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Geochemical Analysis of Coastal Sediments near Larache and Moulay Bousselham, Morocco

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ABSTRACT

The aim of this study is to identify the main pollutants and evaluate the mechanisms of sediment transport from land to sea. This goal is justified by environmental pollution in the area associated with dredging and port activities. The objective is planned to be achieved by investigating the geochemical behavior of major and trace elements in fourteen surface sediment samples collected along the Moroccan Atlantic coast, from the mouth of the Lukkous River to the coast between the cities of Larache and Moulay Bousselam. k0-standardization method of neutron activation analysis using neutrons of the Moroccan Triga Mark II research reactor at the National Centre for Nuclear Energy, Science and Technology, has been used for analysis of collected sediment samples. The enrichment factor analysis revealed high levels of arsenic and chlorine, along with significant calcium enrichment, were found along the Atlantic coast. The enrichment factors (FE) for arsenic and chlorine are in the range of $20 < FE < 40$, and for calcium, the FE is in the range of $5 < FE < 20$. Conversely, some elements exhibited little to no enrichment, suggesting a crustal origin. PCA helped in synthesizing these findings, providing a clearer understanding of the spatial variations in sediment composition based on their multi-elemental signatures. The research examines surface sediments along the Moroccan Atlantic coast, revealing current contamination levels and geochemical behavior. These findings, applicable to similar coastal environments, are crucial for monitoring and managing sediment quality, especially in areas affected by erosion. Additionally, dredging and port activities in this region significantly disturb the sediments, resuspending contaminants and altering sediment composition, which further exacerbates pollution issues. This study offers a comprehensive geochemical characterization of coastal sediments in Morocco, enhancing understanding of sediment contamination and geochemical processes, with implications for environmental protection and sustainable marine resource management.

Keywords: neutron activation analysis, geochemical, major and trace elements, sediments, Loukous River, Atlantic Coast, Triga Mark II.

INTRODUCTION

For a number of reasons, including direct human input, continental transfer by rivers and winds, transport by marine currents, atmospheric deposition, etc., the concentration of major and trace elements in marine sediments can change over time (Milliman, Meade, 1983). As a result, today's seas and oceans receive large volumes of pollutants such as trace metals, which have been or are still being used in a wide range of applications (industrial, medical, agricultural, etc.). It is possible that some of the amounts used for some of these elements were released into the environment as a result of these uses (Maamri, 2001). This metallic pollution constitutes one of the major risks in the world today. This is a current issue that affects all areas concerned with maintaining their coastal heritage at a high level of quality (Ben Bouih et al., 2005). In fact, when present in high concentrations in the environment, several heavy metals can pose serious risks to both human health and other living things (Fakayode, 2005).

Determining the concentrations of major and trace elements in marine surficial coastal marine sediments is of great importance because this abiotic compartment has the capacity to sequester these elements and to interact with other biotic and abiotic compartments of the ecosystem through processes of sedimentation, flocculation, etc (Wang et al., 2019). In addition, through the processes mentioned, there may also be the transfer and incorporation of metals into trophic chains (Luoma, 1989).

The chosen area, spanning from Larache to Moulay Bouselham cities along the Moroccan littoral coast near the Loukous river estuary, experiences severe erosion (El Idrissi et al., 2024). Erosion processes not only affect coastal landscapes but also play a crucial role in sediment dynamics, potentially influencing the distribution of contaminants and the ecological health of the region. Furthermore, dredging and port activities in this region greatly disturb the sediment layers on the sea or riverbed. This disturbance causes previously settled contaminants to be stirred up and reintroduced into the water. As a result, the composition of the sediments is altered, which can lead to increased levels of pollution. These activities not only resuspend harmful substances but also change the natural balance of the sediment, worsening the overall environmental impact.

Considering the intricate interplay between erosion, sediment transport, and the capacity of sediments to sequester metals, it becomes imperative to assess the elemental composition of bottom sediments in this area. Thus, the primary objective of this study is to determine the major and trace element content to evaluate contamination levels along the Moroccan littoral coast between Larache and Moulay Bouselham cities. By employing methodologies such as the enrichment factor (Caritat, 2005) we aim to pinpoint primary contaminants in the study area.

Moreover, this investigation serves a broader purpose beyond contamination assessment. It offers insights into the sources of pollution, identifies sensitive zones, and elucidates the contributing variables. Utilizing techniques like principal component analysis allows for a comprehensive exploration of potential correlations among analyzed elements, thus revealing geochemical signatures inherent to this region.

By bridging the gap between erosion dynamics, sediment contamination, and geochemical processes, this study endeavors to provide crucial insights for environmental management and conservation efforts along the Moroccan littoral coast.

