A combined modelling and geochemical study of the fate of terrigenous inputs from mixed natural and mining sources in a coral reef lagoon (New Caledonia)

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Abstract

Open-cast mining for Ni, Cr and Co was conducted in the south-west part of New Caledonia during the 20th century. Abandoned mining and prospecting sites were severely affected by erosion, resulting in an increase in the load of terrigenous particles transported to the coral reef lagoon. This article assesses the impact of a typical small catchment area (La Coulée River, 85 km² watershed) on two bays (Boulari and Sainte Marie) located near Noumea, New Caledonia's main city. This multi-disciplinary study combines geochemical, sedimentological, and hydrodynamic approaches. Ni and Cr concentrations contained in the geochemical matrix phase of the pelitic fraction were determined. The study of the geochemical signatures together with sedimentological data and 3D numerical simulations of the transport of non-settling particles throughout the lagoon demonstrated that terrigenous inputs from the Coulée River were mainly transported and deposited along the shoreline, reaching areas as distant as Sainte Marie Bay. Although quantitatively low (about 3% of the pelite mass of the bay sediments), the terrigenous inputs in Sainte Marie Bay originating from the Coulée River could be traced. The metal content in suspended matter was over 7000 mg kg^{-1} for Ni and 4200 mg kg^{-1} for Cr.
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1. Introduction

Despite current environmental awareness, biologically degraded conditions in coral reef lagoons bordering land masses and subject to significant terrigenous and anthropogenic inputs are still poorly documented (Mc Laughlin et al., 2003; Muslim and Jones, 2003). Questions about input and transport of land derived material and associated metals in lagoon waters have rarely been addressed specifically, even in target study sites such as the coral reef lagoons of Florida or Australia (e.g. Liston et al., 1992; Caccia et al., 2003; Muslim and Jones, 2003) and most of the existing data have been relegated to grey literature reports.

New Caledonia currently ranks as the third nickel producer in the world. A certain number of saprolitic layers and enriched laterites have been exploited by open-cast mining techniques for more than a century. Open-cast mining requires removal of vegetation and of the overlaying ferricrete and laterite layers (low in nickel content) before the exploitable saprolitic layer can be reached. This method produces huge volumes of overburden (≈2.5 times the volume of extracted ore), generally left on the spot and at best confined by filtering dams of uncertain efficiency. It is estimated that a total of 300 Mm³ of soil has been displaced by direct extraction since the beginning of mining activities (Labrosse et al., 2000). Prospecting and open-cast mining

on hilltops resulted in major landscape and habitat alteration, a large increase in natural soil erosion and subsequent river transport of terrigenous material and associated metals to the coral reef lagoon (Bird et al., 1984). Fringing reefs are especially sensitive to such an increase in sediment deposit and decrease in light penetration, and all pelagic and benthic communities are affected to some extent. The fate of such mining-related terrigenous inputs need to be thoroughly investigated.

Several investigations have been conducted to determine the origin, distribution and fate of terrigenous and anthropogenic inputs in the south-west lagoon of New Caledonia, including physicochemical analysis of the water (Fichez et al., submitted for publication), hydrodynamic and suspended particles transport modelling (Douillet et al., 2001; Ouillon et al., 2004), or biogeochemical cycling (Bujan et al., 2000; Pinazo et al., 2004). This article focuses on the nature and transport in the lagoon of terrigenous inputs originating from a single river catchment affected by old, unrehabilitated mining sites. The study is based on a multi-disciplinary approach associating sedimentology, geochemistry and hydrodynamics.

2. Study area

New Caledonia is located at the southern end of the Melanesian Arc, near the Tropic of Capricorn. Mining activities are almost exclusively conducted on the main island (16,890 km^2). In its south-western part soils are composed of peridotites, harzburgites with orthopyroxenes made of magnesium and iron silicates, and infiltrated by transition metals like Ni, Co, Cr, Fe and Mn (Lillie and Brothers, 1970; Paris, 1981a). Only in rocks from the northernmost part of the island are elements like Pb and Zn present in significant quantities (Antheaume, 1981; Paris, 1981b). The weathering of peridotites results in the formation of nickel- and iron-rich smectites, serpentine, goethite and hematite (Trescases, 1973), and in the migration of transition metals. The latter are strongly concentrated along the weathered profile in the saprolite (also called "garnierite") and laterite layers which are subject to mining extraction.

The present study focuses on the small (85 km^2) watershed of the Coulée River located on the south-west coast of New Caledonia's main island. A small-scale mining operation produced 63,657 tons of nickel ore between 1904 and 1965; as a result of mechanization an additional amount of 362,078 tons was extracted between 1966 and 1980. Mining activity ceased in 1981 but erosion from the initial prospecting and extraction sites continued, and the present terrigenous inputs delivered to the lagoon by the Coulée River are the combined result of natural and anthropogenic influences.

As most rivers of New Caledonia, the Coulée River has a steep upper course and a much flatter lower course where deposits of bedrock weathering products accumulate. Due to the tropical climate conditions in New Caledonia, the hydrological regime is of the torrential type. In the absence of rainfall, the sediment load carried by the rivers is very slight because of the low energy of mechanical processes
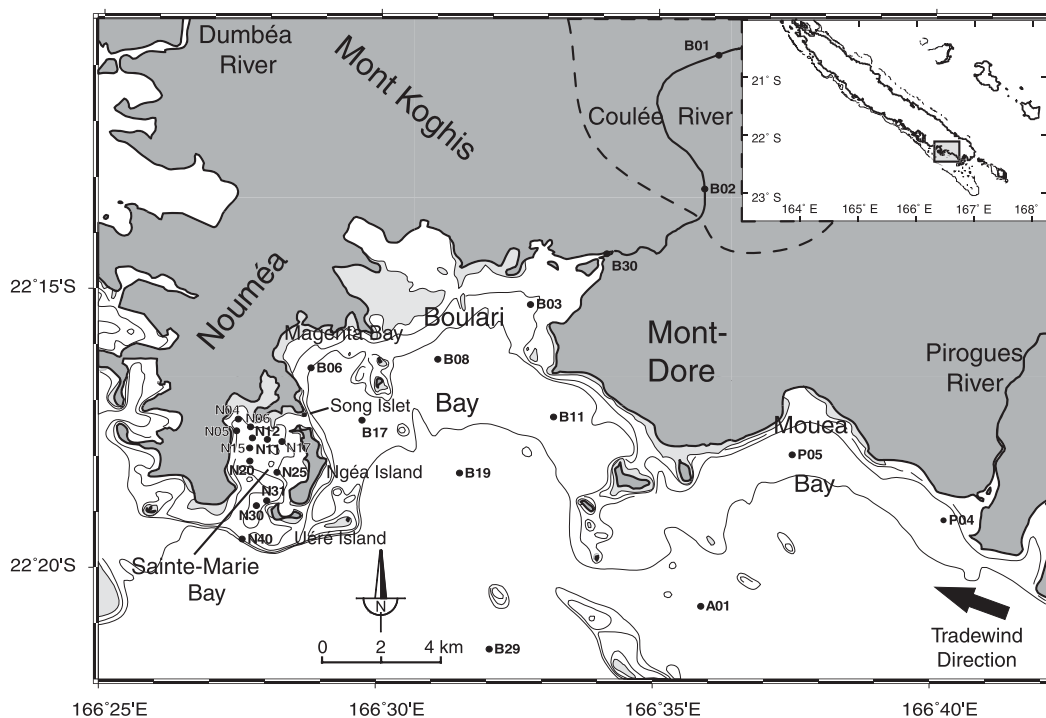

Fig. 1. Study area in the south-west lagoon of New Caledonia and localization of sampling stations. Fringing reefs are shown in light grey. The dashed line represents the external boundary of the former open-cast mining area of Coulée catchment.

such as erosion, transport and sedimentation (Baltzer and Trescases, 1971; Dugas and Debenay, 1982). Rain events reaching 700 mm and more over a 24-h period induce intense weathering of the slopes and flushing of large quantities of suspended matter to the lagoon. Baltzer and Trescases (1971) reported that during cyclone Brenda in 1968, over 20,000 tons of particles were discharged in a single day through the estuary of the Dumbéa River (catchment area $\approx$50 km^2) located a few kilometres away from the Coulée River.

