Marine Pollution Bulletin 59 (2009) 311–322

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Benthic foraminifera records of complex anthropogenic environmental changes combined with geochemical data in a tropical bay of New Caledonia (SW Pacific)

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ARTICLE INFO

Keywords:
Foraminifera
Pollution
Terrigenous tracers
Core
Southwest Pacific

ABSTRACT

During the 1950s, open-cast mining led to an increasing input of heavy-metal-rich terrigenous particles in the bays near Nouméa, detected by geochemical and sedimentological analyses. Even though most of terrigenous metal is unavailable, an impact on the benthos was suspected. Simultaneously, the population of Nouméa increased dramatically, which may impact the neighboring bays. Foraminifera were used for assessing this double impact. Thirteen surface samples were collected as a basis for the interpretation of 27 samples from a 54 cm long core. Paradoxically, the general trends in foraminiferal assemblages with time were consistent with a decreasing impact of pollution and continental influence (e.g., increasing species richness, diversity, density, and decreasing percentages of *Ammonia tepida*). Explanations were found in the urban planning that led to a decrease of freshwater and pollutant inputs. Multiple and contradictory impacts of anthropic activities could be assessed only by a set of complementary tools (i.e., geochemistry and bioindicators).

1. Introduction

In coastal marine environments, anthropogenic impacts are usually assessed by comparing ecosystems within and outside impacted areas. No place on Earth, however, could be considered to be totally free from human impact, and coastal areas are all impacted in some way by human activities, such as increased erosion and sediment run-off, pollutants and excess of nutrients associated with freshwater input, dredging and fishing or tourism industry. As a result, it is difficult to get conclusive information about anthropogenic impacts only by comparing modern coastal ecosystems. The best method for assessing anthropogenic effects would be to place the present environmental situation in its historical context by reconstructing the evolution of past environmental conditions (Fichez et al., 2005).

The use of dated sediment core profiles allows such reconstructions in most of coastal environments, where sediments have sometimes been depositing continuously since prehuman (or at least preindustrial) periods. In these environments, dated sediment core profiles of contaminants have proven successful in plotting the history of the respective contribution of marine, terrestrial and anthropogenic inputs through the last century (Brush and Davis, 1984; Cornwell et al., 1996; Fichez et al., 2005). It has provided useful information about the history of metal inputs (Zwolsman et al., 1993; Grousset et al., 1999), discharge of organic contaminants (Gerritse et al., 1995; Wakeham, 1996; Hendy and Peake, 1996) or nutrient enrichment (Cornwell et al., 1996; Harris et al., 2001; Vaalgamaa, 2004), all consequences of industrial activities and urban wastes.

The presence of contaminants in the sediment indicates anthropogenic impacts, but does not provide information on how the ecosystem was affected. Biological criteria are needed, but only organisms that have hard parts (e.g., mollusks, ostracods, diatoms, and foraminifera) are likely to leave fossils in the sediment, and to provide insights into ecosystem changes. Owing to their sparse distribution, the use of macrofossils should require considerable sampling effort to get a reliable record. Meiofauna have several potential advantages over macrofauna including their small size and high densities, so that smaller samples may be collected, a potentially shorter response time and higher sensitivity to pollution (Heip et al., 1988; Warwick, 1993; Somerfield et al., 1995; Coull, 1999). Meiofauna are regularly defined as those benthic metazoans passing a 500 µm sieve but retained on meshes of 40–64 µm (Higgins et al., 1988). Owing to their size, and even if they are protists, Foraminifera are often included in the meiofauna. Although they are not included in the official protocols for environmental characterization, their usefulness for coastal zone management has been clearly shown. Numerous studies carried out

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doi:10.1016/j.marpolbul.2009.09.014

worldwide during the last decades concluded that they are very sensitive indicators for pollution monitoring (e.g., Boltovskoy et al., 1991; Sharifi et al., 1991; Alve, 1995; Yanko et al., 1999; Coccioni, 2000; Angel et al., 2000; Samir and El-Din, 2001; Scott et al., 2001; Debenay et al., 2001a; Armynot du Châtelet et al., 2004; Scott et al., 2005; Bergin et al., 2006; Burone et al., 2006). Moreover, they are often well preserved in the sediments. Their taxonomy and general ecological distribution is the best known of all microfossil groups from shallow marine environments making their fossil records in sediment cores a useful tool for reconstructing the history of anthropogenic impact on marine ecosystems (e.g., Alve, 2000; Cearreta et al., 2000; Elberling et al., 2003; Hayward et al., 2004; Ruiz et al., 2004).

The main objectives of this study are (1) to investigate the spatial distribution and abundance of benthic foraminifera in two bays affected by direct and indirect sediment run-off from open-cast mining sites, and by the vicinity of a big town and (2) to assess the foraminiferal response to environmental changes in the past decades by comparison with information provided by pollutant concentrations measured in core sediments.

2. Study area

The New Caledonia Archipelago is located in the South-West Pacific Ocean, between 19–23°S and 163–168°E. Its main components are the Main Land and the Loyalty Islands (Fig. 1).

The main island is surrounded by a 1100 km long barrier reef that isolates a 23,400 km^2 lagoon. This study took place in the South-West lagoon that has a surface area of about 5500 km^2 and is approximately 95% covered with soft bottoms (Richer de Forges, 1991). Oligotrophic oceanic waters are driven northwestward by the trade winds trough the South-West lagoon and exit by the passes (Douillet et al., 2001).

A noticeable part of the bedrocks of the southwestern main island is composed of peridotites, the weathering of which results in the formation of nickel- and iron-rich saprolites sensitive to erosion (Baltzer and Trescases, 1971; Trescases, 1973), which are subject to mining extraction. The present study focuses on two bays: Boulari Bay and Sainte-Marie Bay (Fig. 1). Boulari Bay is directly exposed to terrigenous inputs from La Coulée River, which are enhanced by strong erosion at abandoned mining sites. The 85 km^2 watershed of this river was subjected to a small-scale mining between 1904 and 1965 (63,657 tons of nickel ore); 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 (Fernandez et al., 2006). Closer to the town center, Sainte-Marie Bay that connects directly with Boulari Bay on its north-eastern side is exposed to urban inputs. However, simulations of the transport of non-settling terrigenous particles from the mouth of La Coulée River showed that 29.9% of these particles entered Sainte-Marie Bay through its connection with Boulari Bay (Fernandez et al., 2006). The same simulations showed that 30.5% of the particles originating from Pirogues River, a small river located to the south, also entered Sainte-Marie Bay. The result of these terrigenous inputs is that Boulari Bay and Sainte-Marie Bay are significantly enriched in silica compared to the lagoon, the enrichment being significantly higher in the inner stations of Boulari Bay (Jacquet, 2005).

The two bays show clear inshore-offshore gradients (Dalto et al., 2006; Fernandez et al., 2006). In Sainte-Marie Bay, a gradient in organic content reflects the dilution of the organic matter discharged by one of the sewage output of Nouméa city, located close to station N04. A similar gradient existed for Zn, Cu and Pb, which mainly originate from urban activities. In Boulari Bay, a gradient in Ni, Cr, Mn and Co concentrations reflects the dilution of these particulate metals originated from the erosion of soils enhanced by mining activities, and discharged by La Coulée River.

