Geochemical characterization of FE-1 well, Onshore Western Niger Delta Basin, Nigeria

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ABSTRACT: Major oxides and trace elements analysis was carried out on ditch cutting samples of FE-1 well, Onshore, Niger Delta Basin, to define their oxygen condition, paleo-climatic conditions, provenance, tectonic setting, sandstone classification and maturity of the sediments. Sedimentological analysis revealed five main lithofacies comprising of sandstone, shaly sand, mudstone, sandy clay and sandy shale. Geochemical results indicates that the average value of silica (87.1 wt. %) is far higher than the average values of the rest oxides which shows the duration and intensity of weathering and destruction of other minerals during transportation. Bivariate plot of La/Sc versus Th/Co, Zr versus TiO_2, and trace elemental ratios of Th/Sc, Th/Co, Th/Cr, Cr/Th, La/Sc establishes that the source of the sediment are from felsic rock. Different chemical classification schemes characterized the sediments as quartzarenite, lithic arenites and Fe-rich sand. The plot of Log (K_2O/Na_2O) versus Log (SiO_2/Al_2O_3) and K_2O/Na_2O versus SiO_2 all plotted mainly in the passive margin zone. The low average value of uranium content, trace elemental ratios of U/Th, Ni/Co, Cu/Zn, V/Cr and binary plot of Ni/Co versus V/Cr indicated an oxic environment of deposition. However, the binary plot of Ni/Co versus V/ (V+Ni) indicates oxic to anoxic condition during deposition of the mixed marine and terrigenous source input sediment. Binary plot of SiO_2 versus ($Al_2O_3+Na_2O+K_2O$) designates deposition mainly in humid/semi-humid climatic condition. The samples studied have a much higher SiO_2/Al_2O_3 ratio with low Fe_2O_3/K_2O ratio, thus, they are mineralogically mature. The $Al_2O_3/(CaO+MgO+Na_2O+K_2O)$ ratio inferred that there are stable mobile oxides in the samples.

The Niger Delta is an essential sedimentary basin in Nigeria known to have major delta systems and utmost productive petroleum provinces worldwide. This makes Nigeria the greatest prolific oil producer in Sub-Saharan Africa, position as the third main producer of crude oil in Africa and the tenth leading in the world. According to Adenugba and Dipo, (2013), the Nigeria's economy is mainly reliant on its oil sector which make up about 95 % of Nigeria's foreign exchange earnings and about 80 % of its financial incomes. Due to the discovery of oil in commercial quantity in Oloibiri-1 well in 1956, rigorous exploration and exploitation of hydrocarbon in the basin has been ongoing since the early 1960s. Nwajide and Reijers, (1996). Based on the petroliferous nature of the Basin, there has been constant and steady geologic research for both academic and commercial drives for many years. Adebayo, (2011). Major oxides and trace element abundances in sedimentary rocks have added significantly to our understanding of paleo oxygen and paleo-climatic conditions, provenance, tectonic setting, sandstone classification and maturity of sediments. E.g. Obasi *et al.,* (2019); Nath *et al.,* (1997); Jones and Manning, (1994). The aim of this study is to infer the paleo-environment and paleo-climatic conditions, provenance, tectonic setting, sandstone classification and maturity of sediments during the deposition in the considered section of the Niger Delta basin. To attain the objective, a multidisciplinary method of relating sedimentological features, and inorganic geochemical data with their elemental ratio were engaged.

The geologic setting of the basin: The present-day Niger Delta Complex is situated on the continental margin of the Gulf of Guinea in the southern part of Nigeria. It lies between longitudes 4 °E and 8.8 °E and latitudes 3 °N and 6 °N. Reijers *et al*., (1997). The onshore portion of the basin is delineated by the geology of southern Nigeria and southwestern Cameroon. It is bounded in the north by outcrops of the Anambra Basin and the Abakaliki Anticlinorium, and delimited in the west by the Benin Flank, a northeast-southwest trending hinge line south of the West African basement massif. The Calabar Flank, a hinge line bordering the Oban massif, defines the northeastern boundary. The offshore boundary of the basin is defined by the Cameroon volcanic line to the

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east and the eastern boundary of the Dahomey Basin (the easternmost West African transform-fault passive margin) to the west. The evolution of the delta is controlled by pre and synsedimentary tectonics as described by Knox and Omatsola, (1987). It is a large arcuate delta covering an area of about 300,000 km^2

Kulke, (1995), with a sediment volume of 500,000 km^3, Hospers, (1965) and a sedimentary thickness of over 10 km in the basin Depo center. Kaplan *et al.,* (1994). Well FE-1 is located in the Greater Ughelli Depobelt of the Niger delta. (Fig. 1).
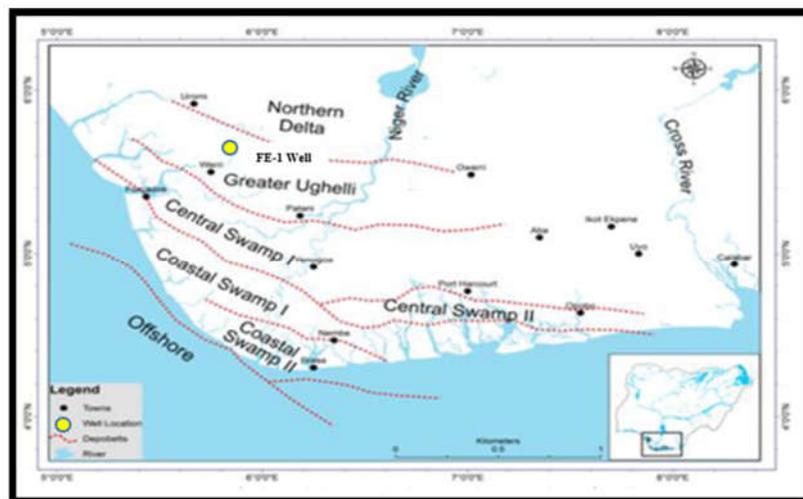

Fig. 1: A map of Niger delta Depobelts showing location of "FE-1" well.

