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Geometry and depositional environment of the sandy aquifers in the Oligocene-Miocene Ogwashi-Asaba Formation, southern Nigeria

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Abstract

The architecture and distribution pattern of the multilayered aquifer system in the Ogwashi-Asaba Formation, southern Nigeria have been investigated. Lithologic logs obtained from seven boreholes within the vicinity of Idumuje-Unor, Issele-Uku, Ogwashi-Uku, Issele-Azagba, Ibusa, Okpanam and Asaba, southern Nigeria, were used to construct lithologic cross section and fence diagram for the area. Interpretation of the cross section shows that there are six sandy units and three aquifer zones (Upper, Middle and Lower) within the study area, while from the evaluation of the fence diagram and length-thickness ratios of the sandy horizons, sheet or blanket sand bodies and pinch-out were recognized. The sheet sand bodies occur in all the three aquifer zones. The extensive and sheet-like geometry of the Ogwashi-Asaba Formation sandstones constitute an excellent reservoir for groundwater in the Niger Delta Basin. Textural evaluation revealed that the sandstones are fine- to very coarse-grained, moderately- to poorly-sorted, negatively skewed and very platykurtic to leptokurtic. Abundance of coarse-grained and negatively skewed sandstone samples indicate the prevalence of high energy conditions during deposition. Bivariate plots of mean grain size versus standard deviation along with skewness versus standard deviation, revealed a predominantly fluviatile systems for the sandstones. Furthermore, discriminant function plots (linear and multigroup multivariant) indicate that the sandstones were deposited in fluvial-deltaic to shallow marine depositional environment.

Keywords: *Aquifer system; geometry; Sheet sand body; Fence diagram; Ogwashi-Asaba Formation; Nigeria.*

1. Introduction

Natural resources including groundwater, oil and gas are contained in sandstone and carbonate (limestone and dolomite) reservoirs. Sandstone reservoirs account for over 50 percent of the World's giant oil fields [1]. According to [2], about 90 percent of our groundwater supply comes from sandstone reservoirs.

The Oligocene-Miocene Ogwashi-Asaba Formation (Fig. 1) is an extensive lithostratigraphic unit of the Niger Delta Basin with a thickness of *c.* 250 m [3-5]. The regional occurrence of this formation in southern Nigeria, makes it a potential aquiferous zone for groundwater resources. [6], described the regional groundwater flow system in the Ogwashi-Asaba Formation and established that static water level in the aquifer ranges between 110 and 180 m. [7], identified multiple aquifers at depths ranging from 50 to 110 m in the Ogwashi-Asaba Formation in parts of Anambra State, southeastern Nigeria. [8], mentioned the existence of two aquifers in the Ogwashi-Asaba Formation about 8 km east of the present study area. [9], reported the occurrence of two aquifers encountered in wells drilled up to 70 m in Ndokwa and Isoko areas of Delta State. Using geoelectric methods, [10] identified aquifers at depths of 140 - 180 m in parts of Niger Delta area. In addition, various researchers [11-18] have used sedimentological and palynological studies to characterize the depositional environment of the Ogwashi-Asaba

Formation. However, no study on the geometry of the sandstone units of the Ogwashi-Asaba Formation has been carried out. Due to the absence of a distinct seismic stratigraphic sequence, a more rigorous way via fence diagram construction was applied in this study to determine the various shapes that exist within the sandy units, their thicknesses, dimensions and environment of deposition. The aim of this study is to determine the geometry and depositional environment of the sandy units within the Ogwashi-Asaba Formation of Niger Delta Basin, southern Nigeria.

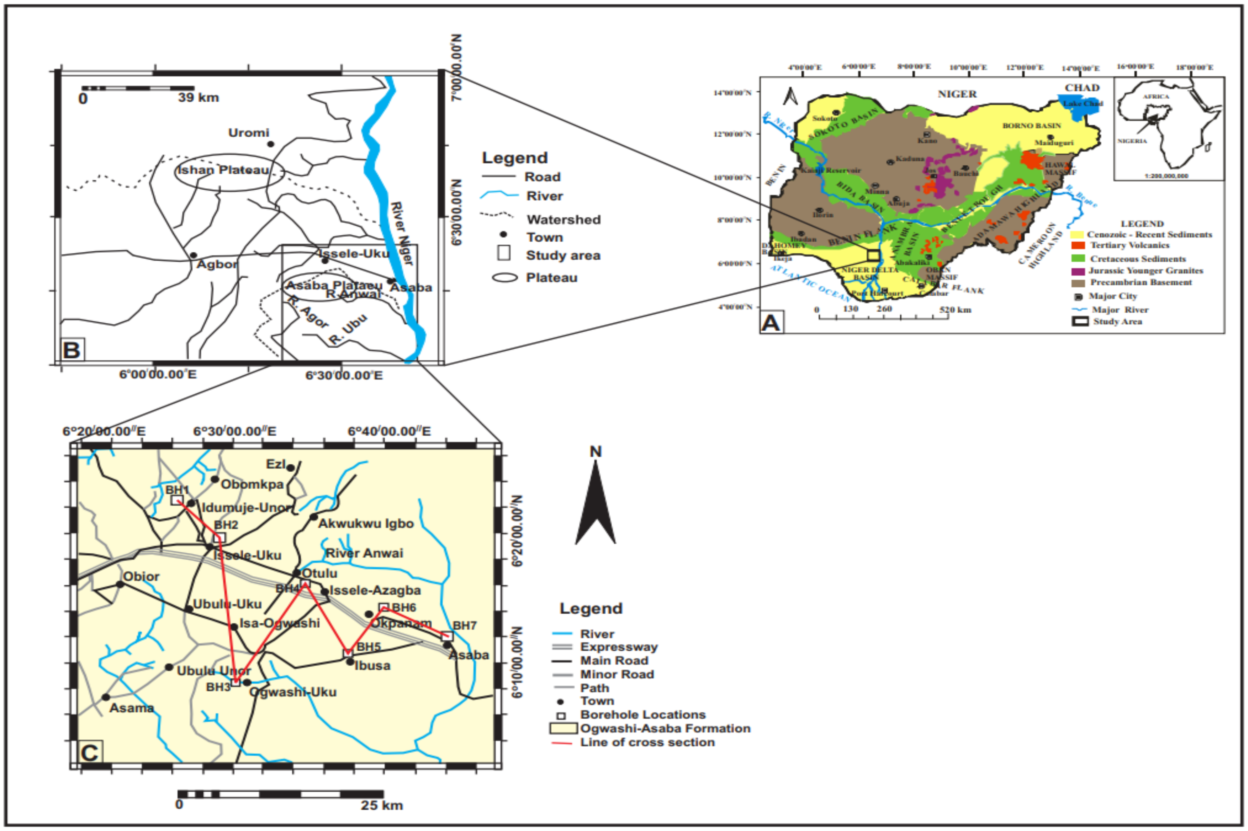

Fig. 1. Location of the study area: (A). Map of Nigeria showing the location of the study area with Africa map inset (B) Drainage map of the study area (C) Map of the study area showing the location of the studied boreholes (BH-1 to BH-7) sections. Note the line of cross-section (red line).