Presentation of the study area

The coastal area located on the Atlantic coast of Morocco, between the cities of Larache and Moulay Bousselham, approximately 35 km apart, offers a dynamic and diverse ecosystem influenced by various geological, geographical, climatic, and anthropogenic factors (El Amari et al., 2016). Characterized by a combination of sedimentary and volcanic rocks, including formations such as cliffs, sand dunes, estuaries, and alluvial plains, this region exhibits varied geology (El Amari et al., 2016).

Human activities, such as urbanization, intensive agriculture, industry, and maritime navigation, exert a significant impact on the coastal environment of this area (El Mrabet et al., 2020). In particular, these activities can lead to the introduction of heavy metals into the ecosystem, primarily through runoff, industrial discharge, and urban waste (Dürr et al., 2005).

Geochemical studies on heavy metals in this region are essential to assess their impact on the health of marine and coastal ecosystems, as well as on human health, due to their bioaccumulation in the food chain (Zourarah et al., 2019). Located in the Gharb plain in northwestern Morocco, this area benefits from a privileged geographical location and considerable water and soil resources, thus promoting remarkable agricultural and agro-industrial development (Allouza, 2002). With 16% of the national irrigation potential, it represents the largest agricultural area in Morocco (Allouza, 2002).

The diversity of ecosystems in the region, including beaches, cliffs, estuaries, and wetlands, makes it a major ecological interest area. Climatically, the region has a Mediterranean climate, characterized by hot, dry summers and mild, rainy winters, with average annual precipitation ranging between 400 and 600 mm and an average annual temperature of around 18 °C. Local geology is dominated by sedimentary formations, mainly limestone, marl, and sandstone, while soils are generally of limestone brown or isohumic type. Vegetation, adapted to arid conditions, consists of maquis, garrigues, and pine forests.

The stretch of Moroccan coastline from Larache to Moulay Bouselham, adjacent to the Loukous river estuary, faces severe erosion (El Idrissi et al., 2024). This erosion impacts coastal landscapes and plays a critical role in sediment dynamics, potentially affecting the spread of contaminants and the ecological well-being of the region. The main human activities in the region include agriculture, fishing, tourism, and exploitation of natural resources. However, these activities can also lead to environmental problems, such as pollution and ecosystem degradation. In summary, the coastal area between Larache and Moulay Bousselham in Morocco holds significant ecological and economic importance but requires sustainable management to preserve its valuable natural resources.

MATERIALS AND METHODS

Sampling and sample preparation

Sampling sites were selected taking into account the lithological diversity of the study area and the distribution of anthropogenic activities. Sampling was carried out in 2024 along the Atlantic coast between Larache and Moulay Bousselham at 14 sites (Fig. 1).

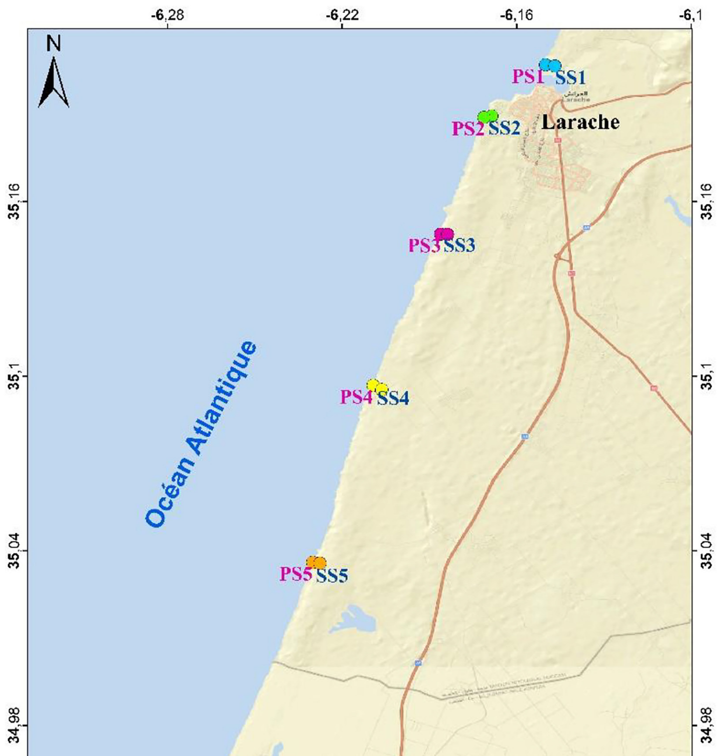

Figure 1. Map showing the distribution of sampling sites along the Atlantic Coast between Larache and Moulay Bousselham

Seven samples were taken directly from the beaches linking Larache to Moulay Bousselham (PS1, PS2, PS3, PS4, PS5, PS6 and PS7), seven other samples taken in parallel, but at a distance of 500 m to 1 km from those on the beaches (SS1, SS2, SS3, SS4, SS5, SS6, and SS7).

