
*British Journal of Applied Science & Technology*
*4(20): 2931-2945, 2014*

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# Geochemistry of Kolmani-1 Well Sediments from the Upper Benue Trough, Gongola Basin, Northeastern Nigeria

**O. M. Oyebanjo[1], T. R. Ajayi[2] and P. Tchokossa[3*]**

*[1]Natural History Museum, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria.*
*[2]Department of Geology, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria.*
*[3]Department of Physics, Obafemi Awolowo University, Ile-Ife, Nigeria.*

***Authors' contributions***

*This work was carried out in collaboration between all authors. Author TRA designed the study, author PT performed the experimental analysis, author OMO wrote the first draft of the manuscript and managed literature searches. Authors OMO, TRA, PT managed the analyses of the study and literature searches. All authors read and approved the final manuscript.*

***Original Research Article***

***Received 22nd December 2013***
***Accepted 13th March 2014***
***Published 24th May 2014***

## ABSTRACT

**Aims:** To assess the source rock characteristics and the depositional environment through Geochemical studies of sediment samples from the Upper Benue Trough.
**Place and Duration of Study:** Department of Geology, Obafemi Awolowo University, Nigeria and The Activation Laboratory Ltd, Ontario, Canada between February 2011 and March 2012.
**Methodology:** Eighteen samples made up of sand, shale, coaly shale, shaly sand and sandy shale, occurring between the depths of 18.3 m and 2725 m were analysed for thirty-four elements, comprising eight major, twelve trace, and fourteen rare earth elements (REE) using the Inductively Coupled Plasma- Mass Spectrometry technique.
**Results:** The results show that the sediments are compositionally rich in $Al_2O_3$ and $Fe_2O_3$. The low $TiO_2$ values of compared to those of Post-Archean Australian average shale (PAAS) suggest that they were derived from more evolved felsic source rock. The relatively low average Rb/Sr and high Th/U ratios indicate that moderate to more intense weathering occurred in the source rock area. The absolute rare earth elements (REE) concentrations were in the order of coaly shale > shale > sandy shale > shaly sand > sand.

**Corresponding author: E-mail: ptchokos@yahoo.com;*

**Conclusion:** The $Al_2O_3/T_iO_2$, Eu/Eu*, Th/Sc, La/Sc, Th/Co, La/Co, and Th/Cr ratios indicate that the sediments were probably derived from felsic source rocks. In addition, the high LREE/HREE ratios and the negative Eu anomaly also support felsic source rocks for the sediments whilst the very low V/Cr ratios indicate that these sediments were deposited under anoxic environment, consistent with the series of horst and graben structural framework model of the Benue Trough.

*Keywords: Geochemistry; sediments; Kolmani-1 well; Gongola Basin; Nigeria.*

## 1. INTRODUCTION

Sedimentary rocks provide important information about previous orogenic conditions, provenance and tectonic setting. Many factors namely, source rock composition, chemical weathering, climate, transport, burial, and diagenesis influence the sediment composition [1,2]. However, certain immobile elements in sedimentary systems such as rare earth elements (REE), Th, Sc, and Co or elemental ratios of these elements have been used to infer source rock compositions as these elements differ in concentration in felsic and mafic sources [1,3,4]. Similarly, geochemical parameters have been used by various authors to understand the paleo-oxygenating condition of ancient sediments [5,6]. Most detailed studies within the Basin have been focused on the organic geochemical evaluation of source rock potentials of the sediment. In this study, the geochemical distribution of major, trace elements and REE patterns are used to provide the source rock characteristics as well as the paleo-oxygenating conditions of sediments in the Gongola basin, Upper Benue trough, Northeastern Nigeria.

### 1.1 Geology and Stratigraphy

The Kolmani-1 well drilled in 1999 to depth of 3000 m is located close to the Kolmani River in Bauchi State within the Gongola basin of the Upper Benue trough (Fig. 1). The basin is a NNE-SSW trending rift basin about 800 km long and 150 km wide containing about 6,000 m thick Cretaceous-Tertiary sedimentary rocks. The basin together with the Yola basin constitute the Upper Benue trough. The Upper Benue trough is separated from the Chad (Borno) basin by a high structural basement known as the Zambuk ridge. The development of the Gongola basin is related to the origin of the Benue trough which has been variously discussed in the literature, remain controversial. King [7] was the first to suggest that the evolution of the Benue Trough was related to the stresses associated with the separation of the African and South American continents. Benkhelil [9] believed that the Benue trough is not a tensional feature but contains sinistral strike-slip faults connected to oceanic transcurrent and that the trough is a collection of pull-apart basins and uplifted blocks. Benkhelil [10] suggested slightly modified model of the strike-slip regarding the evolution of the Benue trough as best explained by a combination of extensional and strike-slip movements.

The stratigraphic succession in the Gongola and Yola basins is illustrated in Fig. 2. The main rifting in the evolution of the Benue trough was immediately followed by sedimentation. Carter et al. [11] recognized the various Formations which Thompson [12] described as a sedimentary sequence covering a considerable area around Gombe township. These are the Bima Formation, Yolde Formation, Pindiga Formation, Gombe Formation, and the Kerri-

Kerri Formation. To the southwest of Gombe township, the sedimentary rocks overlie the Basement rocks.