Tectonic setting of the Niger Delta Basin: Given to Whiteman (1982), the Niger Delta Basin clastic segment was formed along aulacogen that formerly advanced in the course of breakdown of the South American and African plates during the Tithonian - Kimmeridgian (latest Jurassic) to Early Cretaceous. Cretaceous fracture zones conveyed as trenches and ridges in the deep Atlantic define the tectonic framework of the continental margin along the western coast of Africa. The fracture zone ridges divided the margin into individual Basins which form the boundary faults of the Cretaceous Benue Trough that cuts far into the West African Shield. The Benue Trough has experienced a succession of depositional phases, local folding, uplifts and downwarping from the time of its opening for the period of Early Cretaceous (Aptian) to Paleocene. Subsequently, the deltaic sedimentation come to be developed in the southern part of the Benue Trough that assembled in the establishment of the current Niger Delta Basin. Short and Stauble, (1967). Reijers *et al.,* (1997), considered the Niger Delta to be the youngest among the chain of sub-basins in the Benue Trough. On the other hand, Avbovbo and Ayoola, (1981), defined the Niger Delta Basin as that Cenozoic gross offlap clastic succession built out on top of the Anambra Basin. The Anambra Basin underlies the Niger Delta basin and the two are demarcated by an unconformity.

The stratigraphic build up have been measured by the interaction amongst the degrees of sediment supply and subsidence. Deep wells in the basin record three lithostratigraphic succession consisting of substantial and repetitions of marine shale (Akata Formation) and grade upward into interbedded sandstone and shale facies (Agbada Formation) which form the characteristic paralic facies portion of the Delta. The uppermost portion (Benin Formation) of the sequence is a considerable terrestrial sandstone segment. The lithologies of the Cenozoic Niger Delta Basin is generally categorized as continental, transitional and marine identified regularly on the basis of sand-shale ratios. The Clay members are erosional surfaces that are locally in the form of entrenchments, filled with clay deposits recognized only in the subsurface. - Afam Clay, Opuama, Buguma, Qua-Iboe members. Figure

MATERIAL AND METHOD
Six hundred and seventy-eight ditch cutting samples from depths of 2700 ft. - 10,185 ft. intervals were subjected to sedimentological analyses while selected twelve ditch cuttings samples were analyzed geochemically with fused bead X-Ray Fluorescence (XRF) spectrometry for the major oxides and fused bead laser ablation inductively couple plasma mass spectroscopy (LA-ICP-MS) for the trace elements at

Bureau Veritas Minerals laboratory, Vancouver, Canada.

Sedimentological analysis: The processed samples were studied and described by both visual inspection and the use of a reflected light binocular microscope. Physical characteristics such as the lithology, color, texture (grain size, shape and sorting), fossils and accessory constituents (mica flakes, carbonaceous detritus, ferruginous material and calcite) were determined. Dilute Hydrochloric acid was used to test for the presence of carbonate in sample.

XRF and LA-ICPMS analyses: Loss on ignition (LOI) results were determined from the total weight of sample by ignition at 1000 °Ċ for 1 hour using a robotic TGA system. Pulverized ditch cutting samples were casted using 12.22 flux with 4% Lithium nitrate which were added to sample to form glass bead. Major oxides were determined by X-Ray Fluorescence Spectrometry on oven dry of (105^0C). The same set of samples was further analyzed for trace elements using LA-ICP-MS instrumental analyzes. The laser was used to vaporize the surface of the fused sample, while the vapor and any particles were then transported by the carrier gas flow to the plasma of the ICP-MS unit. The rays through the quadrupole were detected and the data passes through quality assurance and check. LA-ICP-MS capitalizes a high productivity robotic fusion technology which provide a fully extracted quantitative analysis for all elements. Detection limits are comparable to industry leading mixed acid trace element ICP-MS packages. Ten major elements, (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MgO, MnO, CaO, Na_2O, K_2O and P_2O_5) reported as oxide percent by weight and 33 trace elements (Ag, As, Ba, Be, Bi, Cd, Ce, Co, Cr, Cs, Cu, Ga, Hf, In, La, Mo, Nb, Ni, Pb, Sb, Sc, Sn, Sr, Ta, Te, Th, Tl, U, V, W, Y, Zn and Zr) reported in ppm. The post-Archean Australian shale (PAAS) and Upper Continental Crust (UCC) values were used for evaluation.

RESULTS AND DISCUSSION
Sedimentological Result: Lithologically, the sequence is categorized by the alternation of sandstone, mudstone, shaly sand, sandy shale and sandy clay facies. The shales are light grey, grey, light brown and brown, fissile and moderately hard. The sands are milky white, light grey, grey, light brown and brown, fine, medium and occasionally coarse - pebble grained, subangular, subrounded and rounded, mostly subangular. Poorly, moderately to well sorted. Index minerals and accessories are dominated by mica flakes and carbonaceous detritus with rare ferruginous material. Some of the sediments within this interval are calcareous while some are not calcareous. Table 1.
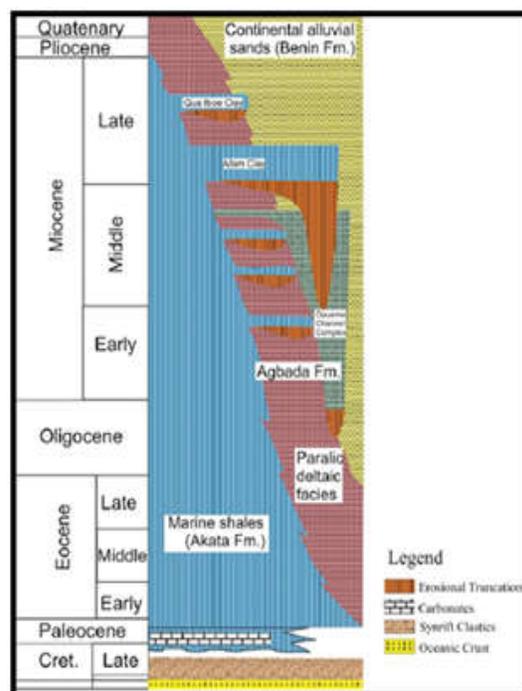
Fig. 2: Schematic representation of the diachronous nature of major lithofacies units, and the stratigraphic relationships of clay-filled channels on the delta flanks. Modified after Doust and Omatsola, (1990) and Lawrence *et al.,* (2002).

