

Relation of Reactive Sulfides with Organic Carbon, Iron, and Manganese in Anaerobic Mangrove Sediments: Implications for Sediment Suitability to Trap Trace Metals

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ABSTRACT



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The accumulation of acid-volatile sulfides and its relation with other trace metal-binding sediment constituents may be important mechanisms to determine the suitability of anaerobic sediments to trap trace metals. An investigation into the relationships among acid-volatile sulfides, total organic carbon, and reactive (hydrogen chloride-soluble) iron, manganese, and trace metals of environmental concern (cadmium, copper, nickel, lead, and zinc) was conducted in anaerobic sediments from a disturbed mangrove ecosystem in Sepetiba Bay (SE Brazil). The two main metal contaminants in the study area (cadmium and zinc) presented levels above regional backgrounds (showing enrichment factors up to 8.5 and 9.1, respectively) and a significant correlation, suggesting a contamination source similarity. Positive correlations among total organic carbon, acid-volatile sulfides, and iron and negative correlations of manganese with total organic carbon and acid-volatile sulfides occurred, probably because of (1) organic matter fuelling of acid-volatile sulfides production and depletion of manganese levels due to manganese oxide consumption by microbial respiration and (2) manganese oxide depletion in reaction with acid-volatile sulfides. The elevated acid-volatile sulfides concentrations and inventories observed, exceeding those of metals of environmental concern, indicate the sediment suitability to trap these metals as metal sulfides. While comparatively low manganese concentrations are probably unable to influence acid-volatile sulfides distribution, results evidenced that acid-volatile sulfides may affect manganese distribution negatively. To our knowledge, this negative metal-sulfur relationship was demonstrated for the first time in sediments from a tropical coastal ecosystem, which may help elucidate the behavior of manganese and manganese-associated elements in anaerobic mangrove sediments.

ADDITIONAL INDEX WORDS: *Trace metals, acid-volatile sulfides, mangroves, sediments, metal-sulfur interaction.*

INTRODUCTION

The accumulation of trace metals in coastal sediments is influenced by metal uptake by a sedimentary solid phase through formation of or adsorption on authigenic minerals. Among metal-binding compounds, metal sulfides have been recognized as key minerals controlling the behavior of metals in anaerobic sedimentary conditions. This role is primarily related to metal sequestering from an aqueous phase by formation of or adsorption on metal sulfides. These trace metal-binding solid phases may include (1) the phase operationally defined as acid-volatile sulfides (AVSs), mainly composed of iron sulfide (FeS), and (2) pyrite (FeS₂) (e.g., HUERTA-DIAZ and MORSE, 1992; OTERO and MACIAS, 2002).

There is much evidence in the scientific literature indicating that incorporation of trace metals by a sediment solid phase as AVSs may affect the distribution of these metals in both dissolved (DI TORO *et al.*, 1992; LEE *et al.*, 2000; TEASDALE *et al.*, 2003) and solid phases (COOPER and MORSE,

1998; GOBEIL, MACDONALD, and SUNDBY, 1997; MACHADO *et al.*, 2004). It is particularly important to note that trace metals that form monosulfides more stable than FeS—such as cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn)—can displace iron (Fe) from FeS, yielding trace metal monosulfides (ANKLEY *et al.*, 1996; CHAPMAN *et al.*, 1998; COOPER and MORSE, 1999). This indicates that although AVS concentrations exceed sulfide-forming trace metal concentrations, the sediment capacity to sequester dissolved trace metals from porewater by yielding trace metal monosulfides is not exhausted (DI TORO *et al.*, 1992; HARE, CARRIGNAN, and HUERTA-DIAZ, 1994; LEE *et al.*, 2000). Since the sediment trapping of metals as AVSs may influence the dissolved metal transport across the sediment-water interface, metal losses from a sediment solid phase may occur when low AVS levels and elevated ratios among trace metals and AVS concentrations are observed (CARBONARO *et al.*, 2005; COOPER and MORSE, 1998; TEASDALE *et al.*, 2003).

