MONITORING OF THE REMEDIATION OF HALIFAX HARBOUR AFTER 250 YEARS OF CONTAMINATION USING FORAMINIFERAL PROXIES

by

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Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

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DALHOUSIE UNIVERSITY

DEPARTMENT OF EARTH SCIENCES

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ABSTRACT

The analyses of benthonic foraminifera in surface sediments and cores from Halifax Harbour (HH), Nova Scotia, Canada, have been used for short-term monitoring and reference environment reconstruction for a wastewater treatment program that started in 2008. The distribution of foraminifera in the surface sediments indicates a lateral environmental variation and positive correlation to the pollution intensity in HH, demonstrating that the environmental quality increases seawards. The treated area (inner Harbour) showed a rapid environmental recovery during the treatment period (2008) and reverted to its former characteristics after treatment stopped in early 2009. This recovery was represented by an increase in both diversity (from <12 to >20 species) and abundance (from 120-880 to 1350-1750 individuals) of foraminifera. Additionally, the assemblage during that period showed a decrease in opportunistic species (<50%), shell deformities (<11%) and inner linings (17%), and a significant increase in calcareous species.

The assemblage in the pre-impact environment, as inferred from cores, has high diversity (>30 species) and abundance (>4000 individuals), a dominant calcareous record (>60%), and lower deformities (3-4%). With the substantial growth of the city of Halifax since the late 1950s, gradual environmental degradation due to organic enrichment in the harbour caused an increasingly negative impact on foraminifera. This decline in environmental quality led to the dominance of opportunistic species (e.g., agglutinated forms such as *Eggerella advena* and *Reophax scottii*), an abundance of shell deformities, and complete absence of calcareous tests, leaving only their inner linings.

The analysis of benthonic foraminifera in two cores from Sydney Harbour (SH) helped to compare contamination types in both areas (domestic in HH vs. industrial in SH). The domestic pollution in HH let to a dominantly agglutinated assemblage with low diversity, low abundance, and high ratios of inner linings. In contrast to HH, the foraminiferal assemblage in SH showed higher diversity (>22 species) and abundance (>4000 individuals), a dominant calcareous record (>50%), and low inner linings (<10%) together with species that were not observed in the cold waters of Nova Scotia (*Ammonia beccarii*).

LIST OF ABBREVIATIONS USED

Ag	Silver
BIO	Bedford Institute of Oceanography
BP	Before present
$CaCO_3$	Calcium carbonate
°C	Degrees centigrade
cc	Cubic Centimetre
CCME	Canadian Council of Ministers of the Environment
cm	Centimetre
cm/s	Centimetre per second
C$	Canadian dollar
Cu	Copper
DO	Dissolved Oxygen
GPS	Global positioning system
Hg	Mercury
HH	Halifax Harbour
H_2O	Water
HRM	Halifax Regional Municipality
%	Percent
µm	Micrometre
Km	Kilometre
L	Litre
M	Mud
m^3	Cubic metre
m^3s^{-1}	Cubic metre per second
m	Metre
mg	Milligram
ML	Million litre
MS	Muddy sand
N	North
NS	Nova Scotia
NW	North West
OC	Organic carbon
P	Peat
p.	Page
PAHs	Polycyclic aromatic hydrocarbons
Pb	Lead
PCBs	Polychlorinated biphenyl
pH	Measure of acidity (log of the reciprocal of the hydrogen ion activity)
pl.	Plate
ppm	Part per million
ppb	Part per billion
psu	Practical salinity unit
S	Sand
s^{-1}	Per second
SE	South East
SEM	Scanning electro microscope
SH	Sydney Harbour
Sl	Silt
spp.	Species (plural)
USA	United States of America
VC	Vibracore
W	West
wt	Weight
WWTF	Wastewater treatment facility
yr	Year
y^{-1}	Per year
Zn	Zinc

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Chapter 1: Introduction

1.1 Contamination in coastal areas

As coastal areas offer numerous advantages related to food supply, ease of defense and methods of transportation (UNEP and UN-HABITAT, 2005), people have been settling along them throughout history. However, over the past two centuries, urbanization and industrialization have led to extensive inputs of a wide range of pollutants to coastal marine environments, including sewage effluent, solid waste, inorganic chemicals, organic compounds, inorganic plant and algal nutrients, and toxic and radioactive waste (Draper, 1998; Garrison, 2002; Raven and Berg, 2004; Marsh and Grossa, 2005; Richard et al., 2007; Middleton, 2008). More than 75% of these pollutants come from land-based human activities (Garrison, 2002). The input of pollutants has caused severe environmental damage, destruction of ecosystems and habitats, and loss of biodiversity in some aquatic systems.

Many studies have documented, monitored, and reconstructed pollution histories using a variety of different tools such as sediment geochemistry, water chemistry, macrofossils, and microfossils (e.g., Alve, 1995a, b; Buckley et al., 1995; Mojtahi et al., 2008; Buosi et al., 2010). Because they dwell in or at the surface of the bottom sediments where contaminants precipitate from the water column, benthonic organisms have been used as a traditional tool for the study of pollution in coastal environments (Pearson and Rosenberg, 1978). Among the benthonic organisms that are increasingly used in environmental pollution research are benthonic foraminifera. They are one of the few benthonic groups that leave a fossil record in the sediment and are small enough to obtain a full record of environmental change.

1.2 Study area (Halifax Harbour)

Halifax Harbour is an elongated NW-SE oriented inlet located on the southeastern seaboard of Nova Scotia, Canada (Fader and Miller, 2008). The harbour, claimed to be the second largest ice-free harbour in the world, extends for over 28 km inland and is connected in the south to the Atlantic Ocean (Fig.1.1). Except in shallow tidal areas, the average water depth exceeds 20 m (Fig.1.1), allowing access for large vessels and making the harbour the largest seaport of Atlantic Canada.

Halifax Harbour, like many other coastal areas, served as a disposal site for the waste materials of urban development of the city of Halifax and surrounding areas (Tay et al., 1992; Buckley et al., 1995; Scott et al., 2005; Walker et al., 2006). Until 2008, approximately 100 outfalls discharged 181 ML/day of untreated sewage, releasing a wide range of organic and inorganic pollutants into the harbour (Halifax Regional Municipality-HRM, 2006; Walker et al., 2006). These high levels of contamination not only affect marine biota, but also gave rise to unpleasant odours, turbid waters, and coastal pollution, further diminishing the recreational value of the harbour (HRM, 2006). The following paragraphs discuss the environmental setting of Halifax Harbour, with an emphasis on pollution and wastewater treatment time-lines of the harbour.

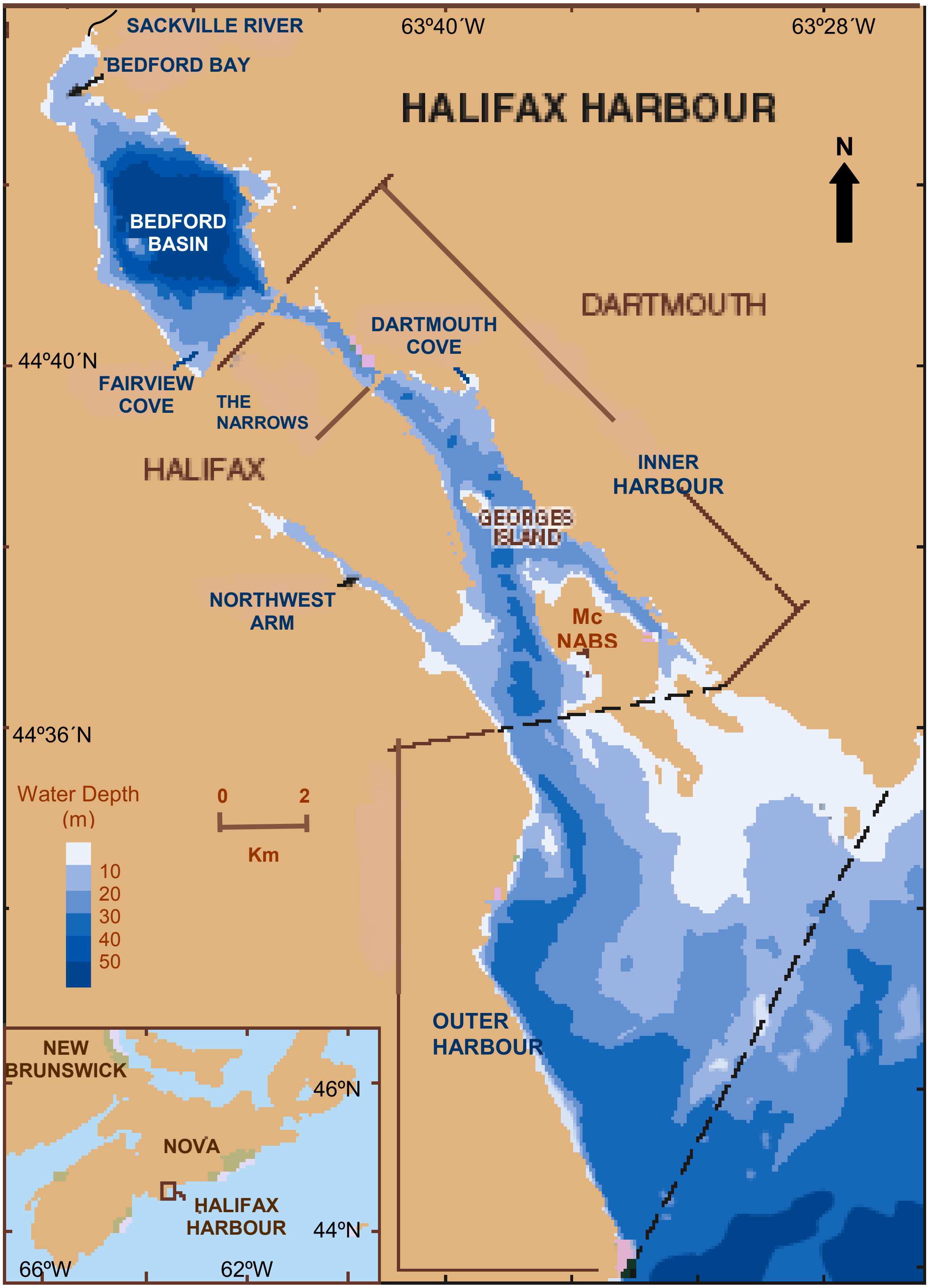

Figure 1.1: The location, geographical classification and water depth (in metres) of Halifax Harbour (from Fader and Miller, 2008).

1.3 Environmental setting of Halifax Harbour

1.3.1 Natural environmental conditions

Halifax Harbour has a complex shape that is controlled by the topography of the underlying Paleozoic Meguma Terrane (Fader and Miller, 2008). Water depths throughout most of the harbour exceed 20 m. The harbour receives a high influx of freshwater from the Sackville River, which flows into the northern end of Bedford Basin (Fig. 1.1), and through sewage outfalls along its margins. The Sackville River, which has a drainage area of 1340 krn2, contributes about 80% of the annual freshwater influx with an average runoff rate of 5.3 m3/s (Water Survey of Canada, 1980).

Due to this influx and its semi-enclosed shape, Halifax Harbour has a two-layered-flow estuarine circulation system in which marine water enters through the harbour mouth below the fresh water that flows over the denser seawater out of the harbour (Fig. 1.2). Stormy weather disrupts this circulation pattern, with ocean waters entering near the surface and fresh waters exiting near the bottom (Fader and Miller, 2008), especially during tropical storms and hurricanes (Shan, 2010).

The mixing of water masses is confirmed by the remarkable horizontal and vertical variations in salinity found throughout the harbour (Fader and Miller, 2008). Near-surface salinities in Halifax Harbour reach their maximum values of about 30.8 psu in March and minimum values of about 27.5 psu in December, although near-surface salinity in Bedford Basin is slightly lower than that in the outer harbour. Shan (2010) demonstrated that the upper 10 m of the water column show significant monthly variation in vertical salinity stratification (Fig. 1.3).

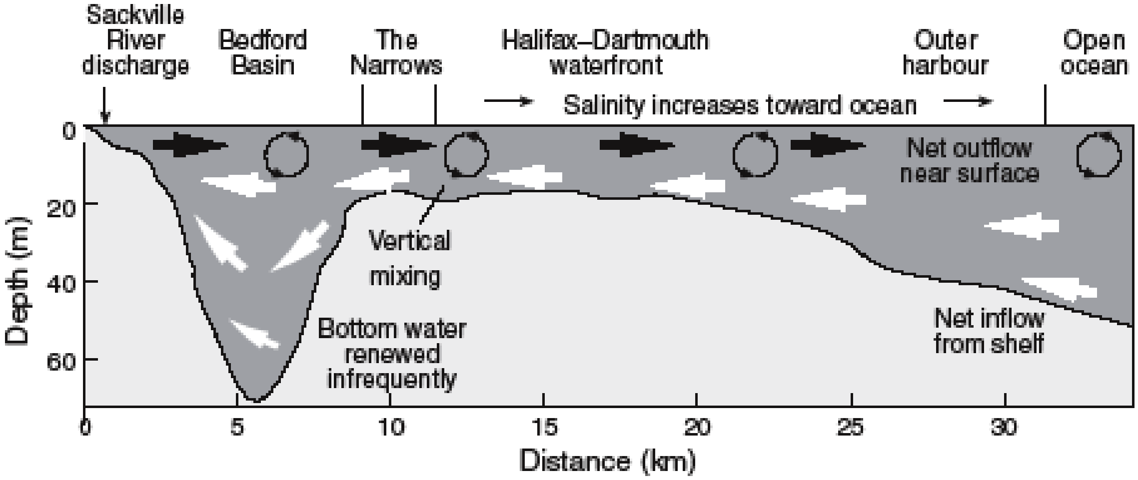

Figure 1.2: The circulation pattern of Halifax Harbour (from Fader and Miller, 2008).

The near-surface water temperatures of Halifax Harbour vary from -1°C in winter to 15°C in summer, with a noticeable monthly variability (Shan, 2010). These temperatures show a horizontal uniformity throughout the whole of Halifax Harbour from September to March, while they are much higher in Bedford Basin than the outer harbour from April to August (Shan, 2010). The vertical temperature stratification in the water column of Halifax Harbour is significantly greater during September from the beginning of fall and decreases gradually towards the end of fall. Surface-layer waters from the head of Bedford Basin to the open sea are cooler than lower-layer waters in winter (January-March) and become warmer from April to August (Fig. 1.4; Shan, 2010).

Dissolved oxygen (DO) in seawater is very important for the biological activities of most marine organisms. The discharge of domestic and industrial wastes in water bodies can affect the amount of DO, as aerobic bacteria use dissolved oxygen to decompose organic matter and convert it into inorganic matter, causing oxygen depletion (Mishra et al., 2006). The concentrations of DO in the surface water of Halifax Harbour range from 8.91-13.88 mg/L, whereas anoxic conditions have been recorded near the sewage outfalls (Halifax Harbour Task Force, 1990).

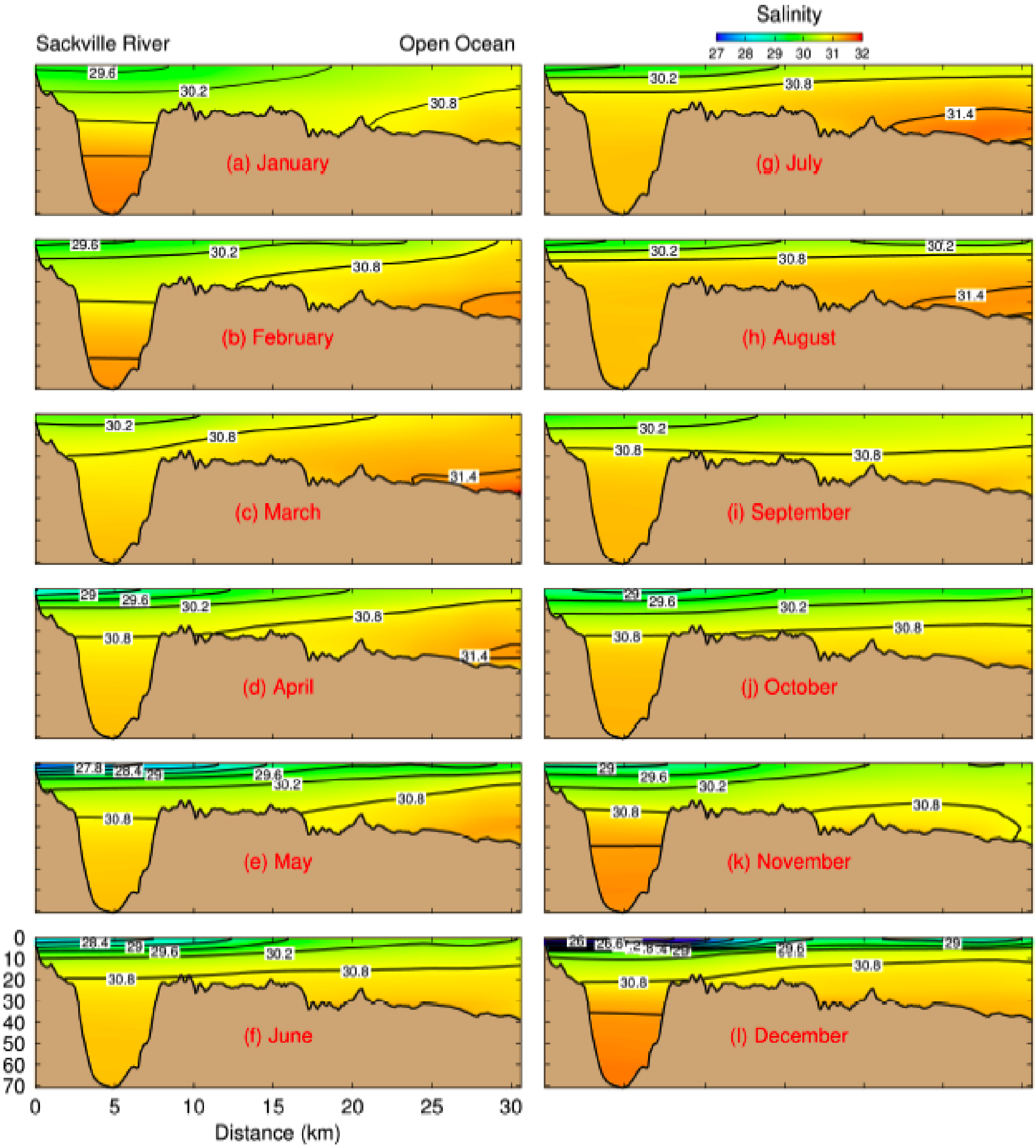

Figure 1. 3: Vertical distribution model of monthly mean Salinities (psu) along a transect from the Sackville River to the open sea, as interpolated from the new gridded climatology (from Shan, 2010).

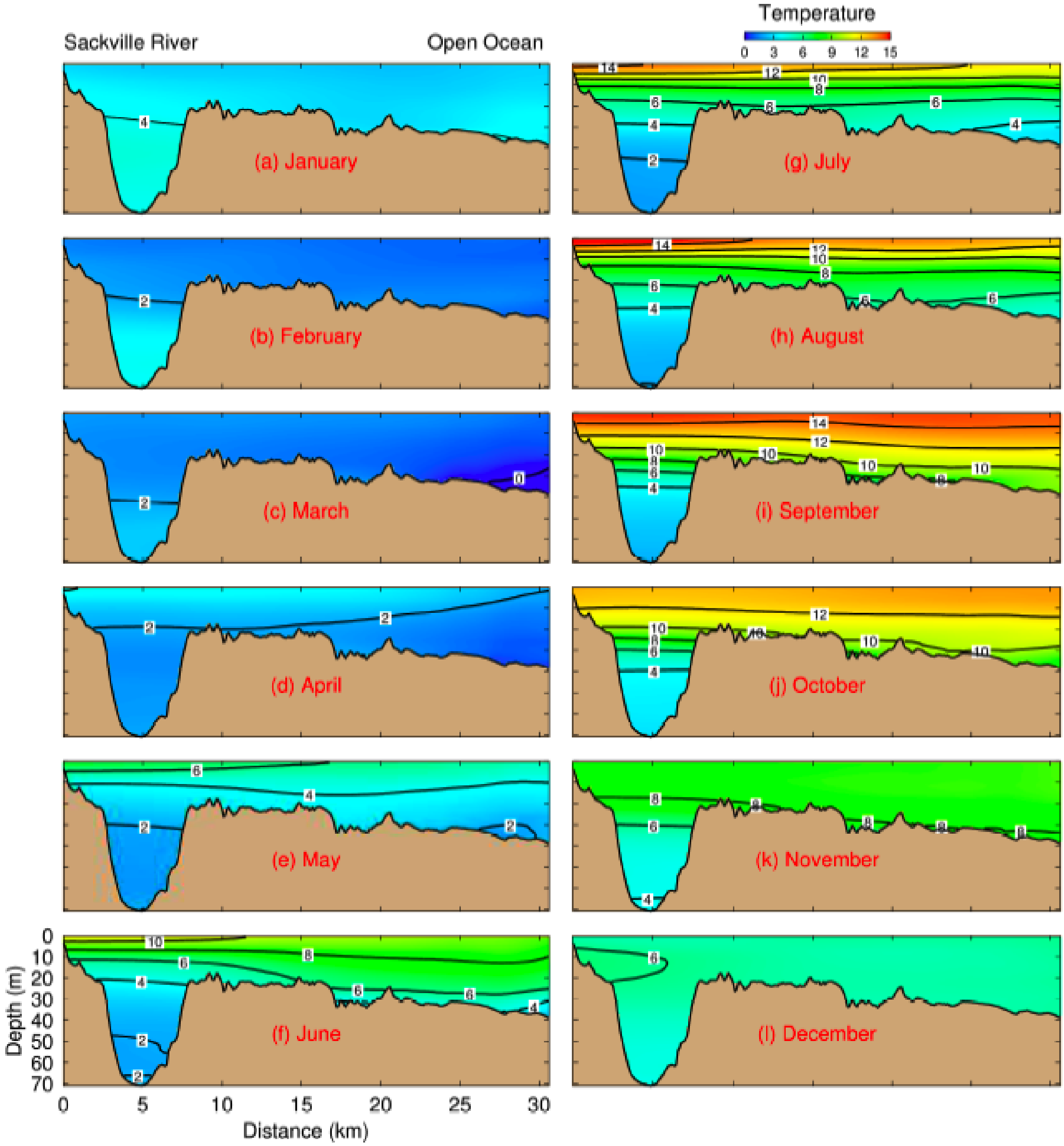

Figure 1.4: Model of monthly mean temperatures (ºC) vertical distribution in Halifax Harbour water along a transect from the Sackville River to the open sea, interpolated from the new gridded climatology (from Shan, 2010).

In Bedford Basin, at the 60 m water depth, DO concentrations in the 1960s were found to be 6.94 mg/L (Krauel, 1969). Later records show that there is a continuous decrease in DO until it approaches zero in the basin as result of poor deep-water exchange. This is due to the consumption of dissolved oxygen by organic matter degradation in sediments and suspended particulate matter (Halifax Harbour Task Force, 1990). In the outer part of the harbour, oxygenation takes place due to water exchange with the open ocean, with less oxygen consumption by the comparatively coarser surface sediments (Halifax Harbour Task Force, 1990). In other parts of Halifax Harbour (e.g., the Northwest Arm) the concentrations of DO are very low due to the higher levels of mud and organic matter (Halifax Harbour Task Force, 1990). A detailed description of the geology, regional setting and history of Halifax Harbour can be found in Fader and Miller (2008).

1.3.2 Pollution in Halifax Harbour

The harbour has been a disposal site for urban waste materials since the founding of the City of Halifax in 1749. Until the beginning of the treatment program in January 2008, the main sources of pollution were approximately 100 untreated sewage outfalls that used to discharge 181 ML/day of sewage materials into the harbour (Halifax Regional Municipality, 2006). These outfalls came from private homes, light industry, government and university laboratories, military bases, and hospitals (Buckley and Winters, 1992; Scott et al., 2005). The sewage materials enriched the harbour with a wide range of organic and inorganic pollutants. Polycyclic aromatic hydrocarbons (PAHs), one of the most widespread organic compounds recorded in the sediments, are considered persistent pollutants, with levels above the minimum established by environmental quality guidelines developed by The Halifax Harbour Task Force (1990) for the use of Halifax Harbour (Hellou et al., 2002). In addition, large amounts of metal pollutants, such as copper, zinc, lead, and mercury, had been released into the harbour from various sources, including sewage outfalls, shipyards, and a former municipal landfill (The Halifax Harbour Task Force, 1990). Buckley and Wnters (1992) estimated the annual input of these metals to the surfacial sediments of Halifax Harbour as follows: copper (10,700 kg/yr), zinc (36,000 kg/yr), lead (34,600 kg/yr), and mercury (185 kg/yr). These amounts are among the highest recorded in marine harbours worldwide (Buckley, 2001).

In addition to the above-mentioned contaminants, "emerging contaminants" (e.g., personal care-, household- and pharmaceutical products as well as flame retardants) have been observed at moderate concentration levels in Halifax Harbour (e.g., Brun et al., 2006; Comeau et al., 2008; Robinson et al., 2009). They also affect the marine biota and give an unpleasant smell to the harbour, diminishing its recreational value (Halifax Regional Municipality, 2006).

1.3.3 ***Timeline and treatment history of Halifax Harbour***

The first record of pollution in the harbour was made by Huntsman (1924), who indicated that there was a pollution discharge in the waterfront area from the Narrows to the Ocean Terminals on the Halifax side and to a lesser extent from Eastern Passage to the Narrows on the Dartmouth side. Huntsman (1924) also mentioned that this pollution emanated from at least thirteen sewers that were depositing raw sewage into the harbour at this time. Starting forty years later, from the late 1960s onwards, consecutive provincial, federal and municipal governments conducted numerous research studies on the growing pollution in the harbour. From these studies emerged proposals and recommended steps to establish a strategy, including sewage treatment, to manage the disposal of waste material into Halifax Harbour.

Because of increasing concern about environmental problems in Halifax waterfront, small sewage treatment plants were built in Bedford and in Eastern Passage (HHTF, 1990). The first one was built in 1970 at Mill Cove to offer secondary treatment for sewage that discharged into Bedford Bay. The second treatment plant was built in 1974 at Eastern Passage to offer secondary treatment. This plant was downgraded to a primary treatment facility in 1987, but is presently being upgraded to secondary treatment once again. However, these two treatment plants treated only about 20% of the sewage that poured into the harbour whereas about 80% of Halifax Harbour sewers remained untreated (JWEL, 2001) until 2008.

In 2007, the Halifax Regional Municipality (HRM) began construction of a three-plant treatment system located in downtown Halifax, downtown Dartmouth, and Herring Cove (on the southwest side of the harbour) (see Fig. 1.5) to provide advanced primary treatment of the sewage outfalls that pour into the harbour. The three facilities were expected to significantly improve conditions in the harbour and were projected to cost CAN$330 million. The first location to open was the Halifax Wastewater Treatment Facility (WWTF), on February 11, 2008, but the opening of the other two plants, although scheduled for later that year, were delayed until 2010. It should be noted that the field sampling for the present study was already completed at the time of the opening of the second and third wastewater treatment facilities.

