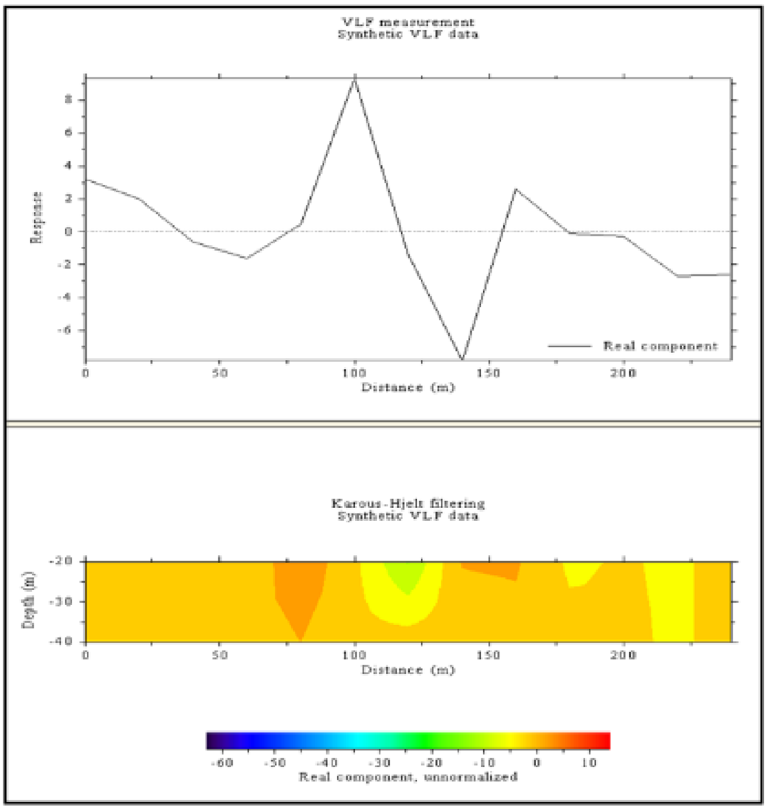


Figure 54: Karous-Hjelt representation of profile 4

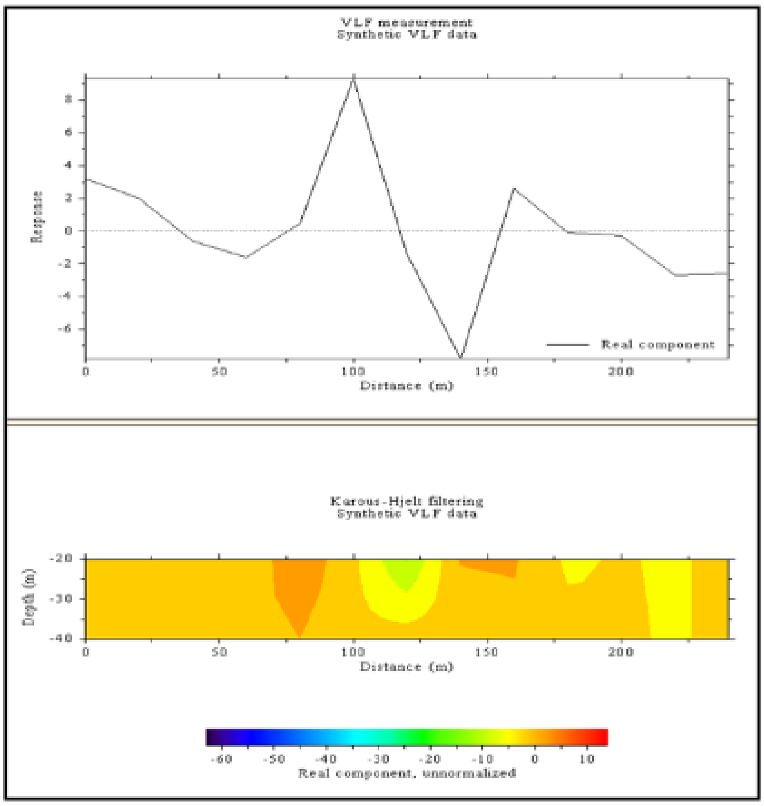


Figure 55: Karous-Hjelt representation of profile 5

Sunmonu, Adagunodo, Adeniji, Oladejo and Alagbe (2015), carried out geoelectric delineation of aquifer pattern in crystalline bedrock in Ogbaagba area of Osun State. This investigation tends to delineate the subsurface in order to understand the aquifer pattern in Ogbagba area. The result showed that 75% of the aquifers in the study area were confined aquifers while the remaining 25% were unconfined aquifers. Also, three probable aquifer units were delineated where clayey sand had 75%, sandy clay constituted 16.7% and fractured bedrock shared the remaining 8.3%. The study revealed that insufficiency of groundwater exploitation in the study area is due to the geologic formation of the aquifers and the depth to which groundwater is being abstracted. If these mistakes are corrected, Ogbagba will henceforth start to enjoy groundwater exploitation adequately.

Also, at Oke-Ogba area in Akure, Ondo State of Nigeria, Alagbe, **Sunmonu** and Adabanija (2010), researched on groundwater exploration with the aim of establishing dominant hydrogeologic factors that are responsible for borehole drilling in Oke-Ogba. The interpretation of magnetic intensities of the profiles revealed a network of geological features such as faults, joints and fractures. The high magnetic intensity at the central portion of the constructed magnetic contour map revealed shallow basement. This was corroborated with quantitative interpreted result, which established overburden thickness to the top of the magnetic basement rock as varied between 3.0 and 21.0 m (Table 5). The study established that geological features are more prominent hydrogeologic indicator for groundwater development in the area.

Table 5: Summary of the Quantitative and Qualitative interpretations of the area.

Profile	Estimate of depth to basement range	Geological structures
1 (AA_1)	4.0-16.0 m	Fault or Fracture
2 (BB_1)	4.0- 21.0 m	Undifferentiated Basement rock, Fault or Fracture
3 (CC_1)	4.0- 16.0 m	Undifferentiated Basement rock, Vein
4 (DD_1)	3.0- 12.0 m	Vein, Undifferentiated Basement

Adagunodo and **Sunmonu** (2013), investigated the groundwater prospect and vulnerability of overburden aquifers of Adumasun, South-western Nigeria, using geoelectric assessment. Inadequate municipal water supply from State Water Corporation, coupled with hydrogeological nature of the terrain makes individuals and corporate bodies to indiscriminately sink tube wells and boreholes within the unconsolidated overburden materials, with glaring lack of concerns for the vulnerability status of aquifers, and possible environmental risk. The resistivity parameters of the geoelectric topmost layer across the area were also used to assess the vulnerability of the underlying aquifers to near-surface contaminants. The thickness of the unconsolidated overburden varies from 3.1 m to 20.1 m (where about 60 % falls within the 10-14.9 m). This shows that unconsolidated materials are not thick and hence averagely low groundwater prospect while 80% of the topmost geoelectric layer in the area has resistivity mostly within the range of 1-100 Ωm which can constitute effective protective geologic barriers for the underlying aquifers.

