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Investigation of hydrologic influence of geologic lineaments in areas of the Lower Benue Trough, Southeastern Nigeria

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Stratigraphic formations, namely, Asu River, Ezeaku, Awgu and Nkporo Groups; belonging to Albian, Turonian, Coniacian and Campanian ages, respectively, underlie the studied region. The formations are dominated by groundwater problematic clastic sediments. This study is aimed at tracing fracture zones for groundwater prospects and delineating hydrological catchments for the watershed management strategy. It commenced with analyses of aeromagnetic and edge enhanced band 5 Landsat 7 ETM+ data, with application of filters like reduction to equator (RTE), first vertical derivatives (1VD), total horizontal gradient (THG) and analytical signal. The THG of the RTE grids was combined with the edge enhanced Landsat data and utilized on-screen lineament discriminations. Results showed igneous intrusive representative lineaments in Asu River Group. Lineaments pinpointing ferruginous structures like ironstones stained the Nkporo Group. Further applications of edge enhanced filters delineated lineaments as river beds, fractures/fault nodes and fold axes. The lineaments trending NW–SE depict fracture axes and river beds, whereas those trending NE–SW represent axial anticlines. Validation of results with electrical sounding verified the relevance of outcropping fractures as conduits through which groundwater discharges from the shallow water table at the northwestern hill range region; producing fluvial systems like river tributaries/catchments. Conversely, the rivers recharge the groundwater via fracture linking to deeper water table downstream.

Keywords. Lineament; fracture; water resource; remote sensing; aeromagnetics; Benue Trough.

1. Introduction

Groundwater is common but its occurrence is not easily determined, especially in areas underlain by low permeable bedrocks, as is the case in most parts of the Nigerian Lower Benue Trough. Bedrocks of the region are dominated by aquicludes formed in shales that are even less permeable than the intercalated aquitards of clay/silt that crisscrossed the entire region. The formations tend to be indurated (Tijani *et al.* 2018) but can be permeable, at fractured or weathered zones. The supposed permeable post-Santonian subordinate sandstone member of Nkporo Group is getting ferruginous due to the presence of cementing iron (oxide) which stain and bind the sediment matrix resulting in low permeable units. In some places, the iron banding result in the formation of

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impermeable plates of ironstone beds that hindered hydrologic connection between the surface and groundwater systems. For this reason, occurrence of groundwater has been difficult in the trough. Edet and Okereke (1997), as well as Olayinka *et al.* (1997) have reported that occurrence of groundwater in the region is due largely to secondary permeability. The permeability of this nature occurs in shear zones such as; faults, fractures and weathered units. Offodile (2002) reported that several boreholes drilled into the shear zones have encountered high drawdowns and eventual failures. This is because, yields of successful boreholes in the region are generally less than 0.3 l/s (Adelana *et al.* 2008).

In this study, the problems relating to groundwater occurrence across the complex sedimentary setting of the Lower Benue Trough have been attributed to the following challenges: (1) scanty presence and poorly connected shear (or fracture) zones; (2) occurrences of fractures or weathered units above saturated zone in many places where the water table is at great depth; (3) little or no hydrologic connection between the groundwater and surface water systems for conjuctive recharge; and (4) reduction of permeability in the sandstone member of the post-Santonian sediments due to sealing of pre-existing (primary) porosity by cementing magnetic iron oxide via ferruginization. Hence, the major objective of the study focused on these challenges including analytical means of identifying them through geomorphological and geophysical surveys, as well as hydrological analyses. This is because solution plans would be possible only if these problems are considered prior to groundwater development in any part of the region.

The study began with regional geomorphologic reconnaissance by analyses of digital elevation model (DEM) and validated by geological analyses of outcropping litho units. These litho units constitute the sedimentary fill of the basin (or trough), most of which host magnetic lineaments. The Basin floor was mapped with respect to the magnetic Basement surface in order to determine relative sedimentary thicknesses using quantitative and qualitative analyses of aeromagnetic data in combination with edge enhanced remotely sensed dataset. The aeromagnetic datasets were interpreted with reference to the geological history of the region (Abdullahi *et al.* 2019a). Onyedim and Awoyemi (2006) similarly mapped the basin floor morphology by delineating the underlying Basement surfaces using aeromagnetic studies. Because amplitudes of magnetic anomalies decrease with increasing depth (William *et al.* 2013), areas of low amplitude enclosures were delineated as places of considerable sedimentary pile (or thickness) due to high depth to impermeable basement top. The depths configuration of most hydro-structural (hydraulic) units within the sedimentary pile were further verified using vertical electrical sounding (VES) which revealed the presence of several fractures formed above phreatic (saturated) zone. As opined by Amela *et al.* (2009), it is practicable to identify hydraulic structures from exploration for locations of suitable groundwater accumulation. Powers *et al.* (1999) have noted that methods which can efficiently detect distribution of electrical pathways can be used to evaluate characteristics of significant hydro-structural response to the electrical parameters. Tijani *et al.* (1996) who worked in adjacent regions of the trough had noted that these hydro-structural units like faults and fractures were emplaced regionally during the Santonian tectonic episode. According to Ukpai (2018), typical fractures in particular act as conduit for flow of both groundwater and electrical charges. Such can host prolific groundwater if they exist in large scale configuration and beneath the water table (i.e., within the saturated zone).

In the study area, shallow water table was identified at the northern hill range region, such that exposed fractures easily link the groundwater to the valley floors, hence, developing a fluvial system that formed river tributaries. Conversely, the rivers recharged the groundwater through fractures that link the water table at the downstream part of the southern region where the saturated zone appears deep seated. Therefore, this characteristic hydrologic interplay is assumed not to have only enhanced surface water supply from springs and rivers upstream, but has also enhanced groundwater occurrences in local aquifers downstream. Water resource mapping in the region can be achieved with the knowledge of this conjunctive relationship between surface and groundwater systems. It is a panacea that can be harnessed for strategic water resource management in the watershed.

2. Geology and lithostratigraphy

Inconsistency of rock evolutions across the Benue Trough (Tavershima 2011) has led to the conventional sub-division of the trough into three geographic parts, namely; Upper, Middle and Lower Benue Trough (Zaborski 1998). In the early

Cretaceous, sedimentation started within the entire trough due to the South Atlantic sea-level rise that resulted in transgression of marine sediments into the entire trough in the mid-Albian age. The transgressive period culminated by succession of different layers of sedimentary rocks, dominated by shales belonging to the Asu River Group, which unconformably overlies the crystalline Basement Complex of Nigeria (table 1).

Most of the Asu River Group was deposited in the early Albian amidst pyroclastic deposits that formed the major bedrock of Abakaliki massifs. In the early-Upper Cretaceous Era, the transgressive phase was terminated by a regressive cycle, which began in the Cenomanian, during which sediments were not deposited in some parts of the Lower Benue Trough (Reyment 1965), particularly in the study area. The Cenomanian regressive period was truncated by another massive marine transgressive cycle that marked the early Turonian period with hard grey to dark shales of Ezeaku Formation, covering the Afikpo province, Nkalagu and Lokpanta areas (figure 1A). The Turonian sediments were capped with the incursion of Coniacian Awgu shale which dominates NE–SW axial anticline extending locally from Agbani to Ndeaboh districts (figure 1B). The anticline is part of features formed due to compressional movement within the earth during the Santonian age when the entire trough was affected by intense tectonic activity (Benkeliel 1988). The tectonism created a series of uplifts and synclinal structures, hence, the undulating topography as visually seen in figure 1(C), as well as linear structures, such as folds, fractures and faults. Freeth (1990) noted that these folds and fractures originated from compressional stress due to movement of the African lithospheric plate in the Santonian period. Umeji (2000) reported that the folds originated from vertical movements due to rising and cooling of magmas during the Santonian period. This led to extensive magmatic activities across the trough (Oha *et al.* 2016), accompanied with emplacement of highlands resulting in local increase of the lithospheric thickness of the crust across the region.

