

MERCURY CONCENTRATIONS IN SEDIMENT PROFILES OF A DEGRADED TROPICAL COASTAL ENVIRONMENT

Julio Cesar WASSERMAN^{1*}, Ana Paula FREITAS-PINTO¹, David AMOUROUX²

¹ Departamento de Geoquímica, Universidade Federal Fluminense

Outeiro de São João Batista s/n°, Centro Niterói, RJ, 24020-007, Brazil. E-mail: geowass@vm.uff.br

² Laboratoire de Chimie Analytique, Bio-Inorganique et Environnement

CNRS EP 132. 2, Av du Président Angot, 64000, Pau, France.

* To whom correspondence should be addressed.

ABSTRACT

The present and past degrees of contamination by mercury were evaluated in the Guanabara Bay by the study of five sediment cores. The cores were sampled from the deltaic mouth of the São João de Meriti River (cores SJ1, SJ2, SJ3, and SJ4), adjacent to a large mangrove stand and in a mangrove stand in Guapimirim (opposite side of the bay). The study area receives most of the domestic and industrial wastes from the metropolitan region of Rio de Janeiro city and, in consequence it becomes increasingly degraded. Among the sources of pollutants, mercury-spilling industries are inventoried in the São João de Meriti River basin. Total mercury concentrations were measured in the sediments by cold vapour atomic absorption spectrometry. The fraction smaller than 63 μm , organic carbon and total sulphur concentrations were also measured. The results show that concentrations of mercury can reach high values (up to 37 $\mu\text{g g}^{-1}$ at a depth of 34 cm in the core SJ4). The base of core SJ1 shows mercury concentrations that probably represent background values, as established elsewhere for the Guanabara Bay (51 ng g^{-1} at the depth of 32 cm). Among the studied cores, only core SJ1 seems to reach background levels.

KEYWORDS: mercury, sediments, estuaries, tropical ecosystem, Guanabara Bay

INTRODUCTION

Sediments from embayments, estuaries and other protected areas of the coastal environment have shown to be crucial compartments for mercury storage [1-4], and transformation [5-8]. In these areas, the lack of hydrodynamic movements favours the development of sediment deposits that are characterised by fine grain size, negative redox potential and high organic matter contents, parameters that highly affect mercury chemistry [1, 9, 10].

A number of coastal and marine environments have been subject to studies on mercury concentrations in sediment profiles [*e.g.*: 11-14]. Some of these works have shown that sediment profiles can be a reliable record of the history of natural [12] and anthropogenic [13] inputs of this pollutant. The lack of strong hydrodynamics and the proximity of a significant anthropogenic sources are crucial factors

that provide focusing of the contaminant and thereby, good historical cores. Furthermore, the more significant are the anthropogenic inputs, the more marked is going to be the differences between the background levels (found in the basis of the profile) and the present contamination [15]. In the tropics, the protected coastal environments are the most favourable sites for the development of mangrove vegetation, where depositional conditions prevails over erosional [16]. Under such conditions, mangrove sediments are going to be a major compartment for metals accumulation [17], where the study of sediment profiles can provide meaningful hints for the understanding of the processes of contamination and cycling of mercury.

In the Brazilian mangroves and coastal environments, studies on mercury contamination are restricted to the metal distribution in sediments and some monitoring programmes [18-24]. Some recent studies have attempted different approaches, assessing the geochemical partitioning and speciation of mercury in mangrove areas [4, 10, 14, 25], underlining the particular behaviour of this metal.

In the present work, the behaviour of mercury in sediment profiles was studied as a function of sedimentary conditions that are outlined by granulometry, carbon and sulphur contents. A comparison between a very degraded site and a mildly degraded one was also performed in order to distinguish levels and behaviour of mercury under both conditions.

STUDY AREA

Guanabara Bay (Figure 1) is a tropical ecosystem adjacent to Rio de Janeiro city. It is one of the largest bay in Brazil, covering an area of 381 km². Its watershed area is more than 4,000 km², where 7 million people live. Its mean depth is 7.7 m, with a maximum depth of 50 m at the entrance of the bay. Some 80% of its area have a depth below 10 m. The residence time estimated for Guanabara Bay waters is 20 days [26, 27].

A number of rivers and channels flow into the bay, forming many sub-basins. The water quality data of the majority of these rivers show a critical situation, especially those located on the northwest coast [28]. Although the continental water volume is small when compared to the inputs of marine waters (mean salinity is between 21 and 30), the mean load of material transported by the rivers is 2×10^5 ton year⁻¹ and of variable nature [22, 26].

About 7,000 industries are installed in Guanabara Bay watershed. They are responsible for 25% of the organic pollution and almost all of the toxic substances and heavy metals released. It is estimated that 22 kg of cyanides, 4,200 kg of phenols, 1,800 kg of sulphides and 4,800 kg of heavy metals are dumped every day by industrial effluents [22, 28].