The sediment samples were collected using polyethylene bags, transferred to the laboratory, then dried in an oven for 24 hours at a temperature of 105 °C before being ground using an agate mill. This process has the benefit of homogenizing the mixture and levelling out the sample›s uneven inclusion distribution. In general, sample processing is minimized by avoiding any steps that could cause the sample to become contaminated or lose some of its constituent parts. Initially, each sample was put into hermetically sealed cylindrical polyethylene capsules in large quantities (average 250–500 mg) and kept there until analysis.

Samples analysis

Sediment samples were irradiated using the Moroccan Triga Mark II research reactor (available flux: 2 to 6.10^{12} $n \cdot cm^{-2} \cdot s^{-1}$) which is directly connected to the Neutron Activation Analysis Laboratory (NAAL) at the National Centre for Nuclear Energy Science and Technology (CNESTEN). Major and trace element measurements were made using the k0-standardization method of the neutron activation analysis. Depending on the half-life of the elements to be measured, two different forms of irradiation were employed: (irradiation of 30 to 60 seconds for elements with short half-lives and irradiation of 5 hours for elements with long half-lives). It should also be pointed out that in the both short and long irradiations, samples were prepared with their flux monitors (approximately 10–20 mg of Al-Au (0.01%) alloy in wire form).

In case of short irradiations, both (sample and flux monitor) are then enclosed in polyethylene shuttles. These were transferred to the core of the reactor via a pneumatic transfer system (PTS) via irradiation, sample by sample.

For long irradiations, each polyethylene rabbit was filled with 8 sediment samples and 10 flux monitors prepared in two columns in sandwich form. The prepared rabbits were then transferred to the "rotary specimen rack" (RSR), which contained 40 irradiation positions.

The gamma rays emitted were determined using a Germanium Hyper Pure Germanium (GeHP) detector. This enables the emitting isotopes to be identified and the concentration of the elements in the initial sample to be determined (Bounouira, 2012). Data acquisition was carried out using Gamma Vision software, and concentration calculations were made using k0-IAEA software.

RESULTS AND DISCUSSION

All the results of the chemical analysis of these samples are presented in Table 1 and Table 2. The geochemical characteristics of major and trace elements in coastal sediments on the Atlantic coast were studied on the basis of the results of the sampling campaign carried out in spring 2024.

The sediments collected on the Atlantic coast between Larache and Moulay Bouselham generally show varying concentrations of major and trace elements, depending on the elements and the samples collected along the coast.

First of all, it can be seen that the samples taken from sites far from the beaches (SS1, SS2, SS3, SS4, SS5, SS6, and SS7) have the highest concentrations compared with the other samples taken directly from the beaches (PS1, PS2, PS3, PS4, PS5, PS6 and PS7) for all elements except Na, Cl and Br, which are relatively high in samples collected directly from the beaches. This can be explained by the fact that the mineral salts containing these elements are more abundant in beach sediments.

The samples collected just in the Loukkous river estuary showed higher values for all the elements, and remained relatively within the same orders of magnitude as the sites with high values.

Regarding the major elements, in the samples collected both close to the beach (PS1–PS7) and farther away from the beach (SS1–SS7), high concentrations of Ca, Al, Fe, and Mg were found in comparison to the other major elements (Na, K, Ti, and Mn).

Near the beach, maximum concentrations of these major elements are generally recorded at sampling points PS6 (Merset lghnem), while minimum values are recorded at sites PS2 (Msitro); whereas for samples far from the beach, maximum concentrations of these major elements are recorded at sites located in the region of Oualad Sakher (SS5), while the minimum values are recorded at the sites located In the Ras R'mel beache (SS1). Concentrations of major elements show wide variations both in sediments collected

Table 1. Concentrations of sediments collected directly from beaches on the Atlantic Coast between Larache and Moulay Bouselham

