Geochemical, Textural and Petrographic Studies of Sandstones of Enagi Formation Northern Bida Basin, North Central Nigeria: Implications for Aquifer / Reservoir Potentials

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ABSTRACT

The provenance, paleoenvironments, and mineralogical studies of the sandstones of the Enagi Formation at Gulu and Kandi in the Bida Basin were investigated for preliminary reservoir quality assessment. The Gulu and Kandi sandstone samples are dominantly medium-grained with moderate sorting and fine to coarse-grained with poor sorting respectively. The quartz, feldspar, and rock fragments plots with average values of 76.2%, 8.7%, and 15.1% at Gulu and 59.3%, 24.6%, and 16.2% at Kandi suggest they are litharenitic and arkosic sandstones respectively. The bivariate plots of standard deviation, skewness, and kurtosis indicate river sands with little input from tidal environments in the Gulu area. The Gulu samples are more of fluvial channel deposits and shoreface lithofacies while the Kandi samples resemble alluvial deposits of a high-energy system. Al_2O_3/ TiO_2, Zr/ TiO_2, and Y/Ni versus Cr/V of the samples suggest a felsic igneous origin with little contribution from a mafic source. K_2O/Na_2O against SiO_2 and TiO_2 against Fe_2O_3+MgO point to a passive margin continental setting for the sediment source. The cementation of moderately sorted, sub-mature texture and litharenitic sandstones in the Gulu area will be low compared with the Kandi poorly sorted and arkosic lithofacies at the deeper subsurface. This study for the first time reports the presence of favorable geological indices for good porosity and permeability development in the Campanian – Maastrichtian sandstone reservoir of Enagi Formation. These results will further drive exploration work in the Bida and other West African Cretaceous rift basins for prospective underground water and hydrocarbon reservoirs.

Keywords: Bida Basin, Enagi, Sandstones, Paleoenvironment, Mineralogy, Provenance

INTRODUCTION

Sedimentary rocks are a product of the earth's surficial process from pre-existing older rocks such as igneous and metamorphic and cover about three-fourths of the earth's surface with abundant resources including water, minerals, and petroleum (Boggs, 2009). They are also good geological environment for agricultural activities. The understanding of the provenance, textural characteristics, mineral composition, process of formation, and depositional conditions of sandstones are very significant geological indices for all exploration efforts. These indices compliment log data in an established exploration field and very useful in de-risking a frontier basin for petroleum exploration. The geological parameters can be obtained from petrography, geochemistry, and grain size studies (Blatt, 1967, Pettijohn *et al.,* 1972, Dickinson, 1985). The need for sustaining the increasing human population and demand for more energy in Nigeria and other developing countries in Africa and beyond have necessitated the drive for underground water and petroleum exploration development. Underground water and petroleum are hosted or accumulated in the same reservoir rocks which could be sandstones or carbonate rocks especially in a sedimentary environment of a frontier basin such as Bida Basin, north central Nigeria (Fig. 1).

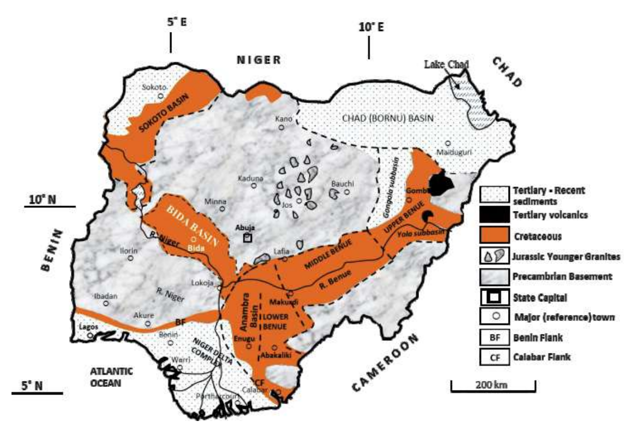

Figure 1: Geological map of Nigeria showing Bida Basin (White Letter) in the North Central (Modified after Obaje *et al* 2020)

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The reservoir quality of any rocks is measured by their porosity and permeability which are essentially controlled by geological indices including provenance, textural and mineralogy composition, and post-depositional changes during burial. Exploration data are scarce in the Bida Basin because of the poor interest of investors and low research funding for the frontier basins in Nigeria in the past decades. There is no exploratory well in the basin except the recent seismic and other geophysical data acquired by the Nigeria National Petroleum Exploration as a result of the nation's need for more clean energy like shale gas. The newly acquired geophysical data in the Bida Basin reveals that the basin's depth to the basement is about 7km. The outcropping sandstones at Kandi village and from the neighboring shallow borehole at Gulu village represent some of the siliciclastic rocks in the basin that could be easily accessed and which may be an important reservoir in the deep subsurface. The sandstones were investigated for the first time in this study through thin-section petrography, grain size, and geochemistry analyses to obtain some geological indices needed for preliminary evaluation of their potential as reservoirs. The results from these studies should suggest the quality of the sandstones in the shallow area as an aquifer for groundwater for the community and petroleum potentials reservoir in the deeper subsurface part of the basin.

GEOLOGY OF BIDA BASIN

Bida Basin (Fig. 2) belongs to the Central and West African rift-related basins which include Dahomey Basin and Benue Trough in Nigeria, Muglad and Melut basins of Sudan, and the Termit Basin of Niger and were formed as a result of the transcurrent movement of the South America and African continental plate in the late Jurassic – early Cretaceous time (Burke, *et al* 1972, Petters, 1978, Okereke, 1988, Genik, 1992, Keller *et al.,* 1992). There are a lot of previous research works in the Bida basin

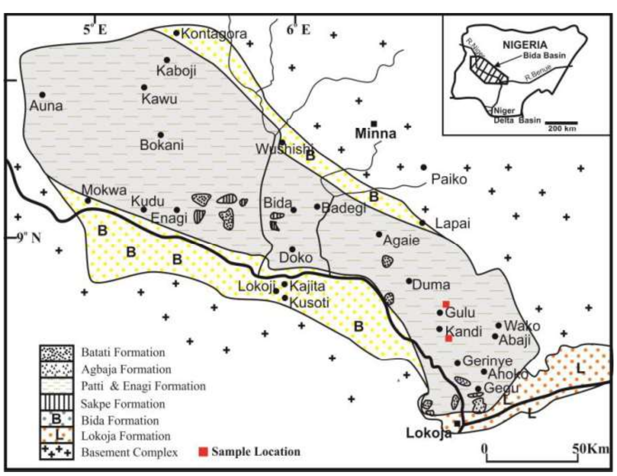

Figure 2: Geological map of Bida Basin in the North Central (Modified after Obaje *et al.* 2013)..

covering the aspect of the stratigraphy (Adeleye and Dessauvagie, 1972; Adeleye, 1974), basin configuration and structures (Ojo, and Ajakaiye, 1989, Udensi and Osazuwa, 2004), sedimentology (Adeleye, 1974, Ojo and Akande, 2006, 2020), and source rock characterization (Obaje et al 2010, 2013, Akande *et al* 2005).