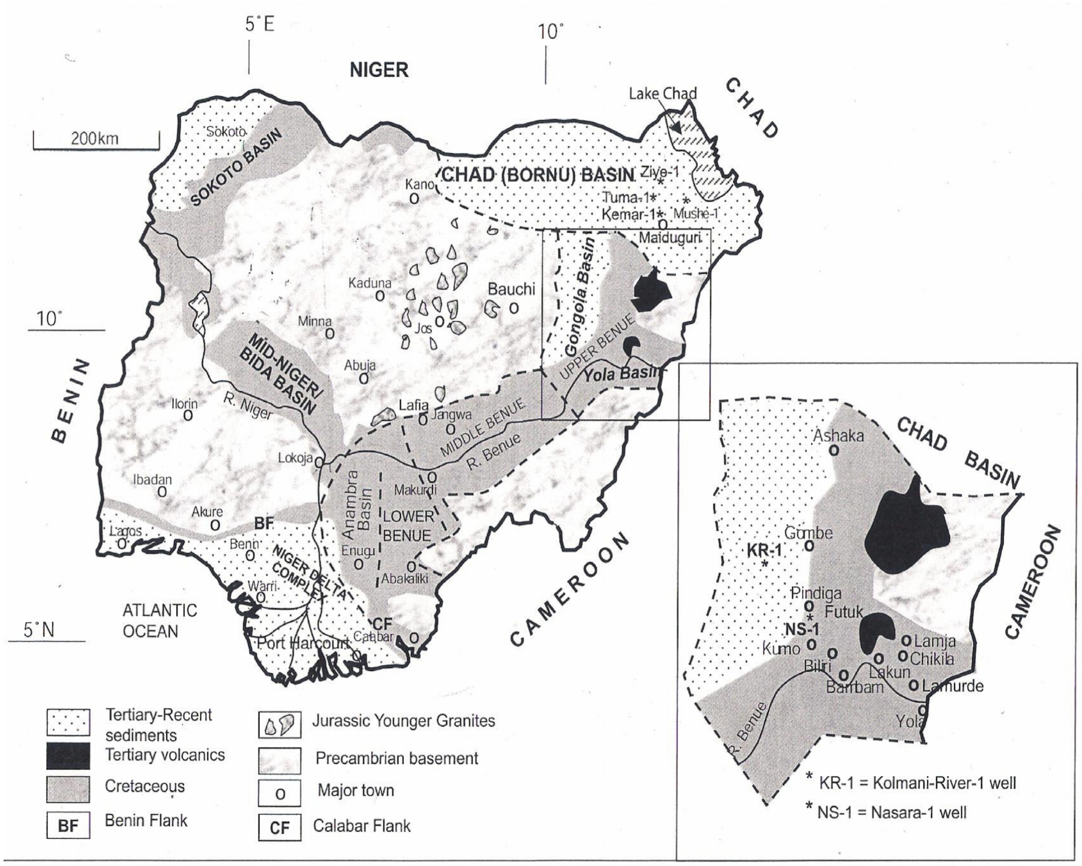


**Fig. 1. Outline geological map of Nigeria showing the location of the inland basins. Inset shows the upper Benue trough with the locations of Nasara-1 and Kolmani-1 wells [8]**

The Bima Formation is the oldest and directly rest uncomformably on Precambrian basement. The Formation was deposited under continental conditions (fluvial, deltaic, and lacustrine) and is made up of coarse- to medium-grained sandstones intercalated with carbonaceous clays, shales and mudstones. The Yolde Formation which is of Cenominian age conformably overlies the Bima sandstone and represents the beginning of marine incursion into this part of the Benue trough. This makes it a transitional unit between the continental Bima Formation and the succeeding marine Pindiga Formation. The Yolde Formation was deposited under a transitional/Coastal marine environment and is made up of sandstones, limestones, shales, clays, and claystones. The Pindiga Formation which constitutes the great part of the Upper Cretaceous sediments in the Upper Benue trough. It consists of calcareous beds and clay/shales, thin, dark grey to blue-black shales interbedded with fossiliferous limestones. Zaborski et al. [13] recognized five members

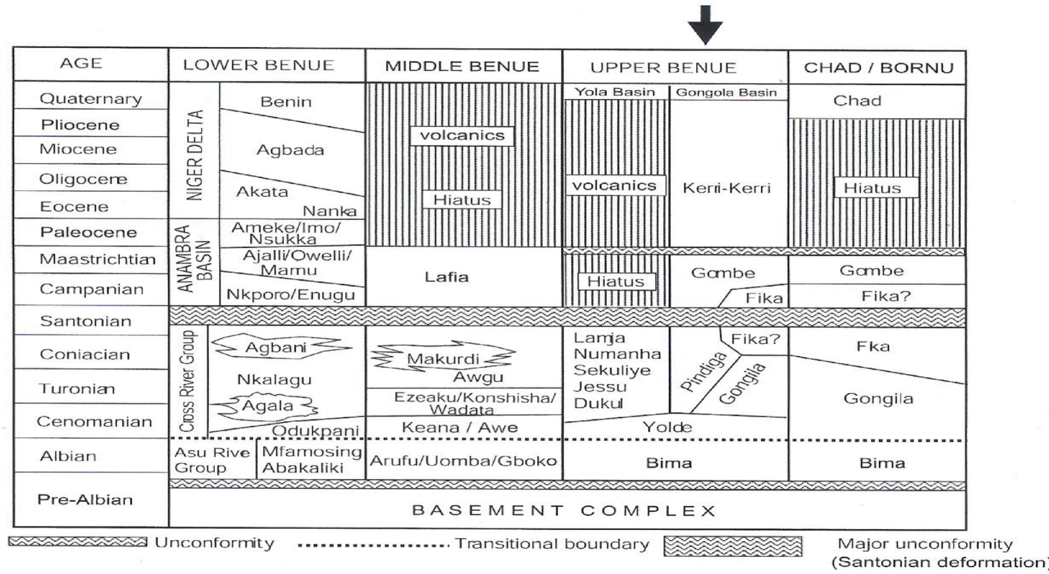


**Fig. 2. Stratigraphic successions in the Benue trough and the Nigerian sector of the Chad basin, with special reference to the Gongola basin [8]**

belonging to this Formation as: Kanawa Blue-grey shales, Dumbulwa sands, Gulani sands, Deba Fulani sands, and Fika Blue-grey shales. The post Santonian sediments are represented by the Maastrichtian Gombe sandstone and the Tertiary Kerri-Kerri Formation. The Gombe sandstone consists of available succession of well-bedded, fine-to medium – grained sandstones, sand and silty micaceous shales with occasional mudstones but also contains coal and lignite. The Kerri-Kerri Formation consists of poorly consolidated, medium- to coarse-grained arkosic sands and grits with interbeds of sandy gravels, minor clays, silt and fine-grained members [12]. Sedimentological features of this Formation were described by Carter et al. [11] and recently by Zaborski [14]. These sediments suffered tectonic deformation in the Santonian and later [11,14] towards the end of the Cretaceous [11] resulting in a folding and faulting of strata.

## 2. SAMPLING AND ANALYTICAL TECHNIQUES

Eighteen representative ditch cutting samples comprising sand, shale, coaly shale, shaly sand, and sandy shale occurring between the depths of 18.3 m and 2725.2 m were selected for analysis. The lithologic description of the samples were carried out with the aid of hand lens and a biostratigraphic microscope.

The samples were pulverized and prepared using the Ultratrace 6 -Total digestion – ICP and ICP/MS as outlined in the Activation Laboratory Ltd (Ontario, Canada) brochure (2010). This digestion procedure combines the 4-acid digestion (Hydrofluoric (HF), Perchloric ($HClO_4$), Nitric ($HNO_3$), and Hydrochloric (HCl) acids). About 0.25 g of each sample was first digested with HF and then followed by $HClO_4$ and $HNO_3$ at 260$^0$C to fuming and is diluted with dilute aqua regia to prepare a solution for the ICP portion. The Varian 735ES ICP and a Perkin Elmer Sciex ELAN 9000 ICP/MS analytical instruments were used for the determination of major, trace, and rare earth elements.

## 3. RESULTS AND DISCUSSIONS

**Major Elements:** Table 1 show the summary of the major element composition and comparison of their averages with other sediments from other parts of the world.

The sands are characterized by relatively low contents of the major elements. The concentration of $Al_2O_3$ ranges from 0.81 wt% to 6.73 wt% with a mean value of 2.29±2.20 wt% with only one of the samples (F2220) having a value of 6.73 wt%. The concentrations of $TiO_2$, MgO, CaO, $Na_2O$, and $K_2O$ are generally below 0.15 wt% in the sands. In comparison with the sandstones of Kudankulam Formation, the sands show very low average concentrations except for $TiO_2$ (010±0.04 wt %) that is comparable to the 0.27 wt% obtained. Furthermore, the sands have relatively low contents of these oxides when compared with the averages obtained for shale. The foregoing probably suggests leaching of the oxides at shallow depths within the sands relative to other lithologies occurring at deeper depths [15].

