



GEOLOGY, SEDIMENTOLOGICAL AND HYDRAULIC CONDUCTIVITY OF AJALI POTENTIAL RESERVOIR SANDSTONE EXPOSED AROUND GRA IN IDAH, NORTHERN ANAMBRA BASIN

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ABSTRACT

The Ajali sandstone is a possible reservoir rock in the Lower Benue Trough (LBT)/Anambra Basin (AB), and understanding its geological, sedimentological distribution is essential for accurate prediction of fluid flow dynamic. Geological, granulometric analysis and laboratory hydraulic conductivity test are integrated for this investigation. Results from geological studies reveals three sandstone lithofacies; namely; AJALI L2A a sandstone intermixed with siltstone, lamination, bioturbated, and crossed bedded, AJALI L2B sandstone mixed with silty clay, crossed bedded and bioturbated and AJALI L2C an excessive weathered sandstone with visible ripple and ridges with all sedimentary features supporting the earlier proposed fluvio-deltaic depositional environments. The granulometric analysis reveals medium to coarse grain, poorly sorted sandstone lithofacies. Hydraulic conductivity test for AJALI L2A crossed bedded and lamination sandstone contributes smaller pore spaces between grains, which reduce overall interconnectivity of the pore network primarily decreasing the fluid hydraulic flow conductivity and thus lowers the permeability value to 75mD. While in the AJALI L2B intermixed with siltstone and clay sandstone, lowers porosity; but cross-bedding may have contributed positively to increase in permeability value to 1850 mD in this lithofacies. The weathered AJALI L2C sandstone with visible ripples and ridges significantly affect the physical properties and pore spaces obliteration by iron oxide, by contributing to reduction in the permeability value to 60 mD. In overall it is concluded that the Ajali sandstones generally will exhibits an average moderate permeability of 662 mD.

Keywords: Ajali sandstone, sedimentological distribution, granulometric analysis

INTRODUCTION

The probable reservoir rocks in both Southern Benue Trough and Anambra Basin are related sandstone lithofacies of the mostly shale lithology of the basin (Abubakar, 2014). Sedimentation in the Anambra Basin is predominantly terrigenous accumulating above 2900 m bulky shale (above 55%), sands (above 35%) and limestone less than 1% (Nwajide, 2005). Hydrostratigraphic units present in the Anambra Basin are divided into the following namely 1) Sandy strata of the Ameki group; 2) The Ajali Sandstone, the sandy strata of the layering the Nsukka Formation, and the upper part of the underlying the Mamu Formation; 3) Sandy beds in the Awgu, Nkporo and of the lower Mamu Formations (Onuoha & Dim, 2016). The main stratigraphic unit is very superficial to form feasible reservoir (Abubakar, 2014), while the Mamu and Nsukka Formations are maybe delta frontage sand bars (Ladipo, 1986; Nwajide, 2005). The Ajali Sandstone is ascribed to fluvial deposition (Onyekuru et al., 2023) categorized by huge channels comprising sand fill of fining uphill rock-strewn sandstones (Nwajide, 2005). The Ajali sandstone development is also related to superficial marine subordinate tidal sand bars (Ladipo, 1986). The possible reservoir sands are laterally extensive with an estimated localize thickness of about 5015 ft (>1000 m) where stacked (Abubakar, 2014). The Maastrichtian age Ajali sandstone is

selected to evaluate the effects sedimentological properties, small scale structures on its hydraulic conductivity as a contribution to understanding of its reservoir physical properties and fluid flow dynamics. The study will investigate sedimentological parameters and evaluate hydraulic conductivity of the fluvio-deltaic Ajali sandstone.

