Trace element geochemistry of kerogens from the central Niger Delta

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Abstract

Trace elements in kerogens isolated from shale samples obtained from oil wells in the central Niger Delta were determined using atomic absorption spectrometry, with the aim to determine the depositional environment and source of the organic matter. The results showed that the concentrations of the elements in the kerogens ranged from 1.50 to 6470.00 ppm and 3.50 to 7946.00 ppm for Wells X and Y, respectively. In both wells, Fe was the most abundant element, while cobalt had the least concentration. Nickel had an enhanced concentration over vanadium in Well X, while the reversed was the case in Well Y. The distribution patterns of the trace elements indicate that most of the kerogens from the two wells have similar origin. The geochemical ratios calculated from the concentrations of the trace elements revealed kerogens from Well X have terrestrial organic matter input, while kerogens from Well Y have both mixed marine/terrestrial organic matter and terrestrial inputs. The concentrations of the trace elements also revealed that the organic materials of samples from Well X were deposited under oxic conditions, while those from Well Y were deposited under oxic–suboxic conditions.

Keywords Kerogen · Trace element · Origin · Depositional environment · Central Niger Delta

Introduction

The distribution of trace elements in sedimentary organic matter or source rock has become an important subject in petroleum geochemistry and consequently in petroleum exploration (Filby 1994; Alberdi-Genolet and Tocco 1999; Akinlua et al. 2007; Galarraga et al. 2008; Akinlua et al. 2010). The abundance, distribution pattern, and ratio of trace elements in kerogens or source rocks have become indispensable tools in the evaluation of depositional environment, origin and thermal maturity of organic matter (Tribovillard et al. 2006; Galarraga et al. 2008; Akinlua et al. 2007, 2010). Trace elements are particularly useful as indicators of palaeoenvironmental condition of sediments because of differential geochemical behaviour at different oxidation states of the elements (Tribovillard et al. 2006). It has been proven over time that the source of organic matter has profound consequence on the abundance of trace elements in kerogens or

source rocks or oils (Lewan 1984; Udo et al. 1992; Akinlua et al. 2007, 2010).

The concentrations of trace elements and their ratios such as cobalt/nickel (Co/Ni), molybdenum/nickel (Mo/Ni), vanadium/nickel (V/Ni) and V/(V + Ni) have been found to be reliable geochemical tools to characterise sediments on the bases of their origin, palaeoredox condition during deposition and maturity (Barwise 1990; Filby 1994; Alberdi-Genolet and Tocco 1999; Tribovillard et al. 2006; Akinlua et al. 2007, 2010). Therefore, in this study, we utilised trace element abundances and their ratios for the characterisation of kerogens from the central Niger Delta since it is cheaper to generate data on trace elements than the data on organic content of source rocks. Also there is paucity of data on trace element geochemistry of kerogens from central Niger Delta.

Geological setting

The Niger Delta sedimentary basin is one of the most prolific hydrocarbon province in the Africa. It is located in the Gulf of Guinea and covers an area of about 75,000 km² (Haack et al. 2000), and consists of 12 km total thickness of regressive clastic sequences as discussed in the literature (Short and Stauble 1967; Avbovbo 1978; Doust and

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Fig. 1 Stratigraphic columns showing the three Formations of the Niger Delta Modified from Doust and Omatsola (1990)

Omatsola 1990; Kulke 1995). The Niger Delta evolution is related or linked with the formation of a rift triple junction during the separation of the South America and Africa plates in the Late Jurassic (Burke 1972; Whiteman 1992), that led to the opening of the Atlantic Ocean and gave rise to marine intrusion as evidenced by marine sedimentation in the Benue Trough and the Anambra Basin during the Cretaceous period (Doust and Omatsola 1990). On the basis of subsurface stratigraphy, the Tertiary Niger Delta is divided into three lithostratigraphic units (Fig. 1), which are Akata, Agbada and Benin Formations. The topmost Benin Formation is a continental deposit of alluvial and upper coastal plain sands with an age ranging from latest Eocene to Recent. The Agbada Formation, which consists of an intercalated sandstone and shale unit, underlies the Benin Formation. It is the major petroleum-bearing unit and began in the Eocene and continues into the Recent. The Akata Formation underlies the entire delta and is typically overpressured. The formation is essentially of deep marine origin and is composed of thick shale sequences with an age ranging from the Palaeocene to Recent (Avbovbo 1978).

