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Inorganic Geochemical Evaluation and Aspects of Rock Eval Pyrolysis of Eocene to Recent Sediments of Soso and Kay-1 Wells, Western Niger Delta, Nigeria

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Abstract
The Niger Delta Basin situated in the Gulf or Guinea, has been penetrated by Soso and Kay 1 well in the western axis. A combined element and organic geochemistry was done to define source rock potential, organic Matter Type, conditions at deposition and their relationship with sediment provenance, Paleoenvironment and tectonic settings.Core samples were collected from 'Soso and Kay 1 Wells' in western Niger Delta (Nigeria) and were subjected to lithological description so as to establish their lithologic characteristics and profile. The core samples, comprising shales, silty-sands, silty-shales, sandy-shale, coal samples and silt sample, were analysed for major, trace and rare earth element using ICP-MS and selected shale samples were also subjected to Rock Eval Pyrolysis and TOC. The results for the major oxides composition revealed that the SiO_2 ranges from 57.4-89.04 wt. %, with an average of 72.5wt. %. The average concentration of TiO_2, Al_2O_3, Fe_2O_3 and MgO are 0.94 wt. %, 10.55wt.%, 5.38wt.% and 0.51wt.% respectively. The Discriminant Function Diagram showed that the sediments were deposited in an Active Continental Margin (ACM). The plots of Log (K_2O/Na_2O) against SiO_2 further confirmed deposition in ACM setting. Further Discriminant Function plots showed a mixed provenance of Intermediate Igneous Provenance and Mafic Field, while the lignite bearing sediments plots within the Quartzo-sedimentary province. The A-K-F ternary diagram indicates deposition in a transitional environment. The Chemical Index of Alteration (CIA) values ranges from 25.51 – 91.9 % while the Chemical Index of Weathering (CIW) ranges from 38.36 – 98.4 %. The Plagioclase Index of Alteration (PIA) ranges from 1.38 - 98.2% while the Ruxton Ratio (RR) ranges from 2.9 – 39 %. These values indicate that the samples had suffered low to moderate chemical alterations. The Chondrite normalised REE pattern showed a high LREE, a flat HREE and a negative Eu anomaly averages 0.89. This confirmed an ACM setting as it is diagnostic of a mixed provenance. Trace element proxies; V/Ni (2.17 and 2.68), V/Cr (0.57 and 1.01), Ni/Co (2.1 and 2.66) and V/(V+Ni) (0.68 and 0.72) for Soso and Kay 1 wells respectively indicates an oxic to dysoxic conditions at deposition.The results revealed that the sediments were derived from a mixed provenance and were deposited within the ACM in a transitional environment amidst oxic to dysoxic depositional conditions yielding a Type II/III and Type III organic matter.
Keywords: Provenance, Tectonic Settings, Discriminant Function diagram.

1. Introduction

The Niger Delta Basin, situated in the Gulf of Guinea, has been extensively studied for its petroleum potentials with respect to reservoir and source rock assessment.

The Cenozoic Delta extends throughout the Niger Delta Province as defined by Klett et al (1997). From the Eocene to the present, the delta has prograded south-westward, forming depobelts that represent the most active portion of the delta at each stage of its development (Doust and Omatsola, 1990). These depobelts form one of the largest regressive deltas in the world with an area of some 300,000 km^2 (Kulke, 1995), a sediment volume of 500,000 km^3 (Hospers, 1965), and a sediment thickness of over 10 km in the basin depocenter (Kaplan et al., 1994)

The Niger delta basin has been well studied by researchers on a universal scale. Several studies have been undertaken on the Niger Delta Basin source rock potential, its organic matter maturity (Ekweozor and Petters, 1982). In addition, detailed organic geochemical investigation of the origin and depositional environment of organic matter exist in literatures. Biomarker distribution, rock eval pyrolysis have also been used to effectively characterise the environment of deposition (Galarraga et al., 2008; Shu et al., 2013). Nonetheless, most of these significant interpretations were based on organic geochemistry with less input from inorganic geochemical signatures. Likewise, elemental analysis of some major and trace elements can provide insight into the activities at the source area of sediments and the depositional environment conditions.

Furthermore, around the world, geochemical studies of sedimentary rocks also provide information regarding source rock composition, paleoclimatic conditions, transport history and tectonic settings (Shaik, 2005). The implication of sedimentary geochemistry in determining the origin of sedimentary suites, their evolution, and source weathering is well established in the literatures (Bhatia, 1983; Cullers, 1994a, 1994b; Cullers et al., 1987, 1988; McLennan et al., 1990, 1993; Roser and Korsch, 1986; 1988; Wronkiewicz and

Condie, 1987). The relationship between tectonic setting and variables such as provenance, relief, physical sorting and weathering, control the composition of sediments. Immobile trace element compositions and rare earth element (REE) abundances in sediments are good indicators of source rock geochemistry, since these elements are little-fractionated by sedimentary processes and low grade metamorphism (Taylor and McLennan, 1985; McLennan, 1989) whilst more mobile elements are helpful for understanding weathering regimes and paleo-environmental conditions (Nesbit and Young, 1984; Fedo et al., 1996).

The fusion of Rock Eval Pyrolysis, Rare Earth Element and element distribution can give more detailed information about the western part of the Niger Delta Basin. This study concentrates on organic and inorganic geochemical signature of the sediments retrieved from Soso and Kay 1 wells to provide a summary of the provenance, Paleoenvironment, tectonic settings , geochemical conditions prevailing at source area, organic matter Type and depositional environmental conditions of Organic matter. This ultimately provides further insight into the use of inorganic geochemistry in Basin Analysis.

2. Geological Settings

The Niger Delta basin occupies the Gulf of Guinea continental margin in the equatorial West Africa between Latitudes 3^0 and 6^0 N and Longitudes 5^0 and 8^0 E. The onshore portion of the Niger Delta Province is delineated by the geology of southern Nigeria and south-western Cameroon. The northern boundary is the Benin flank--an east-northeast trending hinge line south of the West Africa basement massif. The north-eastern boundary is defined by outcrops of the Cretaceous on the Abakaliki High and further east-south-east by the Calabar flank--a hinge line bordering the adjacent Precambrian. The offshore boundary of the province is defined by the Cameroon volcanic line to the east, the eastern boundary of the Dahomey basin (the eastern-most West African transform-fault passive margin) to the west, and the two-kilometre sediment thickness contour or the 4000-meter bathymetric contour in areas where sediment thickness is greater than two kilometres to the south and southwest**.** The province, however, covers 300,000 km^2 and includes the geologic extent of the Tertiary Niger Delta (Akata-Agbada) Petroleum System.

The tectonic framework of the continental margin along the West Coast of Equatorial Africa is controlled by Cretaceous fracture zones expressed as trenches and ridges in the deep Atlantic. Taphrogenic subsidence along fundamental transform faults which had cut through the lithosphere and the landward continuation of the Chain and Charcot oceanic fracture zones (Emery et al, 1975; Delteil et al., 1974), initiated the Benue trough and also later controlled the location of the main axis of subsidence of the Niger Delta. Sinistral trans-current shearing along the fracture zones caused deformation in the Benue Trough and modified the Gulf of Guinea continental margin from the simple pull apart basement structures with half grabens that underlie the West African continental margins north and south of the Gulf of Guinea. (Reijers et al, 1997)

Lithostratigraphy

The sedimentary system in the Niger delta is characterized by high rate of sediment supply and growth fault accommodating large sediment volume. In the Benue Trough, sedimentary infillings lie in the Cretaceous sub-basins such as the Gongola, the Yola, the Abakaliki, the Anambra, and the Afikpo sub basins. The Niger Delta basin can therefore be referred to as the youngest sub basin in the Benue Trough, a region whose stratigraphic and paleogeographic evolution have been controlled by southwards shifting deltaic depocenters (Benkhelil, 1989; Petters, 1985); westward post deformational displacement of depocenters and northward directed marine transgressions (Murat, 1972).

Clays and shales with minor shale intercalation made up the Akata formation. Sediments were deposited in the prodelta and marine environment. The sand percentage here is generally less that 30%. The Akata Formation at the base of the delta is of marine origin and is composed of thick shale sequences (potential source rock), turbidite sand (potential reservoirs in deep water), and minor amounts of clay and silt. Beginning in the Palaeocene and through the Recent, the Akata Formation was formed during lowstands when terrestrial organic matter and clays were transported to deep water areas characterized by low energy conditions and oxygen deficiency (Stacher, 1995). It is estimated that this formation is up to 7,000 meters thick (Doust and Omatsola, 1990).

A coastal marine sequence of alternating sand and shales, the Agbada formation, comprises mostly sands with minor shales in the upper part and an alternation of sands and shales in equal proportion in the lower part. The alternation of sands and shales is indicative of a transitional, fluvio-marine environment and the sand percentage within this formation varies from 30-70% which results in large number of depositional offlap cycle. The formation consists of paralic siliciclastics over 3700 meters thick and represents the actual deltaic portion of the sequence. The Agbada formation on the other hand is the time equivalent to the Ogwashi - Asaba formation further north.

The Benin Formation, a continental shallow massive sand sequence, is made up of coarse grained, gravelly sandstones with minor intercalations of shales and upper delta top lithofacies is characterized by massive continental sands and gravel. The massive sands were deposited in the continental environment consisting of fluvial domain (braided and meander systems) of the upper delta plain. This formation has an approximate thickness of about 2000m. Typical outcrops of the Benin formation can be found around Benin, Onitsha and Owerri.

The most striking structural features of the Niger Delta are the large syn-sedimenatry growth faults, rollover anticlines and shale diapirs which deformed the delta complex (Evamy et al., 1978). These E-W trending faults and folds dominate the structural geology of the Niger Delta. Greater percentage of the oil fields in the Niger Delta is associated with rollover anticlines. However, these structures are gravity controlled and develop simultaneously with sedimentation. Deposition of the three formations occurred in each of the five offlapping siliciclastic sedimentation cycles that comprise the Niger Delta. These cycles (depobelts) are composed of bands of sediments about 30-60 km wide with lengths of up to 300 km over oceanic crust into the Gulf of Guinea (Stacher, 1995). Depobelts represent successive phase of delta growth and are defined by syn-sedimenatry faulting that occurred in response to variable rates of subsidence and sediment supply (Doust and Omatsola, 1990).

Typical of some deltaic structures in the world, marine, mixed and continental depositional environments characterize the Niger Delta. Though the proto delta is thought to have been associated with a Campanian transgression (Asseez, 1976; Novelli, 1974), the modern Niger Delta is believed to have originated during the Eocene. For the purpose of this study, concern lies primarily with the modern Niger Delta. The formation of the modern Niger Delta began during the Eocene and a continued seaward progradation since the Eocene has extended the continental margin to its present position.

Major structure-building growth faults determined the location of each depobelt, (Reijers et al, 1997). The entire sedimentary wedge in the Niger Delta was laid down sequentially in five major depobelts with the oldest depobelt lying farthest inland and the youngest located off shore. Each depobelt is a separate unit that corresponds to a break in regional dip of the delta and is bounded landward by growth faults and seaward by large counter-regional faults or the growth fault of the next seaward belt (Evamy et al, 1978; Doust and Omatsola, 1990). The five major depobelts: Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp, and Offshore, are generally recognized, each with its own sedimentation, deformation, and petroleum history.