Aquifers within the unconsolidated overburden at Adumasun Oniye were mostly capped by impermeable/semi-permeable materials, protecting the underlying aquifers from near-surface contaminants.

One of the problems that may be facing any community as large as Bowen University is the location of portable sources of water. Therefore, Alagbe, **Sunmonu,** and Adabanija (2013), used combined method of very low frequency (VLF) electromagnetic profiling and Side Looking Airborne Radar (SLAR) imagery to study the lineament pattern of the area. Prominent lineaments mapped from SLAR imagery varies from 0.72km to 1.39km for long lineaments and 0.11km to 0.56km for short lineaments (Table 6). The contour map constructed from the VLF data and the lineament density contour map constructed from lineament length values shows the North-eastern parts as feasible and remain the best site for groundwater and any other hydrogeologic development which were shown in Figures 56 and 57.

Table 6: Summary of the length values from lineament map of the area

	1	2	3	4	5
A	0.92	0.79	1.04	0.54	0.51
B	0.46	0.46		0.73	1.39
C	0.46		0.11	0.85	0.19
D	0.31		0.42	0.42	0.73
E	0.74		0.56	0.80	0.72

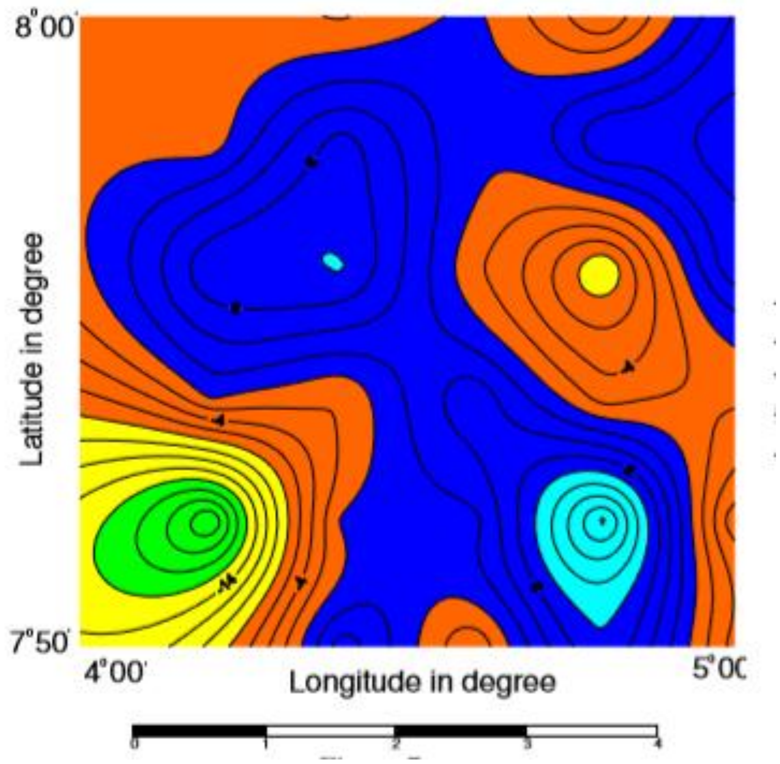


Figure 56: Conductivity contour map of the study area

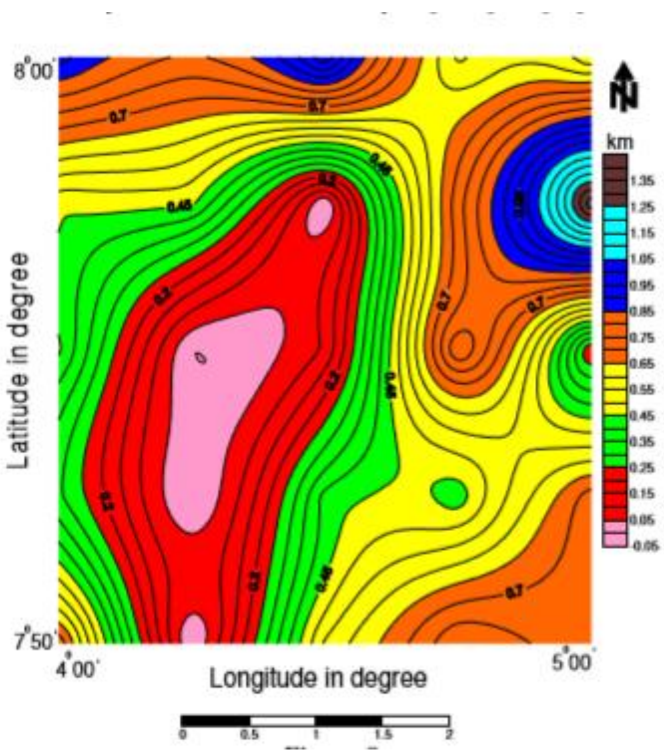


Figure 57: Lineament density contour map of the study area

The most recent on groundwater exploration study was the outcome of our research in Aaba area, Akure, Nigeria. Adagunodo, Akinloye, **Sunmonu,** Aizebeokhai, Oyeyemi and Abodunrin (2018), investigated the groundwater exploration, using Vertical Electrical Sounding (VES) to establish drillable zone(s) for groundwater and recommend the appropriate depth to which boreholes can be sunk to exploit an appreciable volume of water in the subsurface. We inferred from the groundwater potential map (Figure 58) that the eastern and the south-western parts of the area were associated with high groundwater yield. Boreholes could be drilled to an average depth of 22.0 m on these axes. The groundwater potential of the northern, central and southern parts of the area was inferred to be of medium potential. The borehole drilling along these axes can be extended to the depth of 30.0 m. However, the north-eastern and the western zones were characterized by low groundwater potential.

