Geochemistry of Onshore Deposits From Rio-Del-Rey Sub-Basin of The Western Atlantic Margin of Cameroon (Coastal Basin, South West Cameroon): Provenance And Environments of Sedimentation

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Abstract

The Rio del Rey Basin belongs to the coastal basins of Cameroon with Cretaceous to Cenozoic deposits. The Cretaceous (Cenomanian and Campanian-Maastrichtian) and Cenozoic (Paleocene) sediments were studied using major and trace elements geochemistry associated with mineralogical data. The studied samples are mainly made up of Fe-shale and shale with rare intercalations of Fe-sand in the Cenomanian deposits, Fe-shale and shale in the Campanian-Maastrichtian deposits and sub-litharenite, Fe-sand, shale and Fe-shale in the Paleocene deposits. These samples contain high LREE/HREE ratios (9.27–24.23), no to slight positive Eu anomalies ($\text{Eu}/\text{Eu}^* = 1.02 - 1.44$), moderate to high $\text{Al}_2\text{O}_3/\text{TiO}_2$ (10.42–112.93) ratio and their position in the Ce vs. La/Yb, Zr vs. TiO_2 and La/Sc vs. Th/Co diagrams indicate that they derive from mainly felsic associated with subordinate intermediate igneous rocks. The CIA (Chemical Index of Alteration; 61.69–92.76), PIA (Plagioclase Index of Alteration; 62.16–99.47), $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios (0.08–22.125) and Zr/Sc vs. Th/Sc diagram suggest the source rocks have experienced low to high recycling and weathering (Paleocene deposits), high chemical weathering (Campanian-Maastrichtian) and moderate to high chemical watering (Cenomanian deposits). The SiO_2 vs. $\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O}$ plot suggests a predominant semi-arid to arid climate with periodically semi-humid climate during the Paleocene, attested by the evolution of the clay minerals composition with association of illite-chlorite/vermiculite/kaolinite in the Cenomanian sediments and periodic appearance of siderite in the Campanian-Maastrichtian and Paleocene deposits. The Sr/Ba (0.41–2) and U/Th (0.16–0.28) ratios indicate brackish to shallow marine environment of deposition. The Arc-Rift-Collision of two sets of high and low silica rocks and SiO_2 vs. $\text{K}_2\text{O}/\text{Na}_2\text{O}$ diagrams indicate a Collisional or Active Continental Margin tectonic setting similar as the Cretaceous (Lower Mundeck and Logbadjeck Formation) and Paleocene (Nkapa Formation) deposits from the Douala sub-basin, which could reflect the Precambrian basement history linked to the Neoproterozoic orogeny.

Introduction

The geochemical signature has been used to mark as well as the fluvial (El-Ghali et al., 2006), marine (Nothdurft et al., 2004) as marine to brackish (Yang et al., 2017) deposits.

The Rio del Rey Basin (Fig. 1) belongs to the coastal basin of Cameroon whose the genesis is linked to the opening of South Atlantic Ocean from the lower Cretaceous (Njike Ngaha and Eno Belinga, 1987b; Njiké Ngaha et al., 2014). Its localization at the Continent-Ocean transition exhibits it to the continental and marine influences. As the onshore outcrops are scarce, the main informations concerning the stratigraphy are from drilling and geophysics (Regnault, 1986).

Several studies have been carried out in the Rio del Rey Basin based essentially on the bio-stratigraphy and environment of deposition (Njoh and Petters, 2008; Njoh et al., 2013; 2018; Njoh and Taku, 2016), meanwhile the provenance of sediment, the source rocks or tectonic environment are unknown. By another way, geochemical and mineralogical study of sedimentary deposits from coastal basins in Cameroon has been carried out in the Douala Basin essentially, in the Cretaceous deposits (Ngueutchoua et al., 2017; Ngueutchoua et al., 2019a and b) and in the Tertiary deposits (Ngon Ngon et al., 2019). The onshore contact or transition between Cretaceous and Tertiary deposits was identified (Njoh et al., 2018) which constitute a good marker for the knowledge of variation of sedimentation conditions.

In this work, we discuss the provenance, the source rock weathering, the paleo-redox and salinity conditions and tectonic environment of some Cretaceous (Cenomanian and Campanian-Maastrichtian) and Tertiary (Paleocene) sediments from the Rio del Rey Basin. Correlation of our data with those from the Douala Basin which has the same geological history with the Rio del Rey Basin is also presented.

Geological Setting

The Rio del Rey Basin belongs to the coastal basins of Cameroon named “Atlantic Basin” with among others, the Douala and Campo basins. Meanwhile, the Rio del Rey and Douala basins would have a common geological history and parted from each other from the lower Cenozoic by the volcanic massive of Mount Cameroon (Njike Ngaha, 1984; Dumort, 1968). Indeed, its geological history is common with the one of the Douala Basin until Burdigalian time when the onset of uplift of Mount Cameroon creates a barrier. The Rio del Rey Basin is distinguished from the Douala and Campo Basins by the great development of its continental shelf, 80km against 50 and 30km respectively, which ends with a steep slope probably because of the proximity of the Mount-Cameroon volcanic horst (Regnault, 1986).

The stratigraphy and tectonic evolution of the Rio del Rey Basin is similar like others West African coastal basins related to the opening of South Atlantic Ocean (Njike Ngaha, 1987b; Njiké et al., 2014). The Cretaceous biostratigraphic similarities between the deposits of Brazilian and West African Coast suggest that the both basins were likely welded. The genesis and morphology of the Atlantic Basin would be due to the simultaneous action of the N-S distension and dextral sliding (Brunn, 1980) along a transforming fault. A model of a mechanism with a tear and a rotating pole moving from South to North has been proposed by Dickson (1972) as responsible for diachronism of basal deposits (“grès de base”, Dumort, 1968) that would be the consequence of the oceanic expansion mechanism (Morgan, 1972). This basin constitutes the eastern end of Biafra Cone which is one of the two deltaic cones of the great Niger delta (Masclé, 1977). Therefore, it corresponds geodynamically to the fracture system linked to both the Cretaceous graben of the Benue and oceanization.

Because of the abundance of mangroves vegetation and the few access roads, the outcrops are scarce on land, and the available data have mainly been obtained by geophysics and drilling. The thickness of all the sedimentary deposits is greater than 6km, whose the ages varied from Cretaceous to Recent (Dumort, 1968; Regnault, 1986; Njoh et al., 2013). The Cretaceous deposits outcrops on the onshore part of the Basin while the Tertiary sediments overlie the Cretaceous mainly as progradation deltaic sequence offshore and made up of marine and non-marine clastic and biogenic sediments (Njoh et al., 2013; 2018; Njoh et Taku, 2016).