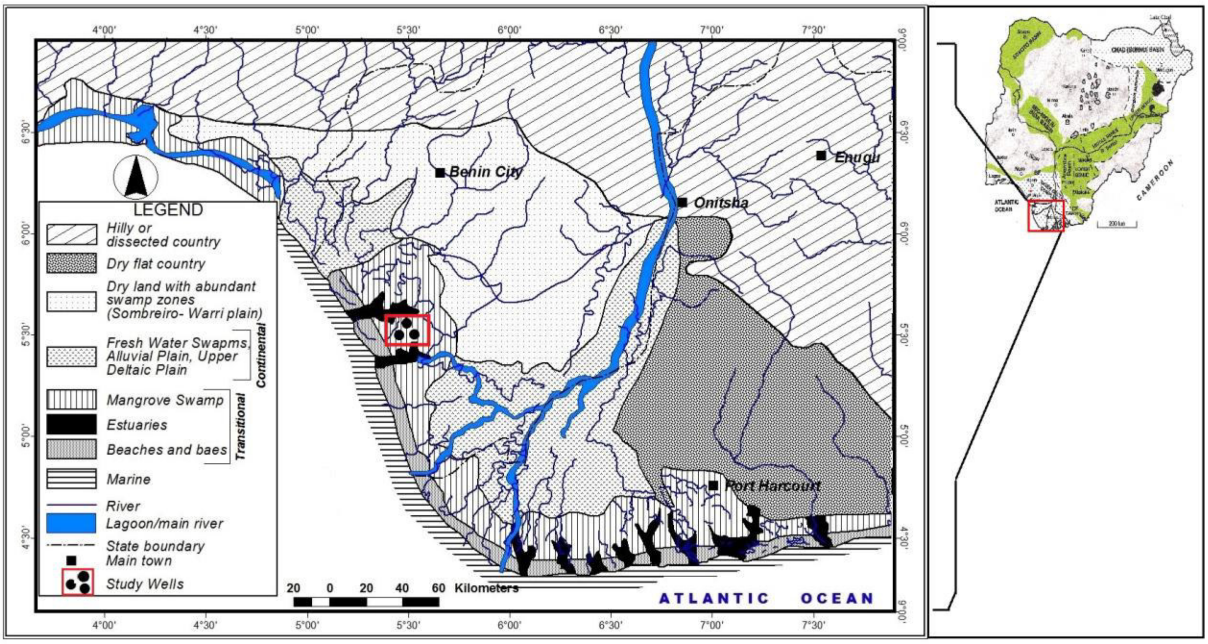


Fig 1. Niger Delta Map Showing the Study Area

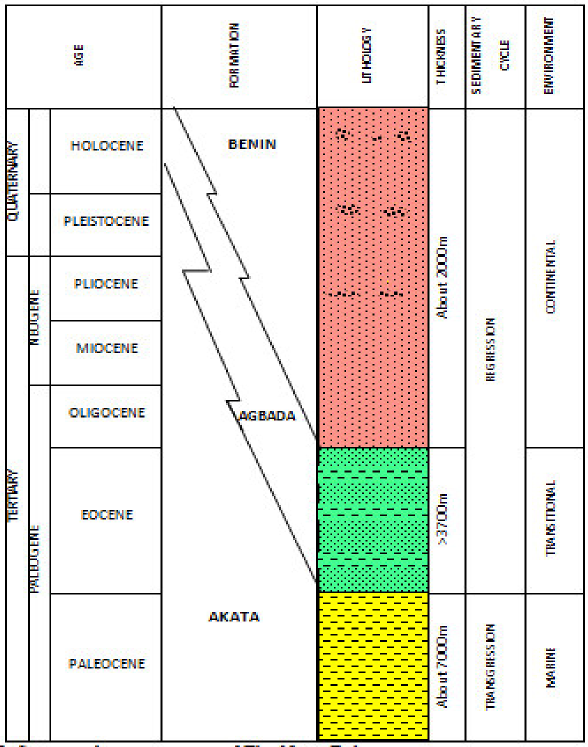


Fig 2: Stratigraphic Nomenclature in the Niger Delta Basin (Adapted from Obaje, 2009)

3. Samples and Methods

A total of 58 core samples were collected from two exploration wells (Kay-1 and Soso Wells) drilled in the Western part of the Niger Delta Basin. The samples were collected from depth ranging from 7,160-13,880 ft. (2182– 4230 meters) and 5760-12480 ft. (1756-3804 meters) at an interval of 100ft respectively from the wells. These was logged and properly described, based on lithological characteristics and presence of carbonate (delineated with the aid of dilute HCL).

The collected samples were stored in correctly labelled polythene bags with reference to the depth from which they were taken. Excellent Quality control was ensured to retain sample integrity in the handling sequence and storage of the samples to prevent contamination. All the samples were selected for Inductively Coupled Plasma Mass Spectrometry. Eleven (11) Shale samples were selected for Total Organic Carbon (TOC) and Rock Eval pyrolysis.

The samples for geochemical analysis were air-dried, crushed and ground to less than 200 mesh. Total Organic Carbon (TOC) and Rock Eval pyrolysis were determined at Weatherford Analytical Laboratory Texas, United States of America using the Walkey and Black Method and the SR Analyser Programmed Pyrolysis respectively while ICP-MS was carried out at Acmelab, Bureau Veritas, in Canada.

The sieved sediments were subjected to digestion by fusion. This procedure necessitated the use of an appropriate flux; the Lithium Metaborate ($LiBO_3$). To achieve digestion, 0.5g of these samples was carefully mixed with 1.5g of the flux in a graphite crucible and heat was applied at a temperature of 900^{o}C in an electric muffle furnace for approximately 30 minutes. The samples were cooled as the crucible and fusion mixture were placed in 300ml of water which contains 10ml nitric acid (HNO_3).

This was vigorously stirred without delay. This practice is fast and the samples dissolved completely in 30 minutes after which they were analysed for their elemental constituents using the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the Geochemical Laboratory of Acmelab, Bureau Veritas, in Canada. Values of major and trace elements were reported in percent and ppm respectively.

Thirty samples, 30, and twenty eight, 28, samples from Kay-1 and Soso wells respectively were selectively analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

4. Results and Discussion

4.1 Major Oxide

SiO_2 is the major constituent with an average of 72.5 wt. %. This is trailed by Al_2O_3 (10.6 wt. %) and Fe_2O_3 (5.4 wt. %), Table 1. TiO_2, CaO, K_2O and FeO have average values of 0.94 wt.%, 0.99 wt.%, 2.91 wt.% and 4.8 wt.% respectively while other oxides; MnO, MgO and P_2O_5 are low in concentration.

Al_2O_3, K_2O, Fe_2O_3, MnO, MgO are less than the PAAS (Taylor and McLennan 1985) while SiO_2 and Na_2O have higher values than the Australian Shale. The depletion of P_2O_5 may be explained by lesser amount of accessory phases such as apatite and monazite. The sandy sequences have higher SiO_2 concentration while the clayey unit have lower SiO_2 content. The shale sequences have high Al_2O_3 concentration and a moderately low SiO_2 concentration while the silty sand, silty shale and sandy shale have low concentration of Al_2O_3 and high SiO_2 concentration.

The SiO_2/Al_2O_3 ratio showed a high values for most of the samples (Table 2) .This is an indication of a high amount of clay in the sediments derived from Soso Well. Relatively, the SiO_2/Al_2O_3 ratio is lower in Kay-1 Well as this implies a lower amount of clay in the sediments from Kay-1 Well. The fairly high content of SiO_2 in most of the samples coupled with fairly low concentrations of TiO_2, Al_2O_3, MgO, CaO and MnO indicated a mineralogically sub-mature to mature sediments. The low ratios of Al/Si (Table 1$\approx$ 0.15) suggest that Si has another source besides the clay minerals as derived by Fu et al (2011).

Aluminium is a good measure of detrital flux. The concentrations of TiO_2 increases with that of Al_2O_3, with a positive correlation of $R=0.91$. This suggests that TiO_2 is probably associated with Phyllosilicates especially with illite (Dabard, 1990). Titanium is mainly concentrated in Phyllosilicates (Condie et al., 1992) and it is relatively immobile compared to other elements during various sedimentary processes and may strongly represent the source rock (McLennan et al., 1993).

Table 1a: Major Oxide (%) Concentration for Soso Well, Western Niger Delta Basin

				Soso Well							
Sample No	**K_2O**	**SiO_2**	**TiO_2**	**Al_2O_3**	**Fe_2O_3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na_2O**	**P_2O_5**
R063	4.66	80.10	0.56	3.55	2.76	2.48	0.00	0.13	0.76	4.95	0.04
R064	4.48	79.01	0.55	3.68	3.89	3.50	0.00	0.08	0.32	4.42	0.06
R065	1.14	89.65	0.37	3.38	2.36	2.12	0.00	0.08	0.24	0.62	0.03
R066	1.76	85.05	0.39	3.23	3.75	3.37	0.00	0.17	0.59	1.68	0.03
R067	1.05	88.21	0.24	2.29	3.58	3.22	0.00	0.15	0.60	0.66	0.01
R068	2.14	81.94	0.66	6.14	3.78	3.40	0.00	0.13	0.27	1.51	0.04
R069	2.18	71.37	1.28	12.37	5.91	5.31	0.00	0.20	0.24	1.07	0.07
R070	4.41	79.39	0.56	6.01	2.93	2.64	0.00	0.18	0.36	3.47	0.05
R071	3.65	67.48	0.95	12.69	5.76	5.18	0.00	0.60	0.85	2.73	0.09
R072	4.70	76.67	0.82	5.23	3.90	3.51	0.00	0.25	0.39	4.44	0.08
R073	2.92	71.48	1.02	11.22	5.59	5.03	0.00	0.56	0.63	1.44	0.11
R074	4.96	78.92	0.54	4.68	2.75	2.47	0.00	0.33	0.60	4.68	0.06
R075	5.19	78.52	0.58	4.91	2.87	2.58	0.00	0.30	0.62	4.36	0.06
R076	3.15	78.26	0.51	6.69	4.46	4.01	0.00	0.28	0.60	1.96	0.08
R077	6.16	78.24	0.43	4.17	2.62	2.35	0.00	0.32	0.74	4.90	0.08
R078	5.12	78.40	0.55	5.19	2.76	2.48	0.00	0.17	0.52	4.74	0.07
R079	5.23	73.91	0.65	6.55	4.03	3.63	0.00	0.35	0.66	4.91	0.07
R080	1.39	83.14	0.26	4.31	3.86	3.47	0.00	0.56	2.25	0.70	0.06
R081	1.66	75.28	0.56	7.74	6.09	5.48	0.00	0.65	1.80	0.61	0.12
R082	2.49	64.17	1.05	15.55	7.38	6.64	0.00	0.76	0.95	0.86	0.15
R083	2.89	69.46	1.00	13.66	5.18	4.66	0.00	0.63	0.73	1.69	0.11
R084	2.66	65.98	1.06	15.77	6.21	5.58	0.00	0.78	0.81	1.03	0.12
R085	2.99	72.17	0.94	12.37	4.56	4.10	0.00	0.55	0.64	1.61	0.08
R086	2.37	67.14	1.21	16.19	5.66	5.09	0.00	0.63	0.49	1.10	0.11
R087	3.55	67.05	0.93	13.02	5.83	5.25	0.00	0.78	0.80	2.70	0.08
R088	3.69	70.24	0.93	12.20	4.63	4.17	0.00	0.55	0.84	2.68	0.08
R089	2.51	70.42	0.46	7.08	4.66	4.19	0.00	0.58	7.76	2.26	0.08
R090	5.23	73.20	0.78	8.25	3.60	3.24	0.00	0.55	0.87	4.21	0.07
Min	1.05	64.17	0.24	2.29	2.36	2.12	0.00	0.08	0.24	0.61	0.01
Max	6.16	89.65	1.28	16.19	7.38	6.64	0.00	0.78	7.76	4.95	0.15
Ave	3.39	75.62	0.71	8.22	4.37	3.93	0.00	0.41	1.16	2.58	0.07

Table 1b: Major Oxide (%) Concentration for Kay-1 Well, Western Niger Delta Basin

					Kay-1 Well						
Sample No.	**K_2O**	**SiO_2**	**TiO_2**	**Al_2O_3**	**Fe_2O_3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na_2O**	**P_2O_5**
R033	0.87	72.78	1.23	11.35	7.01	6.30	0.00	0.13	0.08	0.16	0.07
R034	1.41	75.89	1.03	11.13	5.21	4.68	0.00	0.23	0.20	0.16	0.07
R035	1.59	69.68	1.16	13.39	7.21	6.48	0.00	0.20	0.06	0.16	0.08
R036	2.42	66.60	1.42	16.13	6.64	5.97	0.00	0.41	0.08	0.25	0.08
R037	1.35	84.05	0.53	4.99	4.20	3.78	0.00	0.38	0.50	0.17	0.04
R038	1.89	83.60	0.58	5.02	4.18	3.76	0.00	0.43	0.24	0.23	0.07
R039	2.27	76.70	0.53	6.14	6.64	5.97	0.00	0.75	0.66	0.20	0.16
R040	3.28	66.00	1.42	12.17	7.79	7.01	0.00	0.95	0.70	0.54	0.14
R041	3.16	66.71	1.51	12.86	6.65	5.98	0.00	0.91	1.30	0.78	0.14
R042	2.77	58.76	1.23	17.19	8.41	7.56	0.00	1.04	2.15	0.59	0.28
R043	2.01	81.31	0.63	6.54	4.19	3.77	0.00	0.45	0.50	0.47	0.13
R044	3.31	65.87	1.29	13.53	7.04	6.33	0.00	0.78	0.91	0.79	0.16
R045	3.40	72.29	1.14	11.41	5.12	4.60	0.00	0.55	0.64	0.72	0.13
R046	2.51	66.61	1.09	14.38	6.38	5.74	0.00	0.63	1.86	0.59	0.22
R047	3.72	73.22	1.19	10.01	4.86	4.37	0.00	0.53	0.62	1.36	0.11
R048	2.59	63.74	1.06	13.47	8.39	7.55	0.00	1.04	1.39	0.59	0.18
R049	3.57	69.58	1.16	13.41	5.02	4.51	0.00	0.55	0.94	1.16	0.11
R050	3.29	63.17	1.25	16.02	6.91	6.21	0.00	0.88	1.29	0.86	0.14
R051	2.48	57.39	1.37	19.08	8.98	8.08	0.00	0.95	0.99	0.54	0.15
R052	3.19	67.76	1.48	13.96	5.93	5.34	0.00	0.53	0.69	1.02	0.10
R053	1.06	89.04	0.32	3.44	2.16	1.94	0.00	0.25	1.44	0.31	0.04
R054	3.36	70.64	1.01	12.03	5.26	4.73	0.00	0.48	1.22	1.17	0.09
R055	1.51	80.77	0.75	7.84	3.96	3.56	0.00	0.32	0.71	0.52	0.06
R056	2.23	57.41	1.40	16.47	10.27	9.23	0.00	1.01	1.22	0.56	0.19
R057	2.96	68.56	1.46	14.17	5.46	4.91	0.00	0.60	0.70	1.06	0.11
R058	2.36	60.69	1.36	18.61	7.82	7.03	0.00	0.71	0.64	0.63	0.14
R059	2.10	71.17	1.67	13.92	4.82	4.33	0.00	0.60	0.52	0.77	0.11
R060	2.45	65.27	1.47	15.38	6.62	5.95	0.00	0.75	1.09	0.92	0.10
R061	2.60	60.93	1.33	17.27	8.21	7.38	0.00	0.71	0.73	0.67	0.17
R062	2.04	59.08	1.41	20.53	7.97	7.16	0.00	0.68	0.55	0.45	0.14
Min	0.87	57.39	0.32	3.44	2.16	1.94	0.00	0.13	0.06	0.16	0.04
Max	3.72	89.04	1.67	20.53	10.27	9.23	0.00	1.04	2.15	1.36	0.28
Ave	2.45	69.74	1.14	12.68	6.30	5.67	0.00	0.61	0.84	0.62	0.13

4.1.1 Provenance and Tectonic Settings

Several classification schemes have been proposed to discriminate various origin and tectonic settings (Maynard et al., 1982: Bhatia, 1983, 1986; Roser and Korsch, 1988) is based on major element functions. To infer provenance, a bivariate plot of Discriminant function I and 2 for major oxides after Roser and Korsch, (1988) were plotted following the boundaries between fields as proposed by Roser and Korsch (1988) (Fig 3). Sediments from Soso and Kay-1 wells were scattered all over the fields thus suggesting a mixed provenance for the sediments.

