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Geochemical Composition and Heavy Metals Enrichment of Pond Sediments of the Kanem Region (Republic of Chad)

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Abstract— *Chemical analyses were carried out on sediment samples from ponds of the Kanem region to assess their composition and potential enrichment in heavy metals. The contents of major and trace elements are highly variable. Normalized profiles with Upper Continental Crust show various enrichments and decreases. The contents of major and trace elements often differ from those of recent deposits in the Lake Chad region. The sometimes-high contents of MgO, CaO, and Na2O are associated with the evaporite regime. The composition of the pond sediments, characterized by low Al2O3 content and highly variable SiO2 and other major elements, is distinct from clays and similar to that of sand and marl. The total REE content is lower than the PAAS. The REEs are associated with the fine fraction of sediment. Individual pollution indices reveal varying enrichments of As, Ba, Cd, and Mn, likely attributed to the use of fertilizers for food crops in the ouadis, and Mo, possibly of natural origin. The contents of enriched elements are below the threshold levels for agricultural land use, except for the Ba content of the ouadi of Manpal. The integrated pollution indices show variable global pollution levels. Regardless of the integrated index considered, the Manpal ouadi exhibits the highest level of sediment pollution.*

Keywords— *Chad, Geochemical composition, Heavy Metal, Pollution indices, Kanem, Ouadis, Pond, Sediment, Threshold levels.*

I. Introduction

The landscape of the Kanem region consists of a fossil dune system. Within this erg, the interdunal depressions, in the form of more or less closed basins, are known as "ouadis" in Chad. Ouadis differ from wadis in their morphology and the absence of a river system. The center of the ouadis is often occupied by a pond. The sub-desert climate and high evaporation rate result in the precipitation of various evaporitic minerals in the ouadis. The ouadis are the rare areas of human activity due to the exploitation of sodium carbonate salts, spirulina harvesting, and food crops. Despite being the subject of many research works, there is no data in the literature regarding the chemical composition of the recent deposits in the ponds of the ouadis. In this paper, we present and discuss geochemical results regarding the analyses of major and trace elements from surface sediment samples collected from the ouadis. We aim to evaluate the enrichments in toxic elements using individual and integrated pollution indices and to compare the contents with internationally recognized thresholds.

II. Physiographic And Geological Setting

The studied ouadis are located in the Republic of Chad on the northern edge of Lake Chad in the Kanem region (Fig.1).

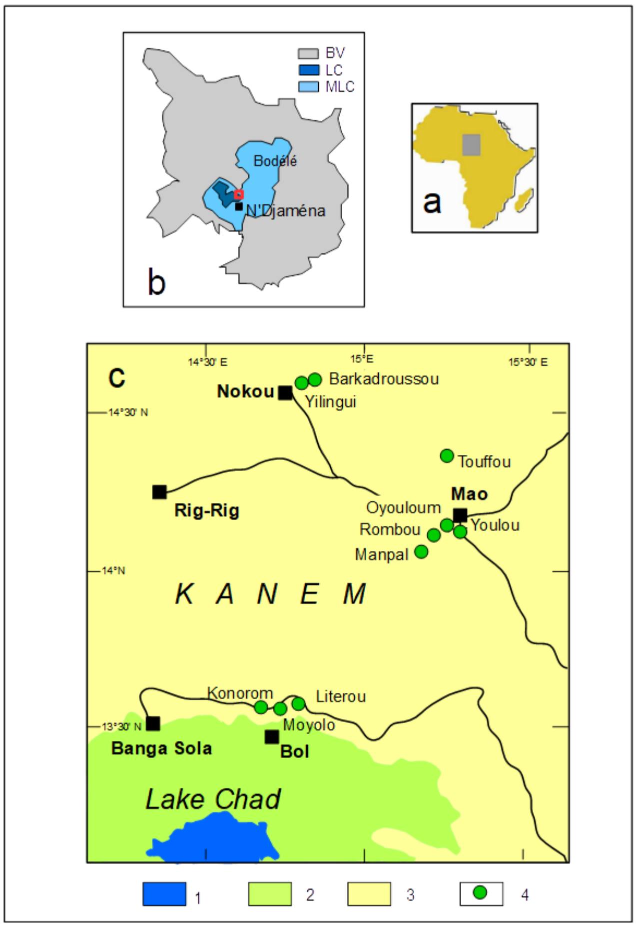

Fig. 1. Schematic map of the northern border of Lake Chad. (a) Location (grey square) of Lake Chad Basin in Africa. (b) Mega Lake Chad. BV: Lake Chad watershed. LC: Lake Chad today. MLC: Holocene Mega Lake Chad. Red square: location of figure c. (c) Location map of the ouadis. 1: Lake Chad, permanent open water. 2: Lake Chad polders. 3: aeolian sand formations and undifferentiated quaternary deposits. 4: ouadis studied.

The Kanem region is situated in the Sahelo-Saharan zone of the Aubréville classification (Aubréville, 1949) and has a sub-desert climate with an annual rainfall of less than 300 mm per

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year. High temperatures prevail, and the mean annual is around 28°C. The landscape is primarily composed of quaternary aeolian sand formations. This fossil erg forms NW-SE oriented dune ridges. The sandy formation was deposited during the Pleistocene Last Glacial Maximum around 200 000 years ago (Servant, 1983; Maley, 2010; Sylvestre, 2014). During the Holocene, between ca. 12 000 and ca. 5 000 cal years BP (Amaral et al., 2013; Sylvestre et al., 2019), climatic conditions were wetter, which allowed the formation of Mega Lake Chad (MLC), covering an area of 350 000 km2 (Schuster et al., 2005; Leblanc et al., 2006a, b). The MLC partially covers aeolian sand formation up to 325 meters high, corresponding to its maximum expansion. During this transgression, the lacustrine series of Labdé (Servant and Servant, 1970), consisting primarily of clay and silt (Dupont, 1967), was deposited on the northern edge of Lake Chad. After ca. 5 000 years cal BP, a change to high arid conditions caused a rapid reduction in the area of Lake Chad (Sylvestre et al., 2019), which is today only 1 500 km2. Labdé's series now outcrops in hollows between dunes and constitutes the floor of ponds within the ouadis.

Ouadis are arid environments characterized by the absence of a watershed or outlet. They depend on rainwater and the exposed Lake Chad aquifer for their water supply. The ouadis typically have surface areas ranging from one to several dozen hectares, with a flat bottom and an average depth of approximately 15 meters compared to the surrounding dunes. They are organized into concentric zones (Abderaman, 1992). The central zone consists of a pond surrounded by muddy soil, followed by a belt of reeds, roniers, and palm doums. The outermost area, consisting of fertile land suitable for agriculture, extends to the foothills of the dunes. In the ponds of the ouadis, carbonate silts are deposited, which contain varying proportions of sand and diatoms. These sands, similar to dune sands, contain less than 2% heavy minerals, primarily consisting of zircon (about 60%) and tourmaline (about 30%), with occasional occurrences of rutile, staurolite, and epidote (Dupont, 1967).

