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MAPPING OF HYDROCARBON PROLIFIC AREAS WITHIN THE CENOZOIC NIGER DELTA BASIN: OBSERVATIONS FROM HIGH-RESOLUTION POTENTIAL FIELD DATA

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Abstract

This study explores a very simple means to map hydrocarbon prolific areas within the onshore Cenozoic Niger Delta Basin using high-resolution potential field data. This was achieved by identifying and superimposing the map of gravity lows on the map of magnetic lows. About six (6) major sub-basins were recognised, namely: the Onuba sub-basin, the Udeonu sub-basin, Ahoada sub-basin, Aba sub-basin, Owerri sub-basin, and Okigwe sub-basin. Among the six sub-basins recognised, Onuba and Udeonu sub-basins are larger than the other sub-basins. The Udeonu sub-basin lies mainly within the central delta cutting across the Greater Ughelli depobelt, the Northern depobelt and the Central Swamps (I and II) depobelts (Early Eocene to Middle Miocene). The Onuba sub-basin lies within the distal delta cutting across the Central Swamp II, the Coastal Swamps (I and II) and the Offshore depobelts (Middle Miocene to Pliocene). The six sub-basins were suggested to lie within the hydrocarbon prolific areas. Out of the major onshore Niger Delta depobelts, the Coastal Swamps (I and II) are the most productive. By implication, the distal part of the delta that lies within the Onuba sub-basin is more productive than the central part of the delta.

Keywords: *Niger Delta Basin; potential field data; sub-basins; and hydrocarbon prolific areas.*

1. Introduction

A sedimentary basin may be described as an area of the Earth's crust dominated by subsidence that allows the net accumulation of sediment [1]. They can range in small size of hundreds of metres to as large as the ocean basin (not necessarily basinal in shape) with essentially two vital elements: a source of sediment supply and an area of sediment deposition. A basin may register the tectonic evolution of the lithosphere that contains numerous Earth resources like fossil fuel, minerals, water resources and may as well be the location of possible environmental challenges like earthquakes, volcanoes, etc. Within a basin or sub-basin, a depocentre can be described as the place where maximum thickness of sediment accumulation is observed over a particular period [1-2]. In a hydrocarbon province, sub-basins are generally attributed to higher net-to-gross reservoir properties depending on sediment provenance and delivery mechanisms [3]. The hydrocarbon columns are controlled not only by the structural geometry and the fault sealing capacity but also by seal distribution, reservoir characteristics and fluid properties. All these represent necessary parameters for evaluating hydrocarbon accumulations [4].

Basement faulting affects delta development and its sediment thickness distribution [5]. This may be dependent on the balance between the rates of subsidence and sediment supply [6]. The sedimentary pattern generated by this balance may have been affected by the tectonics of the basement and its structural configuration [7].

Prior to this study, various hydrocarbons' prolific areas have been established in the extensional part of the onshore Niger Delta that cuts across the depobelts [7-10]. However, it is not very clear if the prolific areas coincide with the sub-basins within the study area. In this study, a simple comparative study was made to map various hydrocarbon prolific areas of the onshore Niger Delta. This was attained using potential field data with the scope to image full scale crustal signal variability for density and iron content in previously identified hydrocarbon prolific areas. This was achieved by identifying and mapping the ''depocentres" within a sedimentary basin. Since depocentres are generally regarded as areas of maximum thickness of sediment accumulation, we expect to recognize them by identifying areas with relatively low density and low magnetic properties.

This study illustrates a very qualitative means of how potential field data could be employed to map sub-basins and hydrocarbon prolific areas using the Cenozoic Niger Delta Basin as a case study. This study involves identifying gravity lows and magnetic lows from the data and superimposing one on the other in order to identify the sub-basins within the Niger Delta. The major sub-basins identified were compared with previously established hydrocarbon prolific centres/belts in the same region.

2. Geological setting of the Cenozoic Niger Delta Basin (CNDB)

According to Daly [11], the petroleum potential of the African continent can be grouped into four main provinces, namely: offshore Mesozoic rifted passive margins; large Cenozoic delta systems; onshore Phanerozoic continental rifts and Palaeozoic cratonic basins. A major portion of the Phanerozoic petroleum potential of the African continent is associated with rift settings [12]. These include, for example, the Jurassic Yemen-Somalia rifts, the Permo-Triassic Karoo system, the Neocomian rift zone at the initiation of the Gondwana breakup, the Cretaceous basins controlled by the West and Central Africa Shear Zone and the Tertiary East Africa rift zone. In Nigeria, the West and Central Africa Shear Zones divide the continental margins into individual basins forming boundary faults of Cretaceous Benue-Abakaliki Trough that cuts across the West African shield [10]. The Benue-Abakaliki Trough represents a failed arm of a rift triple junction that failed to develop during the separation of African plate from South American plate and this lasted from the Albian to the Santonian [13]. The other arms that developed are characterised by the South Atlantic and the Gulf of Guinea in the Equatorial Atlantic.

The Niger Delta Basin is a structural depression linked to the tectonic evolution of the Benue Trough of Nigeria. This depression was formed within the basement complex of the African craton [15]. In Nigeria, the basement complex consisting mainly of granite and gneisses covering half of the landmass with extensive schist belt in the west [16]. The basement complex was subjected to two metamorphic events. The first event occurred at about 2000 ($\pm$250) Ma and the second was at about 600 ($\pm$150) Ma. The first is associated with a pre-Pan-African orogeny while the second is associated Pan-African orogeny [16-17].

The Niger Delta is a coastal basin attributed to the post-rift stage in the Cenozoic times of the passive continental margin. The post-rift stage was characterized mainly by sea-level eustatic change, uplifting and tilting of the African plate, formation, and deposition of clastic rocks and turbidites [18]. The coastal sedimentary basin of Nigeria passed through three depositional cycles, and the first two cycles form the basic framework on which the Niger Delta was built [15]. Sediment deposition into the Niger Delta Basin started in the third depositional cycle in the Cenozoic (Late Eocene) to the present, and this has been attributed to regressive delta sequence. The stratigraphy of the Niger Delta is closely tied to the structural and sedimentary cycles of the Benue Trough. The Niger Delta Basin is divided into three lithostratigraphic units, namely: Akata Formation (marine), Agbada Formation (transitional) and Benin Formation (continental) [10,19]. Three environments of deposition are recognised in the Niger Delta namely: (a) the continental consisting of Bende/Ameki Group, coastal plain sand and deltaic plain (Eocene – Oligocence); (b) the transitional consists of meander belt, backswamp, and mangrove swamps (Oligocence – Miocence) and marine comprises Estuaries, Beach ridges and bars (Miocence – Pliocence) [19]. An outline of the geological map of the Cenozoic Niger Delta Basin is shown in Fig. 1. Details of the geological setting of the Cenozoic Niger Delta Basin have been discussed [6,10,16].