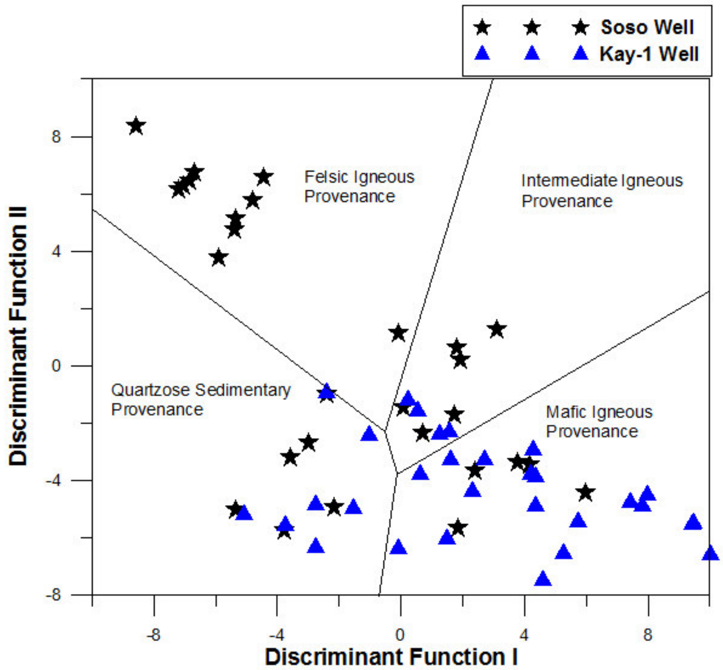


Fig 3: The Discriminant Function Diagram (after Roser and Korsch, 1988) for the provenance signatures of sediments from Soso and Kay-1 well using Major Oxides

DF1= -1.773 TiO_2 + 0.607 Al_2O_3 + 0.76 Fe_2O_3 - 1.5 MgO + 0.616 CaO +0.509 Na_2O – 1.224 k_2O – 9.09

DF2= 0.445TiO_2 + 0.07 Al_2O_3 – 0.25 Fe_2O_3 - 1.142 MgO + 0.438 CaO + 1.475 Na2O +1.426 K_2O – 6.861.

The ratio of major oxides to Al_2O_3 was used to generate the Discriminant Function I and II (Roser and Korsch, 1988). The bivariate plot, (Fig 4) with four provenance fields, show sediments from wells plot on the Intermediate Igneous Provenance fields and the Mafic fields with an overlap on the Felsic Igneous field.

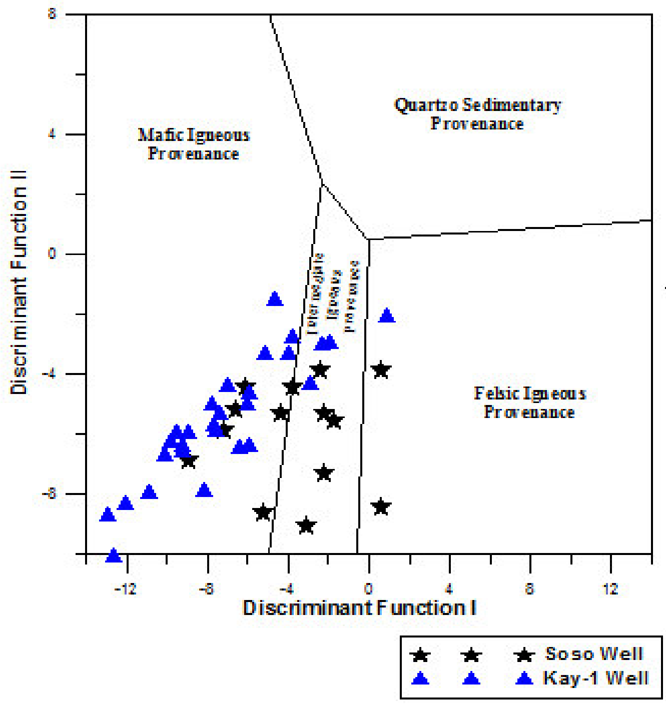


Fig 4: The Discriminant Function Diagram (after Roser and Korsch, 1988) for the provenance signatures of sediments from Soso and Kay-1 Well using Major Element Ratios

DF1= 30.638 TiO_2/Al_2O_3 – 12.541 Fe_2O_3/ Al_2O_3+ 7.329 MgO/ Al_2O_3 +12.031 Na_2O_5/ Al_2O_3+ 35.402 K_2O/ Al_2O_3 - 6.382.

DF2= 56.500 TiO_2/Al_2O_3 – 10.879 Fe_2O_3/ Al_2O_3+ 30.875 MgO/ Al_2O_3 – 5.404 Na_2O/Al_2O_3+ 11.112 K_2O/ Al_2O_3 -3.89.

Al_2O_3/TiO_2 binary plot (Fig 5) gives Discriminant fields for source rocks (Amajor, 1989). The sediments plot on Basalt (mafic) and Basalt to Granite (mafic to felsic) fields respectively.

Table 2: Major Oxide Ratio and Sum (%) of Analyzed samples

	TiO2/Al2O3	K2O/Na2O	SiO2/Al2O3	Na2O+K2O	CaO+Na2O	Na2O/K2O	K2O/Al2O3	MgO/Al2O3	Al2O3/SiO2
Soso Well	0.1578	0.9419	22.5550	9.6146	0.1526	1.0617	1.3131	0.0373	0.0443
	0.1490	1.0141	21.4496	8.9027	0.0728	0.9861	1.2169	0.0225	0.0466
	0.1090	1.8342	26.5131	1.7689	0.3811	0.5452	0.3386	0.0245	0.0377
	0.1203	1.0474	26.3290	3.4389	0.3498	0.9547	0.5446	0.0513	0.0380
	0.1065	1.5904	38.5917	1.7075	0.9126	0.6288	0.4587	0.0653	0.0259
	0.1076	1.4232	13.3462	3.6520	0.1764	0.7026	0.3494	0.0216	0.0749
	0.1038	2.0327	5.7679	3.2541	0.2216	0.4920	0.1763	0.0161	0.1734
	0.0939	1.2701	13.2156	7.8827	0.1048	0.7873	0.7342	0.0304	0.0757
	0.0746	1.3362	5.3162	6.3835	0.3123	0.7484	0.2876	0.0470	0.1881
	0.1562	1.0584	14.6526	9.1398	0.0882	0.9448	0.8981	0.0475	0.0682
	0.0910	2.0236	6.3700	4.3571	0.4369	0.4942	0.2599	0.0502	0.1570
	0.1150	1.0604	16.8473	9.6462	0.1285	0.9430	1.0597	0.0708	0.0594
	0.1182	1.1902	15.9874	9.5570	0.1411	0.8402	1.0574	0.0608	0.0625
	0.0761	1.6024	11.7036	5.1077	0.3065	0.6241	0.4703	0.0422	0.0854
	0.1019	1.2573	18.7416	11.0548	0.1514	0.7953	1.4750	0.0755	0.0534
	0.1053	1.0808	15.0930	9.8595	0.1092	0.9252	0.9859	0.0319	0.0663
	0.0995	1.0647	11.2760	10.1418	0.1339	0.9393	0.7978	0.0531	0.0887
	0.0604	1.9807	19.3034	2.0854	3.2195	0.5049	0.3217	0.1309	0.0518
	0.0724	2.7292	9.7204	2.2722	2.9620	0.3664	0.2147	0.0835	0.1029
	0.0678	2.9049	4.1275	3.3530	1.1079	0.3442	0.1604	0.0491	0.2423
	0.0734	1.7095	5.0856	4.5837	0.4300	0.5850	0.2118	0.0461	0.1966
	0.0675	2.5926	4.1829	3.6902	0.7900	0.3857	0.1688	0.0494	0.2391
	0.0758	1.8614	5.8325	4.5939	0.4008	0.5372	0.2415	0.0442	0.1715
	0.0749	2.1581	4.1472	3.4738	0.4451	0.4634	0.1466	0.0389	0.2411
	0.0718	1.3166	5.1519	6.2548	0.2953	0.7596	0.2731	0.0599	0.1941
	0.0763	1.3780	5.7557	6.3631	0.3137	0.7257	0.3022	0.0448	0.1737
	0.0648	1.1114	9.9412	4.7616	3.4429	0.8998	0.3538	0.0819	0.1006
	0.0942	1.2423	8.8669	9.4395	0.2060	0.8050	0.6335	0.0663	0.1128
Kay-1 Well	0.1087	5.3635	6.4111	1.0294	0.5189	0.1864	0.0764	0.0117	0.1560
	0.0928	8.6437	6.8206	1.5730	1.2008	0.1157	0.1267	0.0209	0.1466
	0.0866	9.9157	5.2023	1.7510	0.3489	0.1008	0.1188	0.0149	0.1922
	0.0880	9.8184	4.1283	2.6687	0.3403	0.1018	0.1501	0.0257	0.2422
	0.1064	8.0095	16.8541	1.5181	2.9890	0.1249	0.2706	0.0765	0.0593
	0.1159	8.2556	16.6375	2.1210	1.0378	0.1211	0.3765	0.0858	0.0601
	0.0856	11.2790	12.4934	2.4663	3.2737	0.0887	0.3690	0.1215	0.0800
	0.1170	6.0334	5.4255	3.8208	1.2876	0.1657	0.2694	0.0777	0.1843
	0.1171	4.0520	5.1860	3.9362	1.6699	0.2468	0.2454	0.0709	0.1928
	0.0717	4.6834	3.4183	3.3633	3.6407	0.2135	0.1612	0.0608	0.2925
	0.0967	4.2410	12.4404	2.4868	1.0614	0.2358	0.3079	0.0685	0.0804
	0.0955	4.2094	4.8700	4.1010	1.1551	0.2376	0.2450	0.0576	0.2053
	0.1003	4.7384	6.3360	4.1152	0.8974	0.2110	0.2978	0.0480	0.1578
	0.0755	4.2162	4.6336	3.1009	3.1300	0.2372	0.1744	0.0438	0.2158
	0.1193	2.7349	7.3133	5.0849	0.4521	0.3657	0.3719	0.0530	0.1367
	0.0788	4.4182	4.7326	3.1771	2.3620	0.2263	0.1924	0.0776	0.2113
	0.0862	3.0803	5.1882	4.7247	0.8095	0.3246	0.2659	0.0408	0.1927
	0.0778	3.8371	3.9433	4.1470	1.5013	0.2606	0.2054	0.0549	0.2536
	0.0718	4.5922	3.0079	3.0228	1.8376	0.2178	0.1301	0.0495	0.3325
	0.1060	3.1334	4.8541	4.2123	0.6727	0.3191	0.2287	0.0380	0.2060
	0.0932	3.3907	25.8985	1.3731	4.6076	0.2949	0.3084	0.0723	0.0386
	0.0839	2.8700	5.8709	4.5334	1.0390	0.3484	0.2794	0.0400	0.1703
	0.0953	2.8725	10.3030	2.0306	1.3607	0.3481	0.1921	0.0402	0.0971
	0.0850	3.9658	3.4856	2.7914	2.1653	0.2522	0.1353	0.0614	0.2869
	0.1033	2.7871	4.8396	4.0279	0.6577	0.3588	0.2092	0.0421	0.2066
	0.0732	3.7278	3.2616	2.9954	1.0158	0.2683	0.1269	0.0383	0.3066
	0.1199	2.7384	5.1121	2.8624	0.6761	0.3652	0.1506	0.0429	0.1956
	0.0957	2.6530	4.2447	3.3682	1.1835	0.3769	0.1591	0.0485	0.2356
	0.0771	3.8695	3.5289	3.2755	1.0815	0.2584	0.1508	0.0413	0.2834
	0.0685	4.4962	2.8773	2.4894	1.2046	0.2224	0.0992	0.0331	0.3476