After only one year of operation, the Halifax plant incurred a massive failure due to a power outage, and raw sewage flowed again into the harbour, causing extensive odour, turbidity and floating debris problems (HRM, 2009). Since June 2010, the three WWTFs have been fully operational and treating sewage. The locations of these treatment plants and the processes that take place inside them are illustrated in Figures 1.5 and 1.6. A more specific description of the wastewater treatment facilities in Halifax Harbour can be found in HRM (2009) and Williams (2010).

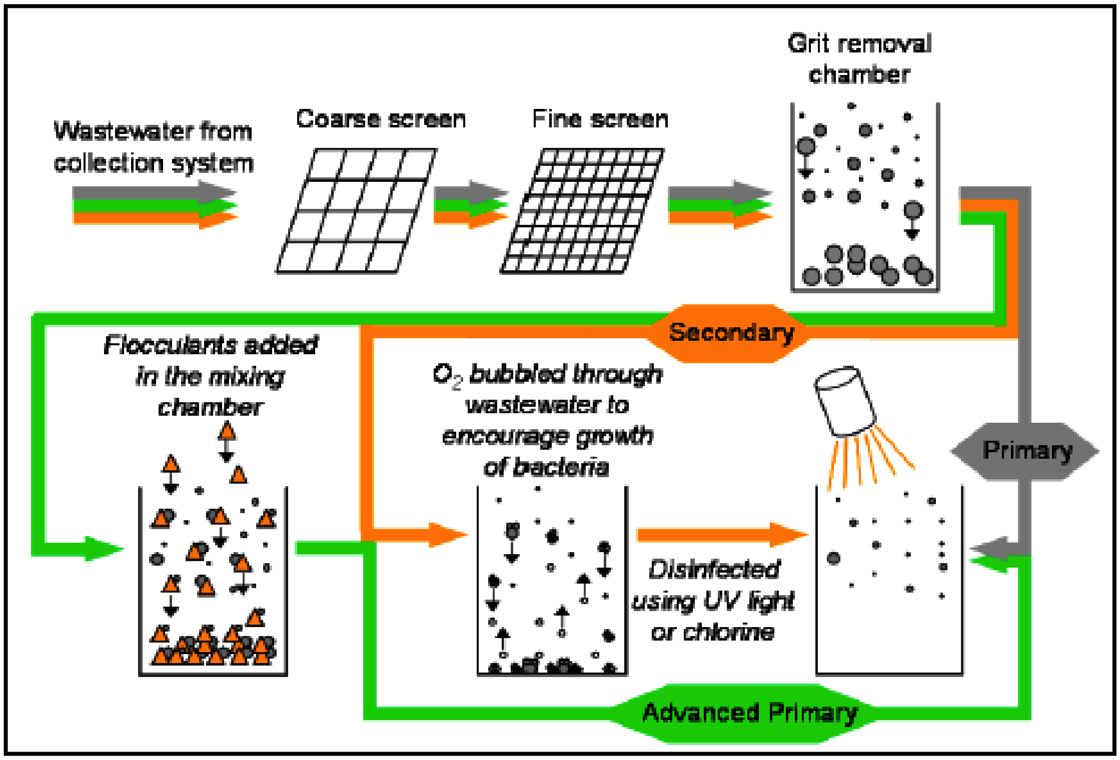

Figure 1.5: Processes in WWTFs in Halifax Harbour (from Williams, 2010).

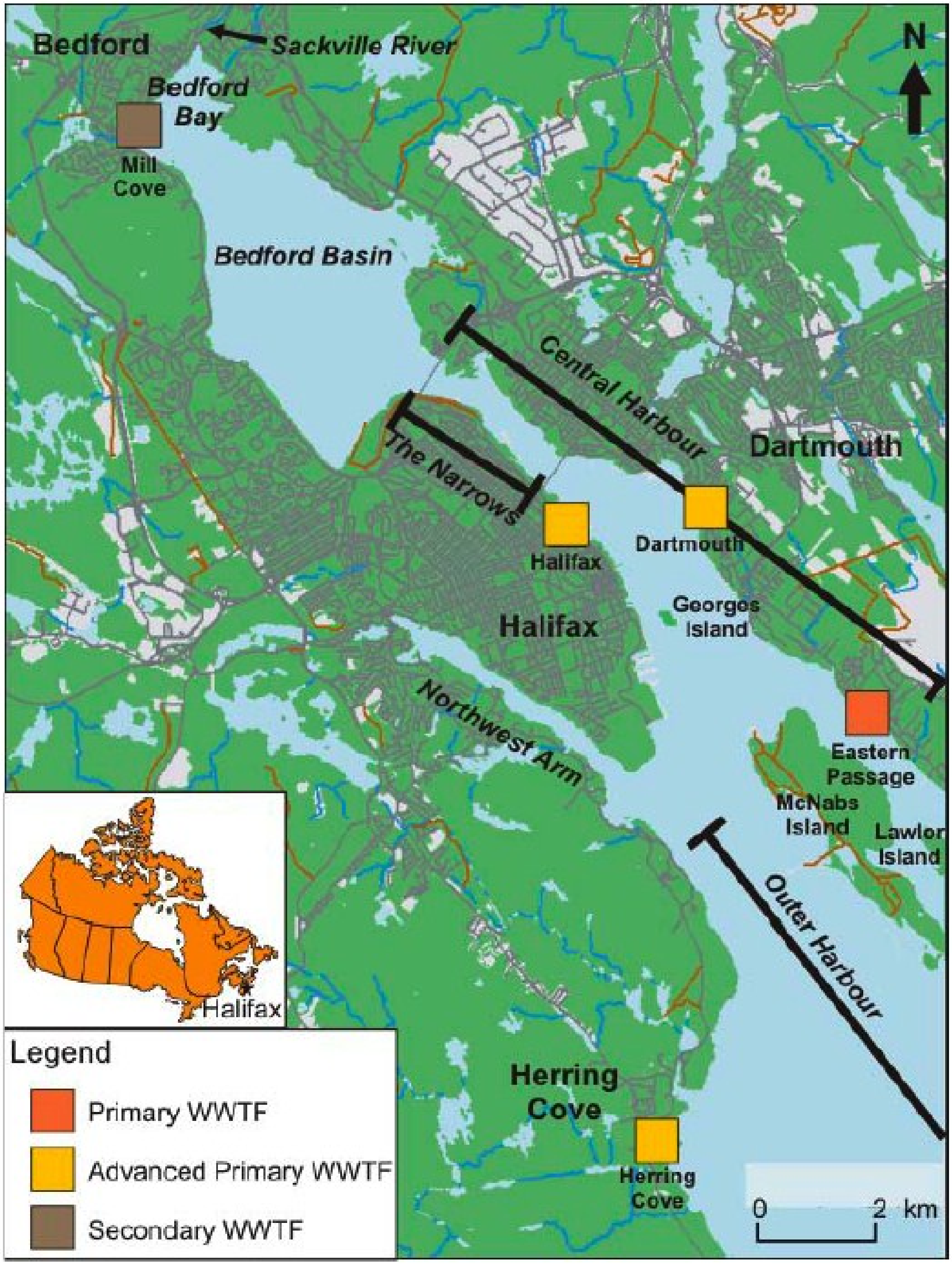

Figure 1.6: The locations of WWTFs in Halifax Harbour (from Williams, 2010).

1.4 Benthonic foraminifera as pollution proxies

1.4.1 Importance of foraminifera as bioindicators

Benthonic foraminifera, one of the most diverse groups of shelled microorganisms in modern seas (Sen Gupta, 1999), live on the surface or within the upper few centimeters of bottom sediments (Murray, 2006; Tarasova, 2006). They are directly influenced by the chemical composition of the sediment-water interface and are characterized by a short reproductive cycle (one month for the small taxa to one year for the larger ones) (Boltovskoy, 1965; Murray, 1991, Tarasova, 2006), high diversity (Schafer, 2000; Scott et al., 2001), wide distribution (Frontalini et al., 2009), specific environmental tolerances (Boltovskoy et al., 1991), and quick response to environmental changes (Scott et al., 2001).

Foraminiferal tests, which can provide concrete evidence of the presence of pollutants (Nigam et al., 2006), appear in large numbers in both the modern and fossil records (Schafer, 2000), thus providing a high degree of confidence in their use for remediation-monitoring studies (Scott et al., 2001). Benthonic foraminifera can tolerate highly stressed environments and are therefore among the last organisms that completely disappear from heavily impacted sites (Scott et al., 2001). The variations in foraminiferal abundance (the total number of individuals per certain sediment weight or volume), diversity (number of species) and test morphology strongly reflect changes in the environmental conditions (Nigam et al., 2006).

1.4.2 History of use of benthonic foraminifera as proxies

The record of pollution effects on benthonic foraminifera and their use as proxies for pollution started at the end of the 1950s (e.g., Zalesny, 1959; Resig, 1960; Watkins, 1961; Bandy et al., 1964a,b, 1965a,b; Boltovskoy, 1965; Seiglie, 1968). In the last two decades, benthonic foraminifera have been increasingly used as pollution indicators (Fig. 1.7) in many kinds of marine environments affected by a wide range of pollutants (e.g., Alve, 1995; Yanko et al., 1999; Geslin et al., 2000, 2002; Samir and El-Din, 2001; Scott et al., 2001, 2005; Murray and Alve, 2002; Mojtahid et al., 2008).

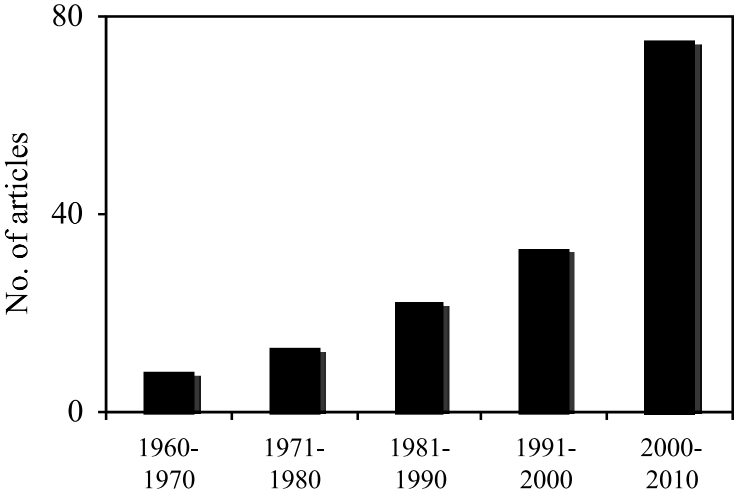

Figure 1.7: Chart showing the gradual increase of foraminiferal research for pollution monitoring since 1960s (modified after Nigam et al., 2006).

1.4.3 Foraminiferal parameters that can be used as environmental proxies

A variety of parameters in benthonic foraminifera can be used as environmental proxies, such as abundance, diversity, test morphology, and assemblage composition (e.g., Alve, 1991, 1995a; Yanko et al., 1994; Geslin et al., 1998; Scott et al., 2001; Frontalini et al., 2009). Previous studies dealing with pollution effects on benthonic foraminifera recorded changes in all or most of these parameters, with different emphases depending on the pollution type and intensity (e.g., Alve, 1995b; Yanko et al., 1998; Geslin et al., 2000; Armynot du Châtelet et al., 2004; Scott et al., 2005; Ferraro et al., 2006; Frontalini and Coccioni, 2008; Frontalini et al., 2009). Generally, there was a decrease in both diversity and abundance of foraminiferal communities as a result of industrial pollution (Alve, 1991, 1995a, b; Yanko et al., 1994, 1999; Debenay et al., 2001, 2005; Coccioni et al., 2003, 2005; Armynot du Chatelet et al., 2004; Cherchi et al., 2009; Frontalini et al., 2009; Romano et al., 2009; Frontalini and Coccioni, 2011; Denoyell et al., 2012).

Shell deformition is another parameter that has been widely recorded in different types (e.g., reduced shell size, aberrant chamber shape, disturbed chamber arrangement, and siamese twins) as a response of foraminifera to adverse environmental conditions (Coccioni, 2000; Geslin et al., 2000). Numerous studies record foraminiferal test deformities as pollution proxies from areas contaminated by heavy metals or other chemicals (e.g., Alve, 1991; Yanko et al., 1998; Samir, 2000; Geslin et al., 2002; Cevison and Hallock, 2007; Luciani, 2007; Fontalini and Coccioni, 2008; Debenay et al., 2008). However, pollution is not the only cause of deformation in foraminiferal shells. Boltovskoy et al., (1991) demonstrated that shell deformities could be also related to changes in natural factors (e.g., temperature, salinity, nutrition, dissolved oxygen, substrate) in the environment. Many authors have also recorded a significant (up to 26%) presence of shell deformities in naturally stressed environments (e.g., Alve, 1991, 1995a; Boltovskoy et al., 1991; Stouff et al., 1999; Debenay et al., 2001; Geslin et al., 2002; Le Cadre et al., 2003; Omaña et al., 2012). Hence, due to the wide range of both artificial and natural environmental factors that may cause deformities, care must be taken when using them as pollution indicators (Geslin et al., 2000, 2002).

1.4.4 Foraminifera in polluted environments

In marine environments affected by sewage outfalls, an area occurs at the source point that contains mostly dead and very rare individuals (Fig.1.8a). It is variously named the “dead zone”, “abiotic zone”, “barren zone”, or “afaunal zone”. Immediately surrounding the dead zone, within a short distance from the source, is another zone marked by low foraminiferal diversity and high abundance, the latter of which is many times greater than in nearby unpolluted areas. The species that dwell in this zone compete and survive in very adverse conditions and are called opportunistic, stress tolerant, or impact tolerant (Murray, 2006). Examples of these species include *Eggerella advena*, *Elphidium incertum* and *E. clavatum*, which are highly competitive and reproductive in stressed environments and occur abundantly near pollution sources (Schafer et al., 1975). The increase of organic matter flux in an environment dissolves calcareous tests, leaving only their organic inner linings, which can be used to detect reducing conditions caused by pollution (Scott et al., 2001).

Alve (1995a) produced a simplified model for the variations in foraminiferal assemblage characteristics with the increase of organic pollution through time (Fig.1.8b). The natural (pre-impact) species are less tolerant to pollution and die out as pollution levels increase. The transitional species can tolerate low levels of pollution but disappear as pollution increases (Murray, 2006). Over time, a decline in diversity and an increase in the number of dead forms occur as pollution increases, followed by the deposition of a sedimentary interval "barren zone" that corresponds to maximum pollution and is devoid of shells. Based on the model introduced by Alve (1995), the reduction of pollution to a point of complete prevention will result in diversification of the foraminiferal assemblage and eventual recovery to the pre-pollution state (Murray, 2000, 2006, Scott et al., 2001). Sediment core studies are very useful for monitoring programs, as they allow for the reconstruction of pre-impact environmental conditions (Alve, 2000; Scott et al., 2001; Murray, 2006). In summary, the analysis of benthonic foraminifera in surface sediments provides a useful short-term (i.e., several years) monitoring tool for remediation programs. Likewise, the analysis of foraminiferal data in sediment cores would provide a long-term (i.e., several decades) and/or baseline reconstruction from sediment cores.

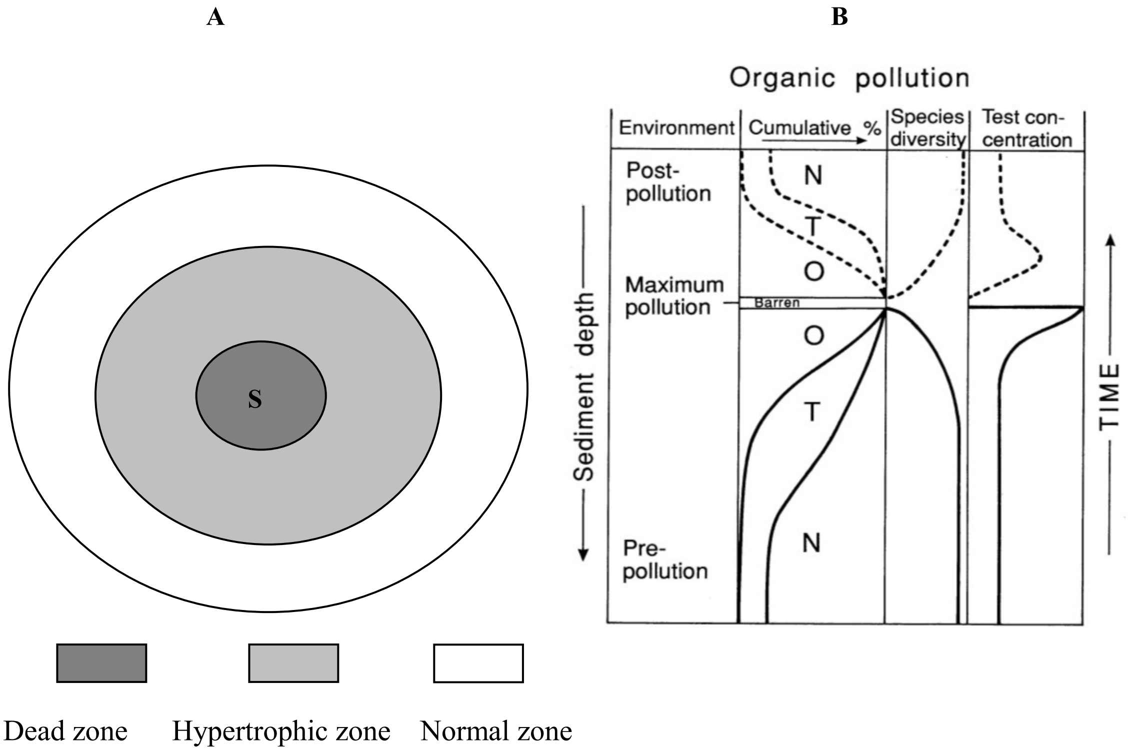

Figure 1.8: Schematic diagram showing the foraminiferal response for organic pollution. A: the foraminiferal distribution around pollution source S, B: model of foraminiferal response to the onset and increase in organic pollution, N: Natural population, T: Transitional population, and O: opportunitic population (after Alve, 1995a).

1.5 Previous work related to this study

Fader and Miller (2008) emphasized that many ocean-related research facilities in the Halifax area have published over 250 research and survey reports on the harbour. The majority of these studies dealt with contamination but focused mainly on the geochemistry of the sediments and water analyses (e.g., Buckley and Hargrave, 1989; Gearing et al., 1991; Winters et al., 1991; Buckley and Winters, 1992, Fader and Buckley, 1997; Williams, 2010). Only one important study was produced on the distribution of benthonic foraminifera in the harbour, in which the author (Gregory, 1971) identified 26 agglutinated species and 58 calcareous species from approximately 120 surface-sediment samples collected from 1968 to 1969. Although sampling and processing techniques at that time were not intended for environmental studies, his results provided a baseline and tool for comparisons for the present study. Gregory's (1971) findings indicate moderate impact conditions represented by the presence of many calcareous shells, few inner linings, and few opportunistic species, compared to the present severe impact conditions characterized by an abundance of relict inner linings and opportunistic species, without an appreciable presence of calcareous tests (this study, Chapter 2).

Miller et al. (1982a) studied the post-glacial history of Bedford Basin and observed a "twofold decrease" in the abundance of benthic foraminifera in the surface samples of their cores as compared to their numbers in the samples dated 250 years ago. Miller et al. (1982a) suggested that this slight foraminiferal degredation in post-European settlement core samples resulted from increased rates of sediment influx and effluent discharge into the area. Edgecombe et al. (1999) studied two long (~5 m) sediment cores from the outer part of the central harbour in front of Georges Island (Fig. 1.1) to reconstruct the postglacial history and sea-level changes of Halifax Harbour over the last 8,000 years. Although Edgecombe et al. (1999) did not pay much attention to the changes of foraminiferal assemblage in the last hundred year, they discovered that the upper sections (~35 cm) of their cores were composed of black mud and had low diversity and an increase in the *Reophax scottii*. In 1995, Haury (1996) collected over 20 samples throughout the harbour, including some from Gregory's 1968 sample locations. Williamson (1999) studied one short core taken from Mill Cove in Bedford Basin to assess the improvement of environmental conditions after a treatment plant failure in 1996 released a large amount of effluent (30 cm-thick layer of black sludge), which has since been oxidized.

Scott et al. (2005) examined two short diver cores collected in 1996 and 1998 from Tufts Cove and Mill Cove, and incorporating the results of that study with those of Haury (1996), publishing the first work on the use of benthonic foraminifera as environmental proxies in Halifax Harbour. Despite the differences in processing techniques between Gregory's (1971) study and subsequent studies, benthonic foraminiferal data indicated a considerable change in the amount of pollution. Scott et al. (2005) observed an overall decrease in both diversity and number of calcareous species and an increase in inner linings, as well as a shift to dominance of opportunistic species (e.g., *Eggerella advena* and *R. scottii*). Scott et al. (2005) demonstrated that the increase of labile organic matter, which has a low pH, in the sediments between late 1960s and late 1990s, caused dissolution of calcite in foraminiferal shells and developed an agglutinated dominant assemblage.

1.6 Statement of problem

In 2008, Halifax Regional Municipality started an advanced primary treatment program without using the study of biological bioindicators as monitoring proxies for the treatment process. In addition, relatively limited knowledge of the pre-industrial environmental conditions (with respect to biological proxies) throughout Halifax Harbour is another gap in the knowledge regarding long-term monitoring of the current treatment program. However, baseline studies are very important for successful environmental monitoring programs (Murray, 2000).

Most of the previous studies (e.g., Buckley and Winters, 1992; Williams, 2010) that dealt with the contamination of HH focused mainly on sediment geochemistry or water chemistry. These studies indicated that concentrations of metals (e.g., Hg, Pb, Cu, Zn, Cr, Ni, Li) in near-surface sediments from Halifax Harbour exceed Canadian environmental guidelines for the area. These pollutants do not decompose and can persist for many decades in the sediments until covered by new clean sediments.

Benthonic foraminifera, on the other hand, react much more quickly to changes in the rate and type of pollution due to their specific environmental tolerances and their rapid reproduction rates (Scott et al., 2001, Murray, 2006, Nigam et al., 2006). These organisms are thus ideally suited to assessing environmental improvements even on smaller temporal or spatial scales (Ferraro et al., 2006; Frontalini and Coccioni, 2008; Frontalini et al., 2009).

1.7 Objectives and research questions of the present work

The present thesis has three main goals. Firstly, this study aims to use benthonic foraminifera as short-term monitoring proxies to assess the effect of the Halifax Harbour Solutions Project on water-sediment surface environmental conditions. Secondly, it aims to reconstruct the pre-impact environmental conditions (with respect to foraminifera) as a “baseline” or “target” environment for monitoring the effectiveness of the recent wastewater treatment program. Thirdly, it also aims to compare pollution levels and effects in Halifax Harbour with those in Sydney Harbour, Nova Scotia, and to document the use of benthonic foraminifera as monitoring proxies and bioindicators in marine environments affected by variable types of pollution. The overall objectives of this research are to answer the following questions:

1-How effective is the wastewater treatment process that is currently taking place, and how long will it take to improve the environmental quality of the harbour’s sediments to levels similar to pre-industrial levels?

2-What is an appropriate reference “baseline" or "target environment" for the present treatment program in Halifax Harbour?

3-How do environmental conditions in Halifax Harbour compare with those in Sydney Harbour, which is heavily affected by industrial pollution?

1.8 Hypotheses, assumptions, and approach

The current resreach is based on two main hypotheses that can be tested in this study, as follows:

1- Foraminifera respond very quickly to any environmental change (either natural or human-induced), even on smaller temporal or spatial scales. Thus, any short-term environmental recovery due to the treatment process currently taking place in Halifax Harbour will appear on the foraminiferal assemblage. This statement hypothesizes that anthropogonic-induced changes in the environment will affect and change benthonic foraminiferal assemblage in that environment.

2- The historical record of foraminiferal assemblage in the unpolluted sediments would offer a target environment for the treatment process. This part of the hypothesis based on the assumption that foraminifera will show a vertical succession in sediment cores in reponse to pollution. This vertical succession begins with foraminiferal assemblage that indicates a non-polluted, normal marine environment and ends with an assemblage that indicates a highly polluted environment.

The hypotheses teseted in this research are based on the assumption that any environmental changes would appear in various foraminiferal parameters (diversity and aundance of the assemblage, abundance of deformed shells, and composition of the assemblage: dominated by calcareous or agglutinated taxa). The first hypothesis was tested by examining benthonic foraminifera in bottom sediments of the harbour for a two-year period. The approach in this part is that the distribution pattern of foraminiferal assemblage will vary based on the closeness or distance from the sources (i.e., sewage outfalls) of pollution. The second hypothesis was tested by the examination of foraminiferal assemblage in sediment cores to establish their historical response to gradual contamination of the area.

Because the contamination of Halifax Harbour is primarily due to domestic waste rich in organic carbon (OC) rather than metal, our key parameter in this study was the abundance of calcareous species versus ratios of organic carbon. A few exceptions were made in certain locations known to be present or former industrial sites (e.g., Tufts Cove-Scott et al., 2005). However, all other possible foraminiferal parameters (e.g., diversity, abundance, and deformities) were tested and considered in this study and compared to some metal contaminants (e.g., Hg, Cu, Zn) that were examined for the same sediment samples by Williams (2010).

1.9 Research strategy

Quantitative analyses vs. statistical analyses are the most common methods in environmental studies carried on the use of foraminiferal assemblages as environmental proxies. Quantitative analyses are based on the total (live+dead) foraminiferal assemblage, while statistical ones are based on living individuals in sediment samples. The use of either one of these two strategies (live vs. total assemblages) is an ongoing controversy in foraminiferal research and many arguments are discussed in detail in the literature about the reliability and usefelness of both of these methods. The research that supports the use of the living foraminiferal assemblage rather the total one in environmental studies is mainly concerned with a possible overrepresentation of foraminifera that were live in the sediments at the time of sampling. This can be a very serious issue in siliclastic sediments where shells may have a dgree of physical degredation (Hallock, 2012) or organic-rich sediments due to the fast dissolution of calcareous shells (Aller, 1982). However, the later assumption may be argued with the fact that the organic inner linings of dissoluted calcareous shells can be counted if the residue was examined in a wet solution.

Because of the taphonomic loss some scientists strongly argue that only live and dead assemblages (not total assemblage) provide a sound environmental interpretation (Murray and Alve 1999a, 1999b; Patterson et al. 1999; Murray and Pudsey 2004). On the other hand, some workers have mentioned that living assemblage in any sample represent a “pulsating patch” (Buzas et al., 2002), and thus the use of total foraminiferal assemblage more adequately reflects the foraminiferal community within an area, as it integrates information about the general conditions more effectively than that of living assemblages (Scott and Medioli, 1980; Hallock et al., 2003; Carnahan et al., 2009).

