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Sediment Characteristics of an Impacted Coastal Bay: Baía de Guanabara, Rio de Janeiro, Brazil

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ABSTRACT

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Baía de Guanabara is one of the largest and most important bays of the Brazilian coastline. Over recent years coastal erosion problems have been registered there, mainly due to increasing urbanization and industrial development related to the oil and gas industry. This paper presents the results of an experimental program aimed at obtaining the rheological and sedimentation properties of the sediments that are on the pipeline routes in the bay. With this information it is possible to assist the municipality in reducing beach erosion and implementing sustainable measures for better coastal development. It was found that the sediments from Baía de Guanabara have sedimentation rates ranging from 0.63 to 13.25 cm/min. Solid content is relatively low, consistent with the fact that they are unconsolidated sediments. The particle size distribution of the sediments reflects the depth of the water column of Baía de Guanabara; the deeper the water column, the coarser the sediment. However, the sediment shows plasticity, suggesting the presence of organic matter derived from the 20 m^3s^{-1} raw sewage discharged into the bay. Fine sediments are found near shore; these are fluvial in origin or come from diffuse pollution sources. Their activity is high, indicating that it might be correlated to the presence of clay minerals. Regarding physical indices, it was found that the finer sediments have higher water contents and porosities but lower particle densities; total and dry. The coarser sediments present grains of spheroidal format, composed mainly of quartz, feldspar and amethyst.

ADDITIONAL INDEX WORDS: *Sediments, rheology, sedimentation properties, Baía de Guanabara.*

INTRODUCTION

Baía de Guanabara (Figure 1) is one of the largest on the Brazilian coast, with an area of approximately 384 km^2, 131 km of coastline and a mean water volume of 1.87 x 10^9 m^3 (Fonseca *et al.*, 2013). It is considered one of the most important bays in Brazil because of its increasing shipping activity, due not only to foreign and domestic trade but also to the oil & gas related activities which take place there. Supply vessels and tankers operate in Baía de Guanabara, delivering and collecting goods for oil rigs and platforms and carrying almost 20% of all Brazilian imported oil.

According to Kjerfve *et al.* (1997), the bay has a central channel with a depth of 30 m, though the authors of this paper found that the bay-averaged water depth is 5.7 m. The bottom sediments are mostly muds, a result of the Holocene transgression and rapid fluvial sedimentation, accelerated by the channelization of rivers and deforestation.

In spite of recent, intensive studies on the pollution of Baía de Guanabara (Azevedo *et al.*, 2004; Carrera *et al.*, 2002; Carrera *et al.*, 2004; Covelli *et al.*, 2012; Soares-Gomes *et al.*, 2010; Valquiria *et al.*, 2011), little data are available on the physical characteristics of its sediments (Amador, 1992; Amador and Ponzi, 1974; Kjerfve *et al.*, 1997; Quaresma, 1997).

Previous studies have generally shown that the bottom sediment distribution of the bay reflects the hydrodynamic forcing, indicated by the sand shoal, and also by sand waves, which exist along the eastern margin of the central channel between the 10- and 26-m isobaths, between Morro do Morcego and Gragoatá. According to Kjerfve *et al.* (1997), the system exhibits waves with heights of between 2.5 and 0.5 m and a wavelength of 98 to 18 m, decreasing in height and wavelength inland, in response to decreasing energy, which in turn explains the progressive increase in mud deposition further into the bay.

The authors of this work also noted the occurrence of extensive mud deposits that cover the interior parts of the bay as a result of active transport of fluvial clastic materials to the bay, accelerated by anthropogenic activities in the drainage basin.

Due to increasing urban and industrial occupation related to the oil & gas industry, Ilha do Governador, the largest island in Baía de Guanabara, has experienced coastal erosion problems over the last few decades (Figure 2). Part of these problems is related to the construction and assemblage of pipelines. Seven pipelines cut across Ilha do Governador coming from Ilha D'Água, the main Oil Terminal in Baía de Guanabara, towards Duque de Caxias Refinery (REDUC).