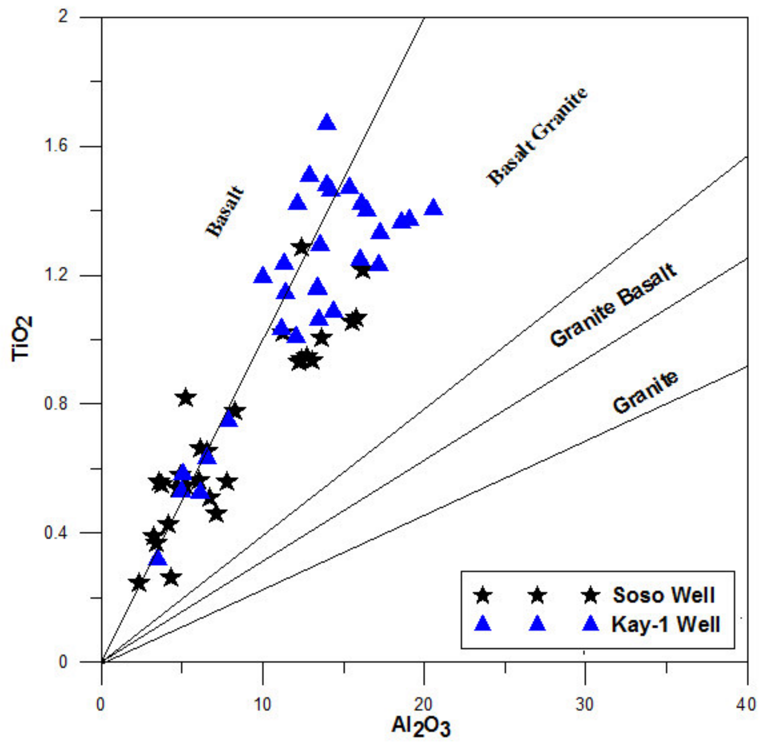


Fig 5: Al_2O_3/TiO_2 bivariate plot, after Amajor, 1989

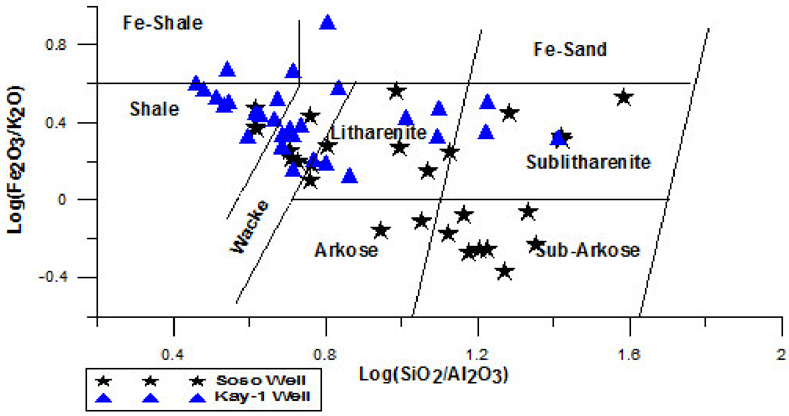


Fig 6: Classification of siliciclastic sediments of well 'Soso and Kay-1', western Niger Delta (After Herron, 1988)

Log (Fe_2O_3/K_2O) vs. Log (SiO_2/Al_2O_3), a standard plot of Herron, (1988) modified (Fig 6) was used to classify sediments from Soso and Kay-1 Wells.

The plots revealed that the sediments penetrated by Kay-1 well dominated by shales, wackes and litharenites, while the shales from Soso well plotted on the shale field with some overlapping into the wacke field while the sandy shales fall within the litharenites and the subarkose. The silty sands also scatter over litharenites, sub-litharenites and subarkose. From all the plots discussed, the sediments can be described as having originated from a mixed provenance**.**

A simplified tectonic classification of continental margins and oceanic basins based on geochemical composition of associated wackes was described by Bhatia (1983). The author defines fields for four tectonic settings being Oceanic Island Arc (OIA), Continental Island Arc (CIA), Active Continental Margins (ACM) and Passive Margins (PM).

The SiO_2 content and the ratio of K_2O/Na_2O of the Samples (Fig 7) were used to decipher their tectonic setting (Roser and Korsch, 1986). Most of the data points from Soso and Kay-1 plotted on the Active Continental Margin fields

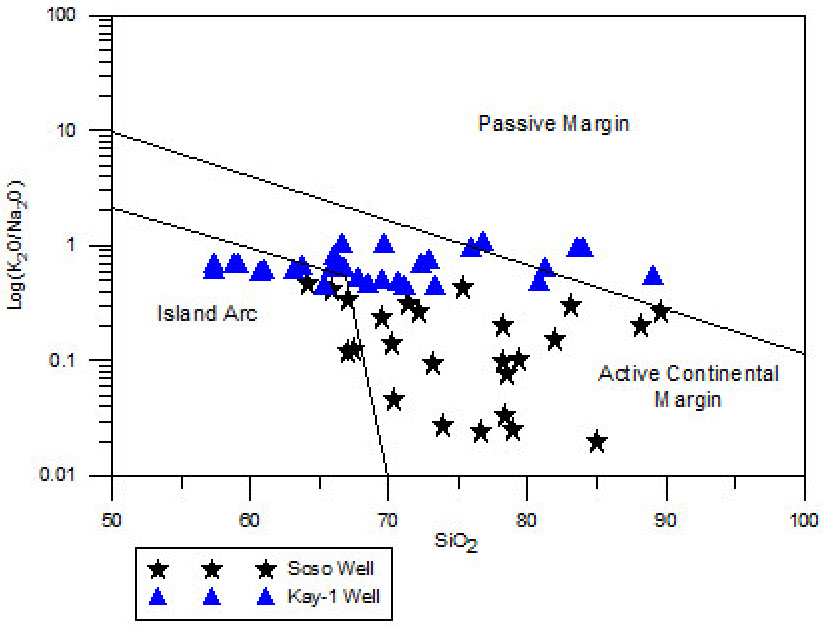


Fig 7: A bivariate plot of Discriminant Function 1 and 2 for Soso and Kay-1 Wells, western Niger Delta Basin.

A bivariate plot of Discriminant Functions I and II (Fig. 8) using oxides of Si, Ti, Al, Fe, Mn, Mg, Ca, Na and K (Bhatia, 1983) was employed in tectonic settings determination and all the sediments , except three plots from wells, plotted on the Active Continental Margin Fields.

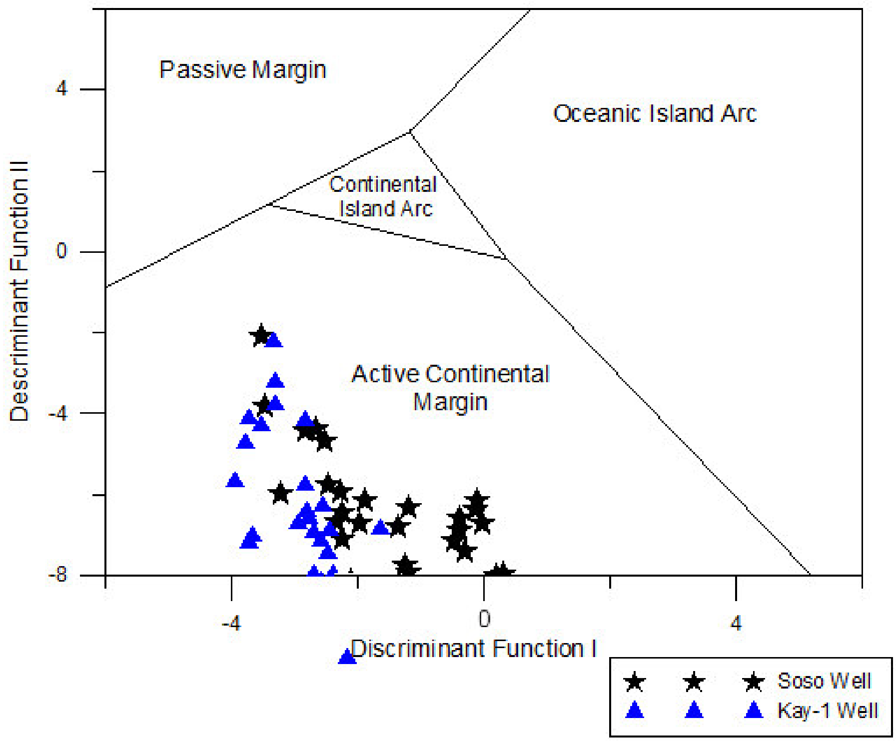


Fig 8: A bivariate plot of Discriminant Function 1 and 2 for Soso and Kay-1 Wells, western Niger Delta Basin.

DF 1 = -0.0447SiO_2 – 0.972TiO_2 +0.008Al_2O_3 - 0.267Fe_2O_3 + 0.208Feo – 3.082MnO + 0.140MgO + 0.195CaO + 0.719Na2O – 0.032K2O + 0.303.

DF 2 = -0.421SiO_2 + 1.988TiO_2 – 0.526Al_2O_3 – 0.551Fe_2O_3 0 - 1.61Feo + 2.720MnO + 0.881MgO – 0.907CaO – 0.177 Na_2O – 1.840K_2O – 7.244P_2O_5 + 43.57.

4.2 Paleoweathering Conditions

In decrypting the weathering history of sedimentary rocks, Nesbit and Young, (1982) proposed a Chemical Index of Alteration, (CIA) value using molecular proportion of some bulk elements. The CIA monitors the progressive alteration of plagioclase and potassium feldspar to clay minerals. The alteration of igneous rock during weathering results in the depletion of alkali and alkali earth metals and the preferential enrichment of Al_2O_3 in sediments. The CIA ([Al_2O_3/ (Al_2O_3+ Na_2O+ CaO*+K_2O)] 100) can also be used as an appraisal of climatic condition that existed during the formations of clastic sedimentary rocks.

In addition to CIA and Plagioclase Alteration Index-PIA (Fedo et al, 1995), other indices that were used to determine the extent of weathering in the source area include the Chemical Index of Weathering , CIW, (Harnois, 1988) and the Ruxton Ratio, RR, (Ruxton, 1968) .These indices are calculated using the formula below:

CIW = [Al_2O_3/ (Al_2O_3+ Na_2O+ CaO*)] 100

RR = SiO_2/Al_2O_3

PIA= 100 [(Al_2O_3 –K_2O) / (Al_2O_3 + CaO* +Na_2O –K_2O)]

The CIA and CIW vary from 25.51–80.33 and 38.36-91.06 with a mean value of 52.79 and 67.10 respectively for Soso Well while Kay-1 well exhibits a CIA and CIW value-range of 53.4-91.9% and 66.2-98.4% respectively.

The sequences have low to moderately high values CIA values with the exception of some silty sand, silty shale and sandy shale sequences which shows very low CIA and CIW values, majority of the samples have CIA and CIW values greater than 50% ; an indication of a low through moderate to high degree of weathering in the source area. The variation in CIA and CIW values could be as result of low concentration of the Alkalis and Alkaline earth elements or perhaps, multiple provenances. This further confirms a mixed provenance for the sediments with varied degree of weathering in the source area.

Low CIA values suggest that some of the sediments could have been sourced from fresh Basalt, fresh Granite and Granodiorites and Feldspars (Table 4). This agrees with the Discriminant diagram (Amajor, 1989, Al_2O_3/TiO_2 binary plot (Fig 5). However they might not have travelled far from the source area. The CIA, CIW and PIA range are shown in the Table 3 from 1.0-90, 66 -98 for Soso and Kay-1 wells

Table 3: CIA, CIW, PIA and RR values for Soso and Kay-1 wells

	Soso Well	Kay-1 Well
CIA	26-80	55-91
CIW	38-91	66-98
PIA	1.0-90	58-98
RR	4.0-39	3.0-26

RR values greater than 30 suggest a weak chemical weathering while those with one digit value indicate medium level of chemical weathering.

The depletion of CaO and Na_2O appears to reflect an intense source area weathering. Much of the chemical variations resulting from weathering is expressed in the Al_2O_3–[CaO + Na_2O] –K_2O system as presented in Fig 9. Paleo-weathering conditions were also predicted using the Al_2O_3-CaO+Na_2O-K_2O (A-CN-K) ternary diagram of Nesbitt and Young (1984).