Based on the above discussion, the strategy applied in this study is the quantitative analyses of total (live+dead) assemblage in 10-cc of surface sediments sediments. It is known that benthonic foraminifera live in the upper centimetre of the sediments so in the total assemblage is the most applicable one in sediment cores.

1.10 Challenges and limitations

The use of benthonic foraminifera as monitoring proxies of coastal marine pollution has increased exponentially over the past fifty years since the early research performed by Resig (1960) and Watkins (1961). Because of their characters, benthonic foraminifera are found to be one of the most sensitive and inexpensive tools for indicating deterioration of coastal environments. However, this scientific approach may face many challenges and limitations that make its application fraught with precaution. One of these limitations and challenges is the effect of taphonomic and digenetic processes (e.g., bioturbation and dissolution) that may impact the resolution and quality of nearshore foraminiferal proxy data in both space and time domains (Pati and Patra, 2012). A continuous assessment of these potential effects and any needed additional chemical or physical measurements should be carried out to have a better understanding of the ecosystem.

Natural factors (e.g., hypersalinity, periodical acidification, and strong hydrodynamics) can also induce environmental stress that can affect the foraminiferal assemblage. Many complexities can be found in foraminiferal responses to environmental stress, which make it difficult to distinguish natural and human-induced impacts on foraminifera. For example, abnormal foraminiferal shells that are known as indicators for pollution can also be observed in pollution-free environments (Alve, 1991). Shell deformities were recorded in high rates within areas that have adverse environmental conditions such as low pH (Le Cadre et al., 2003), hypersalinity (e.g., Zaninetti, 1984; Debenay et al., 2001) or high energy (Geslin et al., 2002). Because of this, changes in foraminiferal assemblages have to be used cautiously in areas that have natural environmental unstability.

1.11 Dissertation structure

Chapter 2 is dedicated to the first objective of this research – the short-term monitoring of the current treatment program in Halifax Harbour. Benthonic foraminifera were examined in approximately 20 surface sediment samples collected on a seasonal basis for a two-year period. Originally, the plan was to examine benthonic foraminifera in surface sediment samples over three years to measure the rate of environmental improvement due to the treatment process. However, following the failure of the Halifax Waste Water Treatment Facility (WWTF) after only one year of operation in 2009, it was decided to shorten the time interval to two years.

During this two-year period, sampling locations were collected for six sampling cycles using a Shipek grab sampler. Samples were collected in October 2007 before the operation of the WWTF in downtown Halifax, three times in 2008 during the treatment period, and two times in 2009 after the failure of the treatment facility (Table 2.1). The results of this research (Chapter 2 of this thesis) are published in the Journal of Foraminiferal Research (July 2012; Dabbous and Scott, 2012). In the dissertation, the introduction that was presented in the publication was moved to be part of the dissertation's introduction to avoid repetition. In addition, a section (Sec. 2.6.4.4, Figs.2.18-20, Table 2.2) was added to discuss the seasonal variability of the foraminiferal assemblage in the area that was under treatment (Inner Harbour) during the study period. My supervisory committee recommended these additions, so they appear only in the dissertation, not in the published work.

Chapter 3 aims to reconstruct a reference "baseline" environment for the treatment program using six long (1.7-4.25 m) sediment cores from Halifax Harbour. Making comparisons between the present-day foraminiferal assemblage and historical assemblages will provide a better understanding of pollution impact over time. This, in turn, will help to assess and develop a likely time frame for environmental recovery in the harbour.

Chapter 4 presents foraminiferal assemblages observed in two cores from Sydney Harbour, Nova Scotia, where the sewage materials are of less impact than the industrial contaminants, as compared to Halifax Harbour. Comparisons between different areas affected by different kinds of pollution are helpful for such monitoring studies, especially as there was, in this particular instance, a permanent closure of the main industrial facility (a steel plant) in the late 1980s in Sydney Harbour. Documenting foraminiferal changes since the closure of the main pollution sources in Sydney Harbour two decades ago may help us to predict the future outcomes of the treatment program in Halifax Harbour. This chapter is the first study that has been carried out on benthonic foraminifera in Sydney Harbour and provides a baseline for future long-term monitoring in this area.

The present researcher took part in all sample collection efforts done in Halifax Harbour for this research. The two cores from Sydney Harbour were kindly provided to Dr. David Scott by CBCL Ltd Company. Julie Griffths examined one of the Sydney Harbour cores (core 4). Otherwise, the author carried out all other analyses presented in this thesis and wrote all the text of the thesis, along with the related publication (Dabbous and Scott, 2012).

Chapter 2: Short-Term Monitoring of Halifax Harbour (Nova Scotia, Canada) Pollution Remediation Using Benthonic Foraminifera as Proxies

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2.1 Abstract

Short-term monitoring of benthonic foraminifera in Halifax Harbour conducted before, during, and after implementation of an enhanced, municipal pollution-abatement program, showed that foraminiferal distribution correlated strongly with the amount of pollution flowing into the harbour.

Before enhanced treatment, the confined, highly-polluted Inner Harbour and Northwest Arm contained a fauna of low abundance and diversity, dominated by non-calcareous species with a high percentage of shell deformities and organic inner linings. In contrast, the foraminiferal assemblage in the outer harbour, where currents carry waste material to the ocean, had high diversity and abundance, few shell deformities and organic inner linings, and contained calcareous species.

During treatment, the composition of the inner harbour assemblage changed dramatically to resemble that of the outer harbour fauna, only to revert to its former characteristics after the treatment plant broke down. Comparisons of foraminiferal proxies to geochemical data indicate that both OC and metals have a strong impact on the foraminiferal assemblage in this area. On the other hand, seasonal variability has little impact on foraminifera in the harbour during the summer seasons only. This study once again shows that benthonic foraminifera are accurate, rapid, and cost-effective proxies to monitor continuous environmental changes in polluted environments.

2.2 Introduction

The worldwide urbanization of coastal estuaries, leading to the continuous discharge of human-induced contaminants, has resulted in the widespread contamination of these environments. The contaminants usually sink from the water column into the bottom sediments that act as a natural trap. Because benthonic organisms dwell in these sediments, they have been used as a traditional tool for the study of pollution impact on coastal environments (Pearson and Rosenberg, 1978). Benthonic foraminifera are one of the most useful groups for these kinds of study because they are among the few organisms that leave a large number of hard shells that record changes in the environmental conditions of the area they used to live in. Benthonic foraminifera react quickly to environmental disturbances because of their short life cycles, high diversity, and specific ecological tolerances of individual species. Detailed discussions about the importance and use of benthonic foraminifera as pollution indicators are presented in Chapter 1 (sec. 1.4).

2.3 Study area (Halifax Harbour)

Halifax Harbour, an elongated NW-SE oriented inlet that extends for over 28 km inland, is located in the southeastern seaboard of Nova Scotia, Canada (Fader and Miller, 2008). Because of its ice-free environment and water depths, the harbour offers a prime location for commercial exchange throughout North America and is a major seaport of Eastern Canada (Fader and Miller, 2008).

However, like many coastal areas, Halifax Harbour served as a disposal site for the waste materials of urban development of the city of Halifax and surrounding areas

(Tay et al., 1992; Buckley et al., 1995; Scott et al., 2005; Walker et al., 2006). Until 2008, up to approximately 100 outfalls discharged 181 ML/day of untreated sewage, releasing a wide range of organic and inorganic pollutants into the harbour (Halifax Regional Municipality-HRM, 2006; Walker et al., 2006). These high levels of contamination not only affect marine biota but also give rise to unpleasant odours, turbid waters, and coastal pollution, further diminishing the recreational value of the harbour (HRM, 2006).

Currently, a three-plant treatment system provides advanced primary treatment to the sewage before it reaches the harbour. A detailed description of the geology, regional setting, and history of Halifax Harbour can be found in Fader and Miller (2008). The environmental setting of the harbour, including its circulation, water depth, temperature, dissolved oxygen concentrations, salinity, and pollution timeline, are described in detail in Chapter 1. More specific description of the wastewater treatment facilities in Halifax Harbour can be found in HRM (2009) and Williams (2010).

2.4 Objectives

The original purpose of the present study was to monitor the treatment program in Halifax Harbour over a three-year interval (2007-2010) by using benthonic foraminifera in surface-sediment samples as proxies to measure the rate of improvement in water quality due to the treatment process. Because of the failure of a new Waste Water Treatment Facility (WWTF) after only one year of operation and the delay in bringing other facilities on-line, the study was shortened from three years to two. This project is one of the first to use benthonic foraminifera as proxies to gauge the effectiveness of short-term treatment programs in polluted marine environments.

2.5 Methods

2.5.1 Sampling

For the present study, 18 to 20 surface-sediment samples were collected three times a year for two consecutive years in Halifax Harbour from stations chosen by the HRM (Fig. 2.1). Periodic collection provided a continuous record of foraminiferal changes related to either natural environmental changes or reduced pollution near the newly operational downtown Halifax WWTF. The sampling period extended from late October 2007 (three months before the commencement of sewage treatment) until August 2009. This period included six sampling cycles: one before treatment, three during treatment, and two after the facility failed. The sampling periods were: 1) spring (March−May); 2) summer (June−August); and 3) fall (September−November). Samples were collected with a Shipek grab sampler (Fig. 2.2) that provided a relatively undisturbed sample. A global positioning system (GPS) located the sampling stations, and the water depth at each station was measured in each sampling cycle (Table 2.1). Generally, a subsample of the top 1−2 cm of sediment at each station was collected in plastic vials and stored in a cold room at Dalhousie University for subsequent processing.

2.5.2 Laboratory

All laboratory techniques used here are derived from Scott et al. (2001). Ten-cm^3 samples were washed in tap water through a 45–500-µm set of sieves, to remove silt, clay, or any excess organic material and to segregate specimens into the appropriate size fractions. The samples were preserved with buffered formalin and stained with rose Bengal for at least 12 hours to differentiate live from dead foraminifera. The tests were kept suspended in liquid to avoid loss of organic inner linings and the very delicate species, *Reophax scottii*. A wet splitter developed by Scott and Hermelin (1993) was used to avoid over-counting when organic matter, sediments, or foraminiferal specimens were overly abundant. Foraminifera were examined in liquid suspension under a binocular microscope for diversity (total number of species/10 cm^3), abundance (total number of live and dead individuals/10 cm^3), and ratios of opportunistic species, organic inner linings, and shell deformities. Species were assigned generic names following Loeblich and Tappan (1987). Normal and abnormal individuals were carefully counted, and selected specimens were photographed with a scanning electron microscope.

Station	Longitude (W)	Latitude (N)	Water depth (m)	Dates (yr/mo/da) of sampling cycles in relation to treatment					
				Before	During treatment			Treatment failure	
				07/10/24	08/03/11	08/07/15	08/10/22	09/04/08	09/08/10
HC	63.5572	44.5707	4.9	X	X	X	X	X	X
HP1	63.5526	44.5657	32.6		X			X	
HP2	63.5492	44.5618	33.8		X	X		X	
HP3	63.5552	44.5573	8.2		X	X		X	
PC	63.5700	44.6123	7.9	X	X	X	X	X	X
RNSYS	63.5785	44.6222	14.3		X	X	X		X
AYC	63.6096	44.6367	22.9	X	X	X	X	X	X
BRB	63.5611	44.6247	11	X	X	X	X	X	X
D1	63.5607	44.6338	18.3	X		X	X	X	X
D2	63.5527	44.6362	27.1	X	X		X		
D3	63.5452	44.6385	23.8	X	X	X	X	X	X
EE1	63.5765	44.6577	21.3	X	X	X		X	X
EE2	63.5720	44.6593	20.4	X	X	X	X	X	X
EE3	63.5678	44.6612	10.4	X	X	X	X	X	X
DC	63.5592	44.6639	5.8			X	X	X	X
TC	63.5994	44.6771	7		X	X	X	X	X
DYC	63.6152	44.6989	12	X	X	X	X	X	X
BST	63.6686	44.7166	12.8	X	X				
MC	63.6696	44.7166	14.3				X	X	
BYC	63.6629	44.7234	9.1	X		X	X	X	X

Table 2.1: Sampling stations, geographic coordinates, water depth, and sampling cycles for each sample station.

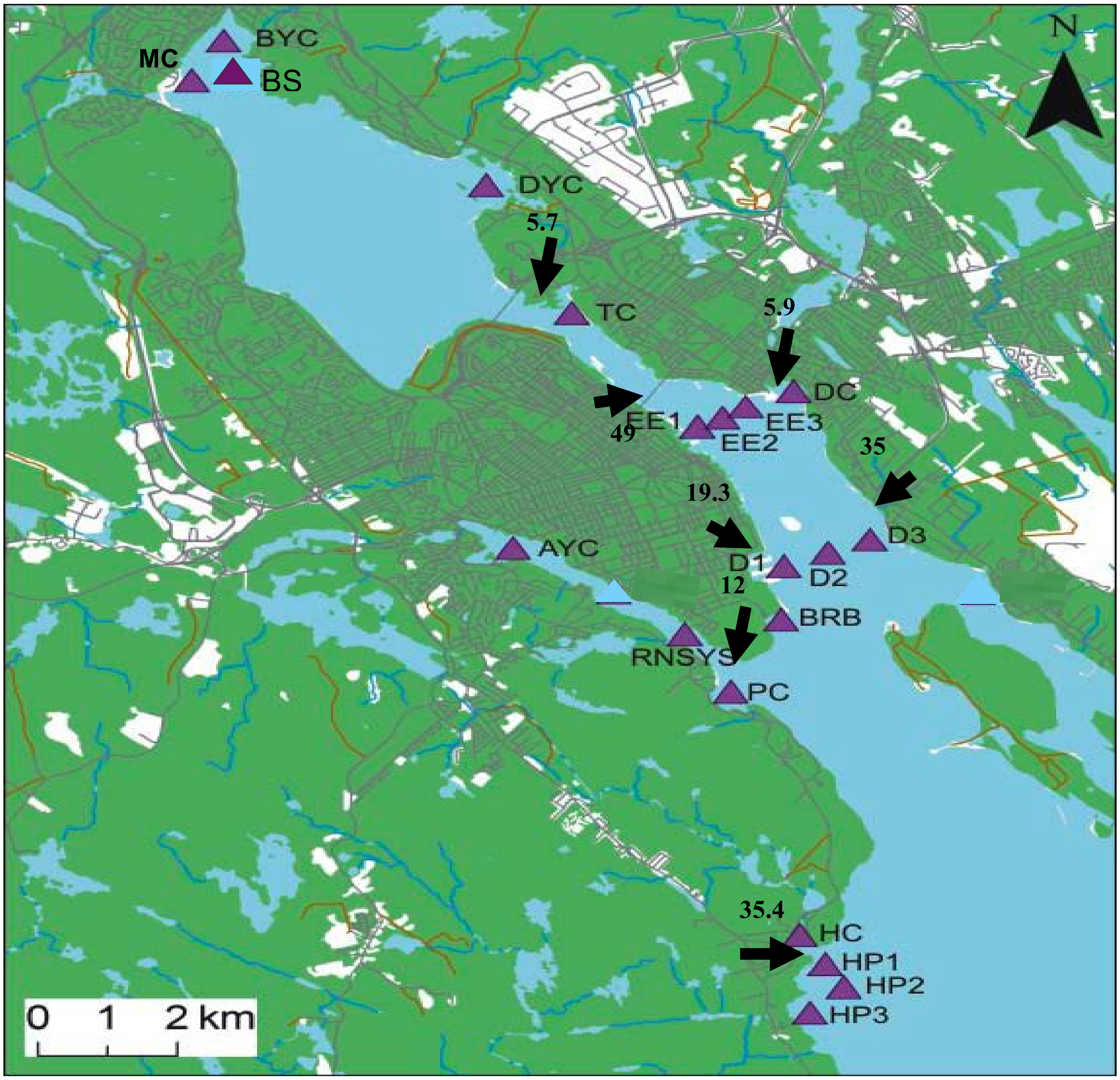

Figure 2.1: Locations of surface samples (triangles) and the main sewage outfalls (black arrows) (from Williams, 2010). The arrows refer to the locations of main sewage outfalls (HHFT, 1990) and the numbers on the arrows refer to the amount of sewage water in ML/day that pours into the harbour based on (HRM, 2006)

Figure 2.2: Photographs showing the sampling using a Shipek sampler: **A**. settling the sampler for opening after pulling it from the water; **B**. taking a sample from the upper few centimeters of the sampler and putting it in a vial for lab processing.

2.6 Results

2.6.1 Generalities

All samples collected during the two-year study contained benthonic foraminifera belonging to 17 genera and 37 species (17 calcareous, 20 agglutinated). Mollusk fragments, echinoid spines, and ostracods were recorded with benthonic foraminifera within the less polluted sites of the outer harbour. Characteristics and components of the foraminiferal assemblage varied from station to station in the harbour but to a great extent were controlled by pollution level. The foraminiferal assemblage was dominated by the tolerant agglutinated species *Eggerella advena*, *Reophax scottii*, *Cribrostomoides crassimargo*, *Spiroplectammina biformis* and *Ammotium cassis*, with the calcareous species *Elphidium excavatum*, *Fursenkoina fusiformis*, and *Haynesina orbiculare* in most samples. Calcareous species were rarely recorded or absent in the inner parts of the harbour, but many of the organic inner linings of their tests were present. Shell deformities were recorded in both living and dead specimens in almost all locations. Planktonic foraminifera were found only at two sample stations in the outer harbour (Fig. 2.1: HP1, HP3).

Because not all sections of Halifax Harbour were treated by the WWTF during the study period, environmental recovery could not be recorded everywhere in the harbour. Only the area affected by the Halifax WWTF (i.e., the inner harbour) showed a considerable change in the foraminiferal assemblage, which reflects environmental improvement during the treatment period. Benthonic foraminifera did not change elsewhere and their composition strongly correlates with pre-existing pollution patterns. The following sections discuss the distribution of foraminifera in different harbour areas that have no environmental changes, as well as the inner harbour that showed improvement due to treatment. All counts of foraminifera mentioned in the following paragraphs are presented in appendices 2A-F at the end of the dissertation.

2.6.2 Outer Harbour

A major sewage outflow (34.5 ML/year) was discharged into the outer harbour at sampling site HC (Fig. 2.1), near where the Herring Cove WWTF was built (Fig. 1.6). This facility, however, became operational in 2010 after sampling was completed and therefore had no influence on the results of this study. Other sampling sites in the outer harbour (Fig. 2.1: HP1–3) are located in unpolluted, open marine waters. These were not collected during every sampling cycle (see Table, 2.1) and their foraminiferal assemblages showed no considerable change or any pollution relationship during the two-year collection period

The foraminiferal assemblages at the HP locations have high diversity, abundance, and large calcareous test ratios along with the lowest content of organic inner linings and shell deformities. Diversity and abundance at these sites varied from 27−29 species, and 3850–5650 individuals (Fig. 2.3; Appendices 2B, 2C). Calcareous foraminifera were more abundant here than at other locations (Fig. 2.4) and, although dominated by *Elphidium* spp., include *Cassidulina reniforme*, *Dentalina ittai*, *Lagena apiopleura*, *L. mollis*, *Oolina borealis*, *O. melo*, and *Quinqueloculina arctica* that are unreported elsewhere in the harbour. Shell deformities are limited to 0.5−3.0% of the population, and organic inner linings are absent or negligible (Figs. 2.5, 6).

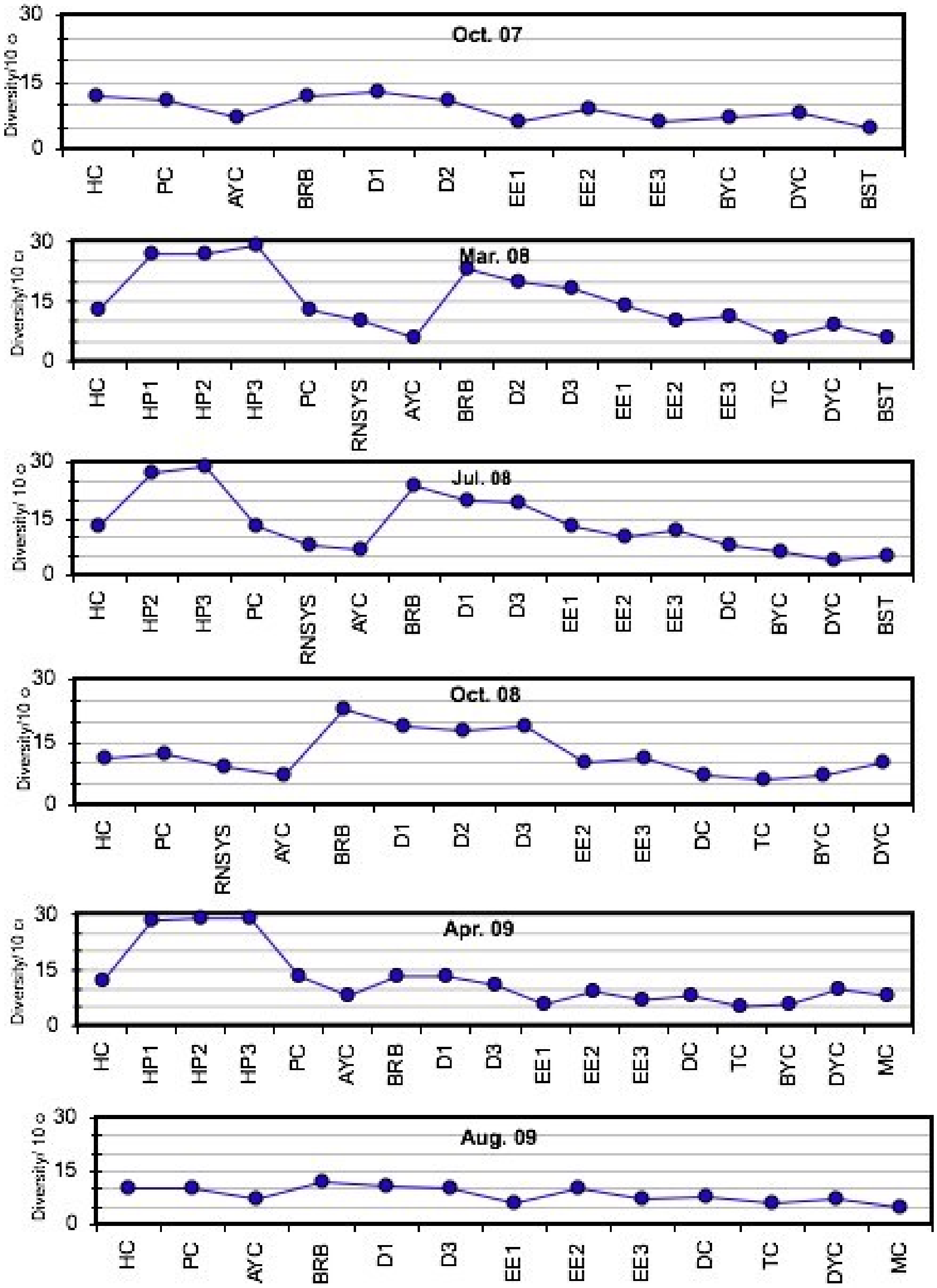

Figure 2.3: The diversity (number of species/10cc) of foraminifera in the grab samples collected from Halifax Harbour in the study period.

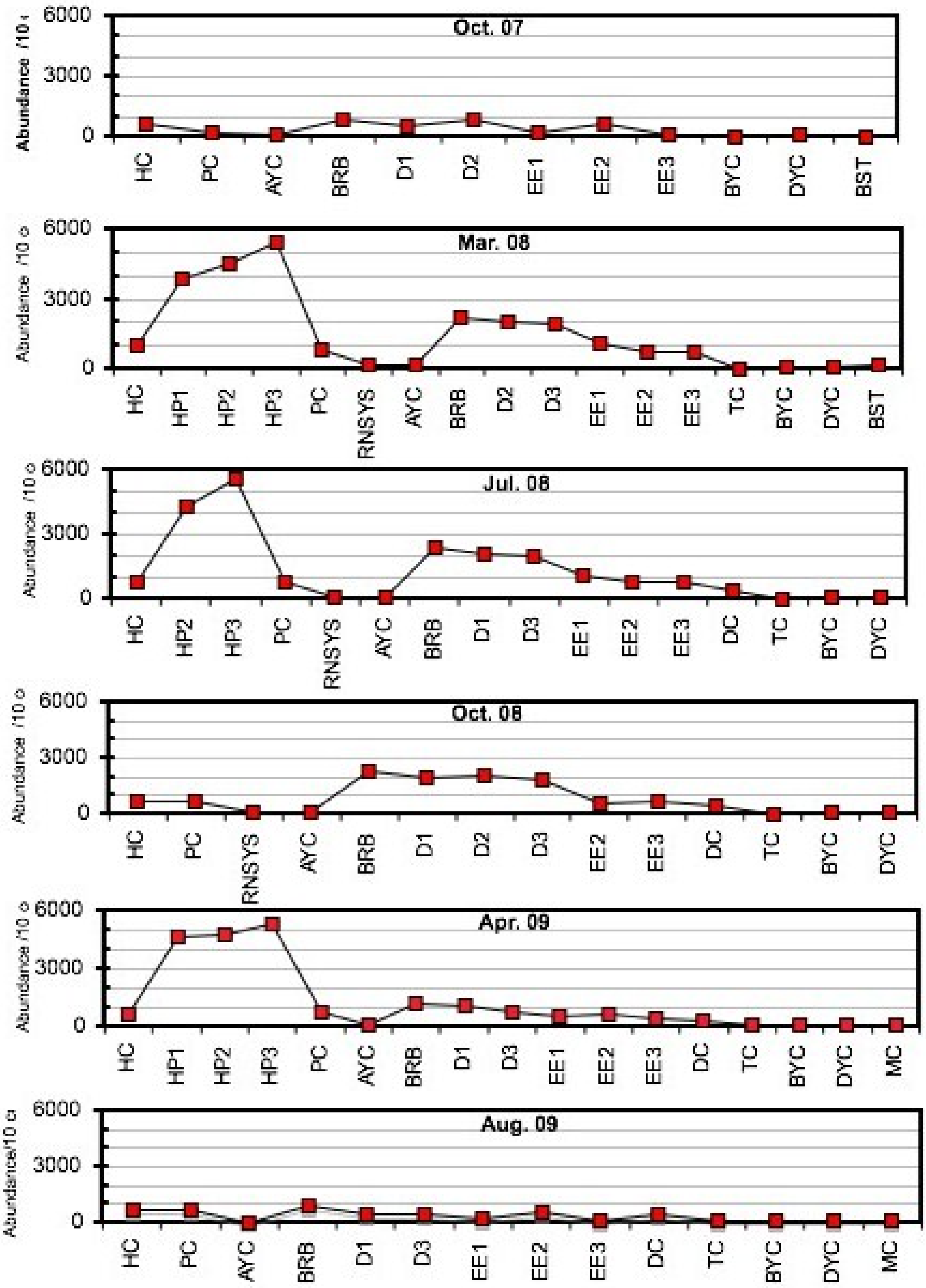

Figure 2.4: The total abundance (number of individuals/10cc) of foraminifera in the grab samples collected from Halifax Harbour in the study period.