Compounds	PS1	PS2	PS3	PS4	PS5	PS6	PS7
Na_2O	0.31	0.38	0.96	0.88	0.90	1.03	1.06
MgO	0.69	0.65	1.07	1.14	0.99	1.17	1.00
Al_2O_3	2.07	0.76	1.68	1.30	1.14	1.79	1.67
K_2O	0.19	0.14	0.31	0.13	0.12	0.28	0.24
CaO	19.38	22.76	17.46	22.49	21.30	24.85	16.65
TiO_2	0.25	0.11	0.30	1.47	0.31	0.21	0.18
MnO	0.04	0.02	0.03	0.03	0.03	0.05	0.03
FeO	1.31	1.05	1.59	1.94	1.41	1.85	1.81
Cl	1003.00	1007.20	9533.00	8679.00	7210.00	9296.00	8840.00
Sc	2.70	1.74	3.34	1.71	2.22	5.24	3.93
V	25.52	11.66	19.54	19.94	13.24	21.16	19.83
Cr	13.89	11.58	16.00	10.47	9.84	14.24	14.70
Co	3.58	2.33	3.90	4.80	2.87	4.87	4.78
Cu	43.42	47.13	9.54	5.06	6.53	39.29	8.98
Zn	22.56	22.20	45.34	28.63	26.37	7.10	19.69
As	12.56	16.14	14.25	10.49	17.57	26.07	14.20
Br	21.80	23.81	20.57	21.59	24.56	20.80	20.56
Rb	9.74	5.58	11.63	15.60	6.54	11.64	8.79
Sb	0.27	0.25	0.37	0.49	0.45	0.52	0.43
Cs	0.16	0.13	0.67	0.67	0.55	0.45	0.35
La	4.85	4.17	7.21	4.65	4.64	8.10	6.38
Ce	14.23	6.31	15.62	16.95	2.69	14.43	11.05
Sm	0.53	0.49	1.25	0.85	0.80	0.73	1.36
Eu	0.33	0.33	0.50	0.69	0.28	0.70	0.65
Tb	0.22	0.19	0.23	0.21	0.14	0.28	0.03
Yb	0.10	0.55	0.65	0.72	0.08	0.45	0.31
Lu	0.01	0.01	0.06	0.08	0.06	0.06	0.45
Hf	0.69	1.07	1.63	1.75	0.76	0.85	0.96
Ta	0.06	0.08	0.16	0.16	0.05	4.77	0.13
Th	0.29	0.35	1.26	1.26	0.85	0.77	0.64
U	0.06	0.05	0.04	0.03	0.05	0.05	0.04

directly from beaches (PS1–PS7) and in sediments collected away from beaches (SS1–SS7).

In sediments collected away from beaches, Na_2O concentrations range from 0.23% to 0.42%, MgO concentrations range from 0.71 to 1.61%, Al_2O_3 concentrations range from 1.41 to 3.24 %, K_2O concentrations range from 0.17 to 0.79%, CaO concentrations range from 7.89 to 30%, TiO_2 concentrations varied from 0.25 to 0.62%, MnO concentrations varied from 0.03 to 0.06% and FeO concentrations range from 1.70 to 6.07%.

In sediments sampled near beaches, Na_2O concentrations range from 0.31 to 1.06%, MgO concentrations range from 0.65 to 1.17%, Al_2O_3 concentrations range from 0.75 to 2.07 %, K_2O concentrations range from 0.12 to 0.31%, CaO concentrations range from 16.65 to 24.85%, TiO_2 concentrations varied from 0.11 to 0.18%, MnO concentrations varied from 0.02 to 0.05% and FeO concentrations range from 1.05 to 1.94%.

The fairly high CaO content reflects the high proportion of calcium carbonate in the two units studied, i.e., the samples taken directly from the beaches and those taken far from the beaches on the Atlantic Coast.

In the case of trace elements, the sediment samples collected show significant levels at most of the sites studied. The spatial evolution of trace elements shows remarkable variation. This trend is uniform for all the trace elements analyzed and

Table 2. Concentrations of sediments sampled collected far from beaches between 500 m and 1 km from the Atlantic Coast between Larache and Moulay Bouselham