The sub-desert climate, with its high evaporation rates, leads to the precipitation of evaporitic minerals in the central zone of the ouadis. These minerals include carbonates such as Mg-calcite, gaylussite, trona, natron, nahcolite, and thermonatrite, chlorides like halite and northupite, sulfates such as gypsum, mirabilite, thenardite, and bloedite, sodium silicates including magadiite, kenyaite, and kanemite, as well as aluminosilicate minerals like mordenite (Maglione, 1968, 1971, 1976; Maglione and Karn, 1975). Under favorable water salinity conditions (Iltis, 1968, 1969), spirulina thrives in the ponds of the ouadis. The ouadis are sites of intense agricultural activity, producing food crops on fertile land. Sometimes, they are also used for the extraction of natron or the harvesting of spirulina. When the water level decreases, the central exposed area is often used for farming, provided the natron content in the sediments is low.

III. Materials and Methods

Ten surface sediment samples were collected from ouadis in the northern part of Lake Chad (Fig.1). These samples consist of either mud collected from water ponds along the shore, or dewatered and dried mud collected from dry ouadis. The mud was collected from the ouadis of Touffou, Barkadroussou, Yilingui, Youlou, Moyolo, and Konorom. The dried mud comes from the ouadis of Literou, Manpal, Rombo, and Oyouloum. The mud was collected between 1 and 2 meters from the shore and the dried mud at depths ranging from 5 to 10 cm below the ground surface. Approximately 1 kg of sample was collected at each point and stored in polyethylene bags. After collection, all samples were air-dried in an oven at a temperature of 30°C, then homogenized and quartered at the Geology, Geomorphology, and Remote Sensing Laboratory of N'Djamena University.

The chemical analysis for both major and trace elements was handled at the "Service d'Analyse des Roches et des Minéraux" Nancy, France. Major and trace element concentrations were respectively measured by ICP-OES and ICP-MS. The samples were ground at 70 µm and then approximately 300 mg of powder was prepared by alkaline fusion with LiBO2 at 1000°C and dissolved in 1N HNO3. Calibration and quality control were done with international geostandards (Carigan et al., 2001).

To study the heavy metal enrichments various indices were calculated based on ten heavy metals (Sb, As, Be, Cd, Cr, Cu, Pb, Hg, Ni, Zn) of high toxic impacts and six other toxic elements (Mn, Co, Mo, Ba, Sn, V) possibly related to anthropogenic activities. The calculation of pollution indices requires the assessment of the geochemical background. There is no data available in the literature to establish a local geochemical background on the Kanem region. Therefore, according to Kowalska et al., (2018), the calculation of pollution indices was performed using the composition of UCC as the background. We calculated the following indices:

- *Single Pollution Index*. The Single Pollution Index (PI) (Gong et al., 2008; Li and Yang, 2008) or Concentration Factor (Cabrera et al., 1999) is a ratio of an element in a sample to the background site value. It is calculated using the following equation:

$$PI = \frac{Ci}{Cb} \quad (1)$$

where Ci is the concentration of metal of interest at a site, and Cb is the LGB site value. The pollution of soils is classified into five categories after Kowalska et al., (2018): PI<1, absent; 1<PI<2, low; 2<PI<3, moderate; 3<PI<5, strong; PI≥5, very strong.

- *Enrichment Factor*. The Enrichment Factor measures the possible impact of anthropogenic activity on the concentration of heavy metals. EF is calculated using the following formula (Sutherland, 2000):

$$EF = \frac{\frac{Ci}{Cie}\text{sample}}{\frac{Ci}{Cie}\text{reference}} \quad (2)$$

where (Ci/Cie)sample is the ratio of concentration between the element of interest and the concentration of an immobile element in the sample, and (Ci/Cie)reference is the concentration ratio between the element of interest and the immobile element in the background. The choice of the immobile element is problematic (Brady et al., 2015). Following Blaser et al., (2000), we calculate the EF using the Zr which is conservative for chemical weathering and has no

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significant anthropogenic source. Soil enrichment was qualified into five categories by Kowalska et al., (2018): EF<2, deficiency to minimal; 2<EF<5, moderate; 5<EF<20, significant; 20<EF<40, very high; EF≥40, extremely high.

- *Geo-accumulation Index*. The Geo-accumulation Index (Igeo), proposed by Müller (1969), is another index used to assess metal contamination in sediments by comparing the concentration of a metal of interest with the background value. The geoaccumulation index is given by:

$$I_{geo} = \log 2\left(\frac{Ci}{1.5Bn}\right) \quad (3)$$

where Ci is the concentration of the element in the samples, and Bn is the background value of the element. Factor 1.5 introduce a dispersion to minimize the effect of lithological variations in the sediment on the background (Abrahim and Parker, 2008; Stoffers et al., 1986). Müller (1969) classified the Igeo values into seven classes: Igeo ≤ 0 (class 0) unpolluted, 0 < Igeo ≤ 1 (class 1) unpolluted to moderately polluted, 1 < Igeo ≤ 2 (class 2) moderately polluted, 2 < Igeo ≤ 3 (class 3) moderately to strongly polluted, 3 < Igeo ≤ 4 (class 4) strongly polluted, 4 < Igeo ≤ 5 (class 5) strongly to extremely polluted, and Igeo > 5 (class 6) extremely polluted sediments.

- *Average Single Pollution Index*. The Average Single Pollution Index (PIavg) was introduced by Gong et al., (2008) to estimate soil quality. PIavg is calculated as follows:

$$PI_{avg} = \frac{1}{n}\sum_{i=1}^{n} PI_i \quad (4)$$

where n is the number of studied heavy metals, and PI is the value for the single pollution index for each metal. Values of PIavg greater than 1.0 indicate lower soil quality due to high contamination (Inengite et al., 2015).

- *Potential ecological risk*. The potential ecological risk (RI) is an index introduced by Hakanson (1980) to assess the degree of ecological risk associated with soil contamination. RI is defined by:

$$RI = \frac{1}{n}\sum_{i=1}^{n} PI_i \times T_i \quad (5)$$

where PIi is the value of the single pollution index for Hg, Cd, As, Cu, Pb, Cr, and Zn. Ti is the toxicity coefficient for each element (Hg, 40; Cd, 30; As, 10; Cu, 5; Pb, 5; Cr, 2; Zn, 2) (Hakanson, 1980) and n is the number of heavy metals. RI was qualified into five grades (Kowalska et al., 2018): RI<90, low; 90<RI<180, moderate; 180<RI<360, strong; 360<RI<720, very strong; RI≥720 highly strong.

- *Background enrichment factor*. The Background enrichment factor (PIN) was introduced by Caeiro et al., (2005) to estimate the overall enrichment of soils. PIN is calculated as follows:

$$PIN = \sum_{i=1}^{n} PIClass_i^{\,2} \times PI_i \quad (6)$$

where PIClass is the class of the Single Pollution Index and PI is the corresponding value. PIN is subdivided into five classes according to Caeiro et al., (2005): 0>PIN>7, clean; 7<PIN<95.1, trace; 95.1<PIN<518.1, lightly; 518.1<PIN<2548.5, contaminant; PIN≥2548.8, highly.

- *Nemerow pollution index.* The Nemerow Pollution Index (PINemerow), developed by Nemerow (1991), is a comprehensive method for assessing the overall degree of pollution in soils and sediments. It takes into account the Average Single Pollution Index (PIavg), the maximum value of the Single Pollution Index (PImax), and the number of heavy metals considered (n). It is defined as:

$$PI_{Nemerow} = \sqrt{\frac{PI_{avg}^{\,2} + PI_{max}^{\,2}}{2}} \quad (7)$$

The quality of soil is subdivided into five grades according to Zhong et al., (2010):

PINemerow <0.7, clean;

0.7≤ PINemerow < 1.0, warning limit; 1.0≤ PINemerow <2.0, slight pollution; 2.0≤ PINemerow <3.0, moderate pollution; PINemerow >3.0, heavy pollution.