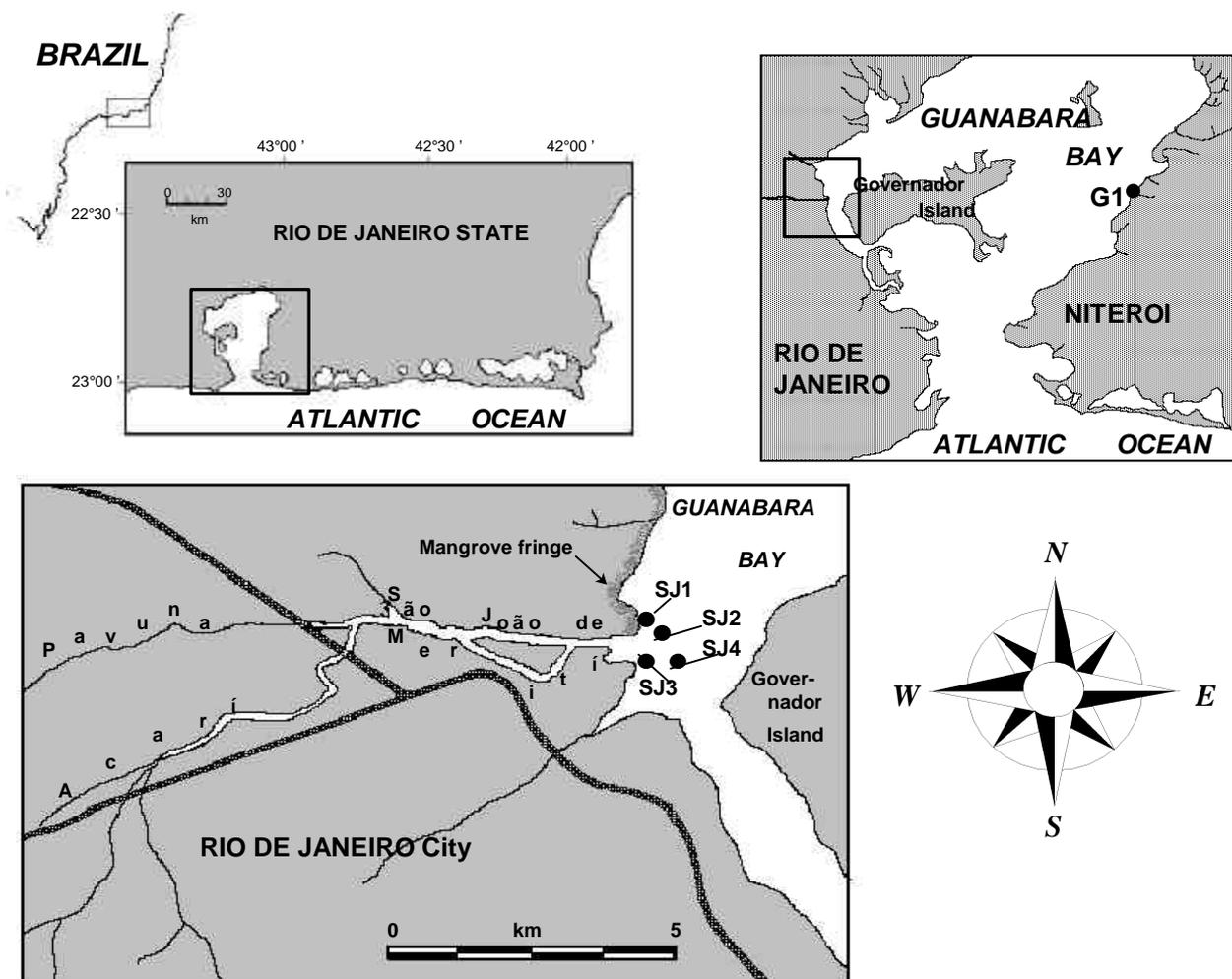


Figure 1 : Guanabara Bay map and core sampling site location.

São João de Merití River is one of the most polluted, and the main source of mercury for the bay. The highest concentrations of mercury in Guanabara Bay watershed were observed in this river estuary [4, 18, 26, 29, 30]. These high concentrations are originated in a chlor-alkali plant installed in its sub-basin. According to estimates from [28], this plant had released 1.46 ton of mercury during the year of 1975. Later, in 1979, the installation of an effluent treatment system reduced the annual mercury loads to 20 kg [28]. Nevertheless, in a more recent survey, [30] estimated that São João de Merití River still furnishes 160 kg Hg year⁻¹ for Guanabara Bay.

Yet the Guanabara bay can be considered a mercury polluted environment, no studies concerning the effects of this metal on human populations has ever been carried out. This gap can be attributed to the fact that although millions of people live in the surroundings of the bay, probably there are no communities living exclusively from the natural resources of the bay. On the other hand studies with various organisms (crab, mussels and fishes; [31] show that yet environmental concentrations can reach high values, only fish species highly placed in the trophic chain, are able to accumulate mercury [31]. Mercury present in the sediments and waters of Guanabara Bay is probably tightly bound to organic matter, and therefore, not available to the organisms.

MATERIAL AND METHODS

Sampling and Storage

Four sediment cores were sampled from the estuary of the São João de Merití River (Figure 1). SJ1 was collected in the tidal flat some 10 m from a large mangrove fringe. SJ2, SJ3 and SJ4 were collected farther from the mangrove but still in the tidal flat. SJ1 and SJ2 are located on the Northern side of the estuary, where mangrove stands still subsist while SJ3 and SJ4 are located in the Southern side of the estuary. Due to the massive inputs of organic matter (mainly domestic sewage) from the São João de Merití River, and the lack of strong tidal currents, the sediments in this region are muddy, completely black along the profile (the profiles never become grey with the depth) and release a strong sulphide odour. Another core (G1) was sampled in the Guapimirim mangrove within the mangrove trees. The Guapimirim mangrove, although located in the Guanabara Bay, is a less degraded environment with considerably smaller inputs of sewage and other contaminants. This core presented a very fine grained granulometry, and was black in the surface, becoming grey with the depth, a strong sulphide odour could be smelled during sampling, indicating a reducing environment.