Experimental

A total of forty-two shale samples, which were obtained from one of the oil companies through the Department of Petroleum Resources, comprising of twenty-three from Well X and nineteen from Well Y from the central Niger Delta were selected using a combination of geophysical well log and visual examination (Fig. 2). The rock samples were pre-extracted with dichloromethane (DCM) using Soxhlet

Fig. 2 Map of the Niger Delta showing location of the study area

extraction for removal of soluble organic matter. Heating mantle with thermostat was used in order to control the heat during the Soxhlet extraction process. The process involves refluxing the rock samples with the solvent for 24 h. Isolation of kerogen from the pre-extracted sample was effected by treatment with HCl for removal of carbonates, removal of carbonates was ensured until effervescence ceases and the silicates were destroyed by treatment with HF, and removal of silicates was ensured until the residual rock material is no longer coarse and concentrated HNO_3 was added for the removal of pyrites. The isolated kerogens were digested into aqueous solution with a mixture of H_2O_2 and HNO_3 to make them amenable to atomic absorption spectrometric analysis. Trace elements in the aqueous solutions were determined by atomic absorption spectrometry (AAS) using PerkinElmer AAnalyst 200 spectrophotometer.

Results and discussion

Distribution of trace elements in the kerogen samples

The concentrations of the trace elements in kerogen samples from Well X ranged from 1.50 to 6470 ppm (Table 1). Iron (Fe) is most abundant element with an average concentration of 3045 ppm, followed by manganese (Mn) that has an average concentration of 120.02 ppm, while cobalt has the least concentration. Nickel (Ni) is the most abundant biophile element, with an average concentration of 63.52 ppm (Table 1). The enrichment of nickel over vanadium in this well (Fig. 3) indicates that oxic conditions prevailed during sedimentation.

Trace elements concentrations of kerogen samples from Well Y ranged from 3.50 to 7946.00 ppm with a mean value of 3317.78 ppm. In this well, iron (Fe) is also the most abundant element with an average of 3317.78 ppm (Fig. 3), followed by manganese (Mn) with concentration ranging from 55.5 to 243.0 ppm with a mean value of 131.05 ppm, while Cobalt has the least concentration. Vanadium (V) is the most

Table 1 Trace elements composition (in ppm) of kerogens from Well X in the central Niger Delta

