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SEDIMENTOLOGICAL AND GEOCHEMICAL CHARACTERIZATION OF DF-2 WELL, ONSHORE WESTERN NIGER DELTA: IMPLICATIONS FOR PROVENANCE, TECTONIC HISTORY AND PALEO DEPOSITIONAL CONDITIONS

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ABSTRACT

The sedimentology and geochemistry of the major oxides and trace elements of DF-2 well, Onshore, Niger Delta, are presented in this study. The study is aimed at describing the sedimentological characteristics as well as using the major oxides and trace elements to investigate the provenance, tectonic history and palaeo-depositional conditions of the well. Selected samples were investigated with fused bead X-Ray Fluorescence (XRF) spectrometry to determine their major oxides and fused bead laser ablation inductively couple plasma mass spectroscopy (LA-ICP-MS) for their trace elements. Sedimentological analysis from the well shows that the lithology ranged from shaly sand, sandy shale, sandstone and shale. The results show the dominance of silicon oxide (SiO_2) contents which ranges from 81.1 to 91.4 wt. % (average of 87.1 wt. %). The low average concentration of Cr<150 ppm and Ni <100 ppm, the ratios of Th/Sc, Th/Co, Th/Cr, Cr/Th, La/Sc, as well as the plots of Th/Co versus La/Sc and TiO_2 versus Zr, all infer a felsic source rock. The discrimination plots of ratioK_2O/Na_2O against SiO_2 and Log K_2O/Na_2O against Log SiO_2/Al_2O_3indicated passive continental margin. Various chemical classifications of the sediments show that the sandstone facies plotted mainly in quartzarenite, sublitharenite and Fe-rich sand domains. The samples were deposited under oxic environment based on the average values of U/Th (0.26 ppm), Ni/Co (2.79 ppm) and Cu/Zn (1.81ppm) and bivariate plot of Ni/Co versus V/Cr. However, the bivariate plot of Ni/Co versus V/ (V+Ni) specifies oxic to anoxic conditions and V/Vi + Ni ratios indicate oxic, suboxic to euxinicpalaeode positional environments for the sediments. Geochemical characterization illustrates mixed marine and terrigenous source input, deposited mainly in semi humid/humid climate. The positive values attained from ratios of $Al_2O_3/(CaO+MgO+Na_2O+K_2O)$ infers mineralogical maturity based on stable mobile oxides content in the studied samples.

KEYWORDS: Felsic Rock, Quartzarenite, Litharenite, Passive Margin, Mobile Oxide, Mature Sediments.

INTRODUCTION

The Niger Delta is situated on the Gulf of Guinea on the west coast of central Africa and extends throughout the Niger Delta Province as defined by Klett *et al.,* (1997). It is one of the world's largest, deltas, with the sub aerial portion covering about 75,000 km^2 and extending more than 300 km from apex to the mouth (Doust and Omatsola, 1990).From the Eocene to the present, the delta has prograded southwestward, forming depobelts that represent the most active portion of the delta at each stage of its development (Doust and Omatsola, 1990, Fig. 1b). According to Kulke, (1995), these depobelts, form one of the largest regressive deltas in the world with an area of some 300,000 km^2. Hospers, (1965) indicated a sediment volume of 500,000 km^3, and a sediment thickness of over 10 km in the basin's depocenter (Kaplan *et al.,* 1994).

The composition of siliciclasticfacies depends on the principal chemical composition of the source rock area and the tectonic history of the depositional basins (Das and Haake, (2003); Jin *et al.,* (2006). Previous researchers such as; Cullers (2000); Cingolani *et al.,* (2003); Armstrong-Altrin *et al.,* (2004); Akinyemi *et al.,*

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(2013); Chen *et al.,* (2016); Mitra *et al.,* (2018); Amiewalan and Lucas, (2020) among others, had worked on the Niger Delta sediments and other Basins to interpret their provenance, tectonic history, paleo-depositional conditions and classification of associated sandstone facies. This study intends to use the major and trace element geochemistry to define the provenance, tectonic history, paleo-depositional conditions of sediments in the DF-2 well, offshore western Niger Delta .This will further enhance the already existing information in this region and would be of immense value to researchers and explorationists.

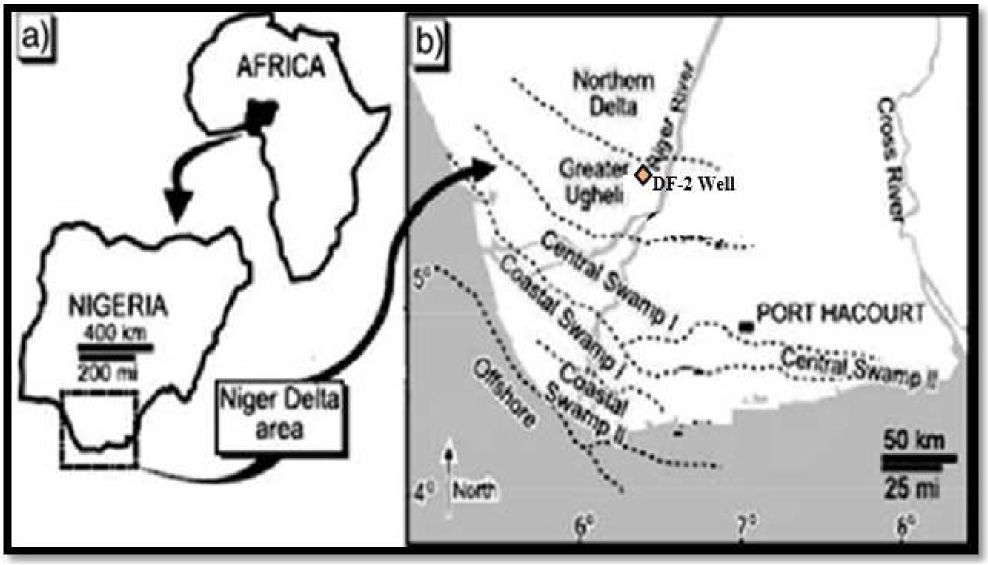

Fig. 1a: Map of Africa showing the Location of Nigeria and the Niger Delta region. 1b. Map of the Niger Delta basin showing the different depositional belts (depobelts) and location of DF-2 well. (After Doust and Omatsola, 1990).

LOCATION OF STUDY AREA AND GEOLOGY

DF-2 well is located in Greater Ughelli Depobelt of the Niger Delta with geographic coordinates of Longitude E5^0 33' 36''.86 and Latitude N6^0 18' 25''.43. Fig 1b.According to Doust and Omatsola, (1990), the Niger Delta basin probably commenced in Albian time, after the opening of the South Atlantic Ocean and the break off of African and South American plates. The disintegration of the Central Africa-South America part of Gondwana happened during the Mesozoic along successions of rift zones of diverse location that met in a triple junction in the present-day Gulf of Guinea occupied by the Niger Delta. The two arms that followed the southwestern and southeastern coasts of Nigeria and Cameroon, advanced into collapsed continental margins of the South Atlantic, while the third, (failed arm)established the Benue Trough. The trough represents a failed arm of a rift triple junction accompanied with the opening of the South Atlantic. Lehner and De Ruiter, (1977), posited that rifting began in this region in the Late Jurassic and continued into the Middle Cretaceous. However, rifting diminished completely in the Late Cretaceous in the Niger Delta region. True Delta expansion started in the Late Paleocene/Eocene, when sediments began to build out beyond the trough between basement horst blocks at the northern flanks of the present Delta area, (Doust and Omatsola, 1990).