Characteristics of the foraminiferal assemblage at locality HC are totally different from the other outer harbour stations. Diversity at this site usually ranged between 10–14 species, while the total abundance was 600–987 individuals (Fig. 2.3). The assemblage is dominated by the agglutinated species *E. advena*, *Miliammina fusca*, and *R. scottii*, associated with the calcareous species *E. excavatum* (Figs. 2.7-12). Other less abundant taxa include *Rosalina bulloides* morphotype *columbiensis*, *F. fusiformis*, *H. orbiculare*, *Trochammina inflata*, *T. lobata*, and *T. ochracea*. Although the ratio of the calcareous species *R. bulloides* morphotype *columbiensis* is less than that of the agglutinated ones, it is significant at this site (Appendix, 2B-F). Organic inner linings at this site represent 23.0–30.5% of the population, while shell deformities reach up to 16% (Fig. 2.6).

The differences in the physical setting (water depth, temperatures, substrates) between HPs and HC sites do not seem to have a major impact on foraminiferal assemblage in these areas, where pollution likely plays the main role in the distribution of foraminiferal assemblage. However, some variations in assemblage can be attributed to differences in natural conditions such as predominance of calcareous ones in deeper waters, coarse substrates, and stronger currents at HPs. This can be also inferred from the dominance of opportunistic species at HC and high ratios of shell deformities and inner linings, whereas they are barely noticed at the other sites (HP1, HP2, and HP3). In addition, the severe reduction in both foraminiferal diversity and abundance at HC is strongly correlated to adverse environmental conditions caused by the enrichment of sewage material, as reported by many other researchers (e.g., Schafer, 1973; Nagy and Alve, 1987; Yanko et al., 1999; Scott et al., 2001, 2005).

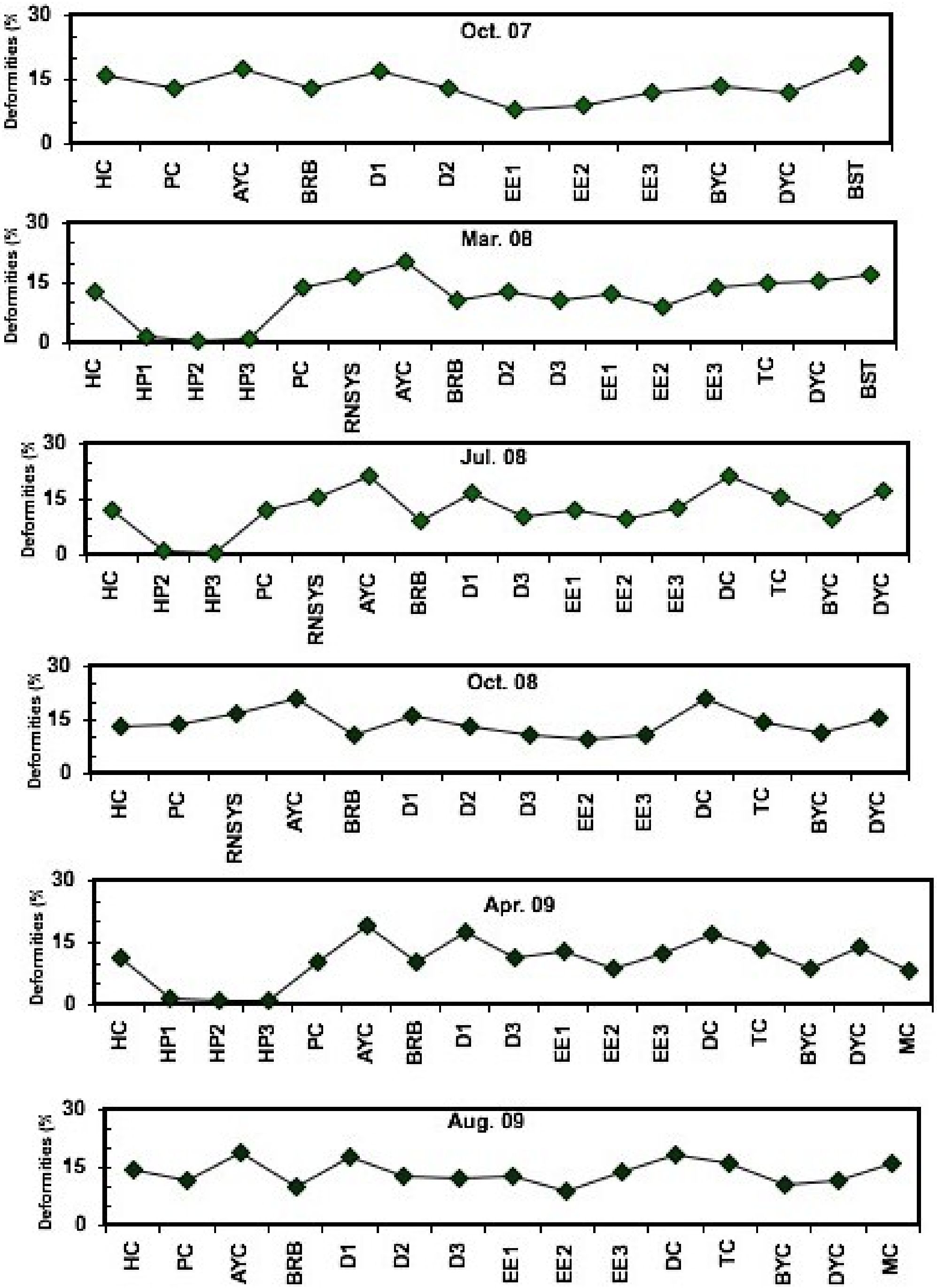

Figure 2.5: Percentages of deformed shells (%) of foraminifera in the grab samples collected from Halifax Harbour during the study period.

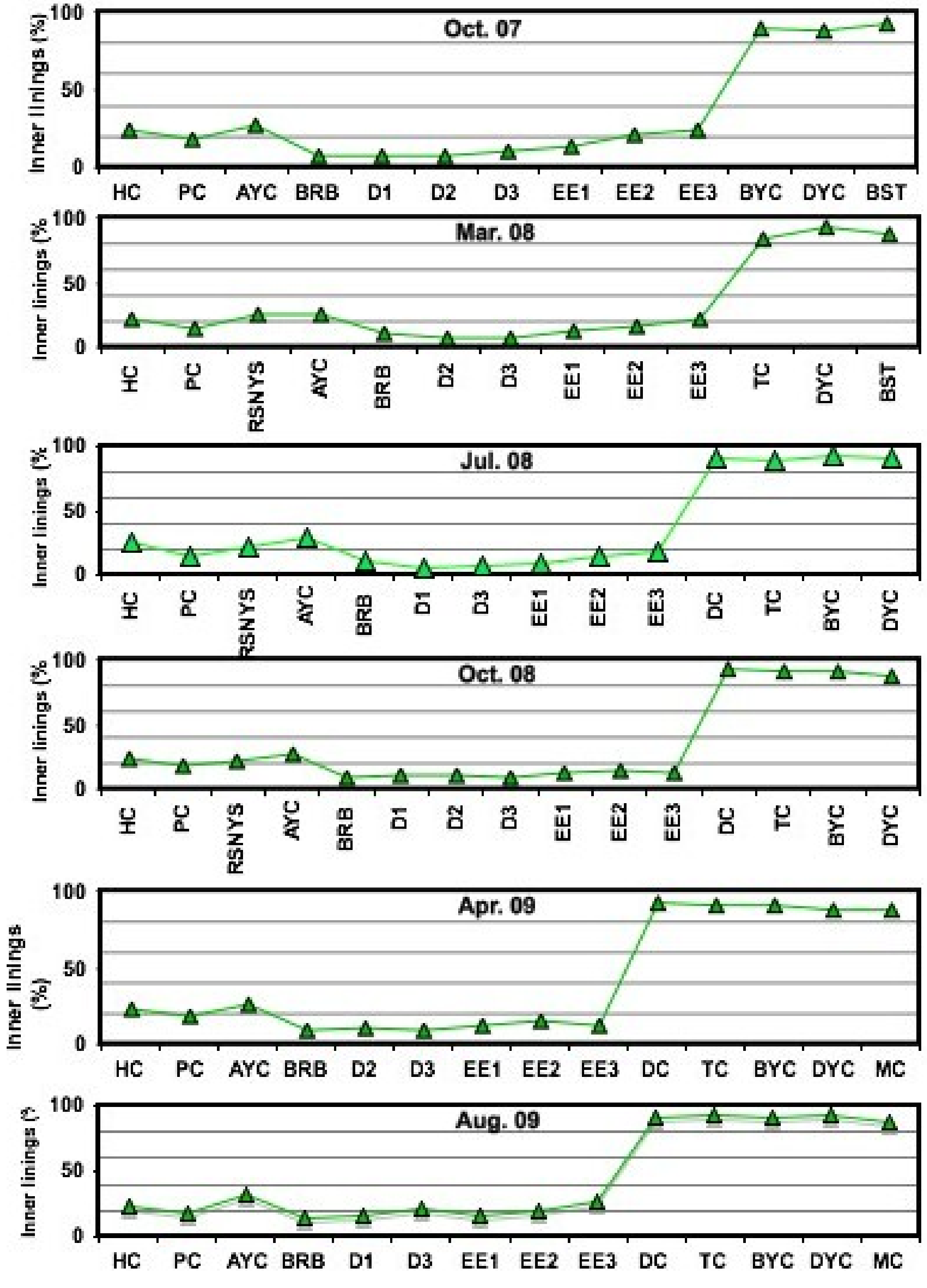

Figure 2.6: Percentages of inner linings (%) of foraminifera in the grab samples collected from Halifax Harbour during the study period.

2.6.3 Northwest Arm

Sampling localities in the Northwest Arm include sites at AYC, RNSYS, and PC (Fig. 2.1). There are no recorded considerable changes in the foraminiferal assemblage in the Northwest Arm that can be attributed to the sewage treatment process during the study period. The proxies of foraminiferal assemblage at the mouth of the Northwest Arm (PC site) is more robust and shows fewer pollution effects than those at the other sites (RNSYS, AYC) further inland.

Diversity varies from 5 species at AYC to 12 at PC, and abundance from 21 specimens at AYC to 690 at PC (Figs. 2.3-4). Organic inner linings and shell deformities both increase towards the inner part of the arm, with the latter ranging from 16.5% at PC to 26% at AYC and the former from 18% at PC to 35% at AYC, respectively (Figs. 2.5-6). The foraminiferal assemblage is dominated by *E. advena*, *R. scottii*, and *E. excavatum* is associated with *A. cassis*, *M. fusca*, *S. biformis*, *T. ochracea*, *E. inceratum*, *E. clavatum*, and *H. orbiculare*. Calcareous species are common at PC but absent or very rare at RNSYS and AYC (Figs. 2.7-12), where agglutinated species dominate.

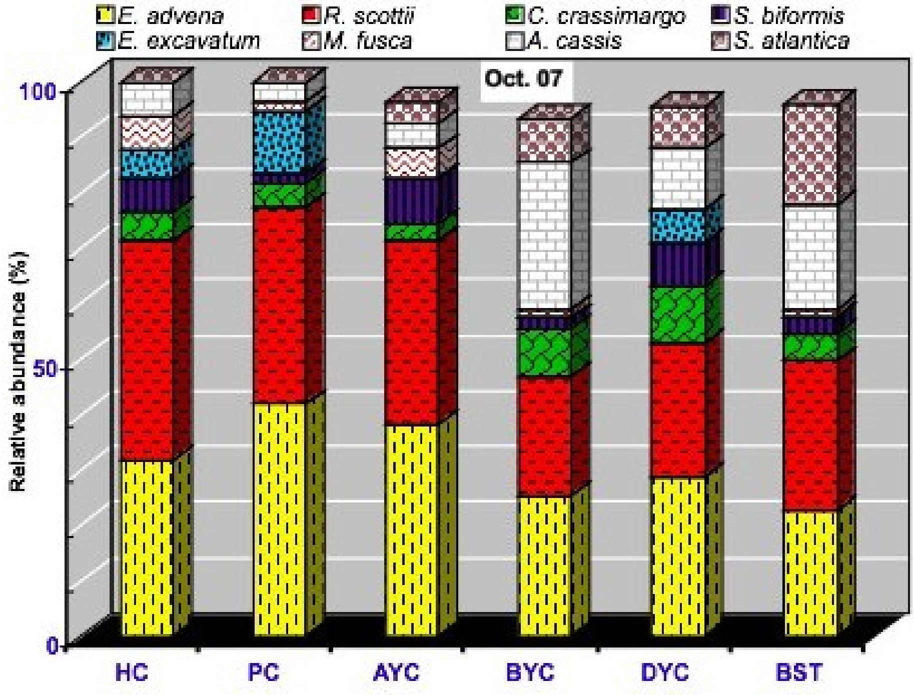

Figure 2.7-previous page: The relative abundance (%) of the most common species in grab samples collected from the harbour (except the inner harbour) in October 2007.

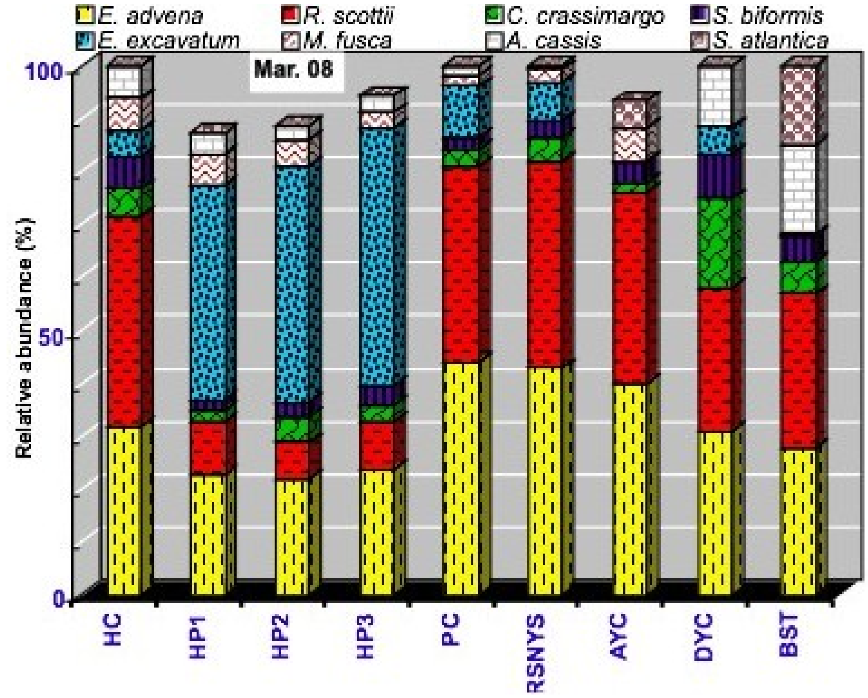

Figure 2.8: The relative abundance (%) of the most common species in grab samples collected from the harbour (except the inner harbour) in March 2008.

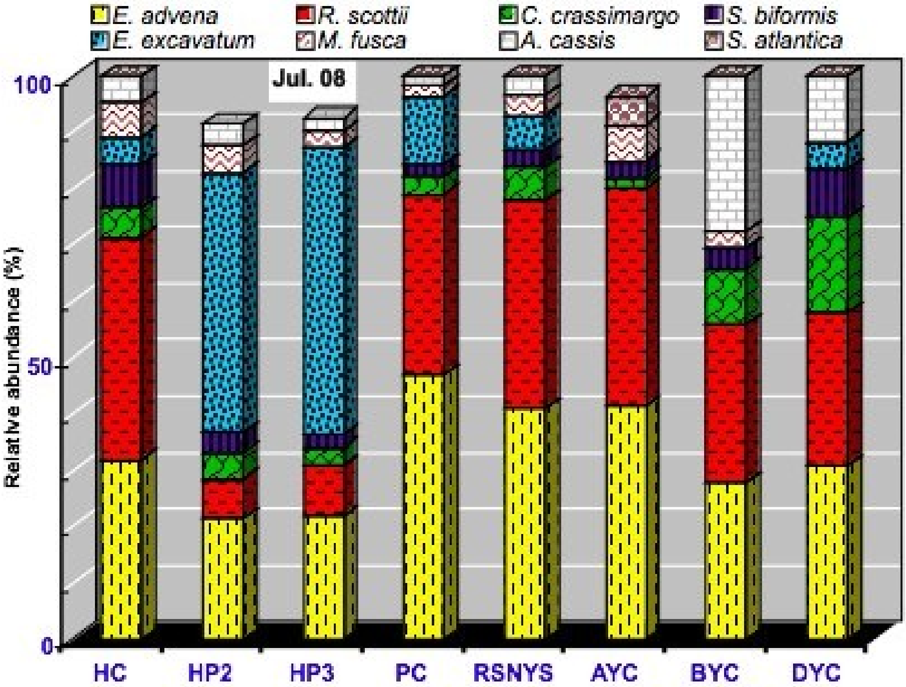

Figure 2.9: The relative abundance (%) of the most common species in grab samples collected from the harbour (except the inner harbour) in July 2008.

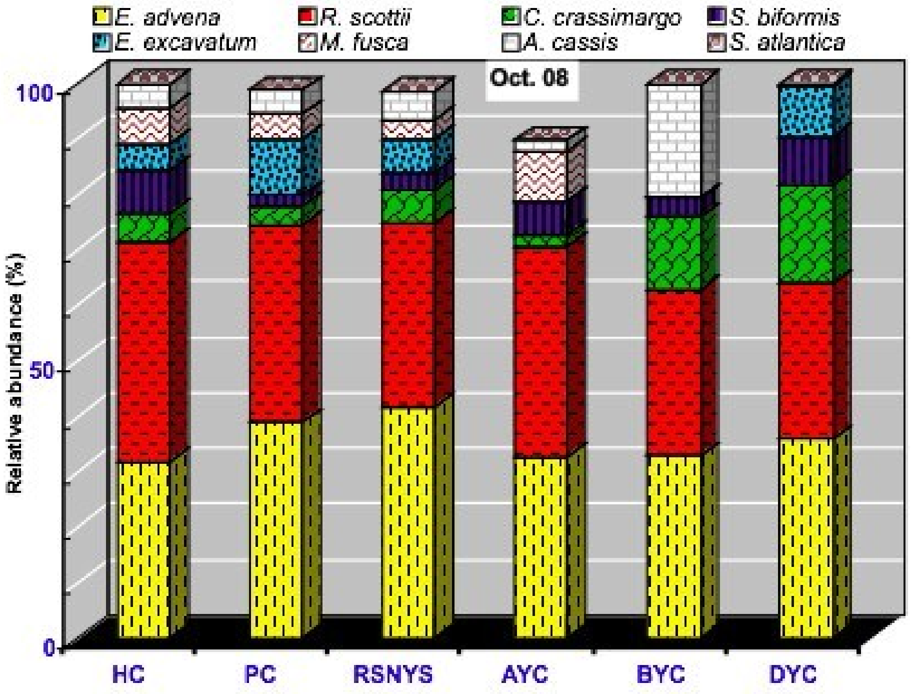

Figure 2.10: The relative abundance (%) of the most common species in grab samples collected from the harbour (except the inner harbour) in October 2008.

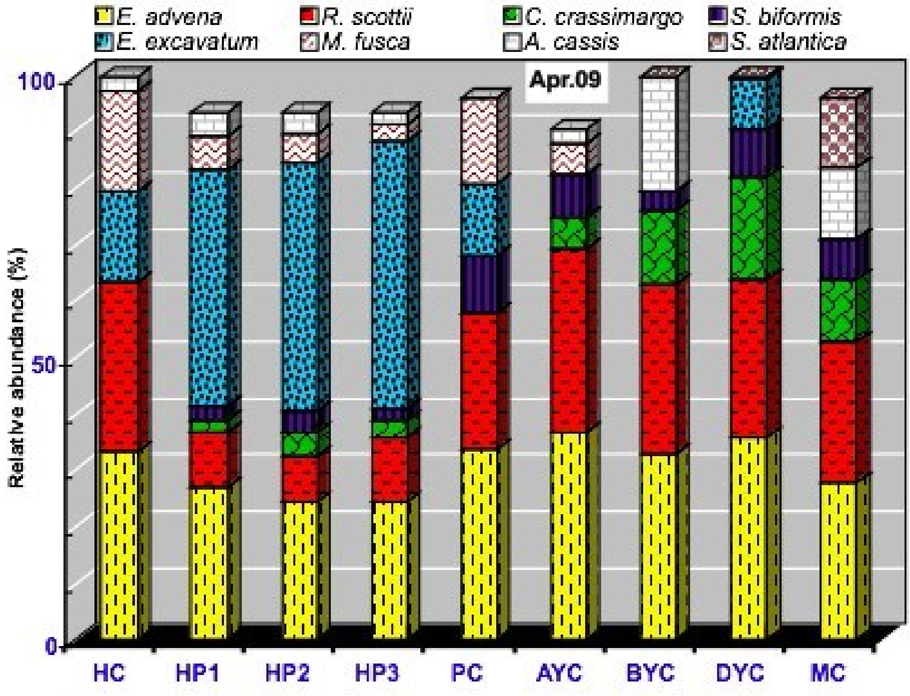

Figure 2.11: The relative abundance (%) of the most common species in grab samples collected from the harbour (except the inner harbour) in April 2009.

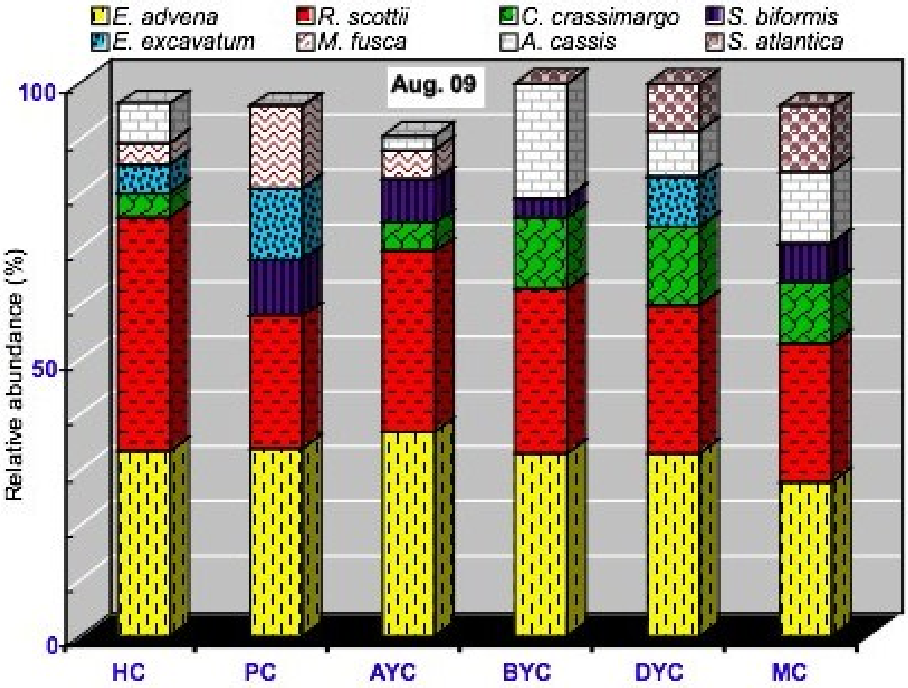

Figure 2.12: The relative abundance (%) of the most common species in grab samples collected from the harbour (except the inner harbour) in August 2009.

2.6.4 Inner Harbour

Nine sampling stations (Fig. 2.1: BRB, D1–D3, EE1– EE3, DC, and TC) are located in the inner harbour, which is one of the most polluted areas in the HH due to the numerous sewage outfalls. The inner harbour was the only part of HH to be treated by the downtown Halifax WWTF during the time of this study. That facility went online in February 2008. During the treatment period, the foraminiferal assemblage changed rapidly in this area until the WWTF failed in January 2009. The following sections represent the results of foraminiferal proxies in the inner harbour prior to treatment (Oct. 2007 sampling cycle), the mean results during treatment (2008 sampling cycles), and the mean results after treatment failure (2009 sampling cycles).

2.6.4.1 Before the treatment process

Benthonic foraminifera in the untreated samples of the inner harbour have very low diversity (6–12 species; Fig. 2.3) and abundance (120–880; Fig. 2.4). Calcareous individuals are rare or represented only by organic inner linings following dissolution of the tests. Values for both organic inner linings (35%; Fig. 2.6) and shell deformities (17.8%; Fig. 2.5) are among the highest throughout the harbour. Deformities are limited to the species *E. advena*, *Spiroplectammina biformis*, *Cribrostomoides crassimargo*, and *E. excavatum*. The opportunistic agglutinated species *E. advena* and *R. scottii*, associated with *C. cribrostomoides* and *S. bioformis*, dominate the assemblage (Fig. 2.13) that also contains lesser numbers of the agglutinants *R. arctica*, *R. fusiformis*, and *S. atlantica*. *Cribrostomoides crassimargo* showed a significant number (~15–20% of its total number) of oversized tests (>500 μm diameter).

The calcareous components in this assemblage include *Elphidium* spp., *F. fusiformis*, and *H. orbiculare*. Some tests of the latter species have arenaceous coverings that act as a sheath (Scott et al., 1977, 2005) to facilitate calcareous shell formation in environments with high organic content. Interestengly, calcareous species were rarely found (<15%) in the inner harbour before sewage treatment began, and *E. excavatum* was recorded only at BRB and D2 (Fig. 2.13). The DC and TC stations were not collected in this sampling cycle (October 2007) so the characteristics of foraminiferal asmblage for this cycle remain unknown.

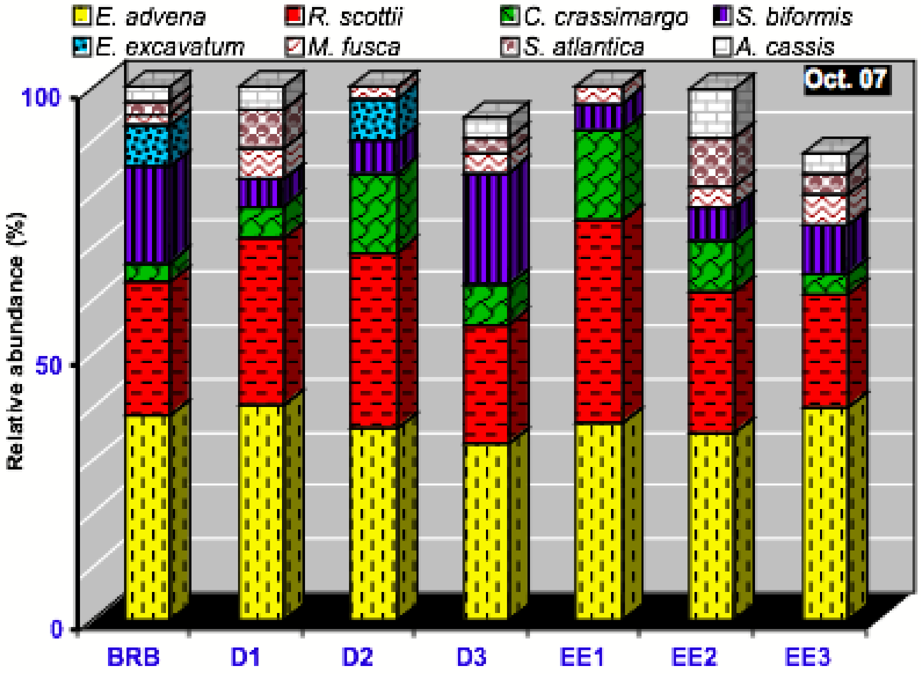

Figure 2.13: Relative abundance (%) of common species in the inner harbour before treatment (October 2007 sampling).