- *Modified Pollution Index*. The modified pollution index (MPI) has been proposed par Brady et al., (2015) by using enrichment factors (EF) instead of Single Pollution Indice (PI) to calculate a modified Nemerow Pollution Index pollution. MPI is defined as:

$$MPI = \sqrt{\frac{EF_{avg}^{\,2} + EF_{max}^{\,2}}{2}} \quad (8)$$

The quality of soil is subdivided into five grades according to (Brady et al. 2015): MPI<1, unpolluted; 1<MPI<2, slightly polluted; 2<MPI<3, moderately polluted; 3<MPI<5, moderately-heavily polluted; 5<MPI<10, heavily polluted; MPI≥10 severely polluted.

IV. Results and Discussion

3.1 Chemical composition

Major elements

The contents of the major elements are shown in Table 1. The concentrations of major elements and the loss by ignition of ouadis sediments are highly variable. Normalized profiles (Fig. 2) with the upper continental crust (UCC) of Runding and Gao (2014) show various increases and decreases depending on the element considered. The profile of the Moyolo ouadi is depleted in almost all elements except SiO2 and P2O5. The profiles of other ouadis are more or less similar to each other, apart from Yilingui and Barkadroussou ouadis which differ by the high values of Na2O and the Manpal ouadi which is not depleted in Fe2O3.

SiO2 contents are very variable (35.2–86.22%) and, apart from the ouadis of Youlou and Barkadroussou, they are slightly depleted relative to UCC. The high proportion of dune sand and diatom frustules explains the high SiO2 values in the Moyolo (86.22%) and Youlou (70.16%) ouadis.

TiO2 (0.07–0.4) contents are lower than that of the UCC and than the average values of Lake Chad sediments (0.71%) (Gac, 1980), muds (0.66%), and polder clays of Lake Chad (0.79%) (Cheverry, 1974). They are also lower than the average value of soils (1.17%) (Kataba Pendia, 2011). In weathering profiles, the Ti value indicates the degree of weathering (Edou-Minko et al., 1995), so the low Ti content suggests a low proportion of highly weathered materials in the ouadis sediments.

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TABLE 1. Distribution of Major and Rare Elements in the ouadis sediments. LD: Limit of determination. BA, Barkadroussou; YI, Yilingui; KO, Konorom; TO, Touffou; YO, Youlou; MO, Moyolo; LI, Literou; MA, Manpal; RO, Rombo; OY, Oyouloum.

	LD	BA	YI	KO	TO	YO	MO	LI	MA	RO	OY
Major elements (%)											
SiO2	0.05	42.39	42.69	48.59	54.02	70.16	86.22	35.62	48.79	51.31	62.21
TiO2	0.02	0.20	0.21	0.41	0.30	0.34	0.07	0.26	0.29	0.39	0.36
Al2O3	0.04	2.84	3.00	9.25	3.95	4.90	0.78	4.53	4.44	5.09	4.91
Fe2O3	0.015	1.93	1.96	3.72	3.25	3.53	0.64	1.93	11.44	2.74	5.48
MnO	0.015	0.17	0.11	0.08	0.13	0.07	0.11	0.18	0.25	0.13	0.10
MgO	0.03	3.99	3.33	3.46	3.61	1.54	0.47	6.41	1.96	3.95	1.26
CaO	0.03	13.31	7.73	11.21	10.57	3.50	2.25	19.69	10.99	11.77	6.16
Na2O	0.02	7.28	9.30	1.56	1.42	0.64	0.07	0.81	0.83	2.44	0.62
K2O	0.03	2.71	3.73	1.62	1.75	1.37	0.15	0.96	1.91	2.32	1.13
P2O5	0.1	0.14	0.31	0.37	0.11	0.11	0.36	0.35	0.51	0.19	0.16
PF		25.55	26.47	18.32	19.76	12.67	8.03	28.10	17.74	19.14	16.18
Total		100.51	98.84	98.60	98.86	98.82	99.07	98.85	99.13	99.44	98.56
Trace elements (ppm)											
Be	1.00	<LD	<LD	<LD	<LD	<LD	<LD	<LD	1.99	<LD	1.62
Rb	0.15	52.59	68.88	58.83	67.21	49.82	6.49	36.19	35.13	73.26	43.30
Sr	0.70	582.60	360.30	615.70	440.80	185.60	64.71	1163.00	374.40	554.90	226.50
Cs	0.02	0.69	0.61	1.92	1.09	1.36	0.21	1.07	1.06	1.35	1.34
Ba	5.50	416.90	332.70	611.10	423.20	272.50	105.80	776.60	354.20	589.20	340.40
V	0.85	20.09	31.27	52.39	30.42	28.67	4.06	30.08	49.79	30.73	39.60
Cr	0.50	19.22	26.28	46.53	26.66	32.41	7.97	25.67	34.88	33.09	50.65
Co	0.08	3.67	3.97	7.69	5.86	7.56	0.80	5.45	17.12	5.98	13.17
Ni	2.0	11.89	12.44	29.97	17.12	15.11	4.98	23.28	26.96	19.35	25.26
Cu	5.0	5.17	9.35	14.49	7.86	8.15	<LD	14.67	12.14	11.05	9.95
Y	0.02	7.47	7.65	16.13	10.57	11.83	2.91	9.87	11.96	13.23	13.20
Zr	1.50	81.97	92.46	129.50	157.70	120.70	78.38	95.10	119.50	190.00	168.00
Nb	0.02	5.11	5.65	10.60	6.96	9.02	1.54	6.60	7.19	8.44	8.83
Mo	0.35	2.53	1.28	0.56	<LD	<LD	<LD	<LD	2.57	0.58	0.87
Hf	0.03	2.33	2.62	3.64	4.32	3.46	2.13	2.58	3.29	5.32	4.67
Ta	0.004	0.43	0.46	0.84	0.61	0.75	0.15	0.52	0.64	0.79	0.78
W	0.80	0.55	0.70	0.56	0.40	0.53	<LD	0.46	0.71	0.53	0.63
Hg	0.005	<LD	0.01	0.01	0.01	0.01	0.01	0.03	0.03	0.01	0.02
Zn	7.0	23.01	24.09	55.25	42.81	37.10	11.12	38.68	45.02	65.77	42.33
Ga	0.02	4.45	4.77	13.49	5.94	7.66	1.36	6.85	7.00	7.71	7.60
Cd	0.02	0.14	0.17	0.25	0.17	0.28	0.15	0.16	0.45	0.31	0.27
In	1.0	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD
Sn	0.30	0.61	0.64	1.65	0.83	1.03	0.38	0.93	0.75	1.40	0.93
Pb	0.45	4.57	4.11	9.68	6.63	7.17	3.59	6.49	6.88	9.86	8.01
Bi	0.1	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD
Ge	0.02	0.57	0.56	1.06	0.73	0.83	0.65	0.71	1.28	0.68	0.94
As	1.2	1.82	1.97	2.17	<LD	3.00	<LD	1.94	11.38	1.94	6.60
Sb	0.2	<LD	<LD	<LD	<LD	<LD	<LD	<LD	0.25	0.22	0.21
Th	0.015	2.77	2.81	7.40	4.66	4.45	1.22	4.27	4.68	5.41	5.09
U	0.01	0.93	0.83	2.15	1.26	1.04	0.39	1.54	1.98	1.68	1.88

Al2O3 (0.78–9.25%) contents are lower than that of the UCC. and lower than the average values of Lake Chad sediments (12.94%) (Gac, 1980), muds (13.93%), and polder clays of Lake Chad (20.30%) (Cheverry, 1974). The low Al2O3 content reflects a low percentage of clay, in agreement with the absence of river sediment input into the ouadis. Additionally, the low Al levels (average <2 mg/L) and high pH of the water from the pond likely prevent clay formation. The sodic carbonate nature of the water, along with silica saturation, favors the precipitation of sodic silicates rather than clay minerals (Maglione, 1971).