The stratigraphy of the Rio del Rey Basin (Fig. 2) is made up from the bottom to the top by:

- Neocomian-Albian unit ("Grès de base", Dumort, 1968) which overlie the Precambrian basement and made up of mudstones, sandstones and conglomerates. These deposits are fluvio-lacustrine;
- Albian-Cenomanian unit (Njoh et al., 2013) which comprises the thin beds of limestone interbedded within a predominantly dark-grey to black shales;
- Turonian-Coniacian unit (Njoh et al., 2013) made up of dark-grey calcareous shales interbedded by marlstones, limestones and siltstones;
- Campanian-Maastrichtian unit (Kita formation, Njoh et al., 2013) made up mainly by calcareous shales;
- Paleocene-recent unit (Akata Formation) which is a pro-deltaic marine shale overlying the Cretaceous sediment;
- Oligo-Miocene to recent unit (Agbada Formation) made up of alternating sands and shales parallel to the deltaic front unit;
- Pliocene-recent (Benin Formation), it is the uppermost unit, which comprises continental coastal plain sandstones with some rare intercalation of mottled clays. Off of Cap-Debunsha, the Benin Formation rests directly on the Akata Formation probably due to current stripping of the Agbada Formation.

Methods

Thin sections of the representative main facies of the Cenomanian, Campanian-Maastrichtian and Paleocene sediments were prepared at Langfang Rock Detection Technology Services Ltd in Hebei (China) and their petrographic study under polarized microscope was carried out at the Laboratory of Petrology and Structural Geology in the University of Yaounde 1, Cameroon.

The X-ray diffraction (XRD) patterns were obtained from a Bruker D8- Avance Eco 1Kw diffractometer (Copper K α radiation, $\lambda = 1.5418 \text{ \AA}$, $V = 40 \text{ 125 KV}$, $I = 25 \text{ mA}$) with Lynxeye Xe energy dispersive detector in the laboratory of "Argiles, Géochimie et Environnements Sédimentaires (AGES)" at the University of Liege, Belgium. The analyses were carried out on the bulk material (non-oriented powder with grinded particles < 50 μm) of shales from the three study sites. The XRD patterns were recorded over the 2θ angular range for the bulk material. The step sizes considered for this analysis was $0.02^\circ 2\theta$, whereas the time per step chosen was 0.25s. The primary optic was motorized in order to illuminate a fixed sample length whatever the angular position (16 mm for bulk). The identification of mineral phases was carried out using Eva software.

Whole-rock geochemical analyses of fifteen (15) samples (06, 03 and 06 samples respectively from Cenomanian, Campanian-Maastrichtian and Paleocene deposits) were carried out at Bureau Veritas Commodities, Vancouver, Canada. Prepared samples (homogenized powder) were mixed with LiBO₂/Li₂B₄O₇ flux. Crucibles were fused in a furnace at 1000°C. The cooled bead was dissolved in ACS grade Nitric acid. Trace elements (including rare earth elements = REE) were determined by the inductively coupled plasma mass spectrometry (ICP-MS). Major elements oxides were obtained by inductively coupled plasma-atomic emission spectrometry (ICP-AES). Loss on ignition (LOI) was determined by igniting a sample split then measuring the weight loss. The assays uncertainties varied from 0.1–0.04% for major elements, 0.1 to 0.5% for trace elements and 0.01 to 0.5 ppm for rare earth elements. Accuracy for REE is estimated at 5% for concentrations > 10 ppm and 10% when lower.

Results

4.1. Field descriptions

Three main outcrops were studied (Fig. 3), two outcrops in Illor area (Djega 1 and Djega 2) and one is Dibonda village (Mesambi Downstream).

- Djega 1 outcrop

It is made up of more than 30m high of monotonous claystones (shale) from road level down the steep scarp up to the river Djega. The deposit is grey dark laminated and generally fissile and contains numerous nodules and lenticular concretions of black claystone. There are abundant fossils of bivalve moulds and casts. The intense reaction with diluted HCl indicates the presence or more or less abundance of carbonate.

- Djega 2 outcrop

The Djega 2 outcrop is a road cut located at a few hundred meters from the first outcrop. This outcrop is about 4m high and made up of alternation of sandstones and shales generally with lenticular disposition (Fig. 4A). The thickness sandstones vary from centimeter to more than one meter with varied color, reddish, grey and brown (Fig. 4B), sometime with shale lenses showing wavy structure, and varied shape leaf fossils (Fig. 4C and D). The thickness of shales deposits varies from millimeter to more than 20cm, generally laminated and grey color with sometime sandstone lenses.

- Mesambi downstream outcrop

This outcrop is located at the left bank of the flowing direction of Mesambi River. The thickness is more than 30m from the bed of the Mesambi River in up slope up to the top. This outcrop is made up of monotonous alternating of shales and marlstones/calcareous shales (Fig. 4E). The shales thickness varies between 2 and 7m, they are green dark to black grey color and generally laminated and fissile, with some nodular levels. They react generally with diluted HCl. The limestones are green dark to grey color with thickness between 5 and 60 cm, and are generally laminated.

4.2. Petrography

- Djega 1

The petrographic analyses show that they are composed of very fine grains of carbonate (siderite > 50%) associated to indifferenciated clays minerals with micrograins of quartz/feldspar (5–15%) and more or less abundant of organic matter. The microstructure is globally cryptocrystalline (Fig. 5A) and laminated.

- Djega 2

The mineralogical composition of studied shales is made up of quartz (15–50%), feldspar (3–15%), muscovite (1–3%), epidote (< 1%) and chlorite (< 2%) distributed in a matrix (40–80%) made up of undifferentiated clay minerals, calcite, and organic matter. The grain shape are generally very angular to angular and size < 0,35mm. The microstructure is fine to very fine clastic heterogranular to sub isogranular (Fig. 5E and F). Two type of facies are distinguished, shales and silty to sandy shales.

The mineralogical composition of sandstones facies is made up of quartz (80–90%), feldspar (5–10%), mica (1–2%), chlorite (< 1%), and oxide (< 1%) with argilo-carbonated matrix (5–7%). The grain shape is very angular to rounded but dominated by angular shape. The grain quartz are sometime polycrystalline. Feldspar is dominated by plagioclase and orthoclase and frequently sericitized and vacuolized. The mica is frequently the muscovite with flaky or needly shape. The grain size of studied sandstones vary either between 0.1-1mm or 0.1 to 2mm giving clastic heterogranular fine to average (Fig. 5G) or fine to coarse microstructures (Fig. 5H).

- Mesambi

The studied shales are composed micrograins of quartz and feldspar (10–20%) associated with some flake muscovite spreaded in the carbonated matrix more or less rich in organic matter and undifferentiated clay minerals. The microstructure is cryptocrystalline (Fig. 5B) to very fine clastic (Fig. 5C).

The limestones/marlstones are made up of calcite (35–50%), quartz and undifferentiated feldspar (35–50%), mica (5–10%) and oxide (1–2%). The quartz and feldspar grain shape are very angular with some sub-rounded. The particle size is < 0.15mm. The mica (muscovite essentially) are flaky or needly, oriented underlining the lamination and sometimes chlorosited (biotite) and sigmoid. The microstructure is fine clastic (Fig. 5D).