Dissolved Inorganic Nitrogen (DIN) did not differ significantly among the ocean, the lagoon and Boulari Bay (≈0.15 μM), but was significantly more elevated in Sainte-Marie (≈0.95 μM) (Jacquet, 2005). Dissolved Inorganic Phosphorus (DIP) concentrations were also significantly higher in Sainte-Marie Bay (0.12 μM) than in Boulari Bay (0.03 μM). The higher values of DIN and DIP in Sainte-Marie Bay reflect the contamination by sewage waters (Jacquet, 2005). It results in higher primary and bacterial production in this bay compared to Boulari Bay. The total chlorophyll *a* (Chl *a*) concentrations did not differ between the ocean and the lagoon but significantly increased in the bays. They were significantly higher in Sainte-Marie Bay than in Boulari Bay. However, no significant

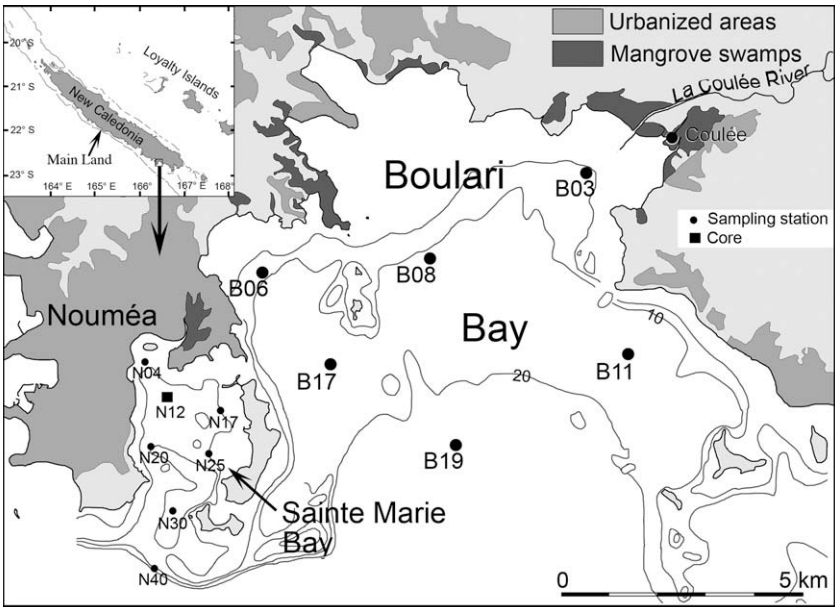

Fig. 1. Location map of the study area and sampling stations.

difference was observed for picophytoplancton and diatom densities between these two bays (Jacquet, 2005). Even if no data are available, it may be inferred that anthropogenic impacts have increased during the last decades because the population of Nouméa has increased almost 10-fold since 1950 (Fig. 2), while urban infrastructures did not improve at the same rate.

Surface sediment characteristics, summarized from Fernandez et al. (2006), are given in Table 1.

3. Material and methods

3.1. Sediment sampling

Sediment samples were collected in December 1997 in Sainte-Marie Bay (6 stations), Boulari Bay (6 stations) and Coulée River estuary (1 station) (Fig. 1). The sampling sites are part of the stations monitored within the framework of the Programme National Environnements Côtiers (PNEC), planned for assessing the effects of anthropogenic and terrigenous inputs on the South-West lagoon. Except for the station Coulée where the sample was collected by hand at low tide, sediment was sampled with a Van-Veen grab made of 316L stainless steel (capacity 1.8 l) ensuring minor disturbance of the sediment top layer. The oxidized surface layer of sediment (1 cm) was retrieved and stored in single-use vinyl bags. A 54 cm core was extracted in Sainte-Marie Bay (Fig. 1) using a specially designed PVC corer operated by SCUBA divers (Harris et al., 2001). The corer consisted of a 1.2 m long PVC tube, 25 cm in diameter, which had been cut in half from top to bottom. The corer was forced down into the sediment to about 0.5 m deep. The corer was then removed vertically and sampled. It was sliced into 2 cm thick segments, giving 27 samples; in each slice, one sediment sample of about 10 g was collected and stored in single-use vinyl bags. For the geochemical study, an aliquot of each sediment sample was grain sized by wet sieving in order to recover the fine material fraction (particles < 40 μm of the sediment). This fine fraction contains more than 90% of the sorbed metal on particles as a result of reactions taking place on their very large specific surface (e.g., Mayer and Fink, 1979; Ackermann, 1980; Deely and Fergusson, 1994; He and Walling, 1996). The fine fraction was frozen for storage before being freeze-dried; freeze-dried sub-samples were separately packaged for sedimentological and geochemical analyses. The coarse fraction was dried at 50 °C and stored for foraminiferal determinations and countings. The coarse fraction of surface samples was stained with Rose Bengal before drying to help recognize living individuals (Walton, 1952; Murray and Bowser, 2000).

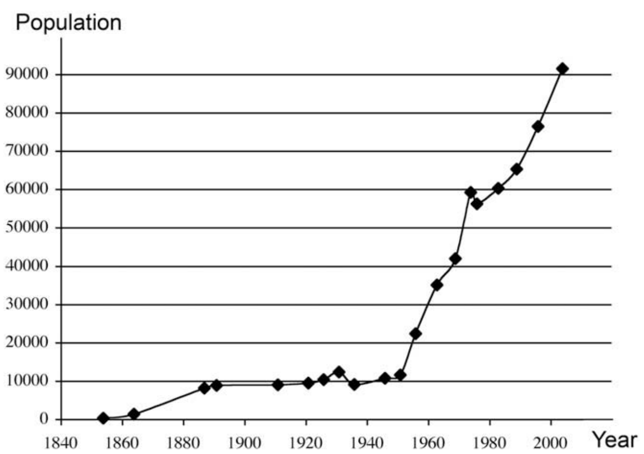

Fig. 2. Evolution of the Nouméa population since 1850.

3.2. Foraminifera determinations and counting

Foraminiferal tests were concentrated by heavy liquid flotation using ethylene trichlorure. The unfloated sediment of the core samples was checked for the detection of remaining tests, but only a few tests were left in the sediment, even in the deeper samples. Rose Bengal stained (living?) foraminifera of surface sediments were grouped with dead tests for the counting (total assemblages) because they were very rare in any sample, and because the objective of this study was to provide general data for paleoenvironmental interpretation. Before examination under a dissecting microscope, each floated sample was split to give approximately 2000 specimens. These specimens were carefully spread over a picking tray with 42 cells. Cells were selected randomly and all the specimens in each cell were counted, until a total of about 300 specimens. Fatela and Taborda (2002) demonstrated that counts as low as 100 specimens are sufficient in studies based on the species representing at least 5% of the assemblage. Species were identified according to Loeblich and Tappan 1988 ordinal classification. Standardized abundances (density) were expressed as total number of specimens per 50 cm^3 of sediment. The relative abundance of each species (proportion) was calculated. The species richness was defined by (1) the number of species identified during the count of the first 100 individuals (SR100) and (2) the number of species identified during the survey of about 2000 specimens (SR2000), including the rare species identified after the count of the first 300 specimens. The rarefaction method, where foraminifera are picked from each sample until no new species were discovered (Ludwig and Reynolds, 1988; Langer and Lipps, 2003), could not be used since each sample from the lagoon of New Caledonia may contain more than 300 species. The specific diversity was calculated using Shannon and Weaver's formula (1963): $H = -\sum p_i \log_2 p_i$, where p_i

Table 1
Sediment characteristics (Mz = mean size according to Folk and Ward (1957); OM = organic matter).