The stratigraphy of the Niger delta has been controlled by the interplay between rates of sediment supply and subsidence. Eustatic sea-level changes and climatic variations have been the control on the sedimentation rate while the subsidence have been controlled essentially by initial basement morphology and differential sediment stacking on unstable shale. In numerous deltaic areas, it is challenging to delineate an adequate stratigraphic nomenclature, (Doust and Omatsola, 1990). Smaller number of lithofacies in the Niger delta makes it difficult to outline appropriate units and boundaries in establishing distinct Formations. However, three Formation names are widely use conforming to the sections of the tripartite sequences, stretching in age from Eocene to Holocene (Short and Stauble, (1967); Avbovbo, (1978); (Fig. 2)

The subsurface Niger Delta sedimentary basin is sub-divided into three stratigraphic units from the oldest to youngest namely; Akata Formations, Agbada and Benin Formations (Short and Stauble, 1967). The Akata Formation with Imo shale as the lateral equivalent is the basal unit of the Niger Delta. It composed mainly of marine shale facies with sporadic lowstandturbidite sand and minor amounts of clay and silt. Thin Akata sands are possibly of turbiditic origin and were deposited in delta-front to deep marine environments (Esan, 2002). The Formation is believed to be the main source rock within the Niger Delta complex. (Ekweozor, and Okoye, 1980; Bustin, 1988). The thickness ranges from 2,000 ft. - 20,000 ft. (600 m to 6,000 m) (Jev et al., 1993). Doust and Omatsola, (1990), estimated the age of the Akata Formation to be from Eocene to Recent. The Agbada Formation which overlies the Akata Formation has the Ogwashi-Asaba and Ameki Formations as their lateral equivalent. The Formation represents the fore set of the Niger Delta and comprised delta front lithofacies, consisting mostly of shoreface and channel sand deposits with minor shale in the upper parts and an alternation of sand and shale of almost equal proportion in the lower part. The clastics accumulated in delta-front, delta-topset, and fluvio-deltaic environments. It is the major petroleum-bearing unit of the Niger Delta (Reijers, (1996), which began in the Eocene and continues into the Recent. The thickness ranges from 9,600 ft. - 14,000 ft. (3,000 m - 4,200 m) (Avbovbo, 1978). The Benin Formation, which is the youngest stratigraphic unit in the Niger Delta, mainly comprised non-marine sands with a few shalyintercalations (Esan, 2002). The shale content increases towards the basal part of the Formation. It is a continental deposit from latest Eocene to Recent, deposited in alluvial or coastal plain environments following a southward shift of deltaic environments (Esan, 2002). The Formation is up to 2,000 m thick. (Avbovbo, 1978).

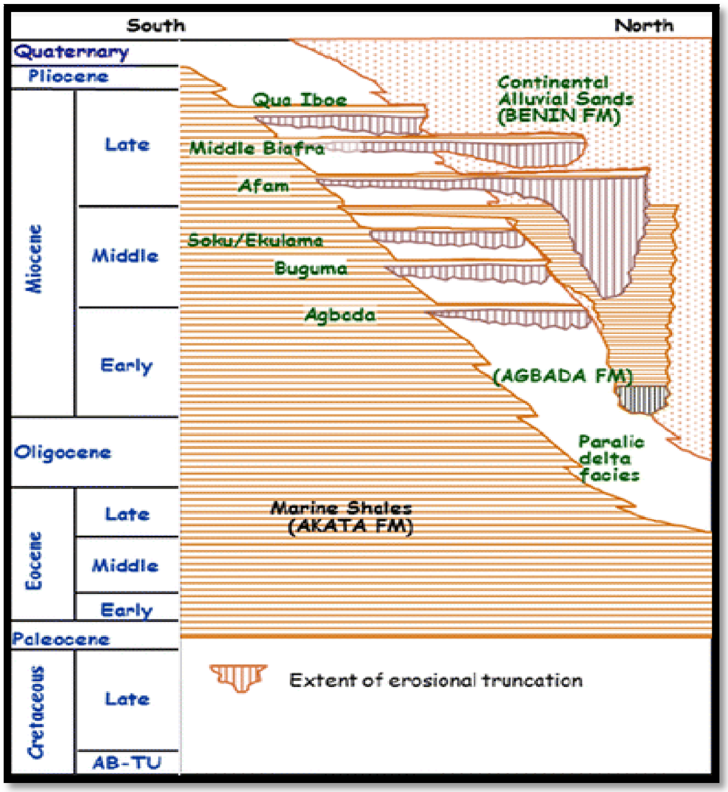

Fig 2: Regional stratigraphy of the Niger Delta showing different Formations (after Ozumba, 2013).

MATERIALS AND METHODS

Three hundred and eighty two (382) ditch cutting samples between intervals 2900 ft. - 9650 ft. from DF-2 well were provided by the Nigerian Petroleum Development Company (NPDC) for this study. Detailed sedimentological descriptions were carried out based on visual inspection as well as reflected light binocular light microscope on the samples to investigate the lithology, texture, color, and environmental sensitive minerals and fossil content. The samples were composited and twelve representatives (DF1, DF2, DF3, DF4, DF5, DF6, DF7, DF8, DF9, DF10, DF11 and DF12 respectively) were selected for this study. A litho-log was established from the sedimentological description as shown in Fig. 3. The oxides composition and fused bead laser ablation inductively couple plasma mass spectroscopy (LA-ICP-MS) for their trace elements composition was carried out at Bureau Veritas Minerals laboratory, Vancouver, Canada.

XRF and LA-ICPMS analyses: Each of the twelve representative samples was pulverized and 20g of each sample was placed in oven at 1000^0C for 1 hour to determine loss on ignition (LOI) using a robotic TGA system. 12.22 fluxes with 4% Lithium nitrate were added to the sample to form glass bead. Major oxides were determined by X-Ray Fluorescence Spectrometry on oven dry temperature of 105^0C. Supplementary analysis was carried out on the same samples using LA-ICP-MS instrument to determine the trace elements composition of the sample. The laser of the instrument was used to evaporate the surface of the fused sample, the vapor and particles generated were conveyed by the carrier gas flow to the plasma of the ICP-MS unit. The rays passed through the quadruple were detected and the data were quality check.LA-ICPMS streamlines the analytical process to a single, cost effective fusion. Detection limits are similar to industry leading mixed acid trace element ICP-MS packages. The results of the major oxides are described as oxides percent by weight and trace elements quantified in ppm as shown in Tables 1 and 2. Both the fused bead X-Ray Fluorescence (XRF) spectrometry for majoroxides composition and fused bead laser ablation inductively couple plasma mass spectroscopy (LA-ICP-MS) for their trace elements composition were carried out at Bureau Veritas Minerals laboratory, Vancouver, Canada.