Geochemical Results (Major Oxide): Table 2 shows the geochemical composition of analyzed samples from the studied FE-1 well with the average data of Upper Continental Crust (UCC) after McLennan, (2001) and Post-Archean Australian average Shale after Taylor and McLennan, (1985) included. The results of the major oxides shows an enriched SiO_2 (81.10 - 90.40) wt. % with an average of 87.10 wt. %. 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. Lindsey, (1999). The value of Al_2O_3 content ranges from 2.37 wt. % to 6.82 wt. %. As indicated by Cingolani *et al.,* (2003), alteration of rocks during weathering results in depletion of alkalis and alkaline earth elements and preferential enrichment of Al_2O_3. The value of Fe_2O_3 content ranges from 2.23 wt. % to 7.78 wt. % and TiO_2 from 0.17 - 1.36 wt. %. Other oxides such as MgO (0.11 - 0.65 wt. %), CaO (0.10 - 0.82 wt. %), Na_2O (0.08 - 0.99 wt. %) and K_2O (0.35 - 1.72 wt. %) are strongly depleted while MnO and P_2O_5 have low concentrations that are less than 1. The low values might probably be due to chemical destruction under oxidizing condition during weathering. From the foregoing, the average value of silica (87.1 wt. %) in FE-1 well is far higher

than the average values of the rest oxides likely due to weathering and diagenetic processes, as sedimentary rocks are enhanced in silica and depleted in iron, magnesium, calcium, sodium, and potassium related to the parent rocks. Also, the average data of the major oxides shows that SiO_2 is higher when compared with PASS and UCC values while the rest oxides are lower than the PASS and UCC values.

Trace Elements Result: As specified by Taylor and McLennan, (1985), the behavior of trace elements during sedimentary processes is complex due to factors including weathering, physical sorting, adsorption, provenance, diagenesis and metamorphism. From the result in table 3, the average values of Ba (Barium) and Pb (Lead) concentration are enriched when compared with those of PAAS and UCC. The general enrichment in Barium may be due to their deposition in a shallow marine condition. Nagarajan *et al.,* (2007). Among the high field strength elements, Zr (Zirconium), Hf (Hafnium) and Nb (Niobium) concentrations are enriched when compared with PAAS and UCC owing to their link with heavy minerals and are also known to be enhanced in felsic rock than that of mafic rocks. The average values of the transition trace elements (TTE) (Sc, V, Cu, Co and Zn) are depleted when compared with PASS and UCC. The general depletion of Scandium is suggesting a relatively felsic source. Cullers and Berendsen, (1998). Transition elements Cr and Ni are depleted in respect to PAAS but slightly enriched comparable to UCC.

The depletion of these elements shows a negligible role of the basic rocks as sources of the rocks. Th (Thorium) concentration is also depleted when compared with PASS and UCC. Sr (Strontium) is depleted when related with PAAS and UCC. According to Wronkiewicz and Condie, (1987), weathering studies show that Sr is rapidly lost during chemical weathering and the amount of this elemental lost is proportional to the degree of weathering.

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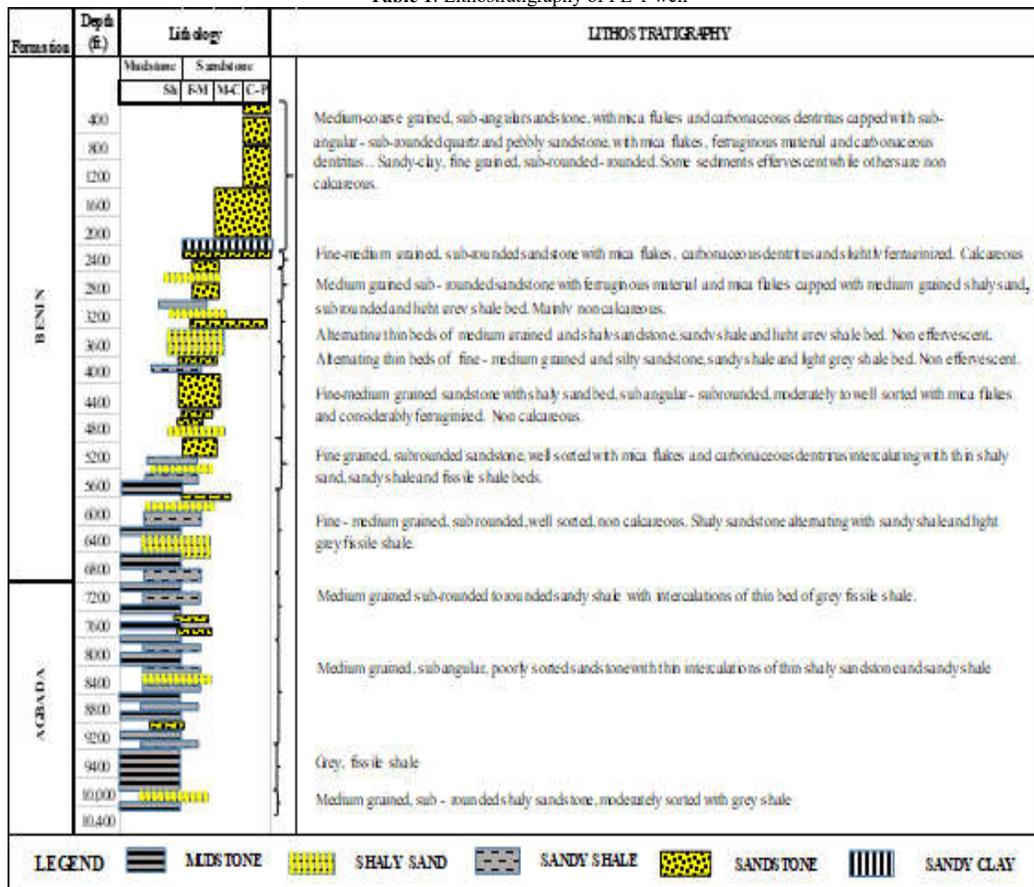
Table 2: Major oxides geochemical composition of FE-1 Well. UCC - Upper Continental Crust (after Mclenna, 2001) and PAAS - Post Archean Australian Average Shale (after Taylor and Mclenna, 1985).