Station	Depth (m)	% Silt + clay	Mz	% Carbonate	% OM	Ni contents (mg kg^{-1})	Fe contents (g kg^{-1})	Zn contents (mg kg^{-1})
B03	7.5	81.5	4.49	17.3	23.8	4913	179.5	8.58
B06	11.5	9.8	3.38	66.8	38.9	852	38.5	9.45
B08	16.8	79.6	4.43	53.3	14.1	2178	93.8	6.53
B11	17.6	71.7	4.20	65.6	15.9	1559	59.0	5.86
B17	18.3	32.7	2.92	58.6	26.7	1065	48.2	7.34
B19	23.8	77.9	4.43	67.1	16.1	1278	109.0	5.94
N04	10.0	57.2	4.42	47.9	18.1	330	28.3	39.43
N12	13.2	59.9	4.45	61.4	15.8	299	24.1	18.79
N17	10.5	12.5	1.44	70.4	28.2	350	17.1	17.88
N20	14.8	44.6	4.01	65.8	13.7	389	26.4	18.64
N30	11.5	14.4	1.31	64.6	22.6	380	21.7	14.65
N40	19.8	6.8	2.30	76.3	58.6	255	13.4	13.58
Coulée	0.5	79.0	4.14	0.2	1.4	7489	259.1	10.64

is the proportion of the *i*th species (%/100), and $\log_2$ the log base two of *pi*.

3.3. Sedimentological analysis

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 normalized 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 1922 grade scale.

3.4. Geochemical analysis

Carbonate content was analyzed by calcimetry (Bonneau and Souchier, 1979) on the fine fraction (<63 µm). Organic matter content was estimated on the same fraction by acid oxidation (Yamamuro and Kayanne, 1995).

The concentrations of three transition metals (Fe, Ni and Zn) were determined using a sequential extraction scheme (Tessier et al., 1979) applied to carbonate lagoon sediments (Fernandez et al., 2006) on the pelitic (<40 µm) fraction. This chemical digestion technique shows great potential for identifying the metal source term and assessing its level of availability (see a review by Cornu and Clozel, 2000).

Zinc concentrations were determined from the first three phases of the digestion (organics, carbonates and oxides) to quantify the chemical fractions of the metal resulting from urban activities. The nickel and iron determinations were carried out from the residual phase, primarily composed of terrigenous material (laterites), extracted with an acidic mixture (HCl/HNO_3) in high pressure vessels made of TFM (Anton Paar, MF100) and subject to micro-wave exposure in an Anton Paar Multiwave. The reagents and chemicals used were Merck, ProAnalysis trade; all materials in contact with the sediment samples were made of PEHD, Nalgène or Teflon, decontaminated by soaking in nitric acid (HNO_3 5%) for 24 h and rinsed with ultra-pure water (Milli-Q).

Iron, Ni and Zn concentrations were analyzed by ICP-OES (Optima 3300 DV, Perkin–Elmer). Results are expressed as absolute concentration, i.e., mass of metal vs. mass of pelite (C_{Pel}, in mg kg^{-1}) according to the relationship: $C_{Pel} = (C{\cdot}D{\cdot}V)/M_i$, where C is the concentration in extraction solution (mg l^{-1}), D is the dilution factor, V is the extraction solution volume (l) and M_i = mass of initial pelitic fraction (kg).

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

Sediment accumulation rates were determined from the decrease in excess ^{210}Pb radioactivity, which was determined by measuring its granddaughter ^{210}Pb considered to be in secular equilibrium with ^{210}Pb (Teksöz et al., 1991). The ^{210}Po measurement was performed in a NUMELEC gridded-chamber (NU 114B model) by alpha counting, following the standardized methods of Flynn (1968) modified by Nittrouer et al. (1979) and further adapted to carbonate rich sediments by Serra et al. (1991). Sediment supported ^{226}Ra radioactivity was measured in each sedimentary slice using gamma spectrometry. The age for changes in accumulation rates was derived from two linear regressions of excess ^{210}Pb versus accumulated sediment (Robbins and Herche, 1993).

3.5. Statistical analyses

Hierarchical (cluster) analyses were performed on a subset of the 20 foraminiferal taxa that comprise more than 5% of the assemblage in at least one sample. The relative abundance of these taxa was treated in Q-mode and R-mode hierarchical analyses, based on Euclidean distance correlation coefficients using Ward's merging criterion, carried out with Statlab for Macintosh (SLP infoware). The combination of R-mode and Q-mode analyses identifies the species typical of each cluster. A factor analysis was also performed on the dataset of relative abundance of the same species, using Statlab for Macintosh. This analysis was used to determine the most discriminant species (those with the greatest contribution to the first axis). The figures are not shown in this paper because they did not provide more information than Q-mode and R-mode hierarchical analyses.

4. Results

4.1. Sedimentology and geochemistry of the sediments

4.1.1. Surface samples

Finer sediments (higher Mz and higher proportion of silt and clays) are in the inner parts of the two bays (Fig. 3), which is a common feature in relation with hydrodynamics. Ni concentration in pelites reached 4913 mg kg^{-1} in the Coulée estuary (B03). The values decreased to 1000–1500 mg kg^{-1} in the southern and south-eastern part of Boulari Bay (B17, B19 and B11) and 852 mg kg^{-1} in its western part (B06) (Fig. 3). In Sainte-Marie Bay, Ni concentrations ranged from 299 to 389 mg kg^{-1} at N12 and N20, respectively, showing evidence of terrigenous inputs even in the northwestern part of the bay where muddy sediments prevailed. The highest values in Sainte-Marie Bay corresponded to the stations located in the channelized central zone.

The distribution of iron was very similar to that of nickel. In Boulari Bay, Fe concentration decreased from 179.5 g kg^{-1} at B03 to 48.2 g kg^{-1} at B17 along the north-east/south-west axis, and less in B06 (38.5 g kg^{-1}). In Sainte-Marie Bay, concentrations of Fe were lower, the highest values being localized in the northwestern part of the bay (N04: 28.3 g kg^{-1}). Zinc in organics and carbonates, and even in oxides showed a different trend (Fig. 3). The Zn concentrations are low and homogeneous off the Coulée River and in Boulari Bay. In Sainte-Marie Bay, Zn concentrations are higher and presented a well-defined shore-coast gradient. The highest values were found in the northwestern part of the bay (N04: 39.4 mg kg^{-1}).

4.1.2. Core samples

From the bottom to the top of the core (Fig. 4), the pelitic fraction and Fe concentrations increase more than 10% and 20%, respectively. The Ni concentration profile clearly identifies a drastic change in the amount of terrigenous metal inputs (greater than 100%), with a sharp increase in concentration (193.5–265.4 mg kg^{-1}) between 29 and 31 cm depth. Zinc concentration in organics increases regularly from the bottom (0.6 mg kg^{-1}) to the base of the 12 top centimeters of the core (0.9 mg kg^{-1}). In the upper (recent) horizons the concentration gradient seems greater, Zn concentrations reaching 1.5 ± 0.4 mg kg^{-1}. From the bottom to the top of the core, carbonates concentrations decrease of about 30%.