4.3. X-ray diffraction analyses

From the X-ray diffraction analyses (Fig. 6), there are three distinctive groups of mineral, nonclay minerals, clay minerals and carbonated minerals. The Cenomanian shales (MK1, MK2 and MK6) have close mineralogical composition, with nonclay mineral (quartz, plagioclase, orthoclase and magnetite and dominated by the quartz), clay minerals (illite, kaolinite and chlorite-vermiculite), with gradual decrease of Kaolinite, and carbonated minerals (calcite, dolomite). Meanwhile, there is some variance in mineralogical composition in the Campanian-Maastrichtian shales (DK1A, DK1N and DK1B) compare to the Cenomanian, with abundant quartz (DK1B) and siderite (DK1A), and the clay mineral is represented by the kaolinite. The Paleocene shales (DK4 and DK10), as those of Cenomanian, contain varied nonclay minerals (quartz, plagioclase, orthoclase and magnetite), clay mineral is only kaolinite and the carbonated mineral is mainly siderite (DK4) with secondary calcite and dolomite. Thus, in the Cenomanian shales deposits, there are kaolinite, illite and chlorite-vermiculite (interstratified) association which appears periodically at the Campanian-Maastrichtian (DK1A) period and no in the Paleocene, and the periodic appearance of siderite during the Campanian-Maastrichtian and Paleocene periods.

4.4. Geochemistry

- Major elements

The major element compositions of the studied samples are represented in Table 1 which shows that SiO_2 (8.11–91.57%), Al_2O_3 (3.57–24.21%) and Fe_2O_3 (0.25–41.52%) are the most abundant and SiO_2 are generally more abundant in the more coarse grains such as DK5 (91.57%), DK7 (91.16) and DK6 (75.12%). The second most abundant group is represented by MgO (0.05–8.30%) and CaO (0.04–16.26%) which are generally less represented in coarse grains. The third most abundant includes Na_2O (0.04–2.37%), K_2O (0.08–3.48%) and TiO_2 (0.13–1.93%). The concentration of other elements are generally < 1% except the sample MK3 with MnO concentration equal to 1.04.

Table 1
Major elements composition (wt. %) and elemental ratios of the studied sample

	Paleocene							Campanian-Maastrichtian			Cenomanian				
	LD	DK3	DK4	DK5	DK6	DK7	DK10	DK1A	DK1B	DK1N	MK0	MK1	MK2	MK3	MK6
SiO ₂	0.01	52.9	8.11	91.57	75.12	91.16	58.24	10.23	48.82	56.19	50.62	51.14	55.47	26.24	55.4
Al ₂ O ₃	0.01	13.97	3.57	4.89	2.56	5.08	20.73	5.2	24.21	18.52	11.35	11.37	16.94	8.04	15.1
Fe ₂ O ₃	0.04	7.87	41.52	0.4	13.42	0.25	3.57	39.89	5.72	7.57	8.2	7.97	7.19	27.02	8.44
MgO	0.01	3.22	8.3	0.05	0.81	0.04	0.62	7.95	1.04	0.85	2.6	2.54	3.04	6.87	3.28
CaO	0.01	5.96	3.76	0.08	0.5	0.09	0.5	3.44	0.04	0.1	10.49	10.39	1.61	4.22	2.83
Na ₂ O	0.01	1.89	0.06	1.39	1.01	1.55	1.71	0.04	0.08	0.43	2.34	2.37	1.39	0.43	1.58
K ₂ O	0.01	2.66	0.29	0.11	0.08	0.13	1.91	0.37	1.77	1.07	1.82	1.8	3.48	1.49	2.83
TiO ₂	0.01	0.96	0.38	0.25	0.13	0.24	1.99	0.48	1.93	1.83	0.5	0.52	0.15	0.52	1.05
P ₂ O ₅	0.01	0.18	0.55	0.02	0.01	< 0.01	0.21	0.35	0.1	0.09	0.14	0.15	0.17	0.12	0.19
MnO	0.01	0.17	0.58	< 0.01	0.16	< 0.01	0.02	0.52	< 0.01	0.01	0.21	0.22	0.04	1.04	0.06
Cr ₂ O ₃	0.01	0.013	0.005	0.003	< 0.002	< 0.002	0.017	0.007	0.022	0.017	0.006	0.007	0.016	0.01	0.01
LOI	-5.1	9.9	32.4	1.2	6.1	1.4	10.2	31.3	16	9.9	11.5	11.3	9.2	23.8	8.9
SUM	0.14	99.693	99.81	99.963	99.9	99.94	99.717	99.777	99.732	99.78	99.81	99.777	98.696	99.8	99.7
SiO ₂ /Al ₂ O ₃	-	3.79	2.27	18.73	29.34	17.94	2.81	1.97	2.02	3.03	4.46	4.50	3.27	3.26	3.66
Na ₂ O/K ₂ O	-	0.71	0.21	12.64	12.63	11.92	0.90	0.11	0.05	0.40	1.29	1.32	0.40	0.29	0.56
K ₂ O/Al ₂ O ₃	-	0.19	0.08	0.02	0.03	0.03	0.09	0.07	0.07	0.06	0.16	0.16	0.21	0.19	0.19
Al ₂ O ₃ /TiO ₂	-	14.55	9.39	19.56	19.69	21.17	10.42	10.83	12.54	10.12	22.70	21.87	112.93	15.46	14.4
K ₂ O/Na ₂ O	-	1.407	4.83	0.079	0.079	0.083	1.116	9.25	22.125	2.48	0.777	0.759	2.50	3.46	1.79
Fe ₂ O ₃ /K ₂ O	-	2.96	143.17	3.64	167.75	1.92	1.87	107.81	3.23	7.07	4.51	4.43	2.07	18.13	2.98
CIA	-	68.45	89.70	75.58	61.69	74.16	83.42	92.04	92.76	92.05	63.59	63.48	73.02	77.38	71.6
PIA	-	74.95	96.47	76.48	62.16	75.11	89.49	98.37	99.47	97.05	67.07	66.88	82.88	88.39	79.5
ICV	-	1.61	15.21	0.47	6.23	0.45	0.50	10.03	0.44	0.64	2.29	2.25	1.00	5.04	1.32
CIW	-	78.70	96.75	76.89	62.90	75.60	90.37	98.48	99.51	97.22	70.80	70.58	85.90	90.34	82.7

LOI = Loss of Ignition; CIA (%) = $[\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O})] \times 100$ from Nesbitt and Young (1982); PIA (%) = $[\text{Al}_2\text{O}_3 - \text{K}_2\text{O} / (\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} - \text{K}_2\text{O})]$ from Nesbitt and Young and Fedo et al. (1995). IVC = $(\text{FeO}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO} + \text{MgO} + \text{TiO}_2) / \text{Al}_2\text{O}_3$ from Cox et al. (1995); CIW = $[\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O})]$ from Harnois (1988). The PAAS values are cited from Taylor and McLennan (1985) and McLennan (2001)

The classification diagram of Herron (1988) has revealed that the studied samples are composed mainly of shales (DK 1B, DK10, MK2, MK6 and DK3) and Fe-shales (MK1, DK1A, MK3, DK1N, DK4 and MK0) associated to Fe-sand (DK6, MK7) and sub-litharenite (DK5 and DK7) (Fig. 7).