The Coulée River estuary opens in the north-east part of Boulari Bay (Fig. 1). On its south-western side Boulari Bay connects directly with Sainte Marie Bay through 500-m wide channel with a 3-m deep threshold located between Ngéa Island and the tip of Ouémo peninsula.

3. Material and methods

3.1. Sediment sampling

Sediment samples were collected in Sainte Marie Bay (12 stations), Boulari Bay (12 stations), Coulée River (2 stations), and close to the Pirogues River estuary (2 stations) (Fig. 1). Sediment was sampled with a lightweight stainless-steel (316L) Van-Veen grab (capacity 1.8 L) ensuring minor disturbance of the sediment top layer. The centimetric surface layer of oxidized sediments was retrieved and placed in single-use vinyl bags (Whirl-pack), frozen for storage before being freeze-dried. Freeze-dried sub-samples were separately packaged for sedimentological and geochemical analyses.

3.2. Sedimentology

Sedimentology studies were conducted according to the method described in Buchanan (1984). Samples were oven-dried (60 °C, 3 days), weighed, and the mud fraction was separated under wet conditions on a 63 μm diameter sieve. The remaining fraction (i.e. gravels and sands) was dried, weighed and sieved on a vibrating granulometric column using the following mesh sizes in ϕ units: −4.32, −4, −3.32, −3, −2.32, −2, −1.32, −1, 0, 1, 2, 3 and 4. The 13 fractions obtained were expressed as weight percentage of the initial bulk sample. Semi-logarithmic cumulative curves were plotted to calculate the mean size (Mz) according to Folk and Ward (1957) and Wentworth grade scale (1922). Carbonate content was analysed by calcimetry (Bonneau and Souchier, 1979) on the mud fraction. The facies of silting and carbonate-terrigenous were defined according to Maxwell (1968).

3.3. Geochemical signature of metals

For the geochemical study, each sediment sample was grain-sized by wet sieve (40 μm mesh size) to isolate the pelitic fraction. More than 90% of the available metal content is found associated with these fine particles, on account of their large cumulated surface area (e.g. Mayer and Fink, 1979; Ackermann, 1980; Deely and Fergusson, 1994; He and Walling, 1996). For wet sieving, 25–30 g of bulk sediment were weighed in polyethylene flasks, homogenized in 100 ml of ultra-pure water (milli-Q, 18.6 MΩ cm^{-1}), gently shaken during 1 h and sieved. The two fractions obtained were dried at 40 °C, weighed and stored in vinyl bags.

Even though legitimate criticisms have been addressed at the method of sequential extractions (Jouanneau et al., 1983; Nirel and Morel, 1990), such chemical digestion techniques show nevertheless great potential for identifying the origin and complexity of sediment-bound metals and can be used as pertinent geochemical signatures (see a review by Cornu and Clozel, 2000). Based on the technique initially developed for river sediments (Tessier et al., 1979), the sequential extraction was applied to carbonate lagoon sediments (Fernandez et al., 2005). Among the 5 extractable metal forms, the refractory one can be considered as the fraction related to the residual mineral matrix. In the lagoon of New Caledonia, this last form provides a clear geochemical signature of the terrigenous contributions (Trescases, 1973; Lathal, 1985; Becquer et al., 1995; Quantin et al., 2002).

The refractory, or so-called residual, form was obtained by digestion with strong acids in Teflon vessels submitted to high pressure and temperature conditions in a microwave oven (Anton Paar/Perkin Elmer). Mass loss was measured for each step of the sequential extraction. The reagents and chemicals used were Merck, ProAnalysis trade; all materials in contact with the sediment samples were made of PEHD, Nalgène or Teflon and decontaminated by soaking in nitric acid (HNO$_3$ 5%) for 24 h and rinsed with ultra-pure water (Milli-Q). After each extraction, concentrated nitric acid was poured in the Teflon vessels which underwent a cycle of decontamination in the microwave oven.

Ni and Cr concentrations were analysed by ICP-OES (Optima 3300 FD, Perkin Elmer). Results are expressed either as absolute concentration, i.e. mass of metal vs. mass of pelite, (C_{Pel}, in mg kg^{-1}, Eq. (1)) or as relative concentration, i.e. mass of metal vs. mass of refractory phase, (C_{Ref}, in mg kg^{-1}, Eq. (2)), according to the relationship:

$$C_{Pel} = (C \cdot D \cdot V)/M_i \tag{1}$$

where C = concentration in extraction solution (mg L^{-1}), D = dilution factor, V = extraction solution volume (L) and M_i = mass of initial pelitic fraction (kg), and

$$C_{Ref} = (C \cdot D \cdot V)/(M_a - M_b) \tag{2}$$

where C = concentration in extraction solution (mg L^{-1}), D = dilution factor, V = extraction solution volume (L), M_i = mass of initial pelitic fraction (kg), M_a = pelitic mass before acid treatment of the geochemical phase (kg), and M_b = pelitic mass of fraction after treatment of the geochemical phase (kg).

The combination of concentrations C_{Pel} and C_{Ref} proved to be very useful for discriminating between different metal sources, and hence for identifying the origin of the inputs.

Analyses were carried out in triplicate to check the reproducibility of the protocol. Certified reference material (SD-M-2/TM, NRCC-BCSS-1) was analysed simultaneously to verify extraction efficiency.

3.4. Hydrodynamic modelling and Lagrangian tracers

Extensive work has been done on hydrodynamic modelling of the lagoon of New Caledonia (Douillet, 1998; Douillet et al., 2001) using a version of MARS3D, a three-dimensional hydrodynamic model (Lazure and Salomon, 1991; Tartinville et al., 1998). The governing equations of the hydrodynamic model express the conservation of mass, momentum and salinity and assume the hydrostatic and Boussinesq approximations (e.g. Blumberg and Mellor, 1987; Ruddick et al., 1995; Estournel et al., 1997). The equations are solved in the σ-coordinate system using the finite difference technique (Blumberg and Mellor, 1987; Lazure and Salomon, 1991). Vertical eddy viscosity is determined using a mixing length turbulence model. The resolution is based on the mode splitting technique (Blumberg and Mellor, 1987). The modelled area stretches from the south of the main island to the north of Noumea, a distance along the shore of 150 km. The horizontal grid size is 500 m and each water column is divided into 10σ-levels. The model was validated in the south-west lagoon of New Caledonia from velocity measurements performed using an Acoustic Doppler Current Profiler.

A Lagrangian tracer method was coupled to the hydrodynamic model. The numerical scheme is a third order Runge–Kutta method. The Lagrangian method can be used to trace the advection of "water particles" originating from different locations. For the purpose of this study, two water masses originating from the Coulée River mouth and from the Pirogues River mouth were considered. 21,000 neutrally buoyant particles were tracked over a period of several months under the double influence of an average tide evolution (M2 and S2 constituents) and of typical trade-wind conditions (110°, 8 m s^{-1}). At the end of each run, the respective percentage of neutrally buoyant particles entering Sainte Marie Bay from the two considered sources could be calculated. Simulations were conducted with particles discharged at four different stages of the tidal cycle (high tide, low tide and intermediate flooding and ebbing times, each of them at the beginning of spring tide) and the percentage of particles entering Sainte Marie Bay from the two sources was averaged from these four simulations.