Up to 19 cm, excess ^{210}Pb radioactivity increases roughly exponentially (Fig. 4). The clear shift in sediment composition and especially in Ni concentrations at 31 cm depth is very likely to be associated with a change in deposition regime. Hence, two linear fits were calculated for the ^{210}Pb data, one below 31 cm and

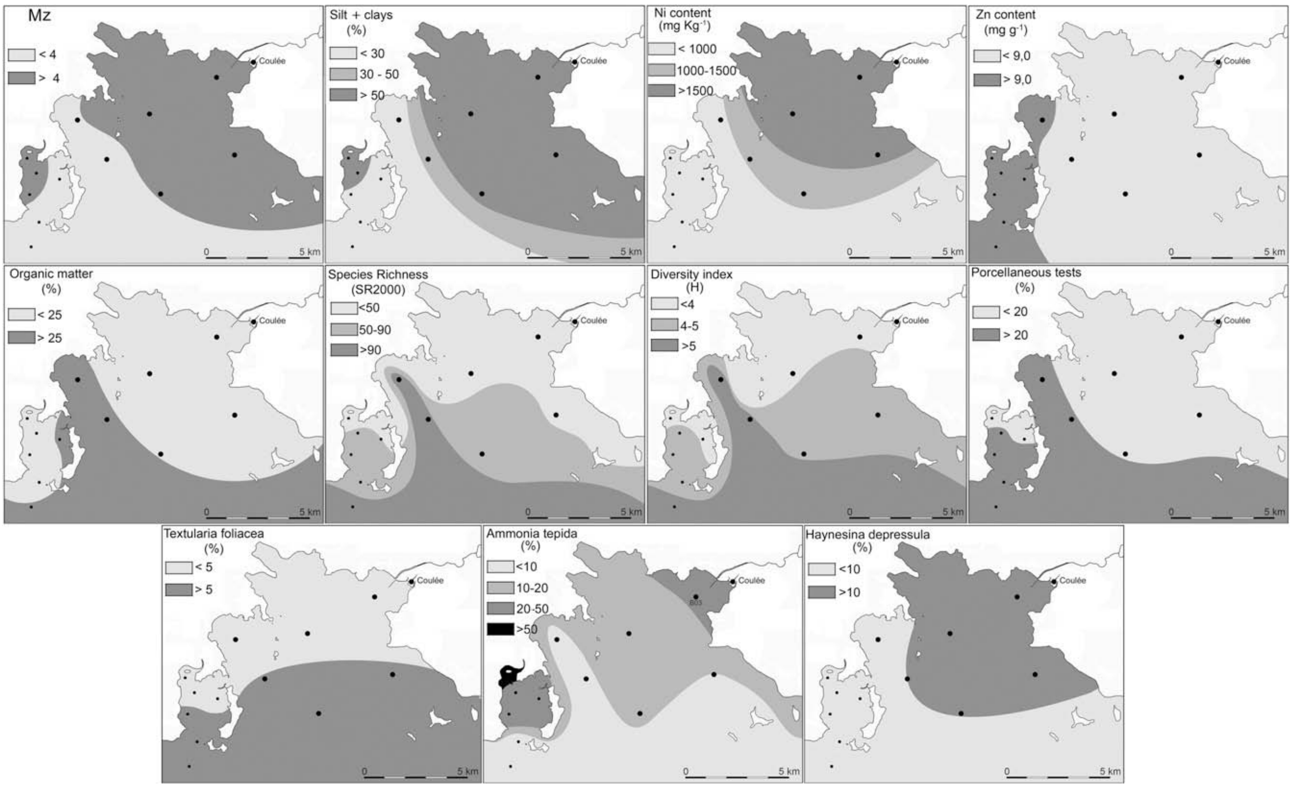

Fig. 3. Foraminiferal and sedimentological parameters distribution in surface samples. The species richness mapped in this figure is SR2000: the number of species identified during the survey of about 2000 specimens. Mz is the mean size according to Folk and Ward (1957).

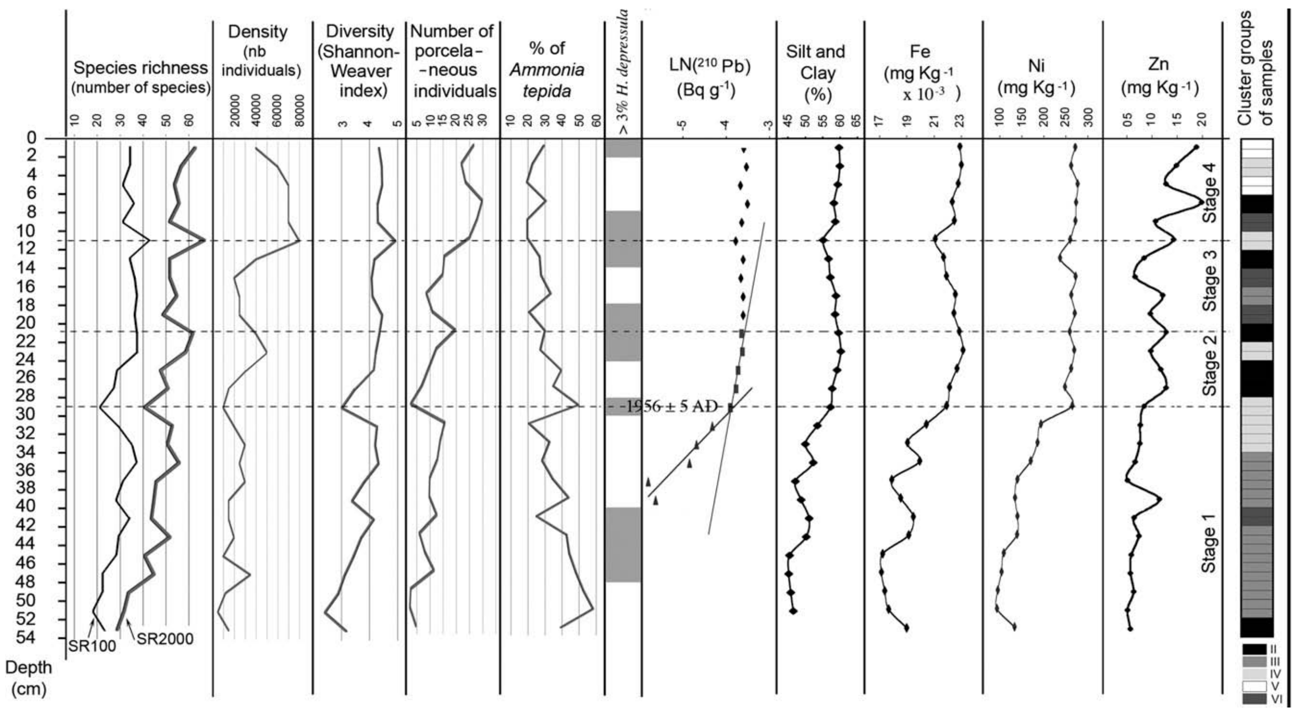

Fig. 4. Changes in chemical and foraminiferal parameters along the core. Explanations for the cluster-groups of samples along the core are found in Fig. 5.

another one between 29 and 21 cm. They yield different sedimentation rates and allow this major environmental change to be dated at 1956 +/− 5 years taking into account the overlaying potentially bioturbated layer, above 19 cm. In this layer, the ^{210}Pb profile indicates almost invariable radioactivities the interpretation of which is questionable. It should reflect intense bioturbation processes and/or large accumulation rates, but none of these hypotheses is corroborated either by foraminiferal assemblages or by organic-bound Zn profiles. Primarily, they are not homogenized, as they should be in case of bioturbation. The magnitude of this phenomenon makes any interpretation difficult, particularly when considering the unsupported ^{210}Pb data alone (Cs^{137} is almost undetectable in this part of the world).