Sample	Depth (m)	V	Cr	Co	Ni	Mn	Fe	Cu
X1	1460	89.00 ± 3.50	13.40 ± 1.30	11.00 ± 1.00	61.00 ± 2.50	212.00 ± 8.00	6470.00 ± 68.18	59.50 ± 4.50
X2	1478	77.00 ± 3.00	7.71 ± 0.70	6.50 ± 0.70	57.00 ± 2.15	189.00 ± 6.01	3250.00 ± 41.53	46.50 ± 3.55
X3	1497	54.00 ± 2.00	16.50 ± 1.50	8.50 ± 0.91	39.50 ± 1.50	155.00 ± 5.00	3088.00 ± 38.18	14.00 ± 1.50
X4	1515	20.50 ± 1.15	15.50 ± 1.50	1.50 ± 0.05	16.00 ± 0.50	171.00 ± 5.50	3650.00 ± 44.10	24.50 ± 0.55
X5	1533	123.00 ± 3.00	11.71 ± 1.05	8.50 ± 0.71	168.00 ± 5.16	202.50 ± 7.00	2270.00 ± 23.50	32.00 ± 2.33
X6	1551	59.00 ± 2.05	9.50 ± 0.95	7.02 ± 0.50	67.00 ± 2.68	99.50 ± 4.10	2041.00 ± 22.35	52.50 ± 2.10
X7	1570	63.00 ± 2.15	14.40 ± 1.14	9.01 ± 0.55	44.50 ± 1.50	107.00 ± 4.50	2170.00 ± 21.05	33.00 ± 3.00
X8	1606	102.50 ± 3.00	8.05 ± 0.85	5.01 ± 0.50	71.00 ± 3.00	161.5 ± 3.00	2470.00 ± 26.88	15.00 ± 1.15
X9	1643	48.50 ± 1.80	7.50 ± 0.00	10.02 ± 1.04	33.50 ± 1.05	87.50 ± 2.50	3088.00 ± 37.18	24.50 ± 1.75
X10	1661	87.00 ± 2.70	21.05 ± 1.73	12.01 ± 1.28	93.00 ± 3.15	117.00 ± 1.80	1201.00 ± 14.02	7.00 ± 0.12
X11	1698	37.50 ± 1.30	11.50 ± 1.05	10.00 ± 1.00	56.00 ± 2.00	106.00 ± 3.50	2201.00 ± 18.55	13.50 ± 1.05
X12	1716	39.00 ± 1.33	6.50 ± 0.05	13.00 ± 1.50	49.50 ± 3.00	78.00 ± 2.00	4101.00 ± 46.15	15.01 ± 2.00
X13	1734	41.00 ± 0.91	13.50 ± 1.35	16.50 ± 1.50	155.00 ± 5.15	249.50 ± 8.30	2332.00 ± 23.02	28.50 ± 2.08
X14	1753	53.50 ± 1.55	17.05 ± 1.70	9.50 ± 0.85	74.00 ± 2.45	64.00 ± 1.85	6374.00 ± 56.22	16.50 ± 1.40
X15	1771	39.50 ± 1.50	6.50 ± 0.05	7.50 ± 0.71	68.00 ± 2.00	92.50 ± 1.95	2370.00 ± 18.84	23.50 ± 1.35
X16	1789	62.50 ± 2.25	8.15 ± 0.85	15.0 ± 1.50	70.00 ± 3.00	75.00 ± 1.50	4332.00 ± 47.71	25.00 ± 2.00
X17	1826	32.50 ± 1.00	12.50 ± 0.98	5.00 ± 0.50	21.50 ± 1.10	65.00 ± 0.95	3894.00 ± 37.19	44.00 ± 2.88
X18	1844	29.00 ± 1.05	9.55 ± 0.65	5.50 ± 0.55	47.00 ± 1.35	159.00 ± 4.23	2104.00 ± 21.00	22.00 ± 1.82
X19	1881	44.00 ± 1.40	5.50 ± 0.01	4.50 ± 0.35	51.50 ± 1.50	82.50 ± 1.90	3101.00 ± 31.05	5.50 ± 0.51
X20	1936	52.50 ± 2.15	17.00 ± 1.50	3.50 ± 0.30	63.50 ± 2.03	101.00 ± 3.10	2101.00 ± 17.71	5.00 ± 0.00
X21	1990	33.50 ± 0.95	6.10 ± 0.05	7.01 ± 0.51	66.00 ± 2.50	51.00 ± 0.75	3332.00 ± 41.05	18.00 ± 2.00
X22	2009	19.10 ± 0.91	9.20 ± 0.95	3.00 ± 0.30	21.50 ± 1.05	44.00 ± 0.60	2374.00 ± 19.75	16.00 ± 1.22
X23	2027	57.00 ± 2.00	11.05 ± 1.05	8.00 ± 0.85	67.00 ± 2.50	91.00 ± 2.10	1721.00 ± 17.05	12.50 ± 1.12
Average		54.96 ± 26.09	11.28 ± 4.22	8.13 ± 3.76	63.52 ± 36.16	120.02 ± 56.24	3045.00 ± 1323.97	24.07 ± 14.78

$n=3$

Fig. 3 Relative distribution of trace elements in kerogens from the wells

abundant biophile element, with a mean value of 97.82 ppm (Table 2). The results in this well show an enhanced concentration of vanadium over that of nickel (Table 2), which suggests deposition of the organic matter in reducing environment (Lewan 1984).