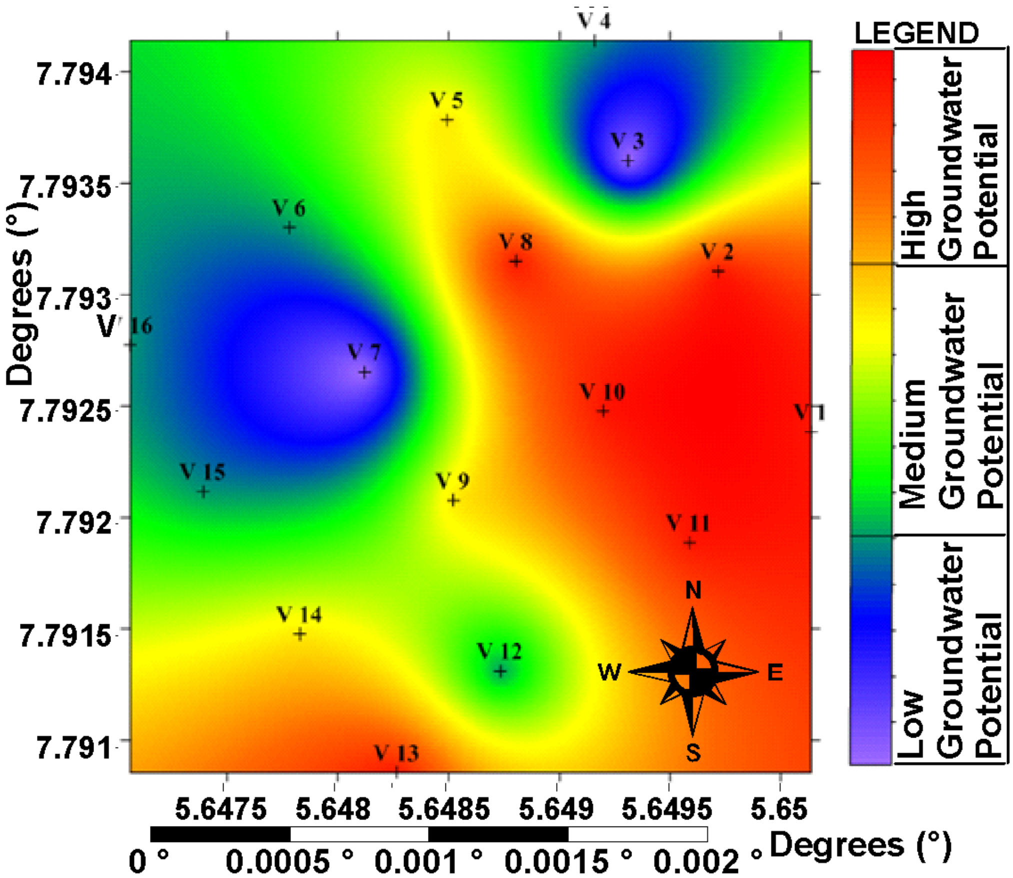


Figure 58: Final groundwater potential map of Aaba area, Akure, Nigeria

6. Solid Mineral Exploration

The desire of Nigeria government to diversify the economy to include mining necessitates the need to rationalize a turn-key approach in exploration of solid minerals to improve the economic base. Minerals occur naturally as inorganic solid with definite chemical composition and organized internal structure (Alva, John and Jasmine, 2009). According to the Federal Ministry of Industry, Trade and Investment (FMTI, 2016), the rock beneath Nigeria soil is rich with variety of solid minerals of various categories ranging from precious metals to various stones and also industrial minerals such as barites, gypsum, kaolin, aurum and marble, but the level of exploration is very low.

In view of this, Olasunkanmi, **Sunmonu,** Adabanija, and Oladejo, (2018), processed, enhanced and analyzed high resolution aeromagnetic data of Igbeti-Moro in order to map geologic structures related to mineral exploration in the area. From the results, lithological boundaries and contacts, intersection of geological structures, faults and magnetic sources depths were established. The magnetic anomalies revealed marble, gabbro, amphibolites and muscovite mineralogy which are distributed within the western, northern and north-eastern parts of the area and bounded by gneiss and older granitoids; which formed the major lithologic unit of the area (Figure 59). The minerals exist at shallow depth range of 0-200 m and have possibly been deposited by intrusion of hydrothermal fluids along quartz schist veins during the deformation that led to the formation of resultant faults. The pattern of occurrence and associated geologic structures showed that the mineral deposits in the area are structurally controlled; which is critical in mining operation.

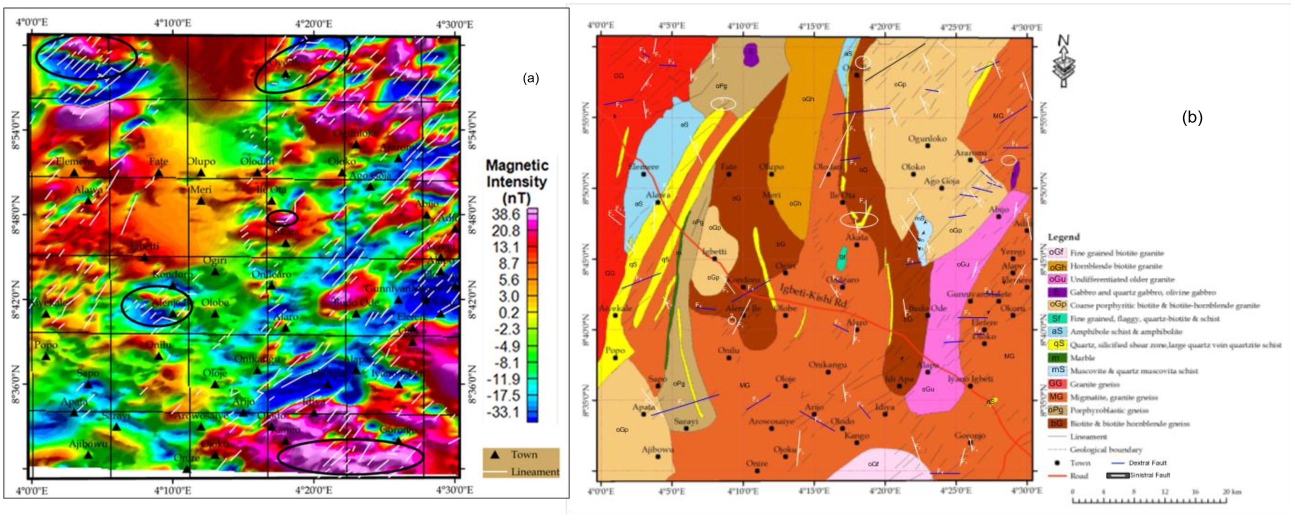


Figure 59: Fault classification maps showing the extracted lineaments from THDR overlaid on (a) RTE magnetic intensity and (b) geological maps

The Upper Benue basin being part of Benue basin is believed to be rift valley and is expected to be a major depositional basin, because rifting structures are often good sites for mineralization. The strategic economic importance and the availability of data from the area aroused the interest of Alagbe and **Sunmonu** (2014), to interpret the aeromagnetic data from upper Benue Basin, Nigeria in search of geological features that are favourable to mineral deposition in the basin.