Despite large uncertainties regarding time evaluation, the calculated date of change of sedimentation corresponds with the officially recorded onset of large-scale open-cast mining activities in the south of New Caledonia (Bird et al., 1984; Mermoud written communication, 1994). Mining activities were responsible for long term erosion of soils with the lagoon acting as a final reservoir of all land-originated material. The corresponding sedimentation mechanisms have been widely studied in Dumbéa Bay (Launay, 1972; Ambatsian et al., 1997). The values from Dumbéa and Sainte-Marie Bays present converging results regarding the decrease in excess ^{210}Pb with sediment depth. Unlike Dumbéa Bay that is directly under the influence of river inputs, Sainte-Marie Bay is only indirectly affected by La Coulée River (11 km away). Nevertheless, even under these conditions, small-scale mining practice affects the coastal zone on a large-scale (Fig. 1).

4.2. Foraminiferal assemblages

A total of 290 taxa were identified, including 176 hyaline, 102 porcellaneous and 12 agglutinated taxa (Appendix 1). Twenty species comprised more than 5% of the assemblage in at least one sample and were used for statistical analyses. The species richness (SR100) ranged from 13 to 59 and (SR2000) ranged from 24 to 112. The density, standardized to 50 cm^3, ranged from about 5000 to about 200,000 individuals (Tables 2 and 3). The dominant species in surface and core sediments were *Ammonia tepida* that may contribute to more than 50% of the assemblage and *Brizalina striatula*, two species typical of environments subjected to the influence of continental waters (reviews in Debenay et al., 2000; Debenay and Guillou, 2002). Two other species were also well represented: *Schackoinella globosa* and *Haynesina depressula*. From the factor analysis, the most discriminant species (with a contribution to axis 1 > 10%) were *A. tepida* (19%), *Textularia foliacea oceanica* (19%) and *H. depressula* (15%).

4.2.1. Surface samples

The assemblage collected at station Coulée, with a high proportion of *Elphidium advenum* and *Quinqueloculina seminulum*, was obviously different from all the other ones and was considered separately.

The distributions of the three species that contribute for more than 10% to the first axis of the factor analysis were mapped, as well as the distributions of the species richness (SR2000) and the Shannon–Weaver index (Fig. 3). Species richness and diversity show similar trends with lower values at the sites closer to the land, in the inner parts of the bays. The highest richness and diversity are encountered in the outer part of the bay, but also between Sainte-Marie Bay and Boulari Bay (stations B06 and B17, Fig. 3). Out of the bays, species richness (SR2000) is often over 100 and diversity over 5 on the lagoon floor (Debenay, unpublished data). The reverse trend was observed for the distribution of *A. tepida*, the higher proportions corresponding to the inner bays. The relative abundance of *H. depressula* was higher (>10%) in Boulari Bay, in front of La Coulée River; *T. foliacea oceanica* comprises more than 5% of the assemblage in the outer part of the bay. The proportion of all the porcellaneous species grouped together follows the same trend as species richness and diversity with values over 20% at stations B06 and B17 and in the outer parts of the bays.

4.2.2. Core samples

The richness of the foraminiferal assemblages of the core samples (SR2000) ranged between 29 and 67. The strong dominance of two major species *A. tepida* and *B. striatula* led to a Shannon–Weaver index always lower than 5 (Table 3, Supplementary material, Fig. 4).

Four main stages could be recognized in foraminiferal assemblages along the core by comparison with the most significant parameters of the surficial assemblages (Fig. 4). In the deeper sediments (Stage 1, 54–30 cm), the species richness, the diversity

Table 2
Relative abundance (% of the assemblage) of the main species in surface samples ("0" indicates percentages between 0 and 1).

	Sainte-Marie						*Boulari*						
Sample	N04	N12	N17	N20	N30	N40	B03	B06	B08	B11	B17	B19	Coulée
Density (nb specimens in 50 cm ^{3})	10,000	40,000	10,000	20,000	15,000	100,000	5000	200,000	25,000	45,000	60,000	40,000	15,000
Abditodendrix rhomboidalis	1	2		2	0	2	1	5			0		
Ammonia tepida	53	28	24	21	3	2	25	1	16	10	7	12	10
Bolivina (Loxostoma) durrandii	2	0	3	1	3	1	2	0	2	7	2	2	
Bolivina pseudoplicata	1	0		2	1		2	2	7	1		3	
Bolivina vadescens	3		5	2	8	0	2	3	13	9	4	8	
Brizalina striatula	7	9	15	4	5	1	11	5	2	1	1	3	13
Cassidulina minuta			0	1	0			1	2	4	1	4	
Elphidium advenum	4	1	3	5	5	1		9		2	2	0	25
Elphidium limbatum		2		1	2			1					5
Epistominella pulchra						0	1		7	2	0	4	
Haynesina depressula		4	5	5			16	1	20	19	10	11	
Haynesina simplex	6	5	3	5	2	0	3	2	1	1	3	2	2
Nonion cf. fabum				2		0	1	0		0	7	4	
Quinqueloculina oblonga	1	7			1	1	1						
Quinqueloculina seminulum			1	6			2	2				1	17
Quinqueloculina spp.	1	3	6	2	5	7	3	9	3	4	6	3	0
Reussella spinulosa	2	0	3	4	6	4	2	1	3	4	3	4	
Rosalina globularis			2	1		1		2	1		2	1	
Schackoinella globosa	3	2	13	6	10	5	9	3	7	5	3	1	1
Textularia foliacea oceanica		3		9	10	11		1	0	6	5	8	
Triloculina laevigata	1	0	1	5	1		3	1	2	3	6	1	14
Species richness (2000 individuals)	41	63	50	60	73	112	44	92	42	47	93	67	24
Species richness (100 individuals)	28	35	28	35	40	57	33	59	26	30	45	38	13
Diversity index	3.08	4.45	3.87	4.49	4.93	5.41	3.98	5.47	3.90	4.29	5.12	4.71	3.29

Table 3
Relative abundance (% of the assemblage) of the 5 main species in core samples ("0" indicates percentages between 0 and 1).

Sample	0–2 cm	2–4 cm	4–6 cm	6–8 cm	8–10 cm	10–12 cm	12–14 cm	14–16 cm	16–18 cm	18–20 cm	20–22 cm	22–24 cm	24–26 cm	26–28 cm	28–30 cm	30–32 cm	32–34 cm	34–36 cm	36–38 cm	38–40 cm	40–42 cm	42–44 cm	44–46 cm	46–48 cm	48–50 cm	50–52 cm	52–54 cm
Density (nb specimens in 50 cm^3)	40,000	60,000	70,000	70,000	70,000	80,000	40,000	20,000	25,000	25,000	40,000	50,000	36,000	15,000	10,000	20,000	30,000	25,000	30,000	15,000	15,000	20,000	10,000	35,000	12,000	5000	15,000
Ammonia tepida	28	23	18	31	20	19	26	27	34	21	28	25	40	35	48	20	32	29	35	43	25	42	44	46	52	58	39
Brizalina striatula	9	6	9	3	10	6	17	12	12	8	12	18	14	24	13	16	9	10	15	14	15	4	12	12	14	12	24
Haynesina depressula	4			2	8	7	4	2		4	5	6	2		3			1	3		6	3	3	4		1	2
Schackoinella globosa	2	9	6	4	6	5	2	14	1	9	3	3	6	3	5	6	4	3	5	7	12	6	3	6	5	6	7
Textularia foliacea oceanica	3	1	3	5	0	0	2	1		1	1		2			0	1	0	0	0	1	0	1	0	1		
Species richness (2000 individuals)	63	57	54	56	52	67	52	52	55	49	62	59	50	51	41	53	51	56	46	45	44	52	41	45	34	32	29
Species richness (100 individuals)	35	35	32	37	32	44	35	37	38	37	38	38	29	28	22	30	36	38	32	29	35	30	29	23	23	19	24
Diversity index	4.49	4.36	4.50	4.44	4.42	4.91	4.22	4.12	4.23	4.50	4.30	4.29	3.50	3.42	2.99	4.24	4.19	4.30	3.82	3.38	4.10	3.70	3.40	3.19	2.85	2.42	3.13