Core samples were immediately sliced every 1 cm until 10 cm with a PVC spatula. Below this layer, the sediment cores were then sliced every 2 cm or 5 cm depending on the core. Split cores were stored in ice boxes (~ 4°C) and immediately transported to the laboratory where they were frozen (-20°C). Within 2 days, a portion of each sample was placed in a ventilated oven at very mild temperature (max. 40°C, the same temperature that sediments are frequently exposed in Rio de Janeiro) for three days. Dried samples were then finely ground and stored in hermetic plastic bags until analyses. The remaining frozen portion of the sample was stored for granulometric measurements.

Analytical

Total mercury: This method, formerly applied by [32] is an adaptation that was applied by [33].

1 g of dried sediment sample was extracted with 5 mL of HCl + HNO₃ (3:1) and 5 mL of bi-distilled water for 5 minutes in a water bath at 60°C. The reaction flask was cooled down and 15 mL of K₂MnO₄ (5%) were added to the extract and again heated in a water bath for 30 minutes. This procedure is supposed to oxidise all the mercury present in the sample to Hg⁺². The extracted samples were in line reduced with stannous chloride to its volatile form Hg⁰ and quantitatively measurements by cold vapour atomic absorption spectrometry. The detection limit was 5.5 ng Hg in the reaction flask (the sample volume used was generally 10 mL), corresponding to a concentration of approximately 40 ng Hg g⁻¹ dried sample.

Accuracy and precision of the analysis were verified by an intercalibration exercise with another laboratory (IPEN-SP) that uses neutron activation analysis [34], showing errors never greater than 7%.

Accessory measurements: Silt-clay fraction (<63µm) was measured by wet sieving.

Total sulphur was analysed in an elemental analyser LECO CS244, where the sample is combusted at 1370°C converting sulphur to sulphate that is measured with an infra-red detector [35].

Total carbon as CO₂ was analysed in an elemental analyser Carlo Erba NA-1500, after combustion at 1020°C. Inorganic carbon was measured by conductimetry in a Westhoff Carmograph and organic carbon was calculated deducting inorganic carbon from total carbon [36]. Inorganic carbon analyses gave systematically below detection level concentrations, so, in the discussion total carbon corresponds to organic carbon.

RESULTS

Comparison with Literature Data

The previous works in the Guanabara Bay of [10, 18, 26, 30, 37, 38], reviewed by [39] show mercury concentrations in sediments ranging between 50 ng g⁻¹ and a maximum of 19,500 ng g⁻¹. Table 1 is a summary comparison between ranges of concentrations reported in the literature and in the present work. When comparing with other works done in Guanabara Bay, it can be observed that the results obtained in this work presented the broadest range of mercury concentrations. This is due, on the one hand to the very low concentrations obtained in the lower layers of the core SJ1, confirming the background values of the bay to be around 50 ng g⁻¹ [37], and on the other hand to the very high values measured in the core SJ4 (up to 37,200 ng g⁻¹) at depths between 20 and 50 cm, that represent the highest concentrations ever measured in Guanabara Bay.

The comparison of the concentrations in the surface layers shown in Figures 2-6 confirms the previously reported range between 1,000 and 3,000 ng g⁻¹ [4], except for core SJ4, where the concentrations in the surface layer reach 11,100 ng g⁻¹ and the whole core do not present concentrations lower than 1,500 ng g⁻¹.

Yet the core G1 is located in Guanabara Bay system, its concentrations are considerably lower, and although the background levels as established above could not be reached (179 ng g⁻¹ in the deeper layer), the range is narrow and varies between 125-219 ng g⁻¹. The comparison between one side and the other of the bay, confirms the more contaminated character of the western part of the bay as stated in the study area section above.

[10] justifies such a significant mercury accumulation in the São João de Merití River as a result of the presence of a chlor-alkali plant and a leather tanning industry upstream in this river, but also as a result of hydrographic conditions that considerably reduces the dispersion of the mercury bearing suspended particles.

Table 1: Comparison of literature concentrations of mercury in Guanabara Bay and other environments.

Site	Range (ng g ⁻¹)	Author
Aveiro lagoon (Portugal)	320 – 343,000	[13]
Santa Gilla lagoon (Italy)	60 – 828,000	[40]
Rivers and estuaries in Guanabara Bay	210 – 19,450	[18]
Numerous rivers and sediments of the Guanabara Bay	50 – 12,070	[29]
Guanabara Bay sediments and two polluted rivers	80 – 9,780	[26]
Two polluted rivers from Guanabara Bay	4,000 – 4,600	[30]
São João de Merití River and estuary	320 – 3,380	[4]
Average shale	400	[41]
Sediment cores from São João de Merití River	51 – 37,200	This study
Sediment core from Guapimirim	125 – 219	This study

The mercury concentrations in the sediment profiles SJ3 (max. 11,050 ng g⁻¹) and SJ4 (max. 37,200 ng g⁻¹) are significantly higher than in SJ1 and SJ2. This point has to be discussed on the light of the hydrodynamic processes occurring in the São João de Merití estuary [42]. This author established that two directions of currents occur in the mouth of the river as a function of tides (Figure 2). During flood tide, when input of suspended matter originated from the river is reduced, the current runs to the north (direction of the cores SJ1 and SJ2), therefore increasing mixture with marine born less contaminated particles. During ebb tide, when the loads of riverine, and more contaminated suspended matter are considerably increased, the direction of the current is southward (direction of the cores SJ3 and SJ4), therefore explaining why these last two cores present higher concentrations. The control of metal concentrations in sediments by hydrodynamic processes is also observed in the neighbouring bay of Sepetiba, Brazil [43, 44].