Major oxides (wt. %)	FE1	FE2	FE3	FE4	FE5	FE6	FE7	FE8	FE9	FE10	FE11	FE12	Average	PASS	UCC
SiO_2	90.20	90.40	91.40	91.10	91.20	90.70	82.80	81.10	83.20	84.60	81.80	86.30	87.10	62.80	66.00
TiO_2	0.18	0.17	0.19	0.17	0.18	0.18	0.99	0.97	0.83	1.00	1.36	1.09	0.61	0.99	0.68
Al_2O_3	2.48	2.37	2.59	2.56	2.58	2.59	4.81	6.82	5.81	3.40	3.32	2.52	3.49	18.90	15.20
Fe_2O_3	2.26	2.23	3.03	3.01	3.01	3.01	5.22	6.72	4.99	5.53	7.78	4.98	4.31	7.22	5.03
MnO	0.03	0.02	0.03	0.03	0.03	0.02	0.05	0.05	0.05	0.05	0.04	0.04	0.00	0.11	0.08
MgO	0.12	0.11	0.14	0.14	0.11	0.12	0.65	0.52	0.54	0.56	1.26	0.65	0.41	2.20	2.20
CaO	0.18	0.18	0.10	0.11	0.11	0.11	0.55	0.76	0.81	0.82	1.27	0.56	0.46	1.30	4.20
Na_2O	0.08	0.09	0.80	0.70	0.80	0.80	0.75	0.71	0.92	0.77	0.99	0.72	0.68	1.20	3.90
K_2O	0.35	0.36	0.36	0.36	0.35	0.35	1.59	1.61	1.59	1.63	1.72	1.46	0.98	3.70	3.40
P_2O_5	0.02	0.02	0.03	0.03	0.03	0.03	0.10	0.23	0.21	0.13	0.26	0.11	0.09	0.16	0.15

Table 3: Trace Elements Composition of FE-1 Well.

Trace Element (ppm)	FE1	FE2	FE3	FE4	FE5	FE6	FE7	FE8	FE9	FE10	FE11	FE12	Average	PAAS	UCC
Ag (Silver)	-0.1	-0.1	-0.1	0.2	0.1	0.1	1	-0.1	1	1	1	-0.1	0.3		
As (Arsenic)	1.1	1.2	1.3	1.3	1.2	1.4	11.6	3.8	5.2	6.7	5.7	3.9	3.7		1.5
Ba (Barium)	655	680	700	740	750	670	883	1670	966	820	1439	1250	935.3	650	550
Be (Beryllium)	0.5	0.6	0.7	0.8	0.8	0.7	2.8	2.2	3.2	3.6	2.6	2.5	1.8		
Bi (Bismuth)	0.03	0.04	0.02	0.04	0.05	0.03	0.24	0.14	0.18	0.16	0.17	0.23	0.1		
Cd (Cadmium)	-0.1	-0.1	0.1	0.1	0.1	-0.1	1.1	-0.1	0.1	0.1	0.2	-0.1	0.1		
Ce (Cerium)	111	126	122	90	80	81	142	100	110	129	105	141	111.4	79.6	64
Co (Cobalt)	3.6	3.6	3.5	3.5	3.5	3.6	13.5	13.5	13.2	13.4	11.1	12.9	8.2	23	10
Cr (Chromium)	20	22	24	21	21	23	104	63	78	92	60	69	49.8	110	35
Cs (Caesium)	0.49	0.51	0.46	0.44	0.45	0.44	4.92	2.7	2.6	3.8	3.1	3.1	1.9		3.7
Cu (Copper)	10	9	11	12	7	8	22	20	21	22	20	18	15	50	25
Ga (Gallium)	4.1	4.1	4.2	4.3	4.3	4.1	28.3	18.7	19.2	18.3	26.1	27.4	13.6	17.50	
Hf (Hafnium)	5.91	9.15	6.12	7.14	6.22	11.1	8.71	10.1	9.11	8.68	12.1	12.6	8.9	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	-0.1		
La (Lanthanum)	10.2	9.8	9.5	11.4	10.9	12.1	70.0	49.9	55.2	58.7	63.2	69.1	35.8	38.2	30
Mo (Molybdenum)	4.1	3.2	3.8	5.1	5.3	3.7	3	4.5	4.1	5.6	7.1	7.3	4.7		
Nb (Niobium)	5.22	5.84	6.11	6.34	6.73	5.12	41	33.9	39.3	38.1	50.2	60.1	24.8	1.9	25
Ni (Nickel)	16	15	14	17	16	17	34	24	21	28	23	21	20.5	55	20
Pb (Lead)	22	28	31	36	29	41	32	38	33	30	37	29	32.2	20	
Sb (Antimony)	0.1	0.1	0.1	0.2	0.2	0.2	0.6	0.1	0.2	0.4	0.3	0.6	0.3		0.2
Sc (Scandium)	2	2	2	2	2	2	14	9	11	10	13	14	6.9	16	11
Sn (Tin)	1.1	1.2	1.1	1	1	1.1	4.4	3.4	3.6	4.2	3.8	3.6	2.5		
Sr (Strontium)	38.2	39.2	40.1	40.8	41.3	37.1	142	177	182	199	119	290	112.1	200	350
Ta (Tantalum)	0.46	0.48	0.51	0.53	0.44	0.45	2.73	2.2	3.8	4	2.6	2.8	1.8		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	-0.2	-0.2		
Th (Thorium)	3.67	3.74	3.39	3.63	3.22	3.58	18.50	13.70	14.20	16.10	14.30	15.20	9.40	14.6	10.7
Ti (Titanium)	1080	1110	1118	1120	1030	1090	8100	6590	5987	7342	8000	87200	3547.3		
Tl (Thallium)	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.6	0.4	0.6	0.6	0.4	0.4	0.2		
U (Uranium)	0.85	0.91	0.99	0.92	0.89	1	3.90	3.20	3.32	3.76	3.45	3.80	2.20	3.1	2.8
V (Vanadium)	18.3	19.2	20.1	22.4	21.6	17.8	127	81.2	77.3	78.9	100.2	110.2	57.9	150	60
W (Tungsten)	1	1	1	1	1	1	2.5	3.5	3	2.8	2.6	2.5	1.9		
Y (Yttrium)	5.19	6.2	6.3	6.1	6.4	5.11	33.9	27.9	29.2	28.4	30.8	31.3	18.1	27	22
Zn (Zinc)	18	21	20	24	16	19	120	135	86	98	128	130	67.9	85	71
Zr (Zirconium)	250	284	310	370	440	430	320	404	380	390	520	401	374.9	210	190

Table 4: Some trace element ratios and weathering indices of the studied FE-1 well samples. Source: Table 2 and 3.