(Shannon–Weaver index), and the species number of porcellaneous tests increased upwards; the density of the total assemblage was almost stable and the percentage of *A. tepida* decreased. Sample 30–28, at the base of Stage 2, was characterized by an abrupt reversal of these trends that reversed again in the overlaying samples, up to 22 cm (end of Stage 2), where another abrupt change occurred. Between 22 and 12 cm (Stage 3), species richness and diversity remained almost stable while the other foraminiferal parameters followed the same trend as in Stage 1. The last abrupt change happened in sample 12–10 cm. All the parameters, except the percentage of *A. tepida*, increased in this sample where the highest density was recorded. The density remained high during the fourth stage, almost to the top of the core and the number of porcellaneous tests continued to increase, but the percentage of *A. tepida* slightly increased. *Haynesina depressula* occurred at each transition between the four stages. It also occurred in the upper sample (0–2), and between 36 and 48 cm deep in the core.

The transitions between the four stages evidenced by foraminiferal assemblages may be related to changes observed in sediments (Fig. 4). The transition between Stage 1 and 2 was dated at 1956 ± 5 using the excess ^{210}Pb. At that time, the sedimentary rate, indicated by the linear regression of excess ^{210}Pb versus accumulated sediment, increased abruptly. At the same time, Ni and Fe contents also increased, showing an intensification of terrigenous inputs while Zn content began to increase and to change towards more irregular patterns. Sedimentary events were less obvious at the transition between Stage 2 and 3, but it corresponded to a stabilization of Ni and a slight decrease of Fe. At the transition between Stages 3 and 4, the Ni and Fe contents showed a transient decrease before returning to almost stable patterns for Ni and a slight increase for Fe. Zinc content increased irregularly about 2-fold during this stage.

4.2.3. Comparison between core samples and surface samples: cluster analysis

The Q-mode cluster analysis carried out on both surface and core samples results in the definition of six major clusters (Fig. 5). Cluster I groups most of the surface stations, except the three innermost stations of Sainte-Marie Bay (N04, N12 and N17), and station B03, close to the mouth of La Coulée River. The samples grouped in cluster II are scattered along the core. Those samples grouped in cluster III are mainly from the deeper part of the core, associated with the inner surface sample of the Sainte-Marie Bay, N04. Samples of cluster IV are mostly from the medium part of the core. Cluster V groups two samples from the top of the core with the corresponding surface sample N12. Cluster VI includes four samples from the upper 20 cm of the core, associated with surface samples B03 and N17, from Sainte-Marie Bay and the inner parts of Boulari Bay.

The R-mode cluster analysis distinguishes three groups of species with two additional isolated species, *A. tepida* and *B. striatula*, which are the dominant species (Fig. 5). Each of the sample clusters (Q-mode) can be related to the species clusters (R-mode). The first Q-mode cluster (I) is related to lower values of *A. tepida* and *B. striatula*, and higher values of the species of R-mode cluster A, mainly *T. foliacea oceanica* and *Reussella spinulosa* (cluster B). The differentiation between Q-mode clusters Ia and Ib results from higher proportions of *Bolivina vadescens, H. depressula* and *Epistominella pulchra* in the samples of cluster Ib. The difference of the other Q-mode clusters between each other depends primarily on different relative abundances of the dominant *A. tepida* (average 44 in cluster III, 24 in cluster VI), but may also be related to the distribution of other species. For example, *S. globosa* presents a higher relative abundance in cluster VI, and *Rosalina globularis* in cluster IV (Fig. 5; Table 2).

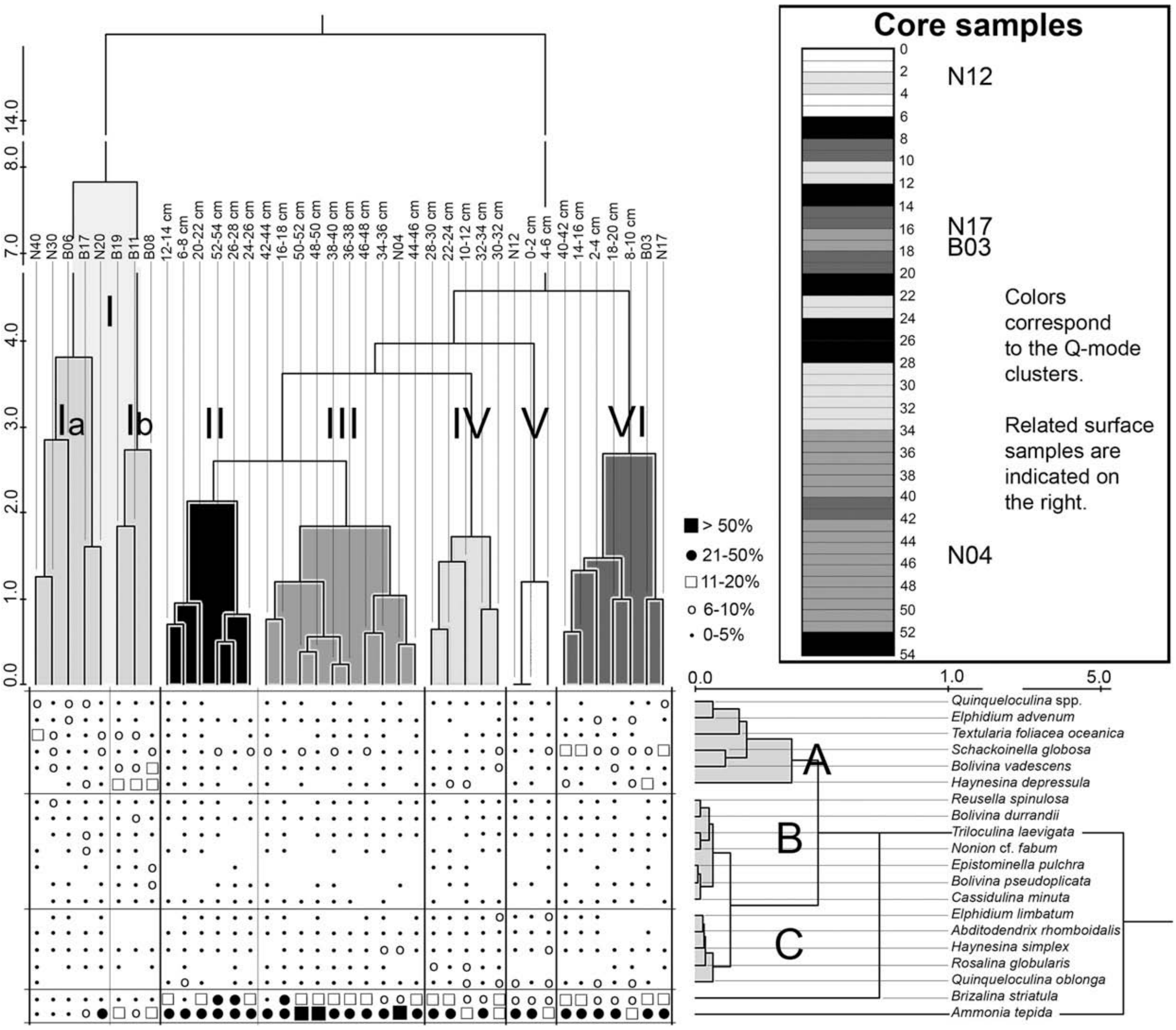

Fig. 5. Q-mode cluster dendrogram (top up) and R-mode cluster dendrogram (right). The Q-mode dendrogram defines six clusters (I–VI), cluster I being divided into two subclusters (Ia and Ib). The R-mode dendrogram defines three species assemblages (A–C) with two isolated species. Relative abundance of each species in each sample is summarized in the chart. Clusters are mapped in the core section (up right).