Table 1. *Stratigraphic sequence of southeastern Nigeria axis of the Lower Benue Trough.*

<table>
<tr><th>Era</th><th>Age</th><th>Stratigraphic sequence</th><th>Structural evolution</th></tr>
<tr><td>Paleocene</td><td>Danian</td><td>Nsukka Formation</td><td rowspan="5">Enugu escarpment (Anambra Basin)</td></tr>
<tr><td rowspan="8">Upper Cretaceous</td><td rowspan="3">Maastrichtian</td><td>Ajali Sandstone</td></tr>
<tr><td>Mamu Formation</td></tr>
<tr><td rowspan="2">Nkporo Group</td></tr>
<tr><td>Campanian</td></tr>
<tr><td>Santonian</td><td colspan="2">Tectonic period</td></tr>
<tr><td>Coniacian</td><td>Awgu Formation</td><td rowspan="4">Abakaliki Anticlinorial axis, Afikpo syncline and Awgumasif</td></tr>
<tr><td>Turonian</td><td>Ezeaku Group</td></tr>
<tr><td>Cenomanian</td><td>Hiatus (Erosion)</td></tr>
<tr><td>Lower cretaceous</td><td>Albian</td><td>Asu River Group</td></tr>
<tr><td>Precambrian</td><td colspan="3">Crystalline Basement Complex</td></tr>
</table>

3. Materials and methods

3.1 *The study area*

The study area covers about three major depocentres, comprising part of the Afikpo syncline around Amasiri, Uburu and Okposi areas; part of the Abakaliki anticlinorium around Ezzamgbo area and part of the Anambra Basin around Emene and Agbani areas. The area is located within latitudes 6°00′N and 6°30′N, and longitudes 7°30′E and 8°00′E at the southeastern Nigerian axis of the Benue Trough. Figure 1(B) depicts the geology of the study area, ranging from the oldest Asu River Group of Albian age dominating the anticlinorium to the youngest Nkporo Group of Campanian age, which in turn is the oldest sediment in the younger Anambra Basin. Between these stratigraphic groups are the Ezeaku Group and Awgu shales of Turonian and Coniacian ages, respectively. Dark shales dominate the Asu River Group with intercalations of minor sandstones, limestones and siltstones (Obaje 2009). Ukpai and Okogbue (2017) reported dominant shale units with subordinate sandstone bodies in the Ezeaku Group which were observed in this study as generally greyish with compact sandstone units in the Amasiri area. It was observed during macroscopic examination of lithofacies that these shales are more indurated than the younger Awgu shale which in turn is less fissile than the overlying Nkporo Group, particularly the Enugu Shale at Emene area. Dipping pattern of the sediments is irregular, mainly NW and SE with uniform strike along the NE–SW direction in agreement with Nwajide (2013) who reported same trend for the serial synclinal and anticlinal axes. Figure 1(B) also showed that Ezeaku Group underlies the major syncline and extends from Nkalagu in the north to Lokpanta in the south, encompassing Amasiri near Afikpo

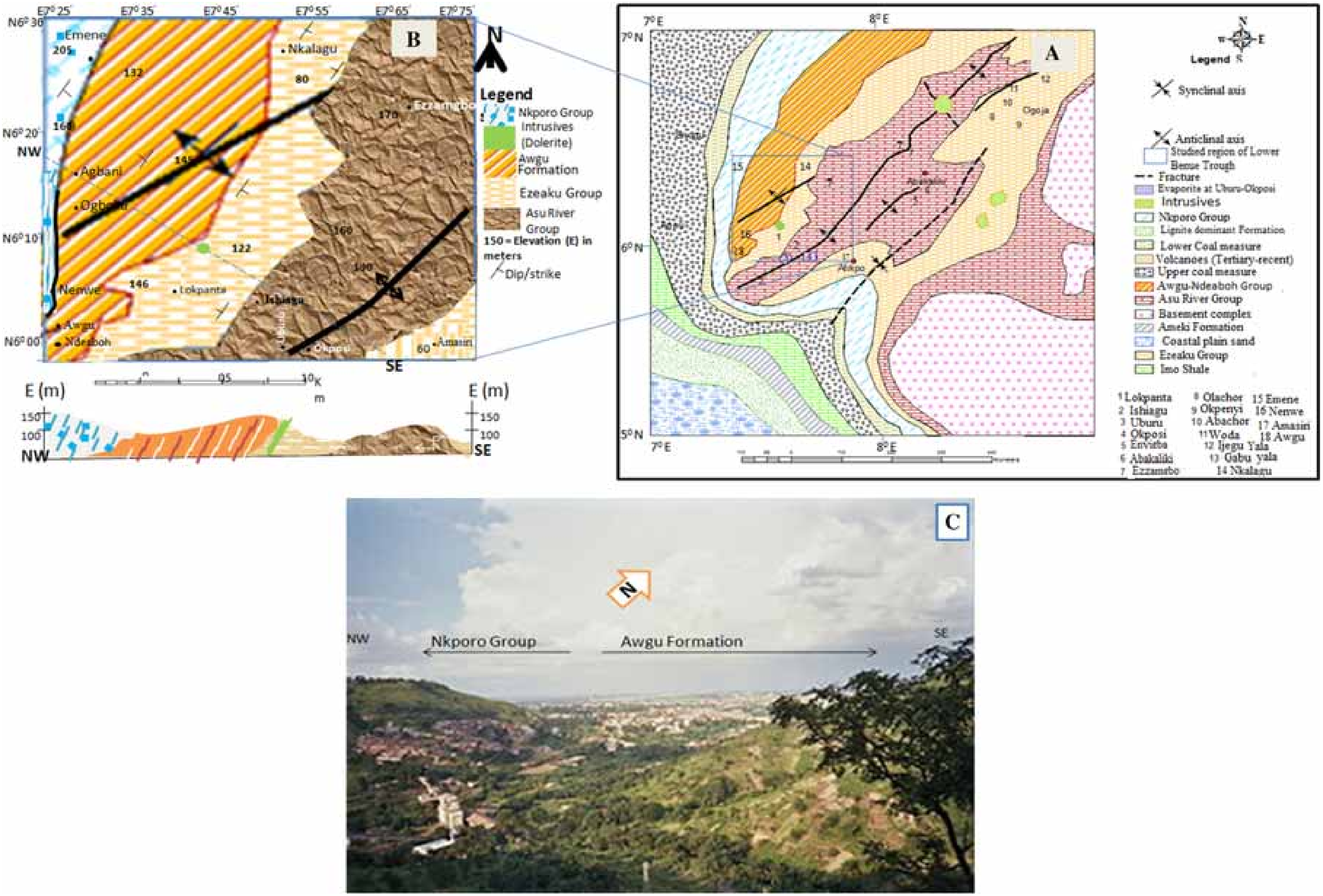

Figure 1. (**A**) Stratigraphic map of the Lower Benue Trough; (**B**) generalized geological map of the studied region; and (**C**) digital photograph showing landform in the southwestern (SW) axis of the cross-section of figure (**B**) near Ogbaku area.

where the elevation above mean sea level is at its lowest value by the base of the synclinorium.

Although these sediments are dominated by shaley aquicludes which inhibit groundwater occurrences, Okogbue and Ukpai (2013) noted that fractures occurring in rocks of this nature can produce groundwater reservoirs or aquifers. The aquifer locations would have been traced relatively to anticlinal flanks where fractures and shear zones occur mostly but their configuration above the water table makes them less important for groundwater occurrences. Consequently, for any specific location to be adjudged as having high aquifer potential, the configuration of hydro-structural units with the water table must be verified whether above or beneath the saturated zone.

3.2 *Methodology*

Between years 2005 and 2010, the Nigerian Geological Survey Agency (NGSA) commissioned Fugro Airborne Surveys to collect high resolution digital airborne magnetic data for Nigeria. The collected data consist of up to 1,930,000 line km of magnetic data flown at 500 m line spacing and 80 m flight height and are divided into sheets of 1° by 1° coinciding with pre-existing NGSA geological sheet numbers. International Geomagnetic Reference Field for 11th generation (IGRF-11) of corrected aeromagnetic data of Nkalagu sheet (302) was acquired and used for this study.

Cultural editing to correct for rough effect, diurnal variations in the airborne magnetometer and initial filtering were performed by contractors to NGSA. The data was IGRF corrected using the 2005 model. A leveling procedure was also applied to account for a number of effects which includes data differences at intersections of tie and traverse line recordings. The resulting data was finally interpolated into a regular grid with a cell size of 100 m using a minimum curvature algorithm with a constant elevation of 80 m.