This intracratonic structured Bida Basin trends NW-SW and has its northern side beginning at Kontagora and ending at Lokoja in the southern part (Obaje, 2013) (Fig. 2). It is bounded by the crystalline basement to Sokoto Basin in the north and Anambra Basin in the south. Sedimentation began in the post-Santonian after the intense tectonic inversion in the Lower Benue Trough that led to the formation of the contiguous Campanian–Tertiary Anambra Basin. Bida Basin is subdivided into northern and southern parts without any clear boundary. Northern Bida Basin consists of Bida Formation succeeded by Sakpe Formation, Enagi Formation, and capped by the Batati Formation while Southern Bida Basin comprises of Lokoja Formation overlain by Patti Formation and capped by the Agbaja Formation (Fig. 3) (Obaje *et al* 2013, Ojo and Akande, 2020).

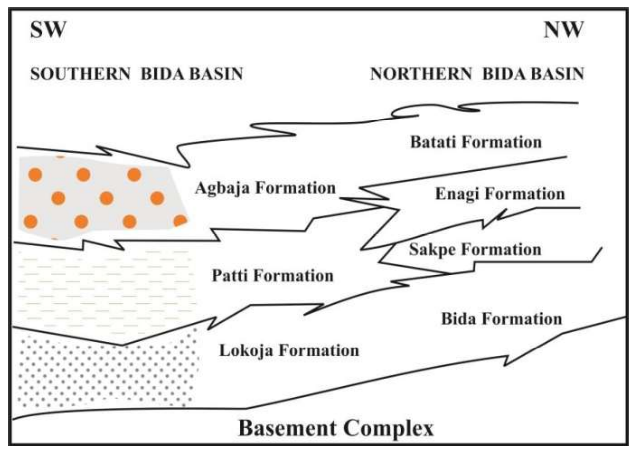

Figure 3: The Stratigraphic successions in the northern and southern parts of Bida Basin (Modified after Akande *et al.,* 2005).

MATERIALS AND METHODS

This work began with mapping the exposed or outcropping successions of the Enagi Formation at the Gulu and Kandi areas of Lapai Local Government, Niger State within the northern Bida Basin. Ditch cuttings from a borehole located at Gulu were described and logged, and fresh samples were collected. A total of fifty (50) samples of sandstones from both the outcrop and borehole were collected and subjected to laboratory analyses including grain size, X-ray fluorescence, major oxides and trace elements, and thin section petrography.

A grain size study was carried out on thirty (30) unconsolidated samples. Each weight of 100g of the sample was obtained and put in a set of sieves as follows; 4.00mm, 2.360mm, 1.180mm, 0.600mm, 0.300mm, 0.150mm, 0.106mm, 0.075mm, <0.075mm arranged in an ascending order of sizes on shaker. The set of sieves was then agitated for about 5 minutes to leave a fraction of samples in each sieve and pan according to their sizes. The individual weight percentage and cumulative percentage were obtained and a graph of phi sizes against cumulative weight percentage was plotted to extract percentiles to calculate statistical parameters for the Graphic Mean (M), Standard Deviation (sorting) (SD), Graphic Kurtosis (K) and Graphic Skewness (SK) based on Folk and Ward (1957).

Thirty-three (33) sandstone samples across the study areas were also selected and impregnated, mounted on a glass plate with Canada balsam, and then ground to a certain thickness with increasingly finer and finer degrees of abrasion. The glass slip was removed during the process, as well as a small amount of Canadian balsam, which acts as an adhesive, which was placed in the center and gently heated until the bubbles were driven out. After that, the sample chip was placed on the slide with the flattering side towards the balsam and glass. The last grinding action expands the slide on the opposing side. The sample slice was then heated after being covered in fresh balsam. Finally, the rock slice was carefully covered with an air bubble-free cover slip or slide, and pressed down. A thin sample is cut, then placed on a glass slide, and honed smoothly with finer abrasive grit until the sample is just 30 microns (0.03mm) thick. Mentholated spirit is useful for removing workout cementing substances. These procedures take place with the use of a microscope, which can be a polarizing petrographic microscope, an electron microscope, or an electron microprobe. A total number of twenty (20) sandstones were subjected to X-Ray fluorescence analysis and eleven (11) major oxides and forty-seven (47) trace elements were obtained.

Results

Lithofacies Description

Sandstones encountered at the depth of 45 m in the borehole drilled at Gulu on the coordinate of latitude N08o 36' 38"and longitude E006o 34' 48" are overlain by beds of claystone and shale (Fig. 4). The sandstones are whitish with grain ranging from fine, coarse, and medium-grained sizes. The fine-grained lithofacies occurred at the basal part of the section. Sedimentary structures were not recorded from the Gulu sandstones because they are all cuttings.

The outcropping sandstone lithofacies at Kandi about 20 km to Gulu on the coordinate of latitude N08°36'38" and longitude E006°34'48". The average thickness of the outcrop is about 3.5 m thick (Fig. 5 This outcrop has very interesting textural characteristics and sedimentary structures. Their textural features show fine, medium, coarse to very coarse texture and poorly sorted to well-sorted grains.