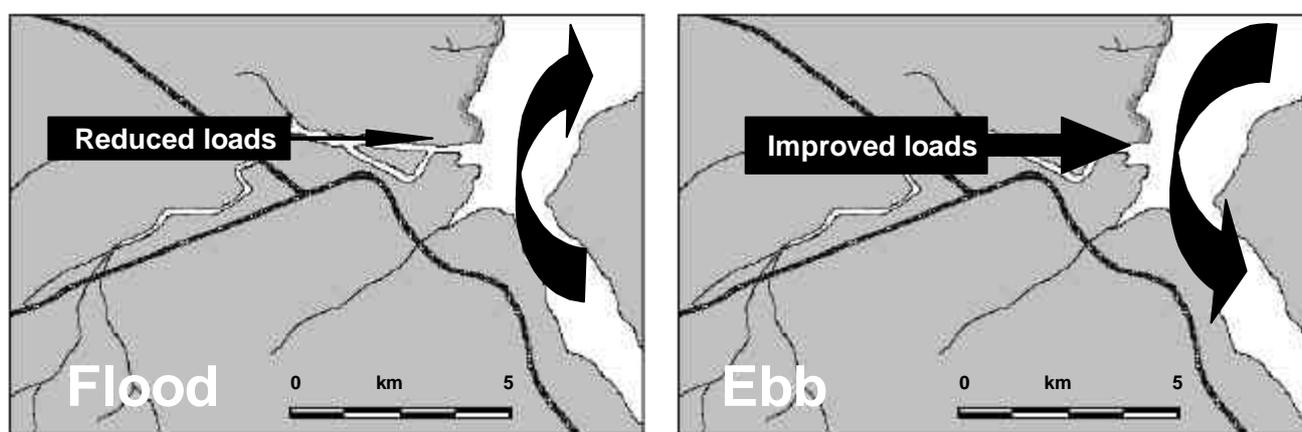


Figure 2: Hydrodynamic movements in the São João de Merití estuary.

Sediment Profiles

Figures 3 to 7 show the concentrations of mercury and the other measured parameters. Although five core samples were studied, only core SJ1 seems depositional, showing a slight increase from the surface to the depth of 3 cm where the maximum concentration is reached. Beneath the third centimetre, concentrations start to fall until the tenth centimetre where natural concentrations are reached. On the other hand ^{210}Pb dating in the São João de Merití River sediments [37], indicate a maximum of contamination at between 12 and 15 cm, corresponding to the years 1969 and 1973. Although the observed reduction in surface concentrations should be attributed to a reduction in mercury disposal, Rego et al. [30] made a mass balance of the mercury loads in the waters of the São João de Merití River and established that around 160 kg mercury are still dumped every year in this river.

As shown in Figure 3, granulometry seems to have little influence on the mercury concentrations in the core SJ1 (Spearman correlation coefficient $r=0.4124$, $n=25$, $p>0.02$). This is probably due to the fact that the samples are all very fine grained ($> 80\%$ silt-clay) and little difference is observed between the layers. On the other hand total carbon and total sulphur present a very good correlation coefficient with mercury ($r=0.9400$, $n=25$, $p<0.01$, $r=0.8731$, $n=25$, $p<0.01$ respectively) indicating that these three variables are controlled by the same factor (anthropogenic inputs). In another work with surface sediments from the São João de Merití River, [4] observed a very poor correlation between mercury and total sulphur, but good relationship between this metal and total carbon. Their results were confirmed by sequential extractions that showed the importance of organic matter as a mercury carrier in the São João de Merití River. Our results indicate that this is not the case in the sediment profiles.

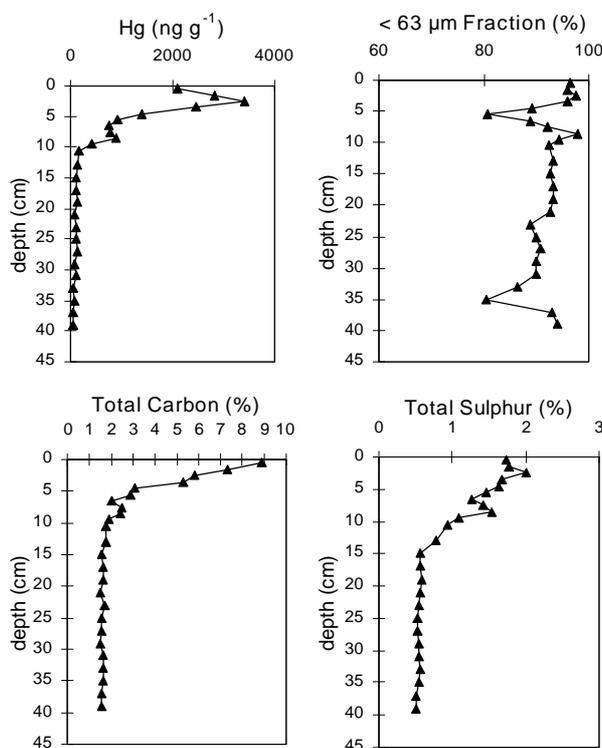


Figure 3 : Mercury concentrations and the other parameters in the core SJ1

The other profiles in the São João de Merití River (SJ2, SJ3 and SJ4, Figures 4 - 6) did not presented such a clear depositional feature as SJ1. None of them reach the background levels, due to the fact that they are subjected to considerably stronger sedimentation rates (at least SJ3 and SJ4, as discussed in the preceding paragraph). Both cores SJ3 and SJ4 present peak concentrations at the depth of 35 cm that can be attributed to a period of maximum contamination (may be between 1968 and 1973 as established by [37]). Core SJ2 is only 16 cm deep and did not reach these peak concentrations, but as in core SJ3, it presents a more recent peak concentrations at the depth 16 cm. As these three cores are located within the deltaic fan of the São João de Merití River and farther from the protection of the mangrove trees, they are not only subject to a stronger sedimentation rate, but also to stronger sedimentation rate variability. Strong summer rains should provide large amount of particles to the sediment column.