The quantitative processes involved grid evaluation and refinement which commenced with separation of residual magnetic influences from regional magnetic data using polynomial fitting expressed in equation 1 as:

$$\text{Regional} = 7622.23 + 0.41x - 0.33y. \qquad (1)$$

In order to enhance subtle anomalies which in many cases are anomalies of interest, a number of filters were applied to the raw TMI data. This was done in the spatial frequency domain by the introduction of fast Fourier transform (FFT). The enhancement routines performed in this study included reduction to pole (RTP), reduction to equator (RTE), first vertical derivatives (1VD), horizontal gradient (HG) and analytic signal (AS). The reduction to pole (RTP) or equator (RTE) filter simplifies interpretation of anomalies by reconstructing the magnetic field as if it were at the pole (i.e., vertical magnetic field and declination of zero). Thus, vertical bodies produced induced magnetic anomalies that are centred on the body and are symmetrical.

First and second vertical derivatives emphasized shallower anomalies and were calculated either in the space or frequency domains. The horizontal gradient enhanced edges, making it possible for linear features to be extracted. The amplitude of the analytic signal (total gradient) possesses considerable advantage over the maximum horizontal gradient due to its lack of dependence on dip and magnetization direction, at least in 2D (Nabighian *et al.* 2005). Owing to the impression that the analytic signal performs well at all magnetic latitudes, Roest *et al.* (1992) extended the notion to 3D using the expression in equation 2, hence

$$|A(x, y)| = \sqrt{\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right]}, \qquad (2)$$

where $|A(x, y)|$ is the amplitude of the analytic signal at (x, y), T is the observed magnetic field at (x, y).

The 1VD was mathematically automated from equation (3), such that;

$$\text{Vertical derivative (VD)} = \frac{T_{(\Delta+Z)} - T_Z}{\Delta Z}, \qquad (3)$$

where $T_{(\Delta+Z)}$ is the magnetic values at change of elevation from Z to $\Delta + Z$, T_Z is the magnetic value at elevation, Z, ΔZ is the change in elevation.

Linear edges or contacts of geologic units were discriminated by enhancing the resulting data with a combination of reduction to equator (RTE) and horizontal gradient (HG) which sharpened up anomalies over the causative structures.

The remote sensing imageries used for this study consist of Landsat 7 ETM+ data which were downloaded from the Global Land Cover Facility (GLCF) website. The data is composed of an array of 8 band imagery (band 1 to band 8). Band 1 senses the blue region of the visible electromagnetic spectrum (0.45–0.52 μm), band 2 green (0.52–0.60 μm), band 3 red (0.63–0.69 μm), band 4 near-infrared (0.76–0.90 μm), band 5 mid-infrared (1.55–1.75 μm), band 6 thermal-infrared (10.4–12.5 μm), band 7 mid-infrared (2.08–2.35 μm) and the panchromatic band 8 (0.52–0.9 μm). The spatial resolution of band 1 to band 5 and band 7 is 30 m each while that of band 6 is 60 m and band 8, 15 m. The study area falls within the scene (path 188 and row 56) of the Worldwide Reference System-2 (WRS-2). The scene was exported to Ilwis 3.1 academic software, where the study area was windowed using the sub-map routine. The various ETM+ bands were then subjected to computer processing.

Lineaments were extracted from spatially filtered Landsat 7 ETM+ band 5 data for the study area, the edge enhancement filter was applied to all bands and the resulting images compared for linear feature clarity. The filtered band 5 image was found to possess the best lineament enhancement, and was thus used for lineament extraction.

Static water level was measured from dug wells around fault zones using a dip meter (Heron model) as used by Ukpai *et al.* (2016) to estimate the water table configuration. This was done by following the principle of the portable (Heron) equipment which is electronically configured to respond with alarming sound upon contact with water surface. It consists of the sound unit, light indicator and a twin wire enclosed in calibrated tape and attached to a metallic probe, which is sensitive to water contact. The actual depth to (static) water level was measured by reading off values on the tape from the ground level immediately the 'click sound' rings with a blinking light indicator, indicating that the probe just had contact with water in the well. The elevation at each well point was measured using a GPS (Global Positioning System) of Garmin eTrex model. The resulting data were mathematically fixed to obtain total heads or hydraulic heads, H (in meter) as thus;

$$E - D = H, \tag{4}$$

where E is the elevation from datum (in meter) and D is the depth to water level from mean sea level (in meter).

The values for the hydraulic heads were plotted on a map to determine either the energy head, groundwater mound, flow directions or both.

Depth and thickness of the water hosting structures were analyzed via vertical electrical sounding (VES), and the resulting data was modeled using IPi2WIN software. Information from the various data sets was then integrated and presented in formats most suitable for hydrogeologic evaluation (figure 2).

4. Results and interpretations

4.1 *Analyses of geological structures*

4.1.1 *Integrated analysis of magnetic parameters*

A 3-D raster map of total magnetic intensity (TMI) depicts the raw source parameter model of the study area (figure 3). This grid shows a maximum magnetic high of about 7930 nT around Agbani and Nenwe (in the west), Onicha/Ugulangu, Amofia (in the south-southeast axis), Oshiru (in the east), Ezzamgbo area (northeast). The magnetic parameter decreased at 10 nT intervals to magnetic lows of less than 7800 nT around Ndeaboh area (at the extreme southwest) and Ogbaku (in the west). Comparing the magnetic intensity with the geology of the region, the magnetic highs correspond with areas where ferruginous sandstones and ironstone deposits exist, except those from Abakaliki province (near the Ezzamgbo and Ezillo areas) to Oshiru–Uburu and Okposi axis where igneous intrusives and vein minerals were identified. These magmatic related bodies were similarly reported in the Abakaliki region by Umeji (2000).

Further interpretation of the TMI data is difficult due to the position of the area at low magnetic latitude, hence the need to simplify the data by the application of relevant filters. Analytical signal, vertical derivatives and horizontal gradient as generated from the reduced to equator (RTE) of the TMI image simplified the interpretation. This is because the analytical signal map (figure 4) clearly defined the extent of the causative bodies. For instance, while high analytical signal values (shown in red) depict the extent and geometry of the causative bodies for the magnetic parameters, the blue colouration in the signal map showed the extent of the thick sedimentary pile (see figure 4). The thickness was generally estimated in the form of depth to the magnetic basement to range from 5 km within the Abakaliki region to 9 km around Ogoja province (Abdullahi *et al.* 2019b) and with

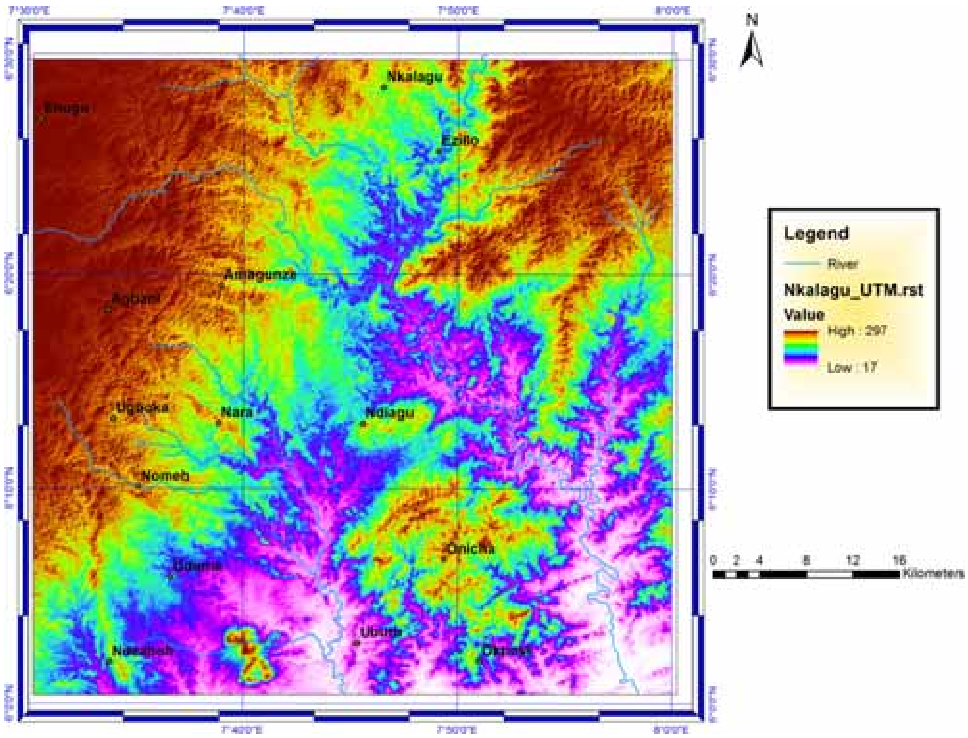

Figure 2. Digital elevation model (DEM) showing geomorphology of the region.