Apart from Manpal ouadi whose Fe2O3 content (11.44%) is similar to that of the UCC, other ouadis have lower Fe2O3 contents (0.64–5.48%). These other ouadis also have lower Fe2O3 contents compared to the average values of Lake Chad sediments (7.79%) (Gac, 1980), muds (6.90%), and clays (7.50%) of Lake Chad polders (Cheverry, 1974), and the average value of soils (7.8%) (Kataba Pendia, 2011).

MnO contents vary, with the ouadis of Manpal, Literou, and Barkadroussou having higher MnO contents (0.17% to 0.25%) than the UCC, while the other ouadis exhibit lower MnO contents (0.07% to 0.13%) close to the UCC. The MnO contents of the sediments are higher than the mean values of Lake Chad muds (0.06%) and clays (0.03%) (Cheverry, 1974), as well as the average value of soils (0.06%) (Kataba Pendias, 2011). The MnO content of the Barkadroussou, Literou, and Manpal ouadis (0.17–0.25%) is higher than the mean value of sediments in the Nigerian part of Lake Chad (0.14%) (Jonathan et al., 2016). The MnO values are not correlated with Fe2O3 (coefficient of determination R2 = 0.33). The high MnO values in sediments are probably related to the high pH of the ouadis water (8.5–10.0) (Maglione, 1969). Indeed, beyond pH 8 the most stable form of Mn is manganese dioxide, the adsorption of which is pH-dependent and quickly reaches around 90%, whereas it is less than 25% below this pH (Chiswell and Mohktar, 1986; Hatje et al., 2003).

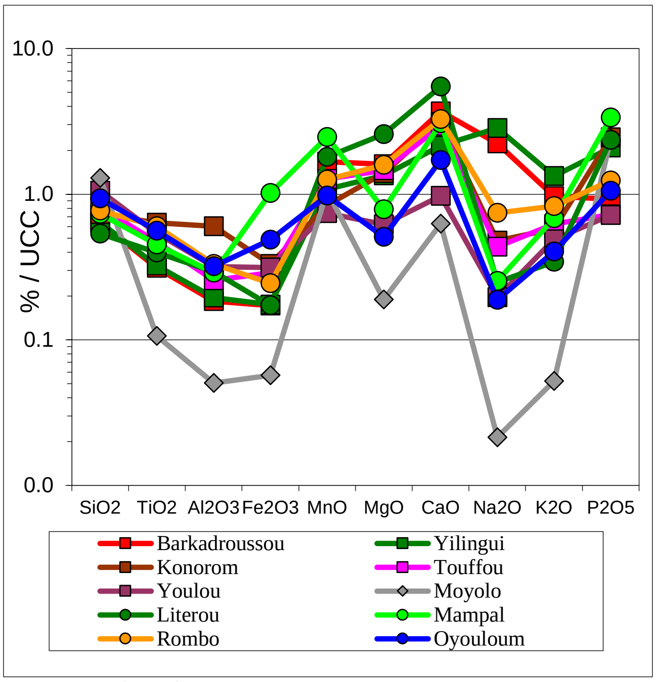

Fig. 2. Profiles of major elements normalized with the Upper continental crust. Normalization values after Runding and Gao (2014).

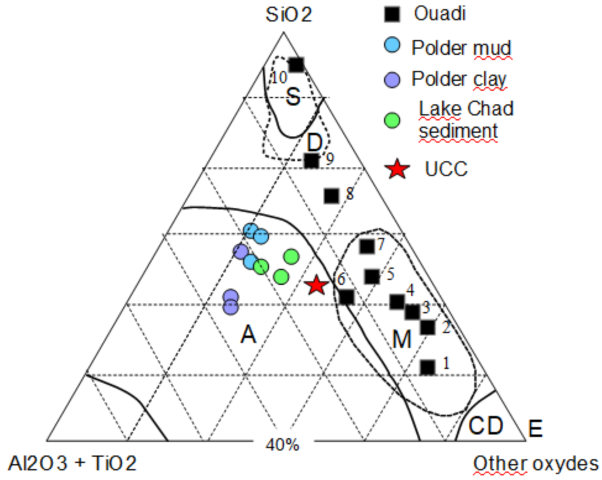

Fig. 3. Ternary diagram SiO2 - Al203 + TiO2-Other oxides modified after Fiori et al. (1989). 1–6: Ouadis; 1: Literou. 2: Barkadroussou. 3: Yilingui. 4: Manpal. 5: Rombo. 6: Konorom. 7: Touffou. 8: Oyouloum. 9: Youlou. 10: Moyolo. Clay and mud of the polders after Cheverry (1974). Lake Chad sediments after Gac (1980). UCC after Running and Gao (2014).

The MgO contents (0.47–6.41) are variable and higher than the UCC, except for the ouadis of Manpal, Youlou, Oyouloum, and Moyolo. Apart from the Moyolo ouadi, the MgO contents are higher than the mean values of muds (0.76%) and clays of the Lake Chad polders (0.89%) (Cheverry, 1974) and, apart from the Oyoulom and Moyolo ouadis, higher than the mean value of Lake Chad sediments (1.35%) (Gac, 1980).

Apart from the ouadis of Youlou and Moyolo, the CaO contents are higher than the UCC. All the ouadis have CaO contents higher than the mean values of mud (0.70%) and clays of the Lake Chad polders (0.47%) (Cheverry, 1974) and the mean value of the Lake Chad sediments (2.06%) (Gac, 1980). The high MgO and CaO contents are due to the evaporation system, which leads to the precipitation of magnesia calcite and occasionally of gaylussite and gypsum (Maglione, 1971, 1976; Maglione and Karn, 1975). The strong CaO-MgO correlation ($R2=0.94$) is related to the predominance of magnesia calcite.

The Na2O contents of the ouadis of Barkadroussou (7.28%) and Yilingui (9.30%) are high, while the Na2O content of the ouadi of Moyolo is low (0.07%). The other ouadis are depleted in Na2O (0.62–2.44%) relative to UCC. Apart from the Moyolo ouadi, the Na2O contents are higher than the average composition of Lake Chad sediments (0.37%) (Gac, 1980) and those of mud (0.23%) and clays (0.24%) of Lake Chad polders (Cheverry, 1974). The high Na2O contents are linked to the evaporation system, which leads to the precipitation of more or less large quantities of sodium carbonate salt and halite (Maglione, 1968, 1971, 1976; Maglione and Karn, 1975). The natron deposits are exploited in the ouadis of Barkadroussou and Yilingui, whose sediments have the highest Na2O content.