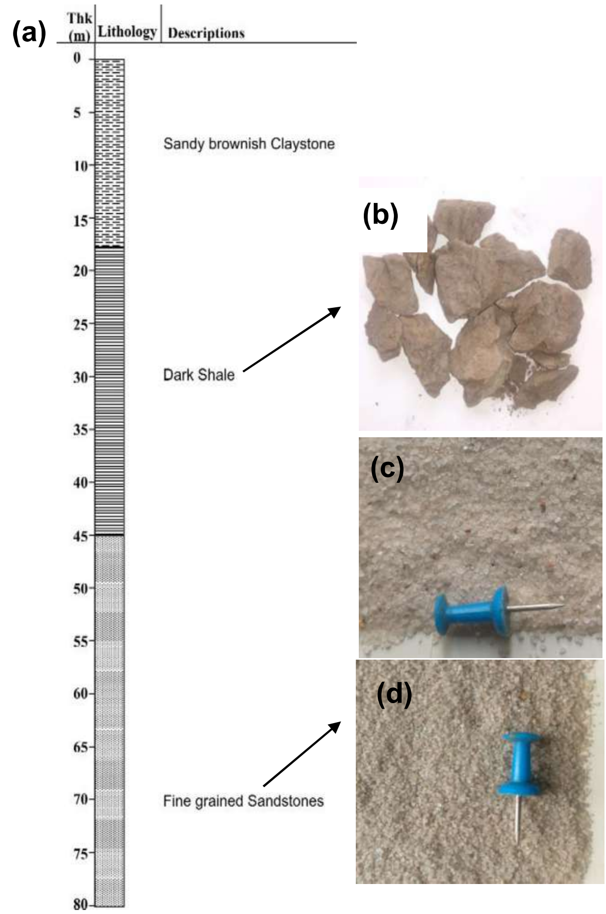

Figure 4: (a) Lithologic section of a borehole that penetrated the Enagi Formation at Gulu, Northern Bida Basin. Photograph of (b) the dark shale and (c and d) the brownish to greyish sandstones.

Figure 5: Field photograph of the laterally extensive outcrop of sandstones at Kandi Northern Bida Basin Sedimentary structures observed are through cross-stratification, planar cross-stratification, herringbone structures, and bioturbation. They are greyish, brownish to reddish colors. Some of the coarse-grained beds have a lot of clay drapes.

Grain Size Results

The grain size distribution of siliciclastic sedimentary rock largely functions in the processes of transportation resulting from the movement of bed loads, saltation, and minor subsurface loads (Folk and Ward, 1957). The grain size data are presented in Table 1 in a statistical format of mean size, standard deviation (sorting), skewness, and kurtosis. Gulu sandstones have mean size varying from 1.06 to 2.78 mm, with an average of 1.7 mm, standard deviation (sorting) ranges from 0.60 to 1.50 mm with an average of 1.0 mm, skewness values range from -0.45 to 0.37 mm with the average of 0.1 mm, and kurtosis from 0.66 to 1.76 mm with an average of 1.0 mm. Kandi sandstones have mean size ranges from -0.30 to 1.37 mm with an average of 0.5 mm, standard deviation (sorting) value ranges from 0.78 to 1.26 mm with an average of 1.0 mm, skewness value ranges from 0.03 to 1.55 mm with an average of 0.6 mm, and kurtosis ranges from 0.02 and 1.02 with the average of 0.3 mm (Table 1).

Table 1: Grain size results and interpretations of sandstone in Gulu and Kandi, Enagi Formation, Bida Basin.

Sample No	M	SD	SK	K	Mean	Standard Deviation	Skewness	Kurtosis
GU41	1.60	1.50	0.08	0.70	Medium grained	Poorly Sorted	Symmetrical	Platykurtic
GU45	2.40	1.12	0.30	1.50	Fine-grained	Poorly Sorted	Positive	Leptokurtic
GU48	2.50	0.60	0.08	0.90	Fine-grained	Moderately Well Sorted	Symmetrical	Mesokurtic
GU51	1.60	0.80	0.00	1.00	Medium grained	Moderately Sorted	Symmetrical	Mesokurtic
GU52	1.06	0.98	0.28	1.21	Medium grained	Moderately Sorted	Positive	Leptokurtic
GU53	2.75	0.79	-0.45	1.76	Fine-grained	Moderately Sorted	Very Negative	Very Leptokurtic
GU54	2.70	0.90	0.37	1.10	Fine-grained	Moderately Sorted	Very Positive	Mesokurtic
GU55	2.78	0.70	-0.18	0.99	Fine-grained	Moderately Sorted	Negatively	Mesokurtic
GU56	1.55	1.21	0.22	0.68	Medium grained	Poorly Sorted	Positively	Platykurtic
GU57	1.31	0.76	0.16	1.38	Medium grained	Moderately Sorted	Positively	Leptokurtic
GU58	1.47	0.96	0.09	0.95	Medium grained	Moderately Sorted	Symmetrical	Mesokurtic
GU60	1.68	1.03	0.13	0.82	Medium grained	Poorly Sorted	Positively	Platykurtic
GU63	1.31	0.76	0.19	1.25	Medium grained	Moderately Sorted	Positively	Leptokurtic
GU66	1.14	0.76	0.00	1.51	Medium grained	Moderately Sorted	Symmetrical	Very Leptokurtic
GU68	1.18	0.98	0.30	1.11	Medium grained	Moderately Sorted	Very Positive	Mesokurtic
GU69	1.42	0.98	0.22	0.66	Medium grained	Moderately Sorted	Positive	Very platykurtic
GU70	1.68	1.02	-0.01	0.84	Medium grained	Poorly Sorted	Symmetrical	Platykurtic
GU72	1.74	1.27	0.16	0.78	Medium grained	Poorly Sorted	Positive	Platykurtic
GU74	1.72	1.01	0.22	1.05	Medium grained	Poorly Sorted	Positive	Mesokurtic
GU76	1.34	1.04	0.07	0.74	Medium grained	Poorly Sorted	Symmetrical	Platykurtic
KD3E	0.00	0.94	1.38	0.81	Coarse-grained	Moderately sorted	Very positive	Platykurtic
KD3F	0.13	1.02	0.93	0.25	Coarse-grained	Poorly sorted	Very Positive	Mesokurtic
KD3G	0.60	1.04	1.55	0.22	Coarse-grained	Poorly sorted	Very Positive	Very Platykurtic
KD4A	0.53	0.85	1.12	0.61	Coarse-grained	Moderately sorted	Very positive	Leptokurtic
KD4C	1.17	1.07	0.77	1.02	Medium grained	Poorly sorted	Very positive	Mesokurtic
KD-5A	0.43	0.91	0.08	0.05	Coarse-grained	Moderately sorted	Symmetrical	Very platykurtic
KD-6A	0.77	1.07	0.03	0.06	Coarse sand	Poorly sorted	Symmetrical	Very platykurtic
KD-6C	1.37	0.81	0.08	0.02	Medium sand	Moderately sorted	Symmetrical	Very platykurtic
KD-7A	0.33	0.78	0.13	0.09	Coarse sand	Moderately sorted	Positive	Very platykurtic
KD-7C	-0.30	1.26	0.37	0.19	Very Coarse sand	Poorly sorted	Very Positive	Very platykurtic