The concentrations of elements in the two wells show no particular trend with depth. The trace elements distribution patterns of kerogens in the two wells (Figs. 4, 5) were used to evaluate their similarity or otherwise. Most of the samples from Well X have similar distribution patterns except some samples (Fig. 4). Kerogen samples from Well Y show similar trace elements distribution patterns (Fig. 5), indicating similar genetic origin.

Table 2 Trace elements composition (in ppm) of kerogens from Well Y in the central Niger Delta

Sample	Depth (m)	V	Cr	Co	Ni	Mn	Fe	Cu
Y1	2243	277.50 ± 7.50	33.50 ± 1.90	24.00 ± 1.25	114.00 ± 4.98	243.00 ± 9.50	5212.00 ± 52.14	56.50 ± 3.50
Y2	2353	134.50 ± 5.65	21.10 ± 1.15	19.00 ± 0.95	61.50 ± 2.12	179.00 ± 6.95	4489.50 ± 44.44	51.50 ± 3.30
Y3	2518	97.00 ± 4.50	17.55 ± 1.05	12.00 ± 0.64	49.00 ± 1.71	157.00 ± 5.25	3307.50 ± 27.71	44.50 ± 3.20
Y4	2573	135.00 ± 5.65	9.00 ± 0.87	17.00 ± 0.89	55.00 ± 1.95	175.50 ± 6.75	5682.00 ± 54.36	21.50 ± 1.15
Y5	2627	124.50 ± 5.05	11.45 ± 0.92	6.50 ± 0.35	45.00 ± 1.50	115.50 ± 4.95	7946.00 ± 78.95	19.00 ± 0.98
Y6	2682	166.00 ± 5.82	18.00 ± 1.23	15.00 ± 0.79	85.50 ± 3.51	193.00 ± 8.15	2522.00 ± 15.10	36.00 ± 2.10
Y7	2737	96.00 ± 3.80	15.05 ± 1.15	11.00 ± 0.71	67.50 ± 2.35	166.00 ± 6.02	1702.50 ± 13.07	43.50 ± 2.25
Y8	2957	110.00 ± 4.15	12.50 ± 0.97	13.50 ± 0.75	77.00 ± 2.85	132.00 ± 4.42	1532.50 ± 12.97	24.00 ± 1.22
Y9	3066	87.00 ± 3.40	6.65 ± 0.65	7.00 ± 0.41	40.50 ± 1.13	181.00 ± 7.86	1489.50 ± 10.42	15.50 ± 0.85
Y10	3121	63.00 ± 2.35	9.95 ± 0.91	8.50 ± 0.62	52.00 ± 1.80	89.00 ± 4.10	2015.00 ± 17.05	14.50 ± 0.82
Y11	3176	89.00 ± 3.55	6.00 ± 0.55	10.50 ± 0.70	66.50 ± 2.30	106.00 ± 4.84	2175.00 ± 19.81	12.50 ± 0.76
Y12	3505	54.00 ± 1.92	4.50 ± 0.27	6.00 ± 0.30	35.00 ± 0.97	97.00 ± 4.78	3682.00 ± 32.26	15.50 ± 0.83
Y13	3615	33.00 ± 2.35	8.75 ± 0.77	3.50 ± 0.17	39.00 ± 1.05	149.00 ± 5.17	2312.50 ± 15.31	13.50 ± 0.79
Y14	3670	36.50 ± 1.25	11.04 ± 0.88	4.00 ± 0.23	13.50 ± 0.65	124.50 ± 5.04	2372.00 ± 17.02	33.00 ± 2.10
Y15	3889	112.00 ± 4.80	7.55 ± 0.71	6.50 ± 0.31	55.50 ± 1.95	106.50 ± 4.68	3031.50 ± 18.97	16.50 ± 1.05
Y16	3944	51.00 ± 1.85	10.08 ± 1.02	9.00 ± 0.68	45.00 ± 1.55	62.50 ± 3.11	2625.00 ± 17.60	42.00 ± 2.40
Y17	4164	34.00 ± 0.96	7.07 ± 0.65	5.00 ± 0.28	38.00 ± 1.01	67.00 ± 3.28	4945.00 ± 48.50	11.00 ± 0.90
Y18	4218	102.00 ± 3.58	15.05 ± 1.25	21.00 ± 1.13	79.00 ± 3.22	91.00 ± 4.14	3702.50 ± 37.17	38.00 ± 3.20
Y19	4273	56.50 ± 2.15	12.85 ± 1.02	6.50 ± 0.37	48.50 ± 1.65	55.50 ± 3.00	2294.00 ± 16.06	33.50 ± 2.20
Average		97.82 ± 57.74	12.51 ± 6.75	10.82 ± 5.99	56.16 ± 22.29	131.05 ± 50.51	3317.78 ± 1686.39	28.53 ± 14.52