The Benue Trough & Study Area

The Benue Trough of Nigeria is a rift basin extending NNE – SSW for about 800 km in length and 150 km in width in central West Africa. The Benue Trough is instinctively subdivided into a lower, middle or central and upper portion (Fig.1). No physical line of division can be drawn to delineate the individual portions, but main localities (town/settlements) that make up the depocentres of the diverse portions have been well acknowledged (Obaje, 1999; Petters, 1982). The depocentres of the Lower Benue Trough comprises mainly areas around Nkagalu and Abakaliki, while those of the Anambra Basin center around Enugu, Akwa and Okigwe. The Middle Benue trough comprises the area from Markurdi through Yandev, Lafia, Obi, Jangwa, to Wukari. In the Upper Benue Trough, the depocentres encompass the Pindiga, Gombe, Nafada, Ashaka, (in the Gongola Arem) and Bambam, Tula, Jessu, Lakun, and Numan in the Yola Arm.



Figure 1: Showing Sedimentary Basins in Nigeria and position of the study area in red (modified after N. G. Obaje (2019))

Geology and Stratigraphic Succession of LBT & AB

In the LBT, sedimentation started with the marine Albian Asu-River Group. The Asu River Group in the LBT characterize by the shales, Limestone and sandstone intercalation of the Abakaliki formation in Abakaliki district and the Mfamosing Limestone in the Calabar border (Petters, 1982). The marine Nkalagu Formation (black shales, limestones and siltstone) Cenomanian – Turonian in age intercalated with sandstones of the Agala and Agbani Formation rest on the Asu River Group. Mid-Santonian disruption in the Benue Trough deformed the major depositional bloc westward which resulted to the formation of the Anambra Basin. Later depositional sedimentation in the LBT, started with the Campanian – Maastrichtian marine

Enugu and Nkporo Formation, overlain by the coaly events of the Mamu Formation. The fluvio-deltaic sandstone Ajali and Owelli Formations conformably on the Mamu Formation and represent its sideways equivalent in most places (Figure 2). The Imo and Nsukka Formations during the Paleocene incursion, marine shales were conformably deposited, and underlying by the Nanka Sandstone of the Eocene period. Further dipping down is the Niger Delta, comprises of; the Akata Shale, and the Agbada Formation make up of the Paleogene alike of the AB.

According to Abubakar (2014), Ajali sandstone is identified as a potential reservoir in the Anambra basin amongst listed petroleum system elements in the region (Figure 3) both in red.

AGE	LOWER BENUE	MIDDLE BENUE	UPPER BENUE		CHAD/BORNU
Quaternary	Benin		Yola sub	Gongola sub	Chad
Pliocene	NIGER DELTA	Volcanics	Volcanics	Kerri-Kerri	Hiatus
Miocene		Agbada			
Oligocene		Akata			
Eocene		Nanka			
Paleocene	Ameki/Imo/ Nsukka	Lafia	Hiatus	Gombe	Gombe
Maastrichtian	Ajali/Owelli/ Mamu			Fika	Fika ?
Campanian	Nkporo/Enugu				
Santonian					
Coniacian	Awgu	Makurdi	Lamja	Fika ?	Fika
Turonian	Agbani Nkalagu	Awgu	Numanha Sekuliye Jessu Dukul	Pindiga Gongila	Gongila
Cenomanian	Agala	Ezeaku/Konshisha/ Wadata			
Albian	Asu River Group Abakaliki	Keana/Awe	Yolde		
Pre-Albian	Mfamosing	Arufu/Uomba/Gboko	Bima		Bima
	Basement Complex				

Unconformity
 Transitional boundary
 Major unconformity (for the Santonian deformation)