The shale data point plots (Fig 9) above the plagioclase and K-Feldspar line on granite trend line suggesting that they have undergone a moderate to high degree of weathering, whereas other sediments have their data point plots below the Upper Continental average of CIA. This suggests a very low to a moderately low degree of weathering in the source area.

Table 4: Rock Types and corresponding CIA values After Nesbit and Young, 1982, Fedo et al, 1995

Rock Types	CIA Ranges
Fresh Basalt	30 – 45
Fresh Granite and Granodiorites	45 – 55
Feldspar	50
Muscovite	75
Illite	75 - 90
Kaolinite	100

This corroborates the deduction made from PIA, CIA, and CIW values.

Some of the analysed sediments plot on the Al_2O_3 corner , implying intense primary weathering process and removal of feldspars and other mobile elements that characterize primary source rock materials while the rest follows the weathering trend of granite (Nesbit and Young 1984) suggesting that they are derived from a common source.

This however indicates that the sediments have suffered some amount of chemical weathering resulting in the breakdown of some amount of feldspar and hence loss of CaO and Na_2O. This does not necessarily designate a higher degree of chemical weathering of these sediments as the mineral sorting by fluvial process could also produce similar results (Nesbit and Young 1989) whereby more Phyllosilicates are incorporated into the flood plain sediments resulting in an increase in Al_2O_3.

According to Nesbit and Young, 1989, the depletion of Na and Ca is related to progressive chemical weathering of granite that destroys plagioclase rapidly leading to Ca or Na bearing phases remaining in the weathering residue. The dominant mineral remains are Kaolinite and Illite. Although the effect of post depositional process altering the mineralogy and chemistry cannot be neglected, the textural and chemical maturity of the sediments studied indicate that their bulk chemistry, including the K- depletion was inherited from the source area.

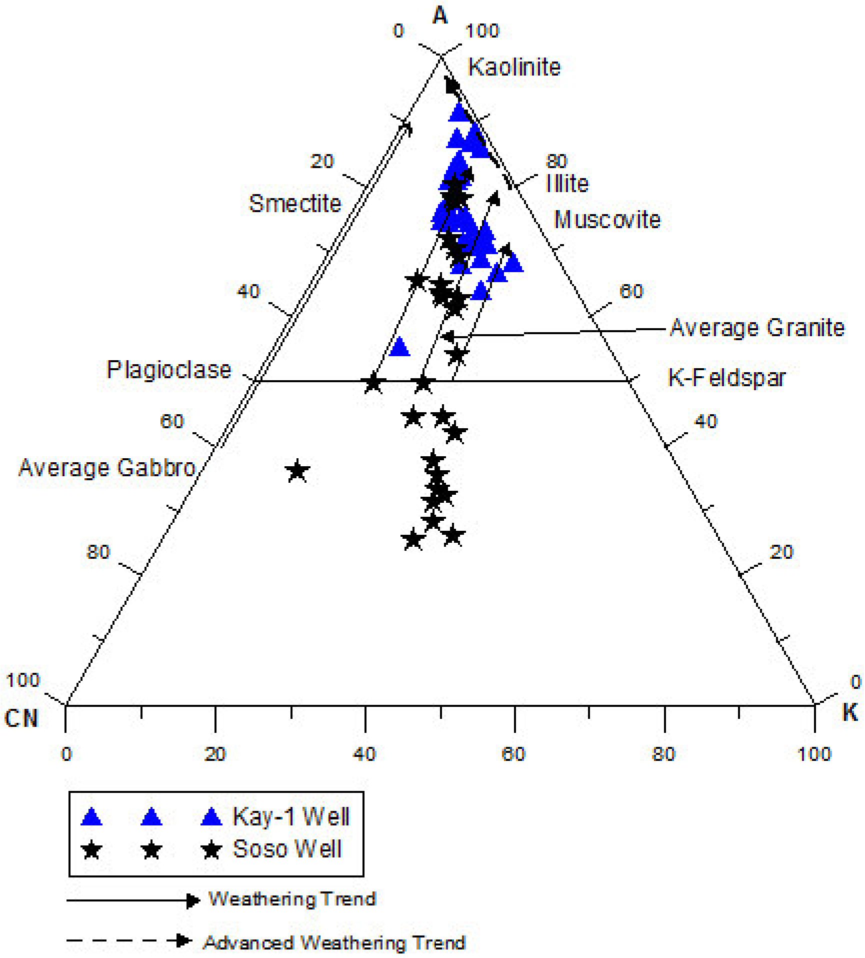


Fig 9: A-CN-K Ternary Diagram; Al_2O_3 - CaO* + Na_2O - K_2O.
(After Nesbit and Young, 1982)

CaO* = CaO in silicates
A: the mole fraction of Al_2O_3, **CN**: the sum of the mole fractions of CaO* and Na_2O
K: the mole fraction of K_2O;

4.3 REE Distribution pattern

The concentrations of REEs are presented in Table 5. Rare Earth Elements were Chondrite normalized with factors from Wakita et al., (1971) and North America Shale Composite, NASC (Haskin and Frey, 1966). This was done to eliminate the abundant variations between elements with even and odd atomic numbers and to compare their normalized REE patterns and fractionations of light REE (La/Sm), heavy REE (Gd/Yb) and total REE (La/Yb) and Eu anomaly ($Eu/Eu^* = Eu/\sqrt{[Sm \times Gd]}$).

$(Gd/Yb)_N$ ratios varies from 1.43 – 2.13 and 1.32-2.21 for Soso and Kay-1 well respectively with a corresponding arithmetic mean of 1.7 and 1.5 respectively while $(La/Sm)_N$ ratio ranges from 0.98 – 1.46 and 1.14-1.56 for Soso and Kay-1 well respectively. $(La/Yb)_N$ ratio ranges from 2.0 – 3.99 and 2.02-4.21 respectively. And the Eu anomaly; (Eu/Eu*) for the wells varies from 0.65 – 0.95 (Soso Well) and 0.8-0.95(Kay-1 Well) averaging at 0.86 and 0.89 for Soso and Kay-1 well correspondingly.

The REE plots (Fig. 10 a,b) show an enriched light REE, negative Eu anomaly. This implies that the sediments in wells have a felsic composition. Also, the quasi-flat HREE suggested a mafic rock input (Fedo et al., 1996).

Table 5a: Chondrite Normalized Rare Earth Element for Sediments in Soso Well, western Niger Delta

La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
1.2244	1.2722	1.2974	1.2352	0.9887	0.8356	0.8638	0.8050	0.7270	0.5850	0.5441	0	0.5027	0
1.0126	1.1080	1.1213	1.0914	0.9141	0.6138	0.6642	0.6289	0.6368	0.4089	0.5441	0	0.3565	0
1.4228	1.4186	1.3796	1.2907	1.0110	0.7387	0.7611	0.6289	0.6021	0.4089	0.4771	0	0.3565	0
1.3318	1.3463	1.3322	1.2657	0.9887	0.8356	0.7891	0.8050	0.7270	0.5850	0.5441	0	0.5027	0
1.2009	1.2407	1.1960	1.1481	0.8239	0.6138	0.7312	0.6289	0.6368	0.4089	0.3979	0	0.3565	0
1.5177	1.5761	1.5405	1.4749	1.2013	0.9818	1.0164	0.9300	0.8653	0.7100	0.6532	0.4949	0.6118	0.4685
1.9844	1.9330	1.8949	1.7991	1.5024	1.2828	1.2926	1.1730	1.1027	0.9530	0.9542	0.7959	0.8617	0.7696
1.4642	1.5329	1.5193	1.4657	1.2013	0.9818	0.9830	0.8050	0.8451	0.5850	0.6532	0.4949	0.5607	0.4685
1.7262	1.7761	1.7745	1.7136	1.4503	1.2159	1.2285	1.1061	1.1139	0.8861	0.9031	0.7959	0.8617	0.7696
1.2467	1.3112	1.3322	1.2766	1.0524	0.8356	0.8638	0.8050	0.8016	0.5850	0.6532	0.4949	0.5607	0.4685
1.8010	1.8198	1.8093	1.7644	1.4424	1.2159	1.2083	1.1061	1.0414	0.8861	0.8751	0.7959	0.7715	0.7696
1.4642	1.4850	1.4613	1.4344	1.1249	0.8356	0.9072	0.8050	0.7270	0.5850	0.5441	0	0.4357	0
1.3716	1.4120	1.4086	1.3757	1.0902	0.8356	0.9072	0.8050	0.7533	0.5850	0.5441	0	0.5027	0.4685
1.2244	1.4174	1.5193	1.5498	1.2540	0.9818	1.0322	0.9300	0.8653	0.7100	0.6990	0.4949	0.5607	0.4685
1.3550	1.3683	1.3486	1.3305	1.0110	0.6138	0.8861	0.6289	0.6990	0.5850	0.5441	0	0.4357	0
1.3010	1.3433	1.3322	1.3242	1.0110	0.7387	0.7611	0.6289	0.6690	0.4089	0.5441	0	0.4357	0
1.3876	1.4463	1.4357	1.4006	1.1249	0.8356	0.8861	0.8050	0.8016	0.5850	0.6532	0.4949	0.5607	0.4685
1.4080	1.5583	1.5893	1.5402	1.2414	0.9818	1.0621	0.9300	0.8653	0.7100	0.6532	0.4949	0.6118	0.4685
1.6299	1.7013	1.7166	1.6976	1.3912	1.0909	1.2285	1.1061	1.0142	0.8069	0.8451	0.7959	0.6990	0.7696
2.0236	2.0262	1.9342	1.8875	1.5733	1.2828	1.3485	1.2821	1.1950	1.0621	1.0414	0.9720	0.9363	0.9456
1.9627	1.9521	1.8666	1.8283	1.5551	1.2828	1.3632	1.2310	1.1761	1.0110	1.0000	0.9720	0.9128	0.7696
2.0344	2.0155	1.9172	1.8705	1.5612	1.2828	1.3485	1.2310	1.1357	1.0110	1.0000	0.7959	0.8617	0.7696
1.9949	1.9600	1.8466	1.7804	1.4424	1.1367	1.2478	1.1061	1.0544	0.8861	0.9031	0.7959	0.8037	0.7696
2.0426	2.0204	1.9128	1.8613	1.5295	1.2828	1.3409	1.1730	1.1461	0.9530	0.9542	0.7959	0.8617	0.7696
1.7286	1.7615	1.7745	1.7632	1.4424	1.2159	1.2571	1.1061	1.0792	0.8861	0.8751	0.7959	0.7715	0.7696
1.8665	1.8382	1.8203	1.7793	1.4342	1.1367	1.2083	1.1061	1.0414	0.8069	0.8129	0.7959	0.7715	0.7696
1.5019	1.6041	1.6162	1.5969	1.2897	1.0398	1.1291	0.9300	0.9031	0.7100	0.6990	0.4949	0.6118	0.4685
1.6532	1.6528	1.6496	1.5952	1.2663	0.9818	1.0764	0.9300	0.8846	0.7100	0.7404	0.4949	0.6576	0.4685

For Soso Well, Chondrite Normalized

Table 5b: Chondrite Normalized Rare Earth Element for Sediments in Kay-1 Well, western Niger Delta