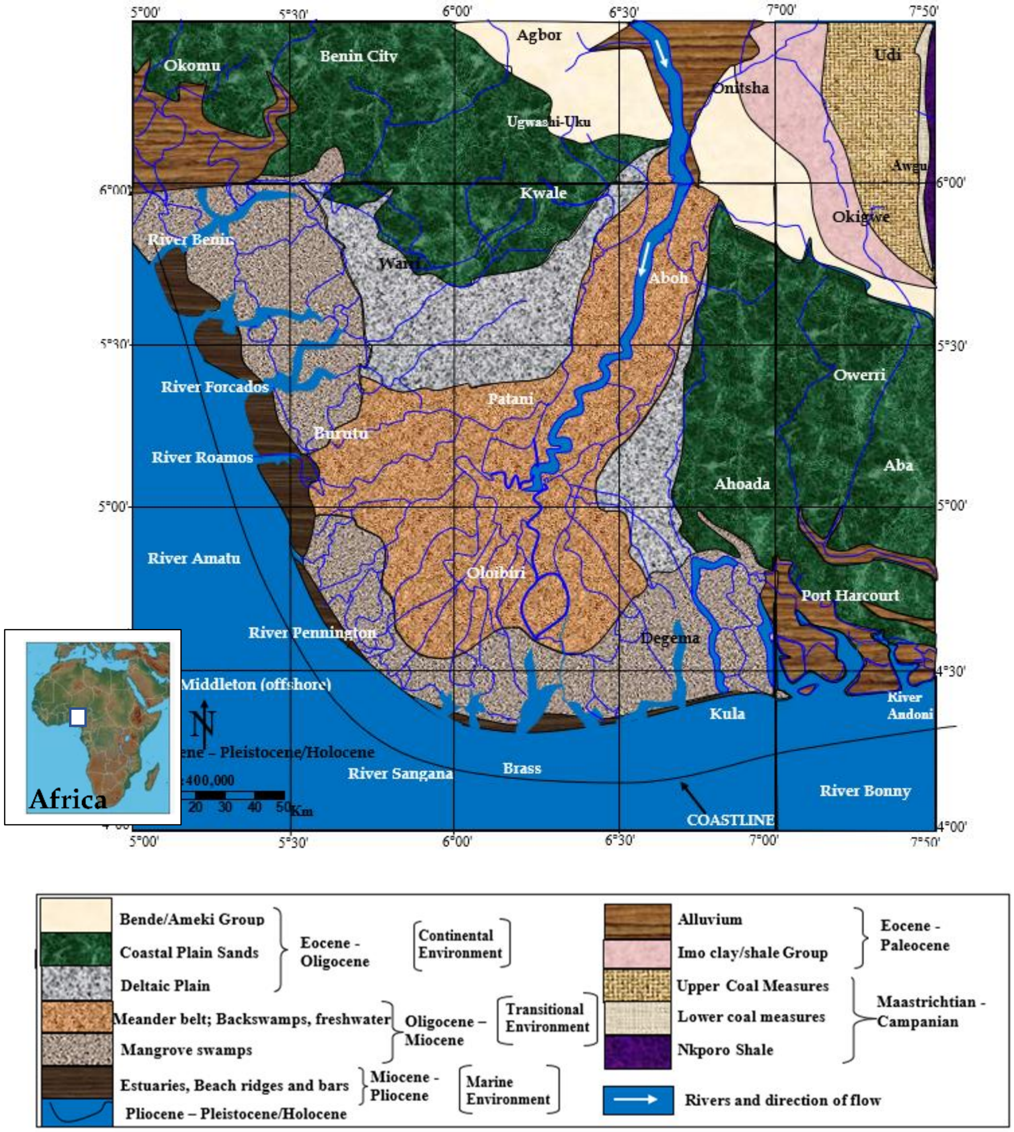

Fig. 1. Outline of the geological map of the Cenozoic Niger Delta Basin (*modified from NGSA 1964 and 2003; Frankl and Cordry,* [19])

3. Niger Delta depobelt province

The development of the Niger Delta took place in discrete structural units (depobelts) that act as sub-basins, and this was as a result of the activity of large growth faults and clay diapers [21]. Doust and Omotola [16] described three prominent depobelt provinces based on geological structure namely: (a) the Northern delta depobelt province that overlies relatively shallow basement, with the oldest generally rotational growth faults that are evenly spaced and increasing in steepness seaward; (b) the Central Delta depobelts province, characterised by well-defined structures with successive deeper rollover crests that shift seaward for any given growth fault; and (c) the Distal Delta depobelt province, characterised by complex structures due to internal gravity systems on the modern continental slope.

The three prominent depobelt provinces can be divided further into seven depobelts based on age [16]: (i) the Northern Delta depobelt, (ii) Greater Ughelli depobelt, (iii) Central Swamp I depobelt, (iv) Central Swamp II depobelt, (v) Coastal Swamp I depobelt, (vi) Coastal Swamp II depobelt, and (vii) Offshore depobelt (Table 1). Other studies identified five depobelts in the Niger Delta by grouping them as Northern, Greater Ughelli, Central Swamp, Coastal Swamp and Offshore depobelts [10,22].

Table 1. The seven prominent depobelts of the Niger Delta Basin based on age (*modified from Doust and Omatsola* [16])

Depobelts	Paralic sequence	Alluvial sands
Northern Delta	Late Eocene to Oligocene	Early Miocene
Greater Ughelli	Oligocene to Early Miocene	Early Miocene
Central Swamp I	Early to Middle Miocene	Middle Miocene
Central Swamp II	Middle Miocene	Middle Miocene
Coastal Swamp I	Middle to Late Miocene	Late Miocene
Coastal Swamp II	Middle to Late Miocene	Late Miocene
Offshore	Late Miocene/Pliocene	Late Miocene/Pliocene

The Cenozoic Niger Delta Basin is one of the world's major hydrocarbon basins with proven reserve of over 37.2 billion barrels of recoverable hydrocarbon (2.93% of the world reserve) at the end of 2011, ranking Niger Delta Province the twelfth largest hydrocarbon province in the World [10,23]. With an estimated 41.4 years at the present rate of production of over 2,457 barrels per day (BP, 2012 report). The Basin has been explored for over 50 years after over 47 billion barrels have been produced [24] and exploration activities are still ongoing. A schematic diagram showing various hydrocarbon prolific areas in the Niger Delta is shown in Fig. 2.