Figure 2: Lithologic Sequence of the Benue Trough

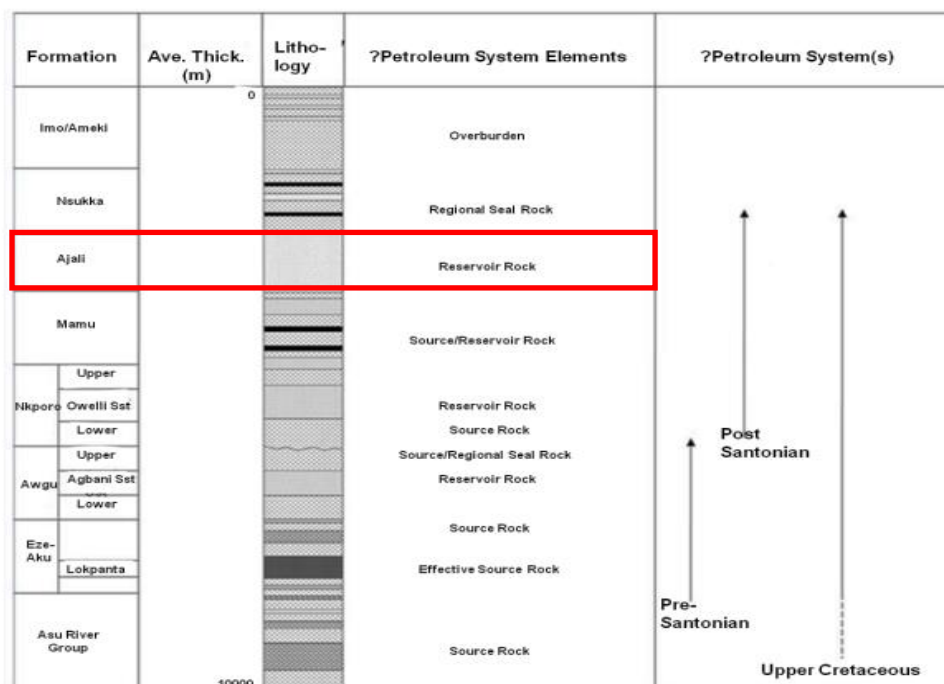


Figure 3: Possible petroleum system (s) in the Southern BT/AB (modified after Abubakar, 2014)

MATERIALS AND METHODS

The methodology includes field mapping and descriptions of the Ajali sandstones exposure within the Iyale in Idah LGA of Kogi State. Field samples was collected within the Government Residential Areas (GRA) and labeled; 2A – C within Iyale. Description of the exposure was carried out in field and coordinates and elevations were taken at each of the locations. This was followed by sedimentological investigation to determine the grain sizes and grain sorting distribution of the unconsolidated sandstones. The samples were subjected to hydraulic conductivity test using the falling Head permeameter all in the Dr Maikanti- NNPC Geological laboratory in IBB University, Lapai, Niger State.

- i. The original mass of the pan measured together with the dry sand- aggregate (W2). Take away the cover-led and unscrew topmost chamber cover cap-led nuts of the permeameter. Measure the internal diameter of the topmost and lowermost chambers respectively. Then we calculate the average internal diameter of the permeameter (D).
- ii. The porous sand is placed in the internal maintain ring at the base of the compartment then place a sieve paper on top of the permeable sand.
- iii. The sand is mix with sufficient distilled water to avoid the particle sizes from segregating to pass into the permeability mold. Enough water is added, such that the mixture can flow without restraint. Using a scrape shape homogeneous sheet, then pour to prepare sand-aggregate into the down compartment, substantial to the beam.
- iv. The tamp device is used to packed in the layer of sand, at an approximate of ten rams of interfere per layer to present consistent exposure of the soil surface. Then compaction is repeated until the sand is at the beam of the permeability cast.
- v. The topmost chamber segment is changed to be sure to place the rubber-band gasket linking the compartment segment.
- vi. The density spring is paced on the permeable sand and chamber led is changed with its seal gasket to secure the led steadfastly along with the led nuts.
- vii. The sand sample extent is measured at 4 points around the perimeter of the permeameter, to calculate the average extent, as the sand sample extent. However, the pan and left over soil kept in drying oven.
- viii. Regulate the altitude of the funnel to allow the constant water altitude in it to linger a little inch over the top of the sand.
- ix. The elastic cylinder connected from the end of the cone to the base vent of the permeameter, with the outlets on uppermost section of the permeameter unlock. A tube is run from the upper outlet to the go downwards to gather water that is released. Unlock the base outlet and permit the water to flood into the permeameter setup.
- x. Sand sample is always soaked before the test in the lab
- xi. When water begins to flow outward of the top adjustable valve, close the adjustable valve, allowing water flow out of the discharge outlet for some time. Then lock the bottom adjustable valve and detach the pipe at the base. Then again, link the cone pipe to the top side port.
- xii. Unlock the base outlet valve to raise the cone to a appropriate altitude to get a almost stable flow of water. Permit sufficient time for the flow model to develop into steady.
- xiii. The time is taken to fill up a level of 200 milliliter by the graduated container, then temperature of the water determine. The procedure is repeated 3 times to calculate the average time, temperature and quantity taken. The taken values are recorded as t, Q, and T, correspondingly.
- xiv. The quantity of the water with time is calculated and recorded
- xv. The straight down distance (H) between the cone head point and the chamber outpouring level is calculated and documented.