For many years, the trend of fine-grained and organic matter-rich mangrove sediments to develop physical and biogeochemical conditions suitable for trace metal trapping has been

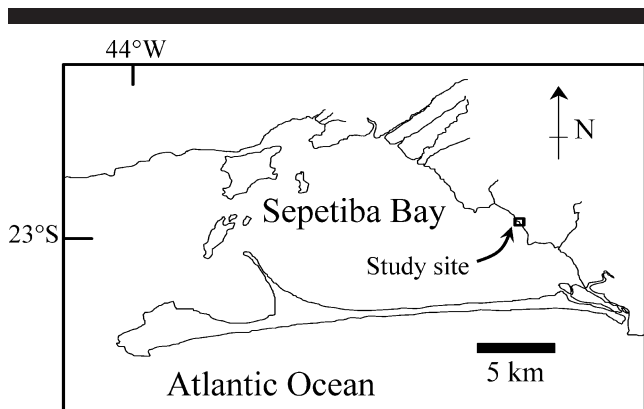


Figure 1. Location of the study site in Sepetiba Bay (Rio de Janeiro State, SE Brazil).

evidenced (ALONGI *et al.*, 2004; CLARK *et al.*, 1997; HARBISON, 1986; MACHADO *et al.*, 2002; SOTO-JIMÉNEZ and PÁEZ-OSUNA, 2001). Such environments can favor the microbially mediated oxidation of organic matter through the sulfate reduction metabolic pathway, resulting in substantial production of sulfide minerals. Temporal and spatial variability in sulfate reduction rates may be high within and between mangrove sites (ALONGI *et al.*, 1998; HOLMER *et al.*, 1999; KRISTENSEN *et al.*, 1992), and physical and chemical heterogeneity of sediment may contribute to highly variable AVS turnover rates in mangrove sediments (NEDWELL, BLACKBURN, and WIEBE, 1994). Moreover, oxygen (O_2) release from mangrove roots and the burrowing activity of benthic animals may induce sediment oxidation, affecting accumulation of metal sulfides (CLARK *et al.*, 1998; MARCHAND *et al.*, 2006), while a positive correlation of root biomass with sulfide production in mangrove rhizospheres has suggested that root exudates can fuel sulfate reducers (ALONGI *et al.*, 2001).

This context indicates that a strong variability in the contribution of sulfide minerals to determine the trace metal behavior in mangrove sediments should be expected. However, there is a scarcity of data on the potential relationship between reactive sulfides and trace metals in such sedimentary environments (BURTON, BUSH, and SULLIVAN, 2006; MACKAY and MACKAY, 1996). Here, we present a preliminary investigation on the potential relations between organic carbon and reactive (hydrogen chloride-extractable) sulfides (AVSs), Fe, manganese (Mn), and metals of environmental concern (Cd, Cu, Ni, Pb, and Zn) within anaerobic mangrove sediments, conducted to evaluate possible implications of these relations for the accumulation of trace metals.

MATERIAL AND METHODS

Study Site

The study site is a mangrove forest located in Enseada das Garças, at the NE coast of Sepetiba Bay, SE Brazil (Figure 1). Substantial information on metal contaminants input and incorporation by aquatic organisms has been recorded in Sepetiba Bay, particularly for Cd and Zn, because of a strong industrial point source of these metals in the northern bay

area (e.g., AMADO FILHO *et al.*, 1999; AMARAL *et al.*, 2005; BARCELLOS and LACERDA, 1994). Enseada das Garças presents an environmental protection area including a mangrove forest surrounded by urbanized and landfilled areas. Previous studies showed elevated trace metal concentrations in sediments from this forest, which are attributable to anthropogenic inputs (LACERDA *et al.*, 1993; WASSERMAN *et al.*, 2001). Besides the role of plants in inducing changes in pore-water chemistry (e.g., dissolved sulfide concentrations decrease due to root O_2 release; LACERDA *et al.*, 1993), bioturbation may also affect trace metal behavior in mangrove sediments, although a low depth (4 cm) of sediment mixing by bioturbation has been observed in Enseada das Garças mangrove forest, as estimated from a ^{210}Pb profile (SMOAK and PATCHINEELAM, 2000).

Sediment Sampling and Analyses

Three short (16 cm in length) sediment cores were collected within a stand of *Avicennia schaueriana* trees in the dry season (June 2001), using acid-cleaned polyvinyl chloride (PVC) tubes (7 cm in diameter), 4 m apart from one another. An attempt was made to collect sediments in a location without visible crab burrows in order to limit effects of bioturbation by macrofauna. Since such a location is less elevated than an adjacent mangrove-vegetated sand flat in the seaward edge of the forest (by up to ~20 cm) and a landfilled area in the south of the site (by up to ~2 m), sampled sediments experience a restriction of surface tidal water flow, suggesting that bringing together restrictions in bioturbation, physical disturbance, and tidal water outflow promotes a predominance of anaerobic conditions within sediments.