The ouadis generally show depleted K2O contents (0.96-3.73%) compared to the UCC. However, the ouadis of Barkadroussou and Yilingui have K2O values similar to or higher than the UCC. The K2O contents in most ouadis are also higher than the average contents of muds (0.55%) and clays of the Lake Chad polders (0.73%) (Cheverry, 1974). The ouadis of Barkadroussou and Yilingi, the richest in Na2O, have the highest K2O contents, which correspond to the precipitation of sylvite associated with the trona in the final stages of evaporation (Dupont, 1967; Al-Droubi, 1976; Maglione, 1976; Gac, 1980).

The P2O5 contents in the sediments of the ouadis are not very variable (0.11–0.51%), and except for than those of Barkadroussou, Touffou, and Youlou, their values are higher than the UCC.

Additionally, the SiO*2* - Al2O3 + TiO2 - Other oxides ternary diagram modified after Fiori et al., (1989) highlights the compositional differences between the ouadis sediments and those of the recent deposits in the Lake Chad basin (Fig.3). In this diagram, due to their low Al2O3 and TiO2 content and their variable SiO2 content, the composition of the sediment of the ouadis ranges from sands and diatomites to marls.

Trace Elements.

The contents of trace elements are shown in Table 1. The trace element values of ouadis normalized at UCC are similar, apart from the decrease in the composition of Moyolo in almost all elements (Fig. 4). Most trace element contents are depleted relative to UCC except the Cd contents, which are always higher than the UCC and sometimes Sr, Ba, Mo, Cd, As, and Sb contents.

The alkali and alkaline earth elements, Be, Rb, Sr, Cs, and Ba, have mean values of 1.75, 49.17, 456.85, 1.07, and 422.26 ppm, respectively. The distribution of these elements is not uniform. Compared to the UCC values, Be and Rb contents are slightly depleted, Sr contents vary with slight increases and decreases, Cs contents are highly depleted, and Ba contents are generally depleted except in the ouadi of Literou. The Sr contents are higher than the average composition of river sediment inputs to Lake Chad (63 ppm) (Gac, 1980). The Sr content is related to CaO content as shown by a strong Sr-CaO correlation (R2=0.92). The Ba content is also probably associated with CaO content, as evidenced by a strong Ba-CaO correlation (R2=0.79).

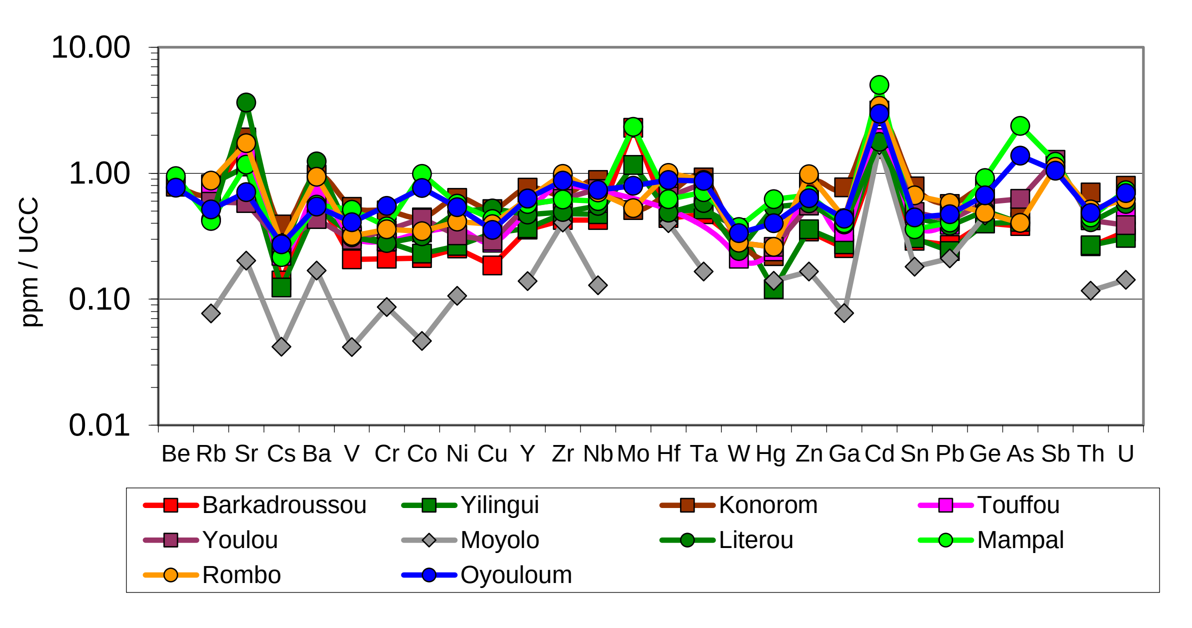

Fig. 4. Profiles of trace elements normalized with the Upper continental crust. Normalization values after Runding and Gao (2014).

The transition metals, V, Cr, Co, Ni, Cu, Y, Zr, and Nb, have mean values of 31.71, 30.34, 7.13, 18.64, 9.78, 10.48, 123.33, and 6.99 ppm, respectively, and are depleted compared to the UCC. The Mo contents are variable (0.56–2.57 ppm), showing small increases and decreases. Hf, Ta, W, and Hg have mean values of 3.44, 0.60, 0.56, and 0.01 ppm, respectively, and are depleted relative to the UCC. The Cr contents are lower than both the average composition of river sediment inputs to Lake Chad (126 ppm) (Gac, 1980) and the mean sediment composition of Lake Chad Nigerian Sector (ranging from 35.75 to 82.41 ppm) (Akan et al., 2012; Jonathan et al., 2016). The Co contents are lower than both the average composition of river sediment inputs to Lake Chad (23 ppm) (Gac, 1980) and the average sediment composition of Lake Chad Nigerian Sector (16.52 ppm) (Akan et al., 2012). The Ni and Cu contents are lower than both the average composition of river sediment inputs to Lake Chad (76 ppm and 32 ppm, respectively) (Gac, 1980) and the average sediment composition of Lake Chad Nigerian Sector (37.36 and 32.84, respectively) (Akan et al., 2012) and (36.84 and 19.37 ppm, respectively) (Jonathan et al., 2016).

The post-transition metals, Zn and Ga, have mean values of 38.52 and 6.68 ppm, respectively, and are depleted relative to the UCC. Cd has a mean value of 0.24 ppm, higher than the UCC. Indium and Bismuth are not present in the samples analyzed. Sn and Pb have mean values of 0.92 and 6.70 ppm, respectively, and are depleted relative to the UCC. The Zn and Pb contents are lower than the average composition of river sediments inputs to Lake Chad (146 ppm and 41 ppm, respectively) (Gac, 1980). They are also lower than the average sediment composition of the Lake Chad Nigerian Sector (125.04–143.75 ppm and 31.15–113.43 ppm, respectively) (Akan et al., 2012; Jonathan et al., 2016). All Cd contents in the ouadis are below the average sediment composition of the Lake Chad Nigerian Sector (1.83–16.52 ppm) (Akan et al., 2012; Jonathan et al., 2016).

The metalloids show different trends. With an average value of 0.80 ppm, Ge decreases compared to the UCC. The As contents vary, showing increases and decreases compared to the UCC when detected. The As content is below the average sediment composition of the Lake Chad Nigerian Sector (766.48 ppm) (Jonathan et al., 2016). The Sb contents, when present in samples, increase compared to UCC.