Figure 4: Filling the permeability



Figure 5: Figure 2: Saturated soil samples on a weighing balance compartment with samples



Figure 6: showing measurement water volume time recorded

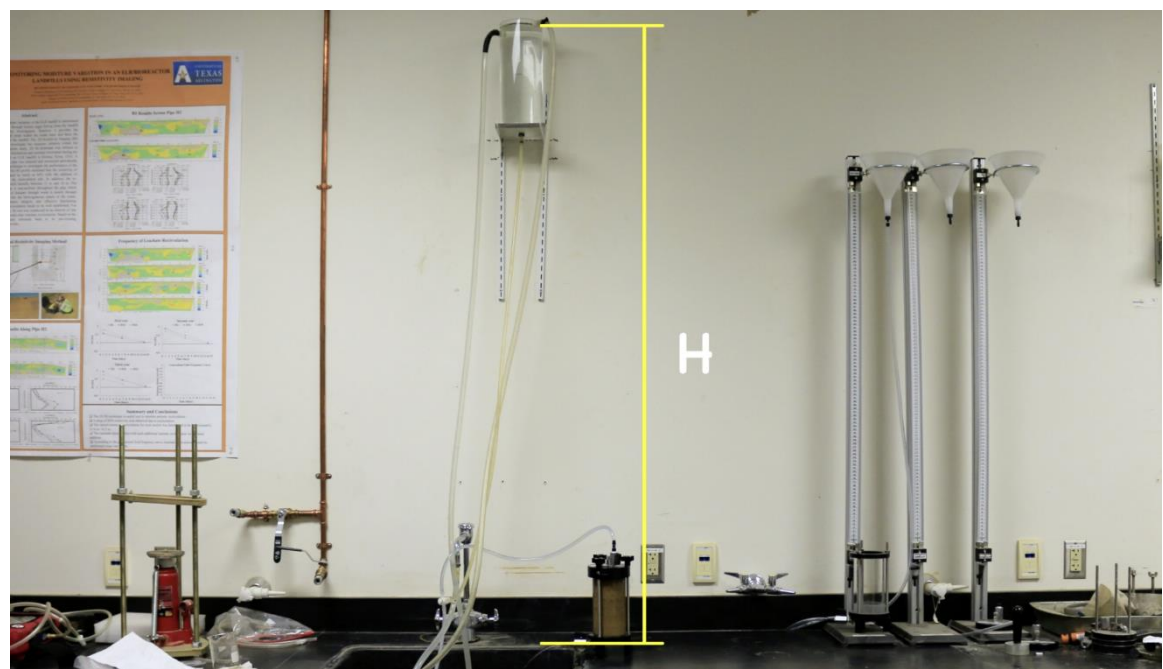


Figure 7: Showing the Head difference between the top of the water source and outlet point of the permeability setup

Granulometric investigation**Procedure**

- i. Foremost, the samples are dissolved gently by soaking in water and kerosene for about 48 hours. Then samples were openly sun dried to remove all water moisture contents.
- ii. The weight of the sand sample was measured through a weighing balances and 0.063 mm sieve size is used to sieve out all clay sized materials from the sand to obtain exclusively weigh of the sand sample.
- iii. The sand samples were passed in a set of sieves pans arranged in order of decreasing aperture. The sieve pans

sizes from 4 millimeter , 2.36 millimeter, 1.18 millimeter, 0.60 millimeter, 0.30 millimeter, 0.150 millimeter,0.75 millimeter, and 0.63 millimeter respectively. The setup is electrically shaken for about 10 minutes.