$Al_2O_3$ and $Fe_2O_3$ contents of the shales are distinctively the highest when compared to other lithologies present. In addition, the $K_2O$ concentrations in samples F6540 and F7020 (2.6 wt% and 3.07 wt% respectively) were the highest relatively to contents in sands, coaly shales, sandy shales, and shaly sands. The Na, K and Fe average contents are generally higher when compared to the black shales of Oshosun Formation in Dahomey basin [16].

The sandy shales show lower $Fe_2O_3$ (5.66±2.08 wt%) and MgO (1.33±0.73 wt%) contents compared to the shales and coaly shales. The $Na_2O$, MgO, $K_2O$, $Fe_2O_3$ and CaO average contents are generally higher when compared to the averages obtained for Ifon sandy clays [17] except for $TiO_2$ which indicates that the elements are enriched in sandy shales of Kolmani well relative to the Ifon sandy clays (Table 1).

$K_2O/Al_2O_3$ ratio in sediments can be used as an indicator of the original composition of ancient sediments. These ratios in clay minerals and feldspars range between 0.0 to 0.3 and 0.3 to 0.9 respectively [2]. In these sediments, $K_2O/Al_2O_3$ ratio varies from 0.03 to 0.24 and generally fall within the clay mineral range, with the sands showing ratio values close to the lower limits (0.03), whilst the values for the shales are close to the upper limits for clay. This suggests probably the presence of kaolinite (or Gibbsite) and smectite (or Illite) as the dominant clay minerals within the sands and shales respectively.

The average $Na_2O/K_2O$ ratios of 0.48, 0.23, 0.39, and 0.43 for the shales, coaly shales, sandy shales, and shaly sands respectively is comparable with the ratios obtained for Ifon shales and this may suggest their leaching from the primary source[15]. The average $Al_2O_3/TiO_2$ ratios for coaly shales and the shales fall within 17-27 which is indicative of chemical immaturity [18].

The sands and shaly sands generally show relatively low average $TiO_2$ content (0.10 wt% and 0.37 wt%) compared with 1.00 wt% and 0.70 wt% for average Post-Achaean Australian Shale (PAAS) [19] and average North American Shale (NASC) [20] respectively. However, the shales, coaly shales and sandy shales with average $TiO_2$ values of 1.01, 0.79, and 0.83 wt% respectively are comparable to the average values of 1.0 for PAAS and 0.7 for NASC. Titanium is believed to be dominantly concentrated in phyllosilicates[21] and is relatively immobile compared to other elements during sediments processes and can strongly reflect the source rocks characteristics[1]. Therefore, the lower values of $TiO_2$ in these sediments relative to those of the PAAS can be interpreted to suggest more felsic source rocks. Hayashi et al. [22] reported that $Al_2O_3/TiO_2$ ratios of most clastic rocks are essentially used to infer the source rock. These ratios increase from 3 to 8 for mafic rocks, 8 to 21 for intermediate rocks, and 21 to 70 for felsic rocks. In the Kolmani sediments, $Al_2O_3/TiO_2$ ratios vary between 9.09 and 31.53, thus indicative of derivation from intermediate to felsic rocks.

**Trace Elements:** Table 2 shows the arithmetic mean and ranges of selected trace elements in comparison with averages of sediments obtained from other parts of the world. Generally, the shales are relatively enriched followed by coaly shales, sandy shales, shaly sands, and sands respectively. This is similar to the result obtained by Armstrong-Altrin et al. [23] where they noted that trace elements are mainly enriched in fine grained sediments than in medium to coarse sediments.

The cobalt values when compared with other compatible elements in the sands are higher and range from 38.8 and 52.2 ppm with a mean value of 43.1±5.32 ppm. The sands are enriched in Co when compared with Ifon sands ( 0.54 – 2.9 ppm) of the Upper Cretaceous Clastic sediments and sands of Hawkes and Webb (1.0 – 10 ppm) [24]. Furthermore, relative to world averages obtained for UCC, the sands of Kolmani well show lower mean values of V (8.0±7.0 ppm), Zn (32.26±28.64 ppm), and Cu (7.26±5.78 ppm). This indicates a relative depletion of these elements in the sands of Kolmani well as against the average composition of the Upper Continental Crust.

The shales unlike the sands show little variation in compatible trace elements. On the average, the shales show higher mean values of 125.2±19.94 ppm, 102.7±24.94 ppm, 47.0±4.47 ppm, 94.14±5.81 ppm, and 36.54±12.67 ppm for V, Cr, Ni, Zn and Cu respectively and lower Co (24.42±3.44 ppm) when compared to the sands. The shales of Kolmani well in comparison with shales of Hawkes and Webb [24] are similar in Co and V but lower in Cr. However, in comparison with the Ifon shales, the average values for Co and Cr are for Kolmani shales lower whilst the mean V values are similar. In addition, relative to world averages for PAAS and NASC, the shales of Kolmani wells show lower Cr, Ni and V mean values but higher mean value in Co.

The Rb/Sr ratios in sediments had been used to monitor the degree of source rock weathering [1], because chemical weathering of source area produces higher Rb/Sr ratios in sedimentary rocks. The average Rb/Sr ratios of 0.18±0.17, 0.51±0.09, 0.54±0.10, 0.57±0.14, and 0.36±0.10 obtained for sands, coaly shales, shales, sandy shales, and shaly sands respectively are comparable to the average UCC value of 0.32[19], but lower than value of 0.8 for PAAS [1]. This suggests that the intensity of the source area weathering was most probably moderate to intense [25]. In addition, the average Th/U ratios of 4.25±2.02, 4.54±0.38, 4.90±0.95, and 5.96±0.76 for sands, coaly shales, shales and sandy shales respectively are relatively higher than 3.5 obtained by Mclennan et al.[1] which indicates more intense weathering in source areas or sediment recycling. In most cases, weathering and sedimentary recycling typically results in loss of U, leading to an elevation in the Th/U ratios.

In considering the environment of sediment deposition, the V/Cr ratio had been used as redox indicator. Gross [26], and Lander green and Manhem [27] obtained V/Cr ratios of 1.1 and 0.75 respectively for oxygen poor recent marine to brackish water sediments and higher values between 2 and 10 for oxygen rich environments. In the Kolmani sediments, the V/Cr ratios vary between 0.08 and 1.47 (except in F540 > 6), suggesting that they were deposited in an anoxic depositional environment. In addition, the crosplot of V versus Ni for the sediments were within the Marine anoxic field (Fig. 3). This implies that the depositional environment is devoid of oxygen and reducing. Furthermore, this is consistent with the series of horst and graben structural framework model of the Benue Trough[9, 10] as such grabens can provide an ideal restricted, oxygen-poor depositional environment for the sediments [17].

**Rare Earth Elements:** The absolute and chondrite normalized values are presented in Table 3. The total REE abundance in the sands range widely from 2.03 to 123.55 ppm with an average value of 48.29±42.76 ppm. All the samples show very similar REE patterns of LREE enrichment, HREE depletion and pronounced negative Eu anomalies. A comparison of the average values for sands, coaly shales, shales, sandy shales, and shaly sands shows that the average absolute REE concentrations were in the order of sand < shaly sand < sandy shale < coaly shale < shale respectively. This agree well with the result of Haskin et al.[28] and further confirms that fine-grained sediments are relatively enriched in the REE as well as in trace elements.