The actinides, Th and U, with mean values of 4.28 and 1.37 ppm, respectively, are depleted relative to the UCC.

Rare Earth Elements.

The contents of Rare Earth Elements in the ouadi sediments are summarized in Table 2. The total REE value is variable, ranging from 24.96 to 122.64 ppm. The Light Rare Earth Elements (LREE) are higher than the High Rare Earth Elements (HREE). The LREE/HREE ratios range from 11.86 to 16.04. The REE spectra of all the samples, normalized to the chondrite of Pourmand et al., (2012) (Fig. 5), show similar shape profiles, parallel between them, with steep LREE and relatively flat HREE shapes and a negative anomaly in Eu (0.64 to 0.77).

The ratio LaN/YbN varies from 8.11 to 12.00. The REE profiles of the ouadis are parallel to those of PAAS (Fig. 5), but the total REE content is lower. According to the decrease in total RREs of sands and total REEs enrichment in the fine-grained fraction of sediments (Taylor and McLennan, 1985;

Cullers, 2000), the highest content in REEs is observed in the Konorom sample, which is the most clay-rich and the lowest in the Moyolo sample, which is richest in sand and diatom frustules (Fig. 5).

TABLE 2. Distribution of Rare Earth elements in the ouadis sediments. Legend as Table 1.
Eu/Eu* = (Eusample/Euchondrite)/[(Smsample/Smchondrite)x(Gdsample/Gdchondrite)]1/2
LaN/YbN = (Lasample/Lachondrite)/(Ybsample/Ybchondrite)

	LD	BA	YI	KO	TO	YO	MO	LI	MA	RO	OY
Rare Earths (ppm) and their ratios											
La	0.02	9.04	10.17	26.09	13.88	15.65	5.41	14.64	16.18	16.93	17.38
Ce	0.03	18.93	21.38	52.08	30.12	32.83	10.46	29.10	33.87	35.89	36.51
Pr	0.004	2.14	2.43	5.90	3.24	3.84	1.25	3.29	3.87	3.90	4.17
Nd	0.016	8.40	9.42	22.69	13.24	14.57	4.67	12.78	15.49	15.99	16.29
Sm	0.050	1.59	1.78	4.18	2.52	2.81	0.87	2.37	2.92	3.04	3.16
Eu	0.002	0.35	0.37	0.88	0.52	0.57	0.16	0.55	0.62	0.63	0.64
Gd	0.005	1.36	1.48	3.42	2.14	2.39	0.66	2.01	2.48	2.54	2.63
Tb	0.001	0.21	0.23	0.51	0.32	0.37	0.10	0.30	0.37	0.40	0.40
Dy	0.004	1.31	1.34	2.89	1.92	2.13	0.55	1.72	2.09	2.35	2.30
Ho	0.001	0.26	0.26	0.53	0.37	0.40	0.10	0.33	0.39	0.46	0.45
Er	0.002	0.74	0.74	1.51	1.07	1.16	0.30	0.94	1.14	1.36	1.28
Tm	0.001	0.11	0.11	0.23	0.16	0.17	0.05	0.14	0.16	0.20	0.19
Yb	0.002	0.77	0.73	1.49	1.08	1.17	0.33	0.97	1.12	1.42	1.31
Lu	0,001	0.12	0.12	0.23	0.17	0.18	0.05	0.15	0.18	0.23	0.21
Σ REE		45.33	50.56	122.64	70.74	78.25	24.96	69.29	80.88	85.32	86.90
Σ LREE		41.80	47.03	115.25	65.67	72.67	23.49	64.74	75.42	78.91	80.77
Σ HREE		3.53	3.53	7.39	5.08	5.58	1.47	4.54	5.45	6.42	6.14
LREE/HRE		11.86	13.34	15.59	12.94	13.02	16.04	14.25	13.84	12.30	13.16
LaN/YbN		8.11	9.55	12.00	8.85	9.19	11.39	10.40	9.95	8.17	9.11
Eu/Eu*		0.71	0.68	0.70	0.68	0.67	0.64	0.77	0.70	0.68	0.67

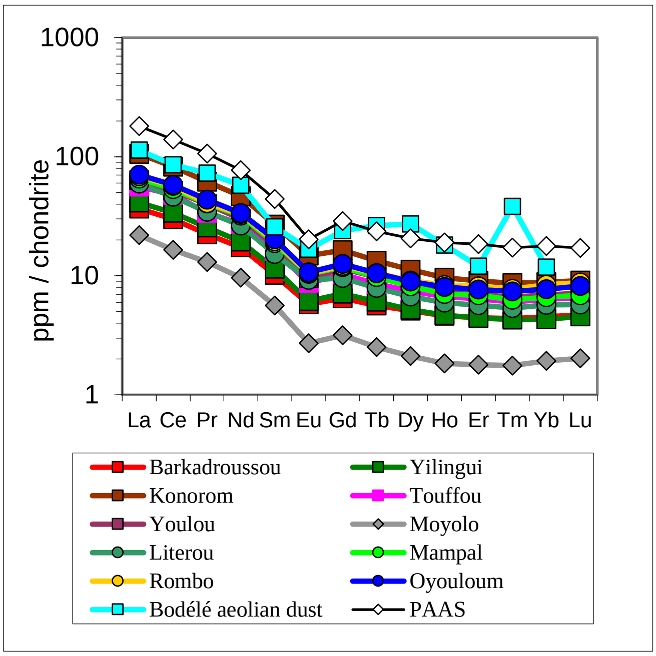

Fig. 5. Chondrite-normalized REE profiles. Normalization values after Pourmand et al., (2012)

The zircons incorporate HREEs preferentially over LREEs leading to HREE abundance and low (La/Yb)N ratios (Taylor and McLennan, 1985). In the ouadis, high LREE/ HREE and high (La/Yb)N ratios are linked to the low proportion of zircons as confirmed by the absence of correlation between total REEs and Zr (R2 = 0.39). The positive correlation with Al2O3 (R2 = 0.94) shows that the REEs are associated with the fine fraction of the sediments. The REE profiles are different from that of the aeolian dust of the Bodélé depression (Moreno et al., 2006), characterized by a strong positive anomaly in Tm (Fig. 4). This shows that aeolian dust deposition from the Bodélé depression is unlikely in the ouadis, although sandstorms are common in the northern region of Lake Chad.

3.2 Heavy metal enrichments

a- Individual indices

Single Pollution Index. The interpretation of PI values, calculated by using (1), are presented in Table 3. Depending on the ouadis considered various degrees of pollution for As, Ba, Cd, Mn, and Mo are observed. The ouadi of Manpal is the most polluted and presents a very strong level of pollution by Cd.

TABLE 3. Single Pollution Index. Soil pollution categories according to Kowalska et al., (2018). Legend as Table 1.