Compounds	SS1	SS2	SS3	SS4	SS5	SS6	SS7
Na2O	0.23	0.28	0.42	0.37	0.27	0.29	0.31
MgO	0.15	0.87	1.15	0.79	1.61	1.12	1.00
Al_2O_3	3.24	2.20	2.23	1.87	2.54	2.45	1.41
K_2O	0.17	0.43	0.67	0.57	0.79	0.50	0.29
CaO	19.51	11.32	7.89	8.99	30.04	22.58	17.35
TiO_2	2.25	0.05	0.10	0.49	0.56	0.62	0.29
MnO	0.05	0.03	0.03	0.03	0.06	0.05	0.03
FeO	1.70	2.18	4.14	2.67	6.07	2.82	1.80
Cl	157.00	196.80	120.60	87.84	225.60	124.10	122.50
Sc	3.30	4.98	7.51	5.23	11.60	4.60	3.51
V	28.00	25.29	24.88	19.43	38.77	37.50	17.82
Cr	18.00	24.40	48.98	33.76	34.75	28.54	15.51
Co	2.57	4.49	11.00	6.94	15.51	6.81	4.36
Cu	66.52	68.60	75.43	100.90	352.80	14.20	7.15
Zn	87.68	133.90	401.70	17.85	480.00	29.81	20.57
As	16.18	12.96	24.50	25.70	54.21	22.04	22.65
Br	7.68	8.42	5.59	3.43	6.07	2.18	2.49
Rb	91.74	22.27	32.22	26.65	24.23	14.57	8.60
Sb	0.41	0.58	0.55	0.62	1.30	1.25	0.33
Cs	0.34	1.06	1.32	0.99	0.75	0.85	0.15
La	7.19	11.73	16.39	11.82	30.29	12.30	8.12
Ce	10.98	16.46	43.82	17.14	71.74	12.37	5.86
Sm	1.52	3.65	4.31	3.01	3.06	1.46	1.25
Eu	4.48	0.81	1.04	0.70	3.87	1.24	0.25
Tb	0.43	0.28	0.56	0.41	0.16	0.35	0.26
Yb	0.10	0.96	0.97	1.18	0.36	0.55	0.41
Lu	0.02	0.03	0.21	0.04	0.06	0.07	0.03
Hf	4.42	4.42	2.62	2.06	7.36	1.33	1.25
Ta	0.11	0.32	0.30	0.24	0.70	0.13	0.10
Th	0.59	2.16	3.76	2.39	3.13	0.56	1.18
U	0.40	0.30	0.45	0.25	0.13	0.25	0.29

Note: Major elements (Na, Mg, Al, K, Ca, Ti, Mn and Fe) are expressed in % while trace elements are expressed in ppm.).

on the different sites. The element with the highest level at all the sampling points was Cl, with maximum value of 9533 ppm; on the other hand, the elements with the lowest levels were Ta (0.10 ppm) and U (0.13 ppm). In all the samples, the rare earth elements measured were generally present at low levels, with maximum values for light rare earth elements (Ce 71.74 ppm) and minimum values for heavy rare earths (Lu 0.02 ppm). The maximum levels of the other elements, La, Sm, Eu, Tb and Yb, were 30.29 ppm, 4.31 ppm, 4.48 ppm, 0.56 ppm and 1.18 ppm, respectively. These levels, considered to be natural, suggest the absence of contamination.

Enrichment factors

In order to identify any possible contamination of the sediment samples collected, we introduced another factor that enabled us to: (i) determine the sources of natural and/or anthropogenic elements in the environment studied (sediments) (Tam and Yao, 1998; Chen et al., 2008); and (ii) establish a quantitative assessment of the degree of pollution for each element. As a result, the enrichment factor was calculated using data from the upper continental crust (Taylor and McLennan, 1995). The enrichment factor was calculated as follows:

$$FE(i) = \{[Ci]/[CFe]\}\ sample/\ /\{[Ci]/[CFe]\}\ UCC \quad (1)$$

where: $\{[Ci]/[CFe]\}$sample is the ratio of the concentrations of element *i* and of the reference element (*Fe*) in the sediments sample. $\{[Ci]/[CFe]\}UCC$ is the ratio of the concentrations of element *i* and the reference element (*Fe*) in the upper continental crust.

The results obtained for enrichment factors in sediments are shown (Figure 2).

Enrichment factors can be used to identify anthropogenic pollution in relation to the natural levels present in the sediment (Wheatcroft, Brooks, 2008). The natural content is compared to the concentration of the element in the sediment (Radakovitch et al., 2008). Limit values have been used as thresholds to separate elements for which other than crustal inputs should be invoked. The purpose of these values is to separate "moderately enriched" and "highly enriched" samples. As a result, the enrichment factors can be grouped into five classes (Table 3):

With the exception of arsenic (As), Br and Cl, the FEs obtained do not exceed the value 20. It should be noted that this element (As) has relatively high enrichment factors at all the stations. Br and Cl show also relatively high enrichment factors at the sampling points near the beaches. (Figure 2) defines several groups of elements:

Table 3. Classes of enrichment factors (Sutherland, 2000)

FE < 2	No or low enrichment
2 < FE < 5	Moderate enrichment
5 < FE < 20	Significant enrichment
20 < FE < 40	Very high enrichment
FE > 40	Extreme enrichment

The elements that show little or no enrichment are Na, Mg, Al, K, Sc, Ti, V, Cr, Mn, Co, Cu, Zn, Rb, CS, rare earth elements, Hf, Ta, Th and U. These elements can be considered to be of crustal origin, deriving from the alteration of silicate rocks.

The element that is moderately enriched (2 < FE < 5) is Sb. This element is therefore likely to be of anthropogenic origin. The FE is very high at SS6 site near the Mersat Lghnem beach. The relative enrichment of this element suggests a strong likelihood of contamination by domestic discharges.