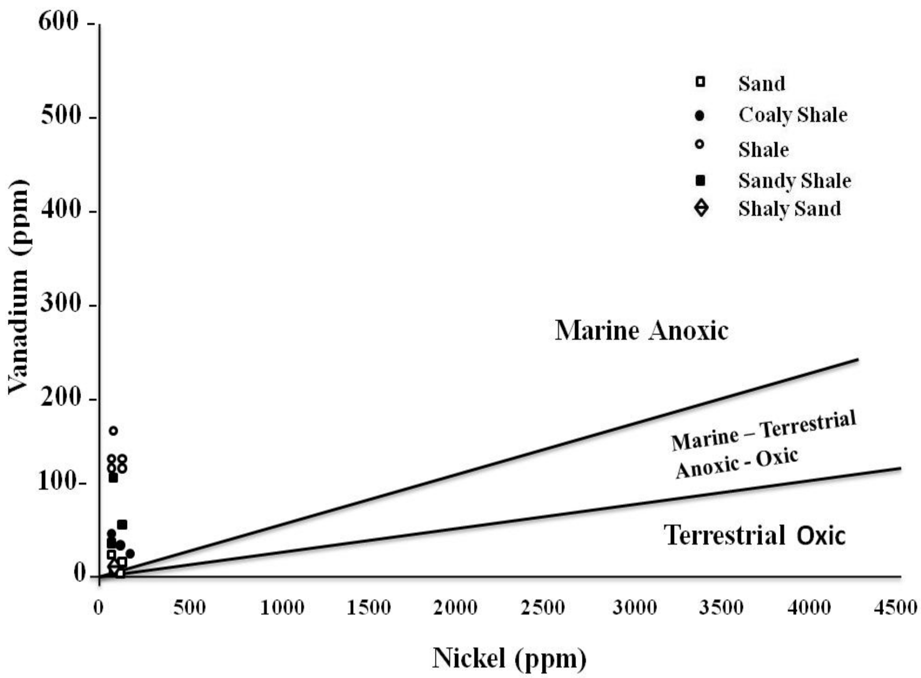


**Fig. 3. Cross plot of Vanadium versus Nickel of Sediments of Kolmani-1 Well, Gongola basin, NE Nigeria [29]**

The $La_N/Sm_N$ and $Ce_N/Yb_N$ ratios show wide variation. The values in the sands ranging from 2.43 to 4.58 and 9.42 to 13.07(except for sample F540 with value of 34.78) represents narrow ranges and these are comparable with values for coaly shale, shale, sandy shale, and shaly sand. The narrow range of $Ce_N/Yb_N$ ratios indicates limited fractionation of LREE relative to HREE [17] while the narrow range for $La_N/Sm_N$ ratios represents little fractionation of the LREE.

**Table 1. Comparison of Mean Major Elements concentration (wt%) and ratios of sediments in Kolmani-1 well with compositionally similar rocks**

| Lithology | Sample Code | $Al_2O_3$ | $TiO_2$ | $Fe_2O_3$ | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | $Na_2O/K_2O$ | $Al_2O_3/TiO_2$ | $K_2O/Al_2O_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sand | F60 | 1.66 | 0.12 | 0.57 | <0.02 | 0.07 | 0.08 | 0.05 | 0.01 | 1.6 | 13.83 | 0.03 |
| | F540 | 1 | 0.11 | 0.2 | <0.02 | 0.06 | 0.07 | 0.02 | 0.01 | 3.5 | 9.09 | 0.02 |
| | F1260 | 1.27 | 0.13 | 0.29 | <0.02 | 0.07 | 0.08 | 0.04 | 0.01 | 2 | 9.77 | 0.03 |
| | F1740 | 0.81 | 0.05 | 0.26 | <0.02 | 0.5 | 0.09 | 0.02 | 0.01 | 4.5 | 16.2 | 0.03 |
| | F2220 | 6.73 | 0.79 | 0.7 | <0.02 | 0.15 | 0.11 | 0.11 | 0.02 | 1 | 8.52 | 0.02 |
| | Mean | 2.29 | 0.24 | 0.4 | | 0.17 | 0.09 | 0.05 | 0.012 | 2.52 | 11.48 | 0.03 |
| | Standard deviation | 2.5 | 0.31 | 0.22 | | 0.19 | 0.02 | 0.04 | 0.005 | 1.44 | 3.36 | 0.01 |
| Coaly Shale | F2460 | 12.53 | 0.56 | 3.87 | 0.17 | 0.42 | 0.27 | 1.08 | 0.03 | 0.25 | 22.38 | 0.09 |
| | F2700 | 14.44 | 1.23 | 3.73 | 0.33 | 0.55 | 0.35 | 1.31 | 0.05 | 0.27 | 11.74 | 0.09 |
| | F2940 | 17.97 | 0.57 | 4.03 | 0.33 | 0.57 | 0.3 | 1.92 | 0.06 | 0.16 | 31.53 | 0.11 |
| | Mean | 14.98 | 0.79 | 3.88 | 0.28 | 0.51 | 0.31 | 1.44 | 0.05 | 0.23 | 21.88 | 0.10 |
| | Standard deviation | 2.76 | 0.38 | 0.15 | 0.09 | 0.08 | 0.04 | 0.43 | 0.02 | 0.06 | 9.9 | 0.01 |
| Shale | F3900 | 18.90 | 1.27 | 9.36 | 1.33 | 0.8 | 0.67 | 1.6 | 0.24 | 0.42 | 14.88 | 0.09 |
| | F4620 | 18.90 | 1.1 | 8.18 | 2.65 | 1.08 | 0.98 | 1.7 | 0.17 | 0.58 | 17.18 | 0.09 |
| | F5820 | 18.90 | 0.88 | 7.33 | 3.32 | 1.67 | 1.2 | 1.83 | 0.3 | 0.66 | 21.48 | 0.10 |
| | F6540 | 18.90 | 0.87 | 7.54 | 2.49 | 0.66 | 1.12 | 2.6 | 0.17 | 0.43 | 21.72 | 0.14 |
| | F7020 | 18.90 | 0.95 | 6.21 | 2.32 | 0.52 | 1.01 | 3.07 | 0.13 | 0.33 | 19.0 | 0.16 |
| | Mean | 18.90 | 1.01 | 7.72 | 2.42 | 0.95 | 1 | 2.16 | 0.2 | 0.48 | 18.85 | 0.12 |
| | Standard deviation | - | 0.17 | 1.16 | 0.72 | 0.46 | 0.2 | 0.64 | 0.08 | 0.13 | 2.9 | 0.03 |
| Sandy Shale | F3660 | 18.90 | 1.09 | 6.71 | 0.83 | 0.67 | 0.5 | 1.68 | 0.14 | 0.3 | 17.34 | 0.09 |
| | F7260 | 11.09 | 0.54 | 3.26 | 0.99 | 0.35 | 0.88 | 2.37 | 0.09 | 0.37 | 20.54 | 0.21 |
| | F7740 | 18.90 | 0.86 | 7.01 | 2.16 | 0.57 | 1.47 | 2.99 | 0.22 | 0.49 | 21.96 | 0.16 |
| | Mean | 16.3 | 0.83 | 5.66 | 1.33 | 0.53 | 0.95 | 2.35 | 0.15 | 0.39 | 19.95 | 0.15 |
| | Standard deviation | 4.51 | 0.28 | 2.08 | 0.73 | 0.16 | 0.49 | 0.66 | 0.07 | 0.1 | 2.37 | 0.06 |
| Shaly Sand | F8220 | 12.36 | 0.42 | 2.96 | 0.66 | 0.67 | 0.82 | 2.99 | 0.05 | 0.27 | 29.43 | 0.24 |
| | F8940 | 8.98 | 0.31 | 3.25 | 0.33 | 1.34 | 1.24 | 2.14 | 0.06 | 0.58 | 28.97 | 0.24 |
| | Mean | 10.67 | 0.37 | 3.11 | 0.5 | 1.01 | 1.03 | 2.57 | 0.06 | 0.43 | 29.2 | 0.24 |
| | Average Ifon Sandy clays (n=2)[a] | 18.39 | 2.18 | 2.33 | 0.9 | - | 0.01 | 0.11 | 0.12 | 0.1 | 8.47 | - |
| | Average Oshosun black shale (n=16)[b] | - | - | 5.59 | - | - | 0.09 | 0.11 | - | - | - | - |
| | PAAS[c] | 18.9 | 1 | 7.22 | 2.2 | 1.3 | 1.2 | 1.7 | 0.16 | 0.71 | 18.9 | 0.09 |
| | NASC[d] | 16.9 | 0.7 | 5.65 | 2.86 | 3.63 | 1.14 | 3.97 | 0.13 | 0.29 | 24.14 | 0.24 |

