Sequential Extraction Procedure for the Speciation of Particulate Trace Metals

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An analytical procedure involving sequential chemical extractions has been developed for the partitioning of particulate trace metals (Cd, Co, Cu, Ni, Pb, Zn, Fe, and Mn) into five fractions: exchangeable, bound to carbonates, bound to Fe–Mn oxides, bound to organic matter, and residual. Experimental results obtained on replicate samples of fluvial bottom sediments demonstrate that the relative standard deviation of the sequential extraction procedure is generally better than ±10%. The accuracy, evaluated by comparing total trace metal concentrations with the sum of the five individual fractions, proved to be satisfactory. Complementary measurements were performed on the individual leachates, to evaluate the selectivity of the various reagents toward specific geochemical phases. An application of the proposed method to river sediments is described, and the resulting trace metal speciation is discussed.

Most studies dealing with particulate metals in natural water systems (i.e., metals associated with suspended matter or bottom sediments) concern total metal concentration. Relatively few attempts have been made to evaluate the speciation of particulate metals, i.e., the partitioning among the various forms in which they might exist. Use of total concentration as a criterion to assess the potential effects of sediment contamination implies that all forms of a given metal have an equal impact on the environment; such an assumption is clearly untenable.

Conceptually, the solid material can be partitioned into specific fractions which can be extracted selectively by using appropriate reagents; considering the similarities between sediments and soils, extraction procedures can be borrowed or adapted from the methods of soil chemical analysis (1). Several experimental procedures, varying in manipulative complexity, have recently been proposed for determining the speciation of particulate trace metals. These procedures can be grouped into (i) methods designed to effect the separation between residual and nonresidual metals only (2-5) and (ii) more elaborate methods making use of sequential extractions (6-14). The former methods normally involve a single extraction and offer a better contrast between anomalous and background samples than does the determination of the total metal concentration. Despite their rapidity and relative simplicity, these techniques suffer from the difficulty of finding a single reagent effective in dissolving quantitatively the nonresidual forms of metal without attacking the detrital forms. The use of sequential extractions, although more time consuming, furnishes detailed information about the origin, mode of occurrence, biological and physicochemical availability, mobilization, and transport of trace metals.

The purpose of this study was to develop and examine the merits of a method of sequential “selective” extractions for partitioning particulate trace metals into chemical forms likely to be released in solution under various environmental conditions. The trace metals Cd, Co, Cu, Ni, Pb, Zn, Fe, and Mn were studied. For convenience, the experiments were performed with bottom sediments, which are more easily obtained in workable quantities than is suspended matter. Although iron and manganese are not generally referred to as trace metals in the literature, they have been so designated in the following sections in order to simplify the presentation of the results.

SELECTION OF FRACTIONS

In defining the desired partitioning of trace metals, care was taken to choose fractions likely to be affected by various environmental conditions; the following five fractions were selected.

Fraction 1. Exchangeable. Numerous studies (15-23) performed on sediments or on their major constituents (clays, hydrated oxides of iron and manganese, humic acids) have demonstrated the adsorption of trace metals; changes in water ionic composition (e.g., in estuarine waters) are likely to affect sorption–desorption processes.

Fraction 2. Bound to Carbonates. Several workers (9, 11, 24, 25) have shown that significant trace metal concentrations can be associated with sediment carbonates; this fraction would be susceptible to changes of pH.

Fraction 3. Bound to Iron and Manganese Oxides. It is well established (26) that iron and manganese oxides exist as nodules, concretions, cement between particles, or simply as a coating on particles; these oxides are excellent scavengers for trace metals and are thermodynamically unstable under anoxic conditions (i.e., low Eh).

Fraction 4. Bound to Organic Matter. Trace metals may be bound to various forms of organic matter: living organisms, detritus, coatings on mineral particles, etc. The complexion and peptization properties of natural organic matter (notably humic and fulvic acids) are well recognized, as is the phenomenon of bioaccumulation in certain living organisms. Under oxidizing conditions in natural waters, organic matter can be degraded, leading to a release of soluble trace metals.

Fraction 5. Residual. Once the first four fractions have been removed, the residual solid should contain mainly primary and secondary minerals, which may hold trace metals within their crystal structure. These metals are not expected to be released in solution over a reasonable time span under the conditions normally encountered in nature.