- iv. The weight of retained sand in each of the sieve mesh pan are all measured using the electronic weighing balance with recorded values in Tables calculated into percentage (%). The sieve sizes are plotted against the percentage weight retained presented on a histogram graphs.

RESULTS AND DISCUSSION**Field studies and Geological description****Table 1: Showing sample ID, locations and descriptions**

Location : IYALE	N07°38'09.1"	E 07°20'00.5"	Elevation : 315m	Lithology & Description
Ajali sandstone				
1 2A (GRA, IDAH)	N07°08'19.0"	E006°45'38.7"	Elevation: 127m	Sandstone mixed with siltstone, crossed bedded & lamination
2 2B (GRA, IDAH)	N07°08'16.6"	E006°45'38.4"	Elevation: 130 m	Sandstone mixed with siltstone & clay, crossed bedded and bioturbated
3 2C (GRA, IDAH)	N07°08'16.4"	E006°45'40.0"	Elevation: 125 m	Excessive weathered sandstone with ripple & ridges visible

Ajali sandstones are distal equivalent of Lafia formation of Middle Benue Trough overlying the Mamu formation in Northern Anambra basin. They are transition beds of

Maastrichtian characteristic of the fluvio-deltaic sandstones. The fieldwork findings are described below.

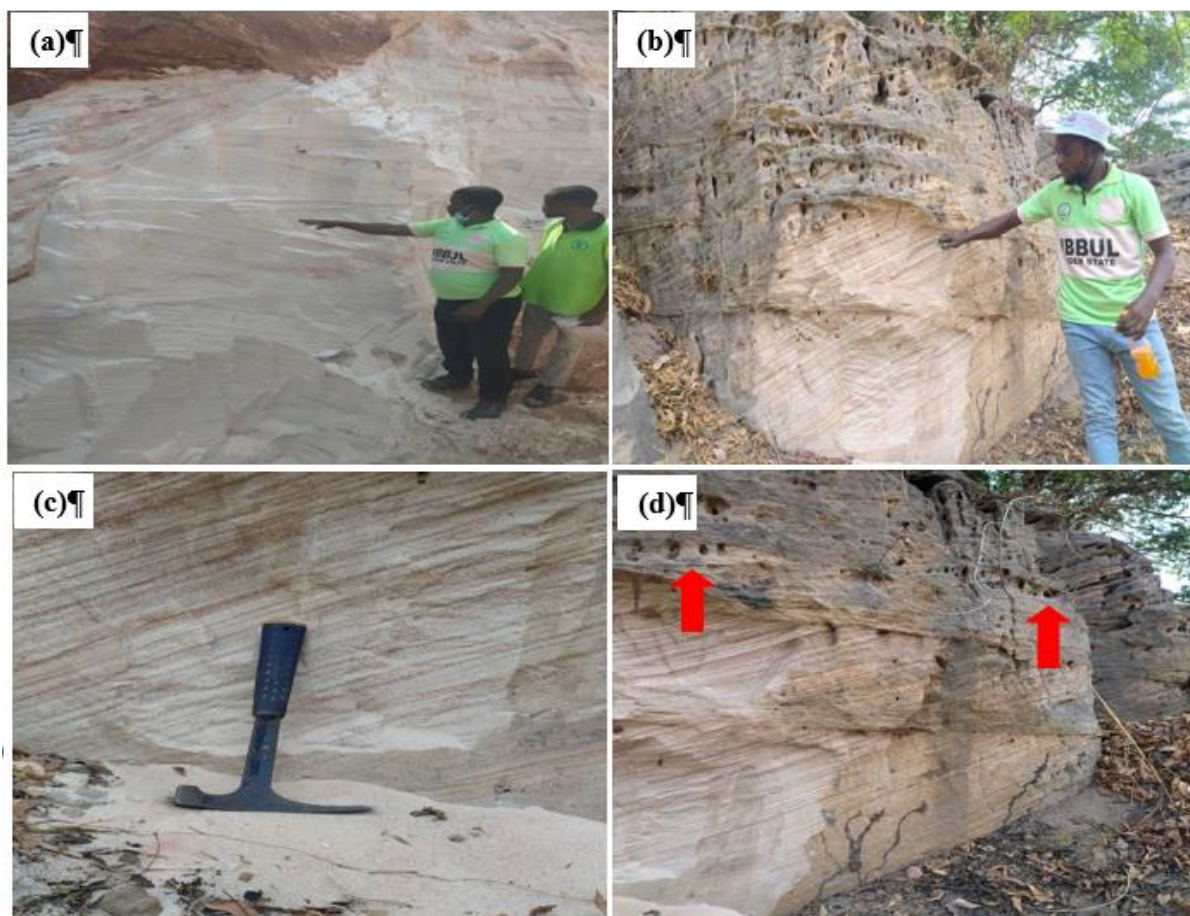




Figure 6: Showing Ajali sandstone weathered and unweathered (a & b) at the sand quarry, very loss whitish sand, poorly cemented and sorted (c & d) gray white sand, friable with shallow bioturbation, crossed-bedded depicted with red arrows (e & f) An excessively weathered Sandstone with visible ripple & ridges depicted with red dotted lines

locality/coordinate

Sedimentary exposure were mapped, logged and samples selected at three locations; A, B and C within Iyale: N07°38'09.1", E 07°20'00.5", Elevation: 315m. 2A (GRA, IDAH), N07°08'19.0", E006°45'38.7", Elevation: 127m, 2B (GRA, IDAH); N07°08'16.6", E006°45'38.4", Elevation: 130m, and 2C (GRA, IDAH); N07°08'16.4", E006°45'40.0", Elevation: 125 m.

Lithofacies Description

The rock types are mainly loss and poorly cemented medium to fine grained sands, intermix with moderate siltstone and clay content (Fig. 6).