2. Hydrology/hydrogeology of study area

The study area (Fig. 1) covering an area of *c.* 1,100-km^2 is drained by some rivers and springs. The area lies in the tropical lowland rainforest of Nigeria with the annual rainfall ranging from 1600 to 2000 mm and average annual temperatures varying from 20 to 30°C. With the high amount of precipitation virtually all year round, the study area is heavily weathered with a thick layer of lateritic sediments showing the lack of rivers in most parts. The sparse dendritic drainage pattern occupies the northeastern to southeastern parts of the study area, drained by three major rivers: Ubu in Ogwashi-Uku, Agor in Ubulu-Uku, and Anwai in Asaba, with Ubu flowing in the lower region (Figs. 1b and 1c).

The surface and groundwater interaction are controlled by climate, geology, topography and anthropogenic factors. In tropical humid regions, the unconfined aquifers are localized and there may exist a hydraulic connection or disconnection between the surface water and groundwater. Hydraulic connection occurs where there is a presence of an unsaturated zone between the surface water and groundwater. The unconfined aquifers are directly recharged by precipitation, with depth to water table varying from 3 to about 60 m [8].

The formation of the aquifer systems can be attributed to the presence of tributaries emanating from rivers (Ubu, Agor and Anwai; Figs. 1b and 1c) and from subsurface recharge through interflow in the unsaturated zone and baseflow. The occurrence of the multi-layered aquifers can be attributed to local, intermediate and regional flow systems. These systems categorize groundwater flow in terms of the size and distribution. Local systems operate at shallow depths and are very dynamic as they interact with the atmosphere. The local system is aided by the presence of the Asaba plateau (Fig. 1b) within the study area contributing to the interchange of groundwater flow and surface water flow in the region. The Ishan plateau (Fig. 1b) provides adequate conditions for intermediate systems to develop in the area. The major aquifer hydraulic characteristics have been derived from geophysical methods [19] with mean transmissivity (T) and hydraulic conductivity (*K*) values of 18.51 and 0.8243 m/day respectively. [19], further estimated T and *K* from pumping tests as 18.58 and 0.8251 m/day, respectively. Although [8] determined transmissivity using Cooper and Jacob method to be 365 m^2/day.

3. Location of study area and geology

The study area is located in the Niger Delta Basin of southern Nigeria within latitudes 6° 10′ to 6° 26′ N, and longitudes 6° 23′ to 6° 39′ E (Fig. 1). This area is underlain by the Ogwashi-Asaba Formation, Niger Delta Basin (Table 1).

Table 1. Stratigraphic units of the Niger Delta Basin [24-25]

Present Niger Delta	Subsurface units		Surface units	
	Oldest/youngest known age	Formation	Oldest/youngest known age	Formation
Continental (fluviatile) deposits, mainly sand	Oligocene/Recent	Benin (Afam clay member)	Miocene/Plio-Pleistocene	Benin
Mixed continental, brackish water and marine deposits, sand- and claystone	Eocene/Recent	Agbada	Oligocene/Miocene	Ogwashi-Asaba
			Eocene	Ameki
Marine deposits, mainly claystone	Eocene/Recent	Akata	Palaeocene/Lower Eocene	Imo

The evolution of the Niger Delta Basin is associated with the failed arm of the triple junction during the separation of the African and South American continental plates during the Early Cretaceous [20-21]. The Niger Delta Basin experienced three depositional cycles with maximum sediment thickness and volume of 10 km [22] and 500,000 km^3 [23], respectively. The Cenozoic Niger Delta Basin is stratigraphically divided into the outcropping units (comprising the Imo, the Ameki, the Ogwashi-Asaba, and the Benin Formations); and the subsurface units consisting of the Akata, the Agbada, and the Benin Formations [24-25] (Table 1). The oldest sediments belonging to the subsurface transgressive lithostratigraphic Akata Formation, with deposition commencing during the Paleocene is composed of mainly shale of marine origin. The Akata Formation is regarded as the main source rock of the Niger Delta Basin. The surface equivalent of the Akata Formation is the Imo Formation. Overlying the Akata Formation is the paralic Agbada Formation with high petroleum content deposited during the Eocene. The Agbada Formation consists of a lower portion comprising equal amounts of sandstone and shale units with an upper segment made up of mostly sands. The lateral equivalent of the Agbada Formation occurs in the southern part of Nigeria between the two towns of Ogwashi-Uku and Asaba, thus referred to as the Ogwashi-Asaba Formation (Table 1) [4,26]. It comprises essentially a succession of coarse-grained sandstone, claystone, sandy clay and carbonaceous shale with the presence of lignite seams intercalations. The lignite seams found within the Ogwashi-Asaba Formation are brownish to black, varying in thickness from a few millimeters to a maximum of 6 m [27]. The Ogwashi-Asaba Formation is underlain by the Eocene Ameki Formation and overlain by the Oligocene-Pleistocene Benin Formation. The Benin Formation consists of continental fluviatile gravel, sand, and claystone (Table 1).

4. Methodology

Subsurface lithologic logs of seven (7) boreholes that penetrated the Ogwashi-Asaba Formation in the Niger Delta Basin, were obtained (Figs. 1, 2 and 3; Table 2). The lithologic logs were used to construct lithologic cross section and fence diagram to ascertain aquifer geometry. In constructing the fence diagram, a plain sheet of paper was superimposed on the topographic map of the study area and then the borehole locations are spotted on the plain sheet of paper. An appropriate vertical scale (1.3 cm = 20 m) was chosen to bring out a clear picture of the fence diagram. The lithologies were plotted against the vertical line representing the length of the section and the correlations of equivalent beds were carried out.

Table 2. Sampling locations and macroscopic descriptions of samples from Ogwashi-Asaba Formation.

Sample #	Location	Borehole #a	Depth of borehole (m)	GPS coordinates	GPS altitude (m)	Colour	Macroscopic description
	Idumuje-Unor	1	250	N06o 21/ 00// E006o 27/ 00//	227		
1	Issele-Uku	2	226	N06o 19/ 55// E006o 28/ 33//	299	reddish	lateritic sandstone
2						reddish	lateritic sandstone
3						red-brown	sandstone
4						red-brown	sandstone
5						red-brown	sandstone
6						red	ferruginized sandstone
7						red	ferruginized sandstone
8						red-brown	sandstone
9						red-brown	sandstone
10						red-brown	sandstone
11						brown	sandstone
12						brown	sandstone
13						brown	sandstone
14						brown	sandstone
15						dark grey	sandstone
16						dark grey	sandstone
17						dark grey	sandstone
18						white	sandstone
19						white	sandstone
20						white	sandstone
21						white	sandstone
22						white	sandstone
23						white	sandstone
	Ogwashi-Uku	3	140	N06o 11/ 56.60// E006o 32/ 50.50//	198		
	Issele-Azagba	4	138	N06o 15/ 47// E006o 34/ 25//	252		
	Ibusa	5	90	N06o 10/ 46.20// E006o 38/ 27.70//	111		
	Okpanam	6	122	N06o 14/ 01.50// E006o 38/ 44//	179		
	Asaba	7	260	N06o 12/ 0.00// E006o 44/ 11.80//	55		

a) see Figure 1.