RESULTS AND DISCUSSION

Lithostratigraphy

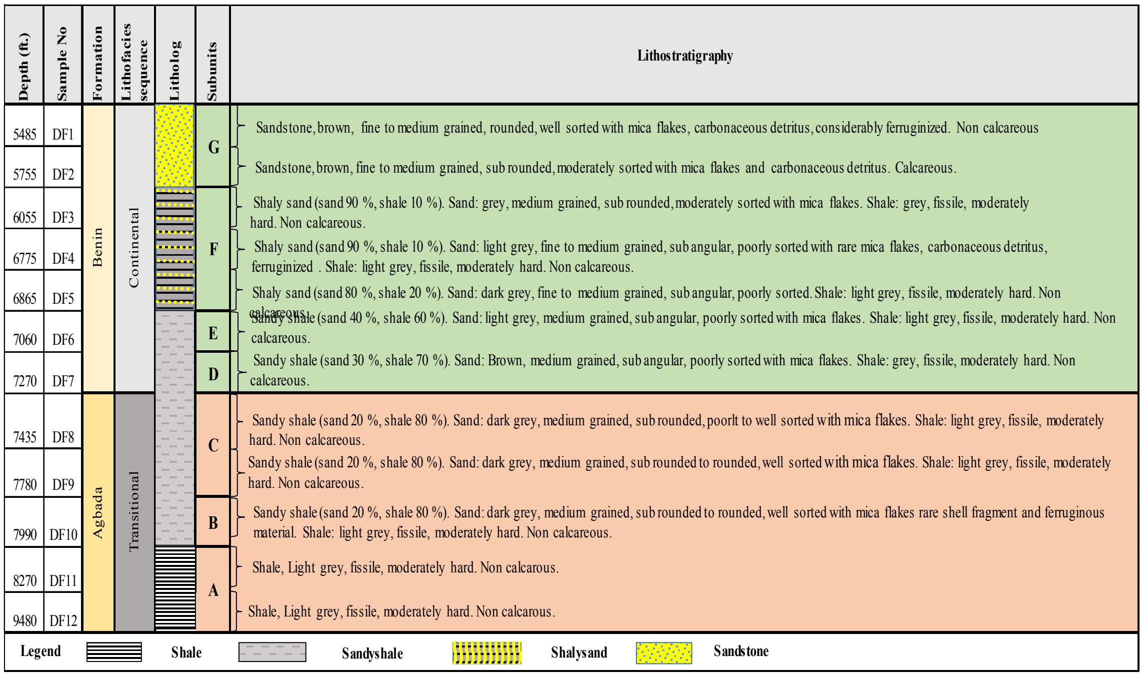

Fig. 3 Simplified composite litho-log of DF-2 well, Western Niger Delta.

The sedimentological analysis ofDF-2 well logrevealed that the lithology ranged from sandstone, shaly-sand, and sandy-shale to shale. The studied sections was divided into two broad lithofacies sequences interpreted as the continental sequence (5485 ft. - 7270 ft.) and transitional sequence (7435 ft. - 9480 ft.) which also correspond with the Benin and Agbada Formations of the Niger Delta. Seven informal sedimentary units were delineated from the analysis. These lithofacies units with their corresponding depths are sub-unit A: (8270 ft. - 9480 ft.), sub-unit B: (7990 ft.), sub-unit C: (7435 ft. - 7780 ft.), sub-unit D: (7270 ft.), sub-unit E: (7060 ft.), sub-unit F: (6055 ft. - 6865 ft.) and sub-unit G: (5485 ft. - 5755 ft.) respectively. Fig.3.

The Transitional Sequence (7435 ft. - 9480 ft.) (Subunits A - C)

This interval is essentially a heterogeneous sequence of alternating sand and shale components, with the basal sample points (8270 ft. and 9480 ft.) predominantly composed of shale. The shale is Light grey, fissile, moderately hard. The sandstones are dark grey, fine to medium grained, sub rounded to rounded, poorly to well sorted. From the gross lithologic and grain attributes, the subrounded to rounded and well sorted sandstone indicating sediment maturity due to weathering and abrasion of the grains during transport. Index minerals are dominated by mica flakes with rare occurrences of shell fragment and ferruginous material. Most of the samples within this sequence are non-calcareous.

The Continental sequence (5485 ft. - 7270 ft.) (Subunits D - G)

This is composed of alternating sequence of sandstone, shaly sand and relatively thin shale. The sands are brown, light to dark grey, fine to medium grained sized, sub angular to sub rounded and generally poorly to well sorted. The shales are grey, dark grey, platy to blocky and hard to reasonably tough. Index minerals are dominated by mica flakes with considerably occurrence of ferruginized material. The samples within this sequence are non-calcareous.

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The result of the major oxides are shown in Table 1

Table 1: Major oxides geochemical composition of DF-2 Well. Post Archean Australian Average Shale (PAAS). Taylor and Mclenna, (1985) and Upper Continental Crust (UCC) Mclenna, (2001).

Major oxides in wt. %	DF1	DF2	DF3	DF4	DF5	DF6	DF7	DF8	DF9	DF10	DF11	DF12	Average	PAAS	UCC
SiO_2	90.90	79.20	81.80	79.60	80.50	93.10	87.50	86.10	83.50	83.20	85.70	79.30	84.20	62.80	66.00
Al_2O_3	2.20	12.90	11.40	2.60	2.10	2.30	3.50	4.20	4.30	4.60	4.40	4.10	4.88	18.90	15.20
Fe_2O_3	1.47	3.47	2.50	2.50	1.48	1.51	3.81	4.12	6.64	5.22	3.16	3.14	3.25	7.22	5.03
MnO	0.03	0.04	0.03	0.03	0.04	0.04	0.04	0.04	0.06	0.06	0.04	0.04	0.04	0.11	0.08
MgO	0.23	0.31	0.32	0.33	0.47	0.47	0.21	0.22	0.98	0.87	0.20	0.42	0.42	2.20	2.20
CaO	1.02	1.03	1.02	12.10	14.20	1.34	0.91	0.89	0.88	1.21	1.33	1.31	3.10	1.30	4.20
Na_2O	0.11	0.23	0.21	0.22	0.16	0.14	0.17	0.16	0.28	0.21	0.18	0.17	0.19	1.20	3.90
K_2O	0.77	0.91	0.85	0.81	0.61	0.51	0.83	0.99	1.51	1.34	0.64	0.75	0.88	3.70	3.40
TiO_2	0.17	1.12	1.14	0.15	0.13	0.12	1.22	1.31	1.37	1.34	0.49	0.32	0.74	0.99	0.68
P_2O_5	0.02	0.07	0.05	0.04	0.04	0.03	0.06	0.12	0.13	0.13	0.04	0.05	0.07	0.16	0.15

As shown in Table 1, there is enormous difference between SiO_2 content and other oxides in all the analyzed samples. For instance, the SiO_2 contents ranges from 79.20 wt. % to 93.10 wt. % (av. 84.2 wt. %.) in the well. According to Lindsey, (1999), silica enhancement shows the degree of sandstone maturity, and the reflection of the extent and strength of weathering and damages of other minerals in the course of transportation. Al_2O_3 content varies from 2.10 wt. % to 12.90 wt. %.Cingolani *et al.,* (2003), opined that the compositional variations of rocks arising from weathering result in the reduction of alkalis and alkaline earth elements and special enhancement of Al_2O_3.

Fe_2O_3 content ranges from 1.47 wt. % to 6.64 wt. %. The low content may be due to weathering. The MnO content ranges from 0.03 wt. % to 0.06 wt. %; MgO from 0.20 wt. % to 0.98 wt. %.; CaO from 0.88 wt. % to 14.20 wt. % while Na_2O varies from 0.11 wt. % to 0.28 wt. %. The low values might perhaps be the result of post depositional processes or from sediment source. Ranges of value of other oxides are; K_2O; 0.51 wt. % to 1.51 wt. %, TiO_2; 0.12 wt. % to 1.37 wt. % and P_2O_5; 0.02 wt. % to 0.13 wt. %.