EXPERIMENTAL

Sampling. Sediment samples were collected at two sampling stations, Saint-Marceland Pierreville, located in the lower reaches of the Yamaska and Saint-François rivers (Québec, Canada), respectively. An Ekman dredge was used to collect a large amount of sediment; without emptying the dredge, a sample was taken from the center with a polyethylene spoon to avoid contamination by the metallic parts of the dredge. The samples were stored at 4 °C for ≤3 days, then dried at 105 °C in a forced air oven. They were subsequently ground in an agate mortar, homogenized and stored at 4 °C until needed.

Leaching Procedures and Reagents. After a critical evaluation of the available literature, the following chemical extraction methods were retained for further study; the quantities indicated below refer to 1 g sediment samples (dry weight of the original sample used for the initial extraction).
(i) Exchangeable. The sediment was extracted at room temperature for 1 h with 8 mL of either magnesium chloride solution (1 M MgCl₂, pH 7.0) or sodium acetate solution (1 M NaOAc, pH 8.2) with continuous agitation.

(ii) Bound to Carbonates. The residue from (i) was leached at room temperature with 8 mL of 1 M NaOAc adjusted to pH 5.0 with acetic acid (HOAc). Continuous agitation was maintained and the time necessary for complete extraction was evaluated.

(iii) Bound to Fe-Mn Oxides. The residue from (ii) was extracted with 20 mL of 0.1 M NaOAc with 0.005 M H₃citrate, as prescribed by Anderson and Jenne (27), or 0.04 M NH₄NO₃+HCl in 25% (v/v) HOAc. The latter experiments were performed at 96 ± 3 °C with occasional agitation and the time needed for complete dissolution of the free iron oxides was evaluated.

(iv) Bound to Organic Matter. A method described by Gupta and Chen (9) was adopted. To the residue from (iii) were added 2.5 mL of 0.2 M H₂NO₃ and 5 mL of 30% H₂O₂, adjusted to pH 2 with HNO₃, and the mixture was heated to 85 ± 2 °C for 2h with occasional agitation. A second 3-mL aliquot of 30% H₂O₂ (pH 2 with HNO₃) was then added and the sample was heated again to 85 ± 2 °C for 3 h with intermittent agitation. After cooling, 5 mL of 3.2 M NH₄NO₃ in 20% (v/v) HNO₃ was added and the sample was diluted to 20 mL and agitated continuously for 30 min. The addition of NH₄NO₃ is designed (9) to prevent adsorption of extracted metals onto the oxidized sediment.

(v) Residual. The residue from (iv) was digested with a H₂PO₄ solution mixture according to the procedure described below for total metal analysis. The "selective" extractions were conducted in centrifuge tubes (polypropylene, 50 mL) to minimize losses of solid material. Between each successive extraction, separation was effected by centrifuging (Sigma Model RC-2B) at 10000 rpm (12000 g) for 30 min. The supernatant was removed with a pipet and analyzed for trace metals (see below), whereas the residue was washed with 8 mL of deionized water; after centrifugation for 30 min, this second supernatant was discarded. The volume of rinse water used was kept to a minimum to avoid excessive solubilization of solid material, particularly organic matter.

Deionized water used in preparing stock solutions and in each step of the leaching procedure was obtained from a Millipore Milli-Q®/Milli-Q® system. All glassware used for the experiments was previously soaked in 14% HNO₃ (v/v) and rinsed with deionized water. All reagents used in this study were of analytical grade or better and were checked for possible trace metal contamination; of all the reagents used, only sodium dithionite showed serious contamination (Zn).

Trace Metal Analysis. Trace metal concentrations were determined by atomic absorption spectrophotometry (Varian Technicon Model AA-5) involving direct aspiration of the aqueous solution into an air-acetylene flame. The following techniques have been employed to liberate exchangeable metals. Of these, NH₄NO₃ (pH 7.0) has been the most extensively used in soil and sediment analysis. However, according to many workers (1, 28, 30), it may also attack carbonates. According to Chapman (28), the solubility of CaCO₃ is much lower in 1 M sodium acetate at pH 8.2, a reagent currently used in measuring the cation-exchange capacity of soils, than in the neutral ammonium acetate. For this reason, NH₄NO₃ was not considered in the present study; the merits of 1 M NaOAc (pH 8.2) and MgCl₂ (pH 7.0), as suggested by Gibbs (8, 13), were examined and are discussed below.