Twenty-three (23) drill cuttings (sediment samples) obtained from borehole 2 were examined macroscopically. The sandstone samples were air dried, disaggregated, weighed, and grain-size analysis was performed using a *Ro-Tap* automatic sieve shaker in order to determine their particle size distribution. Graphic methods [28] were utilized in calculating the statistical parameters: mean grain-size (Mz), standard deviation (σ), skewness (Sk), and kurtosis (K_G). This analysis was carried out in the Sedimentology Laboratory of the Department of Geology, Delta State University, Abraka Nigeria. Depositional environment was evaluated in this study using textural characteristics and discriminant functions (i.e., linear and multigroup multivariant) analysis using equations proposed by [29] and [30]:

***Linear discriminant function (LDF) analysis*:**

1. To discriminate between aeolian process and beach environment:

$Y1 = -3.5688Mz + 3.7016\sigma^2 - 2.0766Sk + 3.1135K_G$;

If $Y1 > -2.7411$ = beach environment and $Y1 < -2.411$ = aeolian deposition.

2. To discriminate between beach and shallow agitated marine environments:

$Y2 = 15.6534 + 65.7091\sigma^2 + 18.1071Sk + 18.5043K_G$;

If $Y2 < 63.3650$ = beach deposition and $Y2 > 63.3650$ = shallow agitated water deposition.

3. To differentiate between shallow marine and fluvial process:

$Y3 = 0.2852Mz - 8.7604\sigma^2 - 4.8932Sk + 0.0482K_G$;

Where: $Y3 < -7.4190$ = fluvial (deltaic) deposit and $Y3 > -7.4190$ = shallow marine deposit.

4. To distinguish between fluvial (deltaic) and turbidity current deposits:

$Y4 = 0.7215Mz - 0.4030\sigma^2 + 6.7322Sk + 5.2927K_G$;

If $Y4 < 9.8433$ = turbidity current deposition and $Y4 > 9.8433$ = fluvial (deltaic) deposition.

Multigroup multivariant discriminant function analysis:

$V1 = 0.48048Mz + 0.06231\sigma^2 + 0.40602Sk + 0.44413K_G$

$V2 = 0.24523Mz + 0.45905\sigma^2 + 0.15715Sk + 0.83931K_G$

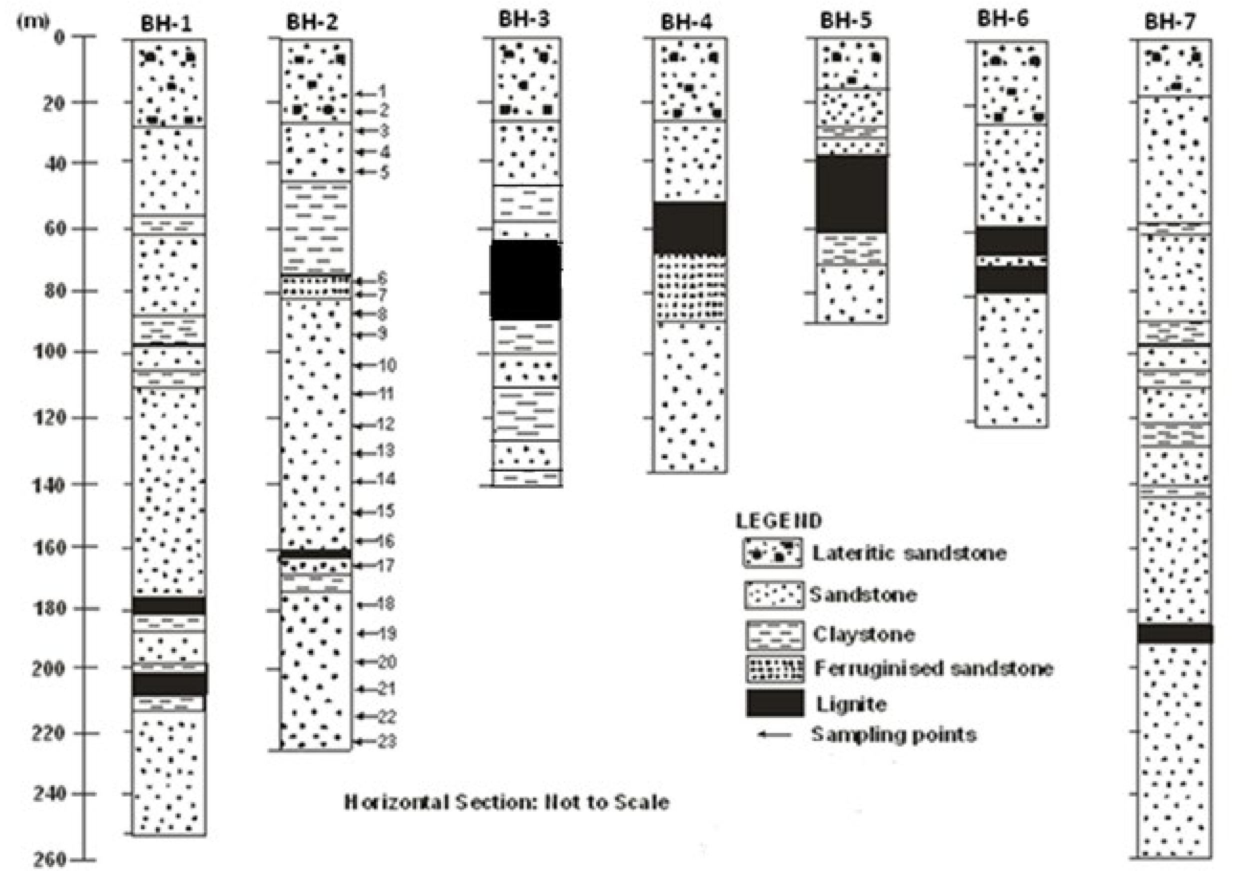

Fig. 2. Lithologic section of the boreholes showing stratigraphic columns and sampling points in the Ogwashi-Asaba Formation.

