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Sedimentology and Paleoenvironments of the Eboco and Adima Sedimentary Deposits (Southeastern Ivory Coast)

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Abstract: The purpose of this work is to determine the lithology, the depositional environment and the mode of transport of Eboco and Adima sedimentary formations. To achieve this objective, thirteen (13) samples of cuttings from a well and a cliff located in the department of Tiapoum (onshore basin, South-East of Ivory Coast) were subjected to sedimentological analyses. These investigations revealed a clay-sand sedimentation. The granulometric analyses of the sands show that they are very coarse to very fine, very poorly classified to fairly well classified with asymmetries towards the coarse and fine. The granulometric curves show two types of facies, namely logarithmic facies that reflect deposition by excess load and parabolic facies that reflect transport of coarse sediments by graduated suspension. The multi-modal pattern shows that these sands have one or more sources of supply. Transport was generally by graded suspension and by bedload. The dispersion diagrams So/Md and Md/sk show that the depositional environment of the sand grains is of river and continental dune type suggesting a continental domain. The morphoscopic study revealed quartz grains generally subrounded to rounded and angular to subangular with a blunt shiny aspect suggesting a relatively close and distant source in an aquatic environment. The mineralogy of the sands is composed of quartz, glauconite, pyrites, carbonaceous debris and iron hydroxide which reflects deposition in a reducing continental environment (pyrites) under marine influence (glauconite).

1. Introduction

The Ivorian sedimentary basin is of undeniable interest. Since the initial discoveries of bitumen occurrences at Eboinda (Adiaké region in the east) in 1896, the Côte d'Ivoire sedimentary basin has been the subject of a number of studies (Spengler *et al.*,1966). These studies have allowed the morphology and precise mapping of the onshore basin to be defined. The sedimentology of the Bingerville region has shown three sedimentary sequences, the earliest of which is Oligocene in age and composed of varves (Assalé *et al.*, 2013). The second sequence is made up of bariolate silty clays and the most recent is of Plio-quaternary age and is lenticular (Digbehi *et al.*, 2001). The work of **(**Assalé *et al.*, 2013**)** has shown that the eastern part of the basin is characterized by an alternating fluvial and mangrove system, ending in an oxidized continental environment or recent lagoon deposits. The study of a bitumen index in the Bonoua region (Kodjoboué) reveals the presence of malta with 70.5% mattenes, pollen grains and spores.

Similarly, (N'zi *et al.*, 2018) characterized the formations in the western part of the basin, which show a dominantly clayey and sandy sedimentation, with sandstone and limestone intercalations, deposited in a shallow, low-oxygen marine environment. In addition, (Gbangbot *et al.*, 2019) carried out a lithostratigraphic, sedimentological, palynological and hydrogeological characterization of the lagoon region.

Although a great deal of work has been carried out in this area, geological information on the Eboco and Adima zones in the Tiapoum department is scarce.

The objective of this study is to characterize the lithology, granulometry and depositional environment of the different formations encountered.

Eboco and Adima are villages located in the Sud-Comoé region, of which Aboisso is the regional capital. This region lies in the south-east of Côte d'Ivoire, with Ghana to the east and the Atlantic Ocean to the south. The region includes several towns, including Tiapoum, where the villages of Eboco and Adima are located. The study area lies between latitudes 05°08.829' North and 05°08.908' North and longitudes 03°04.588' West and 03°04.472' West.

2. Methodology

2.1 Sourcing and preparation of

The material used in this study consisted of seven (07) samples of cuttings from an Adima well and six (6) samples of sediments taken from the Eboco cliff.

2.2 Experiments

We used several methodologies to study the lithology, granulometry and morphoscopy of the sediments. The macroscopic description of the sediments, using both the naked eye and a binocular loupe, enabled us to identify the lithological nature of the formations. This description includes their mineralogical composition, texture and the determination of certain accessory minerals. Mineralogical analysis with a binocular loupe only concerns soft sediments. It is performed with a binocular loupe on fractions between 63 and 250 µm in size. Lower is the fraction, greater is the quantity of heavy minerals. These heavy minerals can provide information on the sediment distributing province. They can also be used to determine the alteration degree of the parent rock. The minerals sought with a binocular loupe are the accessory minerals: glauconite, pyrite, muscovite and tourmaline. Often, certain minerals are essential components of certain rocks (muscovite and glauconite). Minerals provide information on depositional environments. Coloration has been determined by the Musell chart.

To obtain the grain size of the sandy sediments in our samples, a 100 g fraction of sediment was taken from the dried residue of the 63-micron sieve wash. This fraction is placed at the top of a series of 16 sieves superposed in order of decreasing size of the sieve mesh between 500 and 63 µm. The sieves are used to study the particle size distribution of the sand grains. After mixing for 10 minutes, the sieve rejects are successively collected and weighed. The rejects from the various sieves are used to construct particle size curves, which are then used to determine the particle size distribution parameters for particle size analysis.

A certain number of parameters, useful in the granulometric study of a sedimentary columns, are calculated (Brenon *et al.*, 2004). These parameters are mean, classification, deviation, asymmetry, median and mode. Determination of these various parameters requires knowledge of the quantiles, which are determined using EasySeive software (used to calculate quantiles for granulometric analysis). These are quartiles, deciles and pentiles (Vernhet *et al.*, 1976).

3. Results and Discussion

3.1. Lithological characterization of the shaft and cliffs

3.1.1. Lithological characterization of Adima borehole sediments

The lithological analysis of the cuttings from the Adima well identified a single lithology facies with a variation in color. This facies is composed of clay-sand with the presence of pyrite in places in (Figure 1). The variation in coloring has enabled us to define two intervals (A and B)

- Interval A (27-30 m)

The clays are abundant with a proportion of around 60% and are colored 2.5YR6/4 (light reddish brown), 2.5YR3/3 (dark reddish brown) and 20.5YR5/4 (reddish brown). The sand grains are coarse with a reddish-brown color and are rounded to subrounded. Pyrite is trace-shaped. The overall reddish-brown color is caused by the presence of iron oxides or hydroxides, reflecting a semi-arid tropical depositional environment.

- Interval B (30-33 m)

Clays are predominant, with a proportion of around 60% and a color of 7.5YR8/6 or 7.5YR7/8 (reddish yellow), and are loose (friable). Sand grains are translucent, very coarse, rounded to sub-rounded and have the same colors as the clays. Pyrite is absent in this interval. The reddish-yellow coloration is due to the presence of iron hydroxides or iron oxide.

Sediment deposit environments are determined using the So-Md and Md-Sk diagrams from (Moiolar *et al.*, 1968). These diagrams will enable us to differentiate between beach, river, coastal dune and continental dune sand environments.

Quartz grain morphology determines the appearance of the surface and the form of quartz grains. It provides an indication of the distance covered by the sediment and its transport agent. The morphoscopy study was based on the method described in (Pettijohn *et al.*, 1949).

3.1.2. Lithological analysis of Eboco cliff sediments

The lithological analysis of the Eboco cliff sediments shows a single type of lithological facies with color variations (Figure 2**)**. This is a sandy-clay with abundant pyrite. Two intervals (C and D) have been defined on the basis of color variation:

- **Interval C (10-11 m) and (12-15 m)**

These intervals are predominantly composed of clays with a light reddish-gray (2.5YR7/1) coloration (approx. 80%). The sand grains are medium to very fine, rounded to subrounded and angular to subangular, with a color identical to that of the clay. The light reddish-grey color is due to the presence of organic materials and iron hydroxide.