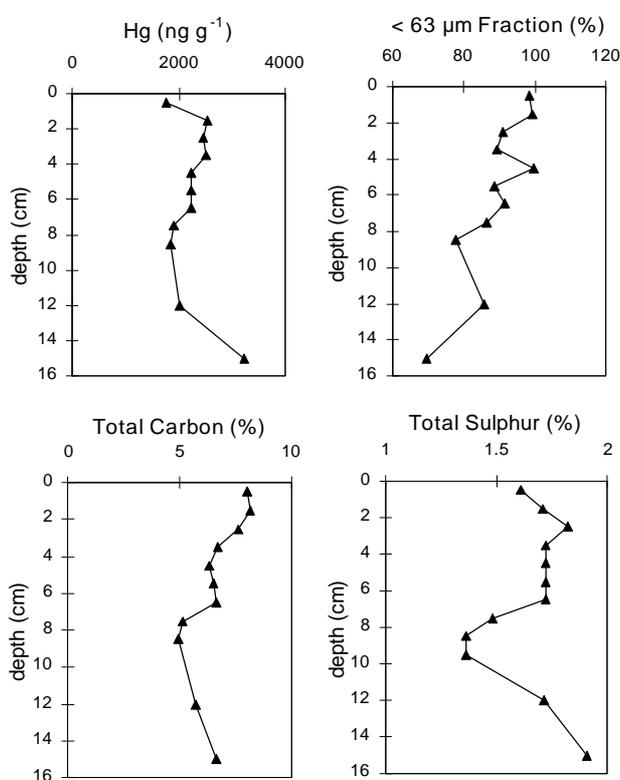


Figure 4 : Mercury concentrations and the other parameters in the core SJ2

Although in core SJ4 it was observed a relatively good correlation between mercury concentrations and fraction < 63 μm ($r=0.5519$, $n=31$, $p<0.01$), SJ2 and SJ3 were found to very poorly correlate these two variables ($r=0.1997$, $n=12$, $p>0.1$ for SJ2; $r=0.1767$, $n=29$, $p>0.1$ for SJ3). This lack of a granulometric control is probably due to the little variation of the granulometry within the sediment profile (always close to 90%). On the other hand total sulphur seem to be an important parameter for mercury distribution. In cores SJ2 and SJ3 total sulphur is the only parameter that presents a good correlation with mercury ($r=0.8003$, $n=12$, $p<0.01$ for SJ2; $r=0.6692$, $n=16$, $p<0.01$ for SJ3) and in core SJ4 it correlates well with mercury and total carbon also correlates with mercury ($r=0.6197$, $n=16$, $p<0.01$ between mercury and total sulphur; $r=0.8637$, $n=16$, $p<0.01$ between mercury and total carbon).