In comparison to the Post Archean Australian Shale (PAAS), we divide the study samples in four groups (Fig. 8A); Djega 1 (Maastrichtian), Djega 2a (Paleocene, fine grains), Djega 2b (Paleocene, coarse grains) and Mesambi (Cenomanian). Groupe 2b samples is generally depleted but more enriched in SiO₂. Groupe Djega 1 samples is more depleted in Na₂O. FeO₂ element is enriched and dominant Group Djega 2a and Djega 1 samples. K₂O element is the more depleted of all elements and more in the Group 2b, whereas CaO is the more enriched of all elements and more in the Group Mesambi elements. Al₂O₃ is always depleted and more depleted in Group Djega 2. TiO₂ is enriched in Groups Djega 1 and Djega 2 samples and more in Group Djega 2b samples.

According to Table 2, positive relationship exists between Al₂O₃ and K₂O (r = 0.70) indicate that they belong to same detrital mineral phase such as orthoclase and between Al₂O₃ and TiO₂ (r = 0.81) is statistically significant.

Table 2
Pearson's inter-element correlation matrix for major elements

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	Cr ₂ O ₃	LOI
SiO ₂	1											
Al ₂ O ₃	-0.0301	1										
Fe ₂ O ₃	-0.7995	-0.4250	1									
MgO	-0.8919	-0.2945	0.9048**	1								
CaO	-0.3113	-0.2306	-0.0017	0.2264	1							
Na ₂ O	0.4918	0.0653	-0.6183	-0.4527	0.3278	1						
K ₂ O	-0.1366	0.6986**	-0.3168	0.0112	0.1421	0.3617	1					
TiO ₂	-0.0891	0.8088**	-0.2619	-0.2758	-0.2341	-0.0905	0.2528	1				
P ₂ O ₅	-0.7551	0.1911	0.5824	0.6583	0.0883	-0.1492	0.2511	0.2069	1			
MnO	-0.6921	-0.4359	0.7305	0.8117**	0.3428	-0.4029	-0.1670	-0.2882	0.2077	1		
Cr ₂ O ₃	-0.2177	0.9598	-0.2383	-0.0896	-0.2227	-0.1428	0.7117	0.7693	0.2803	-0.2514	1	
LOI	-0.9670	-0.0892	0.8377	0.8669	0.2823	-0.6390	-0.0786	0.0617	0.6648	0.7255	0.1113	1
* Correlation is significant at 0.05 (0.46–0.60)												
** Correlation is significant at 0.01 (> 0.60)												

A high positive correlation between Fe₂O₃ and MgO ($r = 0.90$) indicate that they belong to the same detrital mineral phase such as amphibole and between MgO and MnO ($r = 0.81$) is statistically significant.

- Trace elements

The trace elements content of the studied samples is presented in the Table 3. Ba, Rb, Sr, V and Zr show a wide range concentration from 24 to 518 ppm, 3 to 176 ppm, 48 to 388.9 ppm, 9 to 193 ppm and 76.1 to 700.1 ppm, respectively.

Table 3
Trace elements composition (ppm) and elemental ratios of the studied samples

	Paleocene						Campanian-Maastrichtian				Cenomanian					
	LD	DK3	DK4	DK5	DK6	DK7	DK10	DK1A	DK1B	DK1N	MK0	MK1	MK2	MK3	MK6	MK7
Ba	1	479	45	32	24	29	315	70	196	261	518	501	455	214	486	252
Ni	20	37	20	15	15	20	28	24	106	43	36	34	53	39	51	20
Sc	1	12	5	1	3	1	13	7	20	14	7	7	17	10	15	6
Be	1	3	4	2	2	1	1	2	5	2	2	1	6	2	3	2
Co	0.2	15	6.4	0.2	1.6	0.3	10.7	8.3	43.1	10.9	10.7	10.5	18.4	12.9	19.1	9.6
Cs	0.1	5.6	0.6	0.1	0.1	0.1	2.4	1	4.5	2.7	1.9	1.9	9.8	3.7	7.2	2.8
Ga	0.5	18.2	2.6	2.7	1.7	1.4	32.6	5.2	31.3	23.1	11.4	12.9	25.7	10	20.6	9.4
Hf	0.1	10.7	1.9	9.7	5.2	11.1	17.3	2.4	9.4	16.5	8.3	9	6.1	2.6	6.8	5.7
Nb	0.1	20.2	9.2	6.4	3.9	6.1	60.5	10.3	38.6	45.1	11.2	11.6	21.4	10.2	19.9	10.1
Rb	0.1	120.5	10.5	3.5	3	3.4	58.2	13.8	67.4	40.5	60.5	61.4	176.2	75.1	142.2	63.3
Sn	1	4	1	2	11	1	6	1	4	4	2	3	4	2	4	2
Sr	0.5	258.4	68.1	58.2	48	54.4	288.6	65	111.5	113.5	384.1	388.9	187	120.3	211.5	271.8
Ta	0.1	1.5	0.6	0.5	0.2	0.4	4.2	0.7	2.4	3	1	0.7	1.6	0.7	1.4	0.7
Th	0.2	23.8	3.5	5.4	2.2	6.1	25.7	3.8	16.8	19.8	14.1	13.2	21.4	10.4	20.7	11.4
U	0.1	5.3	0.6	1	0.6	1	5.5	1	3.5	4.5	3.7	3.7	4.3	2.5	4	2.6
V	8	77	24	11	10	9	101	50	193	150	44	37	115	51	93	34
W	0.5	1.2	0.7	<0.5	1.9	0.5	2	<0.5	1.4	1.5	0.8	1.3	1.3	0.9	1.4	0.6
Zr	0.1	398.4	76.1	407.9	217.5	454.3	700.1	94.9	342.4	638.6	323.1	351.6	210	91.7	253.2	210.6
Y	0.1	34	27.2	3	2.6	3.1	31.4	33.9	33.8	31.7	33.1	32.5	30.1	22.4	32.4	21.5
Zr/Hf	-	37.23	40.05	42.05	41.83	40.93	40.47	39.54	36.43	38.70	38.93	39.07	34.43	35.27	37.24	36.95
Th/U	-	4.49	5.83	5.40	3.67	6.10	4.67	3.80	4.80	4.40	3.81	3.57	4.98	4.16	5.18	4.38
Th/Co	-	1.59	0.55	27.00	1.38	20.33	2.40	0.46	0.39	1.82	1.32	1.26	1.16	0.81	1.08	1.19
Th/Sc	-	1.98	0.70	5.40	0.73	6.10	1.98	0.54	0.84	1.41	2.01	1.89	1.26	1.04		1.90
U/Th	-	0.22	0.17	0.19	0.27	0.16	0.21	0.26	0.21	0.23	0.26	0.28	0.20	0.24	0.19	0.23
Ni/Co	-	2.47	3.13	75.00	9.38	66.67	2.62	2.89	2.46	3.94	3.36	3.24	2.88	3.02	2.67	2.08
Sr/Ni	-	6.98	3.41	3.88	3.20	2.72	10.31	2.71	1.05	2.64	10.67	11.44	3.53	3.08	4.15	13.59
Y/Ni	-	0.92	1.36	0.20	0.17	0.16	1.12	1.41	0.32	0.74	0.92	0.96	0.57	0.57	0.64	1.08
Co/Th	-	0.63	1.83	0.04	0.73	0.05	0.42	2.18	2.57	0.55	0.76	0.80	0.86	1.24	0.92	0.84
Zr/Sc	-	33.20	15.22	407.90	72.50	454.30	53.85	13.56	17.12	45.61	46.16	50.23	12.35	9.17	16.88	35.10
Zr/Y	-	11.72	2.80	135.97	83.65	146.55	22.30	2.80	10.13	20.15	9.76	10.82	6.98	4.09	7.81	9.80
Y/Hf	-	3.18	14.32	0.31	0.50	0.28	1.82	14.13	3.60	1.92	3.99	3.61	4.93	8.62	4.76	3.77
Th/Y	-	0.70	0.13	1.80	0.85	1.97	0.82	0.11	0.50	0.62	0.43	0.41	0.71	0.46	0.64	0.53
The PAAS values are cited from Taylor and McLennan (1985) and McLennan (2001)																