M-Mean, SD- Standard Deviation, SK-Skewness, and K- Kurtosis

Petrographical Attributes

The mineral identified in the Gulu sandstones is quartz which ranges from 59% to 89.0% with an average of 76.2, feldspar ranges from 4.0% to 18% with an average of 8.7 and the rock fragments range from 5.1% to 27% with an average of 15.1 (Table 3). There are more mono-crystalline mineral grains than polycrystalline grains (Fig. 6)

The mineral constituents of Kandi sandstones show that quartz is the predominant mineral in the samples ranging from 47.1% to 73.3%, with an average of about 59.2% feldspar ranging from 13.2% to 34.8%, with an average of 24.6% and rock fragments ranging from 5.2% to 27.1%, with the average of 16.2% (Fig. 7 and Table 2). The mineral grains are mostly sub-angular to sub-rounded in shape in all the sandstones. Kandi sandstones have more angular mineral grains. Some grains are polycrystalline while the majority are essentially mono-crystalline. The main mineral constituents in thin sections are quartz, feldspar, and rock fragments or lithoclast.

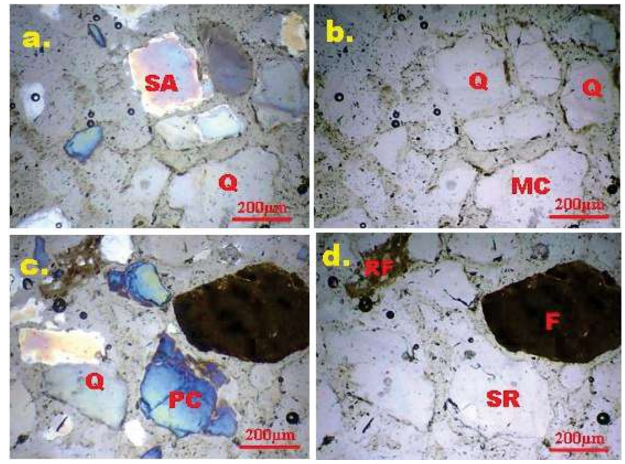

Figure 6: Representative photomicrograph of Gulu sandstones shown in cross-polar (a. and c.) and plane-polar (b. and d.). (Mono-crystalline (MC), polycrystalline (PC), sub-angular (SA), sub-rounded (SR), quartz grains (Q), feldspar (F) and rock fragment (RF), Red arrow= micro-fracture).

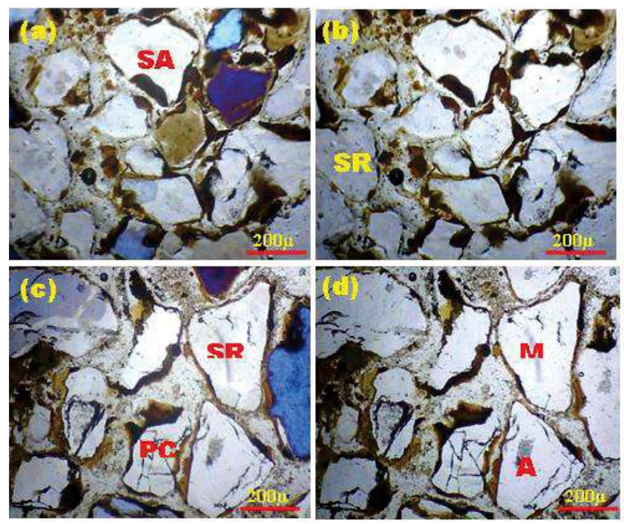

Figure 7: Cross-polar (a. and c.) and plane-polar (b. and d.) representative photomicrograph of the sandstones from Kandi. (Mono-crystalline (MC), polycrystalline (PC), angular (A), sub-angular (SA), and sub-rounded (SR) quartz grains, Red arrow= micro-fracture).

Major Oxides and Trace Elements

The major oxides in the sandstones show enrichment of SiO_2, Al_2O_3, Fe_2O_3, and TiO_2 above the significantly low

Table 2: Percentage modal results of the abundance of framework components of Gulu and Kandi sandstones.

SN	SAMPLE NO	QUARTZ	FELDSPAR	ROCK FRAGMENTS
1	GU41	75.0	11.0	14.0
2	GU45	80.4	14.5	5.1
3	GU48	81.4	11.6	7.0
4	GU51	76.4	10.4	13.2
5	GU54	78.6	13.8	7.6
6	GU52	73.0	6.0	21.0
7	GU54	80.0	4.0	16.0
8	GU56	78.0	5.0	17.0
9	GU58	83.0	4.0	13.0
10	GU60	69.0	4.0	27.0
11	GU62	59.0	18.0	23.0
12	GU64	75.0	6.0	19.0
13	GU68	79.0	6.0	15.0
14	GU70	66.0	8.0	26.0
15	GU72	76.0	9.0	15.0
16	GU74	67.0	17.0	16.0
17	GU76	86.0	4.0	10.0
18	GU78	89.0	4.0	7.0
19	KD 1A	73.7	13.2	13.2
20	KD 1B	56.3	25.0	18.8
21	KD 1C	75.9	19.0	5.2
22	KD 2A	68.8	20.8	10.4
23	KD 2B	56.1	29.8	14.0
24	KD5A	55.2	31.3	13.5
25	KD6A	55.8	25.0	19.2
26	KD6C	50.0	34.8	15.2
27	KD7A	49.1	32.7	18.2
28	KD7C	57.8	27.7	14.5
29	KD3A	68.0	17.3	14.7
30	KD3E	49.0	27.1	24.0
31	KD3F	65.1	16.9	18.1
32	KD4A	60.9	22.7	16.4
33	KD4C	47.1	25.7	27.1

P_2O_5, K_2O, CaO, Na_2O, MgO, and MnO. The values of the most enriched oxides of SiO_2, Al_2O_3, Fe_2O_3, and TiO2, in Gulu and Kandi sandstones, range from 62.07 to 93.18 % (mean 83.47 %), 4.91 to 27.37 % (mean 12.49 %), 0.20 to 2.78 % (mean 1.05 %), and 0.13 to 0.88 % with (mean 0.38 %) and 45.74 to 74.86 % (mean 61.43%), 15.78 to 31.20 % (mean26.05 %), 1.36 to 15.27 % (mean 5.04 %), and 0.13 to 0.50 % with (mean 0.35%) respectively (Table 3). Zirconium, strontium, zinc, nickel, rubidium, barium, chromium, vanadium, etc. are the most enriched trace elements in the Gulu and Kandi sandstones (Table 3).