The paper studies the rheological and sedimentation properties of the sediments that are on the pipeline routes in Baía de Guanabara in order to assist the Municipality in

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minimizing beach erosion problems and implementing sustainable measures to aid in coastal development.

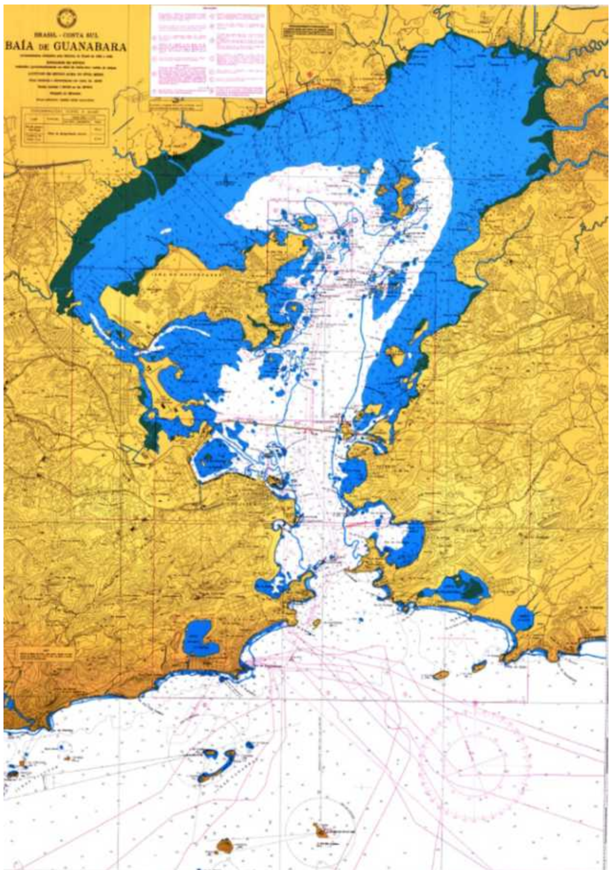

Figure 1. Nautical Chart (#1501) of Baía de Guanabara from the Brazilian Navy.

Figure 2. Example of coastal erosion/slope stability problems in Ilha do Governador.

METHODOLOGY

Sediments were collected along the pipeline routes, indicated by the red lines on Figure 3. The locations of the sampling stations are shown by the yellow hashtags in Figure 3, and their nautical coordinates in Table 1.

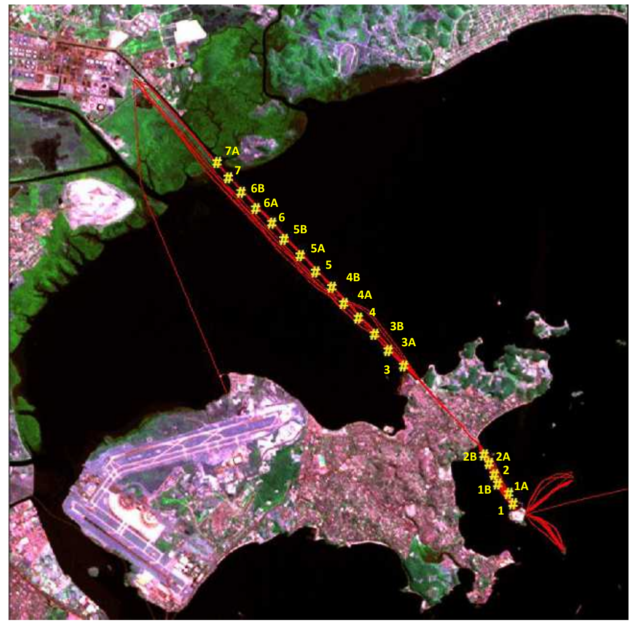

Figure 3. Sediment sampling stations.