Reagents recommended for dissolving selectively the carbonate fraction in sediments generally make use of sodium acetate and/or acetic acid at acidic pH values (6, 9, 24, 31, 32). The procedure selected involves 1 M NaOAc and adjustment of the pH to 5.0 with HOAc. Grossman and Millet (33) reported that organic carbon and free iron concentrations in noncalcareous soil samples were unchanged after contact with this buffer for nine weeks; other workers (6, 9, 32) have demonstrated that lower pH values lead to a partial attack of Fe and Mn oxides. The time required for carbonate dissolution will depend upon such factors as particle size, percentage and type of carbonate present, and sample size (31). To evaluate the optimum time for leaching the carbonate fraction, sediment samples were first extracted during 1 h for exchangeable metals with either 1 M NaOAc (pH 8.2) or 1 M MgCl₂ (pH 7.0), and then further leached with 1 M NaOAc (pH 5.0, adjusted with HOAc); the calcium concentration was measured in centrifuged supernatants after different time intervals. Figure 1 indicates that for both sediments dissolution of calcium was complete within 5 h. This extraction time is likely to be sufficient for most samples of finely divided suspended solids. However, for coarse bottom sediments with high carbonate content, longer leaching times and frequent pH adjustment might be necessary.
Figure 1. Effect of leaching time on calcium concentrations in the NaOAc-HOAc (pH 5.0) extracting solution for sediments previously leached for exchangeable metals with 1 M MgCl₂ at pH 7.0 (●) or with 1 M NaOAc at pH 8.2 (○-○).

Figure 2. Effect of leaching time on iron concentrations in the 0.04 M NH₄OH-HCl-25% (v/v) HOAc extracting solution for sediments previously leached for exchangeable metals with 1 M MgCl₂ and for the carbonate fraction with NaOAc-HOAc (pH 5.0).

subsequent experiments, a leaching time of 6 h was adopted, as longer times would have increased the possibility of attacking fractions 4 and 5.

Hydrogen peroxide in an acidic medium is generally used to oxidize organic matter in soil (1,31) and sediment (6, 7, 9, 12, 14) analysis, even though oxidation of all forms of organic matter may not be complete (1). More efficient methods for destroying organic matter do exist (e.g., concentrated nitric acid used separately or in combination with hydrochloric or perchloric acids), but they usually suffer from a lack of specificity in the sense that they may also effect a partial attack of silicate lattices. In the present study, a method involving treatment with hot hydrogen peroxide in a nitric acid medium was adopted (9).

Procedures for dissolving primary and secondary minerals (residual fraction) usually involve either alkaline fusion (1, 6, 8, 13, 39) or dissolution with mixtures of hydrofluoric acid (1, 7, 9, 11, 12, 25, 32) and some other strong acid (e.g., nitric or perchloric acid). To ensure complete decomposition of the silicates, a large excess of fusing salt must be used, leading to high salt concentrations in the solution to be analyzed for trace metals; this can cause instability and high background readings in atomic absorption spectrophotometry. For these reasons, we selected the HF-HClO₄ digestion procedure described previously.

The overall procedure finally adopted thus involves five successive extractions with: (i) MgCl₂ (pH 7.0); (ii) NaOAc/HOAc (pH 5.0); (iii) NH₄OH-HCl in 25% HOAc (pH ~2); (iv) H₂O₂/HNO₃ (pH ~2) and subsequently NH₄OAc; (v) HF and HClO₄.

Precision and Accuracy. The analytical precision for each of the extraction steps, and for the overall procedure, was tested by subjecting six sub-samples of each of the Saint-Marcel and Pierreville sediments to the sequential procedure described above; the results obtained, together with the detection limit (expressed in micrograms metal per gram of dry sediment), are shown in Table I. Note that the detection limit, defined as twice the base-line noise, could be raised by using higher sediment/solution ratios. As anticipated, the precision is generally low when the concentration approaches the detection limit but improves for higher concentrations; coefficients of variation of 10% or lower are typically observed for metal concentrations amounting to five times or more the detection limit. Precision, while acceptable in most cases for the whole sediment, is expected to improve when the sequential procedure is applied to suspensions or to the fine fraction of bottom sediments (e.g., <20 μm).