5. Discussion

5.1. Surface samples

The New Caledonian lagoon hosts a rich fauna of large symbiont-bearing foraminifera (Debenay, 1985). In the two bays, however, we found typically small foraminifera without algal symbionts. Salinity that varied within a small range in the lagoon and in the bays surrounding Nouméa (35.1–35.6) and varied little among seasons (averages 35.05 in April–May, 35.44 in August, Jacquet (2005)) cannot alone explain the spatial distribution of foraminifera, particularly when considering the highly euryhaline species *A. tepida*. Nevertheless, the input of fresh water discharged by la Coulée and Pirogues rivers certainly has a noticeable impact, at least during the rainy season. The observed distribution of foraminiferal assemblages is consistent with previous studies that show that a limited nutrient influx, whether natural or anthropogenic, should favor heterotrophic taxa. Benthic foraminiferal assemblages shift from predominantly algal symbiont-bearing species to small species lacking algal symbionts in response to a limited anthropogenic nutrient source (Hirschfield et al., 1968; Hallock and Schlager, 1986; Birkeland, 1987; Hallock, 1988; Cockey et al., 1996). Among the species collected in the bays, the two dominant species are *A. tepida* and *B. striatula*.

Ammonia tepida, sometimes reported as *Ammonia beccarii* or *A. beccarii* group in previous works, may tolerate a reduced marine influence that allows it to occur worldwide in paralic environments (Debenay and Guillou, 2002). The tolerance of this species to adverse conditions, including organic and chemical pollution, has been reported for a long time, either in field studies or in culture studies (e.g., Bradshaw, 1961; Seiglie, 1975; Setty and Nigam, 1984; Sharifi et al., 1991; Yanko et al., 1994; Coccioni, 2000; Samir, 2000; Armynot du Châtelet et al., 2004; Nigam et al., 2006; Ferraro et al., 2006; Bouchet et al., 2007). Increased abundance of *A. tepida* is often associated with organic input, such as sewage effluents that may favor its growth (Debenay et al., 2001b). The potential application of *A. tepida* for pollution monitoring has often been mentioned, and is now well established.

In Boulari and Sainte-Marie bays, the distribution of *A. tepida* seems to be inversely related to the proportion of organic matter (Fig. 3): relative abundances higher than 10% were found in stations where the organic matter content was less than 20%. This distribution seems to be in contradiction with previous studies. However, it is consistent with the distribution of meiofauna in the same bays. Dalto et al. (2006) reported that, conversely to what was observed in other areas (e.g., Grémare et al., 2002), there was a clear negative correlation between meiofauna total density and the organic contents of surface sediments. These authors attributed this negative correlation to the extremely low lability of sedimentary organics in the South-West lagoon. In Sainte-Marie Bay, however, relative abundances of *A. tepida* ranging between 20% and 50% were associated with organic matter content close to or over 20%, which may be (at least partly) related to the sewage origin of a more labile organic matter.

Brizalina striatula is also well represented in coastal environments (Debenay et al., 2005) where it may penetrate coastal lagoons and estuaries. It may live in organic rich sediments, but it is sensitive to oxygen depletion that may result from remineralization of accumulated organic matter (Bouchet et al., 2007). Its relationship with pollution is less clearly established, but this species is often mentioned in polluted areas (e.g., Burone et al., 2006; Frontalini and Coccioni, 2008). In the two bays, it was impossible to observe any noticeable trend in the distribution of this species.

Another significant species is *H. depressula*, a euryhaline species that usually lives in intermediate restricted areas (e.g., Debenay et al., 2005). Its distribution should also result from a better tolerance to the terrigenous pollution from La Coulée River. However, (1) the distribution of *H. depressula* is not directly related to the nature of the sediment (Fig. 3), (2) *H. depressula* is not among the species known for their tolerance to contamination, and (3) most terrigenous contaminants bound to suspended silts, clays and organic particles when entering estuarine and coastal environments, and tend to accumulate in muddy sediments where sorption onto particles lowers their bioavailability to organisms (Kennedy, 1984; Green et al., 1993; Chandler et al., 1994; Coull, 1999). Thus, even though salinity gradients were not clearly evidenced, the higher percentage of *H. depressula* in the area under the influence of La Coulée River (Fig. 3) suggests that it should be considered as an indicator of freshwater input. This is probably the result of a higher resistance to lower salinity of this salinity tolerant species (Hayward et al., 1999) that may penetrate into the intertidal seaward part of some estuaries (Murray, 2006).

The distribution of foraminiferal assemblages is not clearly related to the grain size of the sediment (Fig. 3). *Ammonia tepida*, for example, is well represented in the muddy sediment of station N04, but is less abundant at the other muddy station B11. Thus, the structure of the sediment that has long been recognized as the major parameter influencing meiobenthic communities (Warwick and Buchanan, 1970; Heip et al., 1985; Coull, 1988; Somerfield et al., 1995) does not seem to be a decisive factor in our study area.

The decrease of species richness and diversity towards the inner end of the bays (Fig. 3) is consistent with observations made in other restricted environments (e.g., Alve and Murray, 1999; Langer and Lipps, 2006; review in Murray, 2006). This decrease may be stronger when pollution occurs (e.g., Schafer, 1973; Yanko et al., 1998; Thomas et al., 2000; review in Nigam et al., 2006). The higher diversity and richness at stations B06 and B17 may be related to their position, protected from the influence of Sainte-Marie Bay outfall and la Coulée River inputs, due to the general hydrodynamics, as shown by Fernandez et al. (2006).

Summarizing, species richness and diversity are higher towards the lagoon and decrease with increasing continental influence; the bays are characterized by small species without algal symbionts; *H. depressula* should be considered as an indicator of freshwater input; porcellaneous species show a gradient between the lagoon and the inner end of the bays; *A. tepida* is distributed along an inverse gradient and may indicate an enrichment by sewage.

5.2. Core samples

Based on the preceding observations, we propose the following interpretation for the environmental changes detected along the core. The upward increases of Ni and Fe indicate a strengthening impact of terrigenous loadings from La Coulée River as well as sewage pollution in Sainte-Marie Bay.

The trends expected for foraminiferal assemblages were a progressive decrease of species richness and diversity, a concomitant decrease of porcellaneous tests, and an increase of *A. tepida*. The exact opposite was found instead. The first explanation that may be drawn from these paradoxical results is that the metals present in the sediment do not have a decisive impact on foraminiferal assemblages. This opinion is in agreement with Dalto et al. (2006) who concluded that benthic meiofauna was not controlled by metal concentrations in the South-West Lagoon, except by some metals such as Cu and Pb, originating from urban activities that may have a negative effect at the beginning of the rainy season.