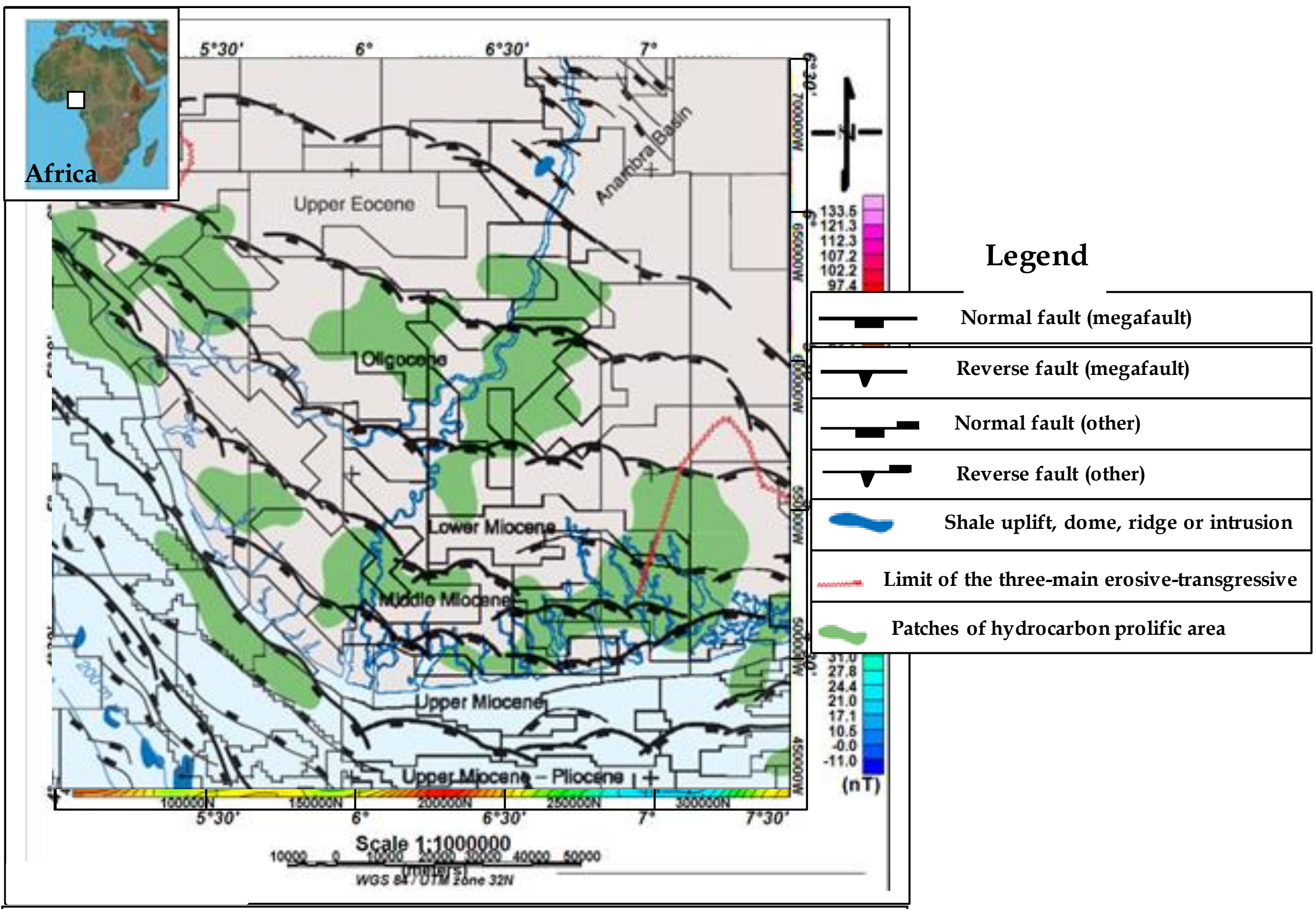

Fig. 2. Schematic diagram showing the location of Niger Delta hydrocarbon prolific areas in green (*extracted from Stacher* [39]*; Saugy and Eyer* [40])

4. Background

As discussed in previous studies [25-28], sedimentary basins, salt diapirs, granite structures and grabens are characterised by negative gravity anomalies (also called gravity lows or gravity minima) while positive gravity anomalies (also called gravity highs or gravity maxima) are characterised by horsts, uplifts and mafic rock materials. The magnetic susceptibility varies from less than 10^{-4} emu/cm^3 for sedimentary rocks to between 10^{-3} and 10^{-2} emu/cm^3 for iron-rich basic igneous rocks [28]. In general, basic igneous rock has high magnetic susceptibility due to their relatively high magnetite content. Acidic igneous rocks and metamorphic rocks have intermediate magnetite content while sedimentary rocks have low magnetic susceptibility due to low magnetite content. However, there are some exceptional cases; some sediment might have high magnetic content. For example, laterites containing maghemite or remanently magnetized hematite [29] or marine sediment with complicated magnetic mineral assemblages [30]. In this study, it was however assumed that there were no exceptional cases and the interpretations will be based on the principles outlined by Sharma [27] and Telford *et al.* [28].

5. Data and processing sequence

Most corrections, in particular drift, latitude, Free-air and Bouguer corrections had already been applied to the gravity data. Therefore, we will focus on their applications rather than acquisition. A high-resolution aeromagnetic data of the Niger Delta was acquired between 2009 and 2010 by Fugro Airborne Survey Ltd, with preliminary interpretation carried out by Patterson Grant and West (PGW) Consultants Canada. The high-resolution Bouguer gravity anomaly data used for this study, cover most part of the onshore Niger Delta area while the high-resolution aeromagnetic data covers the onshore Niger Delta with adjacent offshore (Figs. 3a and b). The acquisition procedures have been discussed by Paterson et al. [31] and Reford et al. [32]. The magnetic data, post-processed and presented in this section, relate to the distribution of magnetic minerals within the sub-surface of the Niger Delta area. The new aeromagnetic data were gridded using a bi-directional gridding technique since the data were acquired along parallel lines. To enhance the geological features, due to deeper magnetic sources, various low-pass phase filters were applied to the aeromagnetic data. The essence of the filters is to eliminate the effects of shallow wavelength anomalies or noise. The two main filters applied included: (i) reduction to equator (RTE) of the magnetic data and (ii) upward continuation of the magnetic data. In this study, the magnetic data were reduced to magnetic equator using an average geomagnetic inclination of -16°.5' and an average geomagnetic declination of -2°.25'. The main purpose of this filter is to position the magnetic data above their causative sources. The data were also upward continued to 2000 m to suppress the effects of cultural noise from the area especially pipeline network or effects of shallow sources and the map was presented in Fig. 3a. Many filters were not applied in this study to avoid the possible attenuation of the geological information that in this case seem to be unnecessary for this interpretation.

6. Procedure

In this study, gravity and magnetic data were used to qualitatively map various sub-basins within the Niger Delta area using Oasis Montaj software. The procedure for identifying sub-basins and hydrocarbon prolific areas are outlined below:

a. identify areas with gravity lows and magnetic lows within the Niger Delta Basin. This is important because regions with negative gravity anomalies or negative magnetic anomalies are often associated with sub-basins or sedimentary basins.
b. superimpose gravity map on magnetic map or vice versa using Oasis Montaj. This is important due to areas where both maps display similar negative anomaly characteristics and were marked as sub-basins and could be related to areas of potential hydrocarbon prolific zones.
c. compare the superimposed maps with sediment thickness distribution map in the same area.
d. compare the results obtained with previously identified prolific belts/centres.