Sediments were extruded and sectioned in 2-cm depth intervals, and sediment samples were rapidly frozen to minimize oxidation. Extraction and analysis of AVSs were conducted using the techniques described by ALLEN *et al.* (1991), with some modifications (MACHADO *et al.*, 2004). Wet sediment subsamples were submitted to an acid distillation with 6 mol L^{-1} hydrogen chloride (HCl), using argon as a gas carrier, and the released hydrogen sulfide (H_2S) was trapped in 0.5 mol L^{-1} sodium hydroxide (NaOH). Sulfide concentrations were determined spectrophotometrically, using the flow injection system described by CASSELLA, DE OLIVEIRA, and SANTELLI (1999). Acid sediment suspensions were filtered for the determination of simultaneously extracted metal (SEM) concentrations. Concentrations of Fe, Mn, Cd, Cu, Ni, Pb, and Zn were determined by flame atomic absorption spectrometry. All analyses were done in sample duplicates to evaluate reproducibility. Duplicate AVS determinations showed reproducibilities within 20%, while the reproducibilities of duplicate metal determinations were within 13%. Total organic carbon (TOC) concentrations were determined in dried sediment subsamples on a LECO carbon analyzer after carbonate removal by acidification; a reproducibility within 3% was obtained for duplicate TOC determinations. Total (live and dead) root content in sediments was estimated after wet-sieving through a 1-mm mesh sieve, which was composed of very fine roots (<2 mm in diameter). Sediment density was determined by weighing a known volume of wet sediment after

Table 1. Concentrations and inventories of studied chemical constituents of mangrove sediments.

	Concentrations		Inventories	
	Unit	Range	Unit	Range
TOC	mmol g ⁻¹	2.7–4.3	mol m ⁻²	314–327
AVSs	μmol g ⁻¹	5.2–121	mol m ⁻²	1.42–4.77
Fe	μmol g ⁻¹	153–267	mol m ⁻²	17.1–21.9
Mn	μmol g ⁻¹	1.5–2.9	mmol m ⁻²	183–209
Cd	nmol g ⁻¹	3.6–15.1	μmol m ⁻²	632–823
Cu	μmol g ⁻¹	0.14–1.35	mmol m ⁻²	37.5–52.3
Ni	nmol g ⁻¹	94–411	mmol m ⁻²	14.1–19.3
Pb	nmol g ⁻¹	106–415	mmol m ⁻²	22.3–26.4
Zn	μmol g ⁻¹	7.1–14.3	mmol m ⁻²	854–1014
ΣSEMs	μmol g ⁻¹	7.7–15.3	mmol m ⁻²	939–1089

Note: Concentration values are from individual layers of each sediment profile ($n = 24$), while inventory values are from integrated sediment profiles ($n = 3$).

AVSs = acid-volatile sulfides, ΣSEMs = simultaneously extracted metals in concentrations of environmental concern, TOC = total organic carbon.

drying. Sediment content of fine (silt and clay) particles was estimated after wet-sieving through a 63-μm mesh sieve.

The sum of concentrations of SEMs of environmental concern will be noted as ΣSEM. Inventories of studied sediment constituents were calculated as the product among the constituent molar concentration, sediment density (g cm^{-3}), and thickness of the depth interval (cm), for each depth interval. Total inventories of a sediment profile were calculated through the sum of inventories from the different depth intervals. Statistical relationships among sediment constituents were evaluated by correlation tests. A significance level of 0.05 was accepted.

RESULTS

Sampled cores were composed of gray, reduced sediments covered by thin, brown, oxidized surface sediment layers (~1 mm thick). The studied sediments have a texture predominantly fine, with the fraction less than 63 μm displaying a slight increase with increasing depth. Contents of less than 63-μm particles ranged from 58.1 to 77.3%. Sediment density generally presented low values, ranging from 0.37 to 0.83 g cm^{-3} , with greater values between depths of 10 and 14 cm. Below depths of 2–5 cm, mats of live and dead fine roots of *A. schaueriana* trees were discontinuously present in the sediment profiles. As indicated by visual examination, these roots were partly covered by reddish coatings rich in Fe oxyhydroxides (CLARK *et al.*, 1998; LACERDA *et al.*, 1993). Low depth-integrated total root contents were observed between cores, ranging from 65 to 125 g m^{-2} .