3.5. Statistics

Squared correlation coefficient R^2 is defined as

$$\rho_{x,y}^2 = \left(\frac{\mathrm{Cov}(X,Y)}{\sigma_x \cdot \sigma_y}\right)^2$$

4. Results

Sedimentological and geochemical data from Sainte Marie and Boulari bays are presented in Table 1.

4.1. Sedimentology

Grain size distributions in the 12 stations sampled in Boulari Bay were consistent (Fig. 2) with a clear trend from

Table 1
Sedimentological and geochemical data collected in the studied area

|	Boulari Bay			Sainte Marie Bay		
	Total	Vicinity of the river mouth	Bay except near the mouth	Total	North-west area	Bay except NW
Grain size						
Mean (μm)	91.8	50.2	103	117	86.1	152
Mean size range (μm)		44.5–56.7	46.4–285		45.8–758	47.0–403
Mud content						
Mean (%)	65.4	88.5	60.8	52.9	70.5	38.2
Range (%)		79.0–98.0	24.9–88.4		12.5–91.5	10.0–84.2
Carbonate content						
Mean (%)	55.6	8.8	65.0	62.7	54.8	69.2
Range (%)		0.2–17.3	48.1–88.0		46.2–65.2	64.6–76.3
Metals in pelites						
Refractory forms (mg kg^{-1})						
$C_{Pel/Ni}$	255–7687	4702–7687	255–2103	172–373	172–285	201–373
$C_{Pel/Cr}$	314–5987	2699–5987	314–1340	128–226	128–194	140–226
$C_{Pel/Zn}$	17.2–309	165–309	17.2–91.2	14.0–57.2	28.8–57.2	14.0–34.9
$C_{Ref/Ni}$	2931–9682	8660–9682	2931–6756	615–2522	615–1283	811–2522
$C_{Ref/Cr}$	2068–7882	4970–7882	2068–4084	366–1919	366–771	471–1919
$C_{Ref/Zn}$	190–389	303–389	190–278	117–193	117–151	117–193
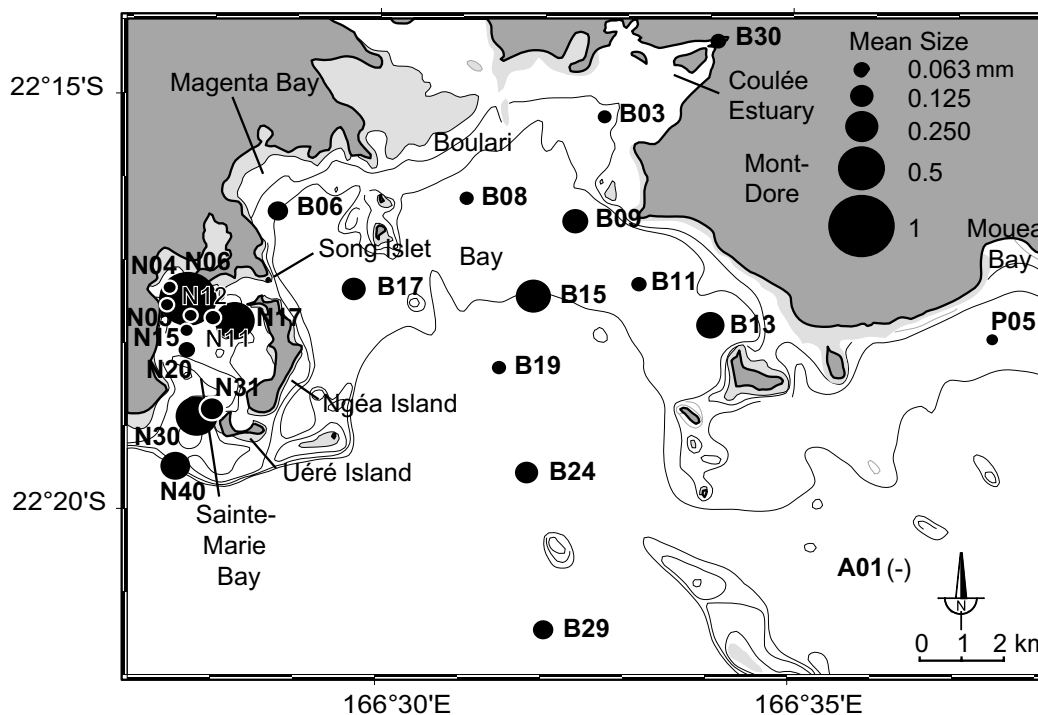
Fig. 2. Mean grain size of surface sediments from the south-western New-Caledonia lagoon. Mean size is proportional to circle area (scale in the top right corner). Missing values (–) for A01.

coast to offshore towards fine sediments. Five stations were classified as *muds* (Mz < 0.063 mm, B03, B08, B11, B19, B30) while six others were classified as *very fine sands* (0.063 < Mz < 0.125 mm; B06, B24, B29) or *fine* (0.125 < Mz < 0.250 mm; B09, B13, B17). Sediment in the last station (B15) corresponded to a *medium sand* (0.250 < Mz < 0.500 mm). Among *muds*, only one sample (B03) was located at a shallow depth (5 m), on the prodelta prism.

In Sainte Marie Bay, one sample did not provide enough sediment for grain size analysis (N25). This station was located in a coral field growing on the muddy bottoms which occupy a large part of Sainte Marie Bay (central and east areas) (Fig. 2). Mean sediment grain size was much more variable in Sainte Marie Bay than in Boulari Bay, ranging from 0.046 mm (*muds*, N12) to 0.758 mm (*coarse sands*, N06). Sediment samples could be classified as *muds* at six stations (N04, N05, N11, N12, N15, N20), *fine sands* at two stations (N31, N40), *medium sands* at two stations (N17, N30) and *coarse sands* at only one station (0.500 < Mz < 1 mm; N06).

From their mud content (particle sizes <63 μm), sediment from Boulari Bay (Fig. 3) could be classified as *pure mud facies* (>80%, B03, B08, B11, B19), *very high mud facies* (40–60%, B09, B15, B17, B24), *dominant mud facies* (60–80%, B29, B30) or *high mud facies* (20–40%, B06, B13). Boulari Bay proved to be heavily subject to silting, with maximum mud content in the Coulée River prodelta (B03: 98%) and minimum mud content of 24.9% (B06) and 35% (B13) on each side of the bay.

In Sainte Marie Bay, the percentage of mud ranged from 11.4% (*moderate mud facies*, N31) to 91.5% (*pure mud*, N12). An area of sediments with high percentage of mud (52.9–84.8%) was identified in the north-western part of the bay (stations N04, N05, N11, N12, N15) clearly identifying a sediment settling area. Elsewhere, and apart from stations N20 (*dominant mud*) and N31 (*high mud*) located in depressions, the silting was moderate (N06, N17, N25, N30, N40).

In the south-west lagoon of New Caledonia, sediment carbonates are essentially of benthic biogenic origin (Chevillon, 1992, 1996). Apart from a generally very low siliciclastic biogenic component, the non-carbonate sediment fraction is of terrigenous origin.

The percentage of carbonates in the <63 μm sediment fraction in Boulari Bay (Fig. 4) ranged from 88% (B29, *high carbonate facies*) to 0.2% (B30, *high terrigenous facies*), the later corresponding to the Coulée River estuarine area. Except for B29 which can be classified as a station predominantly influenced by authigenic lagoon inputs (88.0% $CaCO_3$, *high carbonate facies*), most of the bay can be classified as *transitional facies* between terrigenous and carbonated influences (40–60%, B08, B09, B15, B17) or as *impure carbonate facies* (60–80%, B06, B11, B13, B19, B24).