Fig. 4 Trace elements distribution patterns of kerogens from Well X

Fig. 5 Trace elements distribution patterns of kerogens from Well Y

Origin of the organic matter

Previous studies have shown strong influence of origin of organic matter on the concentrations of trace elements in source rocks or oils especially those that have proven association with organic matter such as V, Ni and Co (Lewan 1984; Barwise 1990; Udo et al. 1992; Akinlua et al. 2007). The geochemical ratios derived from such trace elements have proven to be invaluable tools in evaluating the organic matter input of source rocks. The values of Co/Ni ratio for kerogen samples from the two wells are

presented in Tables 3 and 4. The Co/Ni ratios for Well X samples ranged from 0.05 to 0.30 (Table 4). About five samples (X4, X5, X8, X19 and X20) have Co/Ni ratios less than 0.1 suggesting terrestrial organic matter input, while the remaining samples have Co/Ni ratios higher than 0.1 which suggests marine source input (Udo et al. 1992). The values of Co/Ni ratio for kerogen samples from Well Y varied from 0.09 to 0.31 (Table 4), which suggests that most of the samples have marine organic matter input (Udo et al. 1992). An enhanced concentration of vanadium over that of nickel is an indication of marine organic

Table 3 Geochemical parameters for kerogen samples from Well X

Sample ID	Depth (m)	Co/Ni	V/Ni	Fe/V	V/(V + Ni)	TTE (ppm)
X1	1460	0.18	1.46	72.69	0.59	6915.90
X2	1478	0.11	1.35	42.21	0.58	3633.71
X3	1497	0.22	1.37	57.19	0.58	3375.50
X4	1515	0.09	1.28	178.05	0.56	3899.00
X5	1533	0.05	0.73	18.46	0.42	2815.71
X6	1551	0.11	0.88	34.59	0.47	2335.52
X7	1570	0.20	1.42	34.44	0.59	2440.91
X8	1606	0.07	1.44	24.10	0.59	2833.06
X9	1643	0.30	1.45	63.67	0.59	3299.52
X10	1661	0.13	0.94	13.81	0.48	1538.06
X11	1698	0.18	0.67	58.69	0.40	2435.50
X12	1716	0.26	1.27	105.15	0.44	4302.00
X13	1734	0.11	0.27	56.88	0.21	2836.00
X14	1753	0.13	0.72	119.14	0.42	6608.55
X15	1771	0.11	0.58	60.00	0.37	2607.50
X16	1789	0.21	0.89	35.40	0.47	4587.65
X17	1826	0.23	1.51	119.80	0.60	4074.50
X18	1844	0.12	0.62	72.55	0.38	2376.05
X19	1881	0.09	0.85	70.48	0.46	3294.50
X20	1936	0.06	0.83	40.02	0.45	2343.50
X21	1990	0.11	0.51	99.46	0.34	3513.61
X22	2009	0.14	0.89	124.29	0.47	2486.80
X23	2027	0.12	0.85	30.19	0.46	1967.55
Average		0.15	0.99	66.58	0.48	3326.98