Concentration and inventory ranges of the sediment constituents studied are presented in Table 1, whereas their concentration profiles are showed in Figure 2. Results evidence an elevated trace metal input to the study site, particularly for Zn. Concentrations of this metal composed 81–94% of ΣSEM concentrations, while its inventories constitute 90–93% of ΣSEM inventories. Concentrations of Zn and Cd showed an increase downcore until a maximum enrichment at the 8- to 10-cm depth interval, followed by a decrease in deeper layers. Although the distribution of other elements of

environmental concern did not have a general variability with depth, localized concentration peaks were observed. While concentrations of Cu and Pb reached maximum values at the top sediment layer, Ni concentrations presented greater values at the 4- to 6-cm depth interval. The organic-rich and sulfidic nature of sediments was evidenced by high TOC and AVS accumulations. The greater TOC concentrations were observed in the upper sediment layers, and decreasing TOC concentrations with increasing sediment depth were found below depths of 2 cm. A stronger trend of greater concentration in upper layers was presented by AVSs, which showed maximum values just below the sediment surface, as also observed for TOC. Fe concentrations decreased slowly with increasing depth, whereas Mn distribution displayed an inverse trend.

There was only one significant positive correlation between metals, observed for Cd and Zn ($r = 0.74$; Figure 3). AVSs showed a significant positive correlation with TOC ($r = 0.88$; Figure 4). Contrasting results were observed for the relationships of Fe and Mn with TOC and AVSs (Figure 5), with Fe showing significant positive correlations ($r = 0.75$ and 0.73 , respectively), whereas Mn showed significant negative correlations ($r = -0.97$ and -0.82 , respectively) with both sediment constituents.

DISCUSSION

Elevated AVS concentrations observed here are in the same magnitude of those reported for many anaerobic sedimentary environments, as observed in a degraded mangrove area in Moreton Bay, Australia (with up to 129 $\mu\text{mol g}^{-1}$; BURTON, BUSH, and SULLIVAN, 2006); the Danube River delta; the Black Sea (with up to 153 $\mu\text{mol g}^{-1}$; WJSMAN *et al.*, 2001), and the Tagus salt marshes, Portugal (with up to 225 $\mu\text{mol g}^{-1}$; MADUREIRA, VALE, and SIMÕES GONÇALVES, 1997). However, these values are one or two orders of magnitude above maximum concentrations found in sediments from other mangrove areas, such as Phuket Island, Thailand (with up to 4.4 $\mu\text{mol g}^{-1}$; HOLMER *et al.*, 1994), and Brisbane River estuary, Australia (with up to 22.6 $\mu\text{mol g}^{-1}$; MACKEY and MACKAY, 1996). Such lower concentrations are possibly due to an accumulation of sulfide as FeS_2 rather than as AVSs and a sulfide reoxidation at surface layers due to bioturbation, presence of roots, and tidal mixing (HOLMER *et al.*, 1994).

The relationships among AVSs, TOC, and Fe indicate interactions among trace metal-binding phases. Since organic matter oxidation employing sulfate as an electron acceptor results in AVS production, the organic carbon input, reactivity, and oxidation will affect the accumulation of AVSs and hence that of sulfide-forming metals within sediments (GOBEIL, MACDONALD, and SUNDBY, 1997; TEASDALE *et al.*, 2003). Considering that the contribution of AVSs to determine the sediment suitability to retain trace metals may vary with the proportion among concentrations of these metals and AVSs (ANKLEY *et al.*, 1996; CHAPMAN *et al.*, 1998), the results indicated an AVS accumulation sufficiently high to trap the observed reactive concentrations of trace metals within the studied sediments. Although ΣSEM:AVS ratios frequently approximate or exceed 1.0 in layers below 10 cm (ranging