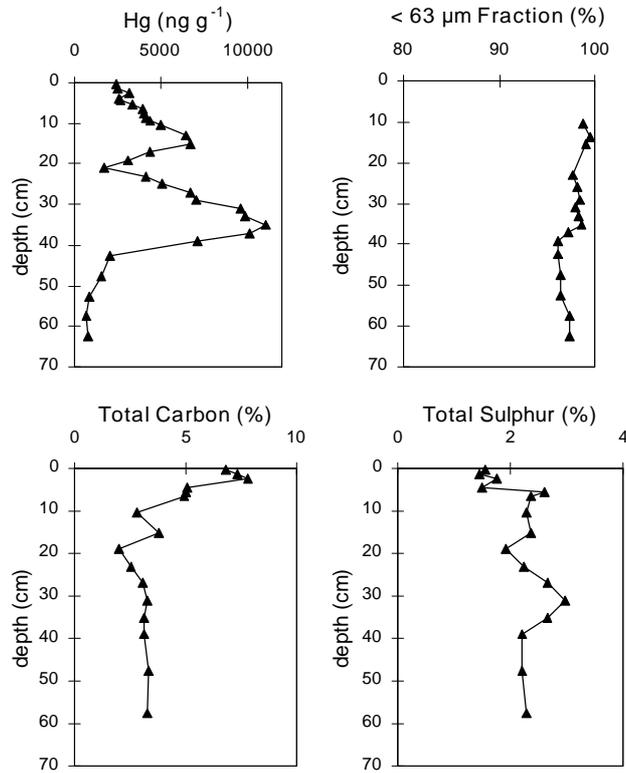


Figure 5 : Mercury concentrations and the other parameters in the core SJ3

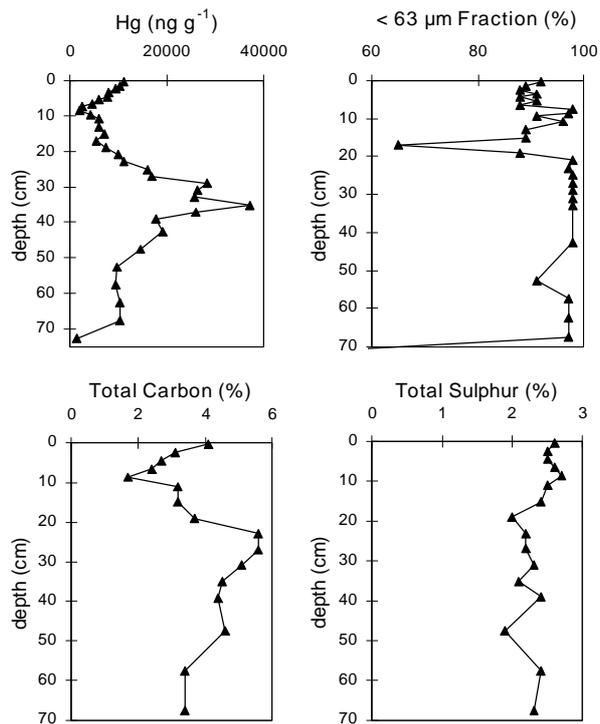


Figure 6 : Mercury concentrations and the other parameters in the core SJ4

Figure 7 present the sediment core G1, which is located in the opposite side of the bay to the São João de Merití River estuary (Figure 1). Yet this core was sampled in an area that is subjected to various forms of pollution (mainly domestic sewage and other non-point-sources) no important source of mercury is recorded. Like the profile SJ1, G1 is located in the tidal flat, just in front of a large mangrove area. The

mercury concentrations are significantly lower than the measured in the other cores of this work, but the values agree with other measurements made in surface sediments of the area [22].

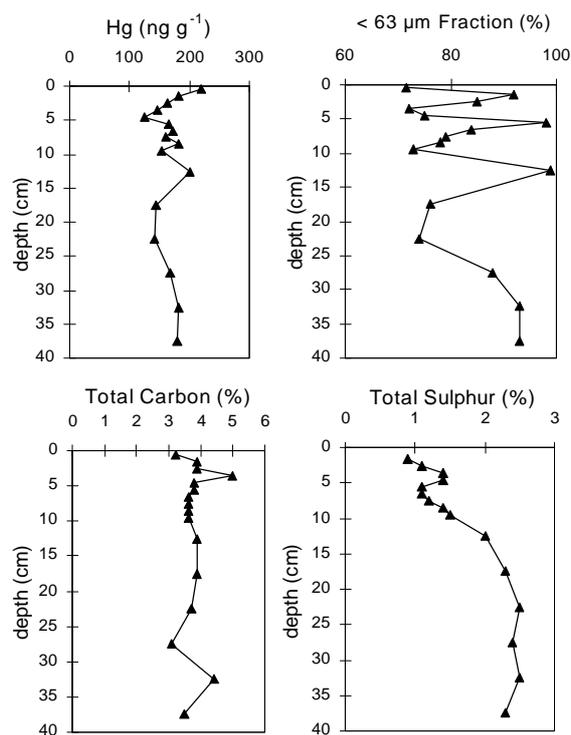


Figure 7 : Mercury concentrations and the other parameters in the core G1

It can be observed in Figure 7 that mercury concentrations fall very rapidly in the first 5 cm (from 219 ng g⁻¹ in the surface to 125ng g⁻¹ at 5 cm) but deeper, no general trend is observed and the concentrations vary within a narrow range. This reduction in concentration is probably associated to the mobility of mercury resulting of the fact that the core is in a tidal flat (this had already been observed in core SJ1). In this core, mercury concentrations do not seem to be controlled by none of the accessory parameters. Except total sulphur, that presents a clear increase in concentrations with depth, the other parameters do not show any tendency, even though significant variations can be observed (like for the fraction < 63 μm, between 71 and 99 %).

DISCUSSION

The mangrove vegetation seems to be a sufficiently protected environment to provide good records of the depositional history of a site. Therefore, in areas where the human activity is intense and where dredging and landfilling is frequent but unrecorded, the presence of mangrove trees that have more than 30 years is a guarantee of the absence of major anthropogenic modifications. That is the probable reason for core SJ1 is perfectly depositional while the other SJ cores do not present this same behaviour. Considering the mercury concentrations in the core SJ1, a rough estimate of depositional rates can be established to be 0.3 cm per year, assuming that the main sources of mercury contamination were installed in the early 60s. For the other SJ cores, our results did not permitted reliable calculations.

Mercury concentrations in cores SJ3 and SJ4 are considerably higher than those measured in cores SJ1 and SJ2, yet they are located in the same area (about 100 m apart). This difference is attributed to hydrodynamic factors that influence settling of sediments originated in the São João de Merití River. Finally, core G1, located in the opposite side of the bay, present significantly lower concentrations (twice higher than the background of the area) showing that the mercury contamination from São João de Merití River is not widespread through the bay.

Based on our data it is suggested that the mercury concentrations are not clearly controlled by any of the measured physico-chemical parameters (% clay-silt fraction, total carbon or total sulphur contents), notwithstanding the work of [4] that, who worked with surface sediments, establishing a good correlation between mercury concentrations and organic matter, further confirmed with sequential extractions. Total carbon or total sulphur contents seem associated to mercury concentrations as a function of the characteristics of the sediment core, but further studies (for example, sequential extractions) are necessary to distinguish when one of these two variables are going to be responsible for the behaviour of mercury. On the other hand, in this work, granulometry did not correlated with mercury concentrations because of the high homogeneity of the sediments (most of the samples are very fine grained).