TTE total trace elements**Table 4** Geochemical parameters for kerogen samples from Well Y

Sample ID	Depth (m)	Co/Ni	V/Ni	Fe/V	V/(V + Ni)	TTE (ppm)
Y1	2243	0.21	2.43	18.78	0.71	5960.50
Y2	2353	0.31	2.19	33.38	0.69	4956.10
Y3	2518	0.25	1.98	34.10	0.66	3684.55
Y4	2573	0.31	2.46	42.00	0.71	6095.00
Y5	2627	0.14	2.77	63.80	0.74	8267.95
Y6	2682	0.18	1.94	15.19	0.66	3035.50
Y7	2737	0.16	1.42	17.73	0.59	2101.55
Y8	2957	0.18	1.43	13.93	0.59	1901.50
Y9	3066	0.17	2.15	17.12	0.68	1827.15
Y10	3121	0.16	1.21	31.98	0.55	2251.95
Y11	3176	0.16	1.34	24.44	0.57	2465.50
Y12	3505	0.17	1.54	68.19	0.61	3894.00
Y13	3615	0.09	0.85	70.08	0.46	2559.25
Y14	3670	0.29	2.70	64.99	0.73	2594.54
Y15	3889	0.12	2.02	27.07	0.67	3336.05
Y16	3944	0.20	1.13	51.47	0.53	2844.58
Y17	4164	0.13	0.89	145.44	0.47	5107.07
Y18	4218	0.27	1.29	36.30	0.56	4048.55
Y19	4273	0.13	1.17	40.60	0.54	2507.35
Average		0.19	1.73	42.98	0.62	3654.67

matter input (Lewan 1984; Barwise 1990). It has also been reported that V/Ni ratio with values greater than 3 indicate marine organic matter, values from 1.9 to 3 indicate mixed marine and values less than 1.9 indicate terrestrial organic matter input (Galarraga et al. 2008). The values of V/Ni ratio for the kerogen samples from Well X ranged from 0.27 to 1.51 (Table 4), suggesting mainly terrestrial organic matter input. While the values of V/Ni ratio of Well Y kerogen samples ranged from 0.85 to 2.77, which suggests that source rock samples from Well Y contain organic matter that are of terrestrial and mixed marine/terrestrial origins. Samples from shallower depths are mainly of mixed organic matter input, while those from deeper depths are of terrestrial organic matter input.

The plot of V/Ni versus Co/Ni (Fig. 6) revealed that most of the samples from Well Y and all the samples from Well X are of terrestrial organic matter origin, while some kerogen samples (nine samples) from Well Y are of mixed marine/terrestrial organic matter origin, which is indicative of Type III and Type II/III kerogens. Dendrogram cluster analysis of the kerogen samples (Fig. 7) using the geochemical ratios of the biophile elements as variables was carried out to determine their similarity or otherwise. Two groups are evident: kerogen samples of mixed marine/terrestrial organic matter origin (nine samples) form one group, while kerogen samples of terrestrial organic matter origin constitute another group. Cluster analysis classified the kerogen samples based on organic matter origin. A plot of vanadium against nickel

Fig. 6 Cross-plot of Co/Ni versus V/Ni indicating that kerogens from the central Niger Delta have both terrestrial and mixed marine/terrestrial origins. (Modified after Galarraga et al. 2008)

Fig. 7 Dendrogram cluster analysis of kerogen samples from the central Niger Delta using Co/Ni, V/(V + Ni) and V/Ni as variables

(Fig. 8) also indicates that most of the samples from the two wells have terrestrial organic matter origin, while some kerogen samples from Well Y have mixed marine/terrestrial origin, which is in agreement with the results of plot of Co/Ni versus V/Ni.