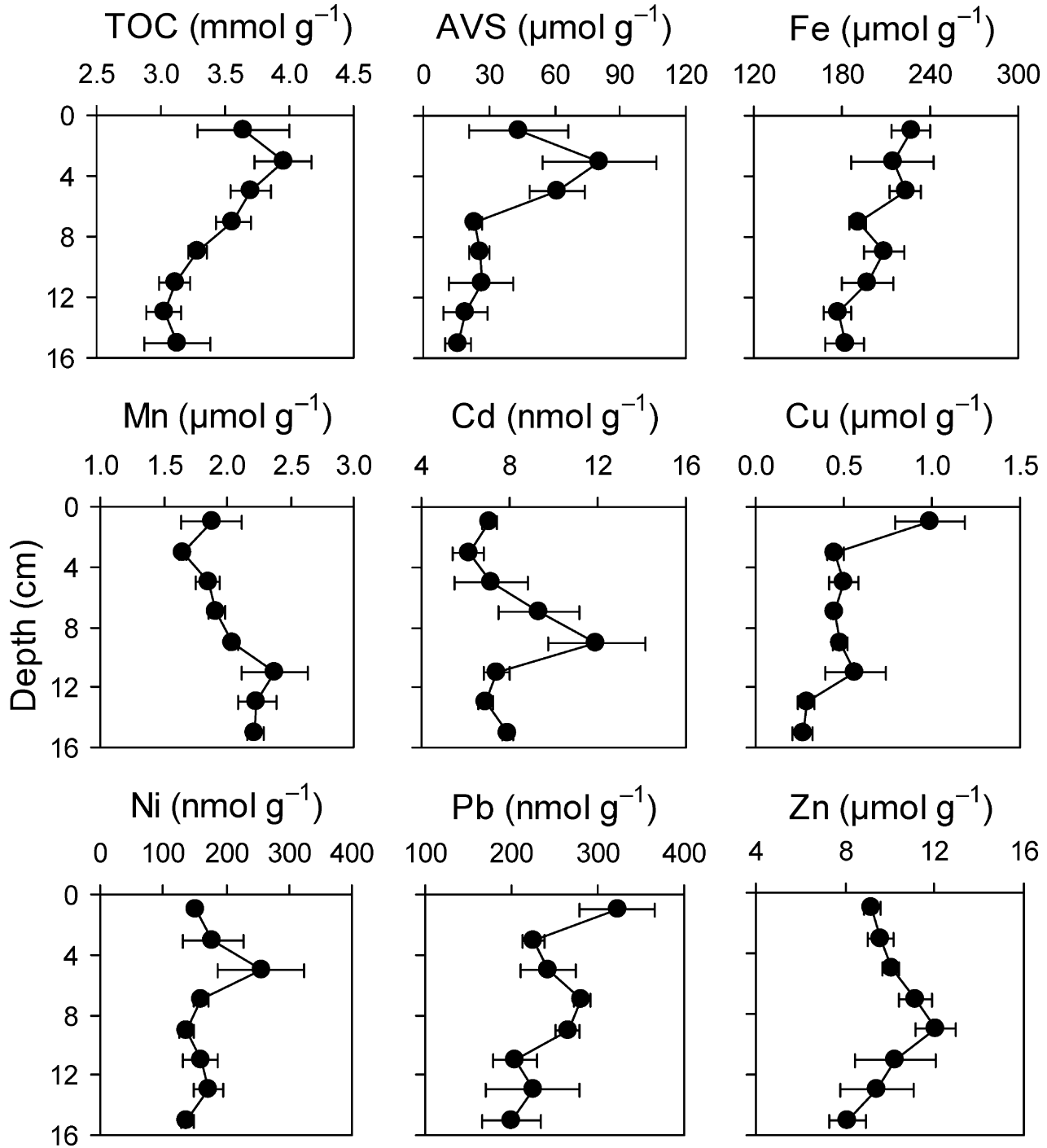


Figure 2. Concentration profiles of studied sediment constituents. Symbols indicate averages, and error bars indicate standard errors of triplicate cores.

from 0.3 to 1.7), such ratios were generally no more than 0.5 (ranging from 0.1 to 0.9) above this depth. This suggests that the studied sediments did not exceed their potential to retain trace metals near the sediment–water interface as metal monosulfides at the time of sampling, even if the observed metal concentrations were only in the form of monosulfides

(which should not be expected because the diluted HCl extraction can solubilize sediment phases other than AVSs, and the dominant forms of reactive metals in coastal anaerobic sediments may be other than sulfides; *e.g.*, O'DAY *et al.*, 2000).