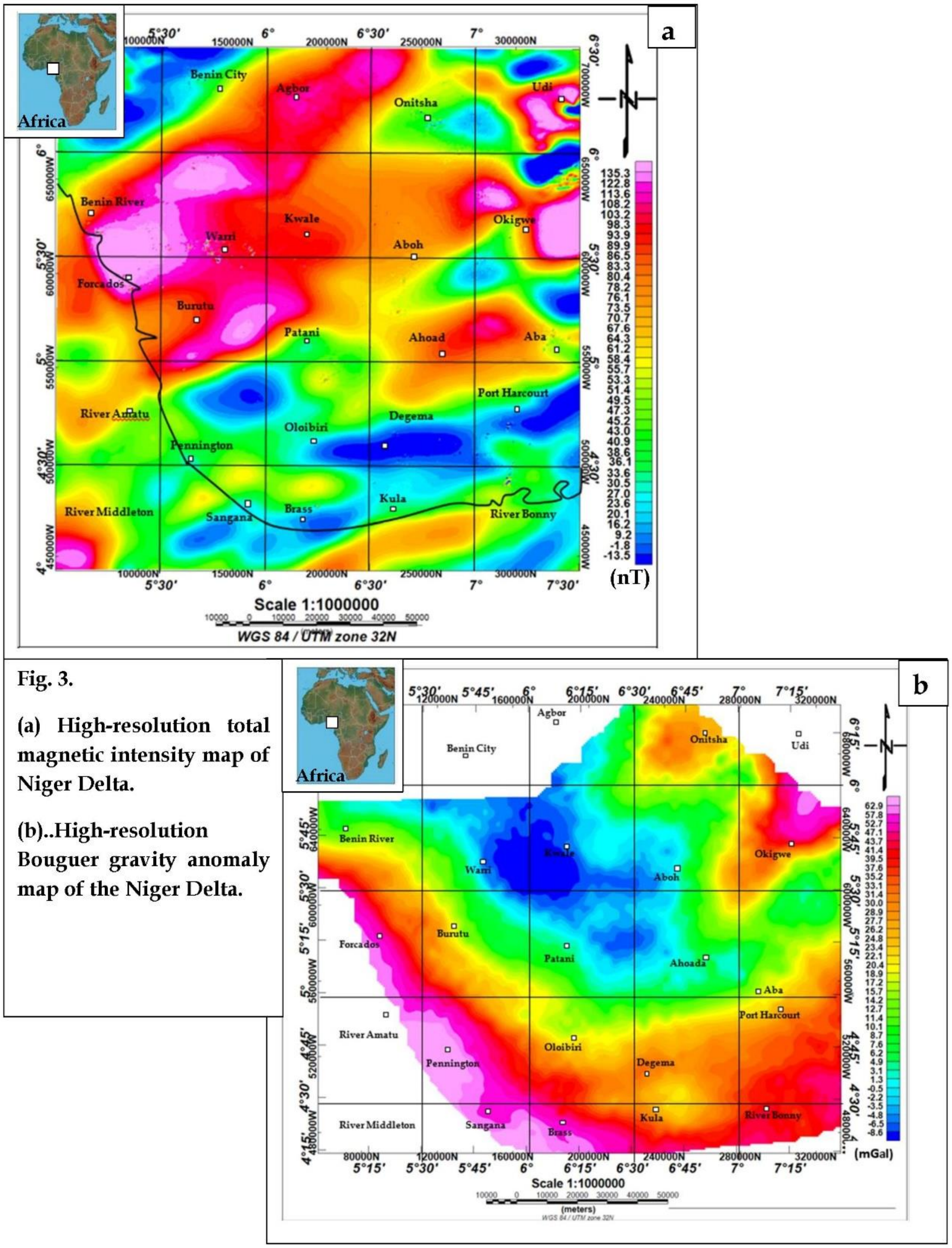

Fig. 3.

(a) High-resolution total magnetic intensity map of Niger Delta.

(b)..High-resolution Bouguer gravity anomaly map of the Niger Delta.

7. Results and discussion

7.1. Sub-basins within the Niger Delta

Within the Niger Delta Basin, nine (9) major magnetic lows were recognised from magnetic map, namely: Sangana magnetic low, Brass magnetic low, Bonny magnetic low, Oloibiri-Pennington magnetic low, Degema magnetic low, Port-Harcourt magnetic low, Ahoada magnetic low, Owerri-Aba magnetic low, and Okigwe-Udi magnetic low (Fig. 4). The magnetic lows recognised are associated with areas of low magnetic anomalies that may represent sedimentary rocks, and in some cases intermediate anomalies that may be associated with granitic rocks. The magnetic lows may be caused by intra-basement faulting and were speculated to represent sub-basins within the Niger Delta Basin.

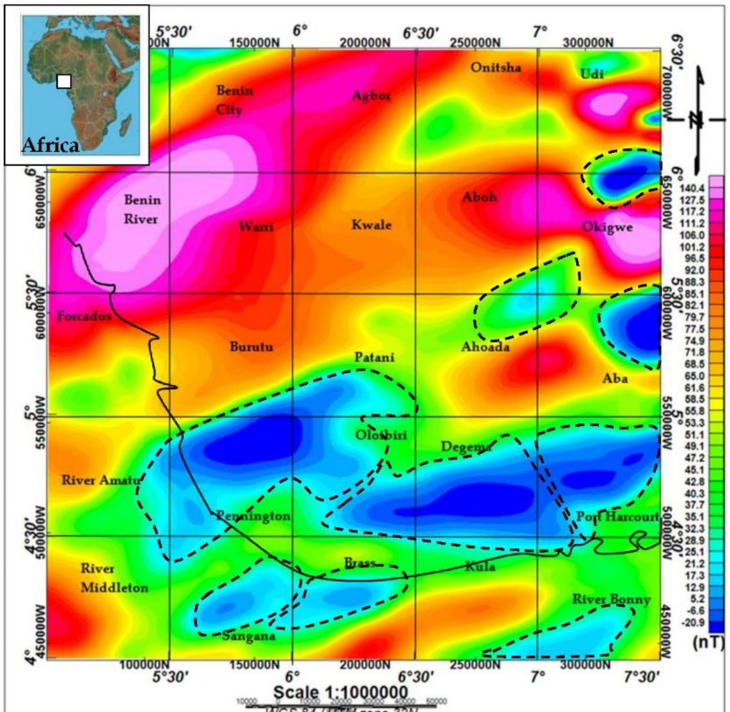

Fig. 4. Magnetic anomaly map of the Niger Delta Basin showing nine (9) major magnetic lows in blue colour.