In Sainte Marie Bay, the percentage of carbonates ranged from 46.2% (N05) to 76.3% (Fig. 4). Only two facies (*impure carbonates* and *transitional*) were observed, the stations with the lowest carbonate percentages corresponding to those in the north-west settling area, which already presented the highest mud percentages (N04, N05, N06).
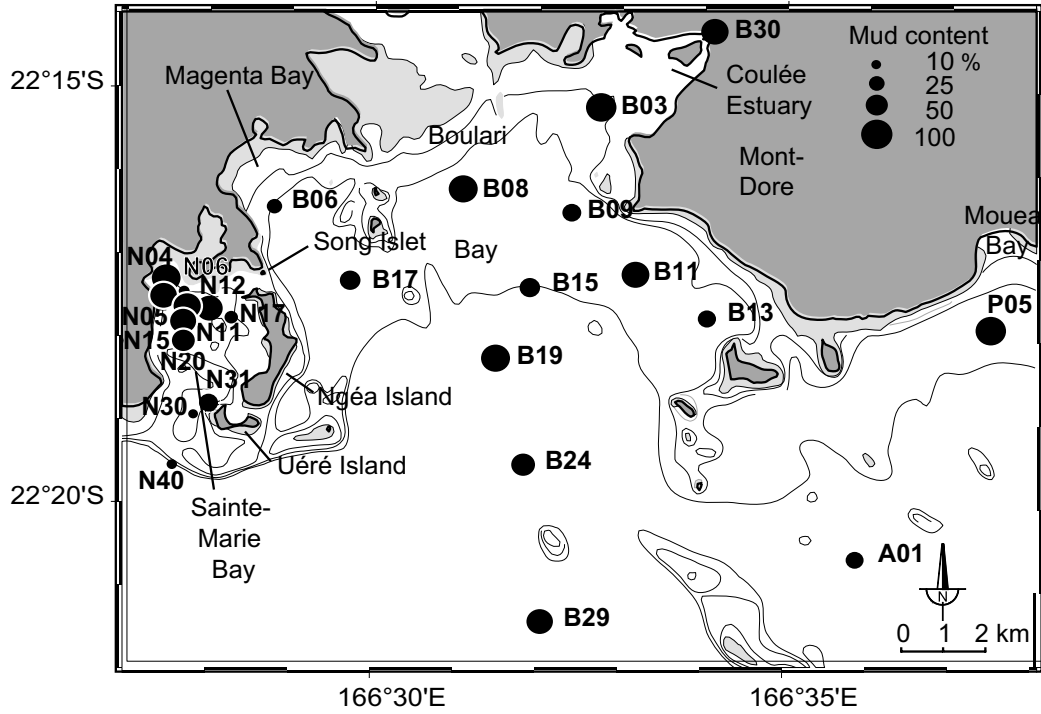
Fig. 3. Mud content (%) in surface sediments from the south-western New-Caledonia lagoon. Content is proportional to circle area (scale in the top right corner).
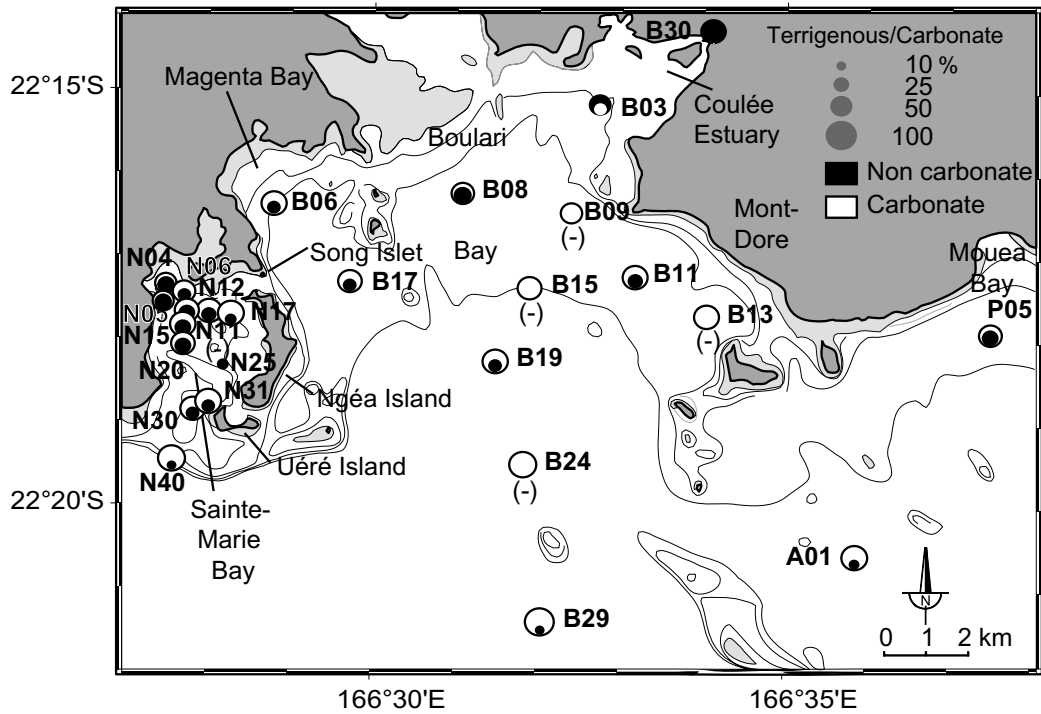

Fig. 4. Carbonate and non-carbonate fractions in % of pelites mass in surface sediment from the south-western New-Caledonia lagoon. Missing values (–) are for carbonate in N25 and non-carbonate in B09, B13, B15 and B24. Content is proportional to circle area (scale in the top right corner).

4.2. Geochemical signatures

Nickel in the residual fraction (Fig. 5) accounts for 77–87% of the total concentration in Sainte Marie Bay pelites

and 85–97% of the total concentration in Boulari Bay pelites. $C_{Pel/Ni}$ (absolute Ni concentration in residual phase of pelites) reached 7028 mg kg^{-1} in the Coulée Estuary (B30), a value of the same order of magnitude as those measured
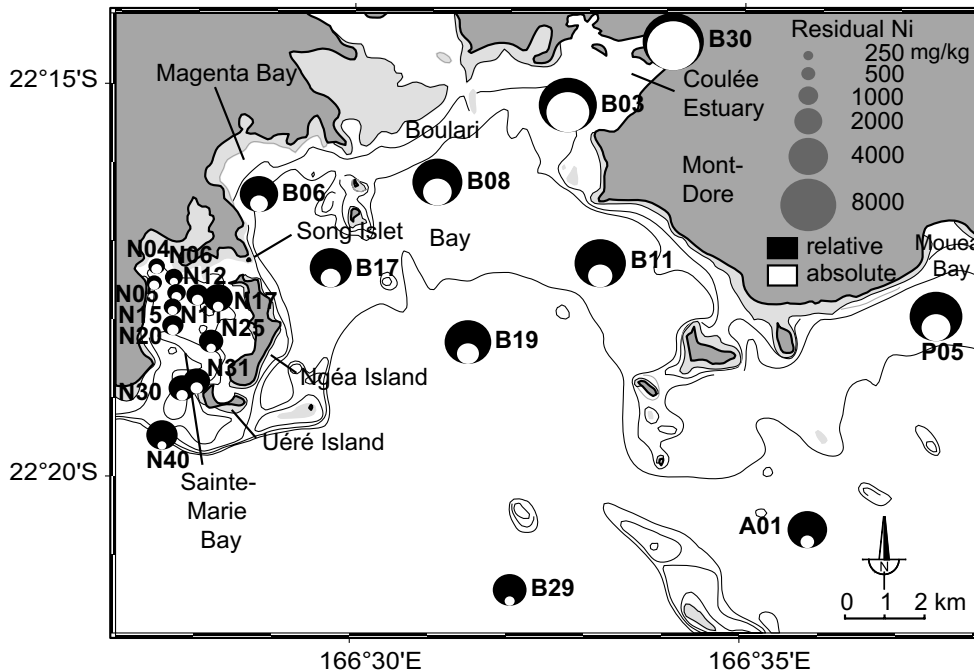
Fig. 5. Residual absolute and relative nickel concentration (mg kg^{-1}) in the pelitic fraction of surface sediments of the south-western New-Caledonia lagoon. Concentration is proportional to circle area (scale in the top right corner).