Table1. *Sampling stations coordinates.*

Sampling Station	Latitude (S gg^{0}mm.mmm´)	Longitude (W gg^{0}mm.mmm´)
1	$22^0$48.600´	$43^0$09.848´
1A	$22^0$48.475´	$43^0$09.906´
1B	$22^0$48.363´	$43^0$10.058´
2	$22^0$48.238´	$43^0$10.100´
2A	$22^0$48.100´	$43^0$10.175´
2B	$22^0$48.000´	$43^0$10.252´
3	$22^0$46.900´	$43^0$11.343´
3A	$22^0$46.700´	$43^0$11.558´
3B	$22^0$46.500´	$43^0$11.745´
4	$22^0$46.300´	$43^0$11.972´
4A	$22^0$46.125´	$43^0$12.166´
4B	$22^0$45.925´	$43^0$12.329´
5	$22^0$45.725´	$43^0$12.549´
5A	$22^0$45.525´	$43^0$12.758´
5B	$22^0$45.325´	$43^0$12.986´
6	$22^0$45.125´	$43^0$13.149´
6A	$22^0$44.950´	$43^0$13.371´
6B	$22^0$44.750´	$43^0$13.574´
7	$22^0$44.562´	$43^0$13.751´
7A	$22^0$44.375´	$43^0$13.898´

A piston corer fitted with a PVC tube of 100 cm length and 3.6 cm internal diameter was used for the sampling. Six cores were collected at each sampling station. The sediments were put in a plastic bucket and a thin PVC film was placed on top of it, in order to minimize moisture loss during their transport to the laboratory.

Sedimentation Properties

The sedimentation properties were assessed through the determination of particle density and the hydrometer sedimentation test.

Particle density is defined as the average density of the solid particles which make up a sediment mass. According to Head (2006), the term particle density replaced specific gravity to comply with international use in ISO Standards. Particle density was determined through the use of the small pyknometer method using the procedure established in BS1377 (1990).

Hydrometer tests were carried out using a system designed and built at Pontifical Catholic University of Rio de Janeiro (PUC-Rio). This system, seen in Figure 4, consists of six Perspex tubes, of 1100 m height and 60 mm internal diameter. Each tube has a metal ruler with 0.5 mm resolution, as can be seen in Figure 5. In order to transfer the suspension with minimal disturbance, a valve was installed on the wall of the tube.

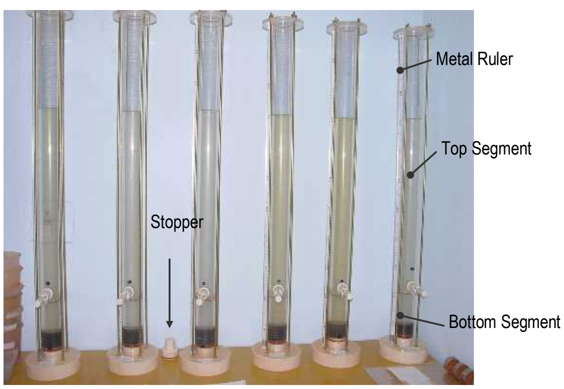

Figure 4. Sedimentation test system.

The test specimen is obtained from the air-dried original sample by riffling, using the fraction that passes a 2 mm sieve. Next, 100 g of dry sediments were mixed with 500 g of sea water and allowed to mix for 24 h.

Sedimentation columns were prepared using 100 g dry soil to 2 L of seawater, *i.e.* the initial solids of each mixture, TS = Ms/Mt (where Ms = mass of solids and Mt = total mass of the mixture) was maintained at about 4.8%. After homogenizing each mixture, each column was stirred up, using a circular motion for about 1 minute, monitoring the descent of the suspended sediment interface over time. The definition of each interface was not always clear to the naked eye, so a common flashlight was used.

At the end of each test, subsamples of supernatant and sedimented solids were collected for evaluation of the total suspended solids content of sedimented solids in each tube.

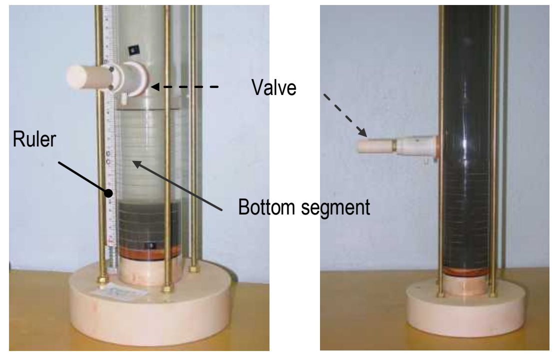

Figure 5. Details of the sedimentation test system.