From the preceding, the mean value of silica (84.2 wt. %) in the studied sediments is extremely higher than the mean values of the remaining oxides, probably due to weathering and post depositional processes, as sedimentary rocks are enriched in silica and reduction in iron, magnesium, calcium, sodium, and potassium in association to the sediment source. The mean value (84.20 wt. %) of SiO_2 is greater than the mean of PAAS (62.80 wt. %) and UCC (66.00 wt. %) values while the mean values of Al_2O_3, Fe_2O_3, MgO, MnO, Na_2O, K_2O, TiO_2 and P_2O_5 are less than PAAS with the exception of CaO. Al_2O_3, Fe_2O_3, MgO, MnO, CaO, Na_2O, K_2O and P_2O_5 are less than UCC with the exception of TiO_2.

TRACE ELEMENTSGEOCHEMISTRY

The results of trace elements variation for the study well is shown in Table 2

Table 2: Trace Elements Composition of DF-2 Well.

Trace element in ppm	DF1	DF2	DF3	DF4	DF5	DF6	DF7	DF8	DF9	DF10	DF11	DF12	Average	PAAS	UCC
Ag (Silver)	0.2	0.4	0.3	0.2	0.4	0.4	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.11		
As (Arsenic)	2.2	3.8	3.4	3.8	4.2	4.0	2.4	2.6	2.8	3.6	10.2	12.2	4.60		1.5
Ba (Barium)	4240	7460	8500	12900	13000	13400	7650	8000	12800	10200	5010	4750	8992.50	650	550
Be (Beryllium)	-0.2	2.8	2.5	2.2	0.4	0.3	2.5	2.8	2.6	3.1	3.4	3.4	2.15		
Bi (Bismuth)	0.04	0.12	0.15	1.16	1.98	1.81	0.05	0.04	0.04	0.06	0.06	0.2	0.47		
Cd (Cadmium)	0.1	-0.1	0.1	0.2	0.3	0.3	-0.1	-0.1	-0.1	-0.1	-0.1	0.1	0.04		
Ce (Cerium)	17.9	99.7	75.4	54.1	13.9	12.2	37	49	33.8	117	111	139	63.33	79.6	64
Co (Cobalt)	3.1	11.8	9.6	8.5	2.7	2.3	8.3	8.0	7.9	10.2	15.2	17.4	8.75	23	10
Cr (Chromium)	30	75	65	45	36	32	89	92	86	94	102	105	70.92	110	35
Cs (Caesium)	0.35	1.89	1.32	1.65	0.27	0.21	0.8	0.8	0.7	1.9	3.9	3.7	1.46		3.7
Cu (Copper)	22	24	35	38	1410	32	24	24	24	22	22	22	141.58	50	25
Ga (Gallium)	3.1	20.2	10.2	18.2	2.9	3.3	17.9	22.1	17.8	25.3	26.1	27.8	16.24		
Hf (Hafnium)	7.3	11.2	9.3	5.9	8.2	6.1	8.4	9.2	6.6	8.3	10.3	12.0	8.57	5	5.8
In (Indium)	0.1	0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.67		
La (Lanthanum)	8.57	51.2	8.5	7.9	6.6	6.9	19.8	18.3	16.4	20.5	52.8	68.3	23.81	38.2	30
Mo (Molybdenum)	2.5	3.0	2.7	2.9	2.0	2.4	4.2	4.4	4.5	3.2	3.6	2	3.12		
Nb (Niobium)	35.14	34.5	30.9	29.1	34.15	32.4	26.8	37.4	26.2	32.8	41.1	45.4	33.82	1.9	25
Ni (Nickel)	10	28	15	18	13	11	30	32	28	34	26	48	24.42	55	20
Pb (Lead)	34	27	24	56	82	51	25	27	22	29	31	33	36.75	20	
Sb (Antimony)	0.3	0.3	1.9	2.2	2.6	2.7	0.3	0.2	0.1	0.1`	0.2	0.4	0.93		0.2
Sc (Scandium)	1.5	9.0	7.1	4.3	1.0	1.4	4.1	5.6	3.5	3.8	11.7	13	5.50	16	11
Sn (Tin)	1.4	4.4	3.9	55	112	60	3.8	3.6	3.6	3.9	4.3	4.4	21.69		
Sr (Strontium)	106	192	141	174	194	190	103	105	106	102	180	200	149.42	200	350
Ta (Tantalum)	0.35	2.2	1.8	1.1	0.28	0.32	1.02	1.14	0.78	1.89	2.14	2.96	1.33		2.2
Te (Tellurium)	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.4	-0.15		
Th (Thorium)	3.21	12.30	10.20	8.40	2.18	3.12	6.23	5.66	4.68	7.14	12.5	17.9	7.79	14.6	10.7
Ti (Titanium)	1020	6960	2190	1290	772	890	4670	4008	2960	5680	7430	8450	3860.00		
Tl (Thallium)	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.2	-0.17		
U (Uranium)	0.74	3.24	2.34	2.21	1.08	1.02	1.58	1.54	1.43	2.41	3.05	3.63	2.02	3.1	2.8
V (Vanadium)	8.6	71.4	56.2	12.7	10.2	9.4	150	210	272	248	152	103	108.63	150	60
W (Tungsten)	2.0	4.0	2.0	4.0	4.0	2.0	2.7	2.9	3.5	2.8	2.5	2.5	2.91		
Y (Yttrium)	5.22	25.5	23.2	7.22	3.98	3.72	14.1	21.7	8.66	28.9	17.5	33.2	16.08	27	22
Zn (Zinc)	25	60	70	90	100	110	74	83	45	76	91	115	78.25	85	71
Zr (Zirconium)	310	409	319	220	250	280	443	445	442	447	448	449	371.83	210	190

The comparative abundance of trace elements in sediment is measured by sedimentation rate, terrigenous influx, biogenic influx, hydrothermal input, diagenesis and eventually, weathering (Leventhal, 1998). Some of these elements are depleted while others are enriched in relation to UCC and PAAS respectively(Table 2).

The average concentrations of Ba (8992.50) is enriched when compared with those of PAAS (650) and UCC (550) and the average of Pb (36.75) is enriched with respect to PAAS (20). Between the high field strength elements, the mean concentrations of Hf, Nb, and Zr are enriched when compared with PAAS and UCC due to their association with heavy minerals. Concentrations of Ce and La are depleted in DF-2 sediments. Among the transition trace elements (Sc, V, Cr, Cu, Co, Ni and Zn), Sc and Co are depleted and Cu is enriched with respectto PAAS and UCC (Table 2). Cullers and Berendsen, (1998), submitted that the overall depletion of Scandium, signifies a reasonably felsic source. Cr, Ni, V and Zn are depleted when compared to PAAS and enriched in relation to UCC. The depletion of Ni and V elements shows an insignificant role of basic rocks as the provenance. The average concentration of Th (Thorium) (7.79) is depleted when compared with PAAS (14.6) and UCC (10.7)as a result of dilution of the elemental concentration by quartz. Sr (Strontium) with a mean value of 149.42 is depleted when related with PAAS (200) and UCC (350). Studies of sedimentary processes have showed that Sr is rapidly lost during chemical weathering and its depletion is in proportion to the degree of weathering (Wronkiewicz and Condie, 1987).

The ratios of some important major oxides and trace elements for this study have been presented in Table 3 for further deductions of sediment source, tectonic setting, sandstone classification, maturity, paleo-oxidation as well as paleo-climatic conditions.

Table 3: Ratios of some important major oxides and trace elements S based on results from Tables 1 and 2.