upstream (B01: 5900 mg kg^{-1}; B02: 7687 mg kg^{-1}) and more than 3 times higher than in Mouéa Bay (P05: 2135 mg kg^{-1}), nearby. $C_{Pel/Ni}$ decreased to 1000–1500 mg kg^{-1} in the southern and south-eastern part of Boulari Bay (B17, B19 and B11) and 803 mg kg^{-1} in it western part (B06). Farther from the Coulée River mouth, sediment $C_{Pel/Ni}$ decreased to 255 and 473 mg kg^{-1} at stations B29 and A01, respectively. In Sainte Marie Bay, $C_{Pel/Ni}$ ranged from 172 to 373 mg kg^{-1} at N06 and N31, respectively, showing evidence of pelites with low nickel content even in the north-western part of the bay where muddy sediments prevailed. The highest $C_{Pel/Ni}$ in Sainte Marie Bay corresponds to the stations located in the channelized central zone. $C_{Ref/Ni}$ (relative Ni concentration in residual phase of pelites) was relatively consistent along the whole river stream (B01: 8709 mg kg^{-1}; B02: 9682 mg kg^{-1}; sampling station locations in Fig. 1) down to the outer estuary (B30: 9607 mg kg^{-1}; B03: 8660 mg kg^{-1}). In Boulari Bay, $C_{Ref/Ni}$ was of the same order of magnitude, except for the stations most distant from the river mouth (B06: 3786 mg kg^{-1}; B29: 2931 mg kg^{-1}). In Sainte Marie Bay, $C_{Ref/Ni}$ was below 850 mg kg^{-1} in the northern part of the bay (N04, N05, N06) where muddy sediments prevailed and above 850 mg kg^{-1} in the channelized central zone of the bay with maximum values of 2205 mg kg^{-1} at N17 close to the threshold passage between Boulari and Sainte Marie Bay and 2522 mg kg^{-1} at N40 at the southern entrance to Sainte Marie Bay.

Despite the resistance of chromites to strong acids (Tessier et al., 1979; Oze et al., 2004) and the resulting potential for underestimating concentrations, chromium in the residual phase represented 83–90% and 91–99% of the total chromium in the pelites from Sainte Marie Bay and Boulari Bay, respectively. The distribution of chromium (Fig. 6) was very similar to that of nickel ($R^2 = 0.86$, $n = 23$). In Boulari Bay, $C_{Pel/Cr}$ (absolute Cr concentration in residual phase of pelites) decreased from 4231 mg kg^{-1} at B30 to 599 mg kg^{-1} at B17 along the same north-east/south-west axis, reached 1664 mg kg^{-1} in Mouéa Bay (P05) and decreased below 450 mg kg^{-1} in the areas furthest from shore (B29, A01). In Sainte Marie Bay, $C_{Pel/Cr}$ readings were relatively consistent, the lowest and highest values being, as for nickel, localized in the north-western part of the bay (N06: 128 mg kg^{-1}) and the central deeper channel (200 mg kg^{-1}). The distribution of $C_{Ref/Cr}$ (relative Cr concentration in residual phase of pelites) also showed a great similarity with that of nickel. $C_{Ref/Cr}$, of 5784 and 4970 mg kg^{-1} in stations B30 and B03, respectively, which clearly identified the Coulée River as the end source term. Elsewhere in Boulari Bay, $C_{Ref/Cr}$ decreased as a function of the distance from the Coulée Estuary, the minimum value of 2026 mg kg^{-1} being reached at station B06, as we had seen for nickel. In Sainte Marie Bay, the distribution of $C_{Ref/Cr}$ also mirrored the distribution of $C_{Ref/Ni}$, with maximum values in the central deeper channel zone, close to the passage between Boulari Bay and Sainte Marie Bay (N17: 1765 mg kg^{-1}) and at the northern entrance to Sainte Marie Bay (N40: 1919 mg kg^{-1}). In its north-western part where terrigenous muddy sediment deposits were identified, $C_{Ref/Cr}$ only reached moderate values of 366 and 400 mg kg^{-1} in N04 and N05, respectively.
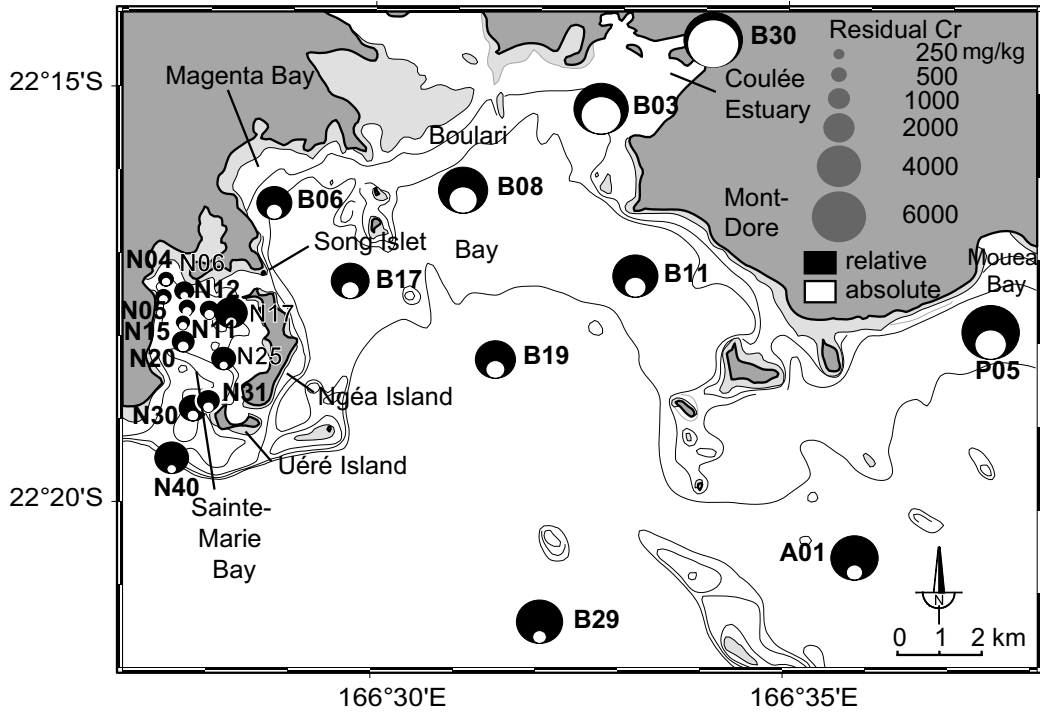
Fig. 6. Residual absolute and relative chromium concentration (mg kg^{-1}) in the pelitic fraction of surface sediments of the south-western New-Caledonia lagoon. Concentration is proportional to circle area (scale in the top right corner).

4.3. Hydrodynamics

Simulations of the transport of non-settling particles from the mouths of the Coulée River and the Pirogues River (Figs. 7 and 8) showed that 29.9% and 30.5% respectively of the particles originating from them entered Sainte Marie Bay. However, whereas particles originating from the Coulée River essentially penetrated through the threshold located between Ngéa and Song Islands, those coming from the Pirogues River entered partly by way of this threshold (19.3%) and partly by the southern entrance to Sainte Marie Bay (11.2%).