Rheological Properties

The rheological properties were determined from the results of particle size distribution, moisture content, liquid and plastic limit tests. All tests were carried out following the procedures established in BS1377 (1990). In addition, the shape of the sediments was determined through the use of a binocular microscope.

RESULTS

Sedimentation properties of the collected samples were determined from the results of particle density and hydrometer tests. Table 2 presents the particle density results obtained (G_s).

Table 2. *Particle density.*

Sampling Station	Gs	Sampling Station	Gs
1	2,726	4A	2,767
1A	2,688	4B	2,787
1B	2,746	5	2,743
2	2,671	5A	2,704
2A	2,703	5B	2,589
2B	2,646	6	2,798
3	2,664	6A	2,748
3A	2,676	6B	2,716
3B	2,644	7	2,564
4	2,736	7A	2,587

Whereas the particle density value of the grains is indicative of the sediment mineralogy (*e.g*., Lambe and Whitman, 1969), the results shown in Table 2 suggests that there is a marked variation in the predominant types of minerals deposited at different points along the pipelines indicating the potential presence of organic matter in the sediment. Such observations are not unexpected, considering that materials with different geological origins are transported to Baía de Guanabara by the various rivers that discharge into it, and that sampling stations 7 and 7A are situated in a mangrove area.

Sedimentation tests, involving the determination of clarification time of the supernatant were performed using a system of sedimentation and experimental methodology developed at PUC-Rio.

Clarifying times and sedimentation velocities, as well as the moisture content and the total solids of the sedimented material and total solids remaining in the supernatant, obtained from the results of the tests of sedimentation/clarification executed, are presented in Table 3.

Table 3. *Clarifying time and sedimentation velocity.*

Sample	Clarifying Time (min)	(h)	Sedimentation Velocity (cm/min)	Sedimented Material W(%)	TS(%)	Supernatant TSS (%)
1	37.5	0.625	1.87	78.62	55.98	3.07
1A	43.0	0.767	1.78	80.54	55.39	3.35
1B	45.0	0.750	1.67	80.85	55.30	3.19
2	46.5	0.775	1.72	88.76	52.98	3.40
2A	45.5	0.758	1.74	80.82	55.30	3.24
2B	10.0	0.167	13.2	86.94	53.49	3.37
3	101	1.692	0.63	120.1	45.43	3.98
3A	81.0	1.650	0.78	114.2	46.68	3.21
3B	77.5	1.292	0.81	112.0	47.16	3.28
4	80.0	1.333	0.81	102.9	49.27	2.91
4A	78.0	1.300	0.81	117.0	46.08	2.76
4B	77.5	1.292	0.82	131.2	43.24	2.70
5	64.5	1.075	0.99	139.3	41.78	3.71
5A	61.5	1.025	1.07	138.8	47.87	11.2
5B	54.0	0.900	1.35	103.1	49.24	3.81
6	82.0	1.367	0.78	124.4	44.55	4.10
6A	79.0	1.371	0.83	121.1	45.23	4.17
6B	113	1.883	0.57	121.8	45.07	2.69
7	28.0	1.467	2.52	134.5	42.63	2.58
7A	62.5	1.042	1.16	127.6	43.92	2.68

The clarifying times and sedimentation velocities indicated in this table were determined in accordance with the graphical procedure described in Figure 6.

The water content (w) and total solids (TS) of the sedimented material were obtained by the gravimetric method (*i.e.* oven drying at 110 °C). The total solids in suspension (TSS) were also determined by the gravimetric method from the supernatant samples collected after the test.

As shown in Table 3, the clarifying time for all sediment samples is less than 2 h, that is, the material settles relatively quickly at all the points investigated, with a sedimentation rate ranging from 0.63 to 13.25 cm/min. The solids contents are relatively low, consistent with the fact that the samples were obtained from unconsolidated sediments.

The rheological properties were determined from the results of particle size distribution, moisture content, liquid and plastic limit tests. The results are presented in Table 4. As can be seen, the particle size distribution of the sediments reflects the depth of the water column of Baía de Guanabara. In the white areas of Figure 1, the coarse fraction (*i.e.* gravel and sand) predominates whereas in the blue areas in Figure 1, the fine fraction (*i.e.* silt and clay) predominates.