Ratios	FE1	FE2	FE3	FE4	FE5	FE6	FE7	FE8	FE9	FE10	FE11	FE12	Average	PASS	UCC
Log (SiO$_2$/Al$_2$O$_3$)	1.56	1.58	1.55	1.55	1.55	1.54	1.24	1.08	1.16	1.40	1.40	1.53	1.43	0.52	0.64
Log (K$_2$O/Na$_2$O)	0.64	0.60	-0.35	-0.29	-0.36	-0.36	0.33	0.36	0.24	0.33	0.24	0.31	0.14	0.49	-0.06
Log (Fe$_2$O$_3$/K$_2$O)	0.81	0.79	0.93	0.93	0.93	0.93	0.52	0.62	0.50	0.54	0.66	0.53	0.72	0.29	0.17
Log (Na$_2$O/K$_2$O)	-0.64	-0.60	0.35	0.29	0.36	0.36	-0.33	-0.36	-0.24	-0.33	-0.24	-0.31	-0.14	-0.49	0.06
Al$_2$O$_3$+Na$_2$O+K$_2$O	2.91	2.82	3.75	3.62	3.73	3.74	7.15	9.14	8.32	5.80	6.03	4.70	5.14	23.80	22.50
K$_2$O/Na$_2$O	4.38	4.00	0.80	0.51	0.44	0.44	2.12	2.27	1.73	2.12	1.74	2.03	1.88	3.08	0.87
Th/Cr	0.18	0.17	0.14	0.17	0.15	0.16	0.18	0.22	0.18	0.18	0.24	0.22	0.18	0.13	0.31
La/Sc	5.10	4.90	4.75	5.70	5.45	6.05	5.00	5.54	5.02	5.87	4.86	4.94	5.23	2.39	2.73
Th/Sc	1.84	1.87	1.70	1.82	1.61	1.79	1.32	1.52	1.29	1.61	1.10	1.09	1.55	0.91	0.97
Th/Co	1.02	1.04	0.97	1.04	0.92	0.99	1.37	1.01	1.08	1.20	1.29	1.18	1.09	0.63	1.07
Cr/Th	5.45	5.88	7.08	5.79	6.52	6.42	5.62	4.60	5.50	5.71	4.20	4.54	5.61	7.53	3.27
U/Th	0.23	0.24	0.29	0.25	0.28	0.28	0.21	0.23	0.23	0.23	0.24	0.25	0.25	0.21	0.26
Ni/Co	4.40	4.17	4.00	4.85	4.57	4.72	2.52	1.78	1.60	2.09	2.07	1.63	3.20	2.39	2.00
Cu/Zn	0.56	0.43	0.55	0.50	0.44	0.42	0.18	0.15	0.24	0.22	0.16	0.14	0.33	0.56	0.35
V/Cr	0.92	0.87	0.84	1.07	1.03	0.77	1.22	1.23	0.99	0.86	1.67	1.59	1.09	1.36	1.71
V/ (V+Ni)	0.53	0.56	0.58	0.06	0.50	0.51	0.79	0.77	0.07	0.74	0.81	0.84	0.56	0.73	0.75
Al$_2$O$_3$/SiO$_2$	0.03	0.03	0.03	0.03	0.03	0.03	0.06	0.08	0.07	0.04	0.04	0.03	0.04	0.30	0.23
Fe$_2$O$_3$+MgO	2.38	2.34	3.17	3.15	3.12	3.13	5.87	7.24	5.53	6.09	9.04	5.63	4.72	9.42	7.23
SiO$_2$/Al$_2$O$_3$	36.37	38.14	35.29	35.59	35.35	35.02	17.21	11.89	14.32	24.88	24.64	34.24	28.58	3.32	4.34
Fe$_2$O$_3$/K$_2$O	6.46	6.19	8.42	8.36	8.60	8.60	3.28	4.17	3.14	3.39	4.52	3.41	5.71	1.95	1.48
Na$_2$O + K$_2$O	0.43	0.45	1.16	1.06	1.15	1.15	2.34	2.32	2.51	2.40	2.71	2.18	1.66	4.90	7.30
Al$_2$O$_3$/(CaO+MgO+Na$_2$O+K$_2$O)	3.39	3.20	1.85	1.95	1.88	1.87	1.36	1.89	1.51	0.89	0.63	0.74	1.76	2.25	1.11
(Fe$_2$O$_3$ + MgO)/(K$_2$O + Na$_2$O)	5.53	5.20	2.73	2.97	2.71	2.72	2.51	3.12	2.20	2.54	3.34	2.58	2.84	1.92	0.99

Provenance: The geochemical characteristics of a rock could be used to determine the provenance of a rock. Both major oxides and trace elements composition of rock have been extensively used to describe the provenance nature. Chen *et al.,* (2016); Mitra, (2018). Cr, Ni are utmost significant source rock indicator owing to their low movement during sedimentary processes.

McLennan *et al.,* (1990). Armstrong-Altrin *et al.,* (2004), submitted that when Cr >150 ppm and Ni >100 ppm in concentration, it infers mafic or ultramafic provenance.
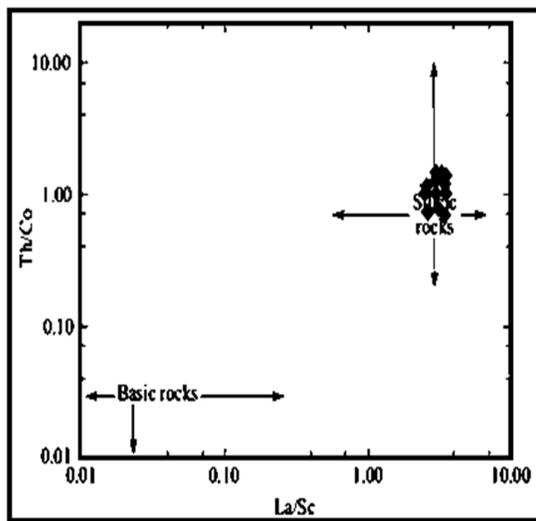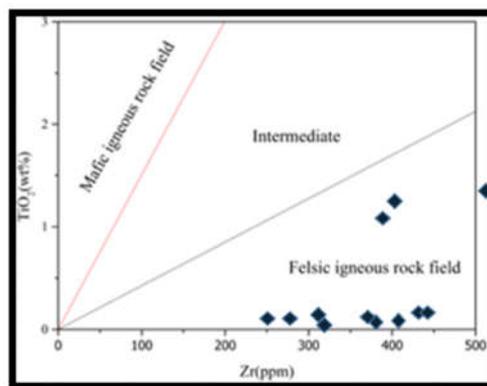
Fig. 4. Plots of Zr versus TiO$_2$. Modified after Hayashi *et al.,* (1997).