Ratios	DF1	DF2	DF3	DF4	DF5	DF6	DF7	DF8	DF9	DF10	DF11	DF12	Average	PAAS	UCC
Log (SiO_2/Al_2O_3)	1.62	0.79	0.86	1.49	1.58	1.61	1.39	1.31	1.29	1.26	1.29	1.29	1.24	0.52	0.64
Log (K_2O/Na_2O)	0.85	0.60	0.61	0.57	0.58	0.56	0.69	0.79	0.73	0.80	0.55	0.64	0.67	0.49	-0.06
Log (Fe_2O_3/K_2O)	0.28	0.58	0.47	0.49	0.38	0.47	0.66	0.62	0.64	0.59	0.69	0.62	0.57	0.29	0.17
Log (Na_2O/K_2O)	-0.85	-0.59	-0.61	-0.57	-0.58	-0.56	-0.69	-0.79	-0.73	-0.80	-0.55	-0.64	-0.67	-0.49	0.06
$Al_2O_3+Na_2O+K_2O$	3.08	14.04	12.46	3.63	2.87	2.95	4.50	5.35	6.09	6.15	5.22	5.02	5.95	23.80	22.50
K_2O/Na_2O	7.00	3.96	4.05	3.68	3.81	3.64	4.88	6.19	5.39	6.38	3.56	4.41	4.63	3.08	0.87
Th/Cr	0.11	0.16	0.16	0.19	0.06	0.09	0.07	0.06	0.05	0.08	0.12	0.17	0.11	0.13	0.31
La/Sc	5.71	0.57	1.19	1.84	6.60	4.93	4.83	3.27	4.67	5.39	4.51	5.25	4.33	2.39	2.73
Th/Sc	2.14	1.37	1.44	1.95	2.18	2.30	1.52	1.01	1.34	1.88	1.07	1.38	1.42	0.91	0.97
Th/Co	1.04	1.04	1.06	0.99	0.81	1.36	0.75	0.71	0.59	0.70	0.82	1.03	0.89	0.63	1.07
Cr/Th	9.35	6.10	6.37	5.36	16.51	10.26	14.29	16.25	18.38	13.17	8.16	5.87	9.10	7.53	3.27
U/Th	0.23	0.30	0.23	0.26	0.49	0.33	0.25	0.27	0.31	0.33	0.24	0.20	0.26	0.21	0.26
Ni/Co	3.23	2.37	1.56	2.12	4.81	4.78	3.61	4.00	3.54	3.33	1.71	2.76	2.79	2.39	2.00
Cu/Zn	0.88	0.40	0.50	0.42	14.10	0.29	0.32	0.29	0.53	0.29	0.24	0.14	1.53	0.59	0.35
V/ (V+Ni)	0.46	0.72	0.79	0.42	0.44	0.46	0.83	0.87	0.91	0.88	0.85	0.68	0.82	0.73	0.75
V/Cr	0.29	0.95	0.86	0.28	0.28	0.29	1.69	2.28	3.16	2.64	1.49	0.98	1.53	1.36	1.71
Al_2O_3/SiO_2	0.02	0.16	0.13	0.03	0.03	0.02	0.04	0.05	0.05	0.06	0.05	0.05	0.06	0.3	0.23
Fe_2O_3+MgO	1.70	3.78	2.82	2.83	1.95	1.98	4.02	4.34	7.62	6.09	3.36	3.56	3.67	9.42	7.23
SiO_2/Al_2O_3	41.32	6.14	7.18	30.62	38.33	40.48	25.00	20.50	19.42	18.09	19.48	19.34	17.25	3.32	4.34
$Na_2O + K_2O$	0.88	1.14	1.06	1.03	0.77	0.65	1.00	1.15	1.79	1.55	0.82	0.92	1.07	4.90	7.30
Fe_2O_3/K_2O	1.91	3.81	2.94	3.09	0.92	2.96	4.59	4.16	4.40	3.90	4.94	4.19	3.70	1.95	1.48
$Al_2O_3/(CaO+MgO+Na_2O+K_2O)$	1.03	5.20	4.75	0.19	0.14	0.93	1.65	1.85	1.18	1.27	1.87	1.55	1.06	2.25	1.11
$(Fe_2O_3 + MgO)/(K_2O + Na_2O)$	1.93	3.32	2.66	2.75	2.53	3.05	4.02	3.77	4.26	3.93	4.1	3.86	3.43	1.92	0.99

Sandstone Petrology

Using Herron (1988) diagram as shown in Fig. 4, majority of the DF-2 samples (70%) plotted mainly in the Fe-sand zone, indicating that they are ferruginous. The rest of the samples (30%) are scattered within the quartz arenite, sublitharenite and litharenite zones. Arising from Pettijohn (1972) plot of log (SiO_2/Al_2O_3) vs. log (Na_2O/K_2O) (Fig. 5), the studied samples plotmainly in quartz arenite with a few in sublitharenite zones. This may perhaps be the consequent of recycling/prolonged abrasion as well sedimentary influx from more than one source.

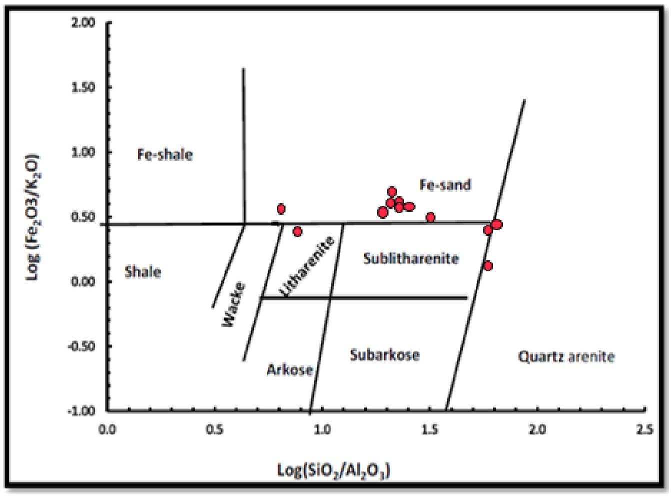


Fig. 4: Chemical classification of the DF-2 well sediments based on log (SiO_2/Al_2O_3) vs. log (Fe_2O_3/K_2O) diagram of Herron, (1988).

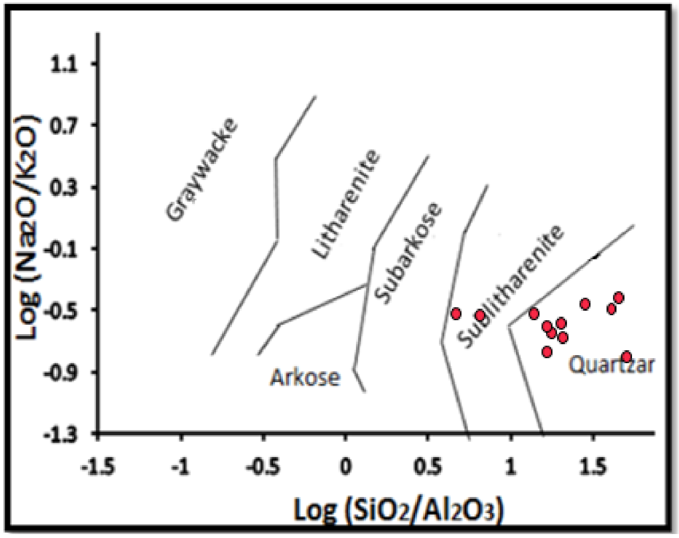


Fig. 5: Chemical classification of the samples based on log (SiO_2/Al_2O_3) vs. log (Na_2O/K_2O) diagram of Petti John scheme, (1972).