Among the terrigenous particles entering Sainte Marie Bay, those from the Coulée River originated from the surface layers and passed the threshold at greater depth (average origin vertical position: 82% of water height; average arrival vertical position: 34% of water height). As an example, Fig. 7A shows that particles departing at 1 m depth (80% of 5 m water height) in front of the Coulée Estuary reached 3 m depth approximately at the beginning of the passage threshold ($\simeq$40% of 5 m height of water). Particles departing simultaneously from the same point but close to the bottom rarely entered Sainte Marie Bay as they tended to remain in the deeper part of the water column (Fig. 7B).
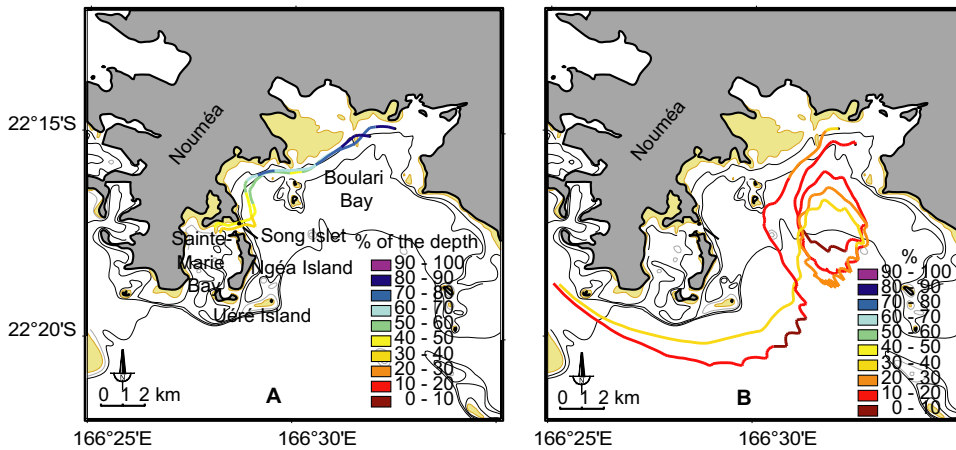

Fig. 7. Examples of trajectory of neutrally buoyant particles originating from Coulée River mouth surface waters (A) and from bottom waters (B) under the influences of tide and mean wind-trade (110°, 8 m s^{-1}). Calculations were stopped when particles entered Sainte Marie Bay or left the study area. Isobaths correspond to 5 m, 10 m and 20 m depths.
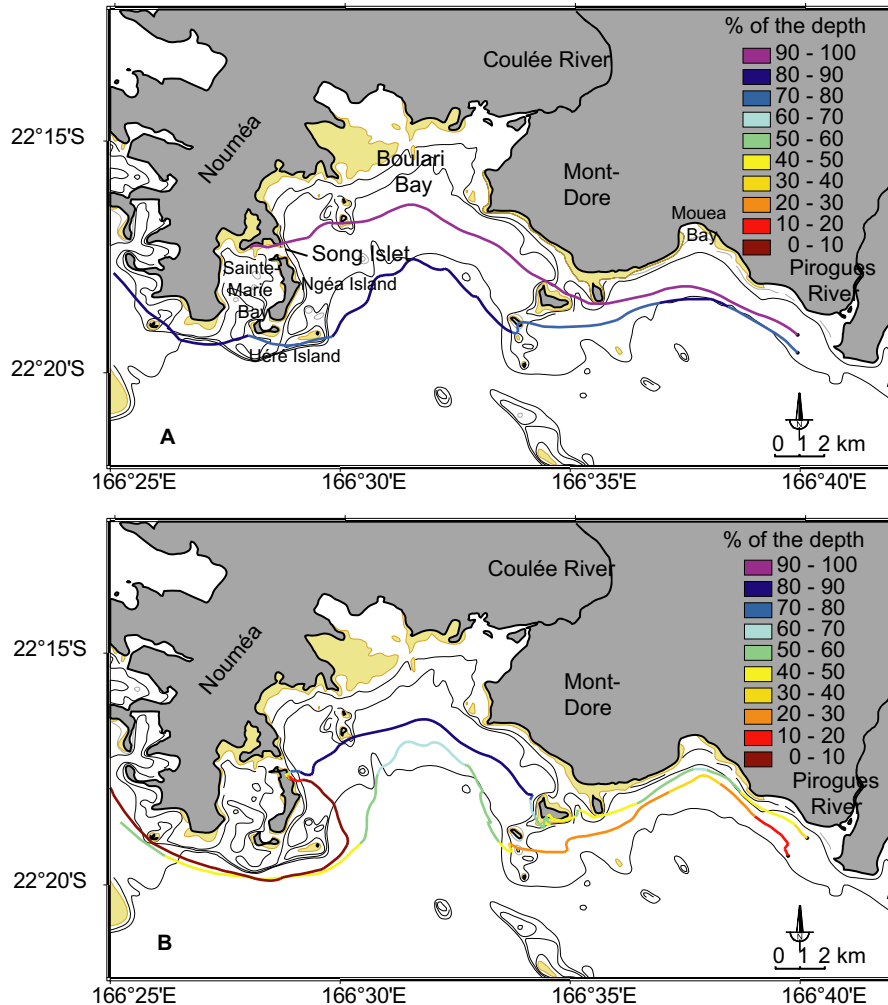
Fig. 8. Examples of trajectory of neutrally buoyant particles originating from Pirogues River mouth surface waters (A) and from bottom waters (B) under the influences of tide and mean wind-trade (110°, 8 m s^{-1}). Calculations were stopped when particles entered Sainte Marie Bay or left the study area. Isobaths correspond to 5 m, 10 m and 20 m depths.

Terrigenous particles from the Pirogues River estuary passing over the threshold originated primarily from the higher part of the water column (average origin vertical position: 61% of water height) and remained at the same level during the whole transport (average arrival vertical position: 64% of water height) (Fig. 8A). Almost none of the particles coming from the lower level of the water column in front of the Pirogues River estuary entered Sainte Marie Bay even though they experienced a double vertical movement, ascending while penetrating in Boulari Bay near Mont-Dore, and descending in the vicinity of Ngéa Island (Fig. 8B).

5. Discussion

Bioclastic particles have different densities and forms, resulting in variable hydraulic behaviours (Chevillon, 1992, 1996). Adaptation of sedimentological indices developed for rivers to coral reef lagoon systems is potentially unreliable. In Boulari Bay and Sainte Marie Bay, the distri-

bution and nature of sediments were not directly related to depth (e.g. Mean size vs. depth, $R = 0.37$) but rather obeyed constraints related to the hydrodynamic regime.

Nickel and chromium concentrations in the residual geochemical phases of the pelites proved to be suitable tracers of the Coulée River inputs into Boulari Bay. These geochemical data indicated that Sainte Marie Bay received significant terrigenous inputs from one major source, the Coulée River. These inputs are diluted with particulate matter resulting from the deterioration of the coasts (B06) or the bedrock (B29). One cannot exclude the effect of re-release of metals from the sediments, which could be significant in the case of nickel (Paris, 1981a; Ambatsian et al., 1997). Simulations of the transport of neutrally buoyant particles agreed with geochemical analyses and demonstrated that inputs originating from the Coulée River were not limited to Boulari Bay and that nearly one third could reach Sainte Marie Bay.

The contribution from the Pirogues River seems moderate and confined to its close mouth (P04) and coastal fringe

(P05); few solid particles appear to be exported towards the north-west (i.e. towards Boulari Bay) despite the currents. Simulations of the transport of neutrally buoyant particles (Figs. 7A and B, 8A and B) showed that particles originating from the Coulée River skirt the coast, possibly after being pulled within a gyre located in the centre of Boulari Bay, and that the particles coming from the Pirogues River only enter the outer half of Boulari Bay. Even though extrapolation of these results to the transport of real settling particles is not straightforward, one may assume that only the transfer of water of the Coulée River is accompanied by the sedimentation of a significant amount of settling particles in Sainte Marie Bay, and that particles brought by the Pirogues River probably settle before reaching Boulari Bay (e.g around P04 and P05).