Calcium (Ca) is the only element to show significant enrichment (5 < FE < 20) at all the stations. This can be explained by the very high Ca levels over the entire study region. These levels range from a minimum of 7.89% to a maximum of 30.04%, whereas the Ca concentration in the upper continental crust is 3%.

Arsenic (As) shows very high enrichments (20 < FE < 40) or even extreme enrichments (FE > 40). The highest enrichment factor for this element is equal to 42.33 and corresponds to site PS6, which is located directly at Mersat Lghnem beach. This area is therefore extremely polluted (FE > 40). On the other hand, for the other sites to the north of PS6, enrichment factor is less significant. However, arsenic enrichment remains very high for the entire study area (20 < FE < 40).

Chlorine (Cl) shows also an extreme enrichments factors (20 < FE < 40), mainly at the sites located directly at the beaches (from PS1 to PS7). This can be explained by the very high Cl concentrations in these stations. These concentrations range from a minimum of 107.20 ppm to a maximum of 9533 ppm whereas the Cl concentration in the upper continental crust is 142 ppm.

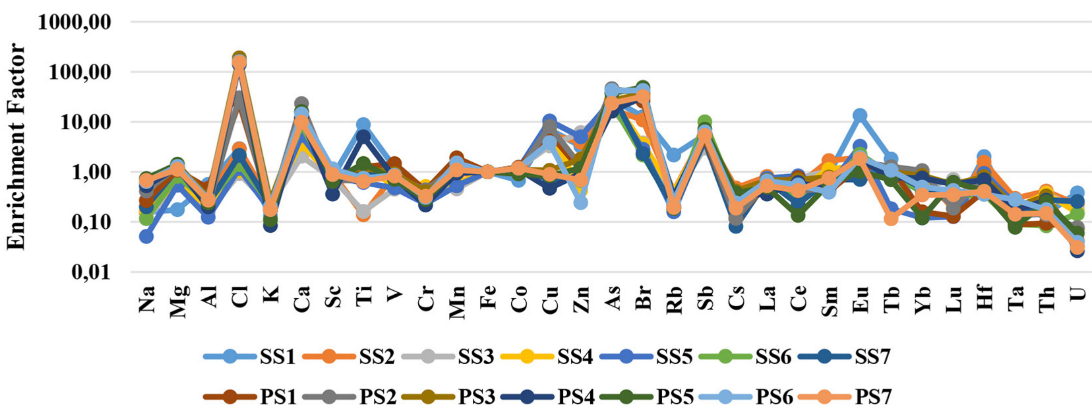

Figure 2. Enrichment factors for sediments at different sampling points between Larache and Moulay Bouselham

Principal component analysis

In order to determine the possible relationships between the various major and trace elements in the sediments collected along the Atlantic Coast between Larache and Moulay bouselham, a principal component analysis (PCA) was carried out site by site using Pearson's coefficient. In this work, PCA was used to study the correlations between the various elements determined and the sampling points in the sites close to the beach (PS1–PS7) and the sites far from the beach (SS1–SS7). The options taken in this analysis primarily reflect the objectives we set ourselves. Our objectives were firstly to obtain different groups of elements on the basis of their correlation coefficients, to highlight the axes of similarity between the groups of elements, and then to identify the chemical elements characteristic of the samples taken from the different sites spread across the study area. In samples taken both near the beach (from PS1 to PS7) and far from the beach (from SS1 to SS7), the statistical treatment was 14 observations and 31 variables (Na, Mg, Al, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Cu, Zn, As, Br, Rb, Sb, Cs, La, Ce, Sm, Eu, Tb, Yb, Lu, Hf, Ta, Th and U). Principal components 1, 2 and 3 account for 76.21% of the overall inertia; 46.15% of the information in the input data table is explained by the first principal component, 15.70% is explained by the second principal component and 14.36% is explained by the third principal component. In the plane formed by principal components 1 and 2 (Fig. 3), the variables most correlated with CP 1 are: Al, K, Sc, V, Cr, Mn, Fe, Co, Cu, Zn, As, Sb, Cs, rare earth elements (La, Ce, Sm, Eu, Tb), Hf, Th and U. Among these variables, the ones that contribute most to forming CP 1, we find two different groups: the first group, made up of Fe, Sc, K and Co, and the light rare earth elements (La and Ce), which are strongly correlated with each other since they define eigenvectors in the same direction, and the second group, made up of Ce, Zn, Cr, Cu, Hf, Th, As, Sm, V, Sb, Al, and Cs. The correlations between these variables are all the stronger the further they are positioned ends of the axis defined by CP 1.