In the study, the interpretation of the data extracted from the aeromagnetic maps of the basin was carried out using automated techniques involving the analytic signal, horizontal gradient magnitude and the log power spectrum techniques to delineate linear geologic structures such as faults, contacts, joints and fractures within the area in a bid to unravel the gross sub surface geology of the area which would, no doubt, help in better understanding and characterization of the area. The result obtained, revealed that the area is divided into three basinal structures; the deep sources ranging between 6.5 km and 10.5 km are associated with some layers of intra-crustal discontinuities; an indicator to feature volcanic eruption in the area. The intermediate depths between 3.5 km and 5.5 km correspond generally to the top of intrusive masses occurring within the basement, a depth deep enough for possible hydrocarbon deposit. Shallow depths between 0.01 km and 2.5 km were attributed to shallow intrusive bodies or near surface basement rocks probably isolated bodies of ironstones formation concealed within the sedimentary pile (Figure 60).

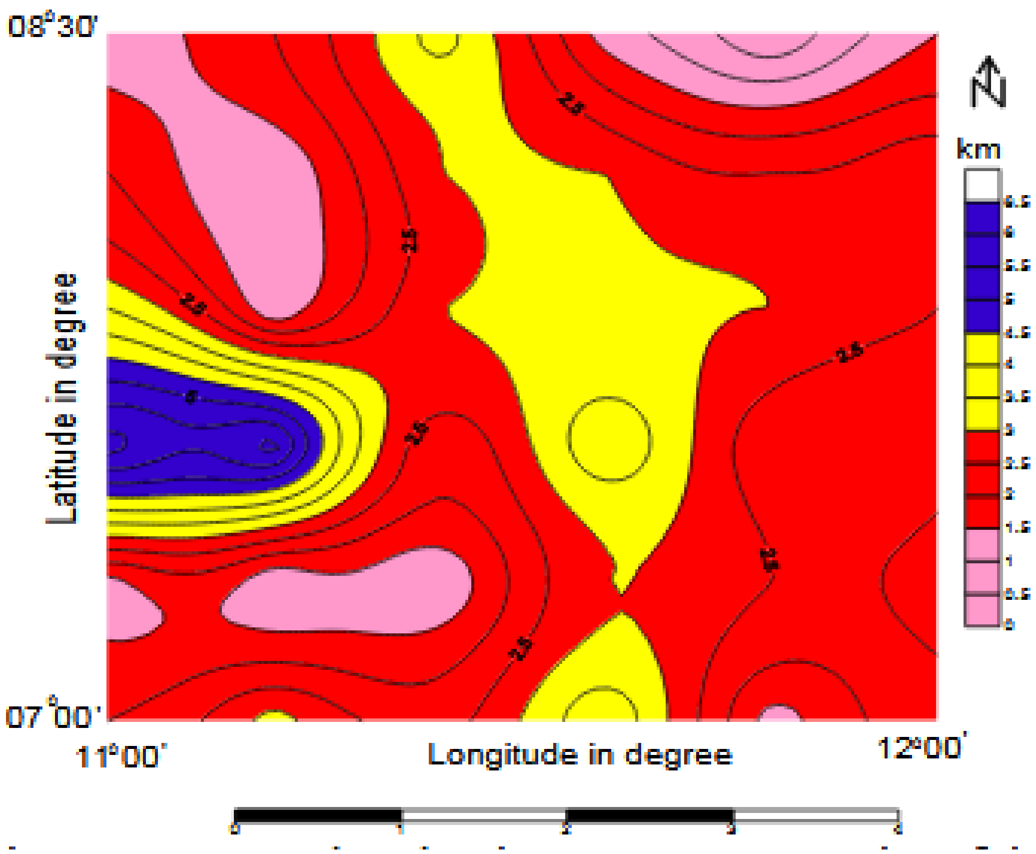


Figure 60: Depth contour map showing basement topography of the area

Garde and **Sunmonu** (1999), worked on the aeromagnetic anomalies over Bida sedimentary basin in Nigeria. The area under investigation is situated in the center of the middle Niger Embayment or Bida basin (Nupe Basin), which extends from Kotangora in the North (Latitude 11^0 N, longitude 4^0 E) to Lokoja in the South (7^0 30' N and 8^0 E).

Our findings showed that the eastern part of the magnetic contour map is complex and center on the suggestive ironstone plateau with 2.0 km as maximum thickness of sedimentary rock. The thickness of the sedimentary strata in the north-western part is 3.0 km. There were no indications of major tectonics such as faults, uplifts, volcanism and large scale igneous intrusions, thus ruling out the possibility of rifting at the origin of the Bida basin. Certain small scales intrusions are indicative of diamond pipes or gold and tin deposits. Prominent areas of possible iron ore deposits in disseminated form could be of potentially economic interest (Table 7).

Table 7: Summary of the characteristics selected profiles indicative of possible mineral deposits.

No	Profile No	Location		Magnetic Indications	Basement Topographic Indications	Tectonic Indications	Economic Indications	Suggested further Investigations
1	P3P3′	9°-9° 30′ N	6° 1.5′ E	Maximum amplitude 7860 γ at the center steep low anomalies southward	Maximum depth 2.18 km toward north end. Average depth is 0.95 km	Major fault sw part. Igneous intrusion in southern part	Diamond pipes	Ground gravity, magnetic & electromagnetic survey
2	P7P7′	9°-9° 30′	6° 3.8′	Maximum amplitude 7860 γ southward steep low in the central part	Maximum depth 1.2 km northward. Average 0.86 km	Major fault sw part. Alluvial deposits under the flood plains Niger river southern part	Iron deposits	Ground magnetic
3	P35P35′	9°-9° 30′	6° 20.0′	Prominent magnitude low 7300 in the north	Maximum depth 2.18 km. Average 1.04 km	Igneous intrusion	Diamond pipe, Gold and Tin	Ground gravity, magnetic & electromagnetic survey
4	P45P45′	9°-9° 30′	6° 26.0′	Maximum amplitude 8200. A prominent low in the north	Max. depth 1.87 km. Average depth 1.16 km	Fault folding	Iron deposits	Ground magnetic
5	P50P50′	9°-9° 30′	6° 28.5′	Maximum amplitude 8000. Highs and lows towards southern part	Max. depth 2.16 km. Average depth 0.98 km	Fault	Iron deposits	Ground magnetic