Low reproducibility of the results is observed for lead in the Pierreville sediment. Leaching and analytical procedures are probably less responsible for this result than is the...
Table I. Detection Limit, Precision, and Accuracy of the Sequential Extraction Procedure as Determined on Two Sediment Samples

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Sediment No. 1</th>
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<td>(Pierreville)</td>
<td>(Saint-Marcel)</td>
<td>(Pierreville)</td>
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A value differing from the mean by more than three times the standard deviation was excluded.

Detection limit, mean value, and standard deviation are all expressed in μg/g of sediment, dry weight.

Unless otherwise indicated, results for six replicate determinations.

Following the sequence described in the text: 1, exchangeable; 2, carbonate...; Σ represents the sum of the five fractions and MT represents the total metal concentration.

A value differing from the mean by more than three times the standard deviation was excluded.

Results for three replicate determinations.

Table 1:

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<th>Fraction</th>
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<th>Sediment No. 1</th>
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<td>(Pierreville)</td>
<td>(Saint-Marcel)</td>
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A value differing from the mean by more than three times the standard deviation was excluded.

Detection limit, mean value, and standard deviation are all expressed in μg/g of sediment, dry weight.

Unless otherwise indicated, results for six replicate determinations.

Following the sequence described in the text: 1, exchangeable; 2, carbonate...; Σ represents the sum of the five fractions and MT represents the total metal concentration.

A value differing from the mean by more than three times the standard deviation was excluded.

Results for three replicate determinations.
heterogeneity of this sediment with respect to Pb, as only one of the two sediments shows a high variability. The high variability reported here for Pb in the Pierreville sediment was also observed during preliminary experiments, despite repeated grinding of the sediment in an effort to improve its homogeneity. Similar problems of low reproducibility for "acid leachable" reported here for Pb in the Pierreville sediment is also found in the various leachates along with the trace metals, that the variability discussed previously for specific fractions are solubilized during each successive extraction and thus are also the desired sediment phases are solubilized, and also the degree to which the remaining phases resist attack. Two types of evidence are considered: (i) the sediment components that are solubilized during each successive extraction and thus are found in the various leachates along with the trace metals, and (ii) the changes in overall sediment composition after treatment with each successive reagent. A knowledge of the principal characteristics of the two sediment samples is a prerequisite to this type of approach. The results of X-ray diffraction on the whole sediments indicate that quartz, plagioclase, and K-feldspar are the major phases whereas chlorite, amphibole, and mica are minor constituents; two other minor phases were identified in the 2-16 \( \mu m \) fraction (dolomite) and in the <2 \( \mu m \) fraction (smectites). Inorganic carbon (0.2-0.4%) C, organic carbon (0.5-0.7% C), and sulfide (0.04-0.05% S) all represent small percentages of the total sediment composition.

Fraction 1. Exchangeable Metals. The low levels of Si, Al, S, and organic carbon found in leachate 1 (Table I) imply that MgCl\(_2\) treatment does not affect silicates, sulfides, or organic matter. Thermodynamic calculations indicate that Fe and Mn oxides should not be significantly solubilized at pH 7.0, and concentrations of Fe in leachate 1 are indeed very low. The slight dissolution of carbonates (2-3%) could be reduced by shortening the leaching time.

Fraction 2. Metals Bound to Carbonates. Dissolution of the sediment carbonate fraction is essentially complete as evidenced by the disappearance of the dolomite X-ray diffraction peak following treatment with the acetate buffer (pH 5.0). Further evidence is provided by the kinetics of the leaching step (Figure 1) increasing the leaching time from 5 to 24 h does not result in higher calcium concentrations in the leachate.

The low levels of Si, Al, S and found in leachate 2 (Table II) indicate that attack of silicate and sulfide minerals by the NaOAc-HOAc reagent is minimal. Furthermore, the organic carbon content of the sediments is undiminished after treatment with the acetate buffer (Table III), suggesting that the organic fraction is also unaffected (cf. 31). The appreciable iron and manganese concentrations found in leachate 2 probably result from the dissolution of divalent salts. Ferrous and manganous carbonate are the logical candidates (42, 43), given the pH values and inorganic carbon concentrations prevalent in natural environments.