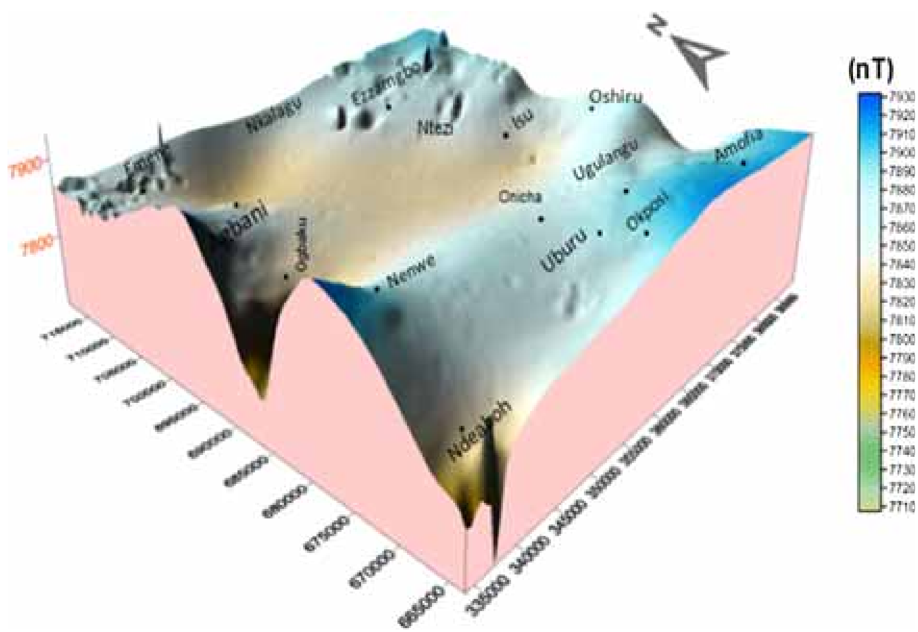

Figure 3. Total magnetic intensity in 3-dimension.

an average of about 6.013 km (Adetona and Abu 2013). Thin sedimentary thicknesses have been estimated in some parts as shallow depth to the Basement at less than 250 m (Ofoegbu and Onuoha 1991). Typical shallow depths to impermeable Basin floor (or Basement top) are suspected in those parts of the trough characterized by magmatic/igneous processes; mostly around the northeastern–eastern–southern periphery of the studied region; comprising the

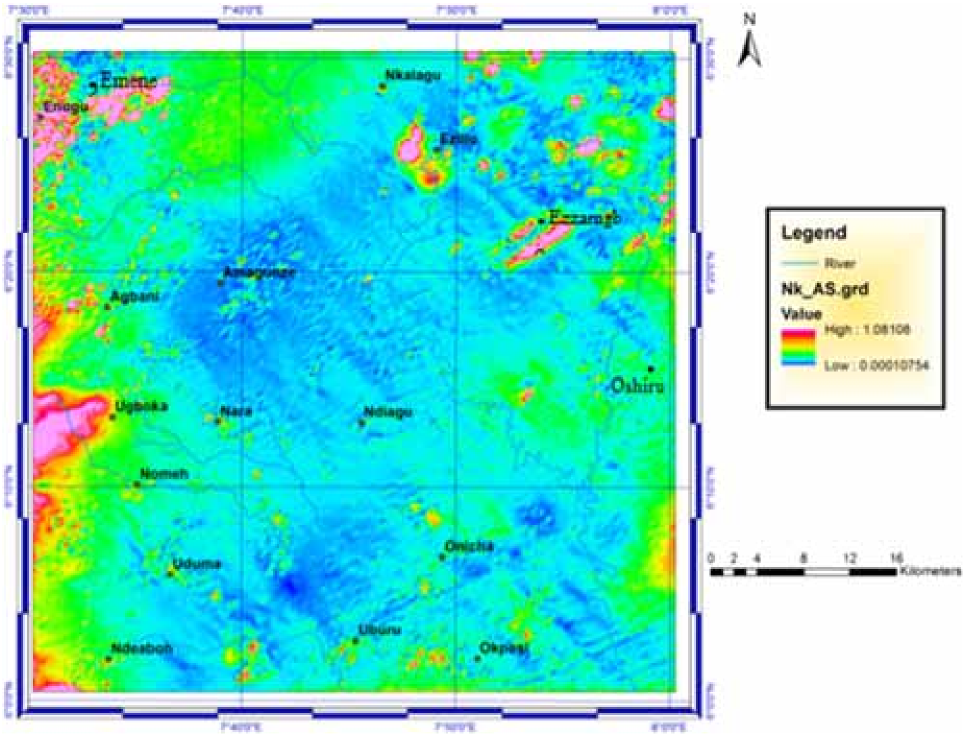

Figure 4. Analytical signal map of the area.

Uburu–Okposi areas in the south, Oshiri in the east, Eziulo–Ezzamgbo and most areas of the Abakaliki province in the northeastern portion. These areas consist of Lower Cretaceous Asu River Group distinguished from Upper Cretaceous sediments with a prevalence of igneous emplacements and ore deposits. This is a proof that the Asu River Group of Albian age overlies the metamorphic basement unconformably; yet shallower depth to the magmatic source beneath the Basin floor than the younger sediments. It means thus, that the post-Albian sediments with minor presence of igneous bodies and absence of ore minerals within the studied region consist of a thick sedimentary pile; such as around Nkalagu in the northern part underlain by Ezeaku Group, and overlain by Awgu shale (Umeji 2013) near Ogbaku in the west and Ndeaboh in the extreme southwest. These areas fall within sediments filled trench-like feature observed on the Basement surface (see figure 3), typical of which was described by Ojoh (1992) near Ndeaboh area as slope mega slump structure.

The first vertical derivative (1VD) grid defined the distribution of the shallow sources of magnetic structures with relatively moderate to high magnetic values across the region. Dominance of the high values was mainly observed separately at Emene (northwest), Eziulo, Ezzamgbo (northeast portions), and slightly aligns along the western axis separately at Agbani and Nenwe, as well as around Uburu–Okposi in the southern portion and Oshiri in the eastern flank (figure 5). The northeastern–eastern–southern axis of the high to moderate magnetic values coincides with regions of known magmatic activities (Umeji 2000; Oha *et al.* 2016; Oha *et al.* 2017) which can be related to fracture filled precipitates of hydrothermal fluids that also produced ore deposits. Configuration of these structures is dominantly NE–SW trend as revealed from the horizontal gradient map (figure 6). In addition, the northwestern–western axis of the magnetic structures coincides mainly with the areas underlain by Nkporo Group exposed to ferruginization, possibly due to the dominance of ironstones and other ferruginous sediments.