	BK	YI	KO	TO	YO	MO	LI	MA	RO	OY
As	0,38	0,41	0,45	0,25	0,63	0,25	0,40	2,37	0,40	1,37
Ba	0,67	0,53	0,98	0,68	0,44	0,17	1,24	0,57	0,94	0,55
Be	0,48	0,48	0,78	0,48	0,48	0,48	0,48	0,95	0,48	0,77
Cd	1,67	1,83	2,82	1,90	3,14	1,67	1,77	5,01	3,43	2,97
Co	0,21	0,23	0,44	0,34	0,44	0,05	0,32	0,99	0,35	0,76
Cr	0,21	0,29	0,51	0,29	0,35	0,09	0,28	0,38	0,36	0,55
Cu	0,18	0,33	0,52	0,28	0,29	0,18	0,52	0,43	0,39	0,36
Hg	0,10	0,12	0,22	0,24	0,26	0,14	0,54	0,62	0,26	0,40
Mn	1,68	1,09	0,84	1,28	0,74	1,06	1,81	2,48	1,27	0,99
Mo	2,30	1,16	0,51	0,32	0,32	0,32	0,32	2,33	0,53	0,79
Ni	0,25	0,26	0,64	0,36	0,32	0,11	0,50	0,57	0,41	0,54
Pb	0,27	0,24	0,57	0,39	0,42	0,21	0,38	0,40	0,58	0,47
Sb	0,50	0,50	0,50	0,50	0,64	0,50	0,50	0,62	0,56	0,52
Sn	0,29	0,30	0,78	0,40	0,49	0,18	0,44	0,36	0,67	0,44
V	0,21	0,32	0,54	0,31	0,30	0,04	0,31	0,51	0,32	0,41
Zn	0,34	0,36	0,82	0,64	0,55	0,17	0,58	0,67	0,98	0,63

Class	Value of PI	Soil pollution
1	PI < 1	absent
2	1< PI< 2	low
3	2< PI< 3	moderate
4	3< PI< 5	strong
5	PI> 5	very strong

Jean-Paul Vicat and Jean-Claude Doumnang Mbaigane, "Geochemical Composition and Heavy Metals Enrichment of Pond Sediments of the Kanem Region (Republic of Chad)," *International Journal of Multidisciplinary Research and Publications (IJMRAP)*, Volume 5, Issue 12, pp. 161-171, 2023.

Enrichment Factor. The EF values calculated according to (2) show moderate enrichments in As, Ba, Cd, Mn, and Mo depending on the ouadis considered, (Table 4). The ouadi of Barkadroussou presents significant enrichments in Mo. The ouadis of Youlou and Manpal have significant enrichment in Cd. The EF >1 (Çevik et al., 2009) or 1.5 (Zhang and Liu, 2002; Elias and Gbadegesin, 2011) suggests a possible anthropogenic source, and EF > 5 denotes a human origin for the element of interest (Atgin et al., 2000). The observed enrichment in the ouadis could therefore be of anthropogenic origin, particularly the enrichment in Mo and Cd in the ouadis of Barkadroussou and Manpal, respectively.

TABLE 4. Enrichment factor. Soil enrichment according to Kowalska et al., (2018). Legend as Table 1.

	BK	YI	KO	TO	YO	MO	LI	MA	RO	OY
As	0,9	0,9	0,7	0,3	1,0	0,6	0,8	3,8	0,4	1,6
Ba	1,6	1,1	1,5	0,8	0,7	0,4	2,5	0,9	1,0	0,6
Be	1,1	1,0	1,2	0,6	0,8	1,2	1,0	1,5	0,5	0,9
Cd	3,9	3,8	4,2	2,3	5,0	4,1	3,6	8,1	3,5	3,4
Co	0,5	0,5	0,7	0,4	0,7	0,1	0,6	1,6	0,4	0,9
Cr	0,5	0,6	0,8	0,4	0,6	0,2	0,6	0,6	0,4	0,6
Cu	0,4	0,7	0,8	0,3	0,5	0,4	1,1	0,7	0,4	0,4
Hg	0,2	0,3	0,3	0,3	0,4	0,3	1,1	1,0	0,3	0,5
Mn	4,0	2,3	1,3	1,6	1,2	2,6	3,7	4,0	1,3	1,1
Mo	5,4	2,4	0,8	0,4	0,5	0,8	0,6	3,8	0,5	0,9
Ni	0,6	0,6	1,0	0,4	0,5	0,3	1,0	0,9	0,4	0,6
Pb	0,6	0,5	0,8	0,5	0,7	0,5	0,8	0,7	0,6	0,5
Sb	1,2	1,0	0,7	0,6	1,0	1,2	1,0	1,0	0,6	0,6
Sn	0,7	0,6	1,2	0,5	0,8	0,4	0,9	0,6	0,7	0,5
V	0,5	0,7	0,8	0,4	0,5	0,1	0,6	0,8	0,3	0,5
Zn	0,8	0,8	1,2	0,8	0,9	0,4	1,2	1,1	1,0	0,7

EF Value	**Enrichment of soil**
< 2	deficiency to minimal
2—5	moderate
5—20	significant
20—40	very high
≥40	extremely high

TABLE 5. Geo-accumulation Index. Classes according to Müller (1969). Legend as Table 1.

	BK	YI	KO	TO	YO	MO	LI	MA	RO	OY
As	-2,0	-1,9	-1,7	-2,6	-1,3	-2,6	-1,9	0,7	-1,9	-0,1
Ba	-1,2	-1,5	-0,6	-1,1	-1,8	-3,1	-0,3	-1,4	-0,7	-1,5
Be	-1,7	-1,7	-0,9	-1,7	-1,7	-1,7	-1,7	-0,7	-1,7	-1,0
Cd	0,2	0,3	0,9	0,3	1,1	0,2	0,2	1,7	1,2	1,0
Co	-2,8	-2,7	-1,8	-2,1	-1,8	-5,0	-2,3	-0,6	-2,1	-1,0
Cr	-2,8	-2,4	-1,6	-2,4	-2,1	-4,1	-2,4	-2,0	-2,1	-1,4
Cu	-3,0	-2,2	-1,5	-2,4	-2,4	-3,1	-1,5	-1,8	-1,9	-2,1
Hg	-3,9	-3,6	-2,8	-2,6	-2,5	-3,4	-1,5	-1,3	-2,5	-1,9
Mn	0,2	-0,5	-0,8	-0,2	-1,0	-0,5	0,3	0,7	-0,2	-0,6
Mo	0,6	-0,4	-1,6	-2,2	-2,2	-2,2	-2,2	0,6	-1,5	-0,9
Ni	-2,6	-2,5	-1,2	-2,0	-2,2	-3,8	-1,6	-1,4	-1,9	-1,5
Pb	-2,5	-2,6	-1,4	-1,9	-1,8	-2,8	-2,0	-1,9	-1,4	-1,7
Sb	-1,6	-1,6	-1,6	-1,6	-1,2	-1,6	-1,6	-1,3	-1,4	-1,5
Sn	-2,4	-2,3	-0,9	-1,9	-1,6	-3,1	-1,8	-2,1	-1,2	-1,8
V	-2,9	-2,2	-1,5	-2,3	-2,3	-5,2	-2,3	-1,5	-2,2	-1,9
Zn	-2,1	-2,1	-0,9	-1,2	-1,4	-3,2	-1,4	-1,2	-0,6	-1,2

Class	**Values of *Igeo***	**Soil quality**
0	$I \leq 0$	unpolluted
1	0-1	unpolluted to moderately polluted
2	1-2	moderately polluted
3	2-3	moderately to highly polluted
4	3-4	highly polluted
5	4-5	highly to extremely high polluted
6	5-6	extremely high polluted

However, the cutoff value for distinguishing between an anthropogenic or natural source of enrichment is variable (1–500) depending on the authors (Reimann and de Caritat, 2005) and also because different backgrounds used produce different results (Rubio et al., 2000).