Lindsey, (1999), recommended four reference sets as guidelines for chemical classification of sandstone.

i) Quartz arenite: log (SiO_2/Al_2O_3) ≥ 1.5

ii) Graywacke: log (SiO_2/Al_2O_3) < 1 and log (K_2O/Na_2O) < 0

iii) Arkose (includes subarkose): log (SiO_2/Al_2O_3) <1.5 and log (K_2O/Na_2O ≥ 0 and log ((Fe_2O_3+MgO)/(K_2O+Na_2O)) < 0

iv) Lithic arenite (subgraywacke, includes protoquartzite): log (SiO_2/Al_2O_3) < 1.5 and either log (K_2O/Na_20) < 0 or log ((Fe_2O_3+MgO)/(K_2O+Na_2O)) > 0.

The average value of log (SiO_2/Al_2O_3) for the DF-2 sediments is 1.24 (Table 3), which is <1.5 and therefore less than the value for quartz arenite as proposed by Lindsey (1999). The average value of log (K_2O/Na_2O) for the sediments is 0.67, which is not in the greywacke range of Lindsey (1999). The average values obtained for log (SiO_2/Al_2O_3) is 1.24 and log (K_2O/Na_2O) is 0.67 whereas the average value of log ((Fe_2O_3 + MgO)/(K_2O + Na_2O)) is 3.43. By this interpretation, the sediments cannot be categorized as Arkosein the concept of Lindsey (1999) criteria number three. The average values attained in this study relate with log (SiO_2/Al_2O_3) < 1.5 and log ((Fe_2O_3+MgO)/(K_2O+Na_2O)) > 0 of the fourth category. Accordingly, the sandstones in DF-2 well arelithicarenites. Lithic arenites usually contain 30-80% quartz and 5-50% lithic fragments. The compositional maturity can vary broadly depending on the nature of the lithic fragments. According to Folk (1974), lithic arenites are immature sandstones occurring as a result of high rate of sedimentation from supra crustal source followed by short transportation and are characteristics of fluvial or deltaic settings.

TECTONIC HISTORY

Several authors such as Maynard et al., (1982); Bhatia, (1983); Bhatia and Crook, (1986); Roser and Korsch, (1986); Kroonenberg, (1994) have developed classification schemes used to discriminate amongst sediments deposited in different tectonic settings. The cross plot of K_2O/Na_2O ratio against SiO_2 (Roser and Korsch, 1986) for this sediments, revealed that they all plotted in the Passive Continental Margin (PM) tectonic settings (Fig. 6). The plot of Log (K_2O/Na_2O) against Log (SiO_2/Al_2O_3) tectonic discrimination diagram of Maynard *et al.,* (1982; Fig. 7), also indicates that the studied samples were deposited in the Passive continental margin (PM) field. Passive continental margins are highly prolific in hydrocarbon as they are related with favorable conditions for accumulation and maturation of organic matter (Obasi *et al.,* 2015). According to Roser and Korsch (1986), passive margin sediments are largely quartz-rich which are derivative from stable continental areas where there are no active tectonic activity.

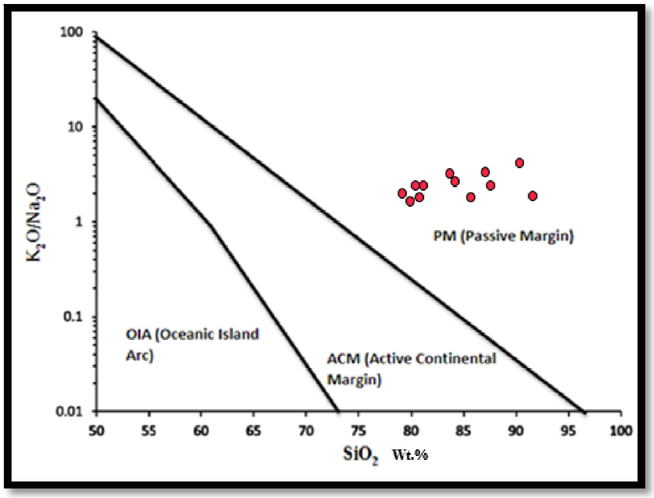


Fig. 6: Tectonic discrimination plot of Roser and Korsch, (1986). Using K_2O/Na_2O ratio against SiO_2 for DF-2 sediments.

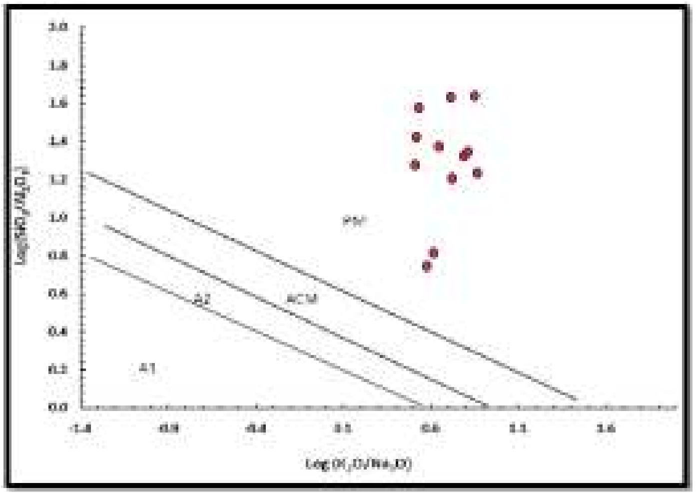


Fig. 7: Log (K_2O/Na_2O) against Log (SiO_2/Al_2O_3) tectonic discrimination diagram of Maynard *et al.,* (1982). Passive Margin = PM, active continental margin = ACM, arc setting, basaltic and andesitic detritus = A1 and evolved arc setting = A2.

PROVENANCE

Trace element concentrations in sedimentary rocks have played an important role in the understanding of crustal evolution in defining provenance. Based on the concepts of Cullers, (2000); Taylor and McLennan, (1985) and as shown in Table 4, it can be seen that ratios such as; Th/Sc, Th/Co, Th/Cr, Cr/Th and La/Sc are significantly different in felsic and basic rocks, which probably permit controls on the typical provenance. These ratios are related with sediments derived from felsic and basic rocks, upper continental crust (UCC) and PAAS values.

From Table 3, the values of the various ratios and their averages are; Th/Sc (1.01 - 2.30, av. 1.42); Th/Co (0.59 - 1.36, av. 0.89), Th/Cr (0.05 - 0.19, av. 0.11); Cr/Th (5.36 - 18.38, av. 9.10) and La/Sc (0.57 - 6.60, av. 4.33). From the above, the ratios of Th/Sc, Th/Cr, Cr/Th and La/Sc fall within the range of felsic rock while only Th/Co fall within mafic rock.

Table 4: Range of elemental ratios of DF-2 well sediments compared to the ratios derived from felsic (Cullers 2000) and mafic rocks (Cullers, 2000), UCC (Taylor and McLennan, 1985) and PAAS (Taylor and McLennan 1985).

Elemental Ratio	Ranges of values in DF-2 well (n=12)	Range of Sediments Felsic rock	Mafic rock	Upper Continental Crust	Post-Archean Australian
Th/Sc	1.01 - 2.30	0.84 - 20.5	0.05 - 0.22	0.79	0.9
Th/Co	0.59 - 1.36	0.67 - 19.4	0.04 - 1.4	0.63	0.63
Th/Cr	0.05 - 0.19	0.13 - 2.7	0.018 - 0.046	0.13	0.13
Cr/Th	5.36 - 18.38	4.0 - 15	25 - 100	7.76	7.53
La/Sc	0.57 - 6.60	2.5 - 16.3	0.43 - 0.86	2.21	2.4

n = number of samples

Ganai and Rashid, (2015), had posited that sensitive diagenetical trace elements such as Zr, Hf, Nb, Y, Sc, V, Cr, Cu, Co, Ni and Zn can infer provenance and environment of deposition owing to their fairly low movement during weathering, transport, diagenesis, and metamorphism. Garver *et al.,* (1996), recommended that when Cr >150 ppm and Ni >100 ppm in abundance, they are indications of mafic or ultramafic source respectively. In this study, the average concentrations of Cr **(**70.92) and Ni **(**24.42**)** are low, confirming felsic rock as the source areas. This is further supported by Fig. 8, which shows cross plot of La/Sc versus Th/Co (Cullers, 2002) and Fig. 9, which indicates the cross plot of Zr versus TiO_2. (Hayashi *et al.,* 1997), all pointing to felsic source rocks for the sediments.