The results also show that even in the sediments where the coarse fraction predominates, they present some plasticity. This might well indicate the presence of organic matter from anthropogenic sources. This fact is based upon the fact that Baía de Guanabara receives *circa* 20 m^3s^{-1} of raw sewage, as Carrera *et al.* (2004) pointed out, and those present no activity (I_A) as Table 4 shows.

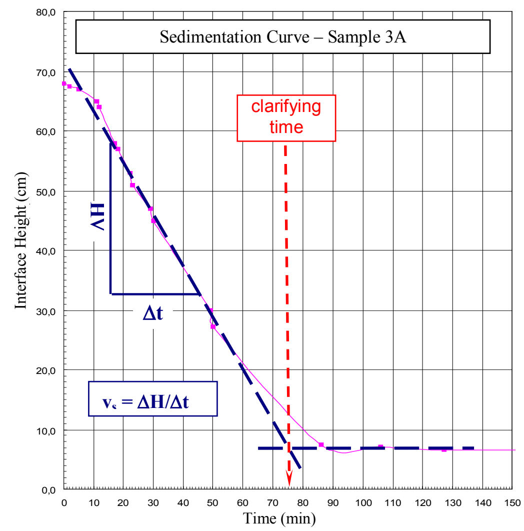

Figure 6. Procedure for the determination of clarifying time and sedimentation velocity.

Table 4. *Rheological Properties.*

Sample	Atterberg Limits (%) W_L	W_P	PI	Grain Size Distribution (%) Gravel	Sand	Silt	Clay	IA
1	32.6	23.4	12.9	-	57	32	11	-
1A	38.0	24.0	13.9	-	54	35	11	-
1B	41.1	25.1	16.1	-	51	37	12	-
2	44.0	23.4	20.6	-	51	36	13	-
2A	38.7	22.6	16.1	2	65	20	13	-
2B	Non Plastic			1	87	7	5	-
3	71.5	35.2	36.2	-	15	56	29	-
3A	66.0	35.6	30.5	-	10	39	51	-
3B	62.0	40.5	21.5	-	10	39	51	-
4	80.7	43.9	36.8	-	6	44	50	-
4A	76.5	44.0	32.5	-	6	40	54	-
4B	92.9	50.1	42.8	-	3	40	57	0.75
5	96.6	44.3	52.3	-	3	44	53	0.99
5A	72.6	47.5	25.1	-	4	42	54	0.47
5B	55.4	41.9	13.5	-	3	48	49	0.28
6	78.9	50.2	28.7	-	5	43	52	0.55
6A	67.7	42.0	25.7	-	10	43	47	0.55
6B	57.2	30.9	26.3	-	24	38	38	0.69
7	81.5	54.9	26.6	-	5	37	58	0.46
7A	78.3	59.3	19.0	-	3	40	57	0.33

Gravel: $\emptyset > 2\ mm$ Gravel: $0.002\ mm < \emptyset < 0.06\ mm$
Sand: $0.06\ mm < \emptyset < 2\ mm$ Clay: $\emptyset < 0.002\ mm$
W_p: Plastic Limit W_L: Liquid Limit
PI: Plasticity Index

The samples that were collected in the blue area in Figure 1 have a higher percentage of fine sediment. These samples were collected close to the mouths of the contributing rivers as well as raw sewage discharge sources. However, as Table 4 shows, the activity observed in these samples is considerable and this could be correlated with the clay minerals present in their constitution.

Table 5 shows the values of natural moisture levels (W_n) of the sediment collected, as well as an estimate of their natural physical indices. The calculations presented in Table 5 assumed that the sediments are saturated by sea water and that this water features, at all collection points, a specific mass (ρ_f) of 1.05 Mg/m^3.