La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
2.2175	2.1140	2.0345	1.8849	1.6021	1.3128	1.4111	1.2310	1.1856	0.9530	1.0414	0.9720	0.9128	0.9456
2.1341	2.0251	1.9466	1.8077	1.5161	1.2506	1.3010	1.1730	1.1139	0.9530	0.9777	0.7959	0.9128	0.7696
2.1406	2.0660	1.9964	1.8613	1.5733	1.3128	1.3774	1.2310	1.2304	1.0621	1.0607	0.9720	0.9586	0.9456
2.2452	2.1469	2.0695	1.9286	1.6394	1.3408	1.4175	1.2821	1.2863	1.1079	1.1139	0.9720	1.0378	0.9456
1.7541	1.6591	1.5507	1.4344	1.1413	0.9148	0.9072	0.8050	0.7533	0.5850	0.6021	#VALUE!	0.5027	0.4685
1.7782	1.6925	1.6162	1.5077	1.2285	0.9148	0.9652	0.9300	0.8239	0.5850	0.6532	0.4949	0.5607	0.4685
1.8647	1.7908	1.7025	1.6138	1.3120	1.0909	1.1165	1.0269	0.9853	0.8069	0.7782	0.7959	0.7368	0.7696
2.0813	2.0022	1.9384	1.8283	1.5093	1.3128	1.2663	1.2310	1.1950	1.0110	1.0000	0.9720	0.9586	0.9456
2.1265	2.0390	1.9664	1.8518	1.5673	1.2506	1.3559	1.1730	1.1663	1.0110	0.9777	0.9720	0.9586	0.9456
2.1761	2.1056	2.0244	1.9205	1.6495	1.3919	1.4301	1.3279	1.2553	1.1079	1.0607	0.9720	1.0193	0.9456
1.8682	1.7779	1.6954	1.5935	1.3632	1.1367	1.1532	0.9300	0.9379	0.7100	0.7404	0.4949	0.6990	0.4685
2.1543	2.0590	1.9854	1.8813	1.6131	1.3128	1.3844	1.2821	1.2553	1.0621	1.0969	0.9720	1.0378	0.9456
2.0866	2.0006	1.9172	1.8181	1.4881	1.2506	1.3174	1.1730	1.1357	0.9530	1.0000	0.9720	0.9363	0.9456
2.0260	1.9655	1.9128	1.8171	1.5488	1.3128	1.3485	1.2310	1.2131	1.0110	1.0212	0.9720	0.9128	0.9456
2.0355	1.9502	1.8763	1.7608	1.4424	1.1781	1.2478	1.1061	1.1139	0.9530	0.9777	0.9720	0.9363	0.9456
2.1350	2.0575	1.9779	1.8650	1.5792	1.3128	1.3979	1.2821	1.2472	1.0110	1.0414	0.9720	1.0000	0.9456
1.9764	1.9355	1.8763	1.7804	1.4808	1.2159	1.2663	1.1061	1.1139	0.9530	0.9542	0.7959	0.8880	0.9456
2.0979	2.0237	1.9625	1.8547	1.5850	1.3128	1.3093	1.2310	1.1950	1.0110	1.0212	0.9720	0.9363	0.9456
2.1543	2.1024	2.0539	1.9482	1.6594	1.3919	1.4239	1.3693	1.3153	1.1079	1.1303	0.9720	1.0378	0.9456
1.9696	1.9247	1.8715	1.7573	1.4881	1.2159	1.2382	1.1730	1.1139	0.9530	0.9031	0.7959	0.8617	0.7696
1.5019	1.4475	1.3796	1.2837	0.9652	0.7387	0.7891	0.6289	0.6021	0.4089	0.4771	#VALUE!	0.3565	#VALUE!
1.9613	1.8723	1.7980	1.6852	1.4175	1.1781	1.2083	1.1061	1.0669	0.8861	0.8451	0.7959	0.8037	0.7696
1.8523	1.7703	1.6954	1.5848	1.3120	1.0398	1.0474	0.9300	0.9031	0.7100	0.6990	0.4949	0.6118	0.4685
2.0938	2.0326	1.9664	1.8805	1.6021	1.3671	1.3844	1.3279	1.2472	1.0110	1.0212	0.9720	0.9363	0.9456
2.1284	2.0401	1.9625	1.8470	1.5551	1.2506	1.3010	1.1730	1.1663	0.9530	0.9542	0.7959	0.8880	0.7696
2.0629	2.0140	1.9854	1.8988	1.6076	1.3408	1.4111	1.2821	1.2632	1.0110	1.0607	0.9720	0.9363	0.9456
2.1070	1.9895	1.8995	1.7702	1.4734	1.1367	1.1978	1.1061	1.0544	0.8861	0.9031	0.7959	0.8337	0.7696
2.0076	1.9306	1.8617	1.7644	1.4881	1.2159	1.2926	1.1730	1.1461	0.9530	0.9777	0.7959	0.9128	0.9456
1.7969	1.8393	1.8517	1.8202	1.5792	1.3128	1.3844	1.2310	1.2218	1.0110	1.0000	0.7959	0.8880	0.9456
2.1139	2.0499	2.0036	1.9181	1.6445	1.3919	1.4363	1.2821	1.2389	1.0110	1.0414	0.7959	0.9363	0.9456

For Kay-1 Well, Chondrite Normalized

4.3.1 Provenance and Tectonic Settings

The sediments deposited in the Active Continental Margins show an REE pattern intermediate between a "typical andesite patterns (McLennan, 1989). Thus, most active continental margin sediments display intermediate REE abundances, variable LREE enrichments and variable negative Eu-anomalies, with Eu/Eu* in the range of 0.6 – 1.0 (McLennan, 1989), as against the Passive Margin provenance is characterized by a uniform REE pattern which is similar to that of PAAS, (McLennan, 1989; Bhatia, 1985).

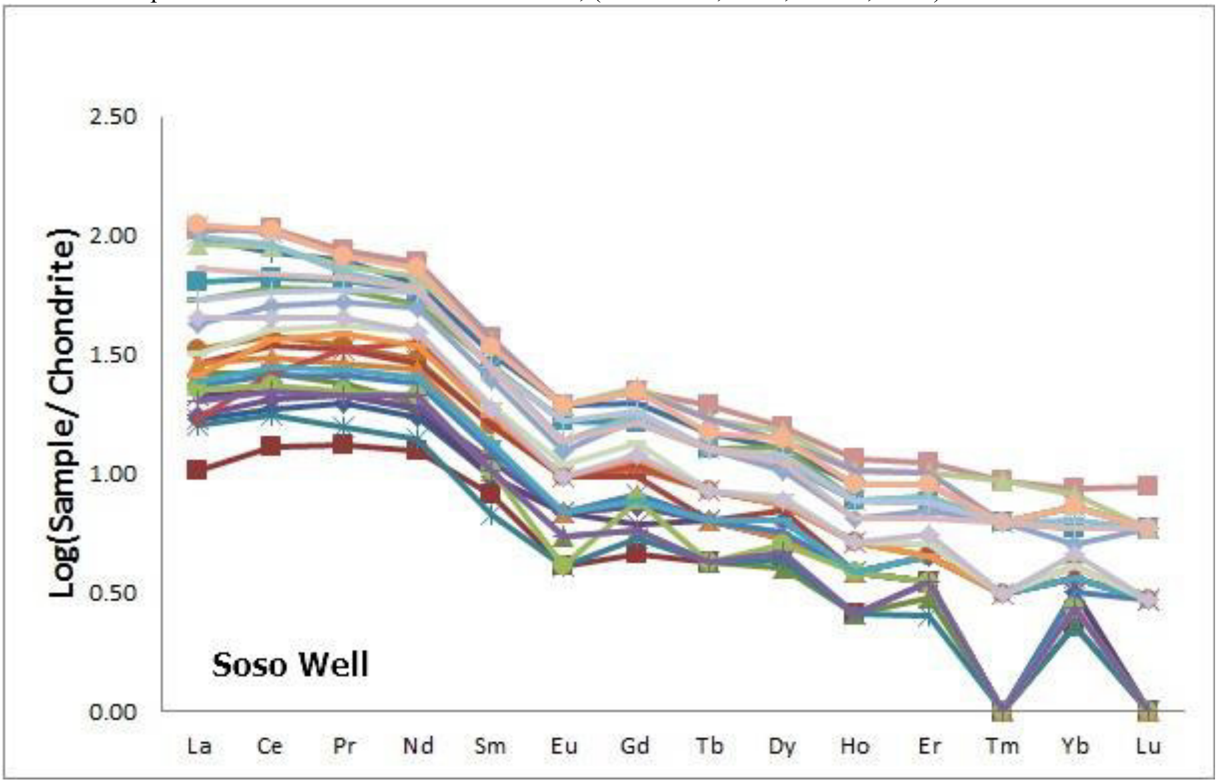


Fig 10 a: Chondrite-Normalized Rare Earth Element plots for the Sediments in Soso Well, western Niger Delta Basin
(Normalizing factor from Wakita et al, 1971)

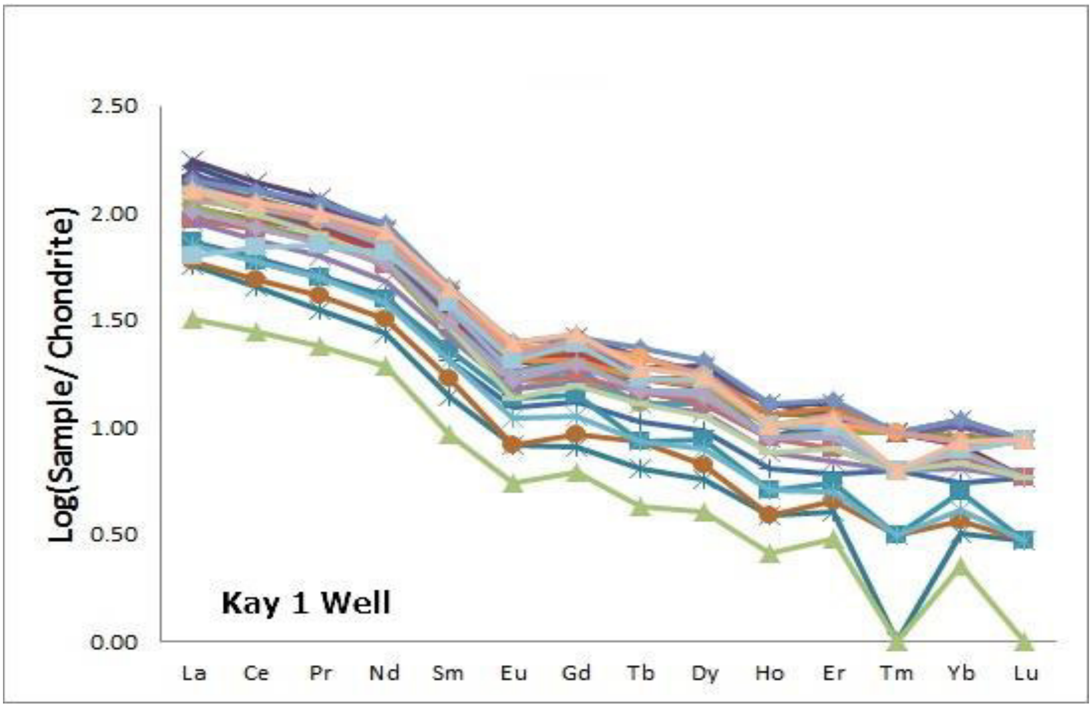


Fig 10 b: Chondrite-Normalized Rare Earth element plots for the Sediments in Kay-1 Well, western Niger Delta Basin (Normalizing factor from Wakita et al, 1971)

The results presented in Table 5 revealed an REE pattern that shows an LREE enrichment (designated by high La/Sm). Compared to the average PAAS and UCC, the sediments from Soso and Kay 1 wells western

Niger Delta have relatively lower LREE (i.e., $La/Sm)_N$; (~0.98 – 1.67). Also, $(La/Yb)_N$ ratios; (~1.97 – 5.46) record a low value with respect to PAAS and UCC and a higher Eu/Eu* ratios record an average of 0.84 relative to PAAS and UCC which are both 0.69. This suggests a deposition in an Active Continental Margin tectonic environment.

Light REE enrichment, negative Eu anomaly suggest a felsic composition for the sediments in Soso and Kay-1 well. McLennan *et al*. (1993) have defined four distinct provenance components on the basis of geochemical compositions (Table 6). These components include the following: Old Upper Continental Crust (OUC), Recycled Sedimentary Rocks (RSR), Young Undifferentiated Arc (YUA), Young Differentiated Arc (YDA) and Exotic components.

The Old Upper Continental Crust Components constitute the old, well-differentiated upper continental crust that is characterized by a substantial Eu anomaly. The Recycled Sedimentary Rocks component comprises recycled sedimentary and metasedimentary rocks. The Young Undifferentiated Arc component represents the young (dominantly mantle derived) igneous arc material (volcanic or plutonic) that has not undergone significant intra-crustal differentiation (i.e., it has not undergone plagioclase fractionation and therefore show no Eu anomalies). The Young Differentiated Arc provenance component constitutes the young (mantle derived) volcanic or plutonic igneous rocks from island and continental arcs that have undergone significant intra-crustal differentiation. The general geochemical characteristics of sediments derived from these four provenance types are summarized in Table 6

Table 6: Geochemical characteristics of sediment derived from different provenance types (After McLennan et al., 1993; Girty et al., 1996)

Provenance Type	Eu/Eu*	Th/Sc	Th/U	Others
Old Upper Continental Crust	0.6 – 1.1	~1.0	>3.8	Evolved major element compositions (eg., high Si/Al, CIA); High LILE abundances: uniform compositions.
Recycled Sedimentary Rocks	0.6 – 1.1	≥1.0	>3.8	Evidence of heavy mineral concentration from trace elements (eg., Zr, Hf for Zircon)
Young Differentiated Arc	0.5 - 0.9	~1.0 to < 0.01	<3.0	Evolved major element compositions (eg., high Si/Al, CIA); High LILE abundances: variable compositions
Young Undifferentiated Arc	~1.0	~1.0 to < 0.01	< 3.0	Un-evolved major element compositions (eg., low Si/Al, CIA); High LILE abundances: Variable compositions.

However, the studied sediments in Soso and Kay-1 wells share the properties of the Old Upper Continental Crust, The Recycled Sedimentary Rocks and The Young Differentiated Arc provenance. This further confirms the mixed provenance source for the sediments retrieved from Soso and Kay-1 wells, western Niger Delta.