On the axis defined by CP 2, the variables most correlated with this principal component are : Mg, U, Tb, Rb, Na and Cl. Other variables (Ca, Mn, Ti, Br, Yb, Eu, Ta and Lu) are close to the centre of the factorial plane, so their correlation is certainly not very strong. These variables are probably better explained by other principal components. For example, Ca, Ti, Mn and Yb are well explained by CP 3, Br, and Lu are well explained by CP 4, Ta is well explained by CP5.

In order to identify the links between the samples and their chemical composition, the coordinates of the observations ("scores") in the CP1 and CP2 factorial planes have been represented (Figure 4). The distribution of samples on the CP1, CP2 factorial plane shows that it is easier to isolate small groups of samples. The first group includes samples that are poorly explained by principal components 1 and 2. These are essentially samples taken far from the beaches (SS2 and SS4). Their location in this set is not

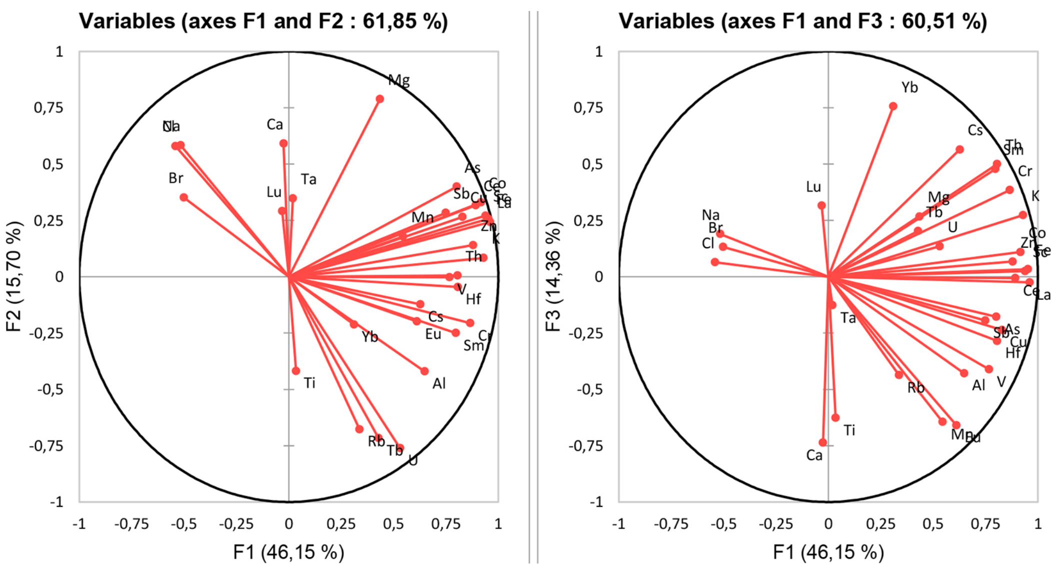

Figure 3. Distribution of variables in the factorial planes formed by CP1 and CP2 and CP1 and CP3

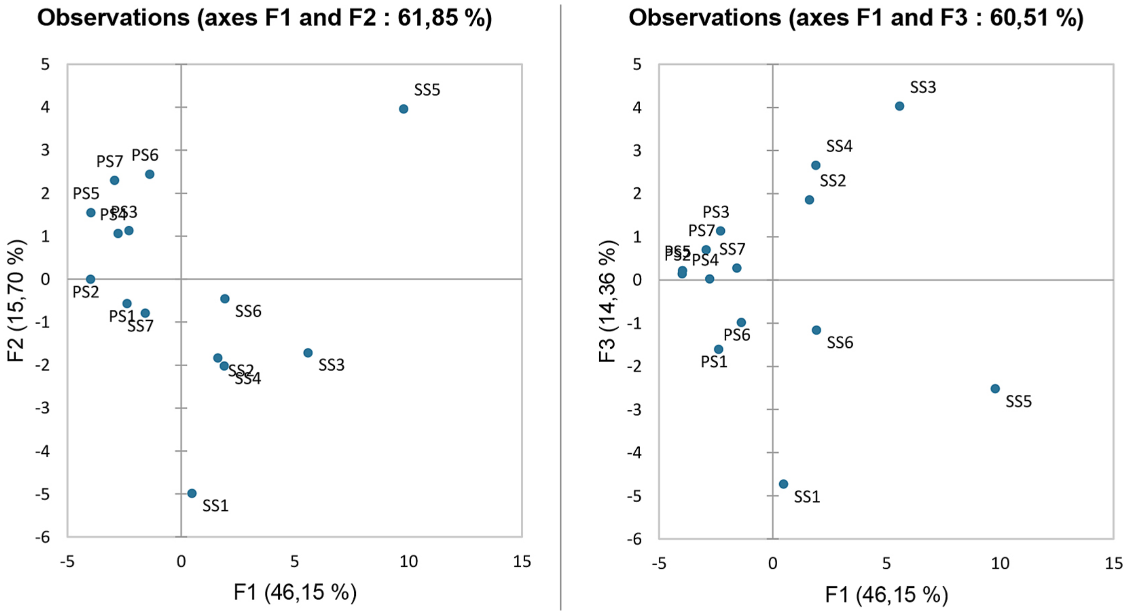

Figure 4. Distribution of observations in the factorial planes formed by CP1 and CP2 and CP1 and CP3