When compared to the PAAS (Fig. 8B), the enrichment and depletion rate is globally more pronounced in the Djega 2 deposits respectively in fine and coarse grains. The Djega 2b (coarse grains) samples are generally depleted except in Zr and Hf elements. There are some trace elements depleted in coarse grains but enriched in fine grains such as Y, U, Th, Ta, Sc, and Nb. Zr element is the more enriched and Cs and Rb elements the more depleted.

- Rare earth elements (REE)

The REE concentrations of studied samples are compiled in Table 4. Globally, the total REE range from 155.73 to 339.08 ppm, 154.64 to 304.45 ppm and from 28.03 to 396.52 ppm respectively in the Cenomanian, Campanian-Maastrichtian and Paleocene deposits. The studied samples are enriched in LREE concentration (26.52–379.4 ppm) and depleted in HREE (1.51–17.99 ppm).

Table 4
Rare-earth elements composition (ppm) and elemental ratios of the studied samples

	Paleocene							Campanian- Maastrichtian			Cenomanian				
	LD	DK3	DK4	DK5	DK6	DK7	DK10	DK1A	DK1B	DK1N	MK0	MK1	MK2	MK3	MK
La	0.1	66.1	18.9	11.6	7	7.7	88.6	27.9	68.7	61.6	42.2	41.9	77.7	46.5	70.9
Ce	0.1	127.3	37.6	17.8	12.3	13.5	173.1	50.2	131.6	119	85.5	80.8	148.5	89.2	142
Pr	0.02	14.28	4.65	1.81	1.27	1.42	19.46	6.6	14.8	13.44	9.88	9.13	16.9	10.06	16.4
Nd	0.3	54.4	20.7	6.1	4.6	4.9	73.2	30.6	53.9	47.6	37.7	35	60.3	38.1	60.6
Sm	0.05	9.84	5.71	0.88	0.71	0.67	12.97	9.05	9.02	7.21	7.09	6.8	10.29	6.86	10.6
Eu	0.02	1.97	2.25	0.18	0.15	0.16	2.91	2.7	1.83	1.48	1.55	1.43	2.05	1.4	2.08
Gd	0.05	8.18	9.48	0.64	0.49	0.54	9.16	12.73	6.61	5.33	6.52	5.99	8.4	5.86	8.72
Tb	0.01	1.2	1.22	0.08	0.08	0.07	1.26	1.64	1.09	0.81	0.95	0.91	1.15	0.82	1.22
Dy	0.05	6.37	5.31	0.5	0.48	0.55	6.68	7.61	6.8	5.15	5.56	5.17	6.04	4.26	6.56
Ho	0.02	1.23	0.81	0.09	0.1	0.14	1.25	1.06	1.39	1.2	1.12	1.04	1.08	0.79	1.22
Er	0.03	3.39	1.76	0.32	0.32	0.39	3.55	2.31	3.95	3.77	3.07	2.75	3.16	2.08	3.22
Tm	0.01	0.46	0.21	0.06	0.06	0.07	0.51	0.28	0.55	0.55	0.4	0.38	0.41	0.29	0.46
Yb	0.05	3.09	1.22	0.49	0.42	0.55	3.39	1.73	3.67	3.84	2.44	2.46	2.72	1.89	2.76
Lu	0.01	0.45	0.18	0.07	0.05	0.1	0.48	0.23	0.54	0.58	0.36	0.33	0.38	0.27	0.42
REE	-	298.26	110	40.62	28.03	30.76	396.52	154.64	304.45	271.56	204.34	194.09	339.08	208.38	327
LREE	-	282.07	99.29	39.01	26.52	28.89	379.4	139.78	286.46	255.66	190.44	181.05	324.14	197.98	311
HREE	-	16.19	10.71	1.61	1.51	1.87	17.12	14.86	17.99	15.9	13.9	13.04	14.94	10.4	15.9
LREE/HREE	-	17.42	9.27	24.23	17.56	15.45	22.16	9.41	15.92	16.08	13.70	13.88	21.70	19.04	19.6
La + Ce + Nd	-	247.8	77.2	35.5	23.9	26.1	334.9	108.7	254.2	228.2	165.4	157.7	286.5	173.8	274
a	-	0.83	0.70	0.87	0.85	0.85	0.84	0.70	0.83	0.84	0.81	0.81	0.84	0.83	0.84
Eu/Eu*	-	1.03	1.44	1.13	1.20	1.25	1.26	1.18	1.12	1.12	1.07	1.06	1.04	1.04	1.02
Ce/Ce*	-	0.96	0.93	0.90	0.95	0.94	0.96	0.85	0.95	0.95	0.97	0.95	0.95	0.95	0.96
Pr/Pr*	-	1.01	0.98	1.02	0.99	1.03	1.02	0.99	1.03	1.05	1.02	1.01	1.05	1.02	1.04
La/La*	-	1.05	1.38	1.19	1.14	1.04	1.01	1.67	0.97	0.92	0.98	1.06	0.93	1.04	0.92
Gd/Gd*	-	1.00	1.23	1.36	1.00	1.80	1.07	1.04	1.03	1.14	1.09	1.02	1.06	1.03	1.06
Eu/Eu* = (Eu _{sample} /Eu _{PAAS})/(Sm _{sample} /Sm _{PAAS}) ^{1/2} (Gd _{sample} /Gd _{PAAS}) ^{1/2} ; Ce/Ce* = (Ce _{sample} /Ce _{PAAS})/(La _{sample} /La _{PAAS}) ^{1/2} (Pr _{sample} /Pr _{PAAS}) ^{1/2} ; (La/Yb) _N = (La _{sample} /La _{PAAS})/(Yd _{sample} /Yd _{PAAS}); (La/Sm) _N = (La _{sample} /La _{PAAS})/(Sm _{sample} /Sm _{PAAS}); (Gd/Yb) _N = (Gd _{sample} /Gd _{PAAS})/(Yd _{sample} /Yd _{PAAS}). The PAAS values from Taylor and McLennan (1985) and McLennan (2001)															