- i. **Sandstones:** At 2A (GRA, IDAH) sandstone mixed with siltstone, rounded to sub rounded, moderate to poorly grains sorted sedimentary rock (Fig 6a & b) at elevation of 127 m. There are bioturbated with indication of vertical worm burrows, lamination & crossed bedded (Fig 6b). There are generally very clean-sharp and loss sands as a normal beach sand, very poorly cemented with minor clay to very low matrix composition.
- ii. **Sandstones:** At 2B (GRA, IDAH) moderately cemented and oxidized sandstone mixed with siltstone, rounded to sub rounded, reasonable to poorly sorted grains sandstones (Fig 6c & d) at elevation 130 m. There are bioturbated with vertical worm burrows (Fig 6d).
- iii. **Sandstones:** At 2C (GRA, IDAH) moderate consolidated and excessive oxidized sandstone intermixed with siltstone, sub rounded to rounded, moderately to poorly sorted sandstones (Fig 2e & f) at elevation 125 m. The sandstone is exposed to weathering oxidizing of Fe (II) oxide to Fe (III) oxide with ripple & visible ridges resulting from influence of surface water erosion.
- iv. **Sedimentary Structures:** There are two main fascinating features which are exhibited in post depositional developed structure in this outcrop as described below.
 - v. **Crossed-bedding:** distinctive structure exhibited in the sandstones with a high-low angle and directional tabular crossed-bedding practical on the sandstones at the three locations (2A-C), Fig.6
 - vi. **Lamination:** Common on the sandstone at almost parallel (Fig. 2a-f)
 - vii. **Ripple marks:** On the sandstones observed at 2C (GRA, IDAH); N07°08'16.4", E006°45'40.0", Elevation: 125 m.
 - viii. **Bioturbation:** A post depositional structure observed at 2A-B consisting *Rhizocorallium* (horizontal to sub-horizontal)

From field description, structural observation reveals distinctive river-setting characteristics with ripple marks, crossed-bedding structures, and bioturbation.