*[a] [17]; [b][16]; [c][23]; [d]PAAS = Average Post-Archaean Australian Shale [19]; [e]NASC = Average North American Shale [20]*

**Table 2. Mean Trace elements concentration (ppm) of sediments in Kolmani-1 well in Comparison with compositionally similar rocks**

| Lihology | V | Cr | Ni | Co | Zn | Rb |
|---|---|---|---|---|---|---|
| Sand(n=5) | 8.0±7.0 | 39.33±32.02 | 7.34±6.41 | 43.1±5.32 | 32.26±28.64 | 2.18±1.24 |
| Coaly shale (n=3) | 31.67±8.51 | 83.03±7.92 | 25.23±2.11 | 27.4±2.20 | 69.80±2.0 | 46.73±13.80 |
| Shale (n=5) | 125.2±19.94 | 102.7±24.94 | 47±4.47 | 24.42±3.44 | 94.14±5.81 | 90.32±23.66 |
| Sandy shale (n=3) | 66.33±34.59 | 87.17±20.95 | 32.17±9.05 | 22.97±4.44 | 82.33±26.90 | 79.2±27.64 |
| Shaly sand (n=2) | 25 | 63.10 | 20.55 | 19.1 | 59.05 | 74.4 |
| HWS | | 30-15 | - | 1-10 | - | - |
| HWSh | 50-2000 | 10-500 | - | 5.5 | - | - |
| PAAS | 150 | 110 | - | 23 | 85 | 160 |
| NASC | 130 | 125 | - | 25.7 | - | 125 |
| UCC | 60 | 35 | - | 10 | 71 | 112 |
| Ish (n=5) | 126 | 164 | - | 26 | - | - |
| IS | 33 | 33 | - | 1.38 | - | - |

| Lithology | Sr | Zr | Ba | Cu | Th | U |
|---|---|---|---|---|---|---|
| Sand(n=5) | 15±6.07 | 50±69.4 | 582±637 | 7.26±5.78 | 3.62±4.97 | 0.66±0.5 |
| Coaly shale (n=3) | 94±28.94 | 186.0±72.38 | 575±102 | 19.37±3.85 | 17.2±3.66 | 3.8±0.5 |
| Shale (n=5) | 174.4±58 | 112.8±35.3 | 272±134.3 | 36.54±12.67 | 17.3±2.77 | 3.7±1.2 |
| Sandy shale (n=3) | 143.6±44.72 | 109.7±56.8 | 863±673 | 21.3±5.09 | 18.7±8.63 | 3.3±1.91 |
| Shaly sand (n=2) | 221 | 40 | 485 | 36.95 | 7.95 | 1.3 |
| HWS | - | | 100-500 | - | - | - |
| HWSh | - | 100-1000 | 450-700 | - | - | - |
| PAAS | 200 | 210 | 650 | 50 | 14.6 | 3.1 |
| NASC | 142 | 200 | 636 | - | 12.3 | 2.66 |
| UCC | 350 | 190 | 550 | 25 | 10.7 | 2.8 |
| Ish (n=5) | - | 417 | 323 | - | 21 | 8.4 |
| IS | - | 272 | 57 | - | 9.2 | 2.7 |

*HWS and HWSh = Hawkes & Webb [24] sand and shale respectively, PAAS & UCC [19]; NASC [20], ISh = Ifon shale and IS = Ifon sand [17]*