7. Hydrocarbon Reservoir Integrity

Nigeria had it so good during the pre-colonial days. Agriculture was the mainstay of Nigeria's economy before the discovery of petroleum in 1956. As part of the efforts to integrate Nigeria into global economy, cash crops were introduced to Nigeria by the Europeans from South America and India. Palm oil became an export commodity in Nigeria as far back as 1558; and by 1830, the Niger Delta, which now produces crude oil, had become the major source of palm oil which dominated Nigeria's export list for more than 50 years. Cotton joined the export list in 1856, while cocoa was introduced and became an export crop in 1895. Together with rubber, groundnut, palm kernel and Bennie-seed in later years, formed the major valuable crops. These cash crops formed the main source of revenue, export and foreign exchange for the government. It is very important to note that the economy generally recorded tremendous self-sustaining growth and expansion before crude oil became the mainstay. Nigeria boasted of its groundnut pyramids in the North and Cocoa in the West. Palm oil also existed in commercial quantity in the East. Revenue from agriculture was appropriately used to build landmark social and economic infrastructure, providing basic services like education, health, water and electricity supply. This enhanced farm settlements and cottage industries to service agriculture, providing vast employment opportunities for the people. In respect of food, the nation was self-sufficient before the era of crude oil. Agriculture provided 95% of the food needed to feed Nigerians, contributed 64.1% Gross Domestic Product (GDP), and employed over 70% of Nigerian population before oil began to be exported (Paul, 2015).

The search for Petroleum in Nigeria started in 1908 at Araromi area of the present Ondo State, by a German Company known as Bitumen Corporation. The search was truncated as a result of the outbreak of World War I (1914-1918). Another three attempts were made by other groups between 1937 and 1954. However, in January 1956, oil was discovered in commercial quantity at Oloibiri, now in Bayelsa State, by Shell BP, and a second discovery was made at Afam, now in Rivers State. The first Cargo crude oil left Nigeria in February 1958, when production stood at 6,000 barrels per day, with revenue accounting for about ₦122 million. This contributed 0.08% to the National Revenue. Since the discovery of this 'hot-cake', virtually all other sources of fiscal revenue for the country have been abandoned. Thus, many believed that discovery of crude oil in Nigeria is a curse but I am of the opinion that its discovery is not the curse but the management of its proceeds. In the light of this, we have worked on some of the oil fields in Nigeria which include 'Jemir', 'Philus', 'Taa' and 'Covenant' fields respectively (Figure 61).

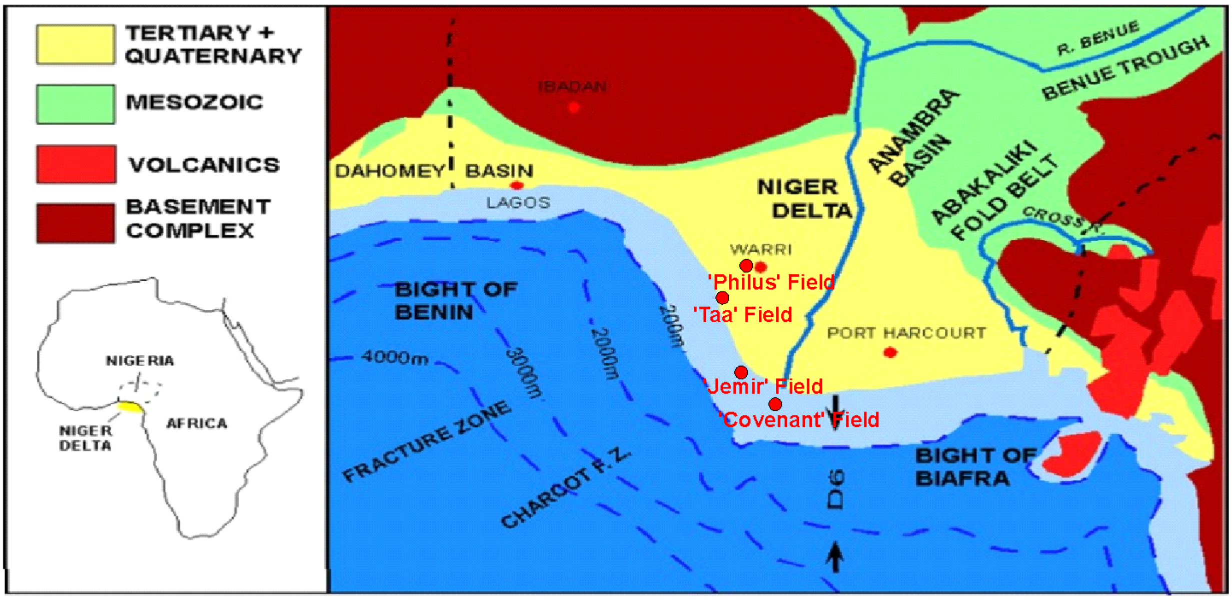


Figure 61: Nigerian geological domains showing the four locations of the area in Niger Delta, Nigeria

Faults generally have sealing properties and compartmentalization. These properties are usually delineated by fault attributes' algorithms using amount of shale on the fault surface and hydrocarbon column heights. Fault could be described as the displacement of a body of rocks by shearing or fracturing along a planar surface known as fault plane.

Most faults produced repeated displacements over geologic time. The fault surface can be horizontal or vertical, or some arbitrary angle in between (as presented in the introductory section). A fault can be a transmitter as well as barrier to pressure communication and fluid flow. Categorizing fault behaviour within these extremes is important for hydrocarbon drilling. In many hydrocarbon reservoirs, sealing faults may be a major determinant of trap. They may also transform large and continuous hydrocarbon reservoir into compartments which then behave as collection of smaller reservoirs. Each compartment may have these properties: fluid characteristics, reservoir's pressure, effective field development and subsequent hydrocarbon recovery. When seal is improperly formed by faults, it prevents accumulation of fluid as the fluids form and transmigrates through structures in the subsurface. The faults architecture refers to the fault shape, size, orientation and interconnectivity. It also refers to the distribution of the overall fault displacement into multiple sub-faults. The rock properties that develop within the fault zones affect a fault's ability to seal.

Since the inception of oil production in Nigeria, 23 oil fields had been abandoned as a result of poor prospect or total drying up of the wells (a big shortage to the economic system of a country that depends solely on Exploration and Production of Oil and Gas). Migration of hydrocarbon from trap is possible when fault leaks. The tendency to identify leaking zones is an essential tool in trap assessment. Faults do not only control the presence of hydrocarbon in a trap, it also controls the volume of hydrocarbons that have been accumulated in a trap. It does not control the volume of hydrocarbons in a trap alone but also control how hydrocarbons are distributed: vertical distribution of hydrocarbon among a series of stacked sands and distribution of hydrocarbon with single sand among series of fault compartments. The leak points in the fault dependent trap limits the volume of hydrocarbons that have been trapped. The tendency to classify leaking and sealing points is the basis in trap assessment.