The structural features are pointing towards the events of the rivers along with influence of tides in a shallow marine. It conversely supports the fluvio-deltaic depositional environments by the earlier workers.

Granulometric results

Textural characteristics of sediments include that, mean (ϕ), sorting-(SD), skewness-(Sk) and kurtosis-(KG) are commonly adopts to analyze grain-size distribution and depositional environment reconstruct of sediments (Azidane et al., 2021). Relationship connecting grain size parameters and transport processes/depositional apparatuses of sediments has been known by inclusive studies (Boggs Jr & Boggs, 2009; Folk & Ward, 1957). Table 2 summarizes parameters for the collected field samples collected. Ajali sandstone 2A, Ajali sandstone 2B and Ajali sandstone 2C samples show grain size ranges from medium to coarse sand.

Sorting values of all sediments reveals poorly sorting (PS). The medium coarse sandstones are dominated in coarse to fine skewed for Ajali A & B except Ajali C that is strongly coarse skewed. The Ajali A & B reveals dominance of Mesokurtic except for Ajali C that indicates Very platykurtic grain size nature.

Table 2: showing grain-size numerical parameters in percentage (%) of the total number at each quarter

Mean (ϕ)	AJALI L2A	AJALI 2B	AJALI 2C
Medium / coarse sand	1.27	1.22	1.0
Sorting (σ)	PS (1.66)	PS (1.93)	PS (1.51)
Kurtosis (KG)	Mesokurtic	Mesokurtic	Very platykurtic
Skewness (SK)	Coarse Skewed (-0.19)	Fine Skewed (1.14)	Strongly coarse Skewed (-2.56)

When sandstone sediment at an high or low value of kurtosis relates that part of sediment reach its sorting somewhere else in elevated-energy environment. Its disparity also reflects flow attribute of the depositing medium (Azidane et al., 2021) and the dominance of coarse size of Mesokurtic to platykurtic nature of sediments reflects the maturity of the sand (Rajganapathi, Jitheshkumar, Sundararajan, Bhat, & Velusamy, 2013). The difference in the sorting values are possibly due to nonstop adding up of fine or coarser sediments in varying extent (Ilevbare & Imasuen, 2020) in the Ajali formation during deposition.

Hydraulic conductivity Determination

To determine the K value using a 25 cm long pipe constant head permeameter, the permeameter was setup with negligible disturbance of the sand sample. Furthermore, three

constant-head tests were carried out for each of the sand sample. The vertical K-permeability (K_v) values be calculated by means of the Darcy equation for K-constant - head tests from the equation (Pliakas & Petalas, 2011):

$$K = \frac{QL}{Aht}$$

K= vertical hydraulic conductivity (m/s)

Q = quantity of flow measured at discharge reservoir (cm^3)

A = cross sectional area of sample ($4,418 \text{ mm}^2$)

L= length of sample between nipple points over which the head loss is measured (mm)

h = head loss in length or difference in manometer readings (mm)

t = elapsed time (s)

K_v : m/s, Q: quantity of flow (cm^3), A: cross sectional area of sample (mm^2)

Table 3: Mean measured values of K_v for the samples

SN	Sample ID	Permeability in Darcy (D) Calculated $K = \frac{QL}{Aht}$	Permeability in mDarcy (mD)
1	AJALI L2A	0.075	75
2	AJALI L2B	1.85	1850
3	AJALI L2C	0.06	60