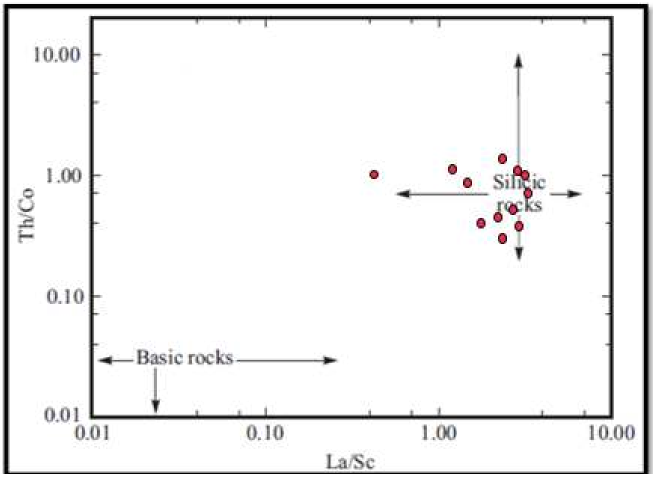


Fig. 8: La/Sc versus Th/Co; after Culler, (2002), indicates the derivation of DF-2 sediments from felsic source rocks.

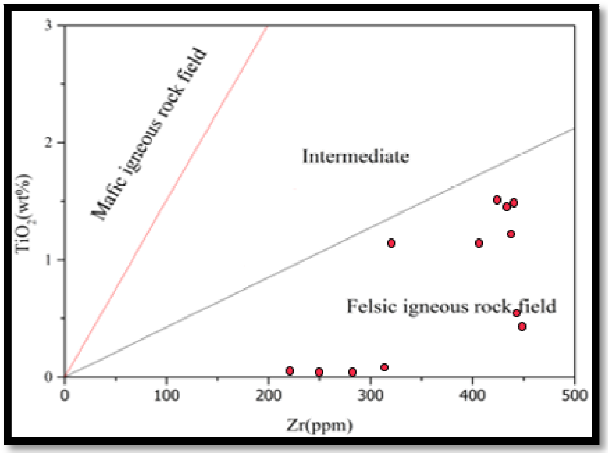


Fig. 9: Cross plots of Zr versus TiO_2, for studied samples (after Hayashi *et al.,*1997).

Paleo Oxygen Condition

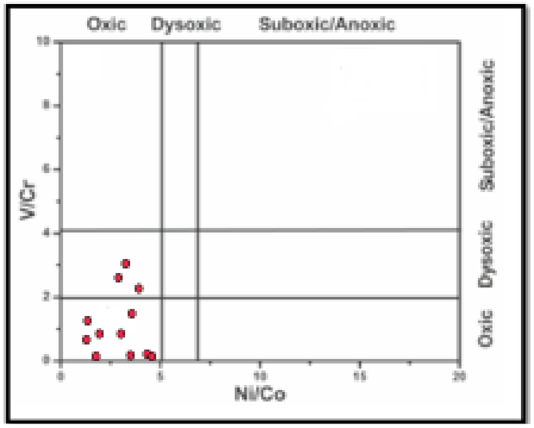


Fig.10: Bivariate plot of Ni/Co versus V/Cr (Suttner and Dutta, 1986) specifies oxic condition during deposition of DF-2 well sediment.

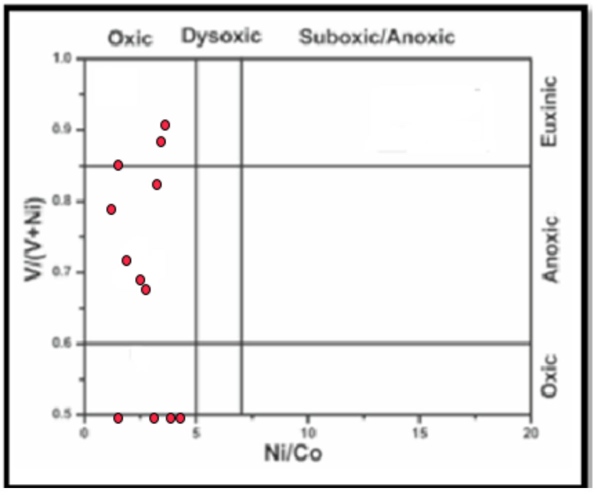
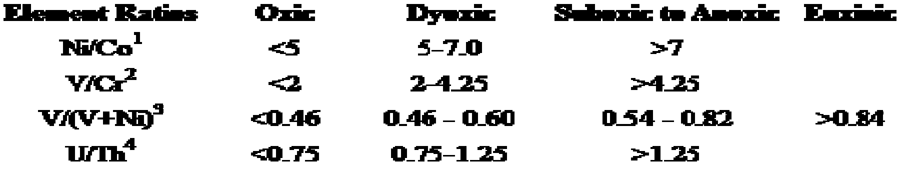


Fig. 11: Bivariate plot of Ni/Co versus V/ (V+Ni) (Rimmer, 2004) shows oxic to euxinic conditions during deposition of DF-2 well sediment.

Table 5: Some trace elemental ratios to define the paleo oxygenation condition of ancient sediments after Jones and Manning, (1994); Nath *et al.,* (1997); Akinyemi *et al.,* (2013);Adebayo *et al.,* (2015a).



Element Ratios	Oxic	Dyoxic	Suboxic to Anoxic	Euxinic
Ni/Co^1	<5	5–7.0	>7	
V/Cr^2	<2	2-4.25	>4.25	
V/(V+Ni)^3	<0.46	0.46 – 0.60	0.54 – 0.82	>0.84
U/Th^4	<0.75	0.75–1.25	>1.25	