Discussion

Provenance

The composition and maturity of sandstones in terms of texture and mineralogy are largely influenced by the parent rock, weathering, and transportation (Hayashi, *et al.,* 1997). Mono-crystalline mineral grain that has been attributed to igneous or some recycled sedimentary is more than the polycrystalline in all the sandstones (Al-Harbi and Khan, 2008). There are some strains or micro-fractures on the polycrystalline grains which could be pointers to the fact that some of the mineral grains are of metamorphic origin (Chima *et al.,* 2018) (Fig. 6 and Fig. 7). Major and trace elements are also very useful in constraining the sediments origin (Garver, 1996, Ngueutchoua *et al.,* 2017, Adeoye *et al.,* 2022). The Al2O3/TiO_2 ratio in mafic igneous rock is always low because TiO_2 is not associated with phyllosilicate minerals and ranges from 3 to 8 when compared with 8 to 21 in an intermediate rock, and a high value of 21 to 70 in felsic igneous rock (Hayashi, *et al.,* 1997, Nagarajan et al., 2015) (Table 3). Therefore, sediment generated from granitic to mixed granitic/basaltic rocks has a chemical composition that can be described by the ratio of Al_2O_3 to TiO_2 ratio (Fig.) (Amajor, 1987). Al_2O_3/TiO_2 ratios of Gulu samples show that the felsic igneous source dominates the provenance of the basal sandstone bed and the intermediate igneous source contributed more i.e. 18.7 - 20.1 to the uppermost beds. All the lithofacies from Kandi

Table 3: Major Oxide (%) of Gulu and Kandi sandstones.

Sample No	SiO_2	Al_2O_3	CaO	Fe_2O_3	TiO_2	P_2O_5	K_2O	Na_2O	MgO	MnO	V	Cr	Cu	Sr	Zr	Ba	Zn	Ni	Rb
GU-45	62.07	27.37	0.18	2.78	0.88	0.52	0.31	0.04	0.08	0.01	87	719	2	367	89	4	255	62	144
GU-48	93.18	4.91	0.14	0.29	0.24	0.49	0.07	0.00	0.05	0.00	45	158	13	455	84	0	114	8	96
GU-54	88.99	7.19	0.12	1.11	0.42	0.44	0.07	0.00	0.04	0.01	9	1	18	147	339	507	58	10	186
GU-57	84.56	9.97	0.18	1.77	0.53	0.50	0.17	0.07	0.03	0.01	201	183	0	266	198	114	37	10	219
GU-60	91.28	6.21	0.13	0.80	0.17	0.49	0.08	0.00	0.07	0.00	9	11	28	53	256	151	220	0	0
GU-66	84.02	13.61	0.15	0.20	0.13	0.53	0.14	0.06	0.08	0.00	2	13	5	128	19	336	10	10	129
GU-69	87.80	9.76	0.11	0.41	0.23	0.39	0.00	0.00	0.04	0.00	3	35	10	137	244	575	206	75	210
GU-72	84.61	12.06	0.12	0.97	0.30	0.46	0.08	0.00	0.03	0.00	38	54	84	278	1,016	304	155	0	166
GU-76	76.41	19.86	0.14	0.81	0.30	0.56	0.12	0.01	0.03	0.00	51	96	17	99	408	32	29	17	36
GU-80	81.76	13.99	0.13	1.34	0.63	0.50	0.11	0.01	0.06	0.00	275	257	71	294	135	656	108	43	303
KD 1A	61.99	28.94	0.26	2.89	0.41	0.51	0.27	0.09	0.10	0.00	103	52	14	179	270	68	17	49	227
KD 1B	64.24	23.57	0.23	2.98	0.50	0.48	0.22	0.04	0.07	0.00	93	174	26	207	327	70	93	20	393
KD 1C	55.62	31.20	0.24	3.84	0.40	0.48	0.21	0.03	0.12	0.01	8	26	22	247	992	1,350	102	1	175
KD 2A	66.53	24.21	0.22	1.36	0.30	0.50	0.24	0.05	0.09	0.00	127	140	38	660	293	90	83	48	288
KD 2A-GC	59.18	28.33	0.26	2.13	0.33	0.37	0.25	0.03	0.08	0.00	47	11	38	975	124	1,350	102	14	175
KD 5A	61.88	25.85	0.21	6.23	0.31	0.53	0.17	0.01	0.10	0.01	43	27	25	561	199	21	15	8	195
KD 6A	60.00	28.08	0.17	5.99	0.39	0.43	0.22	0.01	0.05	0.01	128	1040	6	294	103	12	46	17	196
KD 6C	64.25	26.61	0.18	3.64	0.27	0.56	0.15	0.08	0.03	0.00	352	68	165	181	271	126	82	27	308
KD 7A	45.74	27.96	0.28	15.37	0.46	0.54	0.21	0.10	0.05	0.01	87	719	2	367	89	4	255	62	144
KD 7C	74.86	15.78	0.23	5.96	0.13	0.55	0.15	0.08	0.07	0.01	45	158	13	455	84	0	114	8	96

have ratio values above 21 implying that they are all sourced from felsic igneous rock (Fig. 8). Furthermore, the sandstones within the field of Fe-shale and Fe-sand suggest that these rocks originate from a Fe-bearing bedrock (Abu and Sunkari, 2020a). The Kandi sandstones plot within the Fe-shale rich region probably because of their high contents of Al_2O_3 compared with those of Gulu. The plate tectonic of a provenance does have considerable