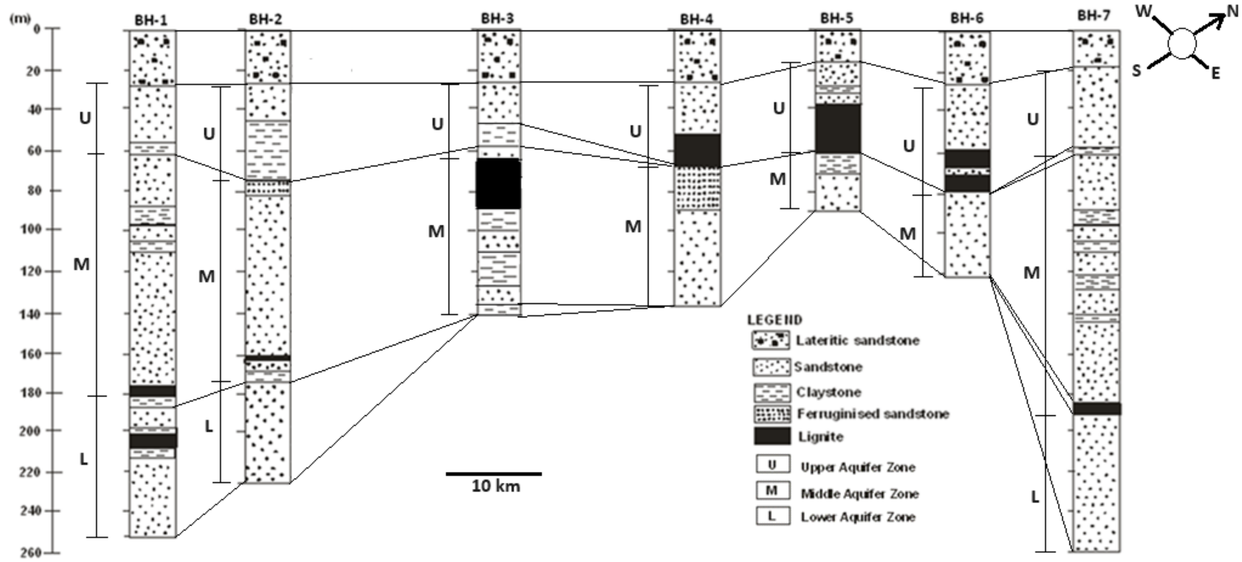

Fig. 3. Stratigraphic cross-section showing aquifer zones in the Ogwashi-Asaba Formation.

5. Results and interpretations

5.1.Stratigraphy of boreholes and macroscopic description

The stratigraphy of the boreholes shows that the sedimentary strata are dominated by sandstone with intercalations of claystone and lignite layers (Figs. 2 and 3). The lignite layers in the boreholes (BH-1, BH-2, BH-3, BH-4, BH-5, BH-6 and BH-7) are 5-27 m thick while the thicknesses of the claystone layers vary from 3 to 32 m. The top and base of the borehole profiles consist of lateritic sand and sandstone respectively except BH-3 which consist of claystone layer (Fig. 2 and 3). The lateritic sandstone is up to 18 to 25 m thick across the study area, and it appears reddish (#1 and 2) in colour (Table 2). The sandstone ranges from red-brown (#3, 4, 5, 6, 7, 8, 9 and 10), brown (#11, 12, 13 and 14), dark grey (#15, 16 and 17), to white (#18, 19, 20, 21, 22 and 23; see Table 2). It also consists of coarse-grained sandstone. The thickness of the sandstone beds ranges from 3 to 84 m. The lithological logs of the seven boreholes are presented in Figures 2 and 3.

5.2. Textural characteristics

The results of the granulometric analysis [28] are presented in Table 3. The graphic mean grain-size of the sandstone ranges from -0.15 Ø (i.e., very coarse-grained sandstone) to 2.37 Ø (fine-grained sandstone). The standard deviation values of the sandstone vary from 0.25 to 2.05 Ø, suggesting that the sand grains are moderately (samples #8, 11, 15, 17, 18 and 23) to poorly-sorted (samples #1, 2, 4, 5, 6, 7, 9, 10, 12, 13, 14, 16, and 22). However, samples #3, 19, 20 and 21 have standard deviation values of 2.05 Ø (very poorly-sorted), 0.25 Ø (very well sorted), 0.43 Ø (well-sorted), and 0.55 Ø (moderately well-sorted) respectively. The sandstones are negatively skewed while the graphic kurtosis ranges from 0.60 (very platykurtic) to 1.26 (leptokurtic).

5.3. Characteristic shapes of aquifer units

The morphology of sand bodies is characterized in terms of specific ratios of width to thickness. Sheet (blanket) sands are uniformly thin, widespread bodies of sands with great horizontal extent in relation to their thickness [31-33].

The cross section in Figure 3 extends for about 72 km from Idumuje-Unor in the west to Asaba in the east of the study area (Fig. 1c), and the top for the section is the mapped succession of weathered materials made up of lateritic sandstone bodies with a thickness of up to 18 to 25 m. Thus, the sandstone body exhibits a truly sheet-like cross-section (Fig. 3). The hydrological fence diagram showing the distribution of the aquifer units in the Ogwashi-

Asaba Formation is presented in Figure 4. Four aquifer units were delineated in this study based on the evaluation of the fence diagram and length-thickness ratios (Fig. 4 and Table 4). These aquifer units appear sheet-like in cross-section. The first aquifer unit in the study area has a total length covering about 72 km with a thickness of up to 18 to 25 m (Fig. 4). The dimensions of the second aquifer unit are length, 67.5 km, and up to 3 to 39 m thick (Fig. 4). These two aquifer units belong to the Upper Zone Aquifer in the Ogwashi-Asaba Formation (Table 4). The third aquifer unit has a length of about 73 km, and the thickness ranges from 4 to 78 m. The fourth aquifer unit comprised sheet sand and pinch-out with limited lateral extent. The dimensions of these aquifer units are 12.5 km (length), and up to 10 to 50 m thick and 31 km (length) and 68 m thick, respectively (Fig. 4). The third and fourth aquifer units belong to the Middle and Lower Aquifer Zones, respectively (Table 4).

Table 3. Graphic measures from the grain-size analysis of sandstones from Ogwashi-Asaba Formation.