- Interval D (11-12 m) and (over 15 m)

These intervals show clays with a yellowish-red (5YR7/8) or reddish-yellow (5YR5/6) color, due to the presence of iron hydroxide. Sand grains are very coarse, rounded to sub-rounded and angular to sub-angular.

3.1.3. Lithological correlation of well and cliff sediments

Reddish brown sandy clay reddish yellow sandy clay: The lithological correlation of the sediments studied shows no facies difference, but the well cuttings are more deeply oxidized than the cliff sediments.

The lithological synthesis reveals that the sediment of Adima well and the Eboco cliff are essentially formed of sandy clay. The Eboco cliff deposits are richer in clay than those of the Adima well, according to (Douzo *et al.*, 2019; Toe bi *et al.*, 2016; Yao et *al.*,2011), reflecting a calm depositional environment at Adima and a more agitated one at Eboco.

In addition, the well cuttings are more oxidized than the cliff sediments. In fact, the cliff sediments, which should be more oxidized than the well sediments, are less oxidized. This would appear to be due to surface leaching associated with runoff, which would have transported the oxidized sediments and deposited them in the well.

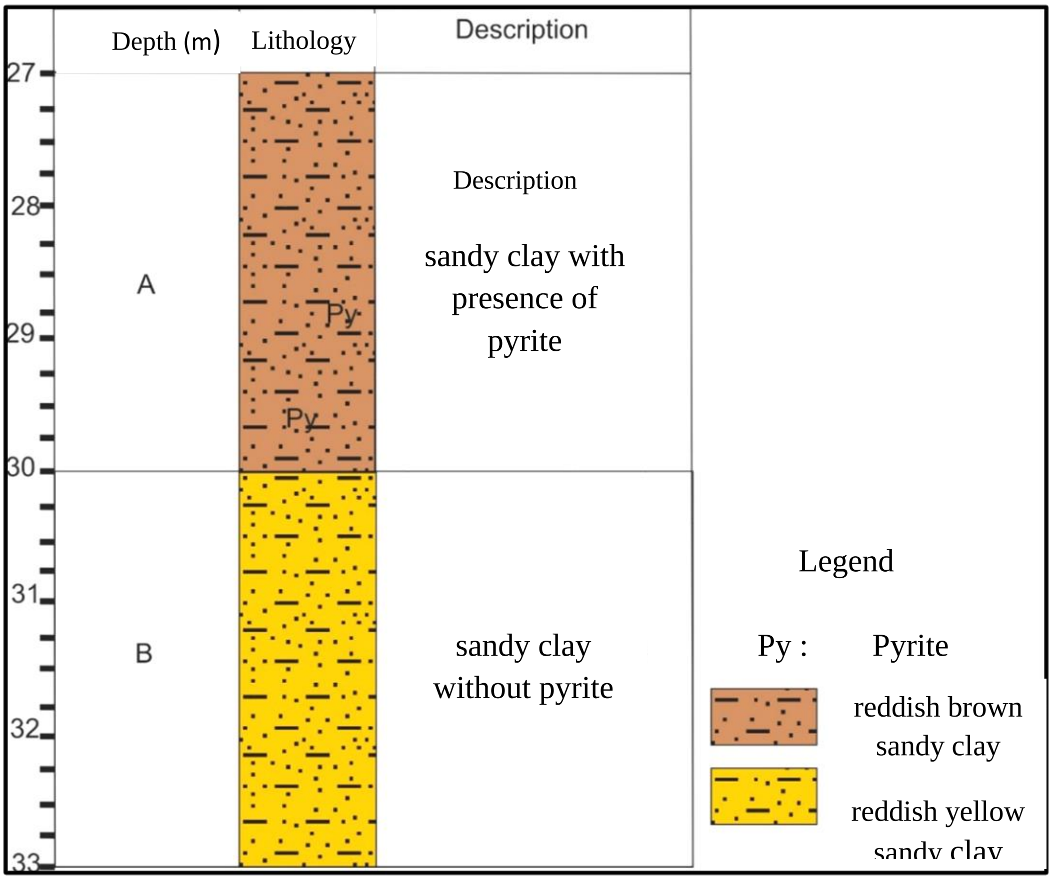

Figure 1: Log of the Adima well

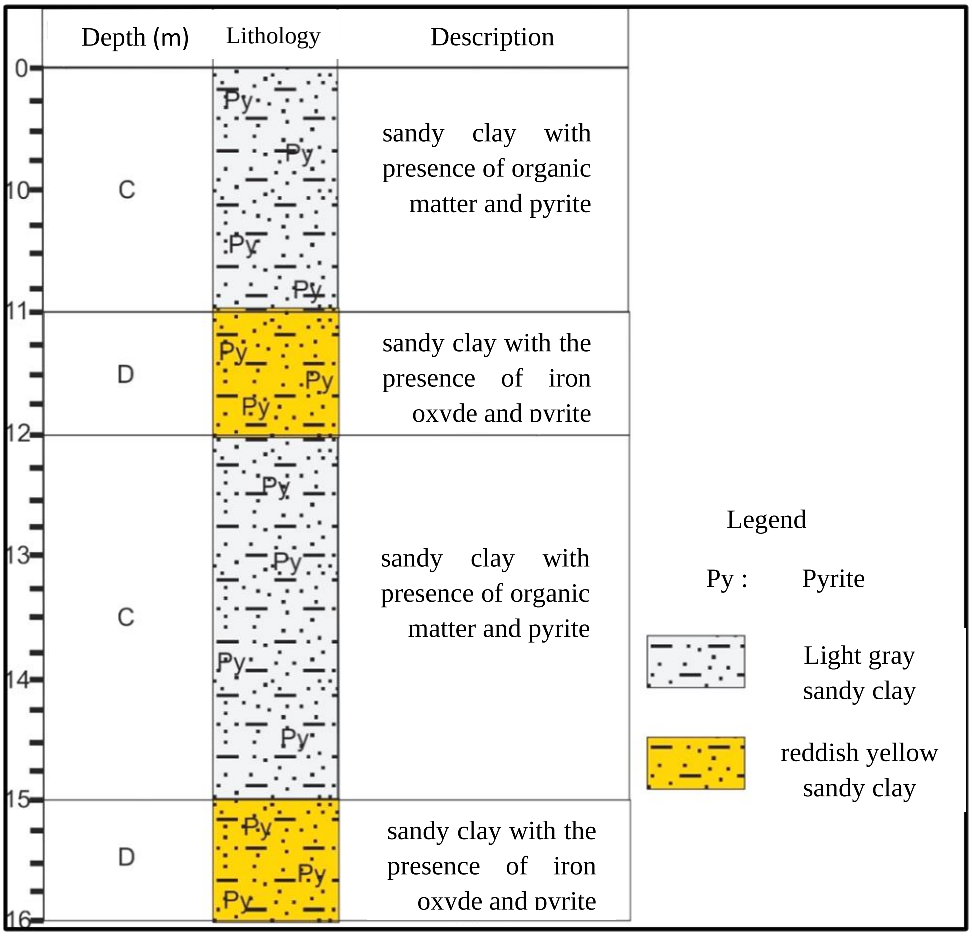

Figure 2: Log lithology of the Eboco cliffs

3.2 Granulometric characterization of the Adima well and the Eboco cliffs

3.2.1. Size distribution of Adima pit and Eboco cliffs

The relative proportions of grain size classes in the Adima well show that sands are predominantly very coarse (53.44%), while sand ranging from coarse (17.3%) to very fine (4.3%) is poorly represented (see Table 1). Eboco cliff deposits have a low proportion of very fine sands (24.22%) compared with the proportions of very coarse, coarse, medium and fine sands, which are represented by (17.62%), (12.33%), (12.95%) and (16.84%) respectively in (Figure 3).