The PAAS normalized REE values (Taylor and McLennan, 1985; McLennan, 2001) indicate a slight positive to positive Eu anomalies (Eu/Eu* vary from 1.02 to 1.44) for the three group and upper to the PAAS (0.65); a slight negative Ce anomalies (Ce/Ce* vary from 0.85 to 0.97) and lower than PAAS (1.05); a slight negatives and positives La anomalies generally (La/La* vary from 0.92 to 1.19 except the DK1A sample (La/La*1.67) with high positive La anomaly; the slight negative to no Pr anomalies (Pr/Pr* vary from 0.98 to 1.03) and no to high positive Gd anomalies (Gd/Gd* vary from 1.00 to 1.80). the PAAS and chondrite normalized REE pattern (Fig. 9A and B) show that the fine grained sediments are more enriched than the coarse grains one (DK5, DK6 and DK7). In Fig. 8A, the REE patterns are approximately flattened with some samples such as DK1A and DK4 enriched in Gd and Eu respectively. In Fig. 8B, the REE patterns indicate globally an enrichment in LREE.

In Fig. 10, the REE contents show positive relationship with SiO₂, Al₂O₃, K₂O, Na₂O and TiO₂ but display a negative correlation with Fe₂O₃, MgO and CaO indicating different origins of these chemical elements.

Discussion

5.1. Geochemical composition

The higher values of K₂O contents compare to those of Na₂O could reflect respectively the abundance of potassium bearing minerals (Moradi et al., 2016) and little plagioclase (Ross and Bustin, 2009). The K₂O contents of Campanian-Maastrichtian samples (0.37–1.77%) are higher than Na₂O contents (0.04–0.43%),

but these values (K_2O and Na_2O values) are variables in the Paleocene and Cenomanian deposits, indicating the abundance of potassium bearing minerals in the Maastrichtian deposits and the variation of composition and proportion between sodium- and potassium-bearing minerals (orthoclase and plagioclase respectively). The MgO contents and proportions (Table 1) indicate the presence of dolomite mineral in the sediment (Zeng et al., 2019). The concentration of this element range from 0.05 to 8.30% and their important proportion in the DK1A, DK4 and MK3 samples indicate the presence of dolomite as indicated by the X-ray diffractions of these samples (Fig. 5). Generally, major elements oxides such as SiO_2 , Al_2O_3 , Na_2O , K_2O and TiO_2 correspond to terrigenous elements whereas CaO , MgO and MnO oxides are related to carbonates (Moradi et al., 2016; Zeng et al., 2019). According to Fig. 9, the positive correlation with REE and SiO_2 , Al_2O_3 , Na_2O , K_2O and TiO_2 and negative relationship with CaO , MgO and Fe_2O_3 indicate that the REE contents in the studied samples are mainly controlled by terrigenous input and the Fe_2O_3 is related to carbonate (siderite). The LREE/HREE ratios of all the studied samples range from 9.37 to 24.23 suggesting an enrichment in LREE (Table 4).

5.2. Sediment maturity and recycling

For compositional maturity and recycling sediments, many ratios/index have been used such as K_2O/Na_2O ratio (Armstrong-Altrin et al., 2016; Ngueutchoua et al., 2017) and ICV index (e.g. Absar and Sreenivas, 2015; Armstrong-Altrin et al., 2015; Ngueutchoua et al., 2017; Tawfik et al., 2017b).

The ICV values of our studied sediments globally vary from 0.44 to 15.21. These ratios vary from 0.45 to 15.21, from 0.44 to 10.03 and 1.00 to 5.04 respectively for Paleocene, Campanian-Maastrichtian and Cenomanian sediments. According to Van de Kamp and Leake (1985), compositionally mature deposits with low ICV values indicate high recycling and compositionally immature sediments with high ICV values are of first-cycle deposits. From our results, the Paleocene deposits are mature (DK5, DK7 and DK10), and sub-mature to immature (DK3, DK6 and DK4 respectively), the Campanian-Maastrichtian sediments are mature (DK1B and DK1N) to immature (DK1A) and the Cenomanian deposits are globally sub-mature.

The K_2O/Na_2O ratios of the studied samples globally vary from 0.08 to 22.125. These ratios vary from 0.08 to 4.83, from 9.25 to 22.125 and from 0.76 to 3.46 respectively for Paleocene, Campanian-Maastrichtian and Cenomanian sediment. This ratio > 1 indicates high chemical maturity (Armstrong-Altrin et al., 2016). From our results, the Paleocene sediments are immatures (DK5, DK6 and DK7) to mature (DK3, DK4 and DK10), the Campanian-Maastrichtian sediments are mature with high amount of sediment recycling and the Cenomanian sediments are sub-mature to mature.

According to scatter diagram of Zr/Sc vs. Th/Sc (Fig. 11) (after McLennan et al., 1993), one part of studied samples are clustered at the end of primary compositional trend and others along the trend involving zircon addition, indicating the sub-mature to mature character of studied sediments.

5.3. Provenance

Several diagrams were used to constrain the provenance of our studied sediments such as Th/Co vs. La/Sc (Fig. 12A) (after Cullers, 2002), Zr vs. TiO_2 (Fig. 12B) (after Hayashi et al., 1997) and Ce vs. La/Yb (Fig. 11C) (after Rao et al., 2011). The trace-elements based provenance discrimination diagram of Cullers (2002) discriminates two major provenance; from basic and silicic rocks. Our studied samples are plotted in silicic rocks provenance domain. The trace-major-elements based provenance discrimination diagram of Hayashi et al. (1997) discriminates three major provenance type; mafic, intermediate and felsic igneous rocks. According to this diagram, the studied sediments originated from felsic rocks mainly with contribution of intermediate igneous rocks. The trace-elements based provenance discrimination diagram of Rao et al. (2011) which discriminates also three major provenances confirms the dominance of felsic provenance of our studied sediments.

The sources of sediments can also be deduced from LREE/HREE ratio and Eu anomaly values (Taylor and McLennan, 1985; Mongelli et al., 1998). According to Cullers (2000) and El-Bialy (2013), basic igneous rocks contain low LREE/HREE ratios and little or no Eu to positive Eu anomalies contrary to silicic igneous rocks. The LREE/HREE values of our studied sediments vary from 9.27 to 24.23 and often upper to the PAAS value (13.27) except two samples (DK1A and DK4), and those of Eu anomalies from 1.02 to 1.44 indicating the heterogeneous source rocks.

The Al_2O_3/TiO_2 ratio is also widely used to constrain the source rocks (e.g. Armstrong-Altrin et al., 2015; Zhou et al., 2015; Ngueutchoua et al., 2017; Tawfik et al., 2017b); this ratio varies from 3 to 8, from 8 to 21 and from 21 to 70 respectively for mafic, intermediate and felsic igneous rocks, this ratio applied to our studied sediments varies from 10.42 to 112.93 corresponding to the heterogeneous source rocks (intermediate and felsic igneous rocks).