S/N	Mz	σ	Sk	KG	Interpretations
1	0.45	1.22	-0.10	1.08	Coarse-grained sandstone, poorly-sorted, strongly coarse-skewed, mesokurtic
2	0.92	1.00	-0.10	1.07	Coarse-grained sandstone, moderately-sorted, near symmetrical, mesokurtic
3	1.32	2.05	0.06	1.18	Medium-grained sandstone, very poorly sorted, near symmetrical, leptokurtic
4	0.57	1.00	-0.10	1.06	Coarse-grained sandstone, moderately-sorted, near symmetrical, mesokurtic
5	0.07	1.39	-0.10	0.67	Coarse-grained sandstone, poorly-sorted, near symmetrical, platykurtic
6	0.50	1.11	-0.10	1.03	Coarse-grained sandstone, poorly-sorted, near symmetrical, mesokurtic
7	1.42	1.85	0.13	1.26	Medium-grained sandstone, poorly-sorted, fine-skewed, leptokurtic
8	1.08	0.94	-0.10	0.60	Medium-grained sandstone, moderately-sorted, near symmetrical, very platykurtic
9	0.48	1.03	-0.20	0.62	Coarse-grained sandstone, poorly-sorted, near symmetrical, very platykurtic
10	1.45	1.18	-0.00	1.08	Medium-grained sandstone, poorly-sorted, near symmetrical, mesokurtic
11	0.45	0.91	-0.10	1.04	Coarse-grained sandstone, moderately-sorted, near symmetrical, mesokurtic
12	1.53	1.30	-0.10	1.24	Medium-grained sandstone, poorly-sorted, near symmetrical, leptokurtic
13	2.37	1.20	-0.10	1.23	Fine-grained sandstone, poorly-sorted, near symmetrical, leptokurtic
14	0.70	1.20	-0.10	1.05	Coarse-grained sandstone, poorly-sorted, near symmetrical, mesokurtic
15	0.95	0.74	-0.10	1.02	Coarse-grained sandstone, moderately-sorted, near symmetrical, mesokurtic
16	-0.17	1.88	-0.20	1.07	Very coarse-grained sandstone, poorly-sorted, near symmetrical, mesokurtic
17	0.20	0.87	-0.20	1.07	Coarse-grained sandstone, moderately-sorted, near symmetrical, mesokurtic
18	0.02	0.73	-0.20	1.07	Coarse-grained sandstone, moderately-sorted, near symmetrical, mesokurtic
19	-0.33	0.25	-0.20	1.07	Very coarse-grained sandstone, very well-sorted, near symmetrical, mesokurtic
20	-0.15	0.43	-0.20	1.07	Very coarse-grained sandstone, well-sorted, near symmetrical, mesokurtic
21	0.12	0.55	-0.20	1.06	Coarse-grained sandstone, moderately well-sorted, near symmetrical, mesokurtic
22	0.87	1.13	-0.10	0.95	Coarse-grained sandstone, poorly-sorted, near symmetrical, mesokurtic
23	1.43	0.92	-0.20	0.83	Medium-grained sandstone, moderately-sorted, near symmetrical, platykurtic
MIN.	-0.33	0.25	-0.18	0.60	Very coarse-grained sandstone, very well-sorted, near symmetrical, very platykurtic
MAX.	2.37	2.05	0.13	1.26	Fine-grained sandstone, very poorly-sorted, fine-skewed, leptokurtic
AVE.	0.71	1.08	-0.10	1.02	Coarse-grained sandstone, poorly-sorted, near symmetrical, mesokurtic

where: Mz= Graphic mean size; σ= Standard deviation; Sk= Inclusive skewness; KG= Kurtosis; MIN.= Minimum; MAX.= Maximum; AVE. = Average

5.4. Description of aquifer zones and sandy units

Nfor *et al.* [7] delineated multiple aquifers in the Ogwashi-Asaba Formation at depths of 30-50 m, 70-90 m and 140-165 m with corresponding static water levels of 40, 69, and 120 m respectively. [6] distinguished two horizons in the Ogwashi-Asaba Formation which consist of medium to coarse sand layers and showed that the static water levels in the first and second aquifers ranges from 30-80 m and 110-180 m, respectively. [8] reported the occurrence of two major aquifers (first and second aquifers) within the Ogwashi-Asaba Formation and noted that the depth to water in the first aquifer ranges from 3 to 25 m while the second aquifer occur at greater depths in Asaba metropolis.

Within the study area, three distinct zones of sandy sediments, each separated by claystone and lignite layers varying in thickness from 2-32 m and 5-27 m, respectively, were identified from boreholes drilled to a maximum depth of 260 m within the Ogwashi-Asaba Formation

(Figs. 2 and 3). The sandy horizons coincide with the Upper, Middle and Lower Aquifer Zones of the Ogwashi-Asaba Formation (Figs. 3).

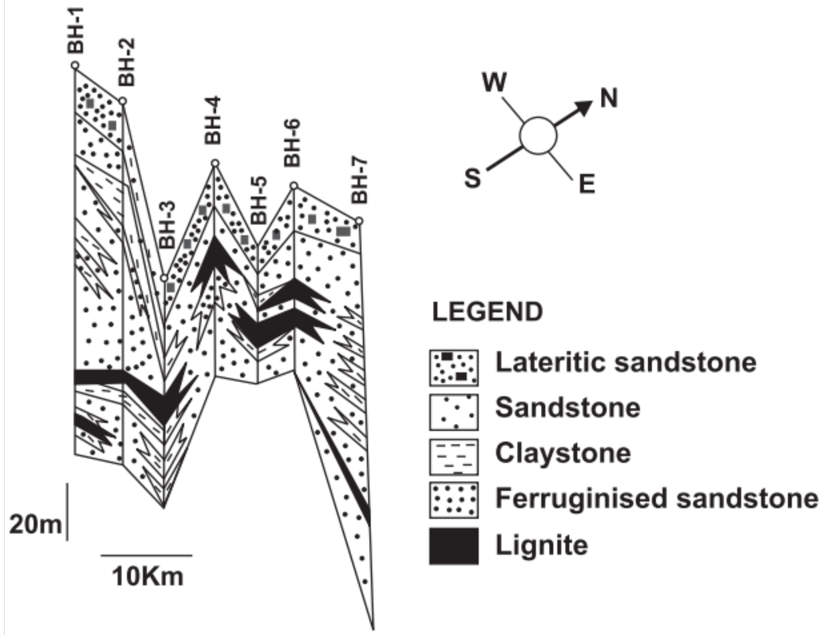

Fig. 4. Hydrogeological fence diagram for Ogwashi-Asaba Formation.

Table 4. Characteristic shapes of aquifer units in the Ogwashi-Asaba Formation.

	Aquifer zone	Length		Thickness (m)	Length/Thick-ness ratio	Geometrical form
		(km)	(m)			
1	Upper	72	72,000	18 to 25	2,880:1	Sheet sand
2		67.5	67,500	3 to 39	1,730:1	Sheet sand
3	Middle	73	73,000	4 to 78	936:1	Sheet sand
4	Lower	12.5	12,500	10 to 50	250:1	Sheet sand
5		31	31,000	68	456:1	Pinch-out