2.6.4.2 Foraminiferal response to the treatment process

Samples collected in March 2008, immediately after the start of the Halifax WWTF, recorded an improvement in foraminiferal proxies. Unlike stations D3 and EE, that were located on the Dartmouth side and thus still impacted by untreated sewage outfalls, the stations close to the Halifax side of the harbour (BRB, D1, D2, EE1, EE2), where the treatment plant is located showed considerable changes in foraminiferal assemblage. Species diversity at these locations increased from < 12 species before treatment to >14 species after the treatment (Fig. 2.3). Likewise, total abundance that was <1000 individuals/10cc before the treatment reached high numbers (>1630 individuals/10cc; Fig.4) in this sampling cycle. Additionaly, organic inner linings decreased significantly from 25-35% in October 2007 to < 25% in March 2008 (Fig. 2.6-

Appendices 2 A, B). Furthermore, the relative abundance of calcareous foraminifera exceeded 25% of the population, reflecting mostly an increase in *Elphidium* spp., but no considerable change (Fig. 2.14) in shell deformities was found (Fig.2.5).

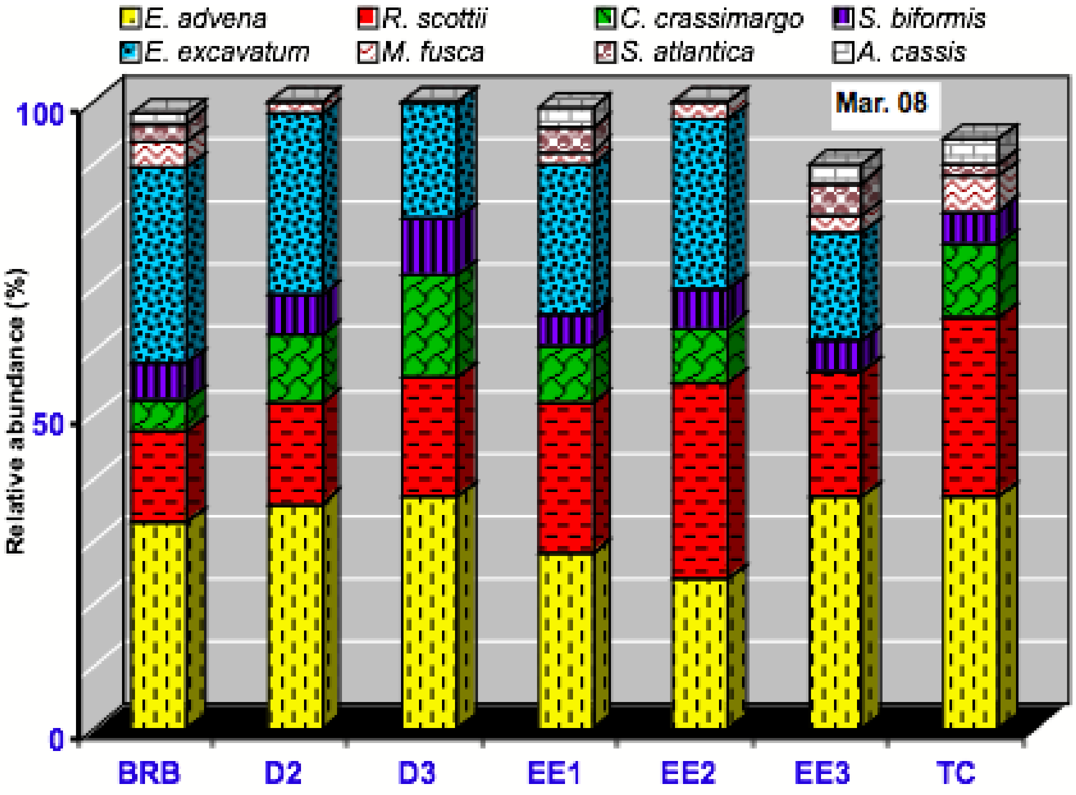

Figure 2.14: Relative abundance (%) of common species in the inner harbour (March 2008 grab samples).

The foraminiferal assemblage through out the inner harbour improved continuously during the rest of 2008. The diversity and abundance during that year recorded their maximum numbers in this study (>19 species, and >2000 individuals-Figs. 2.3,4). On the other hand, calcareous foraminifera were represented by 4 το 6 species that comprised up to 35% of the assemblage (Figs. 2. 15-16), whereas organic inner linings witnessed a considerable decrease (10–25%: Fig. 2.6) during that period. The calcareous species *E. excavatum* became dominant (reaching up to 35%) and well presented along with the agglutinated species *E. advena* and *R. scottii* in most of the stations in that area (Fig. 2.15-16). Other calcareous species such as *Buccella frigida*, *Cibicides lobatulus*, *H. orbiculare*, and *Nonionellina labradorica* were prominent, particularly at the more seaward sites (BRB, D1–D3), although *F. fusiformis* became less abundant than in the previous sampling cycle. There was also a gradual reduction in the number of shell deformities during the treatment period (Fig. 2.6).

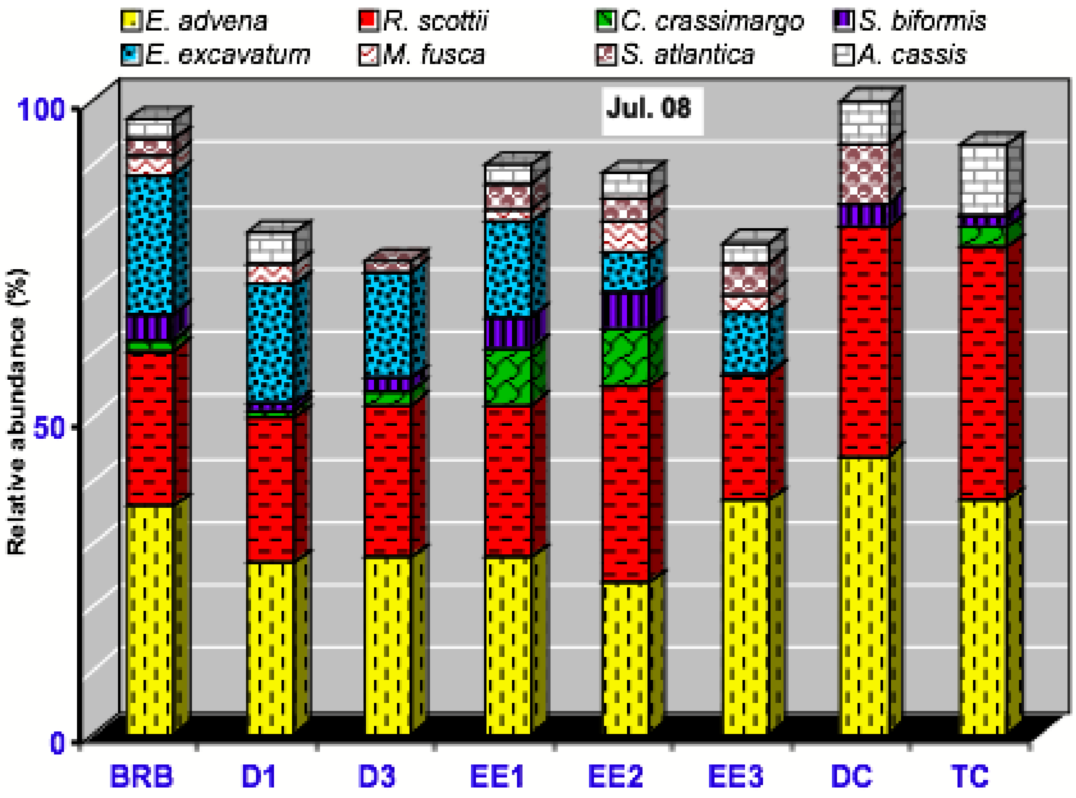

Figure 2.15: Relative abundance (%) of common species in the inner harbour (March 2008 grab samples).

Although most of the sampled site locations in the inner harbour showed an improvement to a certin extent, two stations (DC and TC) did not show any variability that can be interpreted as response to the treatment process during 2008 (Figs. 2.3-4). Furthermore, the diversity and abundance were very low (<6 species, and < 300 individuals; Figs. 2.3-4) at these sites in all of the sampling cycles sampled. These two sites remained untreated throughout the study period and are highly contaminated (Williams, 2010). Interestingly, and despite its adverse conditions, the Tufts Cove (TC) site showed a considerable variability in its living foraminiferal content during the summer season, which will be discussed in seasonal variability below (sec. 2.6.4.4).

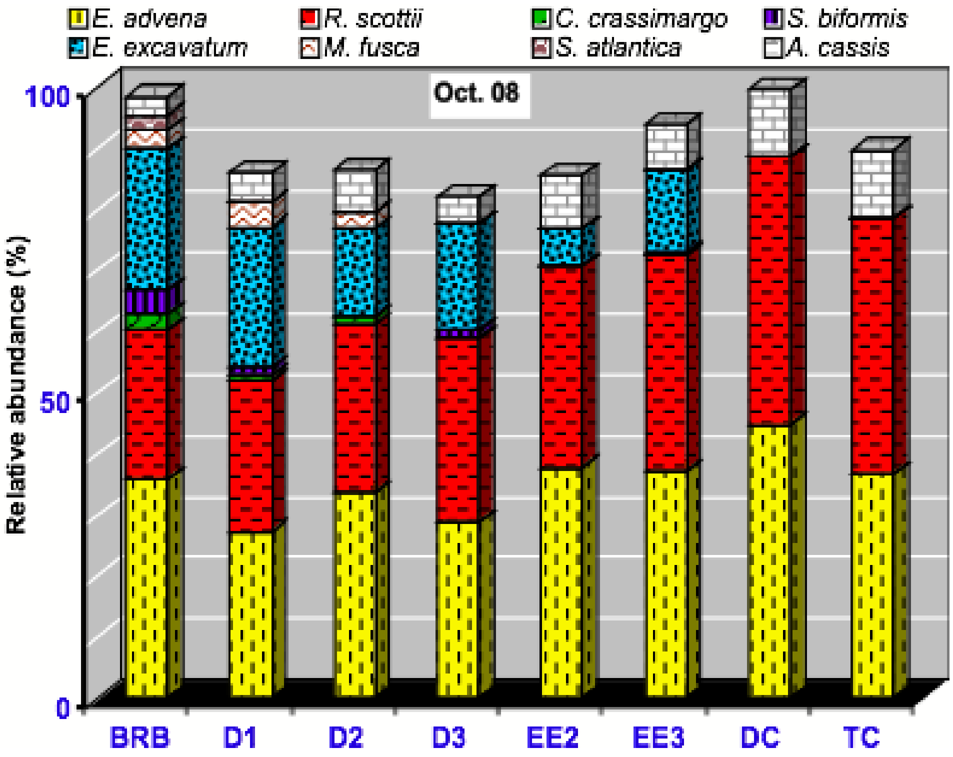

Figure 2.16: Relative abundance (%) of common species in the inner harbour (March 2008 grab samples).

2.6.4.3 Foraminiferal decline due to treatment failure

With the failure of the Halifax WWTF early in 2009 and the subsequent discharge of sewage into the harbour, benthonic foraminifera during the April and August 2009 sampling periods decreased in diversity (8–13 species; Fig. 2.3), abundance (<1370 individuals; Fig. 2.4-Appendix 2E), and ratio of calcareous individuals (<15%; Figs. 2. 17,18-Appendices 2E, 2F). Organic inner linings and shell deformities once again reached high levels, as they were before (Figs. 2.5-6). The assemblage in that period was dominated once more by the agglutinated species *E. advena*, *R. scottii*, and *S. biformis* associated with *A. cassis*, *C. crassimargo*, *R. arctica*, *R. fusiformis*, and *S. atlantica* (Figs. 2.17-18). There was a significant decrease or complete disappearance of the calcareous species *B. frigida*, *C. lobatulus*, *F. eburnean*, *H. orbiculare*, and *N. labradorica*.

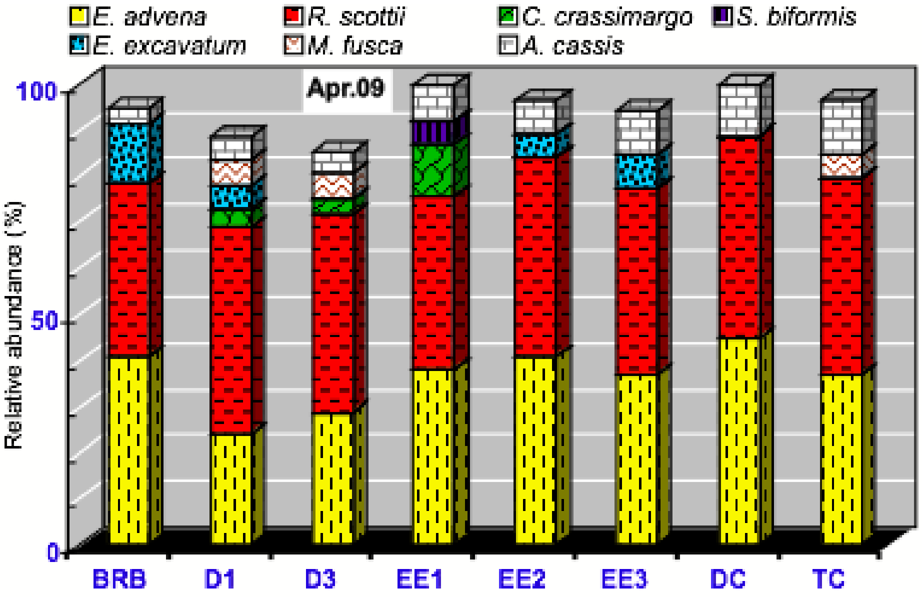

Figure 2.17: Relative abundance (%) of common species in the inner harbour (April 2009 grab samples).

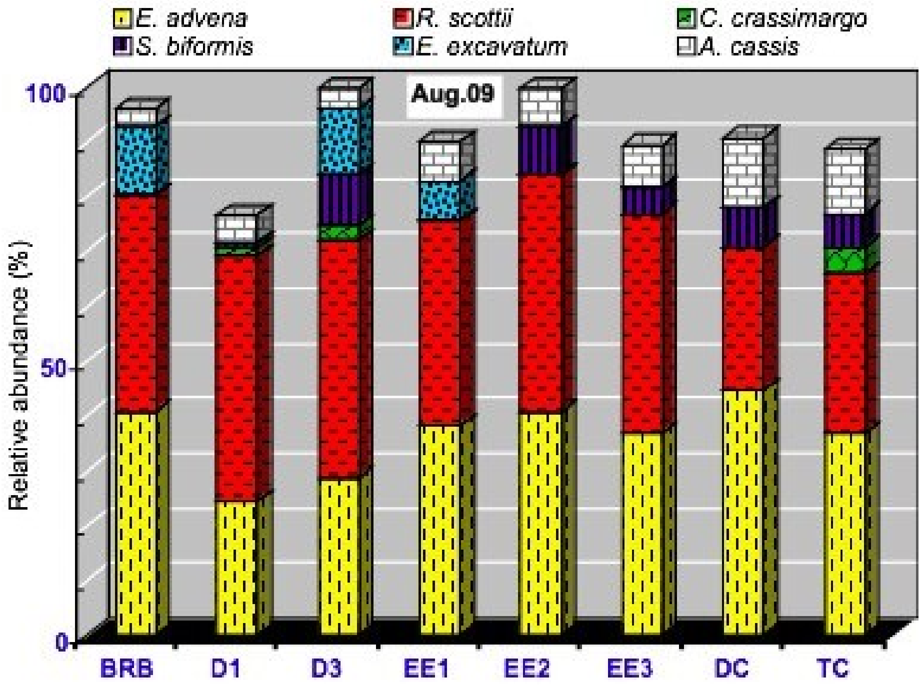

Figure 2.18: Relative abundance (%) of common species in the inner harbour (August 2009 grab samples).

2.6.4.4 Seasonal variability in foraminiferal assemblage

The phytoplankton bloom reaches its highest strength in the spring of the year (March, April, and May), and thus the name "spring bloom" is given to it (Boucher, 1985, Laborde et al., 1999, Fontanier et al., 2003, 2006). The spring bloom actually consists of a sequence of successive events of enrichment of various phytoplankton groups during that period (Lampert, 2001). Although spring is the widely known as the season for the highest phytoplankton bloom, some similar events with lesser strengths are also recorded in the autumn and interpreted as small autumn blooms (Le Corre and Trégure, 1976; Trégure et al., 1979; Li et al., 2005).

There is a strong relation between the phytoplankton blooms regime and variability in foraminiferal fauna that respond very quickly to seasonal environmental changes (Gooday and Huges, 2002; Fontanier et al., 2003, Duchemin et al., 2008). This can be inferred from the increase in the concentration of living foraminiferal individuals attracted by the enrichment of the upper surfacial sediments with phytodetritous particles, specifically in the presence of a strong spring bloom (Fontanier et al., 2006).

Frontanier et al. (2003) recorded a peak increase in the opportunistic taxa of benthonic foraminifera in the surface sediments of the southeastern part of the Bay of Biscay, which exhibits a very strong spring bloom and other little bloom events in the autumn, four to six weeks after the phytoplankton blooms. Duchemin et al. (2005) recorded a maximum foraminiferal density in the northern part of Bay of Biscay shelf in the first third of April 2002. Duchemin et al. (2005) related this phenomenon to the quick response of benthonic foraminifera to the early pulses, recorded in March, of the strong spring phytoplankton bloom in that area.

There are no available measurements of Chlorophyll-a data throughout the HH inner harbour during the study period to use as a source of comparison with living foraminifera as a signal of seasonal variability. However, there is a record of phytoplankton history of Bedford Basin for the last 20 years (Fisheries and Oceans Canada, 2013). Because Bedford Basin is considered as a geographical section of Halifax Harbour, it would be considered here that the phytoplankton data of the basin representing or at least similar to that of the whole area of Halifax Harbour. The record of Chlorophyll-a concentrations in Bedford Basin waters at 5 and 10 m depths during the years 2008 and 2009 (Fisheries and Oceans Canada, 2013- Fig.2.19) indicate that there were major phytoplankton bloom events in the area in the spring (March, April, and May), summer (June, July, and August), and autumn (September, October, and

November) of those two years. Although the spring events, as a world-wide phenomenon, are typically the strongest bloom events, the summer and autumn events in Bedford Basin were similarly large or may even have exceedd that of the spring bloom during this two-year period. The maximum Chlorophyll-a concentrations in Bedford Basin at 5 m water depths during the spring of 2009 reached ~15.5 mg/m^3, while its concentrations at the same depths (5 m) in the summer of the same year exceeds 17 mg/m^3 (Fig. 2.19). Li et al. (2006) demonstrated that the abundance of phytoplankton cells in Bedford Basin during the 15-year period between 1992 and 2007 was low in the spring and high in the autumn because of its dependence on water temperature in the area.

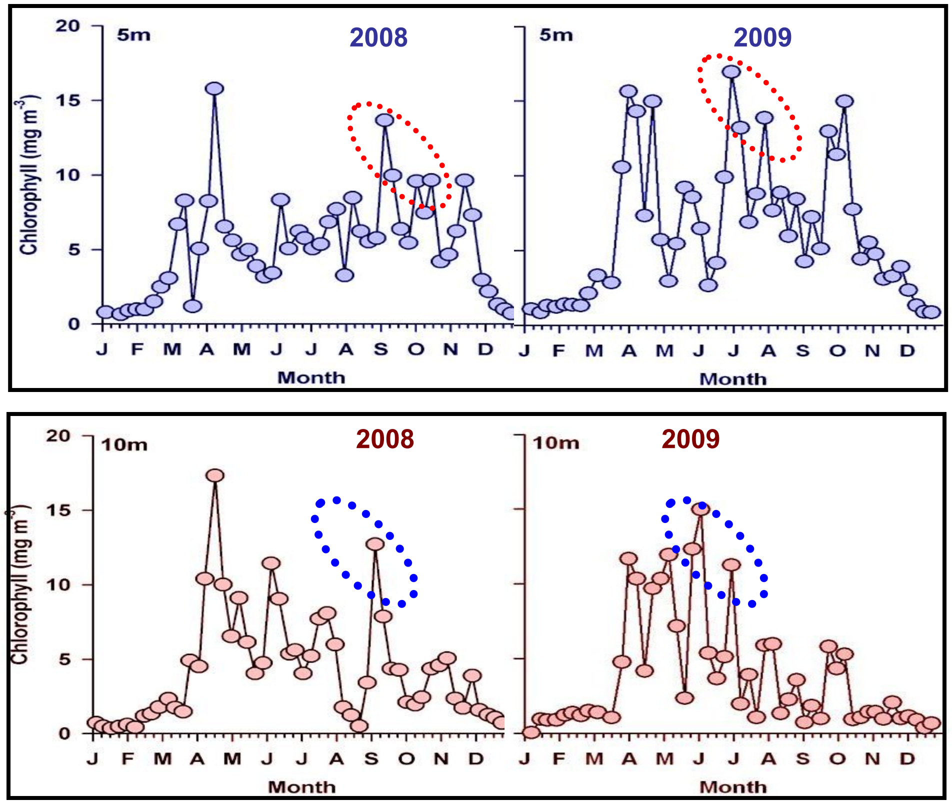

Figure 2.19: Chlorophyll-a concentrations (mg/m^3) in Bedford Basin waters at 5, and 10 m depths during the period 2008 and 2009 (modified from Fisheries and Oceans Canada, 2013).

The percentage of living foraminifera in the inner harbour is always less than 8% of the total abundance (Table 2.2 and Fig. 2.20), with no regular rate of increase during the two-year study period. However, there is a slight increase (2.5 to 6 %) in the percentage of living individuals in both the summer seasons of 2008 (sampled in July) and 2009 (sampled in August) compared to their percentage in the preceding seasons (March, 2008, and April, 2009 – Table 2.2, Figs. 2.20). In July 2008, the number of living individuals increased by about 6% over their number in March 2008. Likewise, the number of living foraminifera in August 2009 increased in all sample locations except DC site by 2.5 to 5 % above their number in the previous season (April, 2009 – Figs.2.19, 20). Noteworthy is that the percentages of living foraminifera in both seasons were at their highest values during these seasons at Tufts Cove (TC) which is the area most polluted by metals (Fig. 2.20).

Station	BRB	D1	D2	D3	EE1	EE2	EE3	DC	TC	Sampling cycle
Total No.	878	489	820	414	193	622	119	NA	NA	2007/10/24
No. of live	69	24	67	32	16	54	13	NA	NA	
Live/total %	7.9	4.9	6.4	7.7	8.3	8.7	11	NA	NA	
Total	2250	NA	2075	1860	1150	765	734	NA	35	2008/03/21
Live	135	NA	115	110	98	69	52	NA	3	
Live/total %	6	NA	5.5	5.9	8.5	8.9	7.1	NA	8.5	
Total	2450	2150	2175	1970	1160	785	755	450	27	2008/07/15
Live	301	205	247	225	135	80	65	17	4	
Live/total %	12.3	9.5	11.7	11.5	11.3	10.2	8.7	3.7	14.8	
Total	2350	1950	2125	1850	1155	630	750	450	17	2008/10/21
Live	127	111	106	113	59	42	48	14	2	
Live/total %	5.4	5.7	4.9	6.1	5.1	6.6	6.4	3.1	9.2	
Total	1250	1120	NA	750	525	625	425	350	95	2009/04/08
Live	107	88	NA	64	41	37	21	17	8	
Live/total %	8.5	7.8	NA	8.5	7.8	5.9	4.9	4.8	8.4	
Total	850	510	810	410	180	630	125	110	17	2009/08/19
Live	83	53	70	45	20	54	11	6	3	
Live/total %	10.3	10.4	8.6	11.1	9.7	9.8	8.8	4.45	13.2	

Table 2.2: Percntages of live individuals throughout the inner harbour during the study period.

Based on these findings, the variability in living foraminifera in the inner harbour during the summer of 2008 (Fig.2.20) can be explained as a response of benthonic foraminifera to the spring (April) phytoplankton pulses (Chlorophyll-a ranges between 15.5 and 17 mg/m^3 Fig. 2.19) or the summer (June) phytoplankton events (Chlorophyll-a ranges between 10 and 12.5 mg/m^3 Fig. 2.19) of that year. Likewise, the increase in living foraminifera in August 2009 can be explained as response of benthonic foraminifera to the phytoplankton events that took place during the summer (July) of 2009 (Chlorophyll-a=15 to 17.5 mg/m^3 Fig. 2.19). Some researchers documented temporal variability in benthonic foraminifera in spring (March, April, May) and summer (June, July, August) and related this variability to the response of benthonic foraminifera to the series of successive events of spring bloom (e.g., Frontanier et al., 2003; Duchemin et al., 2005; Fontanier et al., 2006).

In conclusion, seasonal variability in this part of Halifax Harbour during the study period was deemed to have a relatively minor impact on the foraminifera during the summer seasons only, and could be the response of benthonic foraminifera to the summer and/or late spring bloom events in the area. Although foraminifera at Tufts Cove have a very low diversity (<5), and abundance (<300 individuals) due to the high metal content, the considerable peak of living foraminifera at this location during the two recorded events of seasonal variability remains unexplained. This question could be legitimate, based on the fact that highly polluted sites are usually characterized by the presence of a dead zone (i.e., no living individuals) and low diversity and abundance. This can also be supported by the fact that many other less-polluted sites in the harbour featured a lower number of living individuals during these events.