Discussions

Lithologically the AJALI L2A sample is bioturbated sandstone intercalated with siltstone that exhibits crossed bedded & lamination sedimentary structures. The grains vary from medium to coarse grain, poorly sorted and cemented. Table 2 reveals that size is statistically coarse skewed. Crossed bedding and lamination within sandstone lithofacies is characterize with alternating coarse silty-fine grain, thus poorly sorted containing a wide range of grain sizes. It can affect permeability by creating smaller pore spaces between grains, reducing the overall connectivity of the pore network (Yusuf, 2018). This leads to decreased fluid hydraulic flow conductivity through the Ajali sandstone and lower permeability value to 75mD. Also, the bioturbation intermix the variable sediment grains, resulting in creation of new pathways for fluid flow or the destruction of existing pathways through clogging pore spaces, ultimately affecting permeability. But in some instance, it enhance permeability by increasing the connectivity of pore spaces (Xu et al., 2022). Furthermore, presence of laminations can also influence permeability as grains are poorly connected and may not significantly impact overall permeability (Abdulmutalib et al., 2022). The impact of poor grain sorting, bioturbation, and lamination on a permeability value of 75 mD can vary depending on the specific characteristics of the sediment or rock.

In general, poor grain sorting and bioturbation tend to decrease permeability, while the presence of well-connected laminations can either enhance or hinder fluid flow.

The AJALI L2B sandstone lithofacies intermixed with siltstone and clay, exhibits crossed bedded and also bioturbated. The silt-sized and clay particles potentially can lower porosity and thus permeability value. However, the cross-bedding may have contributed positively within this lithofacies to exhibit a high permeability value of 1850 mD, because it creates interconnected pathways for fluid flow, thereby increasing permeability. Also, it maybe has negative effects on permeability at some instance (Mehmood et al., 2023). Furthermore, bioturbation can also have variable effects on permeability depending on the intensity and extent of mixing. It may have contributes to increase permeability by creating new pathways for fluid flow. The AJALI L2B sandstone to have exhibits permeability value of 1850 mD

depends on the proportions and arrangement of these components within this lithofacies. If potentially this lithofacies maybe characterize with a high and well-connected pore spaces, it may be responsible the high permeability value of 1850 m D. The presence of sandstone generally enhances permeability, while siltstone and clay tend to reduce it. Cross-bedding and bioturbation can exhibits either negative and positive effects on permeability in respect of their extent and intensity of fabric rework.

The AJALI L2C sandstone is weathered sandstone with ripples and ridges visible are common sedimentary structure. However, exposure to excessive weathering can significantly affect both physical properties, and fluid flow dynamic; its permeability. The impact of excessive weathering can lead to a decrease in permeability, as the rock may become more compacted and less porous. Thus, the effect of the excessive weathering potential contributes reduction in permeability value of 60 mD. However, the impact of excessive weathering on permeability is not always positive, and other factors such as vegetation or organic matter can also affect the permeability of the rock.

CONCLUSIONS

The study investigates sedimentological distribution and small scale structure effects of the fluvio-deltaic Agali sandstone and to evaluate hydraulic conductivity of the potential reservoir sandstone as it effects fluid flow dynamic potential of the sandstone.

The bioturbated AJALI L2A sandstone intercalated with siltstone that exhibits crossed bedded & lamination sedimentary structures. The grains vary from medium to coarse grain, poorly sorted and cemented. The crossed bedding and lamination within sandstone lithofacies characterize poorly sorted containing a wide range of grain sizes. It affect permeability by creating smaller pore spaces between grains, reducing the overall connectivity of the pore network leads to decreased fluid hydraulic flow conductivity through the Ajali sandstone and lower permeability value to 75mD.

The AJALI L2B sandstone lithofacies is intermixed with siltstone and clay, which also can lower porosity and thus permeability value. In this lithofacies, the cross-bedding may have contributes positively to a high permeability value of

1850 mD, because it creates interconnected pathways for fluid flow, thereby increasing permeability.

The AJALI L2C sandstone is weathered sandstone with ripples and ridges visible are common sedimentary structure. The excessive exposure to weathering significantly affect both physical properties, and fluid flow dynamic; its permeability. Thus, this potentially contributes to reduction permeability value to 60 mD. In overall it is concluded that the Ajali sandstone generally will exhibits an average moderate permeability of 662 mD.

ACKNOWLEDGEMENTS

The authors thanked the Nigerian National Petroleum Corporation (NNPCL) Limited Chair Professor for frontier basinal studies providing Funds for the field studies and Laboratory facilities to carry out this work

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