The Upper Aquifer Zone, also referred to as the First Aquifer Layer [6,8], has a thickness of about 35 m, extending from 25 to 60 m below ground level and consists of medium to coarse sand with claystone and lignite layer. This zone is overlain across the study area from the ground surface by a 25-m-thick lateritic sandstone. The Upper Aquifer Zone is in atmospheric equilibrium with the atmospheric pressure, as a result, the groundwater level fluctuates and ranges from 3 to 25 m [8] with seasonal rainfall variation. The base of this unconfined aquifer zone is underlain by a prominent claystone layer with maximum thickness of 32 m that demarcates in the western section of the area and by lignite in the eastern section to create a marker horizon (Figs. 3 and 4). A number of authors [4,24,27,34] have identified the claystone/lignite layers which combine to form this marker horizon. The recharge of this surficial unconfined aquifer is directly from rainfall percolation. The dendritic drainage pattern (Figs. 1b and 1c) in the region also plays a significant role in aiding percolation which directly recharges the unconfined aquifer being in hydrostatic equilibrium with subsurface. The depth from surface to the top of the Middle Aquifer Zone (Second Aquifer Layer) [6]; ranges from 60 to 180 m. The thickness of the sands in the Middle Aquifer Zone ranges from 4 to 84 m. The sands vary in grain size from medium to very coarse sand intercalated with claystone and lignite layers. The water in the Middle Aquifer Zone is held at hydrostatic equilibrium due to the occurrence of the confining marker horizons. The recharge of this zone is from the watershed created by the Asaba plateau (Fig. 1b). According to [8], groundwater flow direction is from north to south, laying credence to the Ishan plateau (Fig. 1b) located in the north of the study area as the probable source of recharge. Wells drilled into the Middle Aquifer Zone have been reported to be devoid of pollutants [8]. However, two layers of ferruginised sandstone occur at depths of 77-83 m and 73-95 m in boreholes (BH-2 and BH-4; Figs. 2 and 3), respectively. The third aquifer (Lower Aquifer Zone) occurs at depths greater than 180 m (BH-1, BH-2, and BH-7) but appears to have a relatively limited lateral extent near Asaba (BH-7; Figs. 3 and 4). This zone is about 70-m-thick, extending from about 180 to 260 m below the ground surface. The Lower Aquifer Zone consists of coarse to very coarse sand with intercalations of claystone and lignite layers towards Idumuje-Unor (BH-1) and Issele-Uku (BH-2) to the north while the claystone layer extends further to the south (Fig. 3). The groundwater recharge for this zone is thought to be from the Ishan Plateau located over 80 km from the study area (Fig. 1b).

The examined lithologic section in the study area shows that three boreholes (BH-1, BH-2, and BH-7) were drilled to the Lower Aquifer except for BH-3, BH-4, BH-5 and BH-6 that were drilled to the Middle Aquifer Zone (Fig. 3). BH-1 has a total thickness of 250 m and consists of six sandy units with thickness ranging from 25-57 m, 62-88 m, 98-106 m, 110-177 m, 188-198 m and 215-250 m (Fig. 3). These sandy units fall within the Upper, Middle and Lower Zones, respectively. BH-2 consists of four sandstone units. These sandstone units have thickness ranging from 25-45 m, 77-161 m, 163-167 m and 177-226 m, respectively, each separated by claystone and lignite layers. One of the sandy units belongs to the Upper Zone, two to the Middle Zone and the remaining one to the Lower Zone, respectively (Fig. 3). There are four sandstone units in BH-3 with thickness ranging from 25-46 m, 55-61 m, 95-113 m and 124-138 m. One of the sandstone units falls within the Upper Zone while three fall within the Middle Zone Aquifer (Fig. 3). BH-4 has a total thickness of about 138 m and consists of two sandstone units (25-56 m and 73-138 m). These sandstone units belong to the Upper and Middle Aquifer Zones respectively (Fig. 3). BH-5 consists of three sandstone units with thickness ranging from 15-25 m, 28-37 m and 73-90 m. Two of these sandstone units belong to the Upper Zone while one belongs to the Middle Zone Aquifer (Fig. 3). BH-6 has a total thickness of about 122 m and comprised three sandstone units (25-58 m, 67-70 m and 80-122 m). Two of the sandstone units belong to the Upper Zone while the remaining one belongs to the Middle Zone Aquifer (Fig. 3). BH-7 consists of six aquifer units with thickness ranging from 18-57 m, 60-87 m, 96-123 m, 129-141 m, 144-186 m and 192-260 m. One of the sandy units belongs to the Upper Zone, four to the Middle Zone and the remaining one to the Lower Zone, respectively (Fig. 3).

5.5. Palaeo-depositional environment via bivariate plots

Different authors [18,28,35-40] have used statistical textural parameters of sediments and the trends displayed in bivariate plots to understand the energy conditions, mode of deposition, medium of transportation as well as the depositional environments of the sediments. The depositional environment of the Ogwashi-Asaba Formation sandstones can be obtained from bivariate plots of mean grain size versus standard deviation (Fig.5A), and median size versus sorting (Fig. 5B) proposed by [36,41-43]. The bivariate plot of the graphic mean against standard revealed that 87 % of the analysed sandstone samples plotted in the river field while 13 % were deposited in a beach environment (Fig. 5A). The plot of the median size versus sorting [41,43] suggests that 78 % and 22 % of the analysed sandstones accumulated in river and beach environment respectively; with no influence of wave processes (Fig. 5B).

5.6. Palaeodepositional environment via discriminant function

Discriminant function (linear and multigroup multivariant) analysis proposed by Sahu [29-30] was further utilized to ascertain the depositional environment of the sandstones of the Ogwashi-Asaba Formation. According to Sahu [29-30], the fluctuation in the energy and fluidity factors correlate better with the different processes and environments of deposition. Discriminant function was computed to decipher the environment of deposition using the textural statistical parameters obtained from granulometric analysis (Tables 5 and 6). The linear discriminant function values of Y1, Y2, Y3 and Y4 (Table 5) were used to distinguish between the various processes and environments of deposition. The values of Y1, Y2, Y3, and Y4 for the Ogwashi-Asaba sandstone vary from 0.97 to 17.36, 15.66 to 319.85, -36.70 to 0.22, and 2.16 to 7.19 respectively (Table 5). With reference to the Y1 values, 100 % of the sandstone samples revealed beach environment (Table 5). The Y2 values indicated that 83 % of the samples fall in the shallow agitated marine environment while 17 % belongs to the beach (backshore) environment. For the Y3 values, 65 % of the sandstone samples exhibited fluvial (deltaic) setting while 35 % belong to the shallow marine environment. The Y4 values displayed 100 % turbidity current deposition for the studied sandstone samples (Table 5).