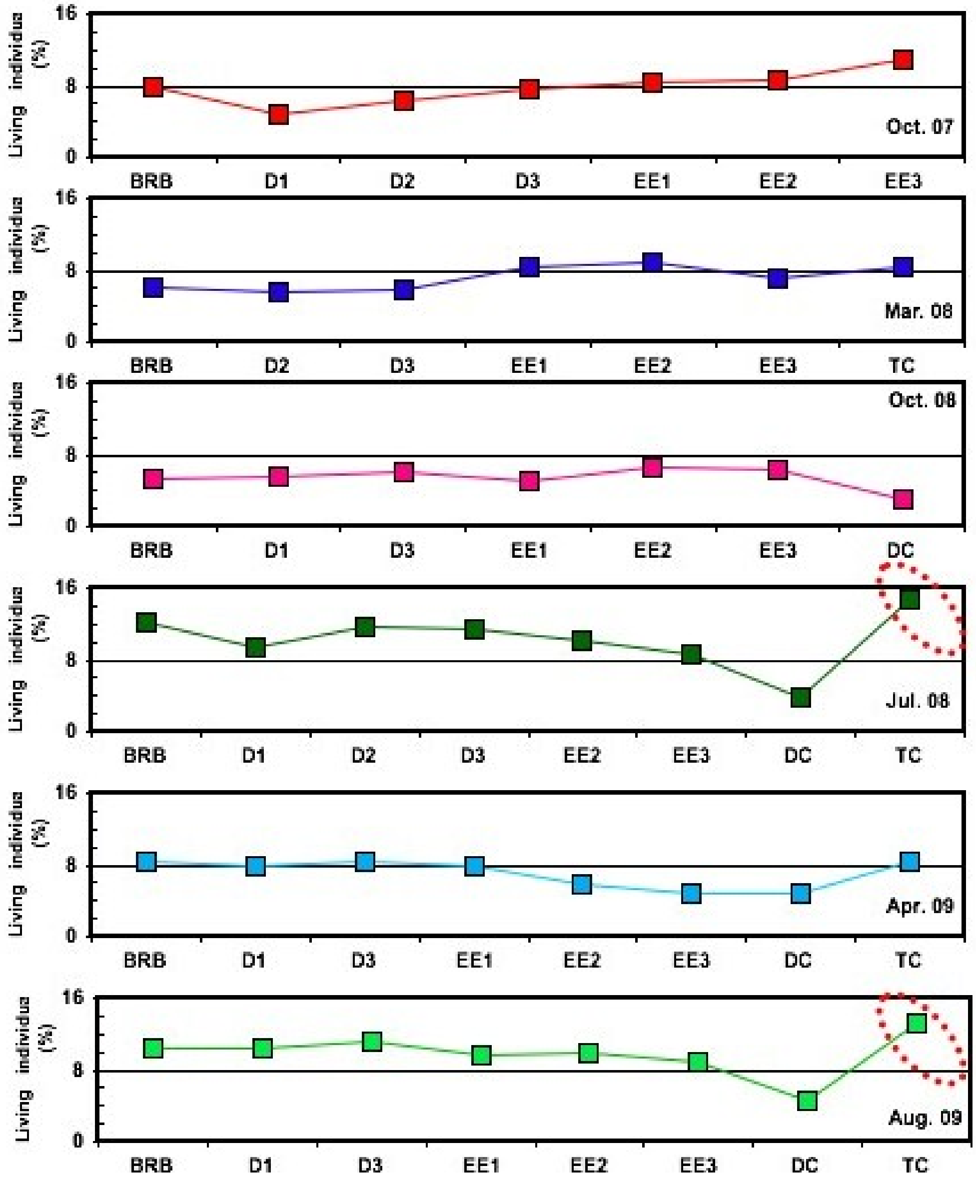

Figure 2.20: Percentages of living individuals (%) in the inner harbour during the study period showing relatively minor impacts of seasonal variability on the foraminiferal assemblage in the area.

2.6.5 Bedford Basin

Of the four sampling stations in Bedford Basin (Figs. 2.1), two (BYC and DYC) were collected on a regular basis and the other two (BST, MC) on an alternating schedule. Throughout the sampling period, there was no considerable variability in the foraminiferal proxies at these sites (appendices 2A–2F). Moreover, the diversity and abundance of foraminifera in this area were the lowest (Figs. 2.3-4) recorded throughout the harbour region, particularly at BST, which has a diversity of 2–4 species and an abundance of 5–7 individuals (Figs. 2.3-4). The total abundance has its highest values in the basin at DYC, where it reaches up to 90 (Fig. 2.4). At BYC, BST, and MC the foraminiferal assemblage is dominated by the agglutinated species *A. cassis*, *E. advena*, *R. scottii*, *C. crassimargo*, and *S. atlantica* while calcareous species are completely absent (Figs. 2.7-12). The foraminiferal assemblage at these stations had the highest ratios of organic inner linings (90–95%, Fig. 2.6), presumably from dissolved calcareous species. On the other hand, calcareous species are well represented at DYC, where there are fewer organic linings than at the other sites in the basin, and diversity reaches ~7 species. The calcareous species *E. excavatum* dominates, with both *E. advena* and *R. scottii*, the foraminiferal assemblage at this station (Figs. 2.3-7).

2.7 Discussion

2.7.1 Distribution patterns of benthonic foraminifera

The distribution of benthonic foraminifera in Halifax Harbour shows a seaward increase in foraminiferal diversity, abundance, and ratios of calcareous species and a decrease in both deformities and calcareous inner linings. The same pattern is also recorded in other harbour areas where there is a variable pollution rate, such as the Northwest Arm, and is considered here to reflect contaminant concentrations that decrease from the inner harbour to the ocean. Although some sites show very low diversity and abundance, there is no indication of a "barren zone" in the harbour, which had been recorded in other areas affected by different kinds of pollution (e.g., Bandy et al., 1964; Schafer et al., 1975; Samir, 2000; Ferraro et al., 2006).

This study found that the agglutinated species *E. advena*, *R. scottii*, *A. cassis*, *S. biformis*, and *C. crassimargo* and the calcareous species *E. excavatum*, *H. orbiculare*, and *F. fusiformis* predominate in Halifax Harbour. The *E. advena-Elphidium* spp. group can successfully tolerate various kinds of pollution to compete and reproduce in stressed conditions (Schafer et al., 1975), and *F. fusiformis* is considered a tolerant species for oxygen-depleted conditions (Alve 1991, 2003; Scott et al., 2005). The presence of agglutinated tests or organic sheaths in some of the *H. orbiculare* indicates dissolution of their $CaCO_3$ tests as a result of high organic content in the environment (Scott et al., 1977, 2005).

Foraminifera from the outer harbour, except for samplings taken at the HC site, can be described as an unpolluted, open-ocean assemblage. In this area, there is a significant increase in diversity, abundance, and ratio of calcareous species, which can be related to the absence of major outfalls. In addition, highly oxygenated seawater from the open ocean helps oxidize the organic carbon of the waste deposits (Fader and Miller, 2008). In contrast, the foraminiferal assemblage in HC shows a positive correlation with the excessive pollution caused by a nearby outfall discharging 34.5 ML sewage/day. At this site, the calcareous species *R. bulloides* morphotype *columbiensis* has significant ratios, which may be related to the tolerance of this species to suboxic conditions (Kaiho, 1999) or shallower depth and turbulent conditions (Scott et al., 2011) that are known in this location.

Gregory (1971) studied samples that covered the inner part of the outer harbour and recorded the dominance of calcareous *Elphidium* spp. Although we did not sample his sites in this area, a sediment core we collected close to them, near McNabs Island, had an abundance of calcareous species and agglutinated *E. advena*. The similarity between our results from the core sediment and those of Gregory (1971) indicates that the outer harbour has a very low pollution rate that did not affect the foraminiferal assemblage in the long term.

The Northwest Arm, which has no treatment facility at the time of the study, is so narrow that currents cannot remove the waste from a major outfall that discharged 12 ML sewage/day before 2008. The foraminiferal assemblage in the Arm shows a high percentage of shell deformities, calcareous inner linings, and rare or absent calcareous tests. The assemblage at the outer station PC indicates slightly better environmental conditions than at the other stations in the Arm. Gregory (1971) noted that the calcareous forms *Elphidium* spp. and *C. lobatulus* were commonly represented in the Northwest Arm, but in this study mostly the inner linings of *Elphidium* spp. were found and no *C. lobatulus*. We think that these changes in foraminifera between Gregory's time (1971) and the present work are mainly related to rising levels of organic waste produced by an increasing suburban population living around the Northwest Arm.

The gradual improvement in the inner harbour foraminiferal assemblages during this study indicates a rapid environmental recovery due to the treatment process, except for sampling stations far from the Halifax WWTF, such as DC and TC that did not show any significant change. The reappearance of the calcareous species *Buccella frigida*, *C. lobatulus*, *H. orbiculare*, and *N. labradorica*, particularly at the outer sites BRB and D1–D3, provides strong evidence to support the positive improvement of environmental conditions in the harbour waters, and indicates a return to assemblages collected by Gregory (1971) from nearly the same locations. The little changes in the number of live individuals in the summer indicate that seasonal variations have no significant impact on the assemblage in the Inner Harbour and pollution is the main factor affecting the foraminiferal distribution in the area.

Gregory (1971) reported a diverse agglutinated and calcareous foraminiferal assemblage in Bedford Basin, while Scott et al. (2005) mostly recorded only the inner linings of calcareous species from the same area. The latter authors related this shift in foraminiferal composition between 1971 and 2005 to the increase in sewage discharged into the basin. The foraminiferal assemblage at BYC is dominated by the agglutinates *A. cassis*, *E. advena*, and *R. scottii*, but lacks calcareous species. Gregory (1971) reported only rare occurrences of *A. cassis* that were found commonly by Scott et al. (2005) and in the present work. This species prefers brackish water, muddy substrates (Ellison and Murray, 1987), and high-suspended organic matter (e.g., Olsson, 1976; Scott et al., 1977, 2005; Alve and Murray, 1999). It is often found in turbidity maximums at the confluence of fresh and marine waters at the head of estuaries (Scott et al., 1977, 1980). The abundance of *A. cassis* and absence of calcareous species at BYC may be explained by the fact that the sampling site is located close to a secondary WWTF outfall, not far from the mouth of the Sackville River. The abundance of *R. scottii* in the basin may be controlled by the same environmental factors, as it has been described as a “muddy” species (John, 1987) and a “typical domestic outfall” species (Scott et al., 2001). The presence of a WWTF outfall close to the BST and MC sites also explains the low diversity, abundance, and high levels of calcareous inner linings at these locations. Because the DYC station is some distance from the Sackville River and the main WWTF outfall at Mill Cove, calcareous species are more abundant there and inner linings are fewer than at the other sites in the basin.

2.7.2 Shell deformities

Abundant shell deformities have been widely recorded in most samples collected for this study except in the outer harbour. These deformities range between 0.5 and 3 % in the outer harbour and between 16-30 % in the inner harbour and Northwest Arm, which are the most polluted parts of the greater Halifax Harbour. The deformed assemblages dominated by *E. advena*, *S. biformis*, *E. excavatum*, and *C. crassimargo* exhibit five morphological deformities: 1) dwarfism, 2) aberrant chambers, 3) oversized tests, 4) poor test development (distorted shell or weak chamber growth) and 5) twinning (Table 2.3). The most widely recorded deformity is dwarfism, which occurs in *E. advena* and *S. biformis* but rarely in other species. Aberrant chambers represent the second largest deformity type (Fig. 2.26.8, 2.27.4), and were found in *E. advena*, *S. biformis*, *H. orbiculare*, *E. excavatum*, *C. crassimargo*, *R. bulloides* morphotype *columbiensis*, and *T. ochracea.* Oversized tests (>500 µm diameter) occur mainly in *C. crassimargo* and in some specimens of *A. cassis* and *E. advena*. Poor test development is rare and mainly limited to *E. advena*, *E. excavatum*, *H. orbiculare*, and *C. lobatulus* (Figs. 2.27.4-6, 2.26.7). Siamese twins are also rare, having been found in only a few specimens of *E. advena*, *S. atlantica*, *E. excavatum*, and *C. lobatulus* (Figs. 2.25.7, 2.27.3).

Although there is some skepticism about the use of shell deformities as pollution indicators (e.g., Boltovskoy et al., 1991; Debenay et al., 2001), the deformities are most abundant where pollution is the most concentrated in Halifax Harbour and are strongly related to variations in pollution amounts. This relationship can also be inferred from the low number of deformities in the less polluted areas (e.g., the outer harbour) and during the treatment period in the inner harbour. This strong positive relationship between shell deformities and contaminants in Halifax Harbour are clearly discusses and shown in the next section.

Species	Type of deformity				
	Dwarfism	Aberrant chamber	Oversized test	Poor test development	Siamese twins
A. cassis			1.16		
C. crassimargo		2.7	4.79		
E. advena	43.29	5.6	2.5	7.48	0.6
E. excavatum		0.7			0.59
H. orbiculare		0.4			
C. lobatulus		3.77	4.49		0.29
S. atlantica			0.77		0.06
S. biformis	8.8	1.25	0.3	3.25	

Table 2.3: Common types of morphological deformities in this study and ratios of different species in each deformity.

2.7.3 Foraminiferal trends vs. chemical data

Comparisons of foraminiferal data and the available sediment geochemistry data (OC and metal concentrations) of the grab samples collected in 2008 and April 2009 indicate that foraminiferal proxies correlate well with the concentrations of these contaminants in the sediments. Figures 2.21-24 illustrate the relationships between several foraminiferal proxies (diversity and/or abundance, percentages of calcareous spp. and deformed shells) and the concentrations of OC and the sum of Cu+Pb+Zn concentrations, as reported in Williams (2010). From these relationships, we can infer that diversity, abundance, and percentages of calcareous species have inverse relationships with OC and metal concentrations in the sediments. In contrast, shell deformities show positive correlations with concentrations of these contaminants. These correlations exist across a wide range of contaminant concentrations, including the relatively clean sediments at the HP locations that have the lowest levels of chemical contaminants (OC<0.6 Wt. %, and ∑Cu+Pb+Zn <75 ppm) among all of the studied locations in all sampling cycles. These HP sites, located in the outer harbour, have the highest number of species (~30), individuals (>4000), and percentage of calcareous species (>80%), as well as the lowest percentage of deformed shells over the study period (Figs. 2.21-24).

Although most of the locations that have high percentages of OC also have high metal concentrations (e.g., TC, DC, AYC, DYC), the fit of the data to the trend lines of foraminifera plotted versus these chemicals indicates that OC has a stronger effect on foraminifera as compared to metals. The highest recorded values of both OC (11.1 Wt.%) and total percentages of metals Cu, Pb, and Zn (4580 ppm) during the study period are those of Tufts Cove (TC) site in the March 2008 samples (Fig. 2.21). By excluding the TC data from both graphs, the slope of the trend line of foraminifera vs. OC will not change significantly, whereas the relationship between foraminiferal parameters and metals will have a steeper slope. Likewise, in April 2009, DC and TC also have relatively high values in both OC (5.48 and 7.28 Wt. %, respectively) and the highest percentages of metals (2038 and 1288 ppm, respectively) during this sampling cycle. If the relationships in Fig. 2.25 are re-examined after excluding these two locations (DC, TC) from the plots, the foramaniferal proxies still have a stronger relationship with OC than with with the sum of Cu, Pb, and Zn.

However, direct comparisons between specific sample sites shows that there are clearly other factors besides OC and metal concentrations controlling these foraminiferal parameters. For example, the DYC site (Bedford Basin) in March 2008 has a similar percentage of calcareous spp. (15%) to that of the D3 site (Inner Harbour), but the sediments show very different values for OC (6.03 Wt.% for DYC and 3.3 Wt.% for D3) and metal content (715 ppm for DYC and 288 ppm for D3). The variability in foraminiferal parameters between these sites is likely related to different environmental conditions (e.g., differences in substrates, salinity, depth, and dissolved oxygen). In general, the DYC site has consistently high values of OC (> 5.5 wt. %) and total metal (Cu, Pb, Zn) content (>500 ppm) and very low values of foraminiferal diversity (<7), abundance (<500), and calcareous spp. (0-5%), which accords with the trends discussed above.

The impact of other environmental conditions can be seen by comparing sites with similar OC contents such as MC (Mill Cove, Bedford Basin), which had OC (3

Wt.%), and D1, D3 and EE1 (Inner Harbour), which had OC (3.1-4.7 Wt.%) in July 2008. The foraminiferal proxies at MC are consistently very low (diversity <5, abundance < 500, calcareous spp. = 0%). This reflects the close proximity of this site to a treated sewage outfall and the effect of fresh water runoff from the Sackville River. This site also shows a high percentage (>80%) of organic inner linings of calcareous foraminifera, which are caused by a drop in sediment pH during the degradation of organic matter by bacteria. In contrast, the foraminiferal proxies in the inner harbour sites mentioned above (D1, D3, EE1) are consistantly higher (diversity 10-23, abundance >750, calcareous spp. = 15-55%) as compared to MC. Williams (2010) showed that there was no significant improvement in the chemical composition at these sites in response to the treatment process (Williams, 2010), so the observed changes in benthonic foraminifera parameters suggests that any improvements are related to changes in the water column, not in the sediments themselves.

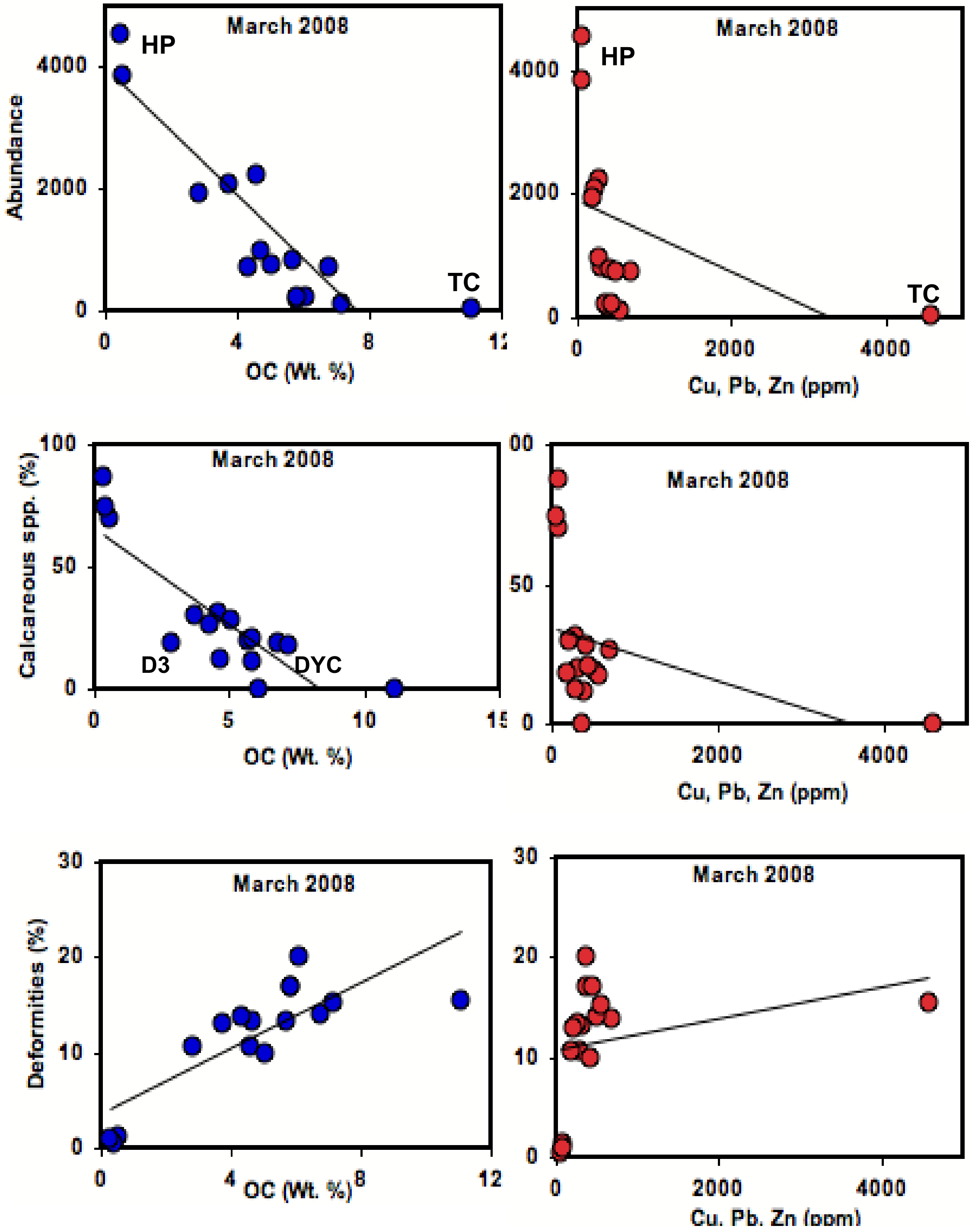

Figure 2.21: Relationships between foraminiferal parameters and both OC (in blue) and metals content (in red) of the grab samples from Halifax Harbour (March 2008-sampling). The chemical data are taken from Williams (2010).

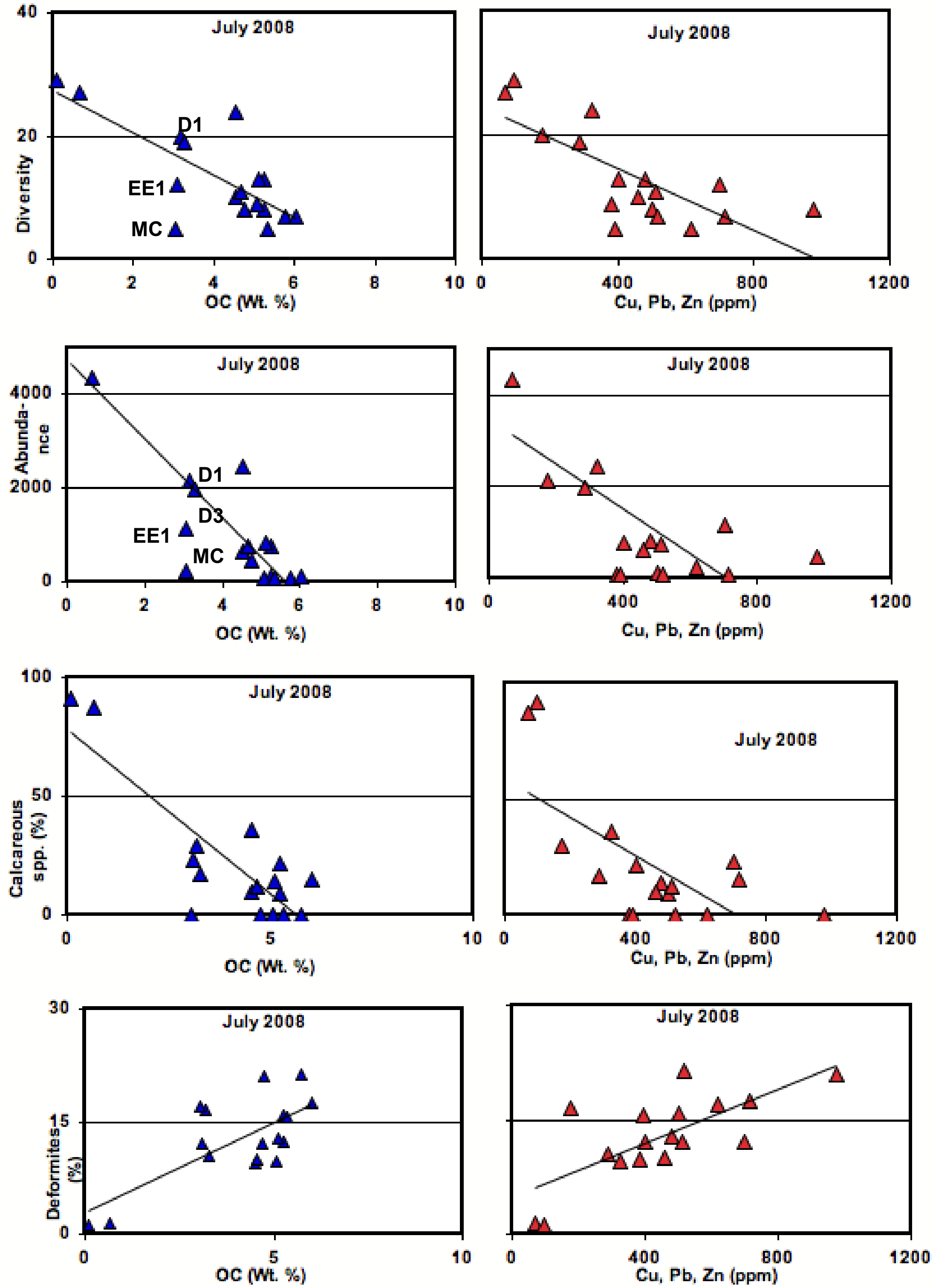

Figure 2.22: Relationships between foraminiferal parameters and both OC (in blue) and metals content (in red) of the grab samples from Halifax Harbour (July 2008-sampling). The chemical data are taken from Williams (2010).