Assuming that the trace metals found in fraction 2 originate solely from dissolution of dolomite, the only carbonate phase identified, one can calculate the following concentrations for these metals in CaMg(CO\(_3\))\(_2\): 190 and 300 ppm Cu, 65 and 70 ppm Ni, 150 and 350 ppm Pb, and 660 and 290 ppm Zn, where the two values refer to Saint-Marcel and Pierreville sediments respectively. These concentrations are far in excess of those reported for carbonate sedimentary rock (44), for deep sea sediments (44), or for calcium carbonate of biogenic origin (45). This raises the possibility that in the preceding extraction the neutral 1 M MgCl\(_2\) did not completely desorb the specifically adsorbed trace metals, the adsorption-desorption processes being strongly pH dependent; lowering the pH to 5.0 in the subsequent extraction would then release the remaining specifically adsorbed trace metals as well as the.

<table>
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<th>bound to Fe-Mn oxides</th>
<th>bound to organic matter</th>
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<td>35</td>
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</table>
| sediment No. 2 (Pierreville) | | | | | 35

Table II. Percentages of Total Si, Al, Ca, S, Inorganic Carbon, and Organic Carbon Concentrations Found in the Successive Leachates
carbonate-bound fraction. Examination of curves of trace metal adsorption as a function of pH (22, 35) suggests that lowering the pH from 7.0 to 5.0 might release in solution a large fraction of specifically adsorbed trace metals from various solid substrates.

**Fraction 3. Metals Bound to Fe-Mn Oxides.** Increasing the leaching time from 6 to 24 h did not result in higher iron concentrations in leachate 3 (Figure 2), indicating that the extraction of reducible iron oxide phases is complete; as manganese oxides are known to be more easily leached than iron oxides (46), it is probable that their extraction is also complete. The low levels of Fe and Mn found in the subsequent leachate (fraction 4, Table I) are an additional indication of the completeness of the extraction.

Thermodynamic calculations suggest that metal sulfides should be solubilized to a large extent at the pH of the extracting solution; however, as shown in Table III, sulfur levels are unchanged in the sediments after extraction with NH₄OH-HCl-HOAc. These results imply that the reduced sulfur present in the sediments studied does not exist as amorphous metal sulfides, but rather as well-crystallized phases (e.g., pyrite) or as organosulfur compounds. The organic carbon content of the sediments is also uniminished after treatment with the hydroxylamine-hydrochloride-acetic acid reagent, indicating that organic matter is not significantly leached. The possible liberation of some metals from labile organic complexes cannot however be excluded. The low levels of Si and Al found in leachate 3 indicate that only slight attack of the major silicate components occurs during treatment with NH₄OH-HCl-HOAc. A relative decrease of the smectites X-ray diffraction peak is noted, suggesting partial attack of these minerals. Contrary to the results of Chester and Hughes (24), however, no evidence of chlorite transformation can be observed from X-ray diffraction analysis.

**Fraction 4. Metals Bound to Organic Matter.** Oxidation of organic matter by acidified hydrogen peroxide, although extensive, is incomplete; sulfide minerals are also extracted to a large extent, as shown in Table III. According to Jackson (1), the remaining organic matter should consist of paraffin-like material and resistant structural (nonhumified) organic matter residues. Stronger oxidizing solutions usually rely upon the use of strong acids, which may seriously attack silicate material. Thus the choice of H₂O₂ represents a compromise between complete oxidation and alteration of silicate material.

The low levels of Si and Al found in leachate 3 indicate that the attack of the major silicate phases is indeed minimal. However, a relative decrease in the smectites and chlorite X-ray diffraction peaks is observed, suggesting a partial alteration of these minerals (Figure 3); mica is also subject to partial transformation, as evidenced by the appearance of a small shoulder on the X-ray diffraction peak.

**Fraction 5. Residual Metals.** The residue remaining after the four preceding extractions consists essentially of detrital silicate minerals, resistant sulfides, and a small quantity of refractory organic material. Treatment with the HF-HClO₄ reagent results in complete dissolution.

Speciation. Having considered in some detail the analytical performance of the proposed sequential extraction procedure, we shall now briefly comment on the trace metal partitioning observed in the sediment samples studied (Table I). Each successive fraction is discussed below: where two concentration values are given, the first refers to the Saint-Marcel sediment and the second to the Pierreville sample.