linked to any element since they are located at the center of the factorial plane defined by the principal axes 1 and 2. A second group is essentially defined by samples, SS3, SS5, SS6, PS1, PS2, PS3, PS4, PS5 and PS6. These samples are well explained by principal component 1. Their location in this group is linked to their composition in Fe, Sc, Cr, Co, rare earth elements (La, Ce, Sm, Eu, Tb, Yb, Lu), Hf, Ta and Th. A third group set is defined by the sample SS1 which is well explained by principal component 2. Its location in this group is linked to their composition in Na, Mg, Cl and Ca. A fourth group is identified by samples SS2 and SS4; these samples are well explained by principal component 3; their inclusion in this group is linked to their is linked to their composition in Yb. Samples SS7 and PS6 in turn describe another set defined by principal component 4 and 5 respectively; their location in this their location in this group is linked to their composition in Ti, Br, Rb and Lu for F4 and Ta for F5.

CONCLUSIONS

In this work, the identification of a maximum of major and trace elements from neutron activation analyses, enabled us to identify composite signatures as characteristic as possible of the sediments sampled. Composite signatures as characteristic as possible of the sediments sampled along the Moroccan Atlantic coast from Larache to Moulay Bousselham cities.

Determination of the enrichment factors revealed the main contaminants in the area studied. The FEs obtained clearly show very high, even extreme. Arsenic enrichment remains very high for the entire study area (20 < FE < 40).

Significant enrichment (5 < FE < 20) of Ca was recorded along the entire Atlantic coast between Larache and Moulay Bousselham cities.

Extreme enrichments factors (20 < FE < 40) have been recorded for chlorine (Cl) at the sites located directly at the beaches (from PS1 to PS7). This can be explained by the very high Cl concentrations in these stations.

The elements that show little or no enrichment are Na, Mg, Al, K, Sc, Ti, V, Cr, Mn, Co, Cu, Zn, Rb, CS, rare earth elements, Hf, Ta, Th and U. These elements can be considered to be of crustal origin, deriving from the alteration of silicate rocks.

The overall statistical processing of the database thus constituted by PCA also enabled us to complete our approach aimed at taking into account as many elements as possible, by synthesizing the results of our analysis.

By synthesizing, the information collected according to factors likely to explain the spatial distributions of sediments characterized by their multi-element signatures, we were able to highlight the main patterns of contamination and their potential sources.

This study successfully identified the main pollutants, namely arsenic and chlorine, in the sediments along the Moroccan Atlantic Coast. The high enrichment factors for these elements indicate significant contamination, particularly near port and dredging activities. By examining the geochemical behavior of these elements, we observed that arsenic and chlorine showed extreme enrichment levels at several sites, underscoring the impact of anthropogenic activities on sediment quality. Furthermore, the mechanisms of sediment transport from land to sea were elucidated through the spatial distribution of these contaminants. The consistent enrichment of calcium along the coast and the elevated chlorine levels at beach sites suggest that sediment transport processes are influenced by both natural factors and human activities.

Our findings indicate that sediments are likely transported from terrestrial sources, where they accumulate pollutants, and are then distributed along the coast through marine processes.This comprehensive approach allowed us to integrate various elements into a cohesive analysis, highlighting key contamination patterns and their potential sources. Our findings have significant implications for sustainable management in the region. The identification of arsenic and chlorine as primary contaminants necessitates targeted pollution control measures. Authorities can prioritize these contaminants in their environmental management plans. Understanding the distribution and enrichment of elements like calcium and chlorine can inform strategies to manage coastal erosion and sediment quality, helping to mitigate further environmental degradation. The data can support the development of policies aimed at reducing contamination sources, protecting marine ecosystems, and ensuring the sustainable use of coastal resources. By disseminating our findings, we can raise awareness among local communities about the contamination issues and encourage their involvement in sustainable practices and conservation efforts.

This study not only identifies key contaminants and their distribution along the Moroccan Atlantic coast but also provides valuable insights for sustainable environmental management, addressing both current and future challenges in the region.

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