Table 5. *Physical indices.*

Sample	Wp (%)	Gs	ρ_f (Mg/m^3)	S (%)	e	n (%)	ρ_t (Mg/m^3)	ρ_d (Mg/m^3)
1	78.66	2.721	1.05	100	2.14	68.2	1.63	0.91
1A	70.23	2.683	1.05	100	1.89	65.4	1.66	0.98
1B	74.12	2.741	1.05	100	2.04	67.1	1.65	0.95
2	84.14	2.667	1.05	100	2.25	69.2	1.59	0.86
2A	48.73	2.700	1.05	100	1.32	56.8	1.82	1.22
2B	37.91	2.641	1.05	100	1.00	50.1	1.91	1.39
3	154.0	2.659	1.05	100	4.10	80.4	1.39	0.55
3A	147.8	2.791	1.05	100	3.96	79.8	1.41	0.57
3B	159.2	2.640	1.05	100	4.21	80.8	1.38	0.53
4	146.4	2.730	1.05	100	4.01	80.0	1.41	0.57
4A	162.8	2.762	1.05	100	4.51	81.8	1.39	0.53
4B	183.4	2.782	1.05	100	5.11	83.6	1.36	0.48
5	192.2	2.738	1.05	100	5.27	84.1	1.34	0.46
5A	198.5	2.699	1.05	100	5.13	83.7	1.34	0.46
5B	201.1	2.585	1.05	100	5.21	83.9	1.32	0.44
6	191.8	2.792	1.05	100	5.37	84.3	1.35	0.46
6A	162.3	2.743	1.05	100	4.46	81.7	1.39	0.53
6B	131.1	2.711	1.05	100	3.53	78.1	1.44	0.63
7	220.7	2.560	1.05	100	5.66	85.0	1.30	0.40
7A	229.5	2.582	1.05	100	5.94	85.6	1.29	0.39

The following expressions were used for the calculation of the void content, e = Vv/Vs; porosity, n = Vv/Vt; total density, ρ_t = Mt/Vt and dry density ρ_d = Ms/Vt, where V, Vs and Vt correspond, respectively, to the volume of voids, solids and total; and Mt and Ms correspond, respectively, to the total mass and mass of solids:

$$e = \frac{G_s w}{S} \tag{1}$$

$$n = \frac{e}{(1+e)} \tag{2}$$

$$\rho_t = \frac{[(1+w)G_s \rho_w]}{(1+e)} \tag{3}$$

$$\rho_d = \frac{\rho_t}{(1+w)} \tag{4}$$

where G_s is the particle density, w is the natural moisture content and S is the degree of saturation.

The results presented in Table 5 clearly show a higher water content and porosity in the sediments that present a higher percentage of fines (*i.e.* silt and clay). On the other hand, the particle density of these sediments was lower in comparison to those with coarser sediment, as well as their total and dry density. This suggests the presence of organic matter in these sediments, probably originating from raw sewage discharges.

Figure 7 shows photographs, obtained from a binocular microscope, of the coarse fraction of the sediments. The sand fraction of all the sediment samples is essentially grains with spheroidal format. They are mainly composed of quartz, feldspar and amethyst. The photographs also show the presence of calcareous shells in the form of plates of various sizes.

CONCLUSIONS

The unconsolidated sediments from Baía de Guanabara have a sedimentation rate ranging from 0.63 to 13.25 cm/min. Their particle size distribution reflects the depth of the water column of Baía de Guanabara; the deeper the water column the coarser the sediment. It was found that these coarse sediments present some plasticity, suggesting the presence of organic matter derived from the discharge of raw sewage based upon the fact that Baía de Guanabara receives c.20 m^3s^{-1} of raw sewage.

Fine sediments are found near shore, originating from the discharges of the contributing rivers as well as diffuse pollution sources. Their activity is high, indicating that it might be correlated to the clay minerals presented in their constitution.

When physical indices are of concern, it was found that fine sediments present higher water content and porosity but a lower particle density, total and dry densities when compared to coarse sediments.

Regarding sediment mineralogy, it was observed that the sand fraction consists essentially of grains with spheroidal format, composed mainly by quartz, feldspar and amethyst. It was also found calcareous shells in the form of plates of various sizes.