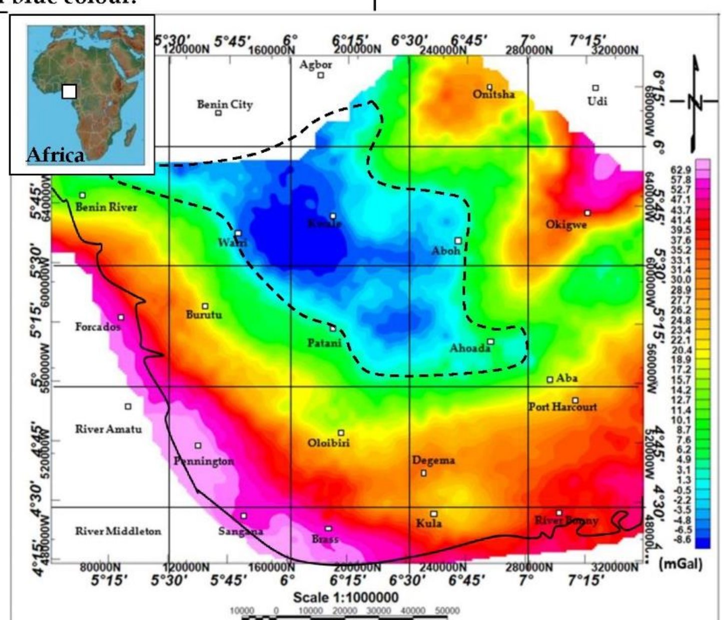

Fig. 5. Gravity anomaly map of the Niger Delta Basin showing a major gravity low in blue colour.

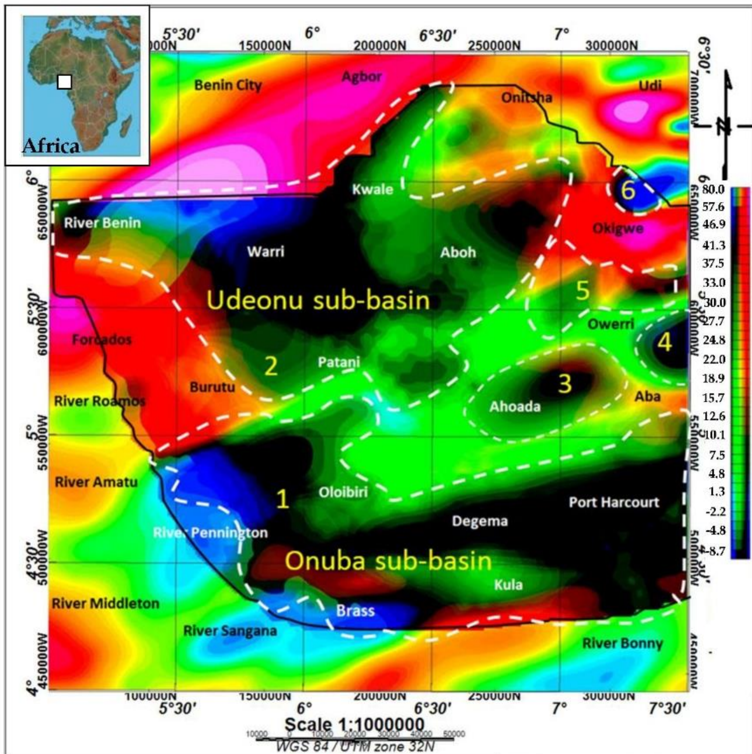

Fig. 6. The super-imposed gravity low map on magnetic low map of the Niger Delta indicating six sub-basins assumed to be related to hydrocarbon prolific areas (black colour).

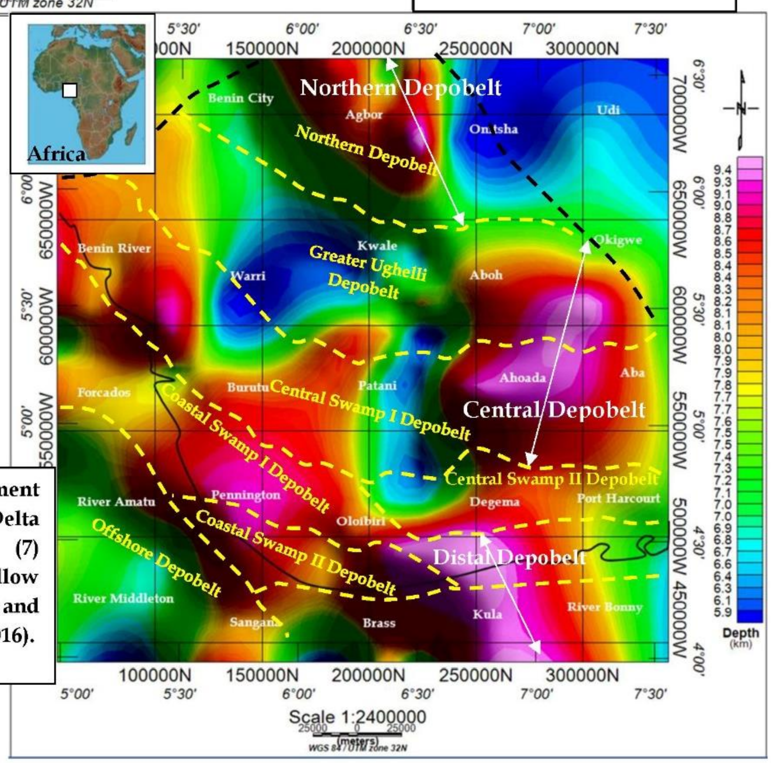

Fig. 7. The thickness of sediment map of the Niger Delta highlighting the seven (7) depobelts in broken yellow colour (modified from Doust and Omotola, 1989 and Onuba, 2016).

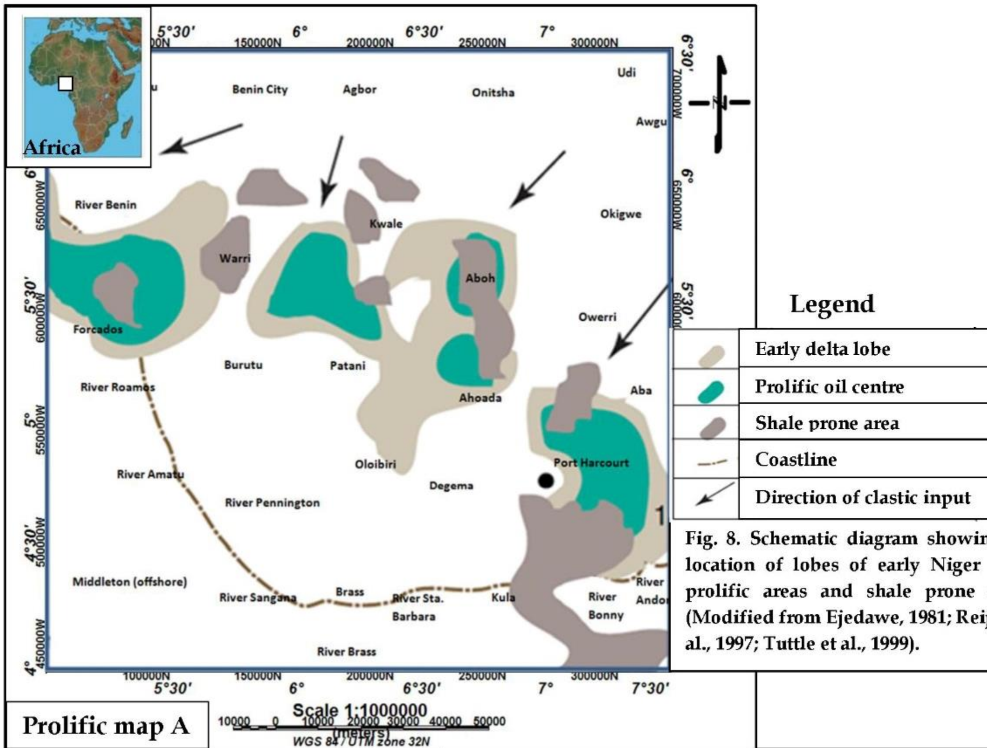

Fig. 8. Schematic diagram showing the location of lobes of early Niger Delta prolific areas and shale prone areas. (Modified from Ejedawe, 1981; Reijers et al., 1997; Tuttle et al., 1999).