## Table 3. Rare earth elements concentration (ppm) of sediments in Kolmani-1 well

| Lithology | Sample | Values | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Ho | Er | Im | Yb | Lu | ∑REE | $La_N/Sm_N$ | $Ce_N/Yb_N$ | LREE/ HREE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sand** | F60 | Ab | 5.70 | 11.50 | 1.10 | 3.90 | 0.70 | 0.13 | 0.60 | <0.10 | 0.40 | <0.10 | 0.20 | <0.10 | 0.20 | <0.1 | 24.43 | 4.46 | 13.07 | 16.36 |
| | | CN | 17.27 | 13.07 | 9.82 | 6.50 | 3.87 | 1.88 | 2.41 | | 1.32 | | 1.00 | | 1.00 | | | | | |
| | F540 | Ab | 7.40 | 15.30 | 1.70 | 5.70 | 1.00 | 0.18 | 0.80 | 0.10 | 0.60 | 0.10 | 0.30 | <0.10 | 0.10 | <0.1 | 33.28 | 4.06 | 34.78 | 14.81 |
| | | CN | 22.42 | 17.39 | 15.18 | 9.50 | 5.52 | 2.61 | 3.21 | 2.13 | 1.98 | 1.43 | 1.50 | | 0.50 | | | | | |
| | F1260 | Ab | 7.10 | 16.50 | 1.90 | 7.70 | 1.62 | 0.37 | 1.70 | 0.20 | 1.30 | 0.30 | 0.70 | 0.10 | 0.40 | <0.1 | 39.87 | 2.43 | 9.38 | 7.40 |
| | | CN | 21.52 | 18.75 | 16.96 | 12.38 | 8.84 | 5.36 | 6.83 | 4.26 | 4.29 | 4.28 | 3.50 | 3.30 | 2.00 | | | | | |
| | F1740 | Ab | 5.00 | 9.10 | 1.00 | 3.20 | 0.60 | 0.10 | 0.50 | <0.10 | 0.40 | <0.1 | 0.20 | <0.10 | 0.20 | <0.1 | 20.30 | 4.58 | 10.34 | 14.54 |
| | | CN | 15.15 | 10,34 | 8.93 | 5.33 | 3.31 | 1.45 | 2.01 | | 1.32 | | 1.00 | | 1.00 | | | | | |
| | F2220 | Ab | 26.00 | 53,90 | 6.20 | 22.10 | 4.20 | 0.75 | 3.60 | 0.50 | 2.70 | 0.50 | 1.40 | 0.20 | 1.30 | 0.20 | 123.55 | 3.40 | 9.42 | 10.81 |
| | | CN | 78.79 | 61.25 | 55.36 | 36.83 | 23.20 | 10.87 | 14.46 | 10.64 | 8.91 | 7.14 | 7.00 | 6.67 | 6.50 | 5.88 | | | | |
| | Mean | Ab | 10.24 | 21.26 | 2.38 | 8.52 | 1.62 | 0.31 | 1.44 | 0.27(3) | 1.08 | 0.3(3) | 0.56 | 0.15(2) | 0.44 | 0.20(1) | 48.29±42.76 | | | |
| | | CN | 31.03 | 24.16 | 21.25 | 14.20 | 8.95 | 4.43 | 5.78 | 5.68 | 3.56 | 4.28 | 2.80 | 4.98 | 2.20 | 5.88 | | | | |
| **Coaly Shale** | F2460 | Ab | 49.00 | 103.00 | 11.60 | 42.70 | 7.90 | 1.59 | 6.8 | 0.90 | 5.10 | 0.90 | 2,60 | 0.40 | 2.50 | 0.30 | 235.29 | 3.40 | 9.36 | 10.98 |
| | | CN | 148.48 | 117.04 | 103.57 | 71.17 | 43.65 | 23.04 | 27.31 | 19.15 | 16.83 | 12.86 | 13.00 | 13.33 | 12.50 | 8.82 | | | | |
| | F2700 | Ab | 48.40 | 101.00 | 11,30 | 41.40 | 7,90 | 1.61 | 6.90 | 0.90 | 5.00 | 0.90 | 2.60 | 0.40 | 2.40 | 0.30 | 226.51 | 3.36 | 9.56 | 10.82 |
| | | CN | 146.67 | 114.77 | 100.89 | 69.00 | 43.65 | 23.33 | 27.71 | 19.15 | 16.50 | 12.86 | 13.00 | 13.33 | 12.00 | 8.82 | | | | |
| | F2940 | Ab | 60.30 | 125.00 | 13.90 | 50.10 | 9.40 | 1.89 | 8.10 | 1.10 | 5.70 | 1.10 | 2.90 | 0.40 | 2.70 | 0.40 | 282.99 | 3.52 | 10.52 | 11.55 |
| | | CN | 182.73 | 142.04 | 124.11 | 83.50 | 51.93 | 27.39 | 32.53 | 23.40 | 18.81 | 15.71 | 14.50 | 13.33 | 13.50 | 11.76 | | | | |
| | Mean | Ab | 52.57 | 109.67 | 12.27 | 44.73 | 8.40 | 1.70 | 7.27 | 0.97 | 5.27 | 0.97 | 2.70 | 0.40 | 2.53 | 0.33 | 248.26±30.39 | | | |
| | | CN | 159.29 | 124.62 | 109.52 | 74.56 | 46.41 | 24.59 | 29.18 | 20.57 | 17.38 | 13.81 | 13.50 | 13.33 | 12.67 | 9,80 | | | | |
| **Shale** | F3900 | Ab | 56.40 | 121,00 | 13.70 | 50.50 | 9.80 | 2.16 | 9.00 | 1.20 | 6.80 | 1.4 | 3.70 | 0.50 | 3.40 | 0.50 | 280.06 | 3.16 | 8.09 | 9.49 |
| | | CN | 170.91 | 137.50 | 122.32 | 84.17 | 54.14 | 31.30 | 36.14 | 25.53 | 22.44 | 20.00 | 18.50 | 16.67 | 17.00 | 14.71 | | | | |
| | F4620 | Ab | 46.90 | 94.70 | 10.90 | 40.30 | 7.60 | 1.72 | 6.80 | 0.90 | 5.30 | 1.00 | 2.80 | 0.40 | 2.60 | 0.40 | 222.32 | 3.38 | 8.28 | 9.92 |
| | | CN | 142.12 | 107.61 | 97.32 | 67.17 | 41.99 | 24.93 | 27.31 | 19.15 | 17.49 | 14.28 | 14.00 | 13.33 | 13.00 | 11.76 | | | | |
| | F5820 | Ab | 44.10 | 95.50 | 11.70 | 46.70 | 10.10 | 2.29 | 9.20 | 1.20 | 6.50 | 1.10 | 2.80 | 0.40 | 2.20 | 0.30 | 234.09 | 2.39 | 9.86 | 8.78 |
| | | CN | 133.64 | 108.52 | 104.46 | 77.83 | 55.80 | 33.19 | 36.95 | 25.53 | 21.45 | 15.71 | 14.00 | 13.33 | 11.00 | 8.82 | | | | |
| | F6540 | Ab | 48.20 | 101.00 | 11.80 | 41.90 | 7.30 | 1.47 | 6.00 | 0.80 | 4.30 | 0.90 | 2.30 | 0.3 | 2.10 | 0.3O | 228.67 | 3.62 | 10.93 | 12.36 |
| | | CN | 146.06 | 114.77 | 105.36 | 69.83 | 40.33 | 21.30 | 24.10 | 17.02 | 14.19 | 12.86 | 11.50 | 10.00 | 10.50 | 8.82 | | | | |
| | F7020 | Ab | 56.90 | 116.00 | 13.20 | 45.90 | 7.70 | 1.44 | 5.80 | 0.70 | 4.00 | 0.80 | 2.10 | 0.30 | 1.80 | 0.30 | 256.94 | 4.05 | 14.65 | 15.17 |
| | | CN | 172.42 | 131.82 | 117.86 | 76.50 | 42.54 | 20.87 | 23.29 | 14.89 | 13.20 | 11.43 | 10.50 | 10.00 | 9.00 | 8.82 | | | | |
| | Mean | Ab | 50.50 | 105.64 | 12.26 | 45.06 | 8.50 | 1.82 | 7.36 | 0.96 | 5.38 | 1.04 | 2.74 | 0.38 | 2.42 | 0.36 | 244.42±23.82 | | | |
| | | CN | 153.03 | 120.04 | 109.46 | 75.10 | 46.96 | 26.32 | 29.56 | 20.42 | 17.73 | 14.86 | 13.70 | 12.67 | 12.10 | 10.59 | | | | |
| **Sandy Shale** | F3660 | Ab | 57.60 | 119.00 | 13.60 | 50.50 | 9.70 | 2.02 | 8.80 | 1.10 | 6.4 | 1.2 | 3.50 | 0.50 | 3.00 | 0.50 | 277.42 | 3.26 | 9.02 | 10.02 |
| | | CN | 174,54 | 135.23 | 121.43 | 84.17 | 53.59 | 29.28 | 35.34 | 23.40 | 21.12 | 17.14 | 17.50 | 16.67 | 15.00 | 14.71 | | | | |
| | F7260 | Ab | 21.90 | 49.60 | 5.80 | 21.8 | 4.00 | 0.88 | 3.30 | 0.40 | 2.30 | 0.40 | 1.10 | 0.2 | 0.80 | <0.10 | 112.48 | 3.00 | 14.09 | 12.13 |
| | | CN | 66.36 | 56.36 | 51.79 | 36.33 | 22.10 | 12.75 | 13.25 | 8.51 | 7.59 | 5.71 | 5.50 | 0.67 | 4.00 | | | | | |
| | F7740 | Ab | 57.2 | 116.00 | 3.40 | 49.80 | 9.80 | 2.20 | 8.70 | 1.10 | 6.00 | 1.10 | 2.70 | 0.40 | 2.20 | 0.30 | 260.90 | 3.20 | 11.98 | 10.50 |
| | | CN | 173.33 | 131.82 | 119.64 | 83.00 | 54.14 | 31.88 | 34.94 | 23.40 | 19.89 | 15.71 | 13.50 | 13.33 | 11.00 | 8.82 | | | | |
| | Mean | Ab | 45.57 | 94.87 | 7.6 | 40.70 | 7.83 | 1.70 | 6.93 | 0.87 | 4.90 | 0.90 | 2.43 | 0.37 | 2.00 | 0,40(2) | 216.93±90.84 | | | |
| | | CN | 138.08 | 107.80 | 97.62 | 67.83 | 43.28 | 24.64 | 27.84 | 18.44 | 16,17 | 12.85 | 12.17 | 12.22 | 10.00 | 11.76 | | | | |
| **Shaly Sand** | F8220 | Ab | 34.30 | 69.50 | 7.60 | 26.70 | 4.40 | 1.04 | 3.50 | 0.40 | 2.20 | 0.40 | 1.00 | 0.1 | 0.80 | <0.10 | 151.94 | 4.28 | 19.74 | 16.96 |
| | | CN | 103.94 | 78.98 | 67.86 | 44.50 | 24.31 | 15.07 | 14.06 | 8.51 | 7.26 | 5.71 | 5.00 | 3.33 | 4.00 | | | | | |
| | F8940 | Ab | 26.00 | 56.80 | 6.10 | 21.60 | 3.80 | 0.87 | 3.10 | 0.40 | 1.90 | 0.30 | 0.90 | 0.10 | 0.70 | <0.10 | 122.57 | 3.75 | 18.44 | 15.45 |
| | | CN | 78.79 | 64.54 | 54.46 | 36.00 | 20.99 | 12.61 | 12.45 | 8.51 | 6.27 | 4.28 | 4.50 | 3.33 | 3.50 | | | | | |
| | Mean | Ab | 30.15 | 63.15 | 6.85 | 24.15 | 4.10 | 0.96 | 3.30 | 0.40 | 2.05 | 0.35 | 0.95 | 0.10 | 0.75 | | 137.26 | | | |
| | | CN | 91.37 | 71.76 | 61.16 | 40.25 | 22.65 | 13.84 | 13.26 | 8,51 | 6.76 | 4.99 | 4.75 | 3.33 | 3.75 | | | | | |
| **Chondrite values*** | | | 0.330 | 0.880 | 0.112 | 0.600 | 0.181 | 0.069 | 0.249 | 0.047 | 0.303 | 0.070 | 0.200 | 0.030 | 0.200 | 0.034 | | | | |