4.1.2 *Extraction of lineaments*

Apart from distal magnetic sources from the crystalline basement (figure 3), Nicholas and Carlton (2008) have noted that the magnetic gradient can be influenced by proximal magnetic structures, such as ferruginous strata and igneous intrusives. The typical ferruginous strata are highlighted with

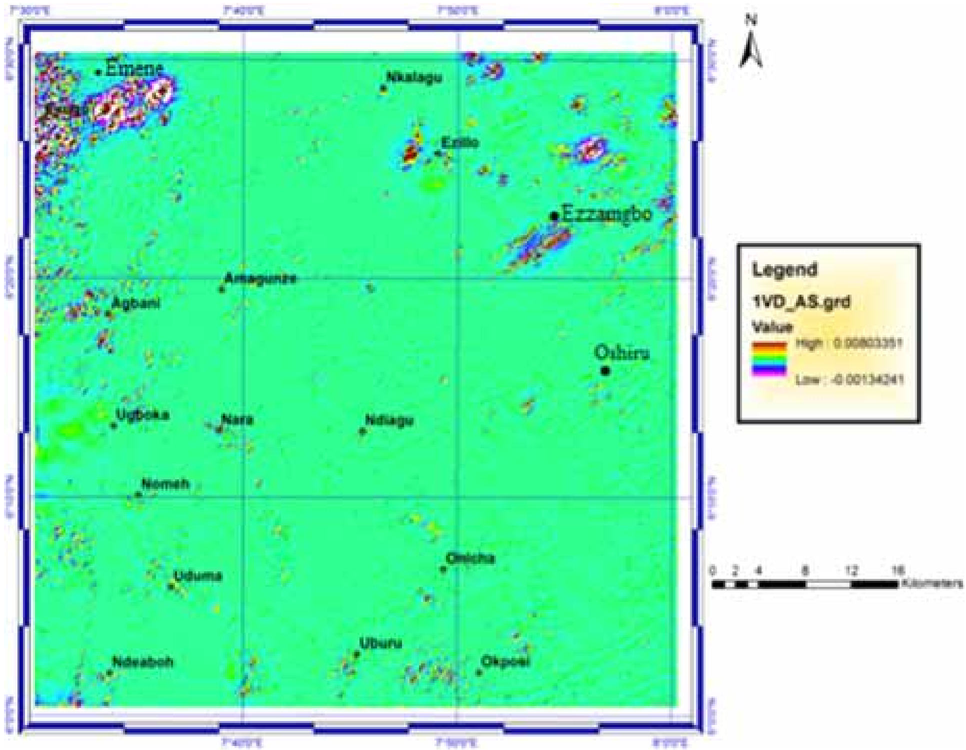

Figure 5. First vertical derivative (1VD) map of the area.

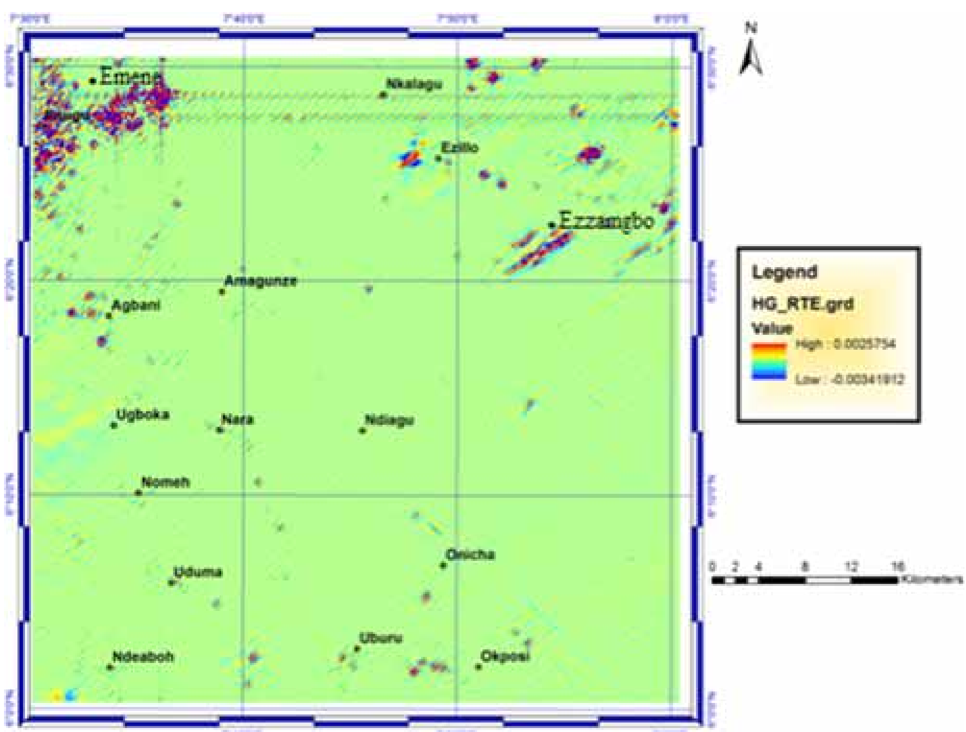

Figure 6. Horizontal gradient map of the area.

sharp edges at a local NE–SW trending anomaly around Emene in the northwestern part of the study area (figures 4–6). This could be inferred as magnetic anomaly due to abundance of linear plates of ironstone (figure 7A and C) and pyritic (iron stained) sediments (figure 7B) that characterize

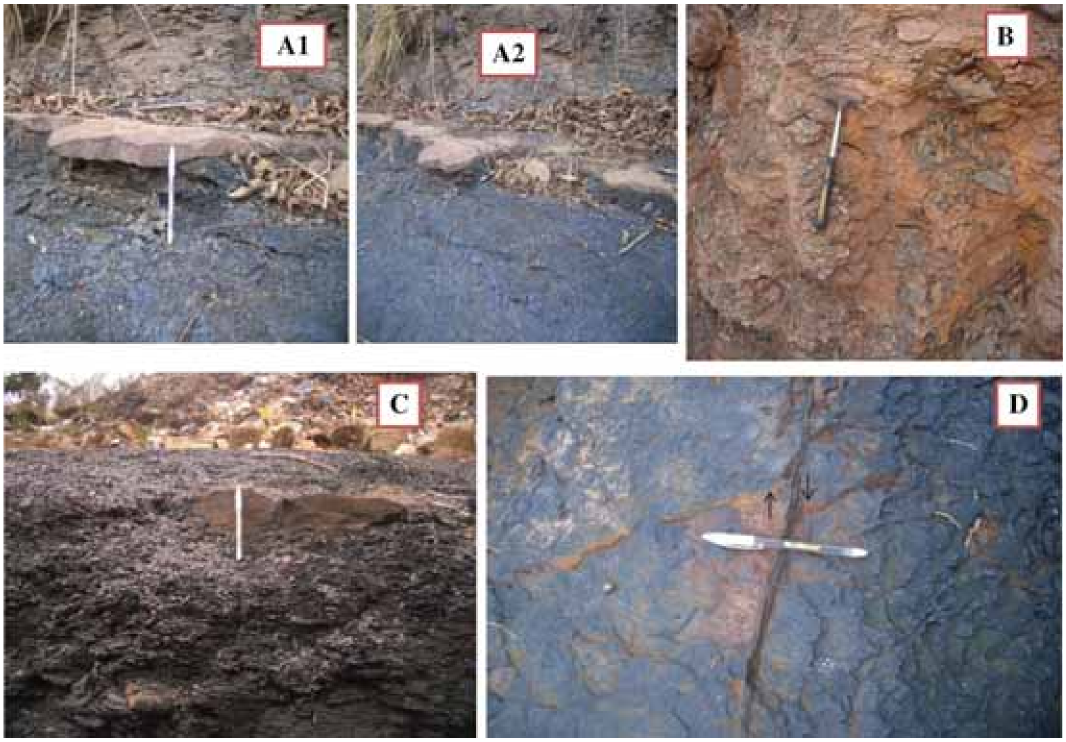

Figure 7. Photos of (**A**) ironstone bed overlying Nkporo shale at Ekulu river bank (Asu River tributary); (**B**) locally ferruginized sediment sandwiched within Awgu shale (located at: N06°04′52.2″ and E007°28′19.7″; (**C**) imbeded ironstone within Enugu shale of Nkporo Group BY the Ekulu River in Emene area; and (**D**) joint structure and displaced fracture within Enugu shale of Nkporo Group outcropping at Emenite villa in Emene area.

the Nkporo Group. This deduction is based on the perceived absence of magnetic bodies, like igneous intrusives/ore bodies in post-Santonian Formations. The ironstones might have been formed from gradations of sedimentary rocks (Harold 1966) that resulted in pyritic shales (see figure 7B) and sandstones in some parts of the area (Petters 1991), particularly the western axis of the studied region, hence, the dotting of amplitudes (high) anomalies in the flank (see figure 4). The ironstone plates form impermeable beds that hinder infiltrations. Other linear pellets of high amplitudes or short wavelength magnetic anomalies (red bands) observed in figure 4 towards the northeast are inferred as igneous bodies, some of which are intrusives around Ezillo and Ezzamgbo areas. These are similar to those earlier identified by Obiora and Umeji (2004) around the same axis of Abakaliki province.