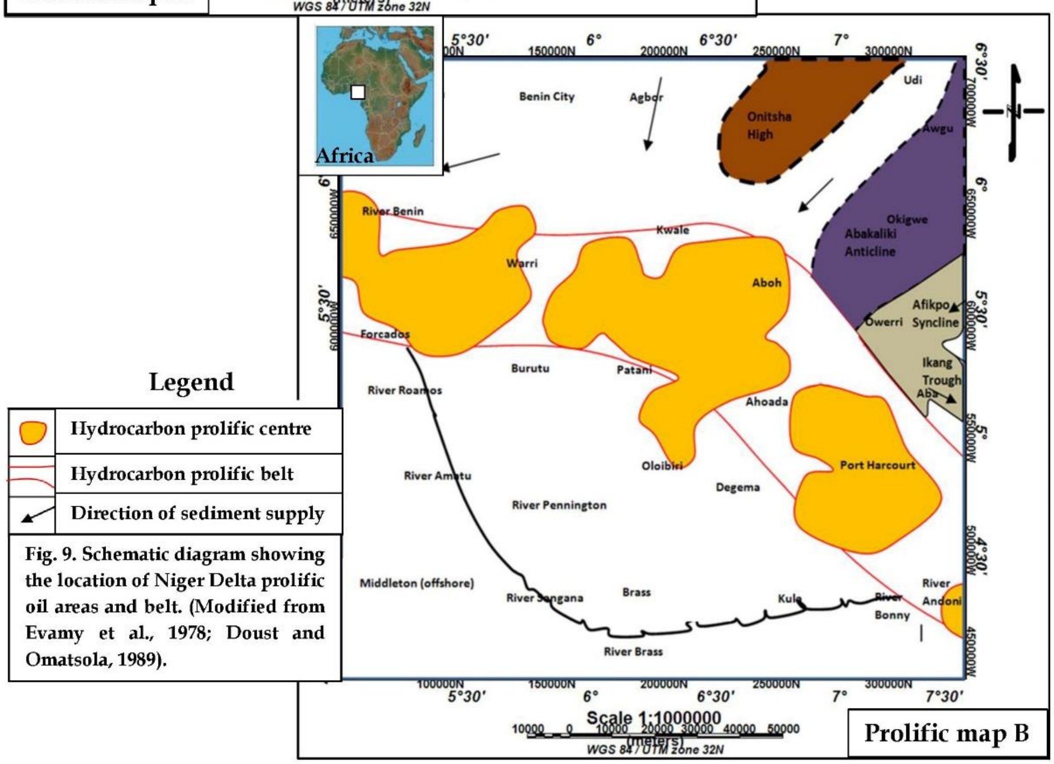

Fig. 9. Schematic diagram showing the location of Niger Delta prolific oil areas and belt. (Modified from Evamy et al., 1978; Doust and Omatsola, 1989).

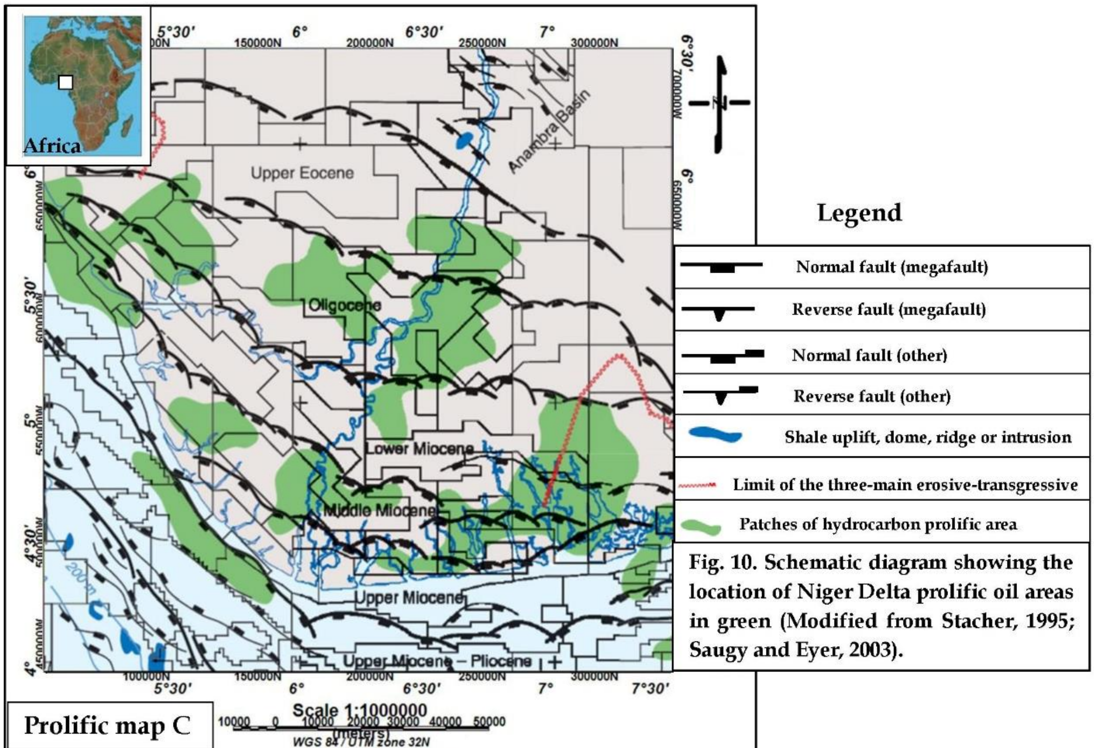

Fig. 10. Schematic diagram showing the location of Niger Delta prolific oil areas in green (Modified from Stacher, 1995; Saugy and Eyer, 2003).