*Haskin et al., 1971[30]

The total REE abundance in the coaly shales range from 226.51 to 282.99 ppm with an average value of 248.26±30.39 ppm, and show LREE enrichment, HREE depletion and pronounced negative Eu anomaly. This pattern is similar to those obtained for shale and sandy shale (Fig. 4).

On the other hand, the total REE abundance in the shales ranges from 222.32 to 280.06 ppm with an average value of 244.42±23.82 ppm. The REE patterns are all similar with a strong negative Eu anomaly (Fig. 4). The pattern also shows enrichment in LREE and depletion in HREE. On the average, the Kolmani shales show REE pattern similar to the NASC (Gromet et al. and the PAAS [19]. Although, the Kolmani shales are slightly more enriched (Fig. 4).

The total REE abundance in the sandy shales show medium variation with values ranging from 112.48 to 277.42 ppm with an average value of 216.93±90.84 ppm. All the samples show similar patterns of enrichment in LREE and depletion in HREE with weak negative Eu anomaly except for sample F7260 with low enrichment and a positive Tm anomaly. However, the shaly sands show similar REE patterns of enrichment in LREE, a flat MREE, depletion in HREE with no pronounced Eu anomaly (Fig. 5). This could be attributed to higher contents of Sr, considering that both ions ($Eu^{2+}$ and $Sr^{2+}$) have comparable ionic sizes and thus tend to preferably substitute for $Ca^{2+}$ in plagioclase [31].

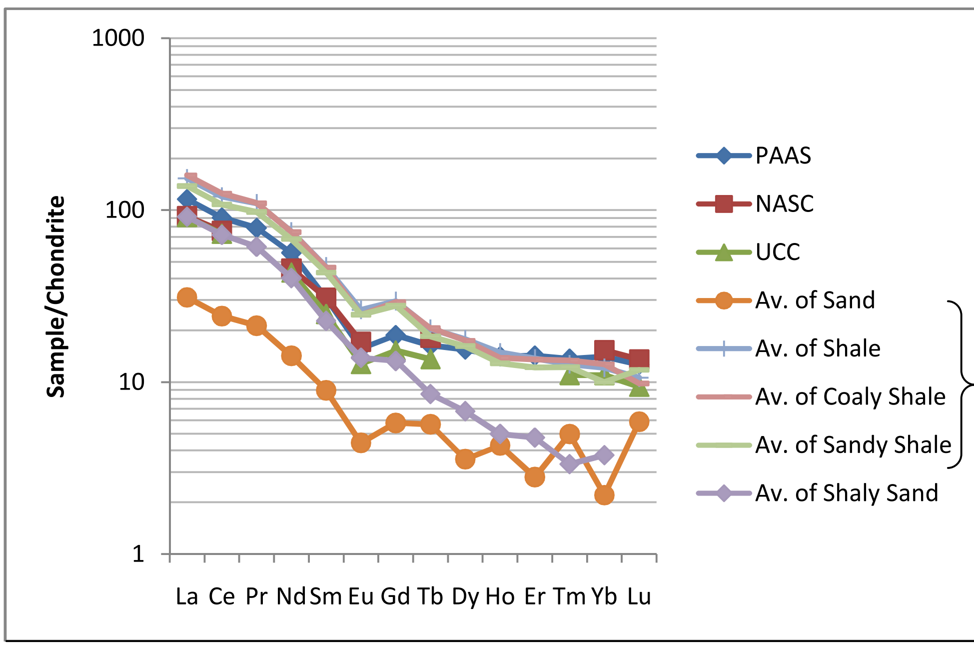


**Fig. 4. Chondrite-normalized REE Patterns of Average Kolmani-1 well Sediments Compared with Averages for PAAS, NASC, and UCC**