Redox-sensitive trace element (TE) ratios are among the major widely used indicators of redox conditions in recent and ancient sedimentary deposits. Trace elements such as U, Th, Cu, Zn, Ni, Co, V and Cr, give a better knowledge on the paleo redox conditions of sediments. High U concentration revealed sediments deposited in oxygen minimum zone (OMZ) whereas low U content infers sediment deposited in oxidizing environment (Nagarajan *et al.,* 2007).Accordingly, the average low U content (average 2.02 ppm) of the DF-2 well sediments favours an oxic condition during sediment deposition. During weathering and sedimentary recycling, Th and U behave in a different way owing to the fact that U is chemically mobile and this action indicates a decrease in the ratio of U/Th. According to Nath *et al.,* (1997), if the ratio of U/Th<0.75, it portrays oxic conditions of deposition, values from 0.75 - 1.25 specifies dyoxic, values >1.25 signifies suboxic to anoxic conditions (Table 5). Relating these values to DF-2 sediments, the U/Th ratios indicates low values from 0.20 - 0.49 (av. 0.26; Tables 3), which confirmed deposition in oxic environment. According to Jones and Manning, (1994). The ratio of Ni/Co in DF-2 well varies from 1.56- 4.81 with an average value of 2.79, and implies oxic environments of deposition (Table 3). Moreover, the Cu/Zn ratios could also be used as a redox proxy; low ratios reveals oxic conditions while high ratios deduce reducing depositional conditions (Deng and Qian, 1993). In the studied sediments, the ratio of Cu/Zn varies from 0.14 to 14.10 with an average of 1.53, and inferring deposition under oxic environments (Table 3).The bivariate plot of Ni/Co versus V/Cr (Suttner and Dutta, 1986; Fig. 10) designates oxic condition during deposition of DF-2 well sediments. This is further supported by the plot of Ni/Co versus V/ (V+Ni) (Rimmer, 2004; Fig. 11), which strongly amplify oxic conditions of deposition for the sediments. Wang, (1996), posited that when V/V+ Ni ratio is >0.84, it submits euxinic conditions, from 0.54 - 0.82 characterize sanoxic condition, 0.46 - 0.60 implies dyoxic conditions and <0.46 infers oxic condition. The V/Vi + Ni ratios for the samples ranges from 0.42 to 0.91 (average = 0.82), (Table 3) which indicate anoxic environment of deposition. As a result, the above constraints submit that the depositional conditions for the studied samples were oxic to euxinic. The Cross plot of vanadium versus nickel after Kafousia, *et al.,* (2010), illustrates that the sediments had mixed marine and terrigenous source input and were deposited under oxic to dyoxic condition. Fig. 12.

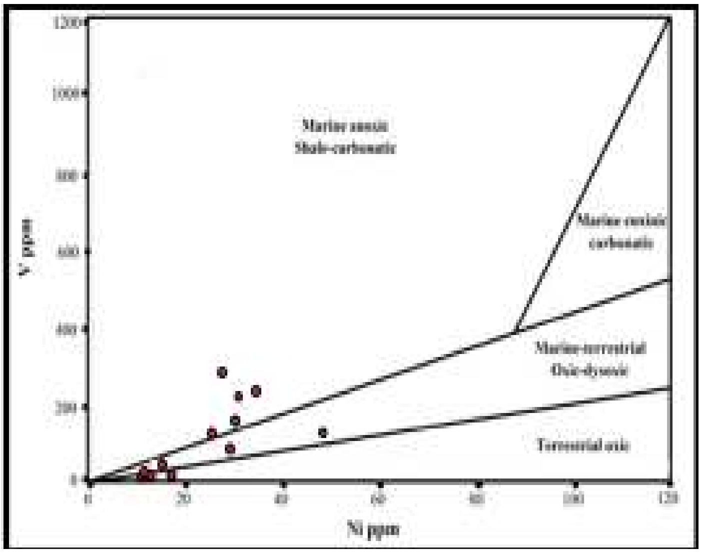


Fig. 12: The Cross plot of vanadium versus nickel of DF-2 samples from studied area shows that the sediments had mixed marine and terrigenous source input and were deposited under oxic to dyoxic condition (Modified after Kafousia, *et al.,* 2010).

MATURITY AND PALAEO-CLIMATE DURING SEDIMENTATION

Potter, (1978), proposed SiO_2/Al_2O_3 as index used to illustrate the degree of sandstones maturity in comparison to mineralogical maturity. Maturity is shown best in quartz, rock fragments, feldspars and grain size determine by the quartz contents in the sediments, because quartz survives contrarily to feldspars, mafic minerals and lithics (Roser *et al.,* 1996). According to Roser *et al.,* (1996), values of SiO_2/Al_2O_3 ratio greater than 5.0 in samples suggest progressive maturity. Potter, (1978), opined that high ratios define mineralogically mature (quartzose rounded) samples, while low ratios denote chemically immature samples. The SiO_2/Al_2O_3ratio for the studied samples varies from 6.14 - 41.32 (av. 17.25) which is greater than 5.0. This infers that the samples are mineralogically mature with low content of fines/mudstone.Na_2O + K_2O (alkali content) indicates the amount of the feldspar content and likewise applicable as a guide for chemical maturity. The alkali content have range of values between 0.77 - 1.79(av.1.07) which shows the presence of feldspars and low chemical maturity. The Fe_2O_3/K_2O ratio ranges from 0.92 to 4.94 having an average of 3.70. The higher SiO_2/Al_2O_3 ratio and low Fe_2O_3/K_2O ratio imply that they are mineralogically more stable and less prone to reactivity during supercritical CO_2 exposure. Farquhar *et al.,* (2014). The obtained ratios for the studied samples are consequently mineralogically mature. Gill and Yemane, (1996), suggested that the ratio of $Al_2O_3/(CaO+MgO+Na_2O+K_2O)$ can be used in defining the stability of mobile oxides. The positive value attained varies from 0.14 - 5.20, inferring that there are stable mobile oxides in the studied samples. The bivariate plot of SiO_2 (revealing quartz content) versus (Al_2O_3 + Na_2O + K_2O) (revealing of feldspar content) (Galarraga, *et al.,* 2008) can be utilized in discriminating the palaeo-climatic condition during deposition. In this study, the samples all plotted in the humid climatic zone, (Fig. 13). This humid condition accelerated weathering processes and enhanced chemical maturity.

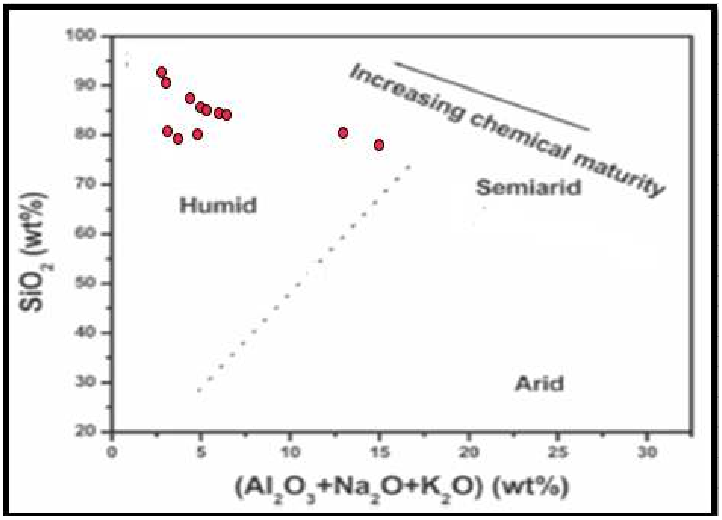


Fig. 13: Bivariate plot of SiO_2 versus (Al_2O_3 + Na_2O + K_2O) to discriminate palaeo-climatic condition during the deposition of the studied samples (Modified after Galarraga, *et al.,* 2008).

CONCLUSIONS

Sedimentological analysis revealed four main lithofacies comprising of sandstone, shaly sand, shale and sandy shale. Geochemical results show that the average value of silica is far higher than the average values of the rest oxides. Silica enrichment is a measure of sandstone maturity, and is a reflection of the duration and intensity of weathering and destruction of other minerals during transportation. Trace elemental ratios of U/Th, Ni/Co, Cu/Zn and binary plot of Ni/Co versus V/Crindicated an oxic environment of deposition. However, the binary plot of Ni/Co versus V/ (V+Ni) showed oxic to euxinic environments of deposition. Trace elemental and major oxides ratios reveals passive continental margin, quartz arenite, sublitharenite, litharenite and Fe-rich sandstone derive from pre-existing igneous rock and the sediments had mixed marine and terrigenous source input deposited mainly in humid climatic condition. It can be inferred that the studied successions of the well were not affected by major tectonic activity.

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