However, the average value of Cr **(**49.80 ppm**)** and Ni **(**20.50 ppm**)** in table 3 have low concentrations which confirm a felsic source area and not mafic or ultramafic rocks as the source areas. Bivariate plot of La/Sc versus Th/Co, Cullers, (2002), (Fig. 3) and Zr versus TiO$_2$, Hayashi *et al.,* (1997), (Fig. 4), establishes that the source of FE-1 well sediment are from a felsic rock. Table 5 denotes a series of trace element ratios (Th/Sc, Th/Co, Th/Cr, Cr/Th, La/Sc) of the FE-1 well sediment in association with trace elemental ratios of the clastics derivative from felsic and mafic rocks which indicates a discrete separation in their values. Cullers, (2000). Evaluation of these elemental ratios with the FE-1 well sediments' elemental ratio evidently reveals that the FE-1 well sediment are derived from felsic rock.

Fig. 3. Plots of La/Sc versus Th/Co. Modified after Cullers, (2002).

Table 5: Range of elemental ratios of FE-1 well sediment compared to the ratios derived from felsic and mafic rocks (Cullers, 2000), Upper Continental Crust (UCC) and Post-Archean Australian Average Shale (PAAS) Taylor and McLennan, (1985).

Elemental Ratio	Ranges of value in FE-1 well	Range of Sediments		Upper Continental	Post-Archean Australian
	(n=12)	Felsic rock	Mafic rock	Crust (UCC)	average Shale (PAAS)
Th/Sc	1.09 -1.87	0.84 - 20.5	0.05 - 0.22	0.79	0.9
Th/Co	0.92 - 1.37	0.67 - 19.4	0.04 - 1.4	0.63	0.63
Th/Cr	0.14 - 0.23	0.13 - 2.7	0.018 - 0.046	0.13	0.13
Cr/Th	4.20 - 7.08	4.0 - 15	25 - 100	7.76	7.53
La/Sc	4.75 - 6.05	2.5 - 16.3	0.43 - 0.86	2.21	2.4
n = number of samples					

Chemical classification: The concentrations of these major oxide groups (silica and alumina, alkali oxides, and iron oxide plus magnesia) have been used to classify sandstones. E.g Herron, (1988) and Lindsey, (1999). The plot of log (SiO_2/Al_2O_3) versus log (Fe_2O_3/K_2O) diagram by Herron, (1988) classifies the FE-1 well samples mainly as quartzarenites with some Fe-rich sands. Figure 5.

From the interpretation of the reference set proposed by Lindsey, (1999), the succeeding rules for the chemical classification of sandstones are:

1. log $(SiO_2/Al_2O_3) \geq 1.5$, then the sandstone is classified as Quartzarenite

2. Greywacke, log $(SiO_2/Al_2O_3) < 1$ and log $(K_2O/Na_2O) < 0$

3. log $(SiO_2/Al_2O_3) < 1.5$, log $(K_2O/Na_2O) \geq 0$ and log $((Fe_2O_3+MgO)/(K_2O+Na_2O)) < 0$, Arkose (including subarkose)

4. log $(SiO_2/Al_2O_3) < 1.5$ and either log $(K_2O/Na_2O) < 0$ or log $((Fe_2O_3+MgO)/(K_2O+Na_2O)) \geq 0$. Lithic arenite (Sub greywacke).

Established on the above sets, the average value of log (SiO_2/Al_2O_3) for the FF-1 sediment is 1.43 which is <1.5. Consequently, set 1 is ruled out. Condition 2 is also ruled out because the average value of log (K_2O/Na_2O) for the FE-1 sediment is 0.14, which is > 0. In the reference set 3, the average values obtained for log (SiO_2/Al_2O_3) is 1.43 and log (K_2O/Na_2O) is 0.14 whereas the average value of log $((Fe_2O_3 + MgO)/(K_2O + Na_2O))$ is 2.84. These values obtained for FE-1 sediments cannot be characterized as Arkose. The mean values achieved correspond with log $(SiO_2/Al_2O_3) < 1.5$ and log $((Fe_2O_3+MgO)/(K_2O+Na_2O)) > 0$, this falls in the fourth set. Therefore, it submit lithic arenites for the sediments under study. The general quartz content in lithic arenites is from 30-80% while the lithic fragments is from 5-50%. The nature of the lithic fragments determines the compositional maturity and the textures varies from sub-mature to mature. Quartzarenite are found to contain more than 95 % silica and less than 15 (%) matrix material and are formed along continental margin, where there is no active tectonic activity thereby favouring large weathering, long abrasion, sorting and multiple sequences of weathering and transportation.
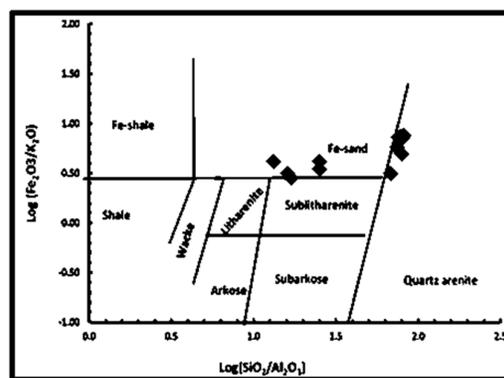
Fig 5. Chemical classification of the FE-1 sediment based on log (SiO_2/Al_2O_3) versus log (Fe_2O_3/K_2O) diagram of Herron, (1988).