According to Garver (1996), the values of $Cr > 150$ ppm and $Ni > 100$ ppm are indicative of mafic –ultramafic rocks in the source area, our studied samples show the value of $Cr < 150$ ppm generally (ranges from < 13.684 to 116.314) and $Ni < 100$ ppm generally (range from < 15 to 51) except one sample (DK1B: $Ni = 106$ and $Cr = 150.524$) which could indicate the presence of ultra-mafic or mafic rock in the source areal, and confirms the heterogeneous characteristic of source rocks dominated by felsic rocks as indicated the previous ratios above.

5.4. Paleo-redox and paleo-salinity conditions

Paleosalinity condition reconstruction of environment of deposition from our studied sediments were highlighted by using the Sr/Ba ratio (e.g. Zheng and Lin, 1999; Xu et al., 2011; Meng et al., 2012; Ngueutchoua et al., 2019a; Zeng et al., 2019). According to Cao et al., 2012, this ratio increases from coastal fresh water to the open and marine water, $Sr/Ba > 1$ in marine sediment and < 1 in fresh water (Jones and Manning, 1994; Shi et al., 1994; Wang et al., 2005). The Sr/Ba ratio values of our studied sediments vary from 0.41 to 2. These values range from 0.54 to 2, from 0.91 to 1.51 and from 0.41 to 1.08 respectively for Paleocene, Campanian-Maastrichtian and Cenomanian deposits, indicating variable salinity linked to continental and marine influences, probably brackish to shallow marine environments.

U/Th and Ni/Co ratios were widely used as there are sensitive to paleo-redox conditions (e.g. Jones and Manning, 1994; Rimmer, 2004; Teng et al., 2005; Tribouvillard et al., 2006; Nagarajan et al., 2007; Zhao et al., 2016b; Dulu et al., 2017; Xie et al., 2018). The U/Th ratio below 0.75 suggests oxic condition and above 0.75 indicates dioxic to anoxic conditions, and Ni/Co ratio below 5, between 5 and 7 and above 7 indicate respectively oxic, sub-oxic and anoxic

conditions. The U/Th (Fig. 13A) and Ni/Co values are respectively < 0.75 (0.19 to 0.28) and < 5 (2.08 to 3.24) indicating oxic conditions. V/Cr ratio is also used (e.g. Bokanda et al., 2019), this ratio < 2 indicates oxic conditions. The Y/Ho ratio ranging between 40 and 90 indicate the sea environment and < 40 the river environment (Bau and Dulski, 1996; Nozaki et al., 1997; Bolhar et al., 2004; Abigail et al., 2010; Bokanda et al., 2019). In our study, this ratio ranges from 22.14 to 33.58 (Fig. 13B), suggesting river conditions.

5.5. Paleoclimate and paleoweathering

The major-elements based paleoclimate discrimination diagram (Sutter and Dutta, 1986) discriminates two main climatic types, humid and arid climates (Fig. 14). The studied samples are plotted in the two domains with predominance of the arid conditions. According to this diagram, the Cretaceous deposits were deposited under essentially semi-arid to arid conditions and the Paleocene facies under alternatively semi-humid and arid conditions.

The relationship between weathering and climate (White and Blum, 1995) and between weathering and temperature (Meunier et al., 2013) were established. The high chemical weathering indicates humid condition and high temperature respectively. The PIA (62.16 to 99.47) and CIA (61.69 to 92.76) values of the studied sample are variables. They range respectively from 62.16 to 96.47 and 61.69 to 89.70 and for the Paleocene deposits, from 97.05 to 99.47 and 92.04 to 92.76 for Campanian-Maastrichtian deposits, and from 66.68 to 88.39 and 63.48 to 77.38 for Cenomanian deposits. These values indicate variable temperature during the different periods of deposition and variable chemical weathering (Nesbitt and Young, 1984; Fedo et al., 1995). Meanwhile, the presence of illite and K-feldspar (See Fig. 6) may indicate a K-addition, and it is noteworthy that the CIA value may be decreased due to K-metasomatism (Fedo et al., 1995). On the A-CN-K diagram (Fig. 15), the studied sediments plotted indicate mainly tonalite and granodiorite composition rocks that have been submitted to low and high chemical weathering under predominant semi-arid climate, with periodically semi-humid climate.

5.6. Tectonic setting

To discriminate tectonic setting from our studied sediments, three main cross plot were used; the major-elements based tectonic setting discrimination diagram of Verma and Armstrong-Altrin (2013) which discriminates three tectonic type, Arc-Rift-Collision of two sets of high-silica rocks [$(\text{SiO}_2)_{\text{adj}} = 63\text{--}95\%$] and low-silica rocks [$(\text{SiO}_2)_{\text{adj}} = 35\text{--}63\%$] (Fig. 16A and B) and the majors elements based tectonic setting discrimination diagram of Roser and Korsh (1986) which discriminates three tectonic types, Island Arc, Active Continental Margin and Passive Continental Margin, of SiO_2 vs. K_2O binary diagram (Fig. 16C).

In the high silica diagram of Verma and Armstrong-Altrin (2013), the samples are plotted in the Rift and Continental Arc, and in the low silica one, all the samples are plotted in collisional tectonic. In the Roser and Korsh (1986) diagram, the samples are mainly located in the Active Continental Margin. The results obtained from these diagrams are globally inconsistent with the geological history of coastal basins of Cameroon and particularly the Rio del Rey Basin which have been performed in a rift and passive tectonic context (Njiké Ngaha, 1984; 2005; Nguéné et al., 1986; Lawrence et al., 2002; Njiké Ngaha et al., 2014). By another way, the Active Continental Margin indicate by these results could reflect the Precambrian basement history which has been experienced the Neoproterozoic orogeny (Nzenti et al., 1994; Toteu et al., 2001; Kroner and Stern, 2004). Same interpretations have been pointed out from many studied deposits such as recent deposits of Western Gulf of Mexico (Armstrong-Altrin et al., 2015) and Cretaceous deposits of the Douala Basin (Ngueutchoua et al., 2019a).

Conclusion

The lithology of the studied samples are diversified following their age, and the whole is made up mainly of shale and Fe-shale associated with Fe-sand and Sub-litharenite according to $\text{Log}(\text{SiO}_2/\text{Al}_2\text{O}_3)$ vs. $\text{Log}(\text{Fe}_2\text{O}_3/\text{K}_2\text{O})$ diagram, and are derived mainly from felsic igneous rocks with contribution of intermediate composition igneous rocks as point out the La/Sc vs. Th/Co, Zr vs. TiO_2 and Ce vs. La/Yb plots.

From the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios, ICV values associated to the A-CN-K diagram, the studied samples vary from immature to mature sediments deposited in brackish and shallow marine environment respectively, as indicate the Sr/Ba ratios (0.41 to 2) and U/Th ratios (0.16 to 0.28).

According to the A-CN-K and $\text{Al}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O}$ vs. SiO_2 diagrams, CIA (61.69–92.76) and PIA (62.16–99.47), the studied samples derived essentially from tonalite and granodiorite rocks compositions that have been submitted to low and high chemical weathering under predominant arid to semi-arid climate, with periodically semi-humid climate during the Paleocene.