Geoaccumulation Index. Table 5 provides the interpretation of Igeo values calculated by using (3). All the ouadis exhibit soil qualities ranging from unpolluted to moderately polluted for Cd. The other ouadis also show soil qualities ranging from unpolluted to moderately polluted, with Barkadroussou for Mn and Mo, Literou for Mn, Manpal for As, Mn, and Mo.

b- *Comparison to threshold levels*

The average As content of ouadis (3.85 ppm) is low and lower than the pre-industrial content of lake sediments estimated at 15 ppm (Hakanson, 1980). The As contents of the ouadis of Oyouloum and Manpal (6.60 ppm and 11.38 ppm, respectively) are higher than the threshold effect level (TEL) of 5.9 ppm for sediments (Smith et al., 1996). Although the As content of the Manpal ouadi (11.38 ppm) is slightly above the maximum permitted concentrations (MPC) for soils (10 ppm) (Taraškevičius et al., 2013), it remains below the maximum possible of 12 ppm for agricultural land use (CCME, 2018).

The average Ba content (422 ppm) is lower than the mean soil content (460 ppm) (Kataba Pendia, 2011). However, the Literou ouadis has a Ba content (776.60 ppm) higher than the MPC for soil (600 ppm) (Taraškevičius et al., 2013) and the possible maximum for agricultural land use (750 ppm) (CCME, 2018). The other ouadis have contents lower than the MPC for soils.

The levels of cadmium in the ouadi sediments (0.15 to 0.45 ppm) are, for the most part, higher than the pre-industrial value estimated at 0.15 ppm (Hakanson, 1980). Except for the Manpal ouadi, they are lower than the average soil content (0.41 ppm) (Kataba Pendia, 2011). The Manpal ouadi has a slightly higher Cd content (0.45 ppm) than the MPC for soil (0.3 ppm) (Taraškevičius et al., 2013) and the established value for uncultivated areas worldwide (0.35 ppm) (Bowen, 1979). However, it remains lower than the TEL of 0.596 mg/kg (Smith et al., 1996) and the possible maximum of 1.4 ppm for agricultural land use (CCME, 2018).

The Mn contents (0.07–0.25%) are higher than the average soil content (0.04%) (Kataba Pendia, 2011) and, except for the ouadi of Youlou, higher than the median sediment content (0.08%) (INERIS, 2020). The Manpal ouadi has a slightly higher Mn content (0.25%) than the MPC for soil (0.19%) (Taraškevičius et al., 2013). The other ouadis have lower contents.

The average Mo content (0.98 ppm) is close to the mean soil content (1.1 ppm) (Kataba-Pendias, 2011). The highest levels observed in the ouadis of Barkadroussou (2.53 ppm) and Manpal (2.57 ppm) are similar to the contents of clay soils (2-2.5 ppm) (Kataba Pendia, 2011) and lower than the MPC for soil (5 ppm) (Taraškevičius et al., 2013) and the Canadian soil quality guideline (5 ppm) for agricultural use (CCME, 2018).

It is nevertheless necessary to relativize the pollution of the sediments of the ouadis highlighted by the single pollution indices. Indeed, the highest contents of As, Cd, and Mo do not exceed the maximum possible for agricultural land use. The Ba content of the Literou ouadi and the Mn content of the Manpal ouadi are slightly above these thresholds, but this is the case for many soils.

c- Integrated indices

Individual indices only calculate the contamination of a single element and do not provide a cumulative view of the presence of several heavy metals. On the other hand, integrated indices take into account multiple elements to assess an overall view of sediment pollution for the elements considered.

TABLE 6. Integrated indices. Interpretation of PIavg after Inengite et al., (2015), RI after (Kowalska et al., 2018), PIN after Caeiro et al., (2005), PINemerow (Mp: moderately polluted; Hp: heavily polluted; Sp: severely polluted) after Zhong et al., (2010), MPI (Unp: Unpolluted) after Brady et al., (2015). Legend as Table 1.

	BK	**YI**	**KO**	**TO**	**YO**	**MO**	**LI**	**MA**	**RO**	**OY**
PIavg	0,61	0,53	0,75	0,54	0,61	0,35	0,65	1,20	0,75	0,78
	No contamination							High contamination	No contamination	
RI	54,93	60,42	91,92	64,77	102,58	53,05	58,93	177,00	111,47	105,51
	Low		Moderate	Low	Moderate	Low		Moderate		
PIN	26,67	20,70	34,51	18,18	56,97	13,76	24,85	197,04	67,23	40,37
	Trace							Lightly	Trace	
PINemerow	1,68	1,35	2,06	1,40	2,27	1,20	1,36	3,64	2,48	2,17
	Mp		Hp	Mp	Hp	Mp		Sp	Hp	
MPI	1,40	1,00	1,09	0,60	1,28	1,05	0,98	2,08	0,89	0,88
	Slightly polluted	Unp	Slightly polluted	Unp	Slightly polluted		Unp	Moderately polluted	Unp	

Average Single Pollution Index. The interpretation of PIavg calculated by using (4) shows a high degree of contamination for the ouadi of Manpal with PIavg value of 1.2 (Tab. 6) The other ouadis do not show any contamination according to the PIavg values.

Potential ecological risk. The interpretation of RI values calculated by using (5) shows a moderate potential ecological risk for the ouadis of Konorom, Youlou, Manpal, Rombo, and Oyouloum and a low risk for the other ouadis (Tab. 6).

Background enrichment factor. The interpretation of PIN values (Tab. 6) calculated by using (6) shows that the sediment of the ouadi of Manpal is slightly enriched. The sediment of the other ouadis show only traces of enrichment.

Nemerow pollution index. The interpretation of PINemerow values (Tab.6) calculated by using (7) show that the ouadis present different pollution levels. The ouadis of Barkadroussou, Yilingui, Touffou, Moyolo, and Literou are moderately polluted. The ouadis of Konorom, Youlou, Rombo, and Oyouloum are highly polluted, while the ouadi of Manpal is severely polluted.

Modified Pollution Index. The interpretation of MPI values calculated by using (8) shows that the ouadis of Yilingui, Touffou, Literou, Rombo, and Oyouloum are unpolluted. The ouadis of Barkadroussou, Konorom, Youlou, and Moyolo are slightly polluted, while the ouadi of Manpal is moderately polluted.

The calculation of the integrated indexes leads to slightly different results depending on the indexes considered. However, overall, the ouadi of Manpal is identified as having the highest pollution level among the ouadis considered.

V. Conclusion

Based on geochemical investigations of the surface sediments of the ouadis, we can conclude that:

- the chemical composition of the sediments differs from those of soils and recent deposits in the Lake Chad region. Their composition in major elements differs from that of clays and is similar to that of sands, diatomites, and marls, depending on the ouadis considered. The trace element contents are variable, higher or lower than those of the recent deposits in the Lake Chad region. The REE profiles show that there is no deposition of eolian dust in the ouadis,

- the single pollution indices, EF, PI, and Igeo, have revealed enrichments in As, Ba, Cd, Mn, and Mo, which vary across the different ouadis. However, these enrichments are generally weak, and the element contents are below or only slightly higher than the threshold levels for agricultural land use,

- the integrated indices, PIavg, RI, PIN, PINemerow, and MPI, show varying degrees of pollution depending on the ouadis and the indices considered. Overall, the Manpal ouadi is the most polluted.

Due to the heavy metal pollution identified, this study recommends monitoring soil quality in the main ouadis that produce food crops.

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