**Fraction 1. Exchangeable Metals.** Concentrations found for exchangeable cadmium, cobalt, nickel, lead, and zinc are lower than their respective detection limits; low concentrations of copper (0.15 and 0.2 ppm) and iron (0.4 ppm) are observed, as are relatively high concentrations of manganese (99 and 38 ppm). For the latter element, fraction I accounts for 14–3% of the total metal concentration. From available evidence on the extraction of exchangeable metals from bottom sediments or suspended solids (8,9,12,13,25,30), these results are to be expected: exchangeable Cd, Co, Cu, Ni, Pb, Zn, and Fe are generally found to represent a minor fraction of the total metal concentration of the solid. The relatively high concentrations of exchangeable manganese suggest that the metal exists in a reduced form; it is recognized (42) that in most natural waters Mn(II) oxidation is a much slower process than Fe(II) oxidation. Our results for exchangeable Mn differ significantly from the findings of Gupta and Chen (9) who reported undetectable concentrations on coastal marine sediments. Possible explanations for this difference include the high ionic strength of seawater, which should favor desorption of Mn, and the higher pH, which should increase the rate of Mn(II) oxidation (42).

**Fraction 2. Metals Bound to Carbonates.** Concentrations found for cadmium and cobalt in fraction 2 are lower than their respective detection limits; the levels of nickel and iron, though detectable, remain low (<4%) compared to the total metal concentrations. For copper, zinc, and manganese, however, the observed concentrations represent an appreciable proportion of the total metal: 16–18% Cu; 13–16% Zn;
13–28% Mn. These results are essentially similar to those reported by Gupta and Chen (9) for marine sediments using a 1 M HNO₃ extraction.

Fraction 3. Metals Bound to Fe–Mn Oxides. With the exception of cadmium, the trace metal levels in fraction 3 are relatively high and represent a large fraction of the total metal concentrations: ~40% Co; >20% for Cu, Ni, and Pb; 13–14% Fe; 15–24% Mn. Assuming that Fe(OH)₃ and MnO₂ are representative empirical formulas for the Fe and Mn oxides, respectively, and that the observed trace metals originate only from Fe–Mn oxides, one can calculate the trace metal concentrations in the Fe–Mn oxide phases (Table IV); the results illustrate the strong scavenging efficiency of Fe–Mn oxides for trace metals (26).

Fraction 4. Metals Bound to Organic Matter. Levels of cadmium and cobalt found in fraction 4 are once again lower than their respective detection limits. The remaining metals are present in detectable quantities, but only in the case of copper and lead does fraction 4 represent a significant proportion of the total metal concentration: ~25% Cu; 16–21% Pb. The absolute concentrations follow the order Fe > Mn > Cu > Zn > Pb > Ni for each sediment (Table I).

Fraction 5. Residual Metals. Without exception, trace metal concentrations found in fraction 5 are higher than those observed in any of the preceding extractions. In the case of cobalt, nickel, zinc, iron, and manganese, the residual fraction accounts for more than 50% of the total metal concentration. This overwhelming importance of fraction 5, amply borne out by the results of others (7–9, 12, 13, 32), illustrates clearly the difficulty of distinguishing between background and anomalous levels of trace metal contamination when only total metal analyses are performed.

CONCLUSIONS

The precision and accuracy of the sequential extraction procedure are generally good, the limiting factor being the inherent heterogeneity of the sediment; analytical performance should thus improve when the procedure is applied to suspensions or to sized fractions of bottom sediment.

The results obtained for fractions 3 and 4 (Fe–Mn oxides and organic matter) indicate that these phases have a scavenging action for trace metals that is far out of proportion to their own concentration. As these fractions constitute important sources of potentially available trace metals (47), they should be considered explicitly when estimating the bio-availability of a particular metal.

For the moment, it is obvious that the distribution of a given metal between various fractions does not necessarily reflect the relative scavenging action of discrete sediment phases, but rather should be considered as operationally defined by the method of extraction. Before metal concentrations measured in a particular fraction can be ascribed with reasonable certainty to well defined geochemical forms or phases, it will be necessary to develop more selective extraction reagents, notably for sulfide bound trace metals. Spiking experiments, involving the addition of known geochemical phases to sediment matrices, would provide valuable information concerning the selectivity of the proposed sequential extraction procedure. Application of the procedure to a wide range of bottom and suspended sediments would also be desirable.

Sequential extraction procedures do, however, offer the major advantage that they simulate to a certain extent various environmental conditions to which the sediment may be subjected; deductions can then be made about the trace metal levels likely to be observed under these conditions in the environment. Possible applications include the evaluation of the effects of dredging operations and the prediction of trace metal behavior in estuarine waters or in anoxic lacustrine systems.

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LITERATURE CITED


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