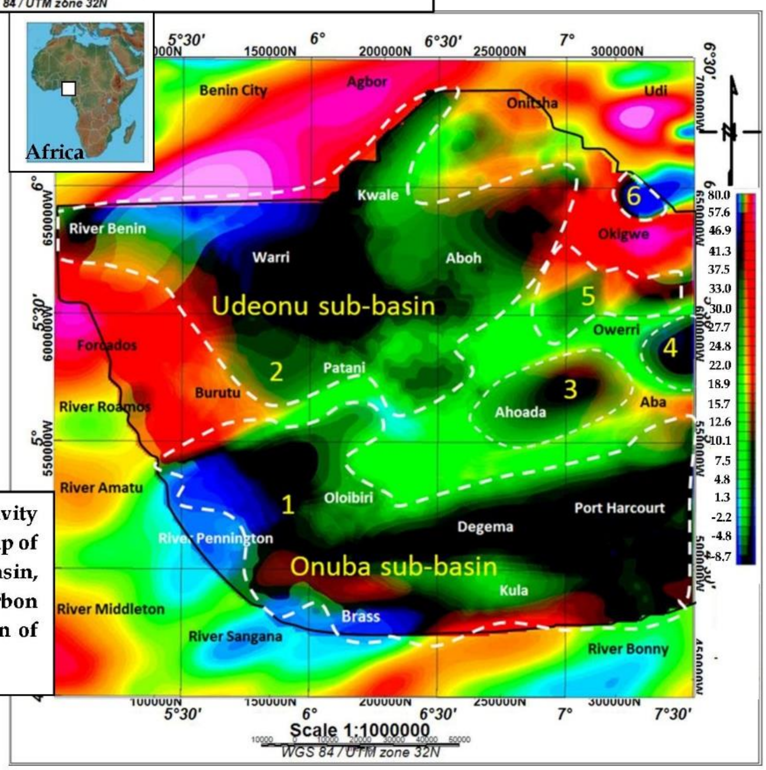

Fig. 11. Super-imposed gravity low map on magnetic low map of the Niger Delta Basin, highlighting some hydrocarbon prolific areas in dark portion of the map.

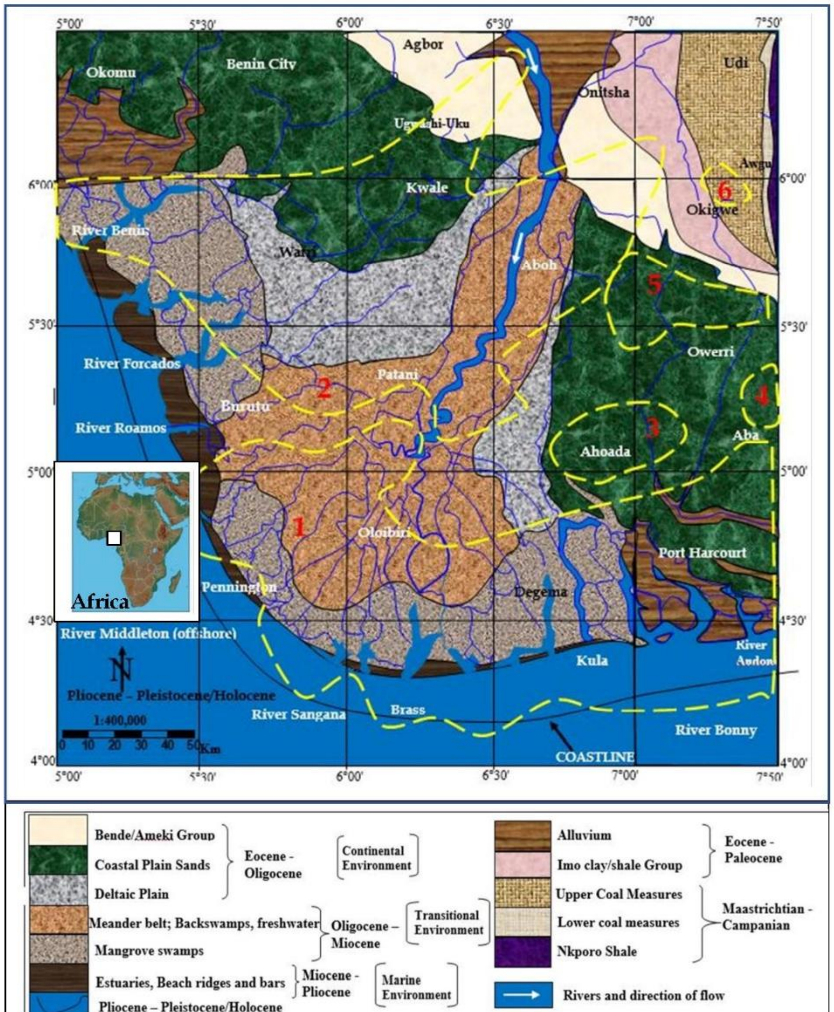

Fig. 12. Outline of the geological map of the Niger Delta indicating hydrocarbon prolific areas in yellow circle (modified from NGSA 1964, 2003 and Frankl and Cordry, 1967)

Six (6) sub-basins were recognised within the Niger Delta Basin by superimposing the gravity low map on the magnetic low map using Oasis Montaj (see Fig. 6). Among the sub-basins recognised, two of them are larger than the other four sub-basins. The two large sub-basins were named: the Onuba sub-basin (1) and the Udeonu sub-basin (2). The areas covered by Onuba sub-basin include: the Sangana, Brass, Kula, Bonny, Pennington, Oloibiri, Degema and Port-Harcourt areas while the areas covered by Udeonu sub-basin include: Burutu, Patani, River-Benin, Warri, Kwale, Aboh and Agbor areas. Other sub-basins include: Ahoada sub-basin (3), Aba sub-basin (4), Owerri sub-basin (5) and Okigwe sub-basin (6).

The Udeonu sub-basin lies mainly within the central part of the Delta depobelt and partly in the Northern Delta depobelt. The Central Delta depobelt is characterised by well-defined structures with successive deeper rollover crests that shift seaward for any given growth fault [16]. The Northern Delta depobelt is underlain by shallow basement and has the oldest generally rotational growth faults that are evenly spaced and increase in steepness seaward [16]. While based on age, the Udeonu sub-basin lies mainly within the Greater Ughelli, Northern and Central Swamp (I and II) depobelts. The Onuba sub-basin on the other hand lies within the distal part of the Delta depobelt province and is characterised by complex structures due to internal gravity systems on the modern continental slope as suggested by Doust and Omotola [16]. While based on age, the Onuba sub-basin lies within Offshore, Coastal Swamp I, Coastal Swamp II, and Central Swamp II depobelts.

The major hydrocarbon prolific areas show some resemblance to the recognised Onuba and Udeonu sub-basins, and these were compared to the thickness of sedimentary unit in the Niger Delta Basin (obtained from Onuba, [34]) and presented in Fig. 6. The results show that most of the prolific areas occur in places where sediments thickness varies from more than 4 km to about 10 km. This implies that these prolific areas have sufficient thickness of sediment to potentially allow hydrocarbon to form [35-37]. It is therefore speculated that the sub-basins identified might act as depocentres for the major hydrocarbon discoveries within the onshore Niger Delta Basin and these sub-basins may be characterised by higher net-to-gross reservoirs depending on sediment provenance and delivery mechanisms [38]. The Onuba and Udeonu sub-basins are hereby suggested to be associated with the major hydrocarbon prolific areas within the onshore Niger Delta Basin and adjacent offshore [16,39-40].