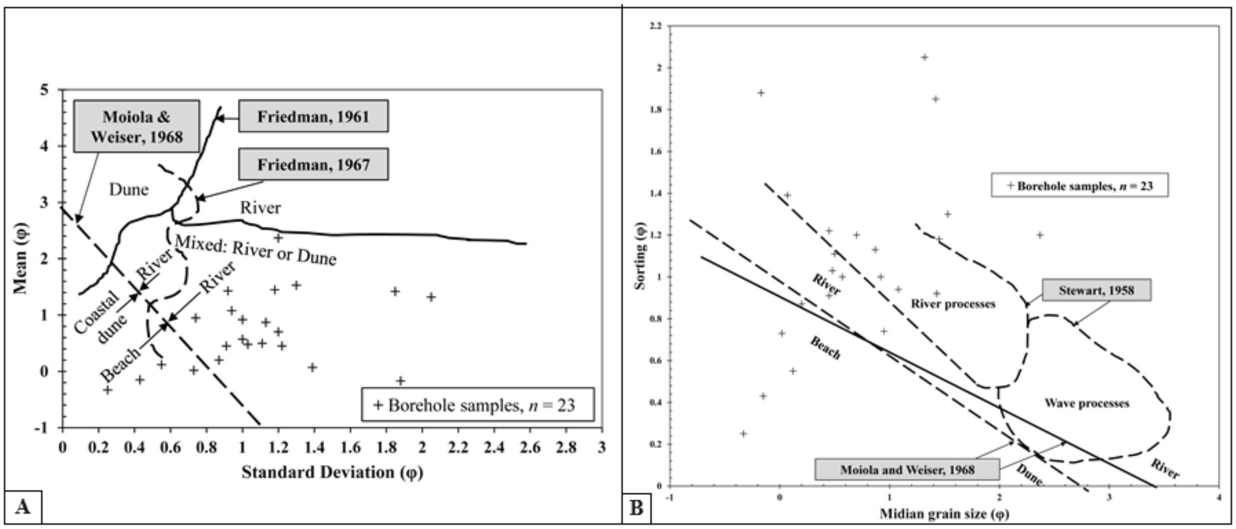

Fig. 5. Bivariate plots of Ogwashi-Asaba sandstone (A) mean grain size versus standard deviation [36,42-43] and (B) skewness versus standard deviation [41,43].

The studied sandstone samples plotted entirely on the beach/shallow agitated environment field on the Y2 versus Y1 binary diagram (Fig. 6A) [44-47]. On the Y3 versus Y2 diagram (Fig. 6B) [44-47], most of the samples (i.e., 78 %) plotted within the fluvial/agitated environment, whereas five samples (i.e., 22 %) plotted in the shallow marine/agitated environment and three samples in the shallow marine/beach environment. Additionally, on the Y4 versus Y3 diagram (Fig. 6C) proposed by [44] and [47], majority of the examined sandstone samples (i.e., 74 %) plot within the fluvial/turbidity current environment while six samples (i.e., 26 %) plotted in the turbidity current/shallow marine environment.

The multigroup discriminant function values of V_1 and V_2 for the sandstone samples ranged from 0.29 to 3.80 (average 1.59), and -0.8 to 0.93 (average 0.39) respectively (Table 6). On the multigroup multivariant discriminant functions plot of V_1 versus V_2 (Fig. 7), the bulk of the sandstone samples (i.e., 78 %) plot in the field of beach environment, whereas the remaining 22 % plotted in the turbidite field.

Both the bivariate plots (i.e., graphic mean versus standard deviation, and median size against sorting), and the discriminant function (linear and multigroup multivariant) suggest diversified environments of deposition for the Ogwashi-Asaba sandstones. These environments range from river (fluvial), beach, shallow marine, to turbidity processes. Such environmental diversification is often a characteristic of sedimentation in a mixed environment where a high energy flowing river empties its loads into a much bigger water body flowing at a relatively low velocity to build a delta.

Table 5. Linear discriminant function values and depositional environments of sandstone samples from Ogwashi-Asaba Formation.

Sample #	Discriminant function				Depositional environments			
	Y1	Y2	Y3	Y4	Y1	Y2	Y3	Y4
1	7.40	123.69	-12.55	5.02	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
2	3.85	99.06	-8.22	5.61	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
3	14.40	319.85	-36.70	5.95	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
4	5.11	92.91	-8.20	5.12	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
5	9.15	139.05	-16.51	2.31	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
6	6.20	106.06	-10.10	4.65	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
7	11.25	272.79	-30.15	7.19	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
8	1.44	84.80	-7.04	3.12	Beach	Shallow agitated marine	Shallow marine	Turbidity
9	4.45	86.07	-8.40	2.16	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
10	3.37	133.83	-11.65	6.08	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
11	4.945	79.03	-6.58	4.74	Beach	Shallow agitated marine	Shallow marine	Turbidity
12	4.86	156.32	-13.86	6.32	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
13	0.96	152.04	-11.26	6.76	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
14	6.23	123.81	-12.05	5.04	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
15	2.00	68.23	-4.06	5.30	Beach	Shallow agitated marine	Shallow marine	Turbidity
16	17.36	246.23	-30.13	2.95	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
17	5.76	69.53	-5.69	4.34	Beach	Shallow agitated marine	Shallow marine	Turbidity
18	5.58	51.91	-3.78	4.32	Beach	Beach	Shallow marine	Turbidity
19	5.07	15.66	0.22	4.26	Beach	Beach	Shallow marine	Turbidity
20	4.86	26.48	-0.81	4.43	Beach	Beach	Shallow marine	Turbidity
21	4.34	37.72	-1.65	4.37	Beach	Beach	Shallow marine	Turbidity
22	4.85	112.77	-10.28	4.29	Beach	Shallow agitated marine	Fluvial (deltaic)	Turbidity
23	0.97	90.37	-6.15	3.93	Beach	Shallow agitated marine	Shallow marine	Turbidity

where: Y1 (Aeolian:Beach) = -3.5688Mz + 3.7016σ2 - 2.0766Sk + 3.1135KG; Y2 (Beach:Sallow agitated marine) = 15.6534 + 65.7091σ2 + 18.1071Sk + 18.5043KG; Y3 (Shallow marine:Fluvial) = 0.2852Mz - 8.7604σ2 - 4.8932Sk + 0.0482KG; Y4 (Fluvial:Turbidity) = 0.7215Mz - 0.4030σ2 + 6.7322Sk + 5.2927KG

Table 6. Multivariant discriminant function values of sandstone samples from Ogwashi-Asaba Formation.

Sample #	V1	V2	Sample #	V1	V2
1	1.6	0.32	14	1.67	0.38
2	1.52	0.66	15	1.21	0.82
3	3.8	-0.6	16	2.53	-0.8
4	1.34	0.56	17	0.97	0.57
5	1.51	-0.3	18	0.75	0.63
6	1.42	0.41	19	0.29	0.76
7	3.43	-0.1	20	0.45	0.75
8	1.3	0.35	21	0.64	0.75
9	1.11	0.13	22	1.58	0.4
10	2.04	0.62	23	1.51	0.63
11	1.15	0.59	MIN.	0.29	-0.8
12	2.3	0.62	MAX.	3.8	0.93
13	2.53	0.93	AVE.	1.59	0.39

where: V1 = 0.48048Mz + 0.06231σ2 + 0.40602Sk + 0.44413KG; V2 = 0.24523Mz + 0.45905 σ2 + 0.15715 Sk + 0.83931KG; MIN. =Minimum; MAX. =Maximum; AVE. = Average