The observed range of AVS inventories (Table 1) is close to that found within the upper-16-cm depth of reducing estua-

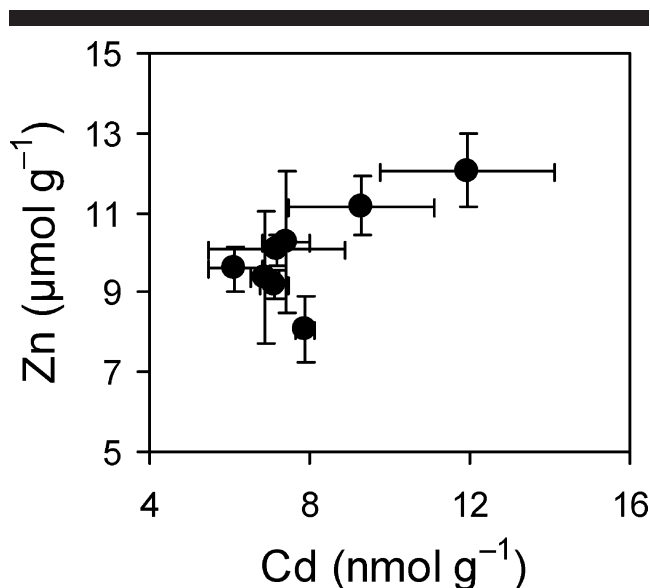


Figure 3. Relationship of Cd with Zn. Symbols indicate averages, and error bars indicate standard errors of triplicate cores.

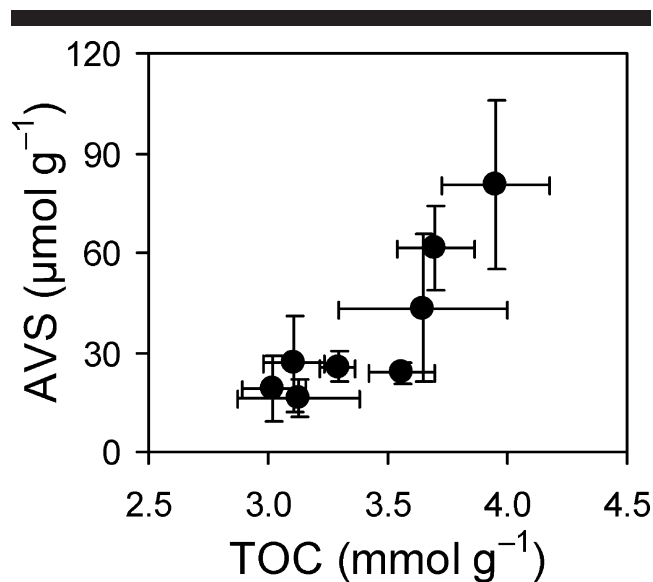


Figure 4. Relationship of AVSs with TOC. Symbols indicate averages, and error bars indicate standard errors of triplicate cores.

rine sediments in Black Sea ($2.1\text{--}5.3\text{ mol m}^{-2}$; WIJSMAN *et al.*, 2001). These values are above inventories (of the top-10-cm depth) reported for sediments under oxygenated waters ($0.3\text{--}1\text{ mol m}^{-2}$) and one order of magnitude lower than values observed in sediments experiencing seasonal anoxia ($35\text{--}55\text{ mol m}^{-2}$) in the United States' Chesapeake Bay (COOPER and MORSE, 1998). Data from COOPER and MORSE (1998) indicate that the evaluation of depth-integrated masses of AVSs and trace metals may be a reasonable basis to assess the spatial and temporal variability in the sediment suitability to retain trace metals. Calculated inventories (Table 1) indicate AVS accumulations 1.5–4.6 times greater than those necessary to bind the amounts of Σ SEMs as metal monosulfides.

The accumulation of Cd and Zn is probably derived from an industrial point source in the study area (BARCELLOS and LACERDA, 1994). These metals showed enrichment factors in relation to total preindustrial concentrations of 2.0–8.5 and 4.5–9.1, respectively, as indicated by background concentrations (1.8 nmol g^{-1} Cd and $1.6\text{ }\mu\text{mol g}^{-1}$ Zn) reported for a ^{210}Pb -dated mangrove sediment core from Sepetiba Bay (MARQUES *et al.*, 2006). This suggests that the correlation between these elements may reflect inputs from the same source. Moreover, diagenetic behavior similarities possibly contributed to such correlation, since trace metals may behave following S, Fe, or Mn redox behaviors (CHAPMAN *et al.*, 1998; SHAW, GIESKES, and JAHNKE, 1990), as previously indicated in Rio de Janeiro coastal sediments by trace metal correlations with AVSs and Fe (MACHADO *et al.*, 2004). However, trace metals of environmental concern were uncorrelated with AVSs, Fe, and Mn in the studied sediments.