The general trends in foraminiferal assemblages indicate a change towards less restricted environmental conditions, i.e., under stronger marine influence and lesser freshwater and pollutant impact. This change may be explained by the hydrodynamics of the bays. Simulations have shown that along-shore currents driven by the trade winds enter Boulari Bay through its wide south opening and partly penetrate Sainte-Marie Bay through its connection with Boulari Bay (Fernandez et al., 2006). They carry a part of the freshwater discharged by La Coulée and Pirogues rivers, leading to increased continental influence in Sainte-Marie Bay. The suspended particles also transported by the currents partly settled in the connection between Sainte-Marie and Boulari bays resulting in a decrease of the water transit with time, and inducing a decrease of freshwater influence and a correlated increase of marine influence in Sainte-Marie Bay. Embankments made at the end of the 1950s enhanced this process. The four main stages recognized in this general trend may be explained by changes in anthropogenic influences and natural conditions:

1. The first one (54–30 cm) results mainly from natural phenomena, even though the increase of Ni and Fe concentrations shows that small-scale mining and prospecting operations were already conducted in La Coulée basin (Fernandez et al., 2006).
2. The abrupt increase of both the sedimentation rate, and the Ni and Fe contents at the beginning of Stage 2 (30–28 cm; end of the 1950s) is the consequence of the beginning of large-scale prospecting that will lead to the extraction of 362,078 tons of nickel ore between 1966 and 1980 (Fernandez et al., 2006; Fig. 6).The concomitant increase of organic-bound Zn resulted from the growth of Nouméa city is probably due to the extensive use of galvanized corrugated iron roofs. Foraminiferal assemblages indicate that the benthos was anthopogenically impacted during this transition (30–22 cm).
3. After this short episode, the changes towards more marine conditions continue. It may be attributed to the extension of Nouméa city that was accompanied by improvement of the sewage system, a better control of the run-off, and embankments in the connecting passage between Sainte-Marie and Boulari bays (Fig. 7). All this results in a decrease of freshwater and pollutant inputs.
4. During the last stage (upper 12 cm) the slight increase in the proportion of *A. tepida* probably indicates a nutrient enrichment, resulting from the increasing growth of Nouméa city where, unfortunately, urban infrastructure did not improve at the same rate as population and urbanization. Sewage system failure that caused the input of nutrients may have favored meiobenthos, including foraminifera.

The transitions between the three last stages are associated with the occurrence of *H. depressula* (Fig. 4) that it may indicate a stronger freshwater influence. The examination of rainfalls registered at Nouméa since 1920 seems to corroborate this hypothesis (Fig. 6). Even if the correlation is doubtful, due to the uncertainties

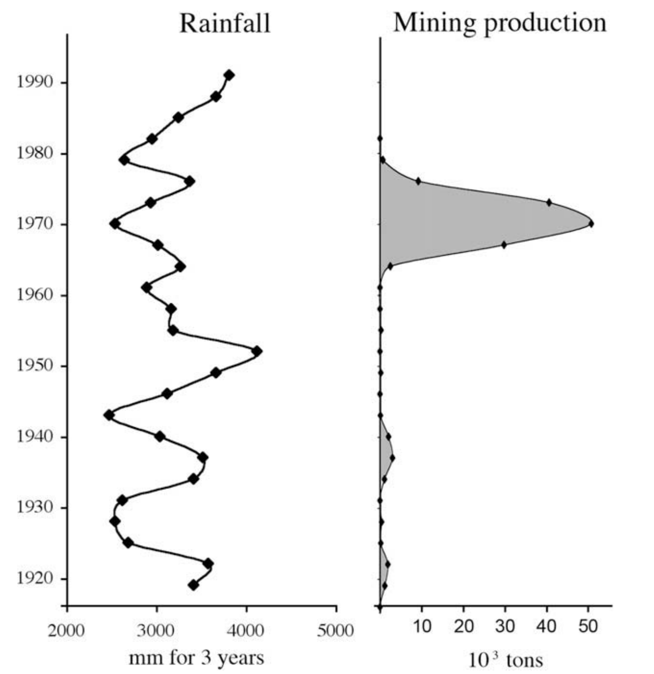

Fig. 6. Rainfall and mining production from 1920 to 1995. Curves are smoothed over 3 years intervals. Rainfall data are from Météo-France Nouvelle-Calédonie. Mining data are from Dimenc (Direction de l'industrie, des mines et de l'énergie) of New Caledonia.

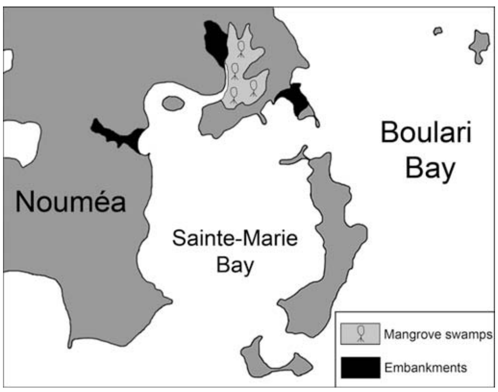

Fig. 7. Location of the embankments made during the urbanization of Nouméa city.

in the sedimentation rates, two major rainy events took place about 1965 and 1975, and should be responsible of stronger freshwater impacts. It must be noted that a strong rainfall event also took place during the transition between Stages 1 and 2, and probably enhanced the impact of mining activities. Rainfall events, through intense weathering of the steep slopes and erosion of abandoned mining and prospecting sites, flush large quantities of freshwater and suspended matter to the lagoon.

The major information provided by the comparison between core and surface assemblages using cluster analyses is the grouping of most samples from the bottom of the core in cluster III, associated with surface sample NO4, from the inner part of Sainte-Marie Bay (Fig. 4 and 5). It is consistent with more restricted conditions at the base of the core. Only the uppermost samples are grouped with station N12 from where the core was extracted. The other core samples are irregularly distributed in the clusters. Only two other surface samples are grouped with core samples (cluster VI). They are from the inner parts of Boulari and Sainte-Marie bays, showing that the conditions remained somewhat restricted during all the period of study.

6. Conclusion

Foraminiferal assemblages collected in the core samples supplement the information available from geochemical data and allow a finer analysis of the environmental changes during the last decades. Comparing burried assemblages with modern ones, and with geochemical data, it become possible to assess the relative impact on the meiobenthos of terrigenous input and urban pollution. The impact of naturally and anthropogenically induced hydrodynamic changes, urban growth, and rainfall events could also be evidenced. This study shows that anthropic activities, associated with climatic events, may have multiple and contradictory impacts on coastal environments. The tools used for assessing these impacts (i.e., geochemistry and bioindicators) may lead to apparently contradictory interpretations, but are complementary to each other.

Acknowledgements

This work was scientifically and financially supported by IRD Camélia and Paleotropique Research Units. The authors are extremely grateful to A. di Matteo and M. Cabon for their respective contribution to sedimentological and geochemical analyses. They also thank L. Breau for his contribution to the interpretation of the geochemical dataset of the core. Thanks are due to A. Cearreta and R. Coccioni for their constructive review of the manuscript and their useful suggestions, and to the guest editors E. Romano and L. Bergamin who made interesting comments and suggestions that greatly improved the paper.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.marpolbul.2009.09.014.

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