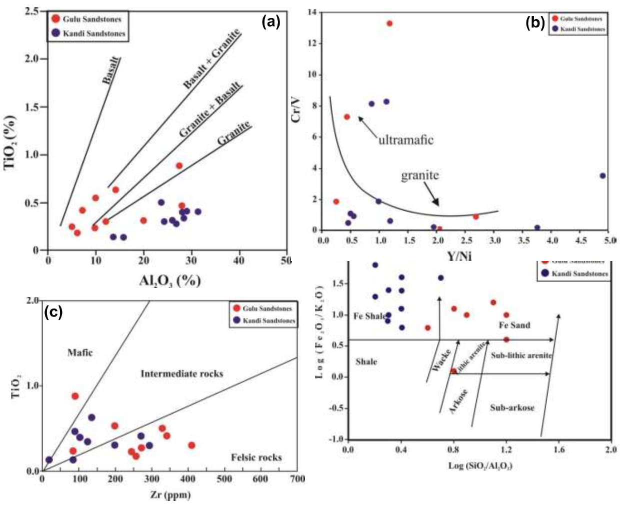

Figure 8: Scatter plots of (a) Al_2O_3 (%) vs TiO_2 (%) (b) Y/Ni vs. Cr/V and (c) TiO_2 (%) vs Zr (ppm), and (d) Log (Fe_2O_3/K_2O) vs Log (SiO_2/Al_2O_3) diagram showing the Basalt, Basalt + Granite, Granite + Basalt, and Granite suggest that the parent rock of Kandi sandstones is granite while Gulu sandstones are from granite + basalt (Herron, 1988, Hayashi *et al.,* 1997, Cullers, 2002, Adeoye *et al.,* 2022)

control on the chemical compositions of the resulting siliciclastic sedimentary rocks. So the chemical signatures are traceable to depict different tectonic settings of the parent rocks of siliciclastic rocks (Bhatia, 1983, Roser and Korsch, 1988, Baiyegunhi et al., 2017). The paleotectonic discrimination plot of bivariate SiO_2 against K_2O/Na_2O (Roser and Korsch, 1988) (Fig. 9) Fe_2O_3 + MgO against TiO_2 (Fig. 10) suggests active continental margin and passive margin as the tectonic region of the parent rock of sandstones of Enagi Formation.

Active continental margins are basins within the subduction zone, continental basins, and pull-apart basins associated with strike-slip fault zones. Whereas, passive continental margins are basins on the continental crust and basins associated with ocean floor spreading failed rifts and Atlantic-type continental margins.

Depositional Environment

The environment of deposition ranges from continental through transitional and then to marine settings. These environments cover the fluvial, eolian, delta, and beach settings where sandstones are often found. The signatures

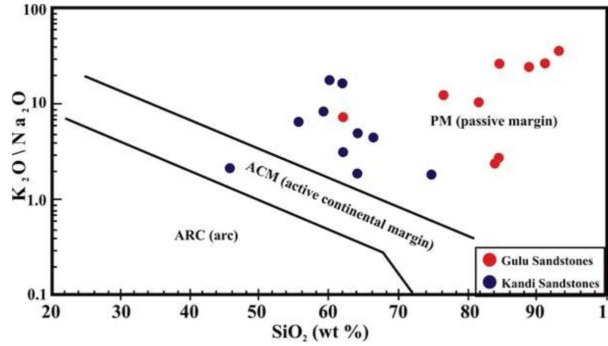

Figure 9: Plot of SiO2 against K2O/Na2O showing palaeotectonic discrimination within passive island arc and Active continental margins, the Kandi sandstones fall within (Roser and Korsch, 1988).

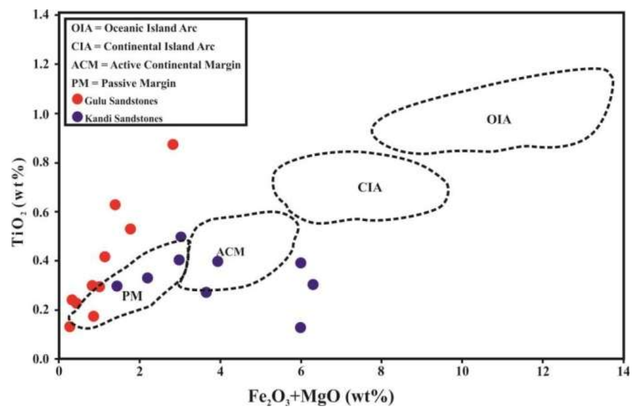

Figure 10: Bivariate plots of (a) TiO2 (wt.%) versus (Fe2O3 + MgO) (wt.%), of the Gulu and Kandi sandstones, Enagi Formation, Bida Basin on the tectonic setting discrimination diagram (Bhatia, 1983).

commonly recorded on sandstones are not only the imprint of the depositional environments but also that of their provenance and transportation processes. They all impact on the grain sizes of the clastic sedimentary rocks (Folk and Ward, 1957, Friedman, 1979 Bui *et al.,* 1990). This makes grain size data an essential and useful tool in the reconstruction of paleoenvironments when integrated with other sedimentary features such as sedimentary structures and associated rock types (Folk and Ward, 1957, Pettijohn, 1975, Friedman, 1979, Bui *et al.,* 1990). Grain size data reveals that the texture of the sandstones from Gulu is predominantly fine to medium-grained. These textures result from suspension and saltation processes of transportation which are later deposited under low energy flow or calm water settings (Ikhane *et al.,* 2013, Warrier et al., 2016). Most of the sandstones at Gulu are moderately sorted, suggesting typical braided and channel deposits with a few poorly sorted ones at the upper and lower part of the well, similar to floodplain deposits (Ojo and Akande 2012). Kandi sandstones are medium-grained to very coarse-grained which may represent saltation and bed load materials commonly deposited at the upper and middle regime or mature stage of the river (Warrier et al., 2016). Kandi outcrops are bioturbated and also reveal alternating poor and moderate sorted lithofacies possibly due to the periodic changes in the energy suggesting tidal channels and shoreface deposits (Ojo and Akande, 2012). The coarse-grained and conglomeratic sandstones deposited on the eroded surface of the underlying medium-grained lithofacies (Fig. 11) show typical braided or channel fluvial deposits similar to Maastrichtian Enagi Formation exposed across the Agbona ridge at Share and Shonga (Ojo and Akande, 2012).