The tectonic setting, collision or active Continental margin is rather related to the Neoproterozoic basement history during the Precambrian orogeny. This basement has been submitted to the erosion during the Phanerozoic time (from Cretaceous) giving the studied sediments.

Declarations

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Figures

Figure 1

Geological map of Rio del Rey Basin (modified from Dumort, 1968; Njoh et al., 2018).

Figure 2

Synthetic log of Rio del Rey Basin (modified from Lawrence, 2002; Njoh *et al.*, 2018)

Figure 3

Lithologic logs from studied area (Djega 2: Paleocene; Djega 1 Campanian-Maastrichtian; Mesambi: Cenomanian)

Figure 4

Field photographs of some outcrops: A) Shales (with sandstones lenses) and sandstones alternation; B) Varied colors of sandstones alternation; C) Grey sandstones with leaf fossils; D) Hand specimen of ferruginous sandstones with leaf fossils. E) Hand specimen of laminated calcareous shale from Mesambi stream;

Figure 5

Microstructures photographs of the studied samples: A) Cryptocrystalline microstructure of carbonated shales of Djega 1; B) Cryptocrystalline microstructure of shale of Messambi stream; C) Cryptocrystalline/very fine clastic microstructure of marlstone/limestone of Messambi stream; D) very fine clastic microstructure of shales of Djega 2; E) very fine clastic microstructure of shales of Messambi stream; F) Fine clastic microstructure of silty shales of Djega 2; G) Fine to average clastic microstructure of sandstone of Djega 2; H) Coarse clastic microstructure of sandstone of Djega 2.

Figure 6

X-ray diffraction of studied samples

Figure 7

Classification of studied sediments according to the scheme of Herron's (1988) diagram.

Figure 8

Stick diagram of average major elements (A) and trace elements (B) and correlation between the deposits from the Djega 1, Djega 2 and Mesambi

Figure 9

Normalized value of PAAS (A) and Chondrite (B) after McLennan (2001) and McDonough and Sun (1995) respectively

Figure 10

Cross plots of A) SiO₂, B) Al₂O₃, C) Fe₂O₃, D) MgO, E) CaO, F) Na₂O, G) K₂O and H) TiO₂ Versus total REE showing that REE contents in studied sediments are mainly controlled by land-derived detritus.

Figure 11

Bivariate plot of Zr/Sc vs. Th/Sc (after McLennan et al., 1993)

Figure 12

Scatter plots of (A) Th/Co vs. La/Sc (after Culler, 2002); (B) TiO₂ vs. Zr, (after Hayashi et al., 1997) and (C) Ce vs. La/Yb, (after Rao et al., 2011) and showing nature of the studied samples

Figure 13

Trace elements ratios: (A) U/Th with inferred depositional conditions for oxic, anoxic and dioxidic water masses and (B) with inferred depositional conditions of sea water and river

Figure 14

Chemical maturity and climate during the deposition of the studied samples expressed by bivariate plot of SiO₂ versus Al₂O₃ + K₂O + Na₂O (After Suttner and Dutta, 1986).

Figure 15

A-CN-K plots (Nesbitt and young, 1984) for the studied samples. The dotted line represents the possible weathering trend of the source rock if no K-addition is involved. The heavy solid line represents possible weathering trend combined with K-metasomatism from the source rock.

Figure 16

Discriminant diagrams to understand the different tectonic settings of the studied sediments: A) Discriminant-function multi-dimensional diagram for high-silica clastic sediments (Verma and Armstrong-Altrin, 2013). The subscript m1 in DF1 and DF2 represents the high silica diagram based on loge-ratios of major-elements. The discriminant function equations are $DF1(Arc-Rift-Col)_{m1} = (-0.263 \times \ln(TiO_2/SiO_2)_{adj}) + (0.604 \times \ln(Al_2O_3/SiO_2)_{adj}) + (-1.725 \times \ln(Fe_2O_3t/SiO_2)_{adj}) + (0.660 \times \ln(MnO/SiO_2)_{adj}) + (2.191 \times \ln(MgO/SiO_2)_{adj}) + (0.144 \times \ln(CaO/SiO_2)_{adj}) + (-1.304 \times \ln(Na_2O/SiO_2)_{adj}) + (0.054 \times \ln(K_2O/SiO_2)_{adj}) + (-0.330 \times \ln(P_2O_5/SiO_2)_{adj}) + 1.588$; $DF2(Arc-Rift-Col)_{m1} = (-1.196 \times \ln(TiO_2/SiO_2)_{adj}) + (1.604 \times \ln(Al_2O_3/SiO_2)_{adj}) + (0.303 \times \ln(Fe_2O_3t/SiO_2)_{adj}) + (0.436 \times \ln(MnO/SiO_2)_{adj}) + (0.838 \times \ln(MgO/SiO_2)_{adj}) + (-0.407 \times \ln(CaO/SiO_2)_{adj}) + (1.021 \times \ln(Na_2O/SiO_2)_{adj}) + (-1.706 \times \ln(K_2O/SiO_2)_{adj}) + (-0.126 \times \ln(P_2O_5/SiO_2)_{adj}) - 1.068$; B) Discriminant-function multi-dimensional diagram for low-silica clastic sediments (Verma and Armstrong-Altrin, 2013). The subscript m2 in DF1 and DF2 represents the low silica diagram based on loge-ratios of major-elements. The discriminant function equations are $DF1(Arc-Rift-Col)_{m2} = (0.608 \times \ln(TiO_2/SiO_2)_{adj}) + (-1.854 \times \ln(Al_2O_3/SiO_2)_{adj}) + (0.299 \times \ln(Fe_2O_3t/SiO_2)_{adj}) + (-0.550 \times \ln(MnO/SiO_2)_{adj}) + (0.120 \times \ln(MgO/SiO_2)_{adj}) + (0.194 \times \ln(CaO/SiO_2)_{adj}) + (-1.510 \times \ln(Na_2O/SiO_2)_{adj}) + (1.941 \times \ln(K_2O/SiO_2)_{adj}) + (0.003 \times \ln(P_2O_5/SiO_2)_{adj}) + 0.294$; $DF2(Arc-Rift-Col)_{m2} = (-0.554 \times \ln(TiO_2/SiO_2)_{adj}) + (-0.995 \times \ln(Al_2O_3/SiO_2)_{adj}) + (1.765 \times \ln(Fe_2O_3t/SiO_2)_{adj}) + (-1.391 \times \ln(MnO/SiO_2)_{adj}) + (-1.034 \times \ln(MgO/SiO_2)_{adj}) + (0.225 \times \ln(CaO/SiO_2)_{adj}) + (0.713 \times \ln(Na_2O/SiO_2)_{adj}) + (0.330 \times \ln(K_2O/SiO_2)_{adj}) + (-0.637 \times \ln(P_2O_5/SiO_2)_{adj}) - 3.631$; C) Scatter plot of SiO_2 vs. K_2O/Na_2O (after Roser and Korsch, 1986)