Table 1: Size distribution of well and cliff sediments

Puits	Echts	Stg	Sg	Sm	Sf	Stf
	A27	25,41	30,58	25,94	12,79	5,06
		29,23	16,45	23,34	19,92	7,96
	A29	72,63	7,59	7,29	10,12	2,08
ADIMA	A30	50,43	16,2	9,89	9,81	4,97
	A31	46,76	27,22	14,54	5,46	4,73
	A32	77,01	10,47	5,34	4,9	2,68
	A33	72,58	12,57	7,72	4,75	2,6
	E10	14,9	10,2	7,84	8,38	55,34
	E11	23,51	17,97	16,2	18,8	24
EBOCO	E12	11,64	17,99	19,09	39,73	10,53
	E13	18,32	11,84	7,7	23,01	34,57
	E14	24,48	12,66	15,06	14,29	36,19
	E15	30,48	15,67	24,74	13,57	14,88

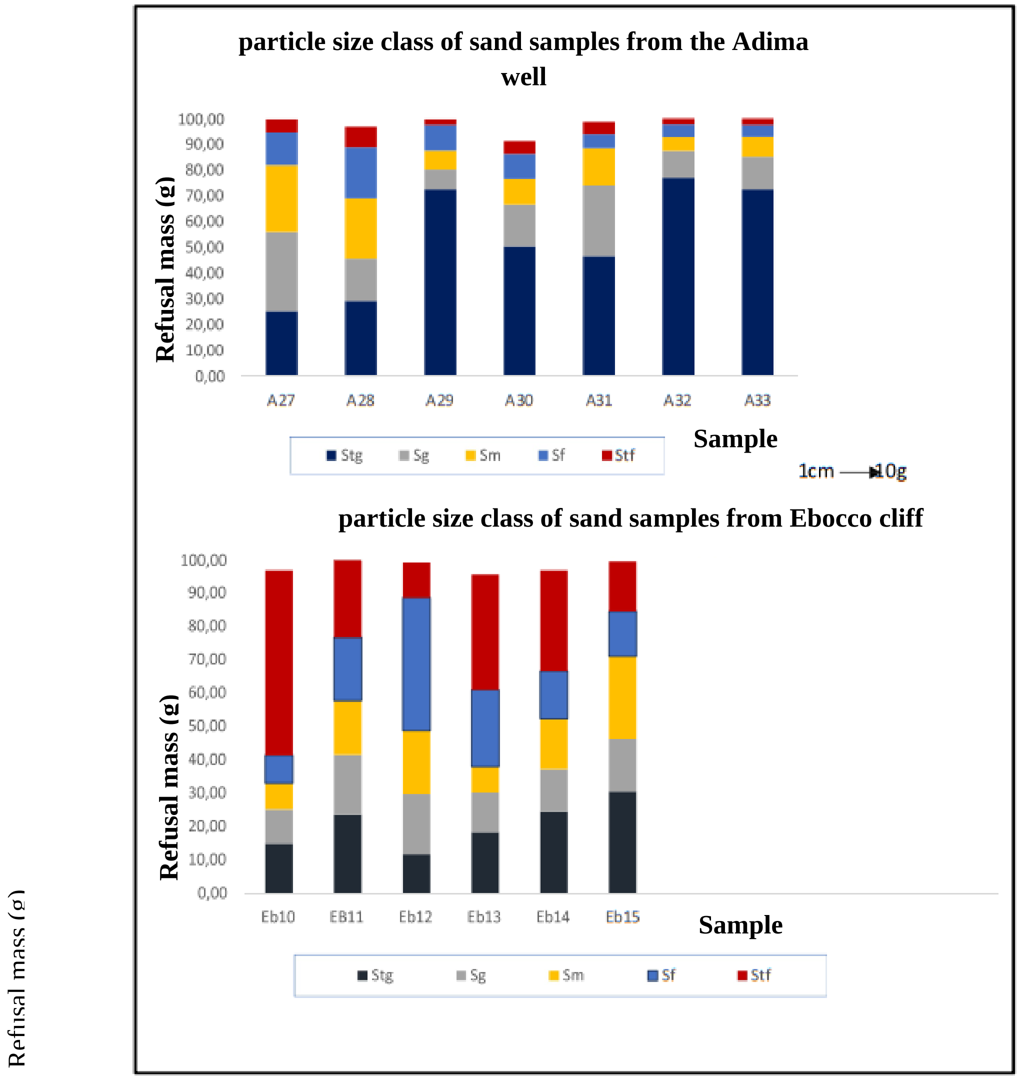

Figure 3: Grain size distribution of sands from the Adima well and the Eboco cliff (*Grain size distribution (in %): Stg: very coarse sands; Sg: coarse sands; Sm: medium sands; Sf: fine sands; Stf: very fine sands).

3.2.2. Granulometric parameters of Adima well and Eboco cliff

The granulometric parameters calculated gave the following results in Table 2.

3.2.2.1. Analysis and interpretation of particle size parameters for the Adima well

The sands from the Adima well are very coarse with averages above 1000 µm and are poorly classified for sediments A27, A28, A29, A30, A31 with standard deviations between 1 and 2. On the other hand, these sands are very poorly classified for sediments A32, A30, A33, with standard deviations between 2 and 4. The A29 sands are asymmetric towards coarse elements, with a negative skewness (SK) of between -0.30 and -0.10. Sands A32 and A33 have grain-size symmetry and the others are asymmetrical towards fines with skewness between 0.48 and 0.87.

3.2.2.2. Analysis and interpretation of granulometric parameters in the Eboco cliffs

Sediments E14 and E15 have averages greater than 1000 µm, suggesting that the sands are very coarse and are poorly classified with skewness between 1 and 2. Sands E10 and E12 are medium-grained with averages between 500 µm and 250 µm, and have standard deviations between 0.5 and 1, showing that they are fairly well to moderately graded. The sands of E13 and E11 are coarse and poorly graded with averages above 500 µm and standard deviations between 1 and 2. Eboco cliff sands generally have skewness towards the fines with skewness between 0.3 and 1.

Table 2: Granulometric parameters of pit and cliff sands

pit and cliff	*Echts*	**Mz*	*So*	Mo	*Sk*	*Md*	*Mz (µm)*
	A27	1,15	1,23	18,21	0,77	0,54	1150,33
	A28	1,5	1,84	10,47	0,87	0,46	1517
	A29	2,39	1,68	39,63	-0,12	2,62	2394,66
ADIMA	A30	2,11	2,03	12,2	0,48	1,52	2115,33
	A31	1,8	1,55	24,11	0,53	1,18	1801,33
	A32	3,53	2,47	32,94	-0,06	3,72	3539
	A33	3,54	2,5	33,68	-0,09	3,8	3543,66
	E10	0,46	0,82	45,07	0,96	0,1	460,33
	E11	0,927	1.37	13,5	0,84	0,35	927,33
EBOCO	E12	0,495	0,7	19,29	0,84	0,24	495
	E13	0,664	1,03	25,82	0,95	0,15	664,33
	E14	1,00866	1,27	24,8	0,85	0,3	1008,66
	E15	1,134	1,41	9.33	0,8	0,462	1134

*Mz: Average; So: Sorting; Mo: Mode; SK: Skewness; Md: Median

3.2.3. Granulometric facies of sediments from the Adima well and the Eboco cliffs

3.2.3.1. Granulometric facies of Adima well sediments

The semi-logarithmic curves for the Adima well show a single type of facies. This is the logarithmic facies. The logarithmic facies is shown by a curve more or less equivalent to a straight line, indicating deposition by excess load following a reduction in the competence of the transport agent (see Figure 4).