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REFERENCES

- 1 A.M. Carro, Rubi, E. , Bollain, M. H. , Lorenzo, R. A. , Cela, R., Study of the distribution of methylmercury and total mercury in grain size fractions of freeze-dried estuarine sediment samples, *Applied and Organometallic Chemistry* **8**, 665-667, 1994.
- 2 R.M. Lent, Alexander, C. R., Mercury accumulation in Devils Lake, North Dakota-effects of environmental variation in closed-basin lakes on mercury chronologies, *Water, Air and Soil Pollution* **98**, 275-296, 1997.
- 3 B.F. Lyon, Ambrose, R. , Rice, G. , Maxwell, C. J., Calculation of soil-water and benthic sediment partition coefficient for mercury, *Chemosphere* **35**(4), 791-808, 1997.
- 4 P.R.G. Barrocas, Wasserman, J.C., *Mercury behaviour in sediments from a sub-tropical coastal environment in SE Brazil*, in: Environmental Geochemistry in the Tropics, J.C. Wasserman, Silva-

- Filho, E.V., Villas-Boas, R., ed., *Lecture Notes in Earth Sciences* 72, pp. 171-184, Springer-Verlag, Heidelberg, 1998.
- 5 F. Baldi, Parati, F. , Filippelli, M., Dimethylmercury and Dimethylmercury-sulfide of microbial origin in the biogeochemical cycle of Hg, *Water, Air and Soil Pollution* **80**, 805-815, 1995.
 - 6 C.C. Gilmour, Henry, E. A. , Mitchel, R., Sulfate stimulation of mercury methylation in freshwater sediments, *Environmental Science & Technology* **26**(11), 2281-2287, 1992.
 - 7 H. Hintelmann, Wilken, R.-D., Levels of total mercury and methylmercury compounds in sediments of the polluted Elbe River: influence of seasonally and spatially varying environmental factors, *The Science of the Total Environment* **166**, 1-10, 1995.
 - 8 L. Xun, Campbell, N. E. R., Rudd, J. W. M., Measurements of specific rates of net methyl mercury production in the water column and surface sediments of acidified and circumneutral lakes, *Can. J. Fish. Aquat. Sci.* **44**, 750-757, 1987.
 - 9 B.M. Miskimmin, Effect of natural levels of dissolved organic carbon (DOC) on methyl mercury formation and sediment-water partitioning, *Bulletin of Environmental Contamination and Toxicology* **47**, 743-750, 1991.
 - 10 P.R.G. Barrocas, J.C. Wasserman, F. Pivetta, T. Jennerjahn, Geochemistry of mercury in sediments from a tropical estuary: Guanabara Bay, Rio de Janeiro, Brazil, in: *International Conference on Heavy Metals in the Environment* 2, pp. 178-181, CEP Consultants, Hamburg, 1995.
 - 11 A.W. Andren, Harriss, R. C., Methylmercury in Estuarine Sediments, *Nature* **245**, 256-257, 1973.
 - 12 R.V. Marins, Lacerda, L. D. , Gonçalves, G. O. , de Pavia, E. C., Effect of root metabolism on the post-depositional mobilization of mercury in salt marsh soils, *Bulletin of Environmental Contamination and Toxicology* **58**, 733-738, 1997.
 - 13 M.E. Pereira, Duarte, A.C., Millward, G.E., Abreu, S.N., Vale, C., An estimation of industrial mercury stored in sediments of a confined area of the lagoon of Aveiro (Portugal), *Water Science Techniques* **37**(6/7), 37-42, 1998.
 - 14 P. Quevauviller, Donard, O.F.X., Wasserman, J.C., Martin, F.M., Schneider, J., Occurrence of methylated tin and dimethyl mercury compounds in a mangrove core from Sepetiba Bay, Brazil, *Applied and Organometallic Chemistry* **6**, 221-228, 1992.
 - 15 U. Förstner, Wittmann, G.T.W., *Metal Pollution in the Aquatic Environment*, 486 pp., Springer-Verlag, Heidelberg, 1983.
 - 16 W.E. Odum, McIvor, C.C., Smith, T.J., *The Ecology of the Mangroves of South Florida: A Community Profile*, 144 pp., U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C., 1982.
 - 17 L.D. Lacerda, Rezende, C.E., *Heavy metal biogeochemistry in mangrove ecosystems*, in: *Global Perspectives on Lead, Mercury and Cadmium Cycling in the Environment*, pp. 289-297, New Delhi, 1991.