4.4 Environment of Deposition

The relationship between Al_2O_3, K_2O+Na_2O+CaO and Fe_2O_3+MgO, Englund and Jorgensen (1973), forms the basis on which this chemical classification was made. The AKF-plot depicts the depositional environment of the analysed sediments by presenting a gradual transition of the sediments of the basin from continental to transitional depositional environment as they basically fall within the transition zone. (Fig: 11)

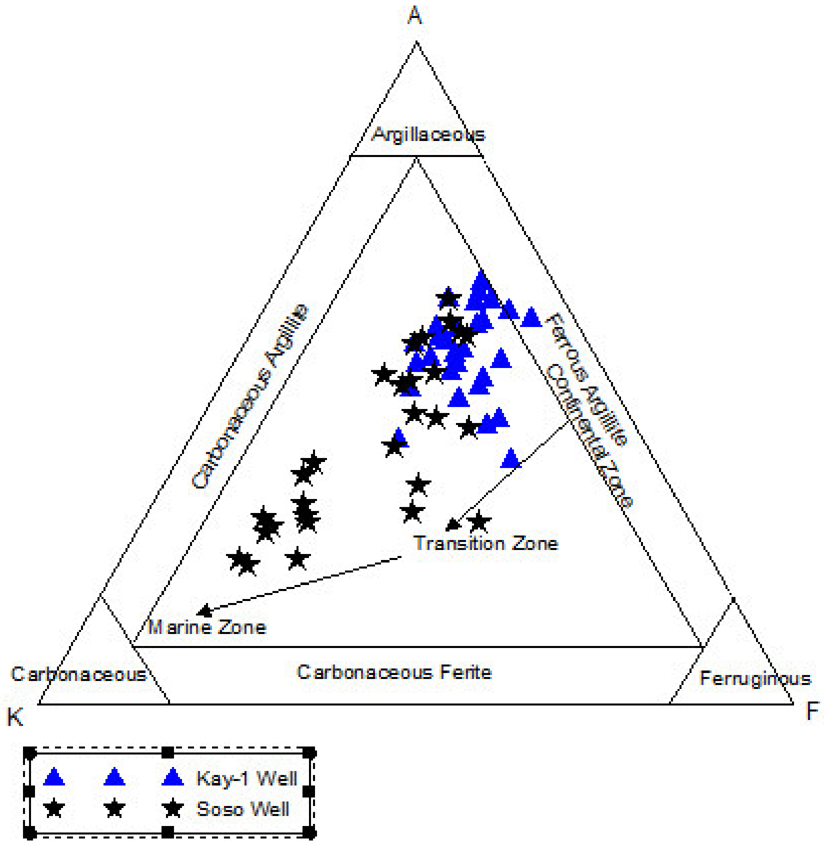
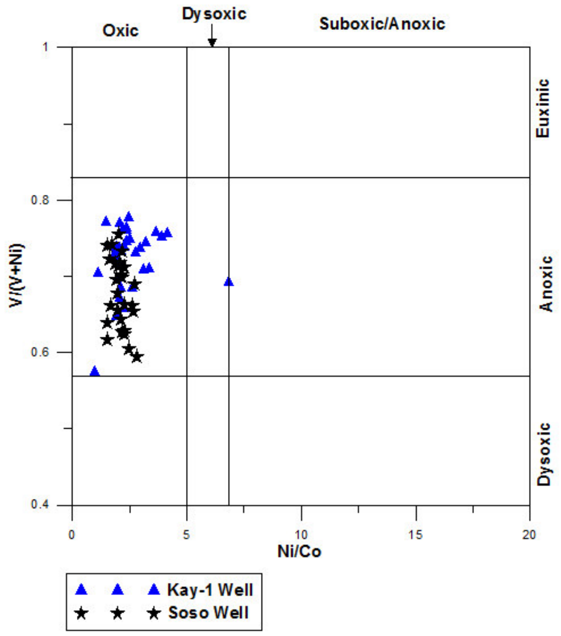


Fig 11: AKF-Ternary Plot for Kay 1 and Soso Wells, western Niger Delta (After Englund and Jorgensen, 1973)

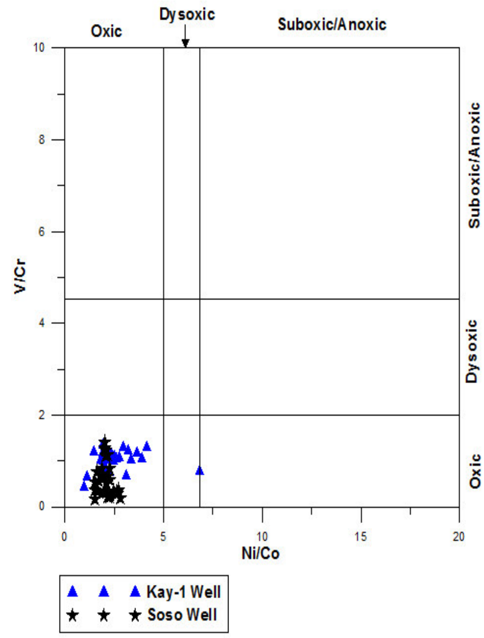
A: Al_2O_3 K: K_2O+Na_2O+Cao, F: Fe_2O_3+MgO

However, there exist several geochemical ratios ;(Mn, V, Cr, Ni, Co, Cu etc) used to determine the conditions of sediment deposition. The data obtained from the trace element analysis shows an inferred condition of deposition of sediments. The trace element indices; V/Ni, V/Cr, Ni/Co and V/(V+Ni) have been used severally to infer paleo-redox condition during sedimentation, Lewan 1984;Hatch and Leventhal, 1992; Jones and Manning 1994; Sageman and Lyons ,2003; Harris et al., 2004; MacDonald et al., 2010; Fu et al., 2011.

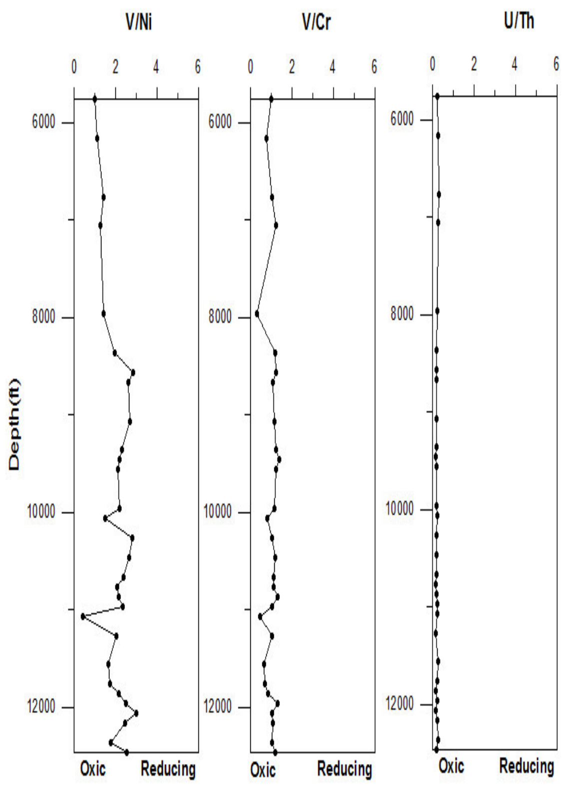
Lewwan 1984 showed that V/(V+Ni) for organic matter that accumulates under euxinic condition should be greater than 5 and less than 0.46 for oxic depositional conditions but between 0.46 and 0.57 for dysoxic condition. This view was supported by Wignal (1994). Hatch and Leventhal (1992), also suggest that V(V+Ni) ratio > 0.84 infers euxinic conditions, 0.5-0.82 infers anoxic conditions. Jones and Manning (1994) were of the opinion that V/Cr ratio of < 2 inferred oxic conditions, 2-4.25 dysoxic conditions and > 4.25 anoxic to suboxic conditions. They also used Ni/Co ratio of <5 to infer oxic conditions, 5-7 for dysoxic condition and > 7 for suboxic to anoxic conditions. However, Ni/Co had been previously used by Dypvik, 1984.



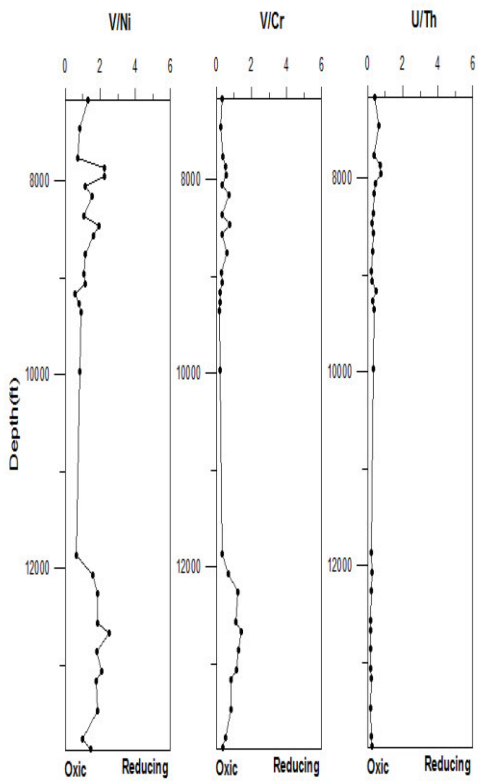
Pot of v/(v+Ni) against Ni/Co



Plot of V/Cr against Ni/Co



Kay-1 Well



Soso Well

Fig 12: Inorganic Geochemical Proxies for conditions of deposition of sediments

It was observed in this study that a fairly good pact exist between the varying indices that estimate redox conditions as the V/Cr, Ni/Co predicts an oxic condition for the analysed sediments while V/Ni gives a suboxic condition and V/(V+Ni) exhibits a dysoxic condition of deposition.

Table 8: Inorganic Geochemical Proxies for sediments from Soso and Kay-1 Wells

	Soso Well			Kay-1 Well			
Proxy	Min	Max	Ave	Min	Max	Ave	Remarks
V/Ni	1.46	3.08	2.17	1.36	3.51	2.68	Mainly Suboxic
V/Cr	0.18	1.41	0.57	0.29	1.35	1.01	Oxic
Ni/Co	1.51	2.83	2.1	0.99	6.85	2.66	Oxic
V/(V+Ni)	0.59	0.75	0.68	0.58	0.78	0.72	Dysoxic

4.5 Rock Eval and TOC

The amount of organic matter present in sedimentary rocks is measured as the Total Organic Carbon (TOC) content. This serves as the screening for source rock analysis. Adequate amount of organic matter measured as percentage total organic carbon (TOC) is a pre-requisite for sediment to generate oil or gas (Conford, 1986) and a measure of the organic richness of sedimentary rocks (Jarvie, 1991).

Rock-Eval pyrolysis helps to define the thermal maturity of the organic matter, its petroleum potential and its ability to generate oil, gas or oil and gas. This pyrolysis gives rise parameters as S1, S2, S3, hydrogen index (HI), oxygen index (OI), production index (PI) and Tmax.

The TOC and Rock Eval results of the analysed shale samples are presented in Table 9. Moderately High TOC values, 4.18-8.09 wt. % ≈ 6.18wt. %. This is an implication for organic matter generation. TOC values above 0.5wt. % is considered as a minimum for clastic source rocks to generate petroleum (Tissot and Welte, 1984, Dow, 1977; Unomah and Ekweozor, 1993).

The values of the free oil content, S1 range from 0.8–14.1 mgHC/g with a mean value of 5.72 mgHC/g, this is greater than 1 for all the samples, except one, and it is indicative of an oil show (Wapples, 1985). The source rock potential (S2) ranges from 5.78 – 32.07mg HC/g rock with a mean value of 14.83 mgHC/g. This is indicative of the quantity of hydrocarbons production, should burial and maturation continue, (Akande et al., 2005; Klenme and Ulmishek, 1991 and Wapples, (1985).

Table 9: Rock Eval Pyrolysis Results for Sediments from Soso and Kay-1 Wells

Client ID	Depth (ft)	RE	RE			GP	Tmax	Ro,%	HI	OI	S2/S3	S1/TOC*100	PI
		TOC	S1	S2	S3	(S1+S2)	(°C)						
w-01	8460	6.09	10.57	13.23	3.35	23.8	427	0.526	217.24	55.01	3.95	173.56	0.44
w-02	12260	4.3	1.61	12.99	2.75	14.6	427	0.526	302.09	63.95	4.72	37.44	0.11
w-03	12560	4.18	3.70	8.03	2.11	11.73	435	0.67	192.11	50.48	3.81	88.52	0.32
w-04	13160	7.27	14.10	17.99	3.58	32.09	428	0.544	247.46	49.24	5.03	193.95	0.44
w-05	13460	6.16	12.11	15.01	3.05	27.12	422	0.436	243.67	49.51	4.92	196.59	0.45
w-06	13760	7.36	11.51	32.07	3.94	43.58	440	0.76	435.73	53.53	8.14	156.39	0.26
S-07	10060	7.78	1.51	21.99	1.75	23.5	433	0.634	282.65	22.49	12.57	19.41	0.06
S-08	10860	5.15	0.80	8.04	1.3	8.84	438	0.724	156.12	25.24	6.18	15.53	0.09
S-09	11760	8.09	1.33	13.86	1.67	15.19	439	0.742	171.32	20.64	8.30	16.44	0.09
S-10	11960	6.8	1.10	5.78	1.1	6.88	436	0.688	85.00	16.18	5.25	16.18	0.16
S-11	12260	4.88	1.08	5.94	1.16	7.02	440	0.76	121.72	23.77	5.12	22.13	0.15

TOC: Total Organic Carbon wt %
S1: volatile hydrocarbon (HC) content mgHC/g rock,
S2: remaining HC generative potential mgHC/g rock. S3: carbon dioxide content. mgCO2/g rock,
%R_0: measured Vitrinite reflectance.
HI: Hydrogen Index; S2x100/TOC, mgHC/gTOC
OI: Oxygen index; S3x100/TOC, mgCO2/gTOC
PI: Production Index; S1/(S1+S2)
GP = Petroleum Generic Potential=S1+S2

Tmax ranges from 422-440°C, an indication of an early to medium maturation stage while the HI varies extensively from 85.0 to 435.73mg HC/g TOC. High S2 and HI values, moderately high TOC content with a high hydrocarbon generic potential, GP are indicative of a very good to excellent source potential for the shale samples (Table 9).