Tectonic Setting: The chemical compositions of clastic rocks are significantly controlled by plate tectonic settings of their provenances, consequently clastic rocks from different tectonic settings possess terrain-specific geochemical signatures. Roser and Korsch, (1986). As proposed by Maynard *et al*., (1982), the Log (K_2O/Na_2O) ratio versus Log (SiO_2/Al_2O_3) ratio is used to determine the tectonic setting of clastic terrigenous sedimentary rocks. The recognized tectonic settings on the discrimination diagram of Maynard *et al*., (1982) are: A1 - arc setting and andesitic detritus; A2 - evolved arc setting, felsic pluton detritus; ACM - Active continental margin; PM - passive margin. When utilized for the samples of FE-1 well, they plotted mainly in the passive margin zone which infer that the tectonic setting for FE-1 well facies is in the passive continental margin. Fig. 6. In addition, the plot of Roser and Korsch, (1986), was also utilized to determine the tectonic setting of FE-1 well sediments. The recognized tectonic settings on the K_2O/Na_2O versus SiO_2 discrimination diagram of Roser and Korsch, (1986) are: the passive margin (PM), active continental margin (ACM) and oceanic island arc (OIA). When utilized for the samples under study, they plotted mainly in the passive margin zone

which also infer that the tectonic setting for FE-1 well facies is passive margin. Fig. 7.
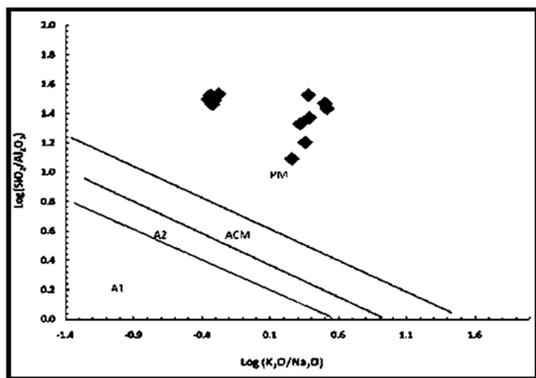
Fig 6: Log (K₂O/Na₂O) versus Log (SiO₂/Al₂O₃) tectonic discrimination diagram of FE-1 well. After Maynard *et al.,* (1982). Al - arc setting, basaltic and andesitic detritus, A2 - evolved arc setting, felsic pluton detritus, ACM - Active continental margin, PM - Passive Continental Margin.

Paleo oxygen Condition: The trace elements data (Table 3) and numerous geochemical ratios generally used to disclose the paleo-redox conditions during sedimentation of siliciclastic rocks are shown in table 4.

Authors such as Jones and Manning (1994) and Nath *et al.,* (1997), have shown that trace element ratios such as Ni/Co, V/Cr, V/ (V+Ni) and U/Th can be used to appraise paleo oxygen conditions of ancient sediment. Trace elements like U, Th, Cu, Zn, Ni, Co, V and Cr present an important role in understanding the paleo redox condition of sediment. Sediment deposited in oxidizing environment generally has a low content of U, while those deposited in oxygen minimum zone (OMZ) reveal higher content of U. Armstrong- Altrin *et al*., (2015a). Consequently, the average low U content (average 2.25 ppm) of the FE-1 well sediments submit an oxygenated condition during deposition.
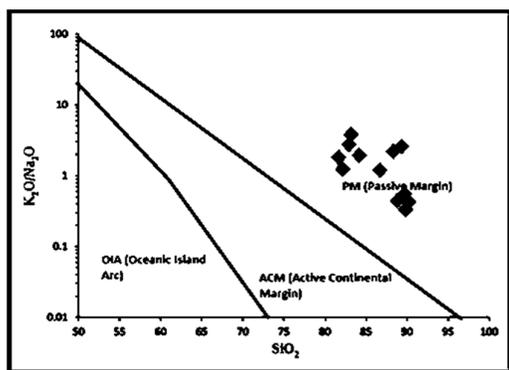
Fig 7: Plot of K₂O/Na₂O versus SiO₂ tectonic discrimination for FE-1 well sediment. Modified after Roser and Korsch, (1986).

Given to Nath *et al.*, (1997), the ratio of uranium to thorium could be used as a redox indicator. Where the U/Th ratios is below 0.75, it infers oxic conditions of deposition, while values from 0.75 - 1.25 indicates dyoxic, values greater than 1.25 infers suboxic to anoxic conditions. Applying this to the studied sediments, the calculated U/Th ratios of FE-1 well shows low values from 0.2 - 0.3 with an average value of 0.2 which infer that the sediments under study were deposited in oxic environments of deposition. Cobalt (Co) is a valuable indicator for depositional conditions and is usually enriched in comparison with Ni in oxic conditions.

Jones and Manning, (1994). Co concentrations in all the analyzed samples are relatively low and range from 3.50 to 13.50 ppm. (Table 3). According to Jones and Manning, (1994), when the ratio of Ni/Co is below 5, it indicates oxic environments, whereas ratios from 5 - 7, it suggest dyoxic, ratios greater than 7 infers suboxic to anoxic environments. The ratio of Ni/Co in FE-1 well ranges from 1.6 - 4.9 with an average value of 3.2 which indicate oxic environments of deposition. Chromium (Cr) is understood to be related only with the detrital faction and is not directly influenced by redox conditions. Author such as Nagarajan *et al.,* (2007) have used V/Cr ratio as an indicator of paleo oxygen condition of sediment deposition. Agreeing to Jones and Manning, (1994), when the value of V/Cr ratio is below 2, it denote oxic conditions while value above 2 denote anoxic conditions.

The V/Cr ratios in FE-1 sediments range from 0.8 to 1.7, with an average value of 1.1 which indicates that the sediments were deposited in an oxic depositional condition. Additionally, the Cu/Zn ratio is also used as a redox constraint. High Cu/Zn ratios infer reducing depositional conditions whereas low Cu/Zn ratios propose oxidizing conditions. Deng and Qian, (1993). Cu/Zn ratio in this study varies from 0.1 to 0.6 with an average of 0.3 which indicates that the samples of FE-1 well were deposited under oxidizing environments.