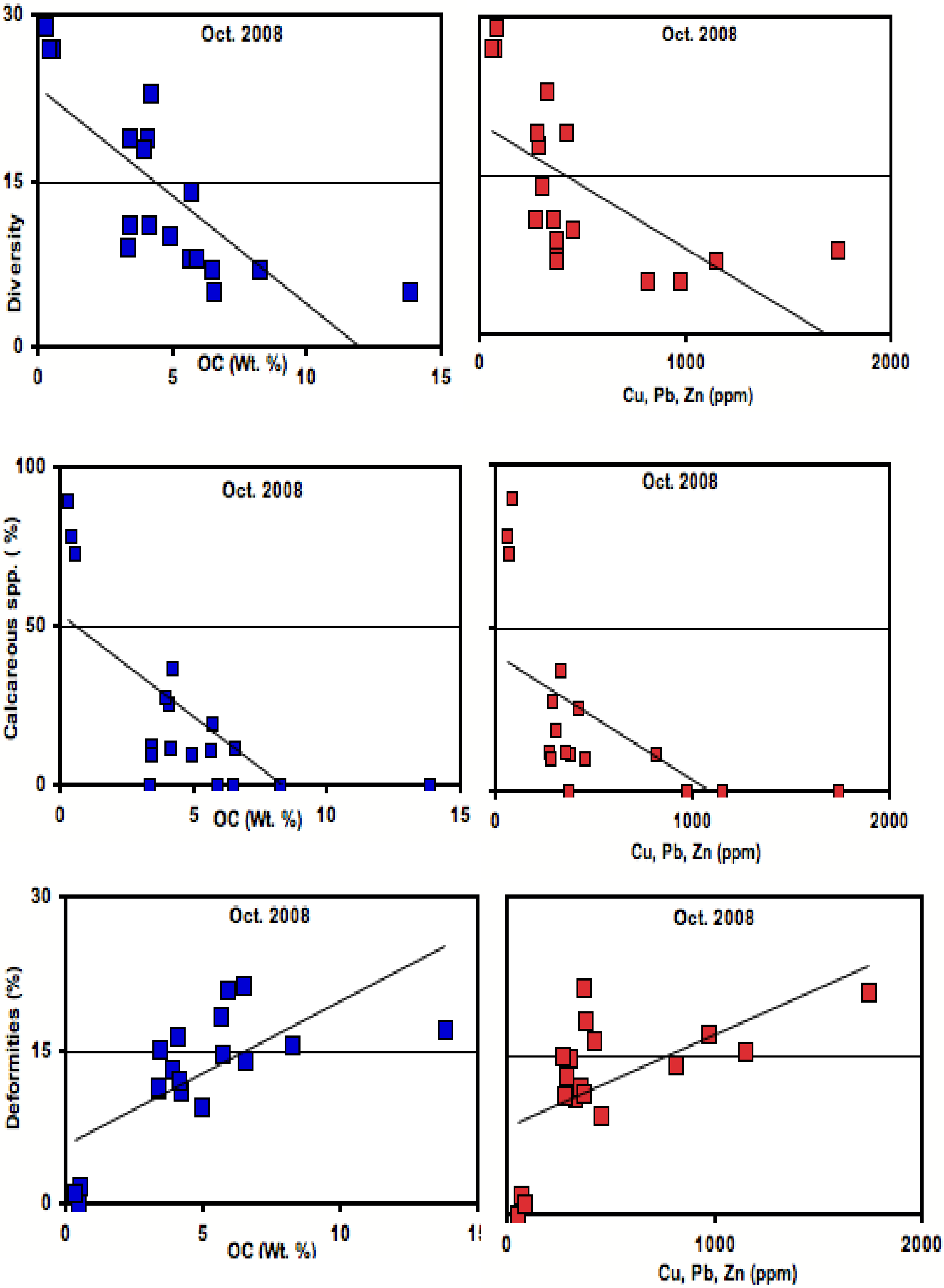

Figure 2.23: Relationships between foraminiferal parameters and both OC (in blue) and metals content (in red) of the grab samples from Halifax Harbour (October 2008-sampling). The chemical data are taken from Williams (2010)

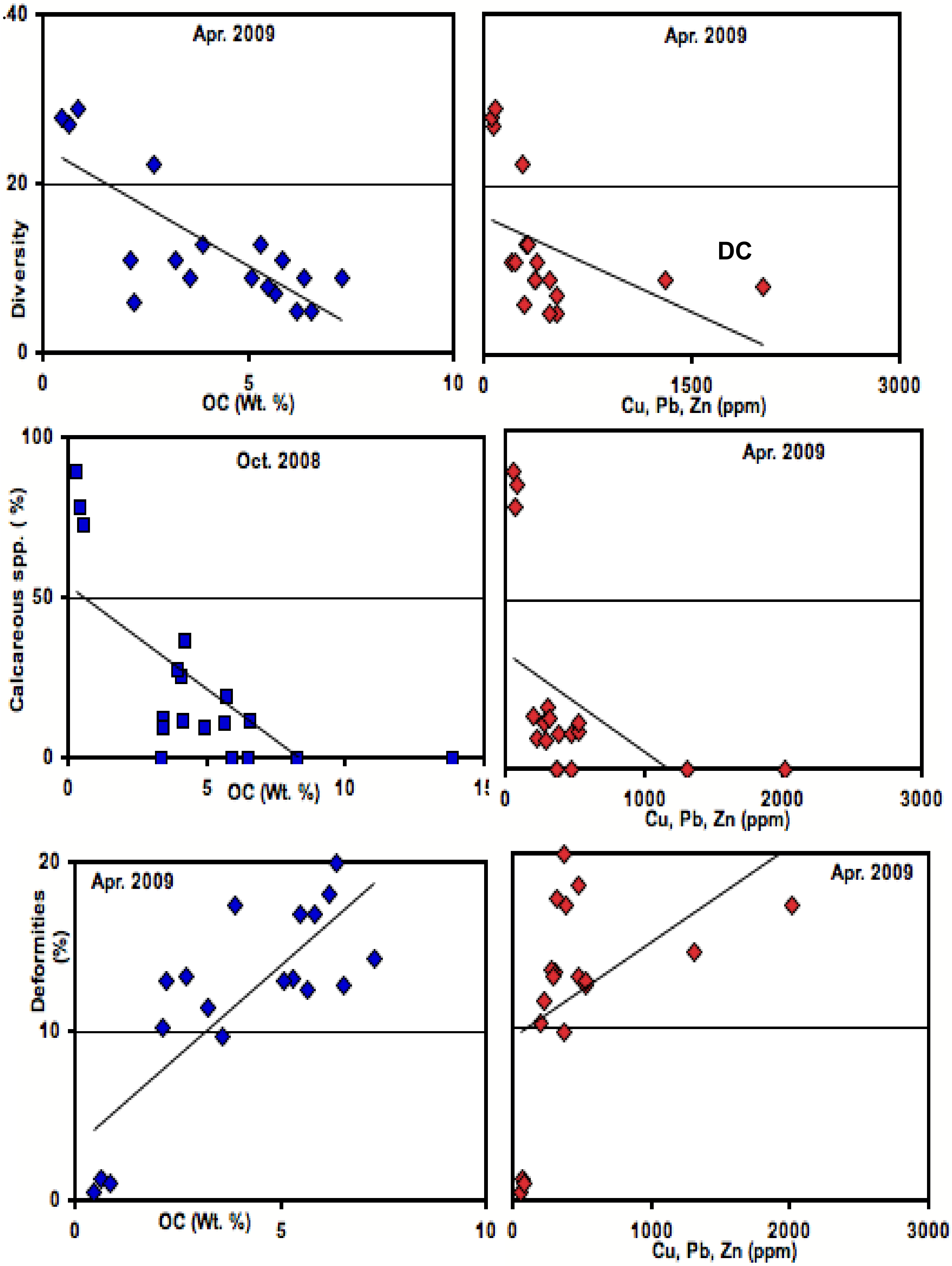

Figure 2.24: Relationships between foraminiferal parameters and both OC (in blue) and metals content (in red) of the grab samples from Halifax Harbour (April 2009-sampling). The chemical data are taken from Williams (2010).

2.8 Conclusions

In this study, benthonic foraminifera in surface sediments provided a useful tool for short-term pollution monitoring during a wastewater treatment program. This study also documents the use of benthonic foraminifera as a rapid, accurate, and cost-effective tool for long-term environmental monitoring, as shown in previous studies in other areas (see review in Scott et al., 2001). We believe that periodic sampling (at least three times a year for this kind of research work) is efficient and accurate in short-term studies because it helps to distinguish seasonal-derived (if they are present) environmental changes from pollution-derived ones.

The quick environmental recovery of the treated area in the inner harbour after the Halifax WWTF went online in February 2008 was inferred by changes in the foraminiferal assemblage during the one-year treatment period, including the reappearance of calcareous species with ratios exceeded 25% of the population. Additionally, this recovery was inferred also by increase in both diversity (14-19 species compared to <12 species before treatment) and total abundance (>1650 compared to <900 individuals before treatment). Furthermore, a decrease in both organic inner linings (<25% compared to 35% before treatment) and shell deformities (<14% compared to 17.5% before treatment), indicating a recovery during the treatment period. The decrease in the latter suggests that shell deformities are strongly related to extreme environmental conditions, either natural or human derived. These biologic changes in the assemblage highlight the resilience of the foraminifera and show that they can respond very rapidly (i.e., within months or even weeks) to beneficial or adverse changes in environmental conditions. Seasonal variations during the study period (from Oct. 2007 to August 2009) had relatively little impact on the foraminiferal assemblage in the area under observation during the summer seasons (July, 2008 and August 2009), only as a response of foraminifera to phytoplankton events in late spring or summer months. This strongly suggests that that the increase or reduction of pollution input plays a pivotal role in the distribution of foraminifera in this area.

Sampling results also indicate relatively open-ocean conditions in the outer harbour except inside Herring Cove, which is polluted by a wastewater outfall discharge of ~15 ML/day. The remainder of the samples collected in the untreated areas of the harbour during the study period did not show any changes in the foraminiferal assemblage, likewise suggesting little significant environmental change. The foraminiferal trends vs. the available chemical data (OC and Cu, Pb, Zn metals, from Williams, 2010) of some of the grab samples (2008 and April 2009 samples) used in this study indicate that both metals and OC have a strong and variable influence on foraminiferal proxies from one site to another throughout the area, with OC being the most effective one. Additionaly, the improvements that were recorded in benthonic foraminifera in the treated part indicate an improvement in the water column more than in sediments that need a longer period of time to naturally accumulate new clean sediments.

This study can be used in the future as a baseline for long-term monitoring of the harbour or other areas. Results indicate that Halifax Harbour will approach pre-impact environmental conditions with the present level of treatment, but complete environmental recovery is unlikely, given the growing population in the Halifax area and the influences of non-point sources of pollution. In future studies, we recommend that foraminifera be used to monitor changes in the inner harbour, Northwest Arm and the HC site, as they are the most highly polluted locations in Halifax Harbour. In addition, this study documents the usefulness of benthonic foraminifera as short- and long-term monitoring proxies in pollution-impacted marine areas around the world.

2.9. Taxonomy

Below is an alphabetical list of the most common foraminiferal species found in Halifax Harbour, each accompanied by their original designation and any other information used for identification. Genera were assigned using Loeblich and Tappan's examples (1987). Additional taxonomy, discussions, and illustrations of most of these species are in Scott and Medioli (1980) and Scott et al. (1977, 1980, 2001, 2005, and 2011). Figure numbers in parentheses denote specimens illustrated in this chapter, all of which are reposited in the Department of Earth Sciences, Dalhousie University, Nova Scotia.

Ammotium cassis (Parker, 1870)

Fig. 2.25.1

Lituola cassis. Parker *in* Dawson, 1870, p. 177, 180, fig. 3.

Ammotium cassis (Parker in Dawson), Loeblich and Tappan, 1953, p. 33, pl. 2, figs. 12–16.

Buccella frigida (Cushman, 1922)

Pulvinulina frigida Cushman, 1922, p. 144.

Buccella frigida (Cushman), Anderson, 1952, p. 144, figs. 4–6.

Cassidulina reniforme Nørvang, 1945

Fig. 2.25.2

Cassidulina crassa d'Orbigny var. *reniforme* Nørvang, 1945, p.41, fig. 6c-h.

Cibicides lobatulus (Walker and Jacob, 1798)

Figs. 2.27.3-7

Nautilus lobatulus Walker and Jacob, 1798, p. 642, pl. 14, fig. 36.

Cibicides lobatulus (Walker and Jacob), Jones, 1994, p. 97, pl. 92, fig. 10; pl. 93, figs. 1, 4-5; p.114, pl. 115, figs 4-5.

Cribrostomoides crassimargo (Norman, 1892)

Haplophragmium crassimargo Norman, 1892, p. 17.

Cribrostomoides crassimargo (Norman), Schafer and Cole, 1978, p. 27, pl. 4, fig. 20.

Dentalina ittai Loeblich and Tappan, 1953

Fig. 2.25.3

Dentalina ittai Loeblich and Tappan, 1953, p. 56, pl. 10, figs. 10-12.

Eggerella advena (Cushman, 1922)

Figs. 2.25.4-9

Verneuilina advena Cushman, 1922, p. 141.

Eggerella advena (Cushman), Cushman, 1937, p. 51, pl. 5, figs. 12–15.

Elphidium clavatum Cushman, 1930

Elphidium incertum (Williamson), var. *clavatum* Cushman, 1930, p. 20, pl. 7, fig. 10.

Elphidium clavatum Cushman, Loeblich and Tappan, 1953, p. 98, pl. 19, figs. 8-10.

Elphidium excavatum (Terquem, 1876)

Fig. 2.26.1-4.7

Polystomella excavata Terquem, 1876, p. 429, pl. 2, fig. 2.

Elphidium excavatum (Terquem) formae Miller et al., 1982b (all formae), pl. 1, figs. 1-20, pl. 2, figs. 1-8, pl. 3, figs. 1-8, pl. 4, figs. 1-12.

Elphidium incertum (Williamson, 1858)

Fig. 2.26.5-6

Elphidium incertum (Williamson), Cushman, 1930, p. 18, pl.7, figs. 8-9.

Elphidium williamsoni Haynes, 1973

Elphidium williamsoni Haynes, 1973, p. 207-209, P1. 24, fig. 7, pl. 25, figs. 6, 9, p1. 27, figs. 1-3.

Fursenkoina fusiformis (Williamson, 1858)

Bulimina pupoides d'Orbigny var. *fusiformis* Williamson, 1858, p. 64, pl. 5, figs. 129,130

Fursenkoina fusiformis (Williamson), Scott et al., 1980, p. 228, pl. 3, figs. 9, 10.

Haynesina orbiculare (Brady, 1881)

Fig. 2.26.8

Nonionina orbiculare Brady, 1881, p. 415, pl. 21, fig. 5.

Haynesina orbiculare (Brady), Scott et al., 1980, p. 226 (note).

Lagena apiopleura Loeblich and Tappan, 1953

Fig. 2.26.9

Lagena apiopleura Loeblich and Tappan, 1953, p. 59, pl. 10, figs. 14, 15.

Lagena mollis (Cushman, 1944)

Fig. 2.26.10

Lagena gracillima (Seguenza) var. *mollis* Cushman, 1944, p. 21, pl. 3, fig. 3.

Lagena mollis (Cushman), Loeblich and Tappan, 1953, p. 63, pl. 11, figs. 25-27.

Miliammina fusca (Brady, 1870)

Quinqueloculina fusca Brady, 1870, p. 286, pl. 2, figs. 2a-c, 3a-b.

Miliammina fusca (Brady), Murray, 1971, p. 21, pl.3, figs.1-6.

Nonionellina labradorica (Dawson, 1860)

Fig. 2.26.2

Nonionellina labradorica (Dawson), Loeblich and Tappan, 1964, pl. 61, figs. 2-5.

Oolina borealis Loeblich and Tappan, 1953

Fig. 2.26.11

Oolina borealis Loeblich and Tappan, 1953, p.68, pl.13, figs.4-6

Oolina melo d'Orbigny, 1839

Fig. 2.26.12

Oolina melo d’Orbigny, 1839, p. 20, pl. 5, fig. 9.

Quinqueloculina arctica Cushman, 1933

Quinqueloculina arctica Cushman, 1933, p. 2, pl. 1, figs. 3a-c.

Reophax fusiformis (Williamson, 1858)

Proteonina fusiformis Williamson, 1858, p. 1, pl. 1, fig. 1.

Reophax fusiformis (Williamson); Brady, 1884, p.290, pl. 30, figs 7-11.

Reophax scottii Chaster, 1892

Reophax scottii Chaster, 1892, p. 57, pl. 1, fig. 1.

Rosalina bulloides d’Orbigny morphotype *columbiensis*

Discorbis columbiensis Cushman, 1925, p. 43, pl. 6, fig. 13.

Rosalina columbiensis (Cushman) emended Lankford and Phleger, 1973, p. 127, 128, pl. 5, figs.10–12.

Rosalina bulloides f. columbiensis (Cushman), Scott et al., 2011, p. 304, pl.25.5.

Saccammina atlantica (Cushman, 1944)

Fig. 2.27.8

Proteonina atlantica Cushman, 1944, p. 5, pl. 1, fig. 4.

Saccammina atlantica (Cushman), Parker, 1952, p.454, Pl.1, fig. 1-2.

Spiroplectammina biformis (Parker and Jones, 1865)

Fig. 2.27.9

Textularia agglutinans d'Orbigny var. *biformis* Parker and Jones, 1865, p. 370, pl. 15, figs. 23, 24.

Spiroplectammina biformis (Parker and Jones), Cushman, 1927, p. 23, pl. 5, fig. 1.

Trochammina ochracea (Williamson, 1858)

Fig. 2.27.10

Rotalina ochracea Williamson, 1858, p. 55, pl. 4, fig. 112, pl. 5, fig.113.

Trochammina ochracea (Williamson), Cushman, 1920, p. 75, pl. 15, fig. 3.

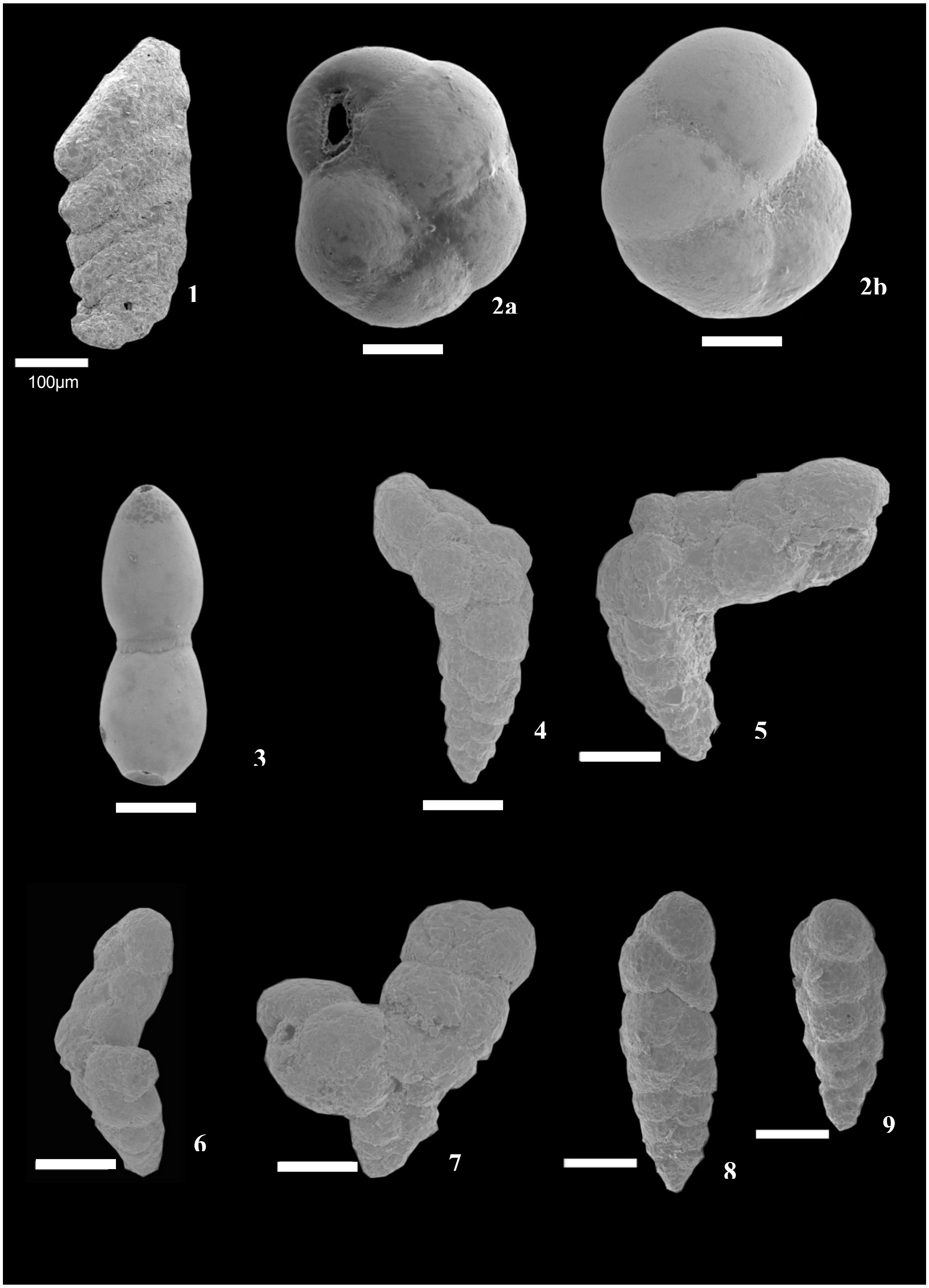

Figure 2.25: 1 *Ammotium cassis*. **2** *Cassidulina reniforme*. **3** *Dentalina ittai*. **4–9** *Eggerella advena* (4–7 are deformed). Scale bar = 40 µm unless otherwise indicated.

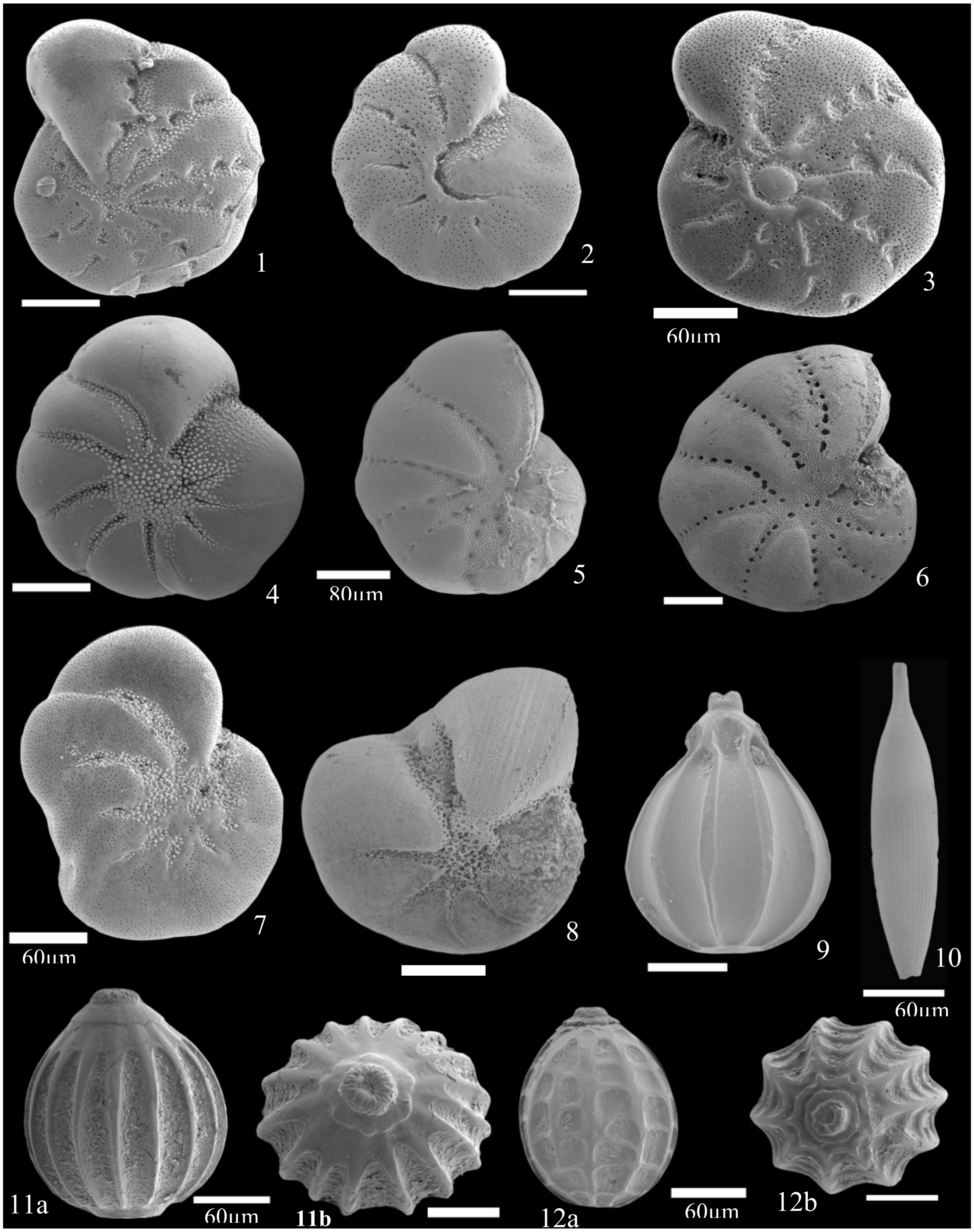

Figure 2.26: 1–4, **7** *Elphidium excavatum* (7 is deformed). **5, 6** *Elphidium incertum*. **8** *Haynesina orbiculare* (deformed). **9** *Lagena apiopleura*. **10** *Lagena mollis*. **11** *Oolina borealis*: 11a, side view; 11b, apertural view. **12** *Oolina melo*: 12a, side view; 12b, apertural view. Scale bar = 40 µm unless otherwise indicated.

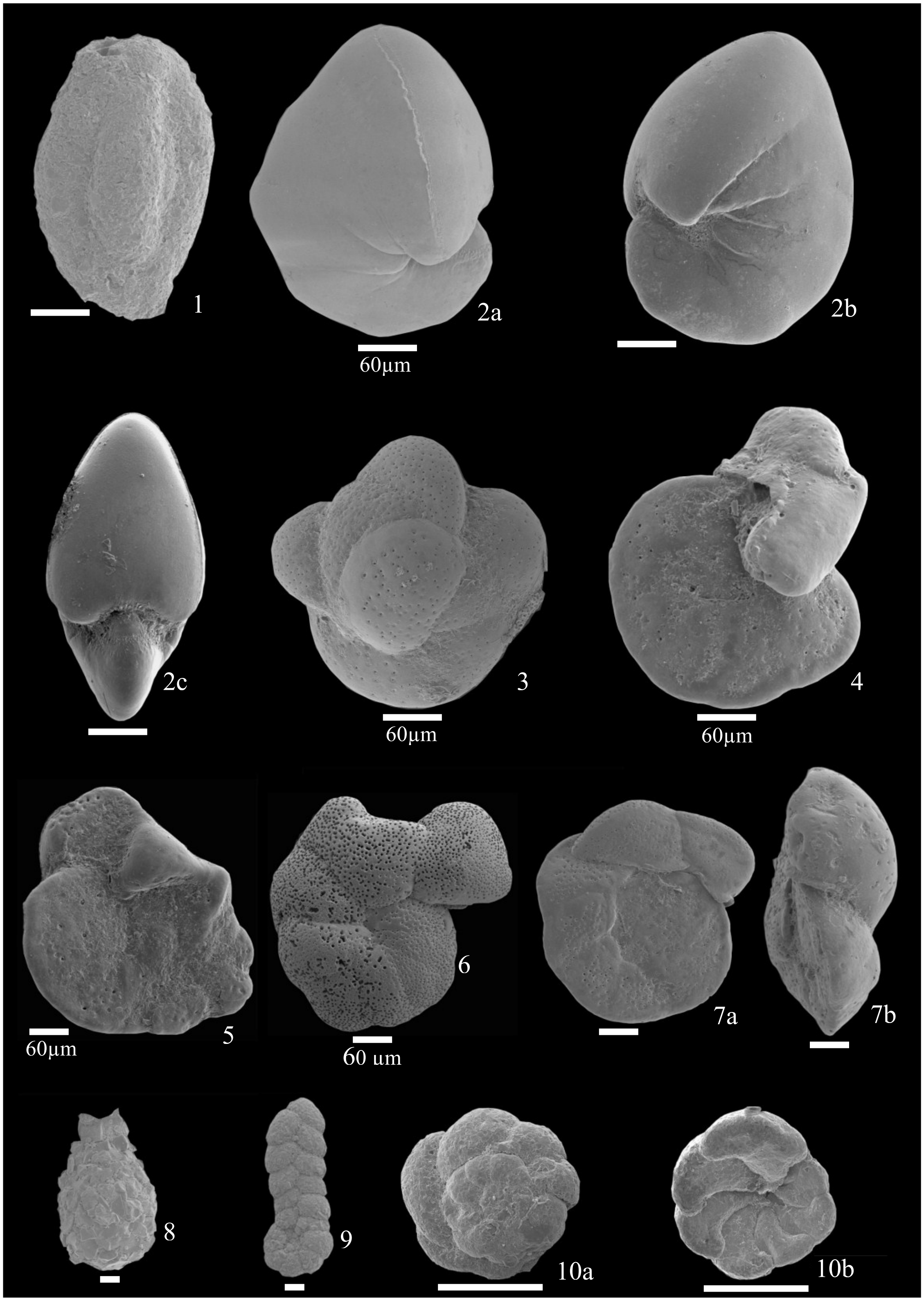
1
2a
60μm
2b
2c
3
60μm
4
60μm
5
60μm
6
60 um
7a
7b
8
9
10a
10b

Figure 2.27-previous page: 1 *Miliammina fusca*. **2** *Nonionellina labradorica*: 2a, dorsal view; 2b, ventral view; 2c, side view. **3–6** *Cibicides lobatulus*, deformed specimens. **7** *Cibicides lobatulus*, normal specimen: 7a, dorsal view; 7b, side view. **8** *Saccammina atlantic*a. **9** *Spiroplectammina biformis*. **10** T*rochammina ochracea*: 10a, dorsal view; 10b, ventral view. Scale bar = 40 µm unless otherwise indicated.