Depositional environment of the organic matter

As the origin of organic matter has profound effect on the concentrations of trace elements so also the depositional environment of the organic matter (Lewan 1984; Barwise 1990; Akinlua et al. 2007, 2010). A number of trace elements have been implicated as palaeoredox condition indicators, which include V, Ni, Co, Mo, Mn, Cu and Cr (McManus et al. 1999; Morford et al. 2001; Algeo and Maynard 2004; Harris et al. 2004; Akinlua et al. 2010; MacDonald et al. 2010; Fu et al. 2011).

There is usually an enrichment of vanadium over nickel in anoxic marine environments (Barwise 1990; Peters and Moldowan 1993; Galarraga et al. 2008). Therefore, V/Ni ratio is a good indicator of anoxic or oxic environment of deposition. The distribution of the trace elements in kerogen samples from Well X (Table 2) shows an enhanced nickel concentration over the concentration of vanadium. The values of V/Ni ratio of kerogen samples in Well X range from 0.27 to 1.51 (Table 3), which indicate that the organic matter of most of the samples was deposited under oxic conditions except those in shallow depths (Fig. 8). The distribution of trace elements in kerogen samples from Well Y (Table 4) shows an enhanced concentration of vanadium over nickel except for samples Y13 and Y17. The values of V/Ni ratio for these samples range from 0.85 to 2.77 (Table 4) which

indicates that the organic materials of the samples were deposited under anoxic conditions. V/(V + Ni) ratio is also a good indicator of depositional environment, high value is an indication of reducing anoxic conditions, while low value indicates oxic to dysoxic conditions (Lewan 1984; Moldowan et al. 1985; Barwise 1990). The values of V/(V + Ni) ratio for Well X kerogen samples ranged from 0.21 to 0.60, indicating deposition of organic matter under oxic conditions. Well Y kerogen samples have V/(V + Ni) values that ranged from 0.47 to 0.74 (Table 4), which indicate that the organic matter of most of the samples was deposited under anoxic conditions, while samples Y13 and Y17 indicate deposition under dysoxic–oxic conditions.

Iron is greatly enriched relative to other elements in all the samples studied with values ranging from 1201.00 to 6470.00 ppm for Well X (Table 2) and 1532.50 to 7946.00 ppm for Well Y (Table 3). This indicates that the organic matter received high Fe oxyhydroxides input due to strong terrestrial influences, and these oxyhydroxides were well preserved under varying oxic and suboxic conditions (Byrne and Kester 1976; Froelich et al. 1979; Burdige 1993; Liu and Millero 2003). The enrichment of Mn over all the other elements (except Fe) in all the samples is a further indication of the oxic and suboxic environments in which the organic materials were deposited (Froelich et al. 1979; Lovley 1991; Burdige 1993; Morford and Emerson 1999).

Chromium is soluble in oxidising conditions and sparingly soluble in reducing conditions (Algeo and Maynard 2004). The concentration of Cr is generally low (only higher than Co) in all the samples with values ranging from 4.50 to 33.50 ppm, which suggests oxic–suboxic depositional conditions for the organic materials. Similarly, Cu is a

Fig. 8 Cross-plot of vanadium versus nickel showing that kerogens from the central Niger Delta have terrestrial and mixed marine/terrestrial source inputs and were deposited under varying oxic to dysoxic conditions (Modified after Galarraga et al. 2008)

redox-sensitive element which is usually enriched in anoxic conditions (Tribovillard et al. 2006). Cu is slightly enriched with average concentrations of 24.10 and 28.53 ppm in Wells X and Y, respectively, which could also be an indication of oxic–suboxic conditions.

Conclusions

The distribution of trace elements in kerogens of shale samples from two oil wells in the central Niger Delta revealed that there is prevalence of terrestrial organic matter with subordinate mixed marine/terrestrial organic matter. The organic materials were deposited under conditions ranging from oxic to suboxic.

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