The results of this study show that sediments coming from Southeastern part of Ilha do Governador have a higher density than those from Northwestern part. While the former present activity and could well be excavated for any engineering purpose using conventional equipment, any excavation in the Southeastern part should be performed by specialist dredging devices.

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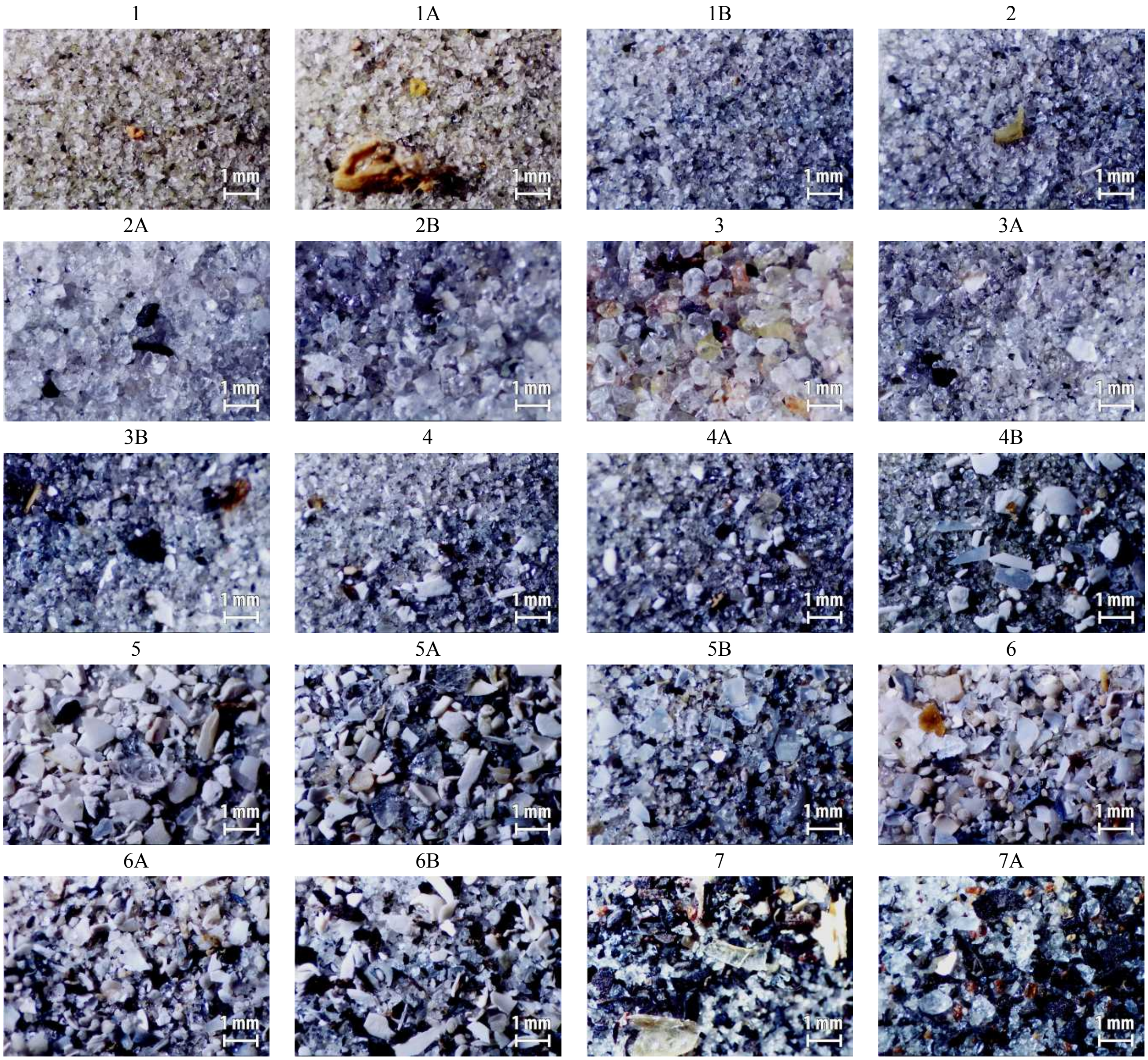

Figure 7. Coarse fraction of sediments.

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