4.5.1 *Organic Matter Type and Quality*

The amount and maceral composition of kerogen determine petroleum potential and can differ vertically or laterally within a source rock, Peters et al 1994. The organic matter type in a sedimentary rock, among other conditions influences to a large extent the type and quality of hydrocarbon (Robert, 1980; Tissot and Welte, 1984).

Cross plot of Hydrogen Index, (HI), mgHC/g TOC versus Oxygen Index, (OI), mgCO_2/g TOC (Fig. 13) as well as the plots S2 mg/g vs. TOC.wt. % (Fig 14) indicates the kerogen type present and the respective petroleum potential, Dahl et al, 2004. This gives kerogen types II/III and type III for the shale samples.

However, the plots of HI and Tmax delineate organic matter quality and maturity (Fig.15). Type II-III points to organic matter having prospects to generate gas and oil at appropriate maturation (Dow, 1977; Peters, 1986). The plots fall within the type II-III and type III kerogen and only one in the type II quadrant, thus indicating that the sediments would generate oil-gas and gas respectively. Peters (1986) suggested that at thermal maturity equivalent to vitrinite reflectance of 0.6% (Tmax 435ºC). Rocks with HI > 300mgHC/gTOC produce oil (strictly analytical of Type II), those with HI between 150 mgHC/gTOC and 300mgHC/gTOC produce oil and gas (comprises more Type II-III than II), those with HI between 50 mgHC/gTOC and 150 mgHC/gTOC produce gas thus indicating the absence of significant amounts of oil generative lipid materials (Type III and IV) and those with HI < 50 mgHC/gTOC are inert. The analysed shale and silty shale samples revealed HI values ranging between 85.0 to 436mg HC/g TOC. This indicates oil and gas prone.

Petroleum generic potential (GP); (S1+S2) ranges from 6.88- 43.58 which are generally greater than 2KgHc/ton of rock expected for good source rock (Dymann et al, 1996). This suggests oil and gas potential (Tissot and Welte, 1984; Dymann et al. 1996; Akande and Ojo 2002).

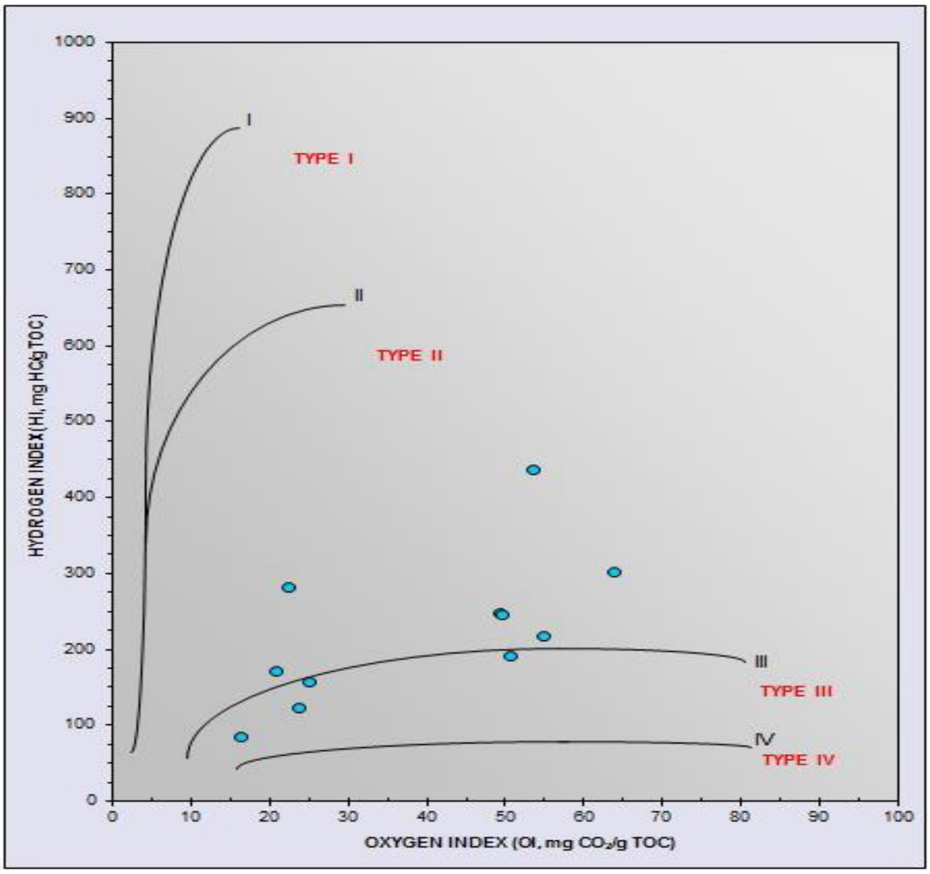


Fig 13: Cross plot of HI, mgHC/g TOC versus Oxygen Index, OI, mgCO$_2$/g TOC

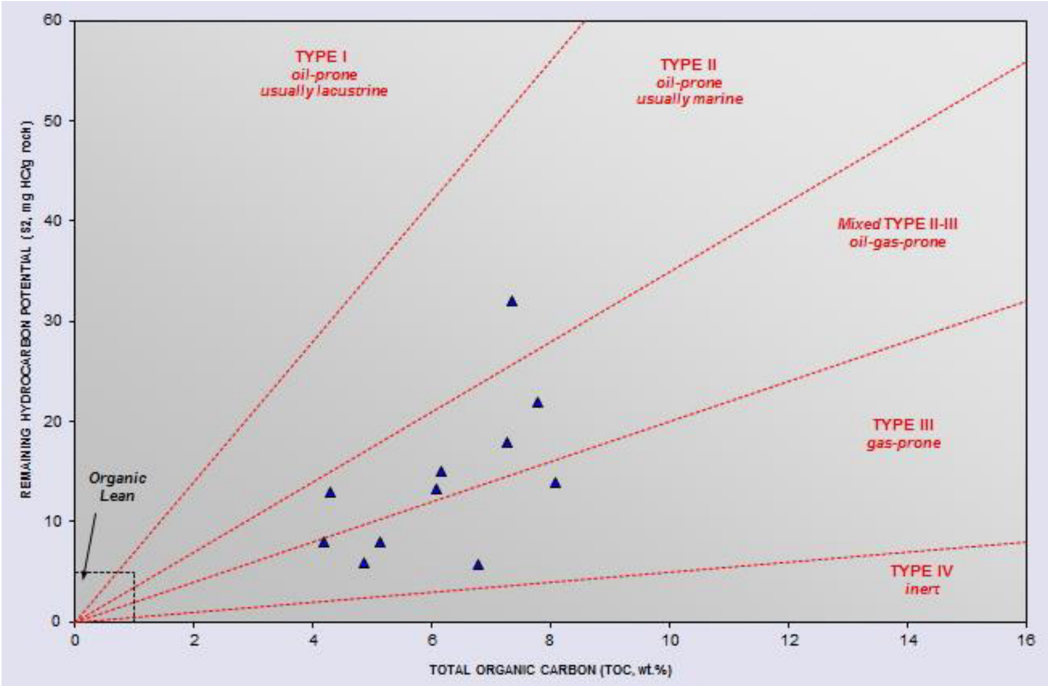


Fig 14: The plots of HI (mgHC/gTOC) against TOC wt. % derived from Rock-Eval pyrolysis of samples from Soso and Kay-1 Well

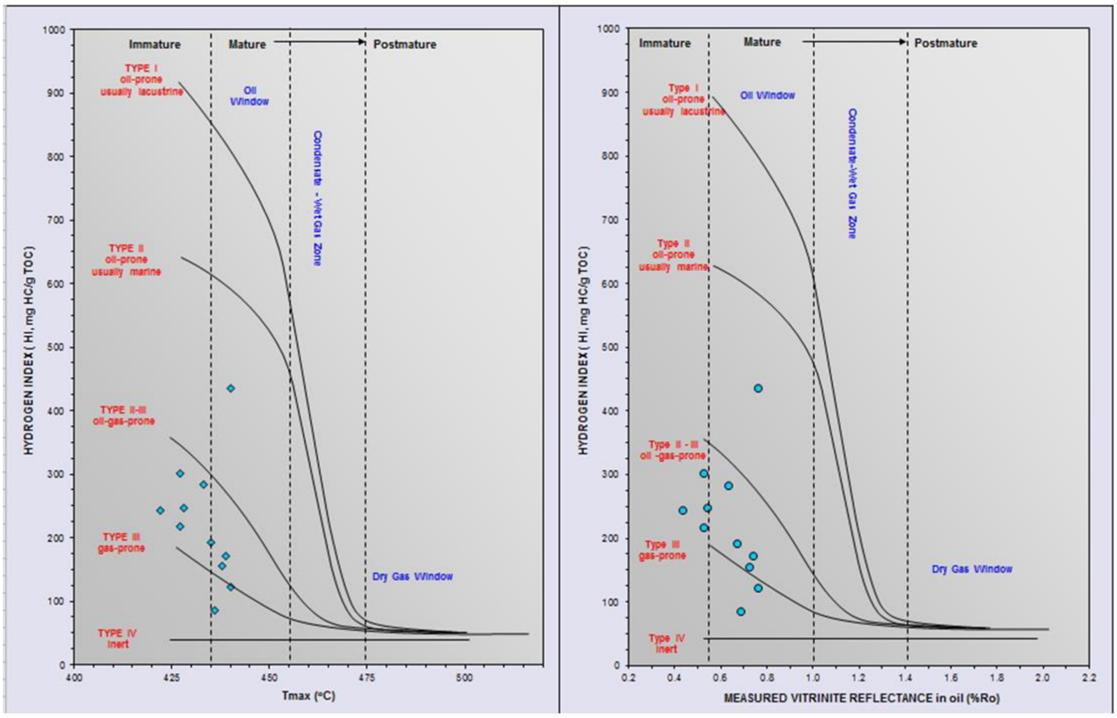


Fig 15: Plot of HI versus Tmax as well as HI versus %Ro, (Kerogen Type and Maturity).

5 Summary and Conclusion

A combined investigation of elements distribution and organic geochemistry carried out on the sediments derived from Soso and Kay 1 Wells western Niger Delta to infer their geochemical characteristics, Paleoenvironment of deposition, depositional conditions and tectonic settings of the source region have revealed the following:

The lithologic study revealed that the well was dominated by argillaceous amidst few arenaceous types of sediments which are rich in SiO_2 and depleted in Al_2O_3 with mean major elemental composition that are fairly in agreement with those of Wedepohl, 1971, NASC, UC and PAAS.

The contents of Al_2O_3 and SiO_2 always change in the reverse direction and a significant amount TiO_2 and K_2O suggest that the sediments are rich in clay minerals. This however has an influence on the organic matter enrichment.

The plots of the sediments from the wells on the tectonic setting discriminant functions diagrams indicate an active continental margin and a mixed provenance

The enrichment of the sediments with High LREE and the negative Eu anomaly suggest a felsic origin while the flat HREE is indicative of a mafic input.

The CIA values for the sediments indicate a moderate degree of weathering in the source area. The application of source area weathering using other parameters; CIW, PIA, and RR values confirmed that the sediments have gone through a low to moderately high chemical weathering in the source area.

TOC and Rock Eval studies of the selected core samples retrieved from the wells, Western Niger Delta Basin show that the sediments have good to excellent organic matter which is of Type II/III and Type III from the Shaly intervals of the Agbada formation. The hydrocarbon source potential indicates predominantly immature to marginally mature sediments which are oil-gas and gas prone.

It could therefore be deduced that the organic matter are derived from derivatives of land vegetation such as plant fragments, spores and pollens and marine planktons, algae and bacteria which have become incorporated into sediments. Most of the world's oil belongs to this group where the H: C ratio is usually 1.4

In general, the results obtained however revealed that all the sediments were sourced from mixed provenances and have undergone a low through moderate to a marginally high degree of weathering and deposited within the Active Continental Margin in a transitional environment in an oxic to dysoxic depositional conditions. In addition, the shales are immature to marginally mature possessing organic matter of Type II and II-III, an indication of oil-gas generation capability.

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