Discrimination of lineaments through the integrated analysis of horizontal gradient (figure 6) and edge enhanced band 5 Landsat 7 ETM+ image (figure 8) displayed the lineaments with various N–S, NW–SE, NNW–SSE, NNE–SSW and NE–SW trends but predominated by the NE–SW trending structures. These trends agree with those of previous studies; meanwhile, Ogunmola *et al.* (2016) attributed the variability to mean that the Basin was exposed to several stress regimes. The lineaments that trend NW–SE are mainly characterizing features such as river beds. These features are separated into northern and western river catchments by a narrow highland (altitude) that aligns southeasterly from the Enugu escarpment through Amagunze, Ndiagu, Onicha and to Okposi (compare figures 2, 8, 9A and 10). The northern group emanate from the Enugu escarpment and Ezzamgbo upland which joined to form Ebonyi River that runs southeasterly (figure 10). The western group of tributaries originate from Enugu–Awgu escarpment (see figure 2) and produced Asu River which flows southwards across Uburu area (see figure 10).

Other lineaments, especially those trending NE–SW represent series of axial anticlines, and perhaps stratigraphic boundaries between different groups of sediments (see figure 1B). The anticlinal structures were formed from the compressional movement of the earth (Burke *et al.* 1971), and on a large-scale host regional fractures (Zaborski 1998). Some of the fractures locally crop out and appear as joints (see figures 7D and 11A). Fractures of this

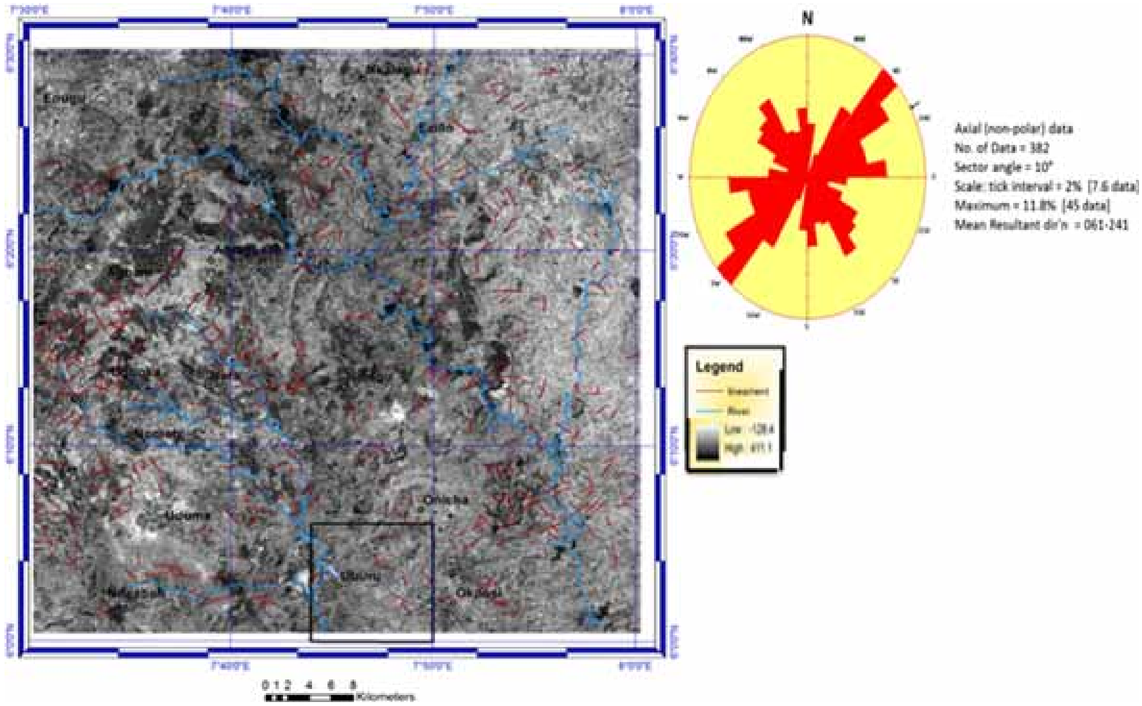

Figure 8. Edge enhanced band 5 Landsat 7 ETM+ data showing interpreted lineaments (outset: rose diagram showing the lineament trends).

nature can hydrologically enhance infiltration of run off water, and where some are hydraulically permeable from or into the water table, they recharge the groundwater from the perennial surface water regime and vice-versa. However, most of the fractures in pre-Santonian sediments, especially those sandwiched in Asu River sediments formed hydrothermal pathways for the passage of fluids released from magma that precipitated vein minerals (figure 11B), hence, abridged the fracture prospects as hydrological flow media which may have significantly hampered the occurrence of groundwater in the region. Nevertheless, some of the magmatic events were not deep-seated but emplaced as volcanic bombs (figure 11C) or as subvolcanic dolerite (figure 11D). According to Akande *et al.* (1990), fractures were tectonically influenced in the Santonian by series of displacements, thereby developing regional fault lines as typically observed along the NE–SW stretch from Oshiri to Uburu–Okposi areas (see appendix 1 of electronic supplementary material, ESM). Most of the faults are locally formed and develop aquiferous zones, commonly along the local fault nodes as typified near Emene (figure 9A). These fault nodes produced local groundwater recharge boundaries as identified around Emene and Uburu–Okposi areas in the northwestern and southern parts, respectively (figure 9B and C).

5. General discussion

The study infers that the prevalent compressional stress of Santonian age, followed the axis of bulk magnetic intensity along the paleo-ridges depicted in the magnetic basement (see figure 3). This stress created NE–SW axial fractures and faults, signified by some corresponding narrow magnetic anomalies (figure 6). Generally, transformation of the magnetic anomalies such that they would be vertical as if observed from ambient magnetic field (Baranov and Naudy 1964) through reduction to equator (RTE), as well as the total horizontal gradient (HG) revealed a dominance of NE–SW trending fractures. This is in agreement with lineaments digitized on screen from edge enhanced band 5 Landsat 7 ETM+ data, which further demarcated some fault lines around Okposi, Uburu and Ugulangu areas in the southern part, stretching northwards into the Agbani area, as well as in the northeast where the trends rotate to the northwest (see appendix 1 in ESM). The subordinate NNW–SSE trending lineaments around Emene area can be attributed to one of the local fault nodes reported by Obi and Okogbue (2004) to characterize the Enugu shale member of Nkporo Group. These representative fault nodes are in contrast azimuth with the resultant regional azimuth established as N061°E (see figure 8; appendix