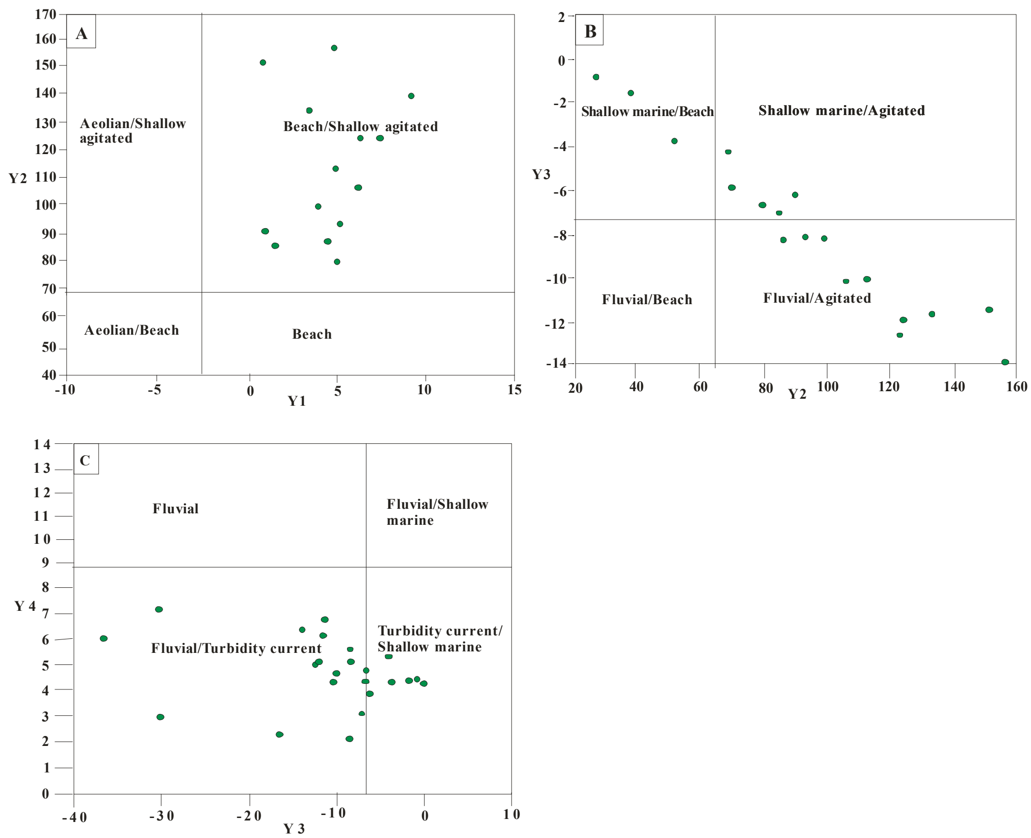

Fig. 6. Linear discriminant function plots for Ogwashi-Asaba Formation sandstone (A) Y2 versus Y1; (B) Y3 versus Y2 and (C) Y4 versus Y3.

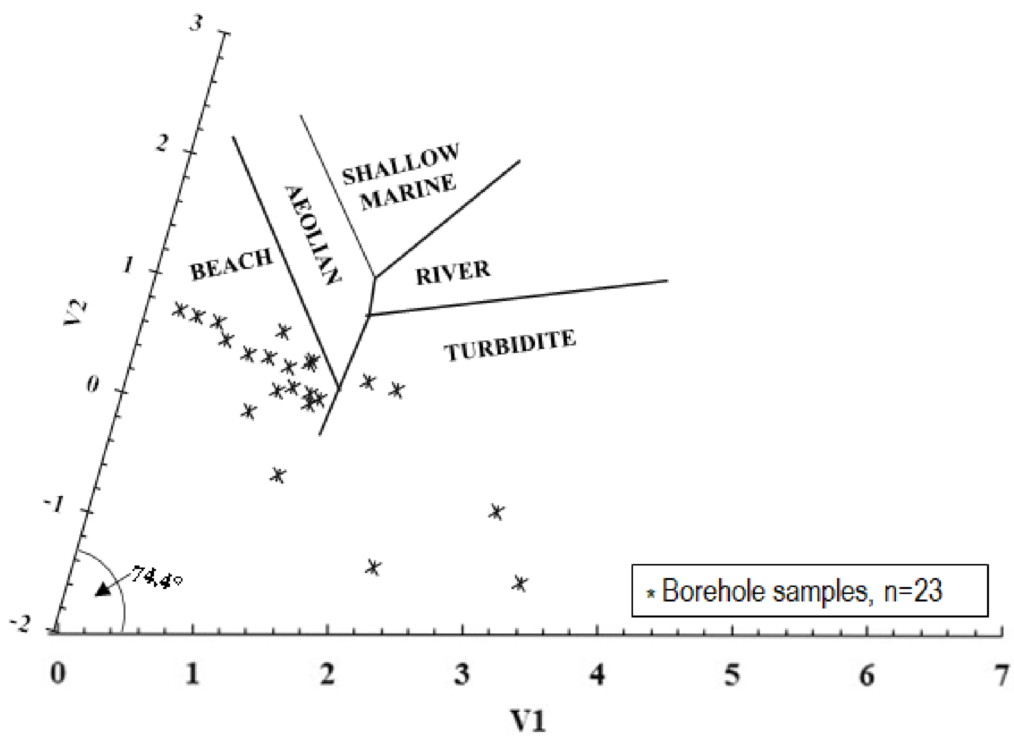

Fig. 7. Multigroup multivariant discriminant functions V_1 versus V_2 plot for the sandstone samples from Ogwashi-Asaba Formation.

6. Conclusions

Sediment samples and lithologic logs obtained from seven boreholes were examined in this study to decipher the geometry and depositional environment of the multilayered aquifer systems in the Oligocene-Miocene Ogwashi-Asaba Formation of the Niger Delta Basin, southern Nigeria. This study revealed the presence of three aquifer layers (Upper, Middle and Lower Aquifer Zones) down to a depth of 250 m, consisting predominantly of coarse-grained sandstone.

Four aquifer units were delineated in this study based on the evaluation of the fence diagram and length-thickness ratios of the sandy horizons. These aquifer units appear sheet-like in cross section. The sheet-like geometry of the Ogwashi-Asaba Formation sandstones is indicative of a prolific reservoir for groundwater in the Niger Delta Basin.The spatial variation in aquifer geometry in the region is controlled by a combination of morphology and sedimentation process. Textural characteristics along with discriminant function diagrams show that the Ogwashi-Asaba Formation sandstones are products of beach and fluvial systems.

Although the geometry of the sandy aquifers of the Ogwashi-Asaba Formation has been delineated, it should be noted that the herein study is based on available subsurface dataset (i.e. limited number of boreholes examined), do not allow for high resolution and regional interpretation of the geometries. More subsurface data (e.g. seismic and well logs) when available will provide further insights in terms the reservoir characteristics and a 3-D static model of not only the geometry of the aquiferous units but also the deeper hydrocarbon prospective sections of the Niger Delta Basin.

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