As specified by Suttner and Dutta, (1986), the binary plot of Ni/Co versus V/Cr can indicate redox condition. When applied to FE-1 well sediment, it indicates oxic condition during deposition. Fig. 8. However, the binary plot of Ni/Co versus V/ (V+Ni) by Rimmer, (2004), indicates oxic to anoxic condition during deposition of FE-1 well sediment. Fig. 9. The cross plot of vanadium versus nickel of FE-1 samples from the studied area shows that the sediments had mixed marine and terrigenous source input and were deposited under oxic to dyoxic condition. Kafousia, *et al.,* (2010). Fig. 10.
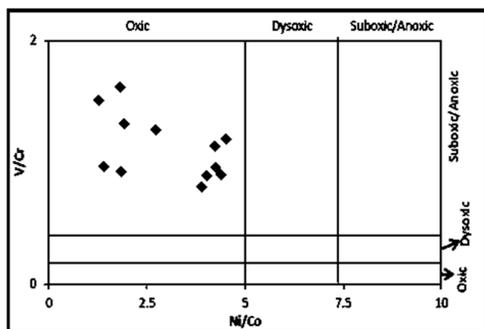
Fig.8: Binary plot of Ni/Co versus V/Cr indicates oxic condition during deposition of FE-1 well sediment. Modified after Suttner and Dutta (1986).
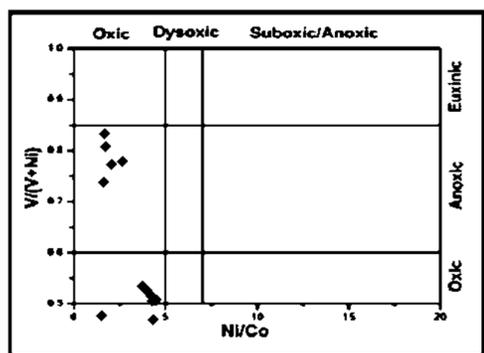

Fig. 9: Binary plot of Ni/Co versus V/ (V+Ni) indicates oxic to anoxic condition during deposition of FE-1 well sediment. Modified after Rimmer, (2004).
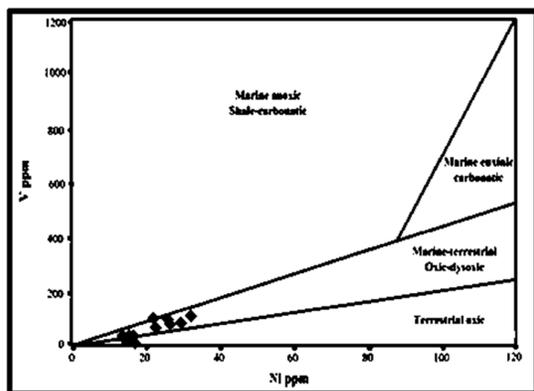

Fig. 10: The Cross plot of vanadium versus nickel of FE-1 samples from studied area shows that the sediments had mixed marine and terrigenous source input and were deposited under oxic to dyoxic condition. Modified after Kafousia, *et al.,* (2010).

Maturity and Palaeoclimate during Sedimentation: The plot of SiO_2 versus $Al_2O_3+K_2O+Na_2O$ in Fig.11 illustrates that majority of the sediments are formed under humid/semi-humid climatic zone. This wet condition quickens weathering process and increase the speed of chemical maturity. As posited by Potter,

(1978), SiO_2/Al_2O_3 index is used to show the extent of sandstones maturity in relation to mineralogical maturity. Maturity is revealed best in quartz, rock fragments, feldspars and grain size.
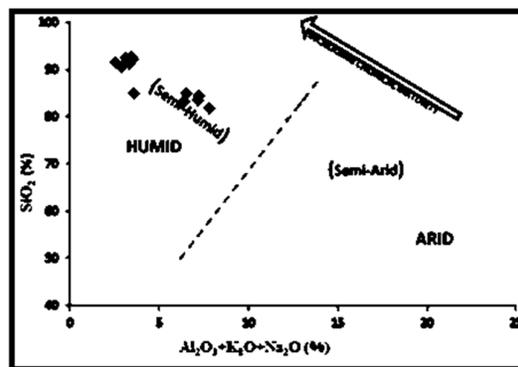

Fig. 11: Binary plot of SiO_2 versus ($Al_2O_3 + Na_2O + K_2O$) indicates deposition mainly in humid climate. Modified after Suttner and Dutta (1986).

Increasing sediment maturity can be determine by the quartz contents in the sediments, because quartz survives differently to feldspars, mafic minerals and lithics. Roser *et al.,* (1996). The average SiO_2/Al_2O_3 ratios in an intact igneous rocks range from ~ 3.0 (basic rocks) to ~ 5.0 (acidic rocks). When the values of SiO_2/Al_2O_3 ratio is > 5.0 in samples, it suggests progressive maturity. Roser *et al.,* (1996). High ratios designate mineralogically mature (quartzose, rounded) samples, while low ratios characterizes chemically immature samples. Potter, (1978). The SiO_2/Al_2O_3 ratio for the FE-1 well samples have ranges of 11.89 - 38.14 with an average of 28.58. The values is > 5.0 which indicates that the samples are mineralogically mature. The high values obtained from the ratio of SiO_2/Al_2O_3 shows that all the samples have low degree of clayness. The higher the SiO_2 content, the lower the degree of clayness. $Na_2O + K_2O$ (alkali content) shows the degree of the feldspar content and also pertinent for index of chemical maturity. The $Na_2O + K_2O$ content varies between 0.43 and 2.71, with an average of 1.66. This indicates the occurrence of feldspars and low chemical maturity. The Fe_2O_3/K_2O ratio varies from 3.14 to 8.60 with an average of 5.71. The samples studied have a much higher SiO_2/Al_2O_3 ratio and low Fe_2O_3/K_2O ratio, thus, they are mineralogically more stable and less prone to reactivity during supercritical CO_2 exposure. Farquhar *et al.,* (2014). From the ratios values, the sediment under examination are therefore mineralogically mature.

The $Al_2O_3/(CaO+MgO+Na_2O+K_2O)$ ratio can be used in determining the stability of mobile oxides as proposed by Gill and Yemane, (1996). The positive

values obtained are in the range of 0.63 - 3.39, which deduce that there are stable mobile oxides in the FE-1 well samples.

Conclusion: Sedimentological analysis revealed five main lithofacies. Major oxides and trace elemental ratios clearly reveals the mixed marine and terrigenous source input sediment are derived from felsic rock in passive margin zone deposited mainly in humid/semi-humid climatic condition. Also, the trace elemental ratios of U/Th, Ni/Co, Cu/Zn, V/Cr and binary plot of Ni/Co versus V/Cr indicated an oxic environment of deposition. However, the binary plot of Ni/Co versus V/ (V+Ni) indicates oxic to anoxic condition during deposition. The samples studied are mineralogically mature with stable mobile oxides.

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