In addition to variability in natural and anthropogenic sources, perhaps the mixing of anaerobic and aerobic processes in mangrove rhizospheres causes vertical and lateral

changes in trace metal form and association with sedimentary phases (CLARK *et al.*, 1998; LACERDA *et al.*, 1993; MARCHAND *et al.*, 2006), contributing to a lack of trace metal correlation with a single sediment constituent and a lack of coincidence in concentration peaks of most metals. Since many solid phases coexist and interact to determine the metal binding to sediments, *e.g.*, organic matter, Fe and Mn oxyhydroxides, and sulfides (CARBONARO *et al.*, 2005; MARCOVECCHIO and FERRER, 2005; SOTO-JIMÉNEZ and PÁEZ-OSUNA, 2001),

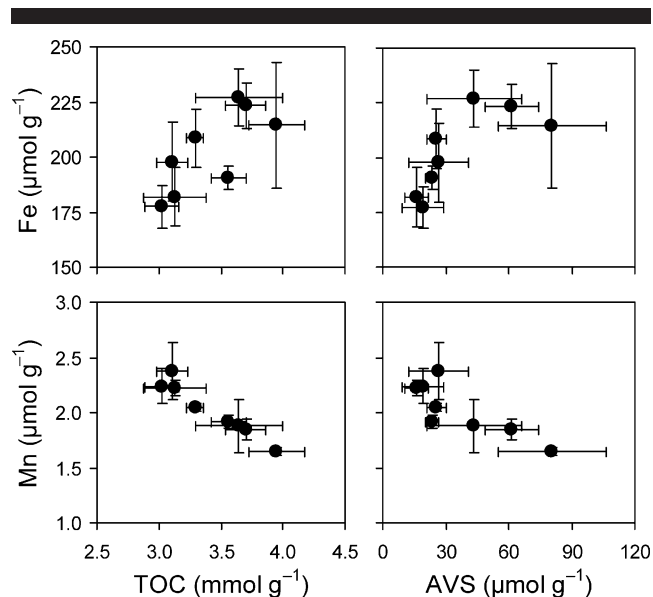


Figure 5. Relationships of Fe and Mn with TOC and AVSs. Symbols indicate averages, and error bars indicate standard errors of triplicate cores.

the combined influences from different phases probably accounted for the observed contrasts in metal accumulation trends (CLARK *et al.*, 1998; MARCHAND *et al.*, 2006; NAYLOR *et al.*, 2006).

Besides the widely evidenced Mn oxide accumulation in oxidized conditions and depletion with its use during organic matter oxidation by bacterial Mn reduction in reduced conditions of sediments in nature (GOBEIL, MACDONALD, and SUNDBY, 1997; SHAW, GIESKES, and JAHNKE, 1990), the complete oxidation of FeS by Mn oxide in marine anaerobic sediments has been experimentally demonstrated (ALLER and RUDE, 1988; SCHIPPERS and JØRGENSEN, 2001). It may be expected that Mn oxides constitute a substantial Mn fraction in the sediments studied because the sedimentation of particulate matter coated with Mn oxide (LACERDA *et al.*, 1988) and Mn oxides and carbonates are probable products of Mn diagenesis in Sepetiba Bay mangrove sediments (GUEIROS *et al.*, 2003; LACERDA, RIBEIRO, and GUEIROS, 1999). Therefore, negative correlations of Mn with TOC and AVSs may be explained by an Mn depletion in layers rich in TOC and AVSs due to a coupling among bacterial decomposition of organic matter employing Mn oxides as oxidants and Mn oxide reduction in reaction with AVSs. This coupling has been previously evidenced by Mn and FeS distributions in coastal sediments (THAMDRUP, FOSSING, and JØRGENSEN, 1994).