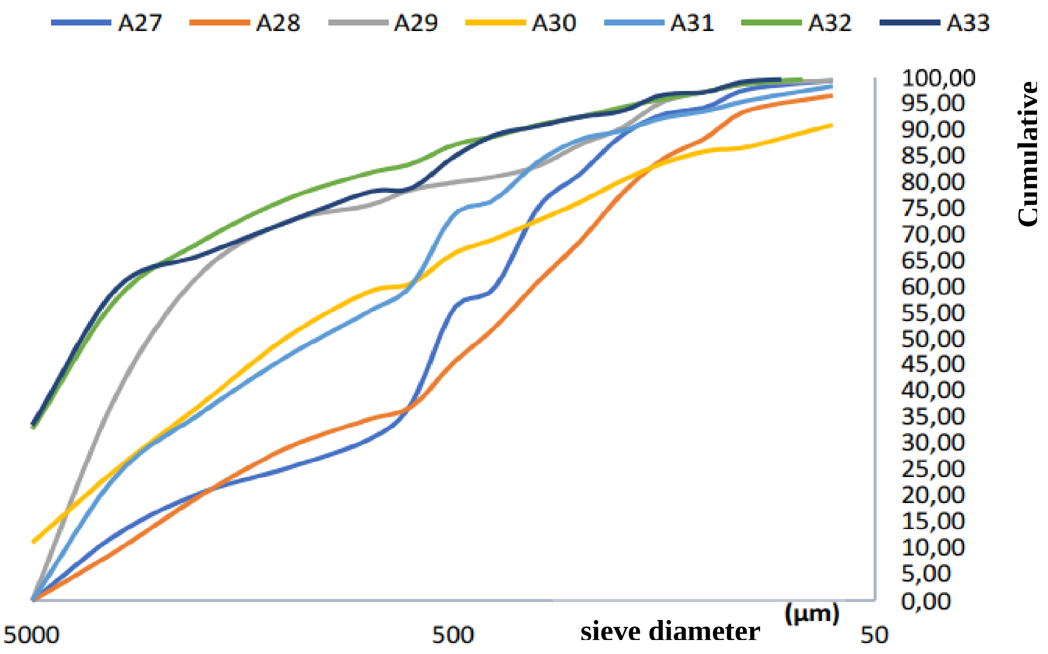

Figure 4: Logarithmic granulometric contours

3.2.3.2. Granulometric facies of Eboco cliff sediments

The Eboco cliff has two types of granulometric facies in (Figure 5). These are logarithmic (Eb11, Eb15) and parabolic (Eb10, Eb12, Eb13, Eb14). The logarithmic facies is represented by a contour more or less similar to a right line. The inclination of this right-hand line varies to a large extent according to the proportion of fine elements. The first, or logarithmic, facies indicates deposition due to excess loading following a diminution in the competence of the transport agent. The second, parabolic facies shows that coarse sediments were transported in graduated suspension, while fine was transported in uniform suspension.

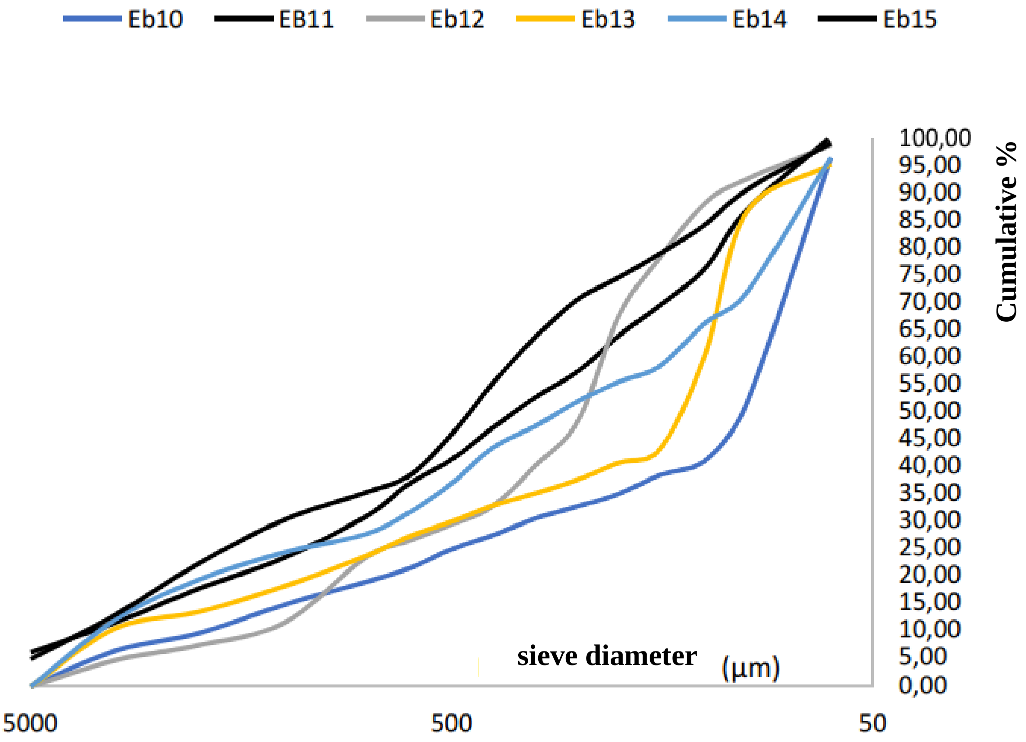

Figure 5: Logarithmic and parabolic granulometric contours

3.2.4. Sources of Adima well and Eboco cliff sands

3.2.4.1. Modal allures of the Adima well sands and the Eboco cliff sands

The sands from the well and the cliff show the same allures. Analysis of the frequency contours reveals four types of allure. These are:

- unimodal allure present in the sediments of the pit (A29) (see Figure 6A).
- bimodal, represented at 80% in cliff sediments (see Figure 6B).
- trimodal allure present in well sediments (A27, A30, A31) (see Figure 6C).and
- the quatrimodal allure present in Adima sediments (A28) (see Figure 6D).

The unimodal allure shows an absence of sediment mixing and corresponds to well-graded medium sands. Bimodal, trimodal and quatrimodal patterns show that there are two, three or four sources of supply, resulting in sediment mixing due to watercourse confluence or irregular water flows. They generally correspond to poorly graded sands. They indicate a mixture of very coarse, coarse and medium-grained sands.