*Corresponding author: E-mail: ptchokos@yahoo.com;

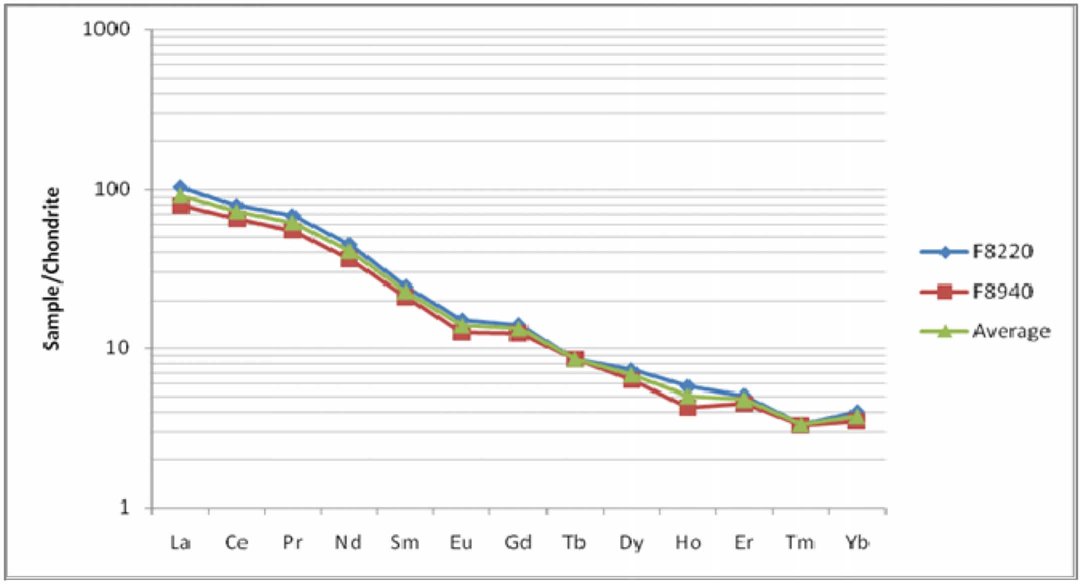


**Fig. 5. Chondrite-normalized REE Patterns of Kolmani-1 well Shaly sands**

**Table 4. Comparison of the Range of Elemental Ratios of Kolmani-1 well Sediments with Felsic and Mafic rocks**

| | This study | | | | | | |
|---|---|---|---|---|---|---|---|
| **Ratio** | **Sand (n=5)** | **Shale (n=5)** | **Coaly shale (n=3)** | **Sandy shale (n=3)** | **Shaly sand (n=2)** | **Felsic rocks[1]** | **Mafic rocks[1]** |
| Eu/Eu* | 0.56-0.69 | 066-0.74 | 0.66-0.67 | 0.67-0.74 | 0.78-0.82 | 0.40-0.94 | 0.71-0.95 |
| Th/Sc | 1.2-2.5 | 0.86-1.22 | 1.47-1.78 | 1.4-1.79 | 1.66-1.90 | 0.84-20.5 | 0.05-0.22 |
| La/Sc | 5.2-7.1 | 2.61-3.79 | 4.84-5.4 | 3.65-4.09 | 6.5-6.86 | 2.5-16.3 | 0.43-0.86 |
| Th/Cr | 0.02-0.17 | 0.11-0.24 | 0.17-0.28 | 0.15-0.26 | 0.11-0.15 | 0.13-2.7 | 0.018-0.046 |
| Th/Co | 0.03-0.36 | 0.64-0.86 | 0.52-0.78 | 0.48-0.96 | 0.38-0.45 | 0.67-19.4 | 0.04-1.4 |
| La/Co | 0.12-0.68 | 1.89-2.78 | 1.66-2.21 | 1.07-2.05 | 1.31-1.86 | 1.80-13.8 | 0.14-0.38 |
| U/Th | 0.13-0.33 | 0.17-0.26 | 0.20-0.23 | 0.16-0.20 | 0.16-0.17 | - | - |
| V/Cr | 0.2-0.79 | 1-1.47 | 0.30-0.49 | 0.35-1.08 | 0.22-0.52 | - | - |

*$Eu/Eu^* = Eu_N/(Sm_N x Gd_N)^{0.5}$*  [1]*[3, 32, 33].*

The similar REE pattern in all the sediments showing relative enrichment in the LREE to the HREE is indicative of REE fractionation in the source area [34]. This is important since intense chemical weathering will favour REE fractionation during sedimentary processes [35]. In addition, the strong negative Eu anomalies suggest that K-rich felsic rocks are important source material for the sediments and a non-selective accumulation of feldspars during sedimentation [36]. Taylor and Mclennan [19] and Cullers [3,32] used the REE patterns and the negative Eu anomaly in sediments REE pattern to infer information regarding their source rocks. They observed that felsic rocks are usually characterized by higher LREE /HREE ratios and negative Eu anomalies whilst mafic rocks show lower LREE/HREE ratios with little or no Eu anomalies. Therefore, the high LREE/HREE ratios (7.40 to 16.96) and the observed negative Eu anomaly confirm that these sediments were derived from felsic rocks. The Eu/Eu*, Th/Sc, La/Sc, Th/Co, La/Co, and Th/Cr ratios are known to be significantly different in felsic and basic rocks and may allow constraints on the average composition of the probable source for the sediments [2,4]. These ratios are compared with those of sediments derived from felsic and mafic rocks (fine fraction) confirm that these ratios are dominantly within the range for felsic rocks (Table 4).

## 4. CONCLUSIONS

The sediments of Kolmani well, Gongola basin are rich in $Al_2O_3$ and $Fe_2O_3$. The low ratios of $Na_2O/K_2O$ suggest intense leaching from the source primarily whilst the Rb/Sr and Th/U ratios indicate more intense weathering in the source area. The relative enrichment in LREE to the HREE indicates REE fractionation during weathering and sedimentation. The absolute REE concentrations were in the order of coaly shale > shale > sandy shale > shaly sand > sand. The $Al_2O_3/T_1O_2$, Eu/Eu*, Th/Sc, La/Sc, Th/Co, La/Co, Th/Cr and the high LREE/HREE ratios as well as the pronounced negative Eu anomaly strongly suggest that the sediments were probably derived from felsic source rocks. The characteristically low V/Cr ratios and all the sediments plotting within the anoxic field on the Vanadium Nickel plot further confirm that they were deposited in an anoxic depositional environment, this is consistent with the horst and graben structural geotectonic setting of the Benue trough with the grabens providing ideal restricted oxygen poor depositional environment.

## ACKNOWLEDGEMENTS

The authors warmly appreciate the Shell Nigeria Exploration and Production Company (SNEPCO) for providing the samples used for this study. We wish to thank our colleagues who critically read the manuscript and made useful suggestions. We are also grateful to the Activation Laboratory, Ontario, Canada for the sample analysis.

### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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*Corresponding author: E-mail: ptchokos@yahoo.com;

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