In the light of the above, Adagunodo, **Sunmonu**, Adabanija, Oladejo and Adeniji (2017), worked on Analysis of Fault Zones for Reservoir Modeling in Taa Field, Niger Delta, Nigeria. We described fault analysis as being crucial in the exploration and production of hydrocarbon because it is the fault that exerts a meaningful control on the migration, entrapment and subsequent compartmentalization of hydrocarbon. Faults' effects on hydrocarbon flow are complex. Some faults allow fluid to pass across them while some reject, which further create series of complications in the geometry of hydrocarbon reservoirs. In order to minimize the risks associated with hydrocarbons' quantification, it is imperative to carry out analysis on the complex nature of faults supporting the traps in the subsurface which this research was aimed to achieve. The fault analysis of Taa field was done using 3D and well log data. Seven reservoirs were mapped on the field with the generation of fault-polygon and fault attributes involving throw analysis, Volume of Shale (Vshale), Shale Gouge Ratio (SGR) (Figure 62), and Hydrocarbon Column Height (HCH) estimations. It was revealed that poor (20 to 40 %) to moderate (40 to 60 %) sealing constitute the SGR of the fault plane in the area (Figure 63). The supportable HCH ranged from 55.7 to 368.4 ft while the structure-supported HCH ranged from 55.7 to 123.4 ft. The difference between the supportable and the structure-supported HCH and the model from SGR confirms that the traps are liable to leak. It was concluded that the faults on Taa field are not properly sealed. Thus, there was migration of hydrocarbon from the field, to the detriment of the stakeholders.

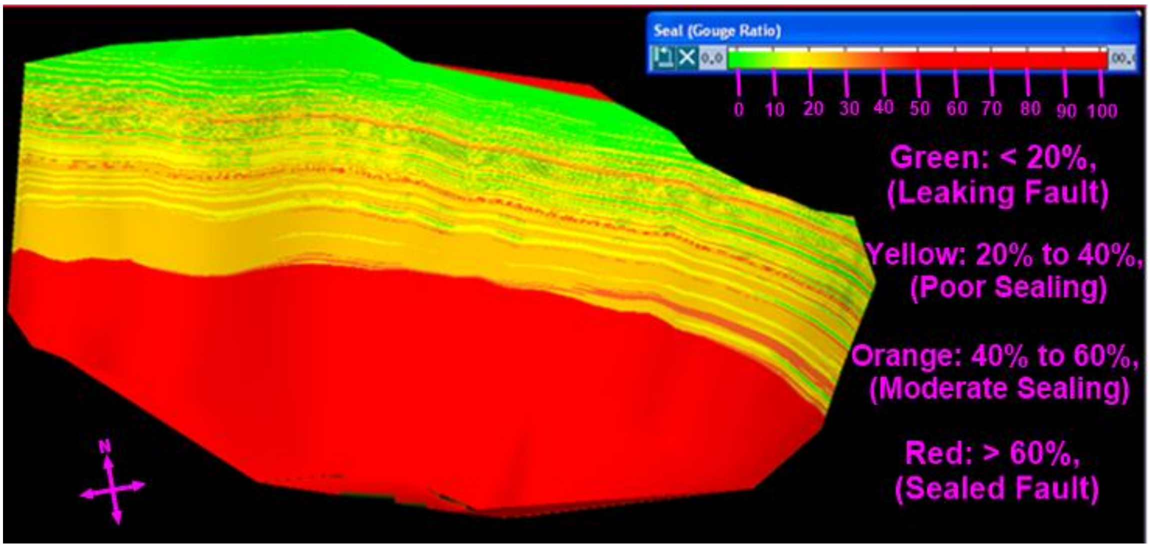


Figure 62: SGR of Taa Field.