7.2. Hydrocarbon prolific areas of the Niger Delta Basin

In this study, two main hydrocarbon prolific areas were identified at the distal and the central part of the delta (Figs 6 and 7). The two hydrocarbon prolific areas were compared to the three (3) previously identified hydrocarbon prolific maps namely: (i) Prolific map A [8-10], (ii) Prolific map B [6, 16] and (iii) Prolific map C [39-40]. The results obtained indicate that all the prolific maps (A, B, C and the present study) lie within the central part of the delta (see Figs. 8, 9, 10 and 11) and cut through the Northern depobelt and the Central Swamp (I and II) depobelts (Early Eocene to Middle Miocene). In addition, the evidence from the same results further suggest that only prolific map C and that of the present study lie considerably within the distal part of the Niger Delta (Figs 10 and 11). This implies that the prolific map C and the one recognised from the present study cut across the Central Swamp II, the Coastal Swamp (I and II) and the Offshore depobelts (Middle Miocene to Pliocene). Omotsola [24] argued that of the major depobelts within the Onshore Niger Delta, the Coastal Swamps (I and II) are the most productive depobelts. If this is true, it could imply that the distal part of the delta could be more productive than the central part of the delta. This study is also in agreement with previous study suggesting that the most hydrocarbon prolific system of the Niger Delta was attributed to the Eocene–Miocene marine shale source rocks and Oligocene–Miocene turbidite reservoir sands [18].

The reservoir properties and source rock characteristics of the Onuba and Udeonu sub-basins within the onshore Niger Delta Basin are highlighted. The known reservoir rock of the onshore Niger Delta mainly comprises sandstone and unconsolidated sands of the Agbada Formation of predominantly Eocene to Pliocene age [6]. Studies suggest that the major reservoirs are observed mainly as the Miocene paralic sandstones with porosity of 40% and Darcy's permeability of 2 and a thickness of 100 metres [41]. The quality and shape of the reservoir rock is attributed to point bars of distributary channels and coastal bars that often cut intermittently by sand-filled channels [42]. The source rock of onshore Niger Delta Basin was suggested to have originated from marine shale of Akata Formation and intercalated shale of paralic sandstone of Agbada Formation [43]. The source rock contains land plant material and is capable of generating hydrocarbons [44]. Ejedawe et al. [45] using maturation models suggested that Agbada shale act as source rock for oil while the Akata shale act as source rock for gas at the central part of the delta. This cuts through the Udeonu sub-basin, Ahoada sub-basin, Aba sub-basin and Okigwe sub-basin. While at the distal part of the delta (the Onuba sub-basin), both Agbada and Akata Shales act as source rock for oil.

The Udeonu sub-basin (Eocene–Miocene) lies mainly within the central part of the onshore Niger Delta Basin that falls within the central prolific map similar to prolific maps A and B. The Udeonu sub-basin of the onshore Niger Delta is characterised by a gravity low and this is may be related to granite structures or grabens with accumulated sediment thickness ranging from 7 km to about 9 km. The magnetic anomaly amplitudes beneath the Udeonu sub-basin range from less than 100 nT to 10s nT. The area with amplitude of less than 10 nT were suggested to be related to sedimentary magnetization contrasts while the area with amplitude of 10s nT were suggested to be related to acidic igneous rocks or deep metamorphic basement [25]. It is thereby suggested that the Udeonu sub-basin is most likely to be underlain by thin continental or transitional crust rather than oceanic crust as previously suggested [6,8,16]. Ejedawe [8], using cumulative probability plot of oil reserve density (ORD) argued that the central Niger Delta hydrocarbon prolific area (Fig. 8), marks the transition zone between oceanic and continental crusts and this zone of weakness was also attributed to the tectonic zone of active subsidence [6,16]. Evamy et al. [6] further suggested that continent-ocean boundary (COB) within the Niger Delta area may serve as a major depobelt where the delta attains a dominant zone of crustal instability.

The Onuba sub-basin (Miocene-Pliocene) lies mainly within the distal part of the onshore Niger Delta Basin. It is underlain by gravity high of some tens of mGal and this may be related to intermediate rocks or uplifts associated with basement fault or anticlinal faults. The magnetic anomaly amplitudes beneath the Onuba sub-basin range from less than 10 nT to 10s nT. Most of the areas with amplitudes of less than 10 nT were related to sedimentary magnetization contrasts within the basin and the areas of 10s nT may be underlain by acidic igneous rocks or deep metamorphic basement due to no strong magnetic anomaly amplitude in this area [25-28]. Based on the above observation, it is hereby suggested that the Onuba sub-basin may likely be underlain by continental crust rather than transitional/COB as previously suggested [6,8,47].

Haack et al. [38] examined the position of the hydrocarbon prolific area in the Niger Delta with respect to oil prone marine source rock deposited adjacent to the central prolific belt. They suggested that source rock accumulation was influenced by pre-Cenozoic structures related to basement structures. This influence may have conditioned the major boundary fault to separate the Niger Delta Basin into (depobelts) that serve as main breaks in the regional dip of the delta [6]. The depobelts have been linked with the activity of large growth faults and clay diapers [21]. These features reflect the very common trapping mechanism for hydrocarbon accumulation in the Niger Delta Basin. Most oil and gas fields in the Niger Delta are characterised by these features. Fig. 12. highlights the geological map of the Niger Delta, indicating hydrocarbon prolific areas.

8. Summary and conclusions

This study was a cursory attempt to map sub-basins and relate them to major hydrocarbon prolific areas within the onshore Cenozoic Niger Delta Basin using magnetic and gravity data. In this study, nine (9) major magnetic lows were recognised from the magnetic map, and they could have been caused by intra-basement faulting. On the other hand, one major extensive gravity low was recognised and may perhaps reflects low density rocks within the Niger Delta Basin.

Based on that, six (6) sub-basins were then mapped by super-imposing gravity low map on the magnetic low map namely: the Onuba sub-basin, the Udeonu sub-basin, Ahoada sub-basin, Aba sub-basin, Owerri sub-basin, and Okigwe sub-basin. Among the sub-basins recognised, two of them are quite extensive with Onuba sub-basin covering Sangana, Brass, Kula, Bonny, Pennington, Oloibiri, Degema and Port-Harcourt areas and the Udeonu sub-basin covering Burutu, Patani, River-Benin, Warri, Kwale, Aboh and Agbor areas. The six sub-basins were suggested to lie within the hydrocarbon prolific areas.

The Udeonu sub-basin lies mainly within the Central delta depobelt cutting across the Greater Ughelli depobelt, the Northern depobelt and the Central Swamp (I and II) depobelts (Early Eocene to Middle Miocene). While the Onuba sub-basin lies within the Distal Delta depobelt province cutting across the Central Swamp II, the Coastal Swamp (I and II) and the Offshore depobelts (Middle Miocene to Pliocene). Out of the major Onshore Niger Delta depobelts, Omotsola [24] argued that the Coastal Swamp (I and II) are the most productive depobelts. If this is true, it could imply that the distal part of the delta that lies within the Onuba sub-basin could be more productive than the central part of the delta.

Insights obtained from this study, if combined with other non-geophysical data and deep drilling operations, might help to identify precise hydrocarbon targets, which could lead to a reduction in operational risks, cost, and time. This idea requires further investigation to understand the nature of the hydrocarbon prolific areas.

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