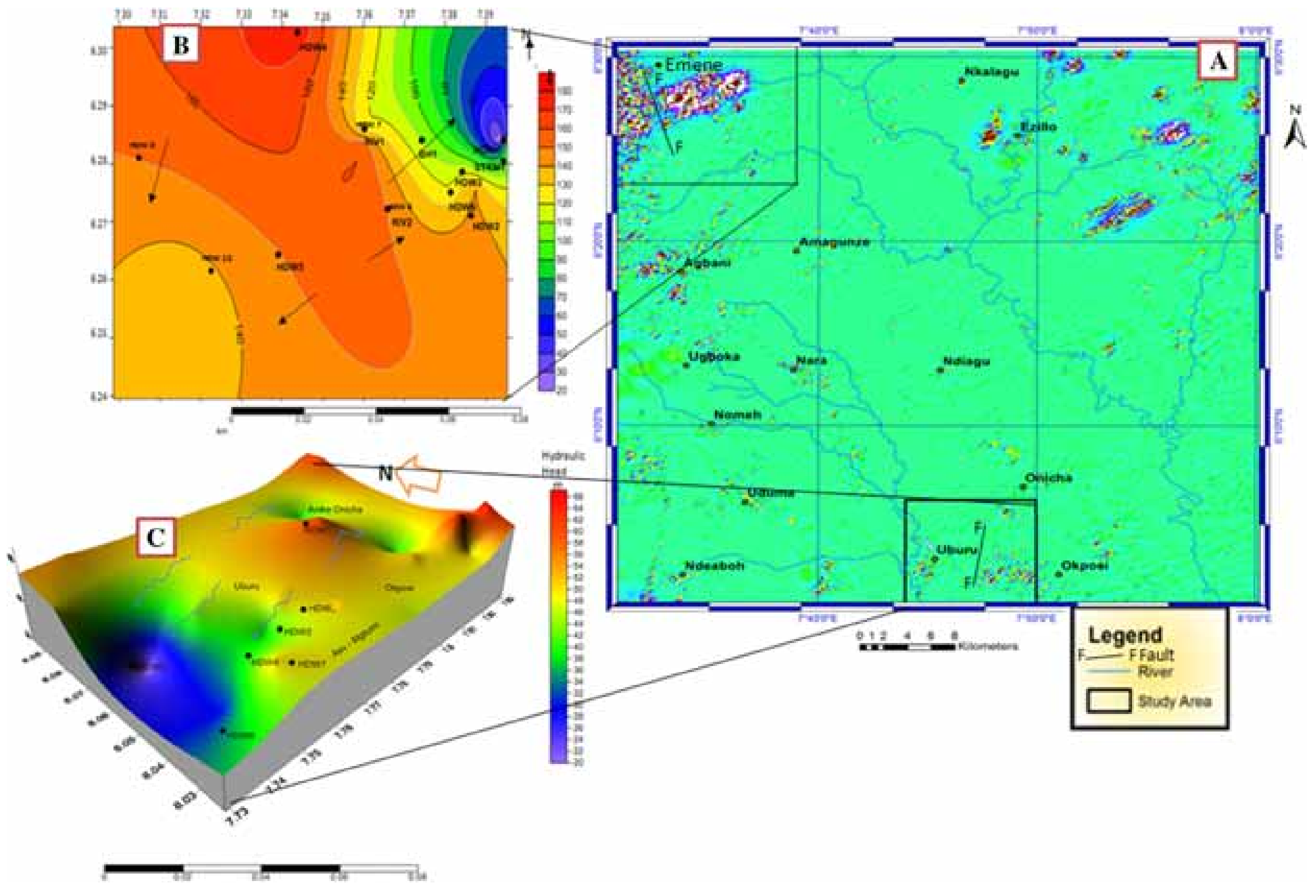

Figure 9. (**A**) Regional map of the area from integrated 1VD and analytical signal showing edges of near surface lineaments and river (stream) beds; (**B**) map of Emene and environs showing local configuration of water table and NW–SE trending groundwater boundary; and (**C**) map of water table configuration in Uburu–Okposi area (in 3-D) showing N–S trend of the local groundwater boundary.

2 of the ESM). With this discrepancy, therefore, further discrimination of the representative lineaments was required. The linear structures were recognized on the aeromagnetic maps as fractures by considering different factors which Gunn (1997) noted to include; (1) sudden discontinuities of magnetic units, and (2) linear magnetic lows due to fissures along a structural plane. Qualitative inspection of the analyzed data by the knowledge of factor (2) indicated fractures formed at edges between magnetic units where the susceptibility is less than the background rocks (Reeves 2005), whereas those displaced as faults were identified where the lineaments are subtle and curvilinear (Grauch and Hudson 2011).

In this study, factor one (1) is the criterion for identification of shear zones (see ESM, appendix 1) and factor (2) enabled the detection of hydrological significance of the NW–SE lineaments as representative of local watershed (see figure 9B) and river/stream beds (see figure 9A). These linear beds sandwich rivers produced from tributaries between different highlands (figure 2). The tributaries are formed as a result of base-flows (figure 12), mostly by hill flanks; and joined to produce the rivers along the NW–SE trending (low magnetic anomalous) shear zones. These base-flows mark points of hydraulic connections between groundwater and surface water systems, where dominance of fluvial process exists. According to Winter *et al.* (1998), such hydraulic interaction is difficult to observe and measure. However, it is believed in this study that permeability created through an outcropped fracture induces the hydraulic interactions between the surface water system and groundwater regime by infiltration/percolation and baseflow. The infiltration/percolation results in the groundwater recharge, and where the causative fractures are linearly connecting, creates a recharge boundary that leads to upwelling of hydraulic heads or formation of groundwater

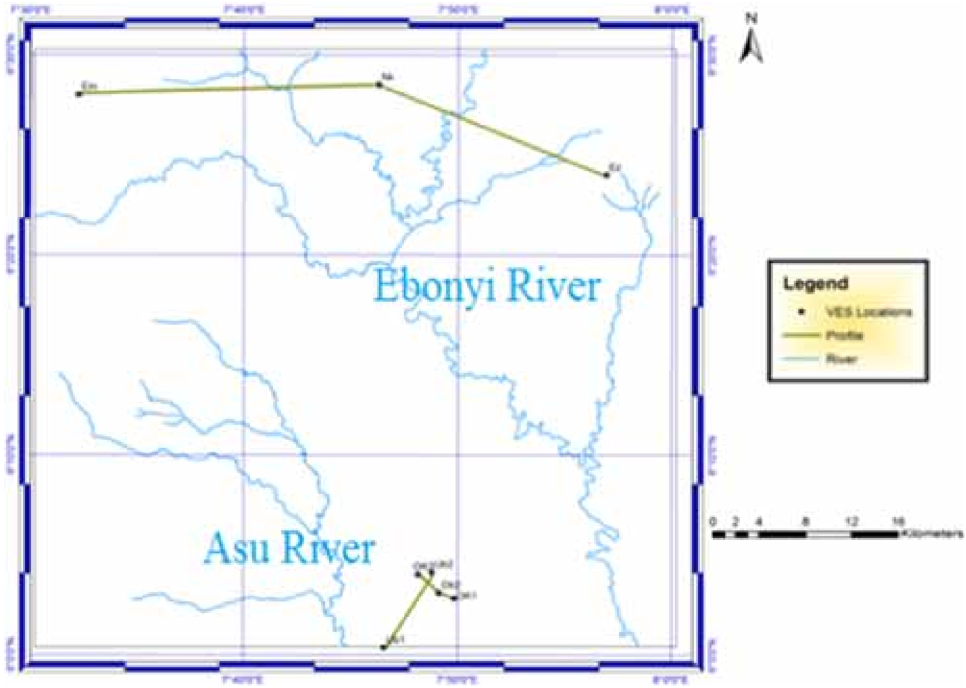

Figure 10. Drainage map of the study area with VES locations and the profile lines.

Figure 11. Photos of **(A)** fracture at Umuchieze; N05°56′53.4″, E007°28′51.8″, southwest of Lokpanta; (**B**) typical vein (indicated with arrow) sandwiched in Asu River shale at a local quarry site, south of Uburu area; (**C**) igneous pebble (indicated with arrow) within younger sediments near Asphalt construction company, N05°55′19.1″, E007°27′15.3″, east of Lokpanta; and (**D**) dolerite vein at N06°08′44.2″, E007°45′52.5″ north of Lokpanta town.

mounds (see figure 9B). Also, at points where the groundwater discharges into the rivers or tributaries, it recharges the surface water bodies by the baseflow. Both hydrological phenomena are prominent where the fractures intersect the earth's surface.

From the VES results (table 2), low layer resistivities, depicting shear zones such as weathered and/or fractured layers form the hydraulic pathways. This reflects permeable zones within the fourth geoelectric layer in the southern portion and the third geoelectric layer in the northern portion.

Figure 12. Fluvial points, showing groundwater seepage (see arrows) into; Asu River (**A** and **B**, as depicted in Ukpai and Okogbue 2017), the valleys of Awgu escarpment (**C** and **F**), and a central valley at Okposi area (**D** and **E**); all formed tributaries of the Asu River.