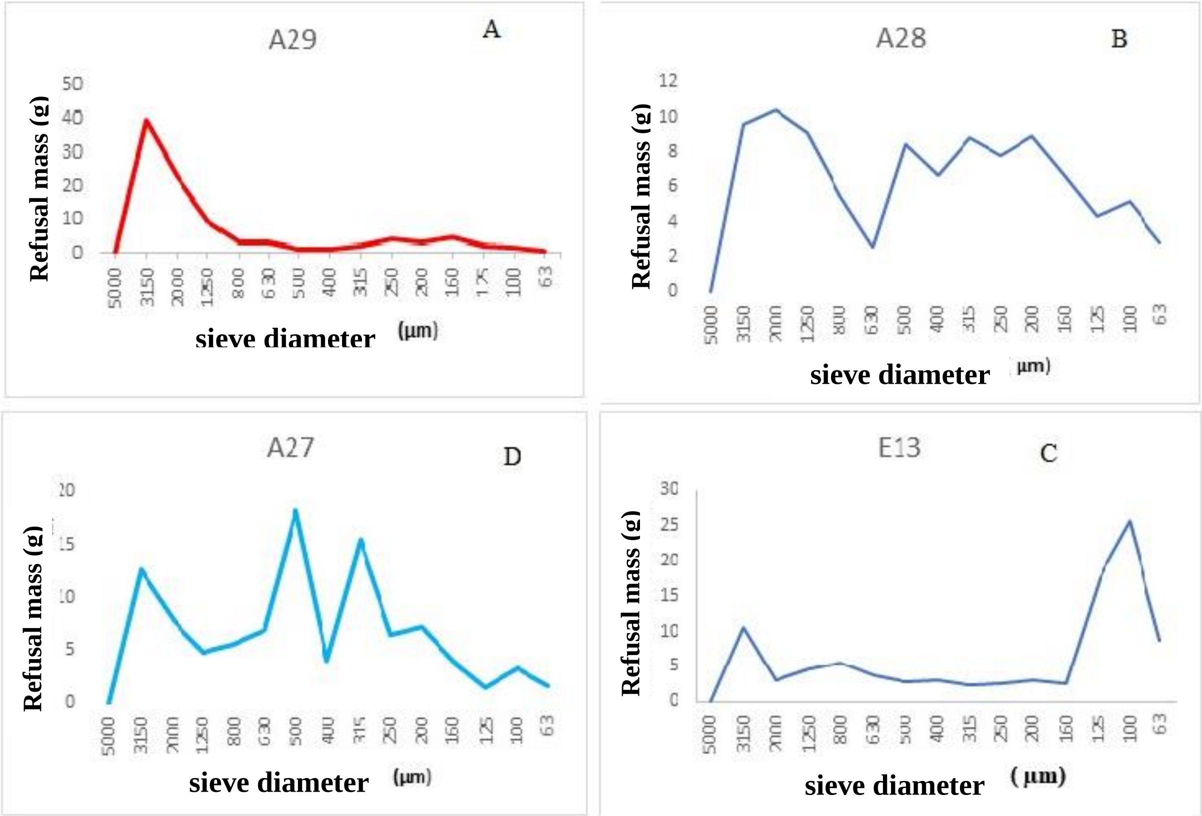

Figure 6: The Modal allures A: unimodal, B: quatrimodal, C: bimodal and D: trimodal

3.3. Paleoenvironment of sediments in the Adima well and Eboco cliffs

3.3.1. Quartz grain morphoscopy in the Adima well and the Eboco cliffs

Morphoscopic analysis of quartz grains was carried out on 300 µm and 400 µm screen rejects using a binocular magnifying glass. This analysis enabled us to determine the appearance and shape of these grains (see Figure 7 and 8). The overall form of the quartz grains in the Adima well is generally rounded to sub-rounded. Quartz grains from the Eboco cliff are generally angular to subangular, sometimes subrounded. Rounded to subrounded grains indicate that the sediments originated from a distant source, while angular to subangular grains indicate that the source of these sediments is close to their depositional environment. Quartz grains from the Eboco cliff and Adima well are generally blunt and shiny, indicating transport in an aquatic environment.

3.3.2. Mineralogy of Eboco cliff and Adima well sediments

A binocular loupe of the sands from the Eboco cliff identified quartz at around 70%, glauconite at around 5%, hematite at around 10%, carbonaceous debris at around 10% and pyrite at around 5%. The sands from the Adima well show the presence of minerals such as hematite at around 30%, quartz at 34%, glauconite at around 20%, carbonaceous debris at around 15% and pyrite at around 1% in (Figure 9 and 10). The presence of iron hydroxide and pyrite indicates a reductive continental-type depositional environment. Carbonaceous debris indicates the presence of organics, and the presence of glauconite is linked to a marine influence. The relative abundance of quartz compared with other minerals is due to its resistance to meteorite alteration and is concentrated in sediments transported by rivers in tropical climates.

Mineralogically, the minerals identified are quartz, glauconite, pyrite, iron hydroxide and carbonaceous debris. The abundance of minerals such as quartz, iron hydroxide and carbonaceous debris indicates a continental depositional environment. According to (Yao *et al.*, 2011), the presence of pyrite and glauconite indicates a marine, shallow, reducing depositional environment, and is indicative of a slowdown in sedimentation. As the depositional environment is continental, their presence in the area is due to a marine influence.