Predominant moderately sorted and positive skewness are typical of river sediments common to constant low to

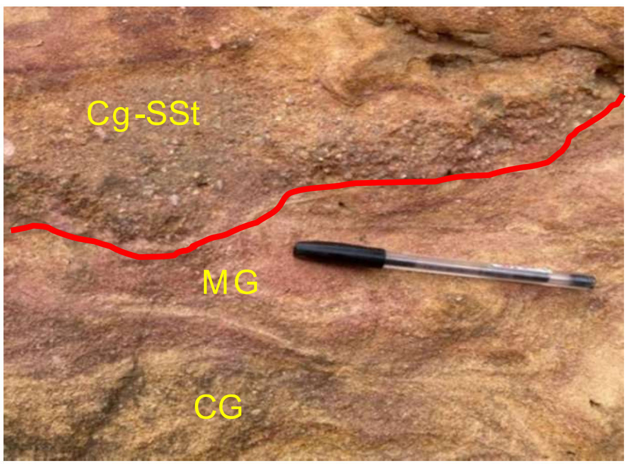

Figure 11: Photograph of conglomeratic sandstones (CgSST) deposited in a scoured erosional surface (red line) above the medium-grained (MG) and coarse-grained (CG) sandstone lithofacies at Kandi, northern Bida Basin.

moderate energy or consistency of the ocean current (Friedman, 1979, Selly, 1985, Tucker, 1988). Poor to moderate sorted and very platykurtic features may suggest that the environment is influenced by low and high energy conditions. The poor sorting texture of the sandstones suggests the influence of a high-energy environment or deposition in a flood plain or fluvial environment (Nton, and Bankole, 2013). The sandstones across the study areas exhibit textural characteristics of symmetrical to very positively skewed and very platykurtic indicating a wide range of grain size distributions dominantly from river to beach or tidal environments. The scattered bivariate plots of standard deviation versus skewness, and Kurtosis versus skewness (Fig. 12) have helped further constrain the paleo-environment (Friedman, 1967 and 1979; Ojo and Akande, 2012, Ojo, 201). These plots indicate that the Kandi and Gulu sandstones plotted majorly within the river sands and very few within the marine and tidal environments. Bivariate plot of standard deviation against mean and Standard deviation against skewness by Friedman, (1967) suggest that all the sandstones were deposited mainly in a fluvial depositional environment with little contribution from tidal processes.

The plot of Fe_2O_3 (%) against MgO (%) and triplot of

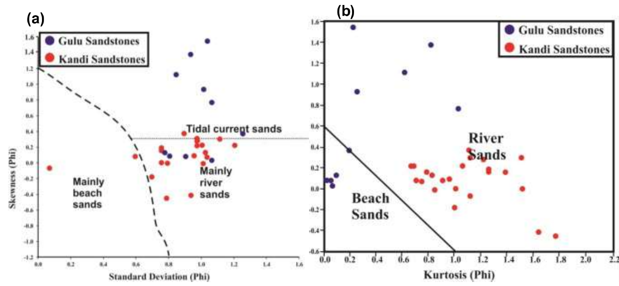

Figure 12: Scatter plots of (a) Standard deviation against skewness, and (b) Kurtosis against Skewness showing the depositional environment of Gulu and Kandi sandstones are influenced mainly by the river and few tidal and beach contributions (modified after Friedman, 1967).

MgO, Fe_2O_3, and SiO_2/Al_2O_3 further confirms that the sandstones are deposited in deltaic and fluvial environments (Fig. 13).

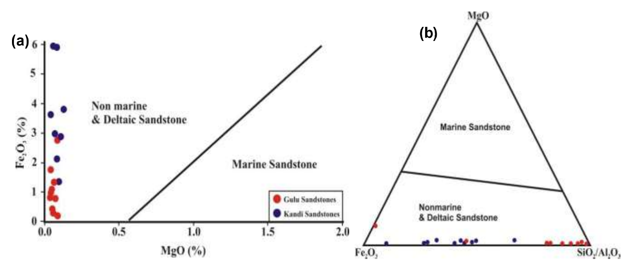

Figure 13: Binary (a) and triplot (b) diagrams showing characterization and differentiation of marine from non-marine sandstones. All the sandstones were plotted in the non-marine and deltaic fields (after Ratcliffe *et al.,* 2007).

Cross stratification is a syn-depositional structure of the sediments which is useful for understanding the behavior of modern bed forms and for interpreting environments of ancient deposits (Allen, 1982). The cross-stratification structures in the Kandi bed (Fig. 14a) form are unidirectional indicating fluvial settings while the bidirectional herringbone structures (Fig. 14b) and worm burrow are indicative of tidal or shallow marine environments. Planar cross-stratification is commonly observed in fluvial (river), aeolian (wind), and tidal environments. Trough cross-stratification is the stratification that is usually formed by the action of currents or waves (Allen, 1982,).

Mineralogy of the Sandstones

The mineral constituents of the eighteen Gulu sandstones reveal that 77.8 % of the samples have quartz minerals dominance ranging from 73 – 89 % and the remaining

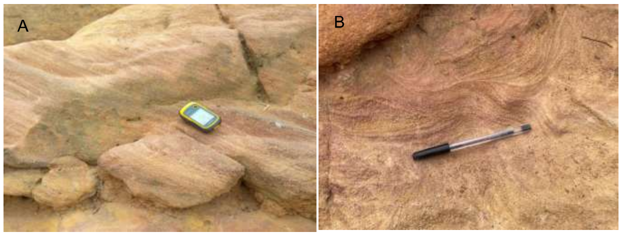

Figure 14: Photograph of (A) cross-stratification and (B) herringbone structures on coarse-grained sandstones at Kandi, northern Bida Basin.

22.2% have fairly low quartz of about 59 – 69%. This indicates a tendency of dominant arenitic lithofacies. The feldspar contents are relatively low, ranging from 4.0 – 18.0 %, and rock fragments from 5.1 – 26.0%. At the Kandi study area, only 13 % of the fifteen (15) sandstones have quartz minerals constituents ranging from 73.7 – 75.9 % while about 87% of the sandstone samples range as low as 47.1 – 68.8% quartz mineral. However, those with feldspar above 25% are 73.3% suggesting a dominance of feldspathic or arkosic lithofacies for Kandi sandstones. The rock fragments generally range between 5.2 to 27.1% in the whole sandstone samples. In summary, the mineral ratios in the study sandstones suggest that the Kandi lithofacies are feldspathic or arkosic while those of Gulu are litharenite. The Pettijohn, (1975) triplot of quartz, feldspar, and lithic (Fig. 15) further confirms that the sandstones from Gulu are more litharenite while Kandi lithofacies are sub-arkose and arkosic. The classification was further supported by the Quartz-Feldspar-Rock Fragments of Folk, (1968) (Fig. 16) confirming Gulu samples as mainly sub-litharenite with very few lithic arkose and feldspathic litharenite whereas Kandi samples as essentially lithic arkose.