- 18 N.P.D.d.M.e.G.-U.F.F.N. Mósca, 101p., *Concentração de Mercúrio nas Águas e Sedimentos da Baía de Guanabara, Rio de Janeiro, RJ Brasil*, M.Sc dissertation, Universidade Federal Fluminense, 1980.
- 19 CETESB, Avaliação da contaminação por metais pesados e pesticidas organoclorados na água, ictiofauna e outros organismos aquáticos do complexo estuarino lagunar de Iguape-Cananéia, CETESB, São Paulo, 1986.
- 20 CETESB, Metais pesados no estuário e Baía de Santos, CETESB-SP, São Paulo, 1986.
- 21 G.G.J. Eysink, Pádua, H.B., Martins, M.C., Presença do mercúrio no ambiente, *Ambiente* **2**(1), 43-50, 1988.
- 22 FEEMA, Projeto de Recuperação Gradual do Ecossistema da Baía de Guanabara - Indicadores Ambientais de Degradação, Obras e Projetos de Recuperação, Fundação Estadual de Engenharia do Meio Ambiente, Rio de Janeiro, 1990.
- 23 C. Vargas-Boldrini, Navas-Pereira, D., Metais pesados na Baía de Santos e estuários de Santos e São Vicente. Bioacumulação, *Ambiente* **1**(3), 118-127, 1987.
- 24 C. Vargas-Boldrini, *Mercúrio na Baixada Santista*, in: Riscos e Consequências do Uso do Mercúrio, S. Hacon, Lacerda, L.D., Pfeiffer, W.C., Carvalho, D., ed., pp. 161-195, FINEP, Rio de Janeiro, 1990.
- 25 P.R. Barrocas, J.C. Wasserman, The mercury in Guanabara Bay: a historical summary, in: International Symposium on Perspectives for Environmental Geochemistry in the Tropical Countries, J.J. Abrão, J.C. Wasserman, E.V. Silva-Filho, ed., pp. 454-460, Universidade Federal Fluminense, Niterói (Brazil), 1993.
- 26 A.D.L. Rebello, Haekel, W., Moreira, I., Santelli, R., Schroeder, F., The fate of heavy metals in an estuarine tropical system, *Marine Chemistry* **18**, 215-225, 1986.
- 27 V.M.B. Coelho, Fonseca, M.R.M.B., Problemas de eutroficação no Estado do Rio de Janeiro, FEEMA, Rio de Janeiro, 1981.
- 28 FEEMA, Levantamento de Metais Pesados no Estado do Rio de Janeiro, Fundação Estadual de Engenharia do Meio Ambiente, Rio de Janeiro, 1985.
- 29 FEEMA, Levantamento de Metais Pesados no Estado do Rio de Janeiro, Fundação Estadual de Engenharia do Meio Ambiente, Rio de Janeiro, 1986.
- 30 V.S. Rego, Pfeiffer, W.C., Barcellos, C.C., Rezende, C.E., Malm, O., Souza, C.M.M., Heavy metal transport in the Acari-São João de Meriti river system, Brazil, *Environmental Technology* **14**, 167-174, 1993.
- 31 A.P. Freitas-Pinto, Costa, M., Amaral, O., Moreira, I., Mercúrio total em mexilhões da baía de Guanabara, in: Seminário Nacional sobre Riscos e Consequências do Uso do Mercúrio, S. Hacon, Lacerda, L.D., Pfeiffer, W., Carvalho, D., ed., pp. 196-201, FINEP, Rio de Janeiro, 1990.
- 32 W.R.a.O. Hatch, W.L., Determination of sub-microgram quantities of mercury by atomic absorption spectrophotometry, *Analytical Chemistry* **40**(14), 2085-2087, 1968.

- 33 O. Malm, Pfeiffer, W.C., Bastos, W.R., Souza, C.M.M., Utilização do acessório de geração de vapor a frio para análise de mercúrio em investigações ambientais por espectrofotometria de absorção atômica, *Ciência e Cultura* **41**(1), 88-92, 1989.
- 34 A.M.G. Figueiredo, D. Favaro, J.C. Wasserman, Aplicação do método de análise por ativação com nêutrons à determinação de metais pesados em sedimentos, in: Congresso Geral de Energia Nuclear, 1994.
- 35 ASTM, *Standard test method for sulphur in petroleum products (High Temperature Method)*, in: American Standard Methods D1552, pp. 606-611, APHA/AWWA/WPCF, 1988.
- 36 D.J. Verardo, Froelich, P.N., McIntre, A., Determination of organic carbon and nitrogen in marine sediments using the Carlo Erba NA-1500 Analyser, *Deep Sea Research* **37**, 157-165, 1990.
- 37 I. Moreira, Godoy, J.M., Mendes, L., Cronologia da poluição por mercúrio na Baía de Guanabara, in: Seminário Desenvolvimento e Meio Ambiente, Pontifícia Universidade Católica, Rio de Janeiro, 1991.
- 38 P.R.G. Barrocas, *Geoquímica do Mercúrio em Sedimentos do Rio São João de Meriti: Sistema da Baía de Guanabara - RJ - Brasil*, M.Sc. dissertation, Universidade Federal Fluminense, 1994.
- 39 P.R. Barrocas, J.C. Wasserman, O mercúrio na Baía de Guanabara: Uma revisão histórica, *Geochimica Brasiliensis* **9**(2), 115-127, 1995.
- 40 S. Degetto, M. Schintu, A. Contu, G. Sbrignadello, Santa Gilla lagoon (Italy): a mercury sediment pollution case study. Contamination assessment and restoration of the site, *The Science of the Total Environment* **204**, 49-56, 1997.
- 41 K.K. Turekian, Wedepohl, K.H., Distribution of the elements in some major units of the earth's crust, *Bulletin of the Geological Society of America* **72**, 175-192, 1961.
- 42 E.S. Amador, Assoreamento da Baía de Guanabara - taxas de sedimentação., *Anais da Academia Brasileira de Ciências* **52**(4), 723-742, 1980.
- 43 C.M. Leitão-Filho, *Distribuição de Metais Pesados nos Sedimentos superficiais da Baía de Sepetiba, Rio de Janeiro*, M.Sc dissertation, Universidade Federal Fluminense, 1995.
- 44 J.C. Wasserman, Silva-Filho, E.V., Patchineelam, S.R., Bidarra, M., The role of hydrodynamic patterns on suspended matter metal behaviour as related to sediments in Sepetiba Bay (Brazil), in: International Conference on Heavy Metals in the Environment, J.D. Farmer, ed. 1, pp. 531-534, CEP Consultants, Edinburg, 1991.