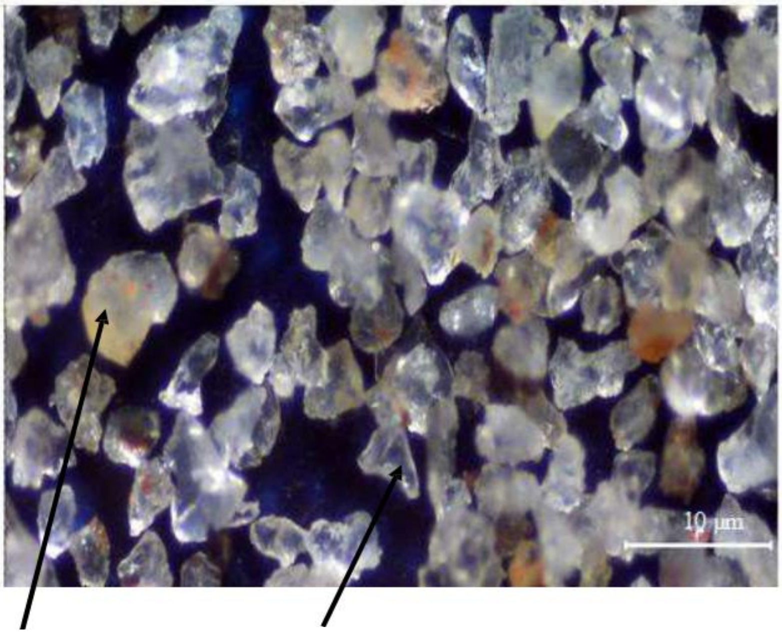

Figure 7: Blunt, shiny quartz grains, subangular quartz and angular quartz

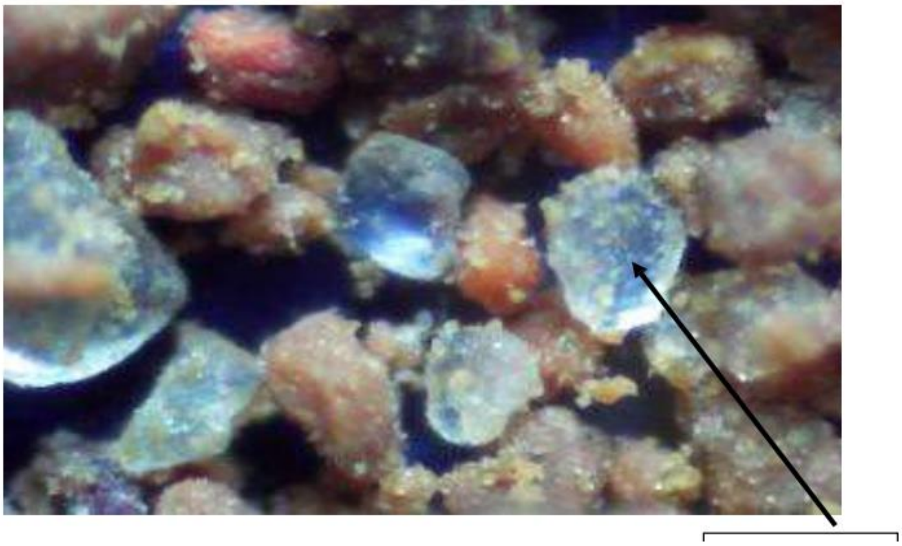

Figure 8: Shiny, rounded quartz grains

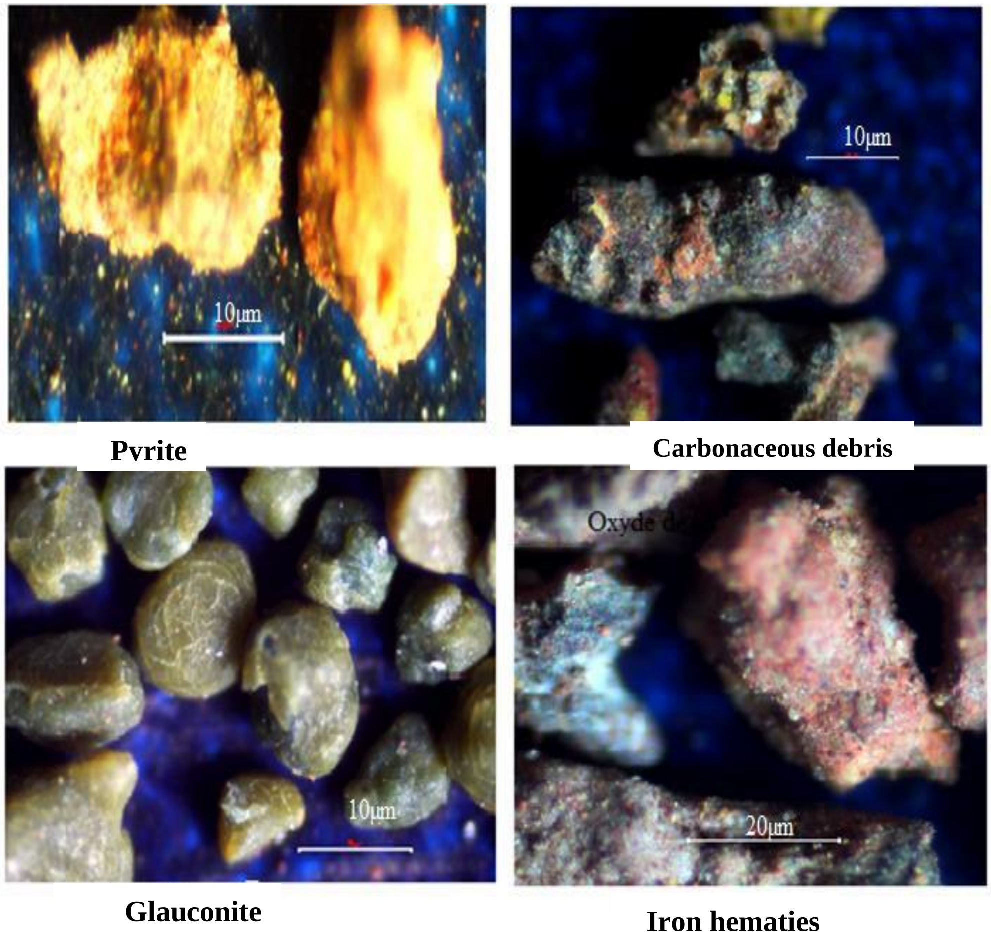

Figure 9: Pyrites, carbonaceous debris, glauconites and iron hematites in the samples

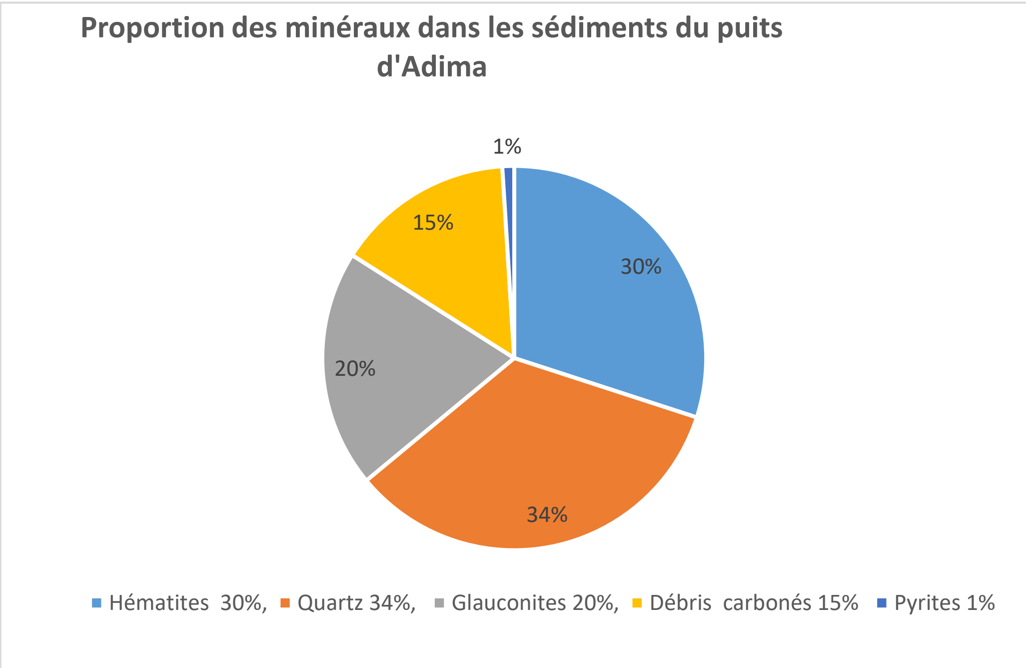

Figure 10: Diagrams of mineralogical proportions for the Adima shaft and the Eboco cliff.

3.3.3. Mode of transport of sands from the Adima well and the Eboco cliff

The visher test analysis applied to sediments from the well and the cliff identified three modes of transport. These are bedload, saltation and suspension (see Figure 11 and 12). The mode of transport of the Adima sands is suspension (approx. 61.9%) and cartage (approx. 20%). (Table 3) shows this suspension would be a graded suspension due to the strong water current that prevailed. Medium sands are transported by saltation (approx. 17.14%). The dominant mode of transport of sediments from the Eboco cliff is bedloading at around 58.51% in (Table 4**)**. Medium and fine sands are transported by saltation at 21.27% and suspension at 20.21% respectively.