The sub-litharenite nature, moderate sorting, and sub-angular to sub-rounded mineral grains of Gulu sandstones suggest that the rocks have been transported moderately far from the source, subjected to intense weathering that reduces the feldspar contents, and probably formed from parent rock rich in quartz and low in feldspar content such as granite (Hussain et al., 2006, Akinlua *et al.,* 2016, Chima *et al.,* 2018). The dominance of quartz minerals with 70% and above composition in Gulu sandstone suggests they are more mineralogically mature. The low clay mineral contents in Gulu sandstones will help reduce the clogging of pore space and lower the cementation rate during lithification. The Kandi sandstones are texturally and mineralogically immature to sub-mature suggesting a short transportation history and relatively less potential for reservoir (Ogungbesan and Akaegbobi, 2011, Ojo, 2012). The concentration of SiO_2, Al_2O_3, K_2O, Na_2O, and Fe2O3 are useful in classifying sandstones into quartz arenites, greywacke, arkose, or lithic arenite (Pettijohn *et al.,* 1972; Herron, 1988). Chemical classification of sandstones has been carried out through their ratio (Lindsey, 1999). If log $(SiO_2/Al_2O_3) \geq 1.5$, the sandstone is classified as quartz

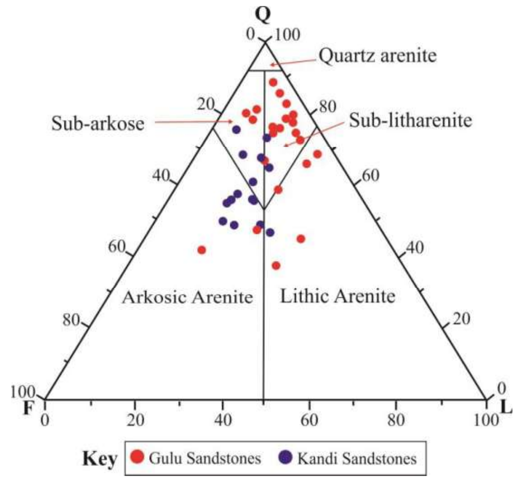

Figure 15: Quartz, feldspar, and lithic ternary plot of sandstone classification suggesting sub-lithic arenite for Gulu and sub-arkose to arkosic arenite for Kandi (Pettijohn, *et al* 1975).

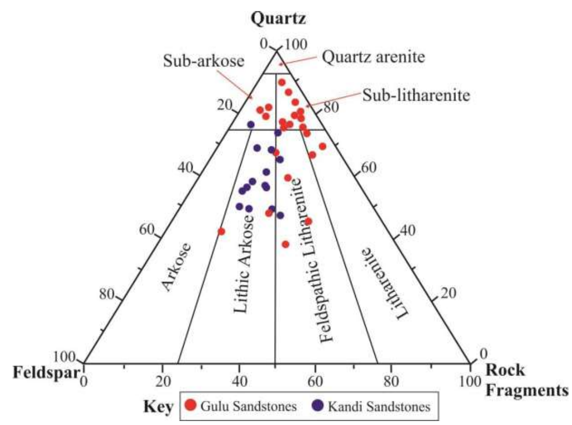

Figure 16: Quartz-feldspar-rock fragments ternary plot of Kandi sandstone classification (Folk, 1968).

arenite. None of the sandstones have values of log (SiO_2/Al_2O_3) to be greater than 1.5 but the Gulu sandstones range mainly from 0.8 to 1.3 while Kandi sandstones range from 0.2 to 0.7. This shows that the sandstones from the Gulu area tend closer to being arenitic than those in the Kandi area. If log (SiO_2/Al_2O_3) is < 1, log $(K_2O/Na_2O) < 0$, it is a Greywacke; and when log (SiO_2/Al_2O_3) is less than 1.5, log $(K_2O/Na_2O) \geq 0$ and log $((Fe_2O_3+MgO)/(K_2O+Na_2O)) < 0$, the sandstone is classified as Arkose; and lastly when log $(SiO_2/Al_2O_3) < 1.5$, log $(K_2O/Na_2O) < 0$ or log $((Fe_2O_3+MgO)/(K_2O+Na_2O)) \geq 0$, then the sandstone is classified as lithic arenite (Sub greywacke) (Lindsey, 1999). These guidelines suggest that the sandstones of Kandi and Gulu are mixed ranging from being arkosic at Kandi and lithic arenite in Gulu. This is consistent with their mineralogy from petrography (Table 2). The chemically less stable minerals such as plagioclase feldspar during weathering and transportation are very few in Gulu samples but slightly sustained in Kandi sandstones as also reflected in the plot of Zr against TiO2 which confirms the dominance of felsic minerals in Gulu sandstones. The majority of Kandi sandstone plots are close to and within the intermediate minerals. So sandstones in Gulu are more mature in texture and mineralogy than Gulu sandstones. The sub-mature to mature textural characteristics, coarse grain, dominance quartz mineral (litharenite), and dominant moderate sorting of the sandstones from Gulu are geological indices for a good porosity and permeability which will enhance the rock's reservoir potentials for underground water and hydrocarbon exploration. This is because cementation at the deeper subsurface will be less compared with the arkosic samples at the Kandi area.

CONCLUSIONS

This study integrated geology, grain size, thin section, and geochemistry studies to evaluate the provenance, textures, mineralogy, and depositional environments and predict the preliminary reservoir quality of the Campanian-Maastrichtian sandstones of Enagi Formation in the northern Bida Basin, Nigeria. The following conclusions were reached.

i. The sandstones of Gulu are fine to medium-grained, moderately to well sorted, and sub-angular to sub-rounded grain indicating exposure to moderate distance of transportation away from the source. They have mineralogical and textural sub-mature features and are classified as lithic arenite.

ii. Kandi sandstones are medium to coarse-grained, poorly to moderately sorted, and sub-angular to sub-rounded grain shapes suggesting mineralogically and texturally immature to sub-mature features. They are essentially arkosic sandstones

iii. The sandstones are deposited mainly in a fluvial depositional environment with little contribution from tidal environments.

iv. The sandstones are largely from the felsic to intermediate rocks from a passive margin paleo-tectonics.

v. The candidate sandstones with the best reservoir potential are those of the Gulu area because they are moderately sorted, texturally, and mineralogically more mature, with lesser clay or feldspar constituents that can enhance cementation at the deeper subsurface.

vi. These sandstones should be suitable for underground water aquifers at the shallow subsurface and hydrocarbon reservoirs at the deeper subsurface.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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