The stoichiometry of FeS oxidation by Mn oxide is (1) $\text{FeS} : 4\text{MnO}_2$ if FeS is directly oxidized to sulfate (ALLER and RUDE, 1988) or (2) $\text{FeS} : 1.5\text{MnO}_2$ if elemental sulfur is produced as an intermediate, which will involve additional employment of Mn oxide to oxidize it, with a stoichiometry of $\text{S}^0 : 3\text{MnO}_2$, to produce sulfate (SCHIPPERS and JØRGENSEN, 2001). Since Mn concentrations were 2–71 times lower than AVS concentrations, results indicate that a substantial AVS depletion via oxidation by Mn oxide is unlike to occur in the sediments studied, while AVS accumulation is able to affect Mn distribution significantly (Figure 5).

Few field data have evidenced the negative interaction between AVS and Mn in coastal sediments (*e.g.*, BERTOLIN *et al.*, 1997; THAMDRUP, FOSSING, and JØRGENSEN, 1994). In mangrove sediments, trace metal cycling has received increasing attention in the last decades, and conceptual models describing trace metal diagenesis in such environments have considered many processes affecting trace metal trapping (CLARK *et al.*, 1998; MARCHAND *et al.*, 2006). ALONGI *et al.* (1998) observed an elevated Mn efflux from sediments in a site colonized by 2-year-old mangrove vegetation and suggested that Mn reduction may be chemical rather than biological. Inverse depth distributions of Mn in relation to FeS_2 (ALONGI *et al.*, 1998) and total S (ALONGI *et al.*, 2005; MARCHAND *et al.*, 2006) have been found in some mangrove sediment profiles. However, we think that the negative AVS–Mn relationship and its importance for the distribution of Mn has not been previously evidenced for mangrove sediments.

Mn frequently presents a dynamic behavior in mangrove sediments (*e.g.*, GUEIROS *et al.*, 2003; HARBISON, 1986; MARCHAND *et al.*, 2006). If Mn oxides and AVSs coexist and interact (as appear to be the case of the studied environment), the Mn behavior is possibly influenced by Mn oxide reactions

with AVSs and a negative relationship among these sediment constituents may have implications for other trace metals that AVSs and Mn oxides are able to trap (*e.g.*, Cu, Ni, and Zn; NAYLOR *et al.*, 2006). Such metals may suffer remobilization during reactions among its binding compounds, contributing to determine its distribution and partitioning among sediment phases.

The AVS concentrations in intertidal sediments may vary (OTERO and MACIAS, 2002) or not (KOSTKA and LUTHER, 1995) among seasons. Although there is a lack of information on temporal variabilities of AVS distribution in mangrove sediments in nature, results of previous studies have indicated that conditions of lower bacterial sulfate reduction rates occur during dry season in comparison with the warmer wet season (ALONGI *et al.*, 2001; HOLMER *et al.*, 1999), suggesting that a lower AVS production during dry season may be expected. The results presented here reflect the dry season conditions only, but it may be expected that temporal variabilities in physicochemical conditions occur in Sepetiba Bay mangrove sediments (with more reducing conditions occurring during dry season; GUEIROS *et al.*, 2003), affecting the biogeochemical controls on trace metal accumulation. Consequently, care is requested to apply the interpretations showed here to other locations and seasons, considering physical, geochemical, and plant cover dissimilarities among sedimentary environments. Further investigations are necessary to elucidate the contribution of AVSs for the trapping of sulfide-forming trace metals within mangrove sediments.

CONCLUSIONS

The results found in the present study, reflecting dry season conditions, indicate that diagenetic processes (involving carbon–iron–sulfur interactions) produced sufficient AVSs to trap the reactive concentrations of Cd, Cu, Ni, Pb, and Zn within the upper sediment layers from the studied mangrove sediments. The geochemical controls on trace metal retention within sediments appear to be affected by significant positive and negative interactions among main sedimentary constituents generally involved in this retention, and the importance of AVSs in such interactions may be accentuated near the sediment–water interface in the study site, where more elevated AVS concentrations were recorded. The proportion among the amounts of sulfide-forming metals of environmental concern and AVSs appears to be a promising tool to evaluate the suitability of anaerobic sediments to trap metals such as Cd, Cu, Ni, Pb, and Zn in the form of metal sulfides, which may be valid for fine-grained, organic matter–rich mangrove sedimentary environments, as indicated in this preliminary study. To our knowledge, the negative relationship among AVSs and reactive Mn compounds was demonstrated for the first time in sediments from a tropical coastal ecosystem, which may contribute to elucidate the behavior of Mn and the behavior of other trace metals associated with Mn oxides in mangrove sediments experiencing anaerobic conditions.

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