Although narrow (≈500 m) and relatively shallow (≈3 m deep), the threshold passage between Ngéa and Song Islands allows significant imports of terrigenous material to enter into Sainte Marie Bay. Naturally sheltered from the dominant trade winds, Sainte Marie Bay is a favourable site for sedimentation especially in the channel which circumvents the coral fields. Simulations of particle trajectories together with high nickel and chromium concentrations in the residual phase down-current from the threshold (N17) strongly support this pattern.

The contribution of the Coulée River terrigenous inputs to Sainte Marie Bay sediments can be estimated by a simple two end source mixing model (Faure, 1986). This evaluation calls upon the mixture of two sources of particles, indexed by CR (Coulée River) and Bg (Background), from which the characteristics and the proportions differ, according to Eq. (3):

$$[Ni] = [Cr] \cdot \left(\frac{[Ni]_{CR} - [Ni]_{Bg}}{[Cr]_{CR} - [Cr]_{Bg}} \right)$$
$$+ \frac{[Ni]_{Bg} \cdot [Cr]_{CR} - [Ni]_{CR} \cdot [Cr]_{Bg}}{[Cr]_{CR} - [Cr]_{Bg}} \quad (3)$$

where $[Ni]_{CR} = 7028$ mg kg^{-1}, $[Ni]_{Bg} = 100$ mg kg^{-1}, $[Cr]_{CR} = 4231$ mg kg^{-1}, $[Cr]_{Bg} = 120$ mg kg^{-1}.

If one accepts the assumption that the resulting mixtures of metals do not undergo a process of transformation, then nickel and chromium in the residual phase can be considered as conservative geochemical signatures on a time scale of the local transport phenomena. The Coulée River end term signature is given by the ratio $[Ni]_{CR}/[Cr]_{CR} = 1.66$ measured at B30. The value of the second source term is provided by the geological background measured in the deep layers of a sediment core from Sainte Marie Bay (Fernandez et al., 2002): $[Ni]_{Bg}/[Cr]_{Bg} = 0.83$. The linear regression ($R^2 = 0.998$, $n = 5$) fits the model (Fig. 9) demonstrating that stations B30, B03, B08, B17 and N17 were localized along a dilution gradient from the Coulée River end point source and their order relatively closely related to the simulated particle trajectories. These results strongly support the hypothesis that sedimentation in Sainte Marie Bay largely originates from the Coulée River
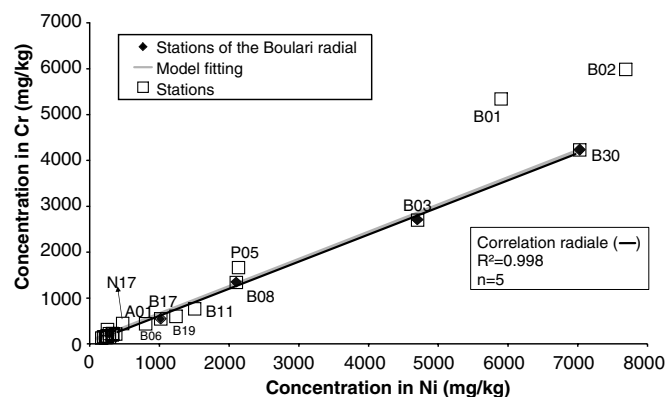

Fig. 9. Experimental values of [Cr] vs. [Ni] in the refractory phase of the pelitic surface sediments, and dilution straight line based on a two chemical components mixing model.

exports. According to Eq. (3), about 2.5% of the material released from the Coulée River was deposited at station N17. Other stations which deviated from the dilution line either corresponded to river sediments (B01 and B02) with pelitic fractions highly enriched in chromium, or to stations in Boulari Bay with a nickel excess (B06, B19, B11).

These results match the preliminary studies on sedimentary records carried out on the Sainte Marie Bay area (Fernandez et al., 2002), showing increasing terrigenous inputs over the last century, as demonstrated by both of the clear shifts in sediment composition in Ni and Cr. These environmental changes correspond also with a change in the deposition regime of particulate matter, sharply increasing about fifty years ago, with ^{210}Pb dating yielding two different sediment accumulation rates. The proposed date of sedimentation change corresponds with the beginning of large scale and extensive open-cast mining activities in the southern part of New Caledonia (Bird et al., 1984; Mermoud, 1994).

6. Conclusion

Natural and mining-related terrigenous inputs delivered to the lagoon by the small Coulée River catchment are not limited to Boulari Bay but a significant fraction is exported mainly westward due to prevailing along-shore currents generated by the trade winds. Part of this terrigenous export enters Sainte Marie Bay and is deposited along a general north-south axis. In this bay, the terrigenous contribution represented more than 7000 and 4200 mg kg^{-1} of suspended particulate Ni and Cr respectively, exported towards areas initially marginally affected by terrigenous inputs. Even though a very large part of terrigenous metal can be considered as unavailable, these terrigenous inputs will, in the long term, inevitably result in an increase in the exchangeable fraction which has a high likelihood of being absorbed by living organisms and thus enter the food chain. When comparing the total nickel ore production of the Coulée basin (425,103 tons in one century) with the planned nickel production of New Caledonia for the

coming years (nearly 20 million ton yr^{-1}), it appears evident that precautions will have to be taken to limit metal contamination of the lagoon due to weathering and erosion of the soils.

Acknowledgements

References

Ackermann, F., 1980. A procedure for correcting the grain size effect in heavy metal analyses of estuarine and coastal sediments. Environment Technology Letters 1, 518–527.

Ambatsian, P., Fernex, F., Bernant, M., Parron, C., Lecolle, J., 1997. High metal inputs to close seas: the New-Caledonia Lagoon. Journal of Geochemical Exploration 59, 59–74.

Antheaume, B., 1981. Extraction minière et métallurgie. In: Sautter, G. (Ed.), Atlas de Nouvelle-Calédonie. ORSTOM, Paris, graphe 41.

Baltzer, F., Trescases, J.J., 1971. Erosion, transport et sédimentation liés aux cyclones tropicaux dans les massifs d'ultrabasites de Nouvelle-Calédonie. Cahiers ORSTOM Série Géologie III (2), 221–244.

Becquer, T., Bourdon, E., Pétard, J., 1995. Disponibilité du nickel le long d'une toposéquence de sols développés sur roches ultramafiques de Nouvelle-Calédonie. Comptes Rendus Académie des Sciences de Paris IIa 321, 585–592.

Bird, E.C.F., Dubois, J.P., Iltis, J.A., 1984. The impact of opencast mining on the rivers and coasts of New Caledonia. The United Nation University, NRTS-25/UNUP-505, 53 p.

Blumberg, A.F., Mellor, G.L., 1987. A description of the three-dimensional coastal ocean circulation model. In: Heaps, N.S. (Ed.), Three-Dimensional Coastal Ocean Model. American Geophysical Union, Washington DC, pp. 1–16.

Bonneau, M., Souchier, B., 1979. Pédologie 2: Constituants et propriétés du sol. Masson, Paris, 459 p.

Buchanan, J.B., 1984. Sediment analysis. In: Holme, N.A., McIntyre, A.D. (Eds.), Methods for the Study of Marine Benthos, second ed. Blackwell Scientific Publications, Oxford, pp. 41–65.

Bujan, S., Grenz, C., Fichez, R., Douillet, P., 2000. Evolution saisonnière du cycle biogéochimique dans le lagon sud-ouest de Nouvelle-Calédonie. Application d'un modèle compartimental. Compte Rendu de l'Académie des Sciences de Paris, Life Sciences, Ecology 323, 225–233.