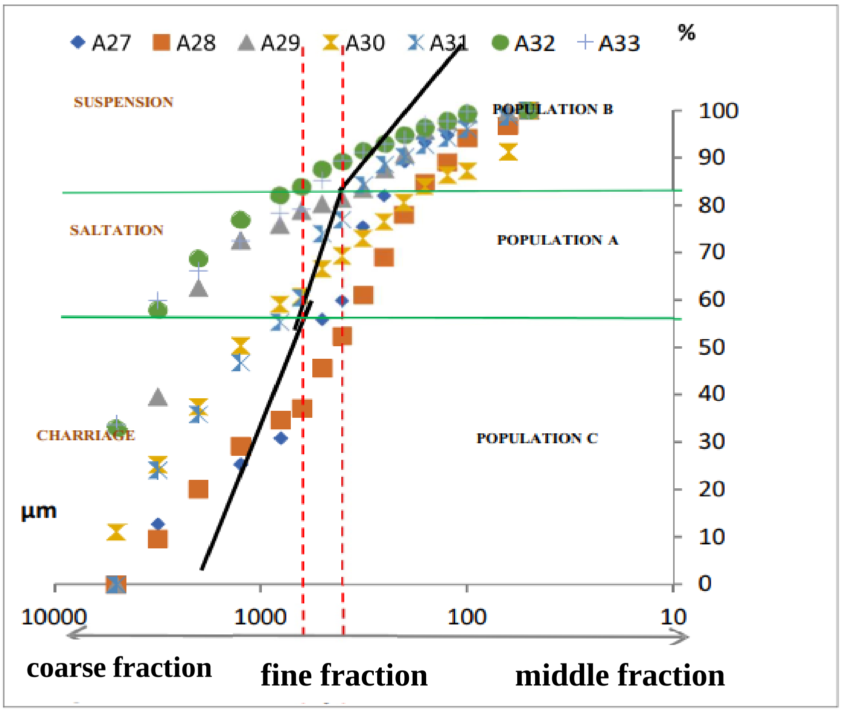

Figure 11: Visher diagram (1969) applied to well sediments

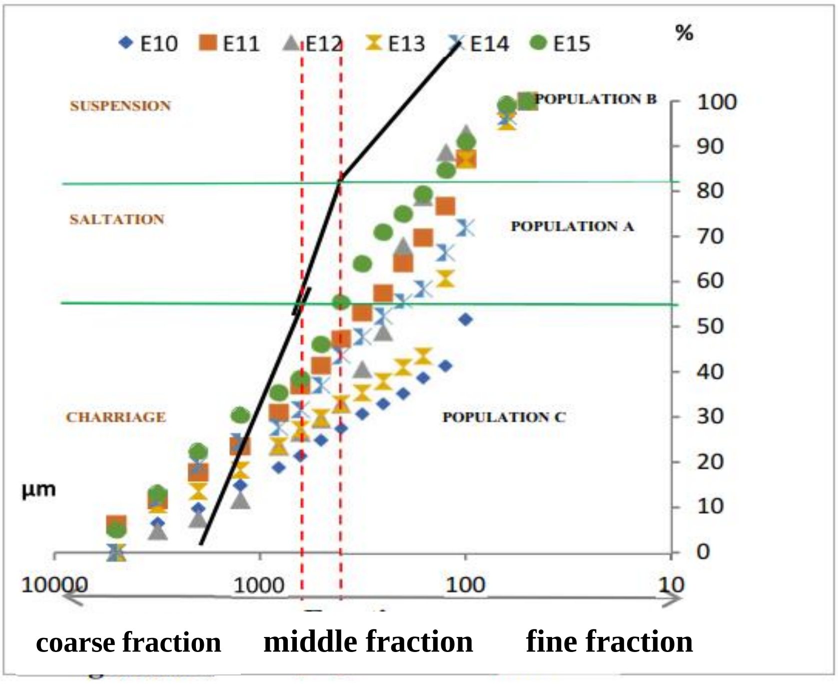

Figure 12: Visher diagram (1969) applied to cliff sediments

Table 3: Visher test statistics for Adima well sediments

ADIMA	POPULATION A	POPULATION B	POPULATION C
NUMBERS	18	65	22
PROPORTION (%)	17 ,14	61,9	20,95

Table 4: Eboco well visher test statistics

EBOCO	POPULATION A	POPULATION B	POPULATION C
NUMBERS	20	19	55
PROPORTION (%)	21,27	20,21	58,51

3.3.4. Depositional environments for sediments from the Adima well and the Eboco cliffs

The So/Md diagram shows 100% dispersion in the river domain and the Md/Ski diagram shows 60% dispersion in the continental dune domain for Adima sediments in (Figure 13**)**. The deposition environment is river and continental dune. The So/Md diagram shows 90% dispersion in the river domain and the Md/Ski diagram shows 80% dispersion in the continental dune domain for Eboco sediments in (Figure 14**)**. The deposition environment is therefore river and continental dune. In terms of grain size, the sand fraction as a whole shows very coarse, coarse, medium, fine and very fine sands overall, which implies that they were deposited with very high energy for the coarse fractions and low energy for the fine fractions. Sands are fairly well classified to very poorly classified in all the formations studied. The work of **(**Assalé *et al.*, 2013**)** shows that the classification reflects a granulometric mixture. This mixing is due either to a sudden drop in transport energy, or to the confluence of streams. The frequency curves identified in our work show four main modal patterns. These are unimodal, bimodal, trimodal and quatrimodal, reflecting one, two, three and four sources respectively. These results are in line with those identified by **(**Assalé *et al.*, 2013**)** in the eastern onshore basin of Côte d'Ivoire. The grain-size curves obtained show logarithmic and parabolic facies. The logarithmic facies, also defined by (Toe bi *et al.*, 2016), characterizes deposition by excess load as transport velocity decreases in calm environments. The condition of the surface (shiny blunt) and the shapes of the quartz grains in the Eboco sediments (sub-rounded to rounded) reveal that the sands in this borehole were transported by water far from their source, probably from the surrounding Birimian basement formations. In addition, the sub-angular appearance of the grains suggests that they were transported by suspension over short distances during flooding. Cracking, on the other hand, is the result of impact between grains during transport. These results are in line with those of N'zi *et al.*, 2018 in the western part of the Ivorian onshore sedimentary basin.