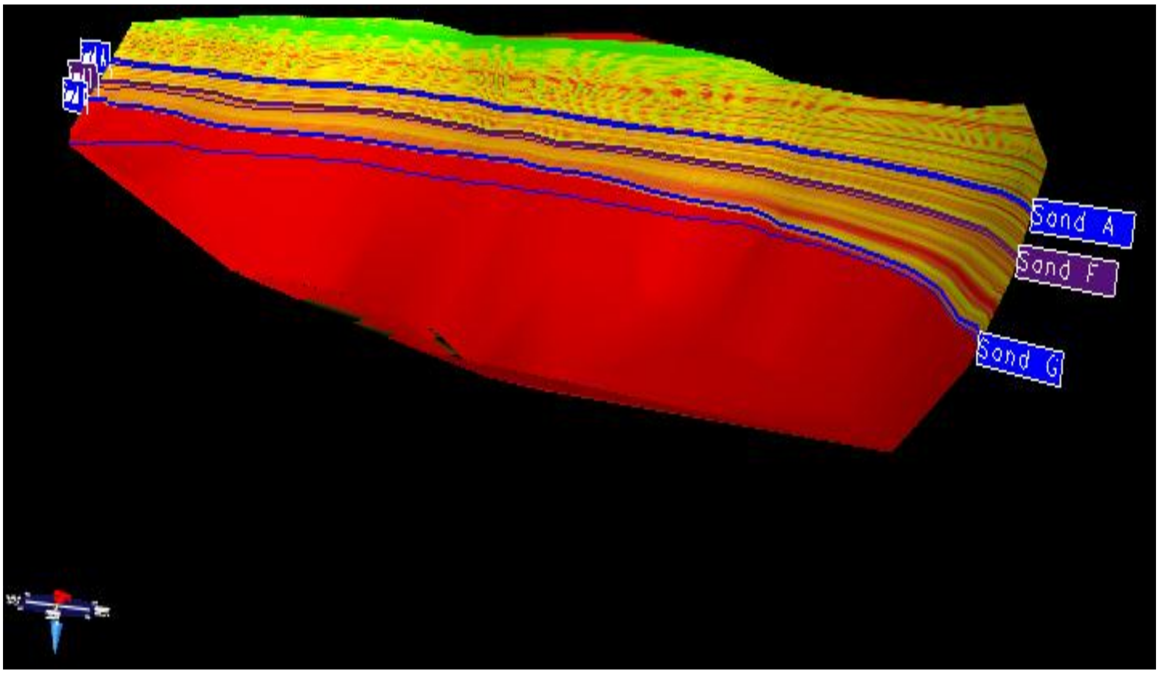


Figure 63: superimposition of SGR on reservoir sands

The investigation carried out on fault plane of Jemir field: an offshore field by Adagunodo, **Sunmonu** and Adabanija (2017), revealed another mystery. The outcome of the study is contrary to the opinion of most people in Exploration and Production settings in Nigeria. It was believed that since normal faults dominate the Niger Delta Basin, there would be no fault seal problem in the area. In this study, traditional reservoir characterization involving petrophysics and volumetric analyses were integrated with seal integrity analysis. This would enable us to know whether the supporting fault in the studied area would be able to trap hydrocarbon properly or not, and to also know the column height of hydrocarbons that have migrated out of trap in Jemir field. The six reservoirs that were mapped revealed that Jemir field has good porosities that could hold sufficient hydrocarbon for exploration. The seal integrity analysis supporting the six reservoirs (Figure 64) showed that the Shale Gouge Ratio (SGR) varied from leaking (< 20%) to sealing (> 60%) as well (Figures 65 and 66). As revealed from the Hydrocarbon Column Height (HCH) estimation, at least hydrocarbons of heights 284.5 to 1, 136.9 ft have migrated out of the trap through the supporting fault plane.

These results enabled us to know that further delay in exploitation of hydrocarbon in Jemir field could result to migration of hydrocarbons from that reservoir to the next available trap (probably another field), which might have resulted to shortage on the side of the company involved.