Caccia, V.G., Millero, F.J., Palanques, A., 2003. The distribution of trace metals in Florida Bay sediments. Marine Pollution Bulletin 46 (11), 1420–1433.

Chevillon, C., 1992. Biosédimentologie du grand lagon nord de la Nouvelle-Calédonie. Etudes & Thèses, ORSTOM, Paris, 224 p.

Chevillon, C., 1996. Skeletal composition of modern lagoon sediments in New-Caledonia: coral, a minor constituent. Coral Reef 15, 199–207.

Cornu, S., Clozel, B., 2000. Extractions séquentielles et spéciation des éléments traces métalliques dans les sols naturels. Analyse critique. Etude et Gestion des Sols 7 (3), 179–189.

Deely, J.M., Fergusson, J.E., 1994. Heavy metal and organic matter concentrations and distribution in dated sediments of a small estuary adjacent to a small urban area. Science of the Total Environment 153, 97–111.

Douillet, P., 1998. Tidal dynamics of the south-west lagoon of New Caledonia: observations and 2D numerical modelling. Oceanologica Acta 21 (1), 69–79.

Douillet, P., Ouillon, S., Cordier, E., 2001. A numerical model for fine suspended sediment transport in the south-west lagoon of new Caledonia. Coral Reefs 20, 361–372.

Dugas, F., Debenay, J.P., 1982. Carte sédimentologique et carte annexe du lagon de Nouvelle Calédonie au 1/50,000—Noumea, Mont Dore, La Tontouta, Prony. Notices explicatives no. 76, 86, 91 et 95. ORSTOM, Paris.

Estournel, C., Kondrachoff, V., Marsaleix, P., Vehil, R., 1997. The plume of the Rhone: numerical simulation and remote sensing. Continental Shelf Research 17 (8), 899–924.

Faure, G., 1986. Principles of Isotope Geology, second ed. John Wiley and Sons, New-York, 589 p.

Fernandez, J.-M., Moreton, B., Fichez, R., Breau, L., Magand, O., Badie, C., 2002. Advantages of combining ^{210}Pb and geochemical signature determinations in sediment record studies: application to coral reef lagoon environments. In: Fernandez, J.-M., Fichez, R. (Eds.), Environmental Changes and Radioactive Tracers. IRD Editions, Paris, France, pp. 187–199.

Fernandez, J.M., Breau, L., Cabon, M., Fichez, R., 2005. Distribution et variabilité des métaux de transition dans les sédiments du lagon sud-ouest de Nouvelle-Calédonie, Collection Sciences de la Mer, Note technique no. 3, IRD Nouméa.

Fichez, R., Chifflet, S., Douillet, P., Gérard, P., Ouillon, S., submitted for publication. Biogeochemical typology and temporal variability of lagoon waters in a coral reef ecosystem subject to terrigenous and anthropogenic inputs (New Caledonia). Marine Pollution Bulletin.

Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study of significance of grain size parameters. Journal of Sedimentary Petrology 27, 3–26.

He, Q., Walling, D.E., 1996. Interpreting particle size effects in the adsorption of Cs-137 and unsupported Pb-210 by mineral soils and sediments. Journal of Environmental Radioactivity 30 (2), 117–137.

Jouanneau, J.M., Latouche, C., Pautrizel, F., 1983. Analyse critique des extractions séquentielles à travers l'étude de quelques constituants des résidus d'attaques. Environmental Technology Letters 4, 509–514.

Labrosse, P., Fichez, R., Farman, R., Adams, T., 2000. New Caledonia. In: Sheppard, C. (Ed.), Seas at the Millenium, an Environmental Evaluation, vol. 2. Elsevier, Amsterdam, pp. 723–736.

Lathal, M., 1985. Altération et pédogenèse sur roches ultrabasiques en Nouvelle-Calédonie. Ph.D. Thesis, University of Dijon, 331 pp.

Lazure, P., Salomon, J.C., 1991. Coupled 2-D and 3-D modelling of coastal hydrodynamics. Oceanologica Acta 14 (2), 173–180.

Lillie, A.R., Brothers, R.N., 1970. The geology of New-Caledonia. New Zealand Journal of Geology and Geophysics 13 (1), 159–167.

Liston, P., Furnas, M.J., Mitchell, A.W., Drew, E.A., 1992. Local and mesoscale variability of surface water temperature and chlorophyll in the northern Great Barrier Reef, Australia. Continental Shelf Research 12, 907–921.

Maxwell, W.G.H., 1968. Atlas of the Great Barrier Reef. Elsevier, Amsterdam, 258 pp.

Mayer, L.M., Fink, L.K., 1979. Granulometric control of chromium accumulation in estuarine sediments in Maine. Estuarine and Coastal Marine Science 11, 491–503.

Mermoud, Y., 1994. Processus de dégradation du milieu naturel dans le bassin versant de la Rivière des Pirogues. Mémoire de Licence, Université Française du Pacifique, Centre de Nouméa.

Mc Laughlin, C.J., Smith, C.A., Buddemeier, R.W., Bartley, J.D., Maxwell, B.A., 2003. Rivers, runoff, and reefs. Global and Planetary Change 39, 191–199.

Muslim, I., Jones, G., 2003. The seasonal variation of dissolved nutrients, chlorophyll a and suspended sediments at Nelly Bay, Magnetic Island. Estuarine Coastal Shelf Sciences 57, 445–455.

Nirel, R., Morel, P.M., 1990. Pitfalls of sequential extractions. Water Resources 24, 1055–1056.

Ouillon, S., Douillet, P., Andrefouet, S., 2004. Coupling satellite data with in situ measurements and numerical modelling to study fine suspended sediment transport: a study for the lagoon of New Caledonia. Coral Reefs 23 (1), 109–122.

Oze, C., Fendorf, S., Bird, D.K., Coleman, R.G., 2004. Chromium geochemistry of serpentines soils. International Geology Review 46 (2), 97–126.

Paris, J.P., 1981a. Les ressources minérales de Nouvelle-Calédonie. Mémoire 113, BRGM, Orléans, pp. 219–224.

Paris, J.P., 1981b. Gîtes minéraux et substances utiles. In: Sautter, G. (Ed.), Atlas de Nouvelle-Calédonie. ORSTOM, Paris, graphe 40.

Pinazo, C., Bujan, S., Douillet, P., Fichez, R., Grenz, C., Maurin, A., 2004. Impact of wind and freshwater inputs on phytoplankton biomass in the coral reef lagoon of New Caledonia during the summer cyclonic period: a coupled three-dimensional biogeochemical modelling approach. Coral Reefs 23 (2), 281–296.

Quantin, C., Becquer, T., Berthelin, J., 2002. Mn-oxide: a major source of easily mobilisable Co and Ni under reducing conditions in New Caledonia Ferralsols. Comptes Rendus Geoscience 334, 273–278.

Ruddick, K.G., Deleersnijder, E., Luyten, P.J., Ozer, J., 1995. Haline stratification in the Rhine-Meuse plume: a three-dimensional model sensitivity analysis. Continental Shelf Research 15, 1597–1630.

Tartinville, B., Deleersnijder, E., Lazure, P., Proctor, R., Ruddick, K.G., Uittenbogaard, R.E., 1998. A coastal ocean model intercomparison study for a three-dimensional idealised test case. Applied Mathematical Modelling 22, 165–182.

Tessier, A., Campbell, P.G.C., Bisson, M., 1979. Sequential procedure for the speciation of particulate trace metals. Analytical Chemistry 51, 844–851.

Trescases, J.J., 1973. L'évolution geochimique supergène des roches ultrabasiques en zone tropicale. Formation des gisement nickélifères de Nouvelle-Calédonie. Ph.D. Thesis OA 8708, Université Louis Pasteur, Strasbourg.

Wentworth, CK., 1922. A scale of grade and class terms for clastic sediments. Journal of Geology 30, 377–392.