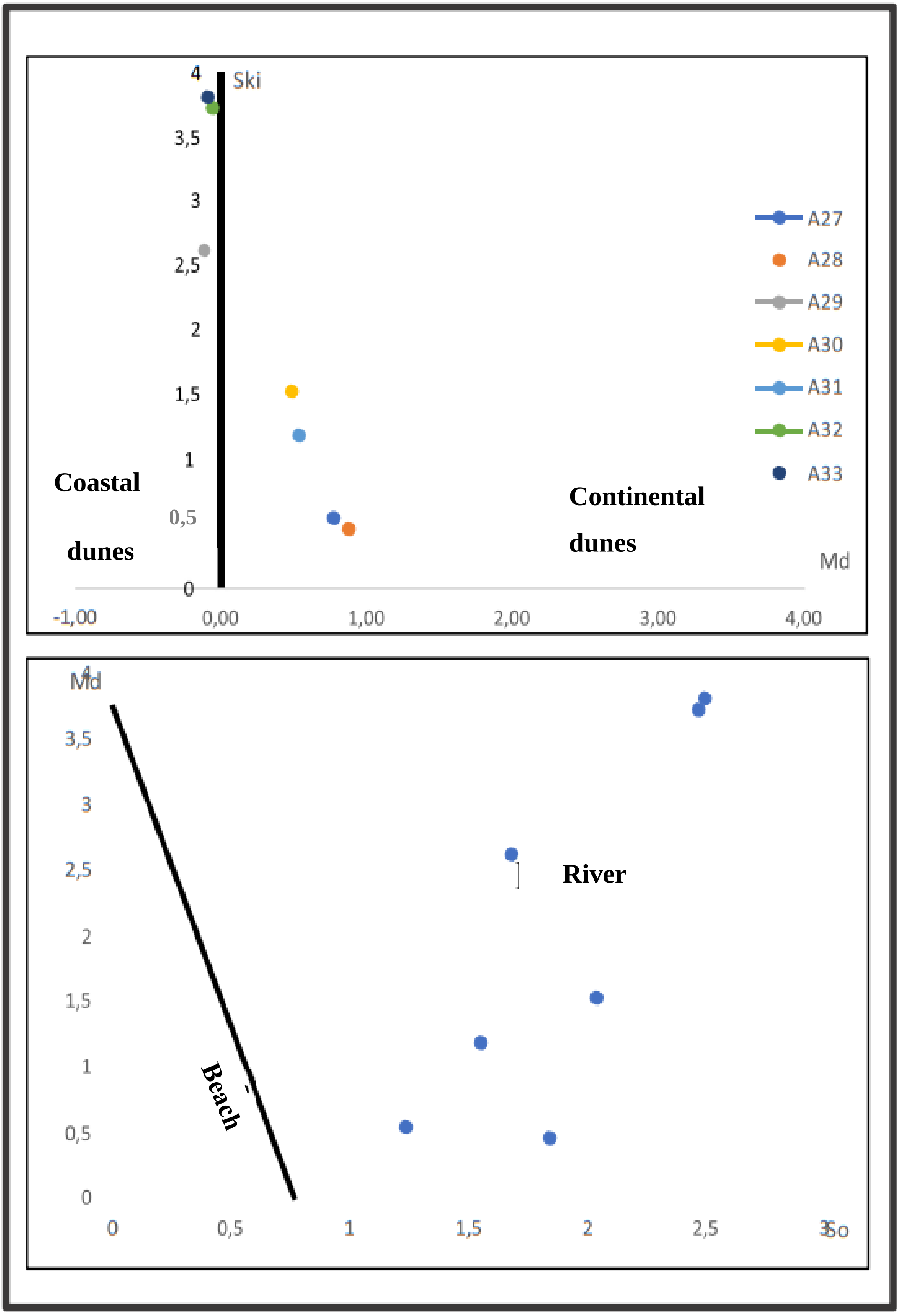

Figure 13: Md/SK and So/Md scatter plots for ADIMA well sands

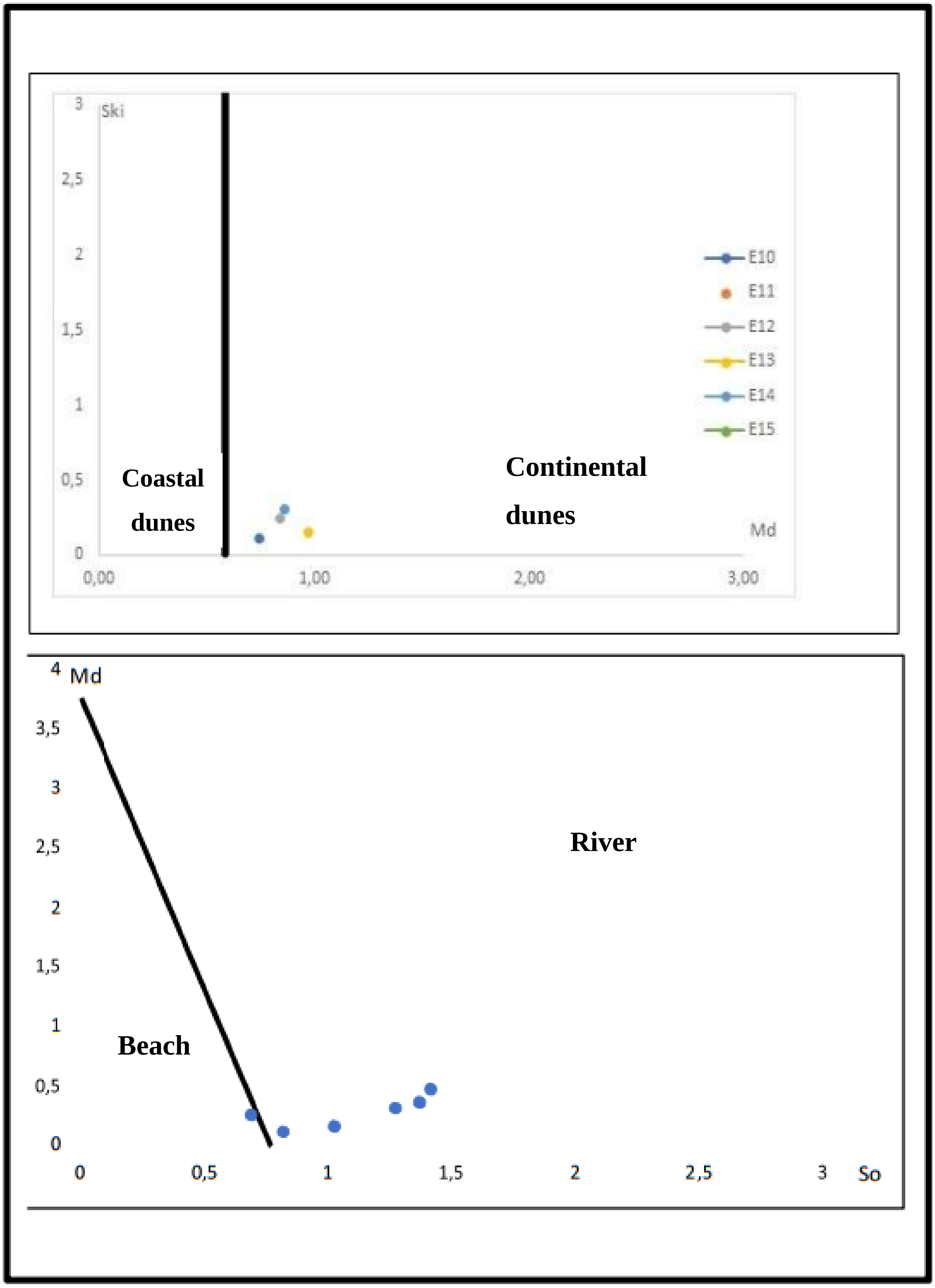

Figure 14: Md/SK and So/Md scatter plots for the Eboco cliffs

Conclusion

This study, carried out in the Tiapoum region, highlighted the lithology, morphoscopy, mineralogy, grain size and depositional environment of the Eboco cliff and Adima shaft formations. The lithological description identified a lithological facies composed of sandy clays with color variation and trace pyrite. The coloration is generally reddish-brown, and reddish-yellow in the shaft, due to the presence of iron oxides or iron hydroxides. On the cliff, the coloring is generally light reddish-gray, probably due to the presence of organic matter, and reddish-yellow, probably due to the presence of iron hydroxides or oxides.

The granulometric parameters of the sands show that the proportion of very coarse and very fine sands is abundant, in contrast to coarse, medium and fine sands. The sands are fairly well classified to very poorly classified, with symmetries and asymmetries towards coarse and fine. The particle size distribution curves for sands are logarithmic, reflecting deposition due to excess load following a decrease in deposition energy velocity, and parabolic, reflecting graded suspension transport for coarse sediments and uniform suspension for fine sediments. The frequency curves obtained are unimodal, reflecting a single source. Bimodal, trimodal and quatrimodal curves reflect a mixture of inputs from several provinces.

The dominant mode of sediment transport is graded suspension and bedding. Quartz grain morphoscopy shows that grains are predominantly rounded to subrounded in the Adima well, reflecting a distant source of sand generation. Those in the Eboco cliff are generally angular to subangular, reflecting a proximal source. The blunt, shiny appearance of these grains indicates that they were transported in a fluvial environment. The sediment deposition environment is river and continental dune, indicating a continental domain. Binocular observation of the samples identified minerals such as quartz, glauconite, pyrite, carbonaceous debris and iron hydroxide.

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