Table 2. *Results of the VES survey showing layer resistivities (ρ) and corresponding depths (d).*

VES	Name of location	ρ_1 Ωm	ρ_2 Ωm	ρ_3 Ωm	ρ_4 Ωm	ρ_5 Ωm	ρ_6 Ωm	d_1 m	d_2 m	d_3 m	d_4 m	d_5 m	RMS (%)
1	Okposi 1	44.3	692	50.4	33.4	516	–	1.1	3.03	32.3	89.7	–	
2	Okposi 2	273	942	291	128	821	463	2.12	10.9	22.0	53.7	84.5	0.049
3	Okposi 3	585	7016	226	97.3	1900	–	1.13	4.9	29.1	70.2	–	**0.097**
4	Uburu 1	511	8071	1074	46	87.3	1.6	0.75	2.1	17.2	46.8	148	0.142
5	Uburu 2	271	4194	135	717	6703	3555	0.767	7.34	19.2	48.5	96.8	0.128
6	Ezzamgbo	2.79	88073	46.2	–	–	–	1.00	3.83	–	–	–	–
7	Awgu 1	15087	150	98899	–	–	–	19.0	50.2	–	–	–	–
8	Awgu 2	23.1	5.24	3232	–	–	–	20.5	35.0	–	–	–	–
9	Emene	0.629	95.7	8613	–	–	–	0.50	1.34	–	–	–	–
10	Nkalagu	155	909	233	301	1200	–	0.94	4.02	18.6	38.8	–	0.139

The third geoelectric layer aligns from the deep saturated zone to the vadose zone of depth as shallow as 1.5 m near Emene area (figure 13A). Around Nkalagu, the thickness increased to about 15 m between confining fresh shale and clayey top soil layers at the depths of 5 m and 20 m, respectively (figure 13B). In Ezzamgbo, the thickness extends to the near surface depth of about 3.5 m at the base of a confining clay layer (figure 13C). Across the southern region, the fourth geoelectric layer is confined by clay/mudstone units at the top and by unweathered fresh shale underneath (figure 13D and E). Typical of such confining unit is a low permeability zone, hence defined as aquitard (Ukpai and Okogbue 2017) that can confine fluid/water within the permeable weathered zone under pressure. It appears, therefore, that the confined hydrologic conduit of this nature constrained the groundwater to discharge to the fluvial system at the point where the groundwater pressure intersects with that of the atmosphere, thereby producing springs, stream channels and

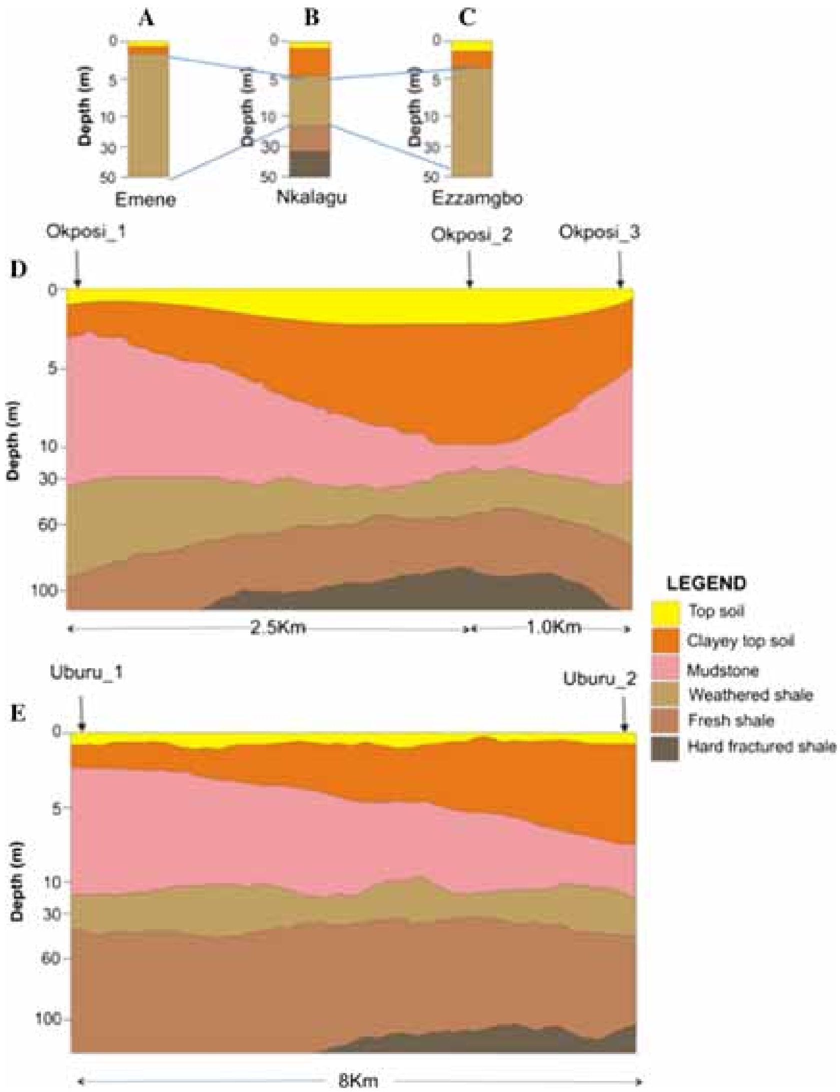

Figure 13. 2D schematic cross sections of the interpreted VES layer across the survey area (**A**) Emene, (**B**) Nkalagu, (**c**) Ezzamgbo, (**D**) Okposi area, and (**E**) Uburu area (see figure 10 for the locations).

river tributaries at valley floors in the northern region. This assertion is deduced from VES results (figure 13A–C) across the profile lines (see figure 10).

This indicates that the river tributaries that originate from the western areas (see figure 10) were created due to the intersections of the shallow subsurface flow system with the hill flanks. The weathered units form conduits for groundwater discharge. At the southern downstream, deep potentiometric surface (water table) is attributed to the fact that the aquifers can scarcely be recharged through direct rainfall as it is overlain by thick low permeable mudstone/claystone units that formed aquitards from depths of about 20 m around Okposi to about 36 m in Uburu (see figure 13D and E). The mudstone unit is absent and claystone is extremely thin upstream (see figure 13A–C), hence, permits infiltration of rainfall that raises the water table, such that it can intersect the ground surface at the escarpments. This would better be confirmed by the wider nature of the river channels towards the southern region (see figure 10), indicating lower permeability downstream than at the upstream (catchment) area (Fetter 2007). However, configurations of the geoelectric layers show that water-bearing aquifer aligns towards (Asu) River where it interconnects and gets recharged (compare figures 10, 13D and E) via infiltration from the River. For this reason, it is safe to believe that both Asu and Ebonyi rivers hydrologically exhibit effluent rivers at the western portion, as well as at the northern portion and become influent rivers that recharge the aquifer system at the southern portion.

6. Conclusions

The geology of the study area comprises a succession of pre-Santonian sediments consisting of part of the Asu River Group in the Abakaliki anticlinorium, with part of the Ezeaku Group in the Afikpo syncline, as well as Awgu shales around the Enugu escarpment; all belonging to the Albian, Turonian and Coniacian periods, respectively. These sediments are capped by the post-Santonian Nkporo Group; all together generally comprising of low permeable shales that form aquicludes across the region. The lower Cretaceous Asu River Group contains numerous magmatic bodies, whereas the upper Cretaceous sediments are dotted with cementing ferruginous rock materials. These affect the hydrologic potentials of the sediments. For this reason, groundwater occurrence problems exist in the area, although aquifers can occur at shear (fracture) zones, particularly where their configurations are beneath the water table. These hydrostructural units are concealed as lineaments, and were identified by integrated analyses of aeromagnetic and Landsat 7 ETM+ datasets. The outcome was validated using vertical electrical sounding (VES) with hydrological techniques through quantitative and qualitative evaluations. The lineaments with NW–SE trend coincide with riverbeds whereas those with NE–SW trend represent fracture zones mostly hosted within surface linear structures such as anticlinal axis. The anticlines and associated synclines were emplaced by internal compressive movement of the earth during the Santonian tectonic episode. The movement further displaced some fractures thereby generating small scale faults, while some were subjected to hydrothermal fluid flow that later cooled as vein minerals. The vein bodies impede the permeability characteristics of the affected fractures that existed in the region, thereby putting off their hydrologic potentials which would have hampered the groundwater occurrences. Generally, groundwater occurs where the fractures are open and lie beneath the water table to produce aquifers. In places where the water table outcrops the aquifers seeps to the surface, especially by hillsides in the western and northern highlands. The dominance of fluvial processes at the seepage zones results in surface flows that produced different tributaries, hence, forming river catchments. The western and northwestern catchment areas feed the Asu River and Ebonyi Rivers, respectively, both drain the study area following major shear zones to the south. In the southern region, the water table is deeper and recharged from the river systems at points where the permeable fractures are hydrologically linking the water table with the river beds. So, upstream, the rivers are effluent but turn to influent rivers downstream. Thus, the water supply used by the populace in the southern part of the studied region are enhanced by natural implementation of conjunctive use of surface and groundwater regimes. This hydrological characteristic can be employed for water resource management.

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