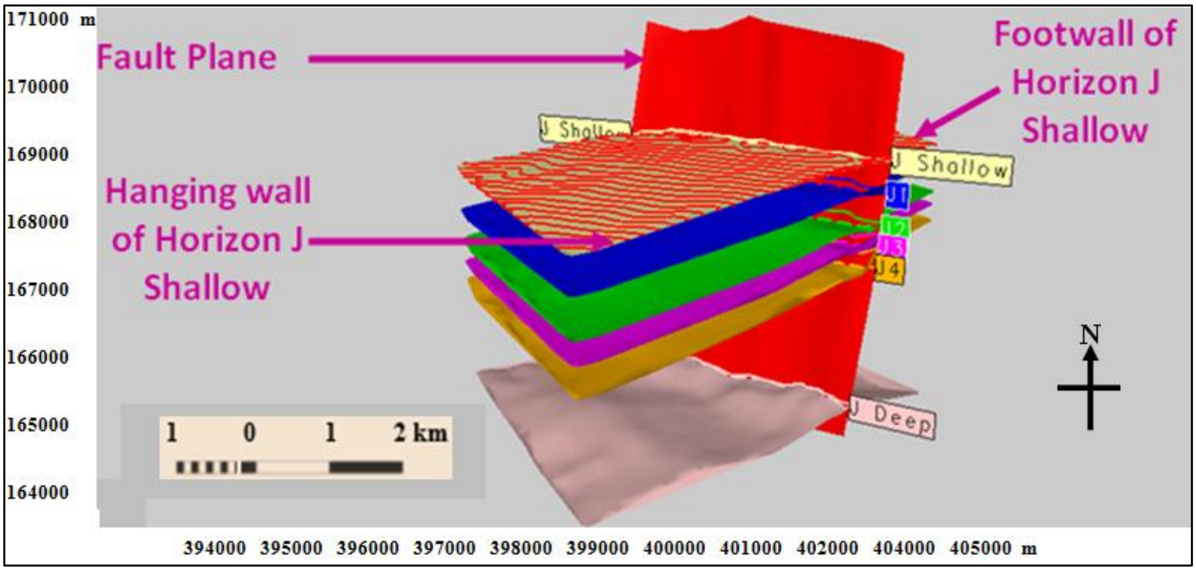


Figure 64: Structural Model of Jemir Field

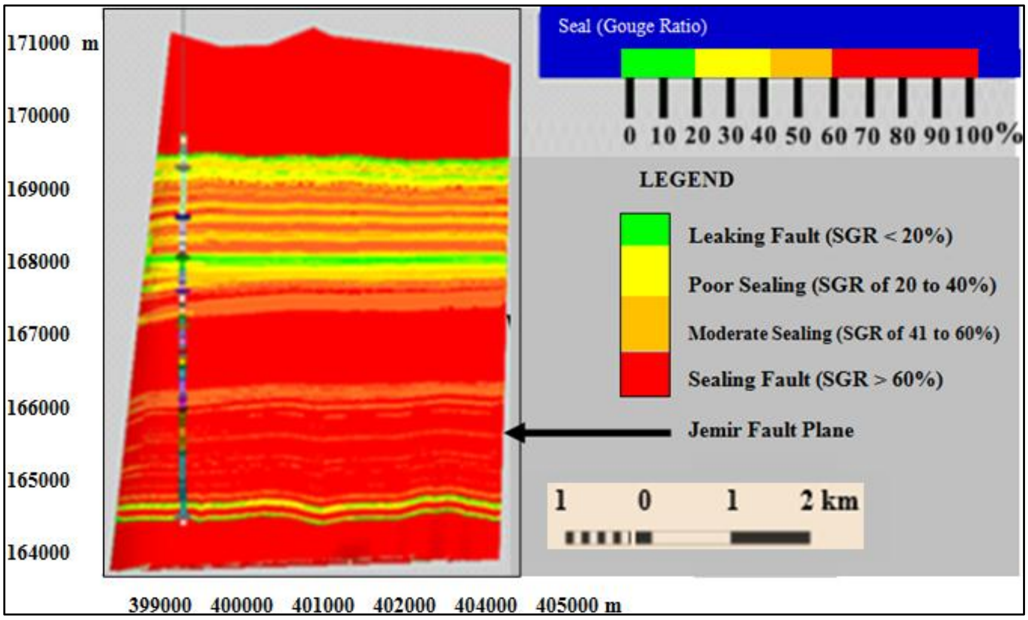


Figure 65: SGR of Jemir Field

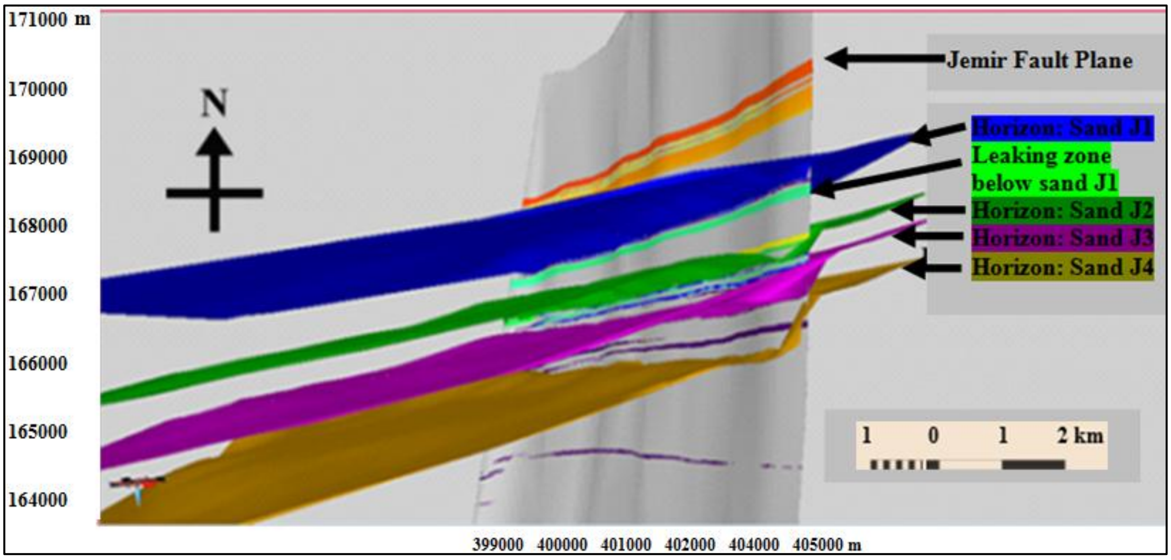


Figure 66: SGR and some Horizons of Jemir Field

Sunmonu, Adabanija, Adagunodo and Adeniji (2016), worked on the Reservoir Characterization and by-passed pay analysis of Philus field in Niger Delta, Nigeria. This was done with a view to assessing the economic viability and profitability of the volume of oil in the seven reservoirs that were mapped. Apart from the existing trap (Discovery) on Philus field, new trap (New Prospect) was discovered (Figure 67). Porosity of 0.24 was obtained for all the reservoir sands. However, the volumetric analysis showed that the Stock Tank Original Oil in place of discovery trap varied from 1.6 to 43.1 Mbbl, while that of new prospect trap varied from 18.1 to 211.3 Mbbl. Based on the outcome of the study, we recommended the recalculation of oil reserve and drilling of another well on proposed new prospect trap to the stakeholders of Philius field.

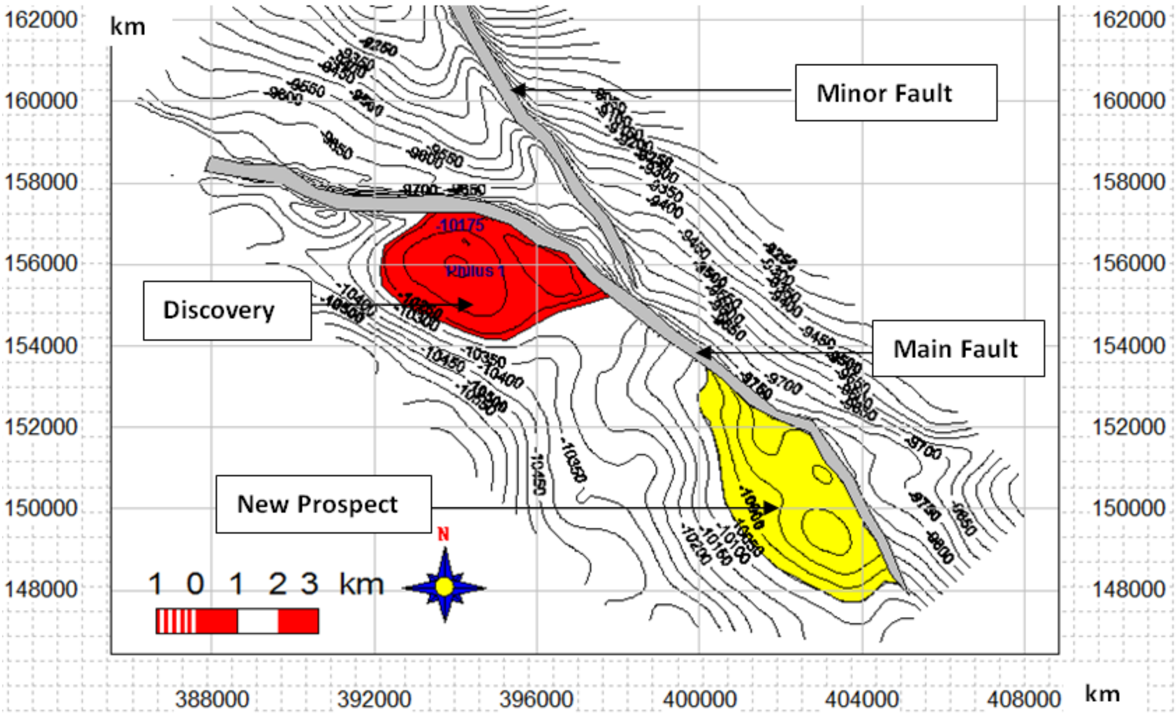


Figure 67: Depth structure map of Philius field showing discovery and proposed new prospect traps

CONCLUSION

The fault patterns established from our investigations shows the history of earthquake occurrence and tremors in India and Nigeria. The investigations were also indicative of the fact that the areas were not immune from experiencing crustal movement if they are seismically active. Thus, earthquake triggering activities should be avoided along the identified fault plane and sustainable seismic stations should be built around fault zones of Ibadan, Ilesha, Abeokuta, Okiti-Pupa and other coastal areas of Nigeria.

The heterogeneous nature of the earth subsurface is a critical factor to be considered in siting of infrastructure to avert loss of lives and destruction of properties which our studies have proven to be the resultant effect. Consequently, infrastructures such as road, railway, high-rise building, and dam should not be constructed along the incompetent zones.

Our findings, using Environmental Geophysics approach have revealed that the delineated contaminants in soil and water do not pose any health risks to the communities involved. However, there is need to prevent indiscriminate disposal of wastes by locating landfills or waste dump areas far away from the residential areas.

We have been able to evaluate the geo-structural setting of the subsurface structures of some areas with a view to characterizing the sites for groundwater exploration for domestic and industrial uses, and competent zones for engineering purposes. Thus, designated areas in our findings should not be used for any other purpose outside what they have been recommended for.

We have been able to show the importance of evaluating reservoir connectivity and seal integrity, as a method of reducing the risk of drilling dry wells and uncertainty of overestimation of hydrocarbons in a field without considering whether the faults supporting the traps are sealing or leaking. The new prospect on Philius field could fetch the nation about 12.3 trillion naira when drilled. The delineated marble in the investigated area should be explored.

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O semi oooo, O semi ooo

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