Chapter 3: Benthonic Foraminifera as Proxies for Reconstruction of the Pre-European Settlement Environment of Halifax Harbour, Nova Scotia, Canada

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3.1 Abstract

Benthonic foraminifera in sediment cores from Halifax Harbour, Nova Scotia, were used to construct a "baseline" environment for assessing the efficiency of a recent wastewater treatment project after 250 years of untreated domestic and industrial pollution. High diversity (>30 species), dominant calcareous species (>60%), and low percentages of shell deformities (3-4%) characterize the foraminiferal assemblage of pre-impact times. With the beginning of organic-rich wastewater input, there was a gradual decline in foraminiferal diversity, total abundance, and calcareous species upward in the sediment cores.

Heavy pollution associated with the increased population growth of Halifax since the 1960s has caused a dramatic change in the foraminiferal record. An agglutinated foraminiferal assemblage developed, with dominance of the high organic-tolerant species *Eggerella advena*. Additionally, there is a large decrease to a complete absence of calcareous tests, leaving only organic inner linings after the dissolution of carbonate due to the relatively low pH in the organic-rich sediments. Shell deformities with variable modes and intensities are strongly related to pollution amounts.

3.2 Introduction

The extensive input of domestic and industrial pollutants associated with urbanization and industrial expansion has caused severe damage to coastal marine environments around the world. These pollution issues have become a global matter of concern in the last century. One of the ways to assess remediation in polluted areas is to compare the area with a non-impacted environment with similar natural features and conditions. The most accurate method of such an assessment for bottom sediments is to compare the recent environment of an impacted area with its historical background.

Because there is generally no documentation of the pre-impact environmental conditions of an area, knowledge about this history can be gained mainly by studying the fossil record of the original biota that used to live during these times and are preserved now in deeper sediments. Foraminifera are the best known among all the microfossil groups to have a good fossil record and specific environmental tolerance, and so they are useful in reconstructing the pre-impact history of polluted environments (e.g., Scott et al., 1990, 2001; Hayward et al., 1999; Sen Gupta, 1999; Debenay, 2000; Murray, 2006). The importance of benthonic foraminifera, the history of their use as environmental indicators, and case studies using this approach were discussed in detail in Chapter 1.

Although many studies have used benthonic foraminifera as proxies for the remediation of environmental pollution, only a few studies have focused on their use in sediment cores for the reconstruction of the historical or pre-impact “baseline” environment (e.g., Ellison et al., 1986; Nagy and Alve, 1987; Alve, 1991, 2000; Schafer et al., 1991; Scott et al., 2001, 2005). The goal of the present work is to reconstruct a reference environment (with respect to benthic foraminifera) for the wastewater treatment processes that started in 2008 in Halifax Harbour using pre-impact foraminiferal assemblages from sediment cores. In addition, this study aims to document the historical degradation of foraminiferal populations in Halifax Harbour as a result of pollution input to better understand the present-day environmental conditions in the harbour sediments.

3.3 Importance of the present work

From 2007 to 2010, the Halifax Regional Municipality (HRM) constructed three wastewater treatment plants at a cost of CAN $330 million to provide advanced primary treatment of the more than 100 sewage outfalls that pour into the harbour (HRM, 2012). Additional details about the environmental setting of Halifax Harbour, including the pollution history and past and current treatment programs, can be found in Buckley and Winters (1992), Fader and Miller (2008), Williams (2010), Shan et al. (2011), and Chapter 1 of this thesis.

A significant data gap for this clean-up project is a lack of detailed information on the pre-impact conditions of Halifax Harbour that could be used to help gauge the success of the source-reduction measures. Additionally, most previous studies that dealt with the environmental pollution of Halifax Harbour focused on water or sediment chemistry and used surface grab samples or short cores (e.g., Williams, 2010). Although geochemical studies can indicate the composition and type of contaminants, benthonic foraminifera are more effective in providing a detailed historical reconstruction of the impacts of these pollutants on the ecosystem and biota of the area (Alve, 2000).

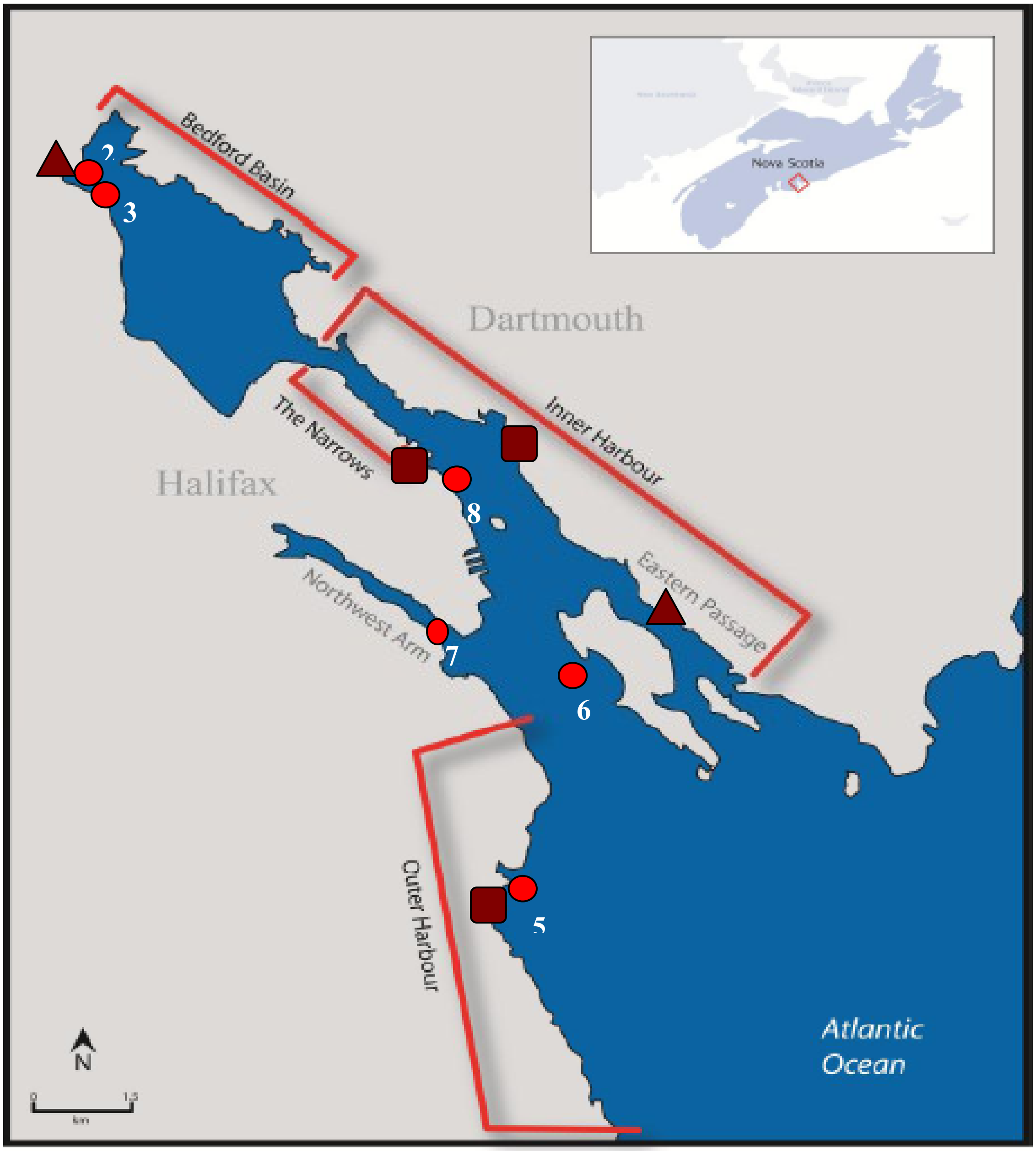

Figure 3.1: Study area and location of vibracore stations (red circles), 2008-2010 wastewater treatment plants (brown rectangles), and older treatment plants (brown triangles) (base map from Weston, 2010).

3.4 Materials and Methods

3.4.1 Choice of sampling locations

Although the choice for the locations of vibracores collected in this present study was not our decision, we nonetheless believe that the site distribution is reasonable. Since Halifax Harbour is an estuary environment affected by numerous environmental parameters, the chosen locations should represent all possible environments in the harbour. For that reason, two cores are located in the outer harbour where there is an open marine condition with less or no pollution and /or strong fresh water runoff. Due to the special environmental situation (shallow depths, strong pollution impact, leisure boating activities) of the Northwest Arm, core number 7 was collected from that geographic location.

The central portion of the harbour is the most polluted part. As well as forming the ‘bridge’ between the Atlantic Ocean and Bedford Basin, it is considered a source for many of the sediments carried into the basin. Hence, the two treatment plants were built on both sides (downtown Halifax and downtown Dartmouth WWTFs) of the harbour in this section, rendering our choice for core selection here all the more reasonable. Core number 8 was collected from the Halifax side of this part of the harbour, while another core (core 9 – not studied in this research work) was collected from the Dartmouth side. Bedford Basin is the deepest section of the harbour and receives a strong freshwater runoff from the Sackville River at its northern end. Additionally, many sewage outfalls affect the basin and it also boasts a treatment facility that was built in the 1970s (Mill Cove Treatment Facility). Because of these influences, two sediment cores (vibracore 2, and vibracore 3) were collected from the basin.

3.4.2 Sampling procedure and data analysis

Six long (1.7-4.5 m) vibracores were collected from the harbour (Figs. 3.1, 3.2) in November 2008 using the Rossfelder vibracoring system. Immediately after collection, the cores were stored in a 4 °C refrigerated cold room, then later split into two halves lengthwise, X-rayed, photographed, and sub-sampled at the Bedford Institute of Oceanography (BIO). The sampling interval was 1 cm for the upper meter and every 10 cm to the base of each core. The archive halves of the cores were stored at BIO for any future requirements. The geographic coordinates and water depths are given in Table 3.1. The laboratory techniques applied in this research are the same techniques explained in Chapter 2 (see section 2.5.2), except a Rose Bengal staining solution was not used.

Stations	Latitude (N)	Longitude (W)	Water-Depth (m)	Core length (cm)	Sedimentation Rate (cm/y)
20080530002VC	44^{0}71.60	-63^{0}66.86	13.7	293	NA
[b]1	44^{0}71.61	-63^{0}66.86	16.2	25	**0.26**
20080530003VC	44^{0}71.29	-63^{0}66.41	17.1	271	NA
[b]2	44^{0}71.51	-63^{0}66.99	15	23	**0.32**
20080530005VC	44^{0}56.43	-63^{0}55.26	30	171	NA
20080530006VC	44^{0}60.98	-63^{0}53.84	21.3	407	NA
20080530007VC	44^{0}61.71	-63^{0}57.07	12.5	402	NA
[b]8	44^{0}61.72	-63^{0}57.05	15.5	35	**<0.21**
20080530008VC	44^{0}56.21	-63^{0}57.10	20.1	362	NA
[a]30	44^{0}65.01	-63^{0}56.82	NA	13	**0.90**
[a]32	44^{0}64.89	-63^{0}56.97	NA	73	**0.74**

Table 3.1: Vibracore stations, geographic coordinates, water depth and core lengths. Sedimentation rates based on previous works [a]: Buckley et al., 1995, and [b]: Williams, 2010.

Figure 3.2: Photograph showing the Rossfelder vibracorer.

3.4.1 Sedimentation rate and chronological dating

No age dating was carried out in this study. Previous chronological studies indicate that sedimentation rates are variable throughout the study area (e.g., Cranston, 1994; Buckley et al., 1995; Williams, 2010). Cranston (1994) used geochemical gradients in pore water and organic carbon (OC) concentrations to determine modern sedimentation rates from 0.04-0.30 cm/year. Buckley et al. (1995) did a detailed chronological analysis of sub-samples from 11 sediment cores to determine sedimentation rates in Halifax Harbour. Their ^{210}Pb dating results provided a mean sedimentation rate of 0.5 ± 0.3 cm y^{-1}, and a range of 0.15 to 1.2 cm y^{-1}. Buckley et al. (1995) mentioned that the values of natural (i.e., excluding areas around major sewage outfalls) sedimentation rates are generally highest in the outer harbour, intermediate in the Northwest Arm, and lowest in Bedford Basin. On average, the sedimentation rate estimates by Buckley et al. (1995) are much higher than those by Cranston (1994). Based on foraminiferal content of two undated short (22 cm and 60 cm) sediment cores at the mouth of Mill Cove in Bedford Basin, Scott et al. (2005) pointed out that the sedimentation rates would be greater than the highest values given by Buckley et al., (1995) because of the close vicinity of these cores to a wastewater treatment plant outfall.

Williams (2010) examined the geochemistry of the harbour sediments based on the same vibracores used in the present work and collected an additional set of short slow cores that were used for ^{210}Pb dating. She examined four slow cores collected from Bedford Basin, Northwest Arm and Herring Cove using ^{210}Pb and ^{137}Cs dating, and examined sulphate and ammonium gradients in pore water. Her ^{210}Pb and ^{137}Cs results suggest a low average sedimentation rate (<0.21 cm yr^{-1}), while the pore water analysis suggests a present-day sedimentation rate of 0.10 cm yr^{-1} at the mouth of the Northwest Arm and of 0.15 cm yr^{-1} at Herring Cove. Comparing her results with those of Cranston (1994) and Buckley et al., (1995) suggests that there has been little change in the sedimentation rate over the past 15 years.

Because of funding constraints, no age dating was carried out for the vibracores used in this study. However, the sedimentation rate estimates from nearby sites by Buckley et al., (1995) and Williams (2010) were applied to our cores. A sedimentation rate of 0.26 cm/yr that was estimated by Williams (2010) for her slow core 1 was applied for our vibracore 2 in Bedford Bay. Additionally, the sedimentation rate (0.32 cm/yr) that was estimated by Williams (2010) for her slow core 2 is applied to our vibracore 3.

For vibracore 8, located in the inner harbour, the age boundaries are based on the mean (~0.82 cm/yr) of two sedimentation rate estimates (0.74 and 0.90 cm/yr) by Buckley et al. (1995) (cores 32, and 30 respectively, Table 3.1). The estimated sedimentation rate (<0.21 cm/yr) for slow core 8 of Williams (2010) is applied to vibracore 7 in the Northwest Arm. There are no published sedimentation rate estimates that could be applied to vibracores 5 and 6 in the outer harbour.

3.5 Results

3.5.1 Core 2 (near Mill Cove, Bedford Basin)

Chemical analyses indicate that the upper 22 cm of sediment were lost from core 2 during the vibracoring process (Williams, 2010). For that reason, corrected depths are used in the description and in Fig. 3.3 (corrected depth = core depth + 22 cm). The foraminiferal assemblage in core 2 is characterized by a low diversity (<10 species), low total abundance (<1000 individuals), and a complete absence of calcareous species except at two corrected depths (48 and 78 cm, Fig. 3.3). Despite their limited numbers, benthonic foraminifera in this core outline three distinct environmental zones from the base to the top, including a 25 cm peat layer. The lower zone (not shown in Fig. 3.3) is about 85 cm thick and extends from the base of the core to 208 cm corrected depth. This zone is composed mainly of yellow coarse sands in the lower part and medium to fine white sands in the upper part (Fig. 3.4) and is completely barren of foraminifera and other marine fauna. The 45 µm fractions of the samples investigated from this zone were examined for fresh water testate amoebae, but none were found. Above this zone there is a peat layer (25 cm thick), which extends from 208 to 183 cm corrected depth.

The second zone, from 183 to 62 cm corrected depth and located directly above the peat layer, includes the first record of benthonic foraminifera at ~ 180 cm corrected depth. The foraminiferal assemblage in this zone has low diversity (8 species/10 cc) and abundant (600-700 individuals/10 cc). The agglutinated species predominate the assemblage, whereas calcareous ones appear only in very low relative abundance (~2.5%- Fig. 3.3) at 78 cm corrected depth. Although calcareous species are almost absent, only few inner linings are present in this section of vibracore 2. Likewise, shell deformities are as low as ~3% in this part of core 2 (Fig. 3.3). The agglutinated species *E. advena* dominates the assemblage in the lower two thirds of this zone, with relative abundances up to 90 %. *Ammotium cassis* gradually dominates the assemblage in the upper third of the zone with a relative abundance up to 55 %.

In the upper zone of vibracore 2, extending from 62 cm to 23 cm corrected depths, there is a noticeable gradual decrease in abundance to approximately 250 individuals per 10 cc near the top (Fig. 3.3). The second record of calcareous species in vibracore 2 appeared in this zone at 48 cm corrected depth (Fig. 3.3). The foraminiferal assemblage in this zone is dominated by species *A. cassis*, and *C. crassimargo* (Fig. 3.3). Although *E. advena* was the dominant species in the sequence below, it became less dominant in this part of the core (<15%). Shell deformities and organic inner linings reached high values (between 20% and 40%) in this zone (Fig. 3.3).

Figure 3.3 represents the profiles of the main foraminiferal proxies (diversity, abundance, and deformities) in the upper 127 cm corrected depth of vibracore 2. Because the main concern of the present part of this study is the foraminiferal assemblage of the last two to three centuries, foraminifera of lower parts of the core that may be thousands of years in age are not presented in the diagram. This applies as well to all cores used in the present work.

3.5.2 Foraminiferal trends vs. OC and Cu, Pb, Zn metals in Core 2

Comparisons between foraminiferal proxies (diversity, abundance, and deformities) and the available chemical data (OC, Cu, Pb, Zn-from Williams (2010) for vibracore 2 (Fig. 3.5) indicate that benthonic foraminifera in that core do not have a strong relationship with the amount of organic carbon (Fig. 3.5 – blue coloured plots) in the sediments. This coincides with the relatively constant values of OC (5.8-7.7 Wt.%) throughout the core.

The total concentrations of Cu, Pb, and Zn are relatively low (45-184 ppm) throughout most of the core and seem to have little impact on benthonic foraminifera (Fig. 3.5 – the red coloured plots), especially in the upper 20 cm in this core, compared to OC. On the other hand, shell deformities showed a positive relationship with concentrations of metals (Fig. 3.5), which indicates that shell deformities are more sensitive to metal contaminants than OC in the sediments. These trends suggest that other environmental parameters in this area (e.g., salinity, substrates, pH) have a stronger impact on benthonic foraminifera than contamination. Consequently, examination of benthonic foraminifera should be accompanied by environmental measurements for any future studies in this area.

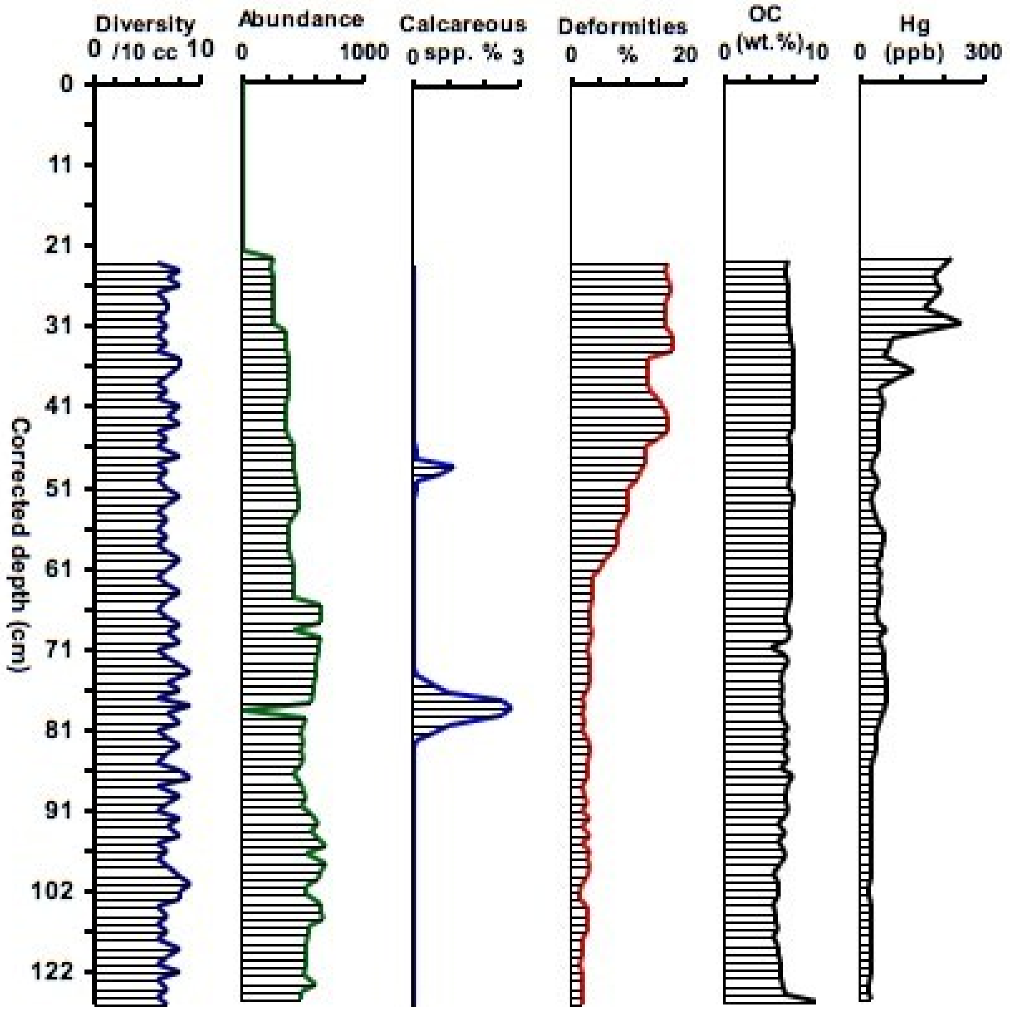

Figure 3.3: Foraminiferal assemblage characteristics and some chemical data (OC-wt%, Hg-ppb) in the upper 127 cm of Core 2 (Mill Cove, Bedford Basin). Diversity and abundance are represented in numbers while deformities and calcaresou species are in percentages. Organic carbon and Hg data are taken from Williams (2010). Depths on Y-axis are corrected depths.

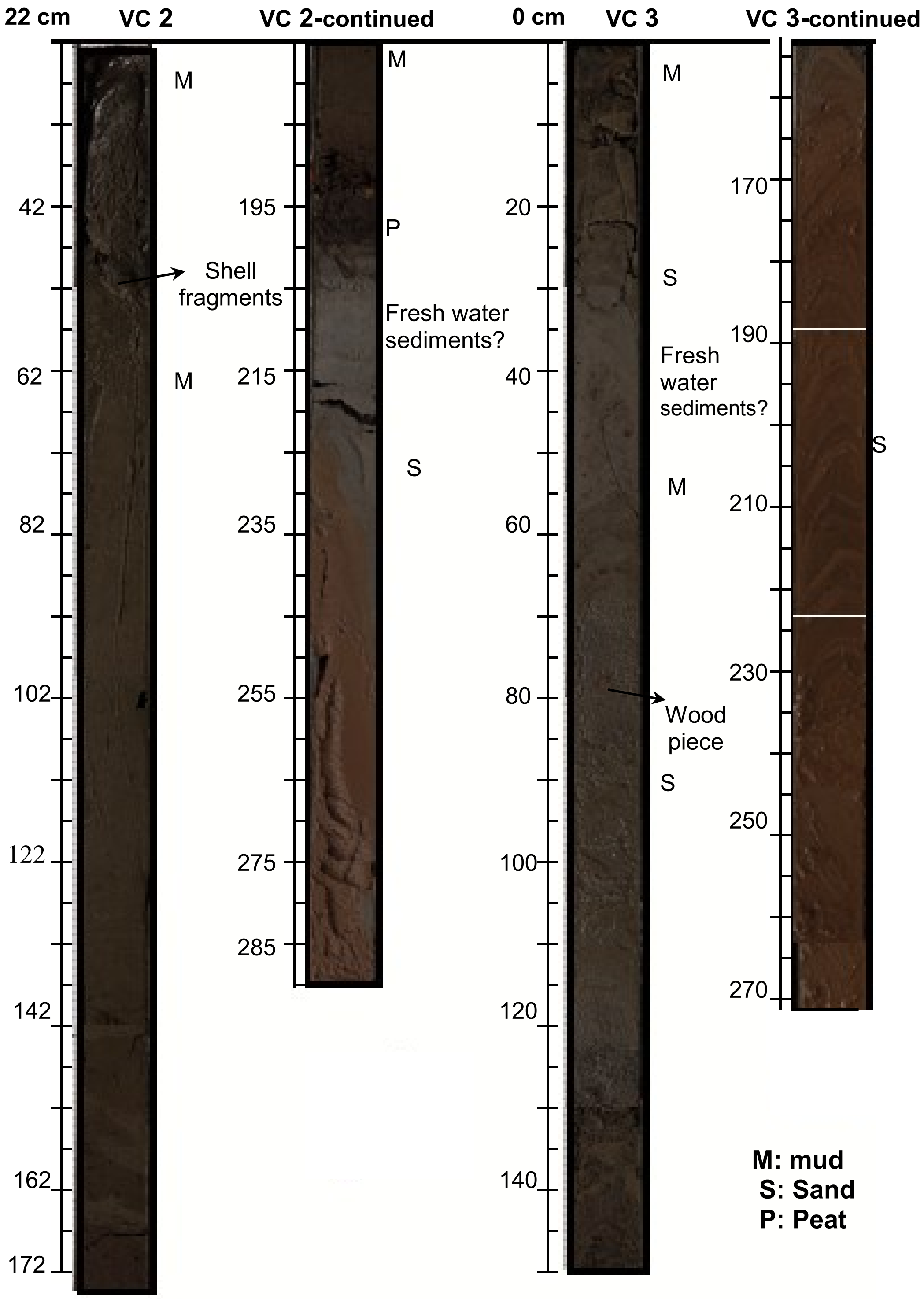

Figure 3.4: Photographs of vibracores 2 and 3 with some sedimentological characteristics. Because the upper 22 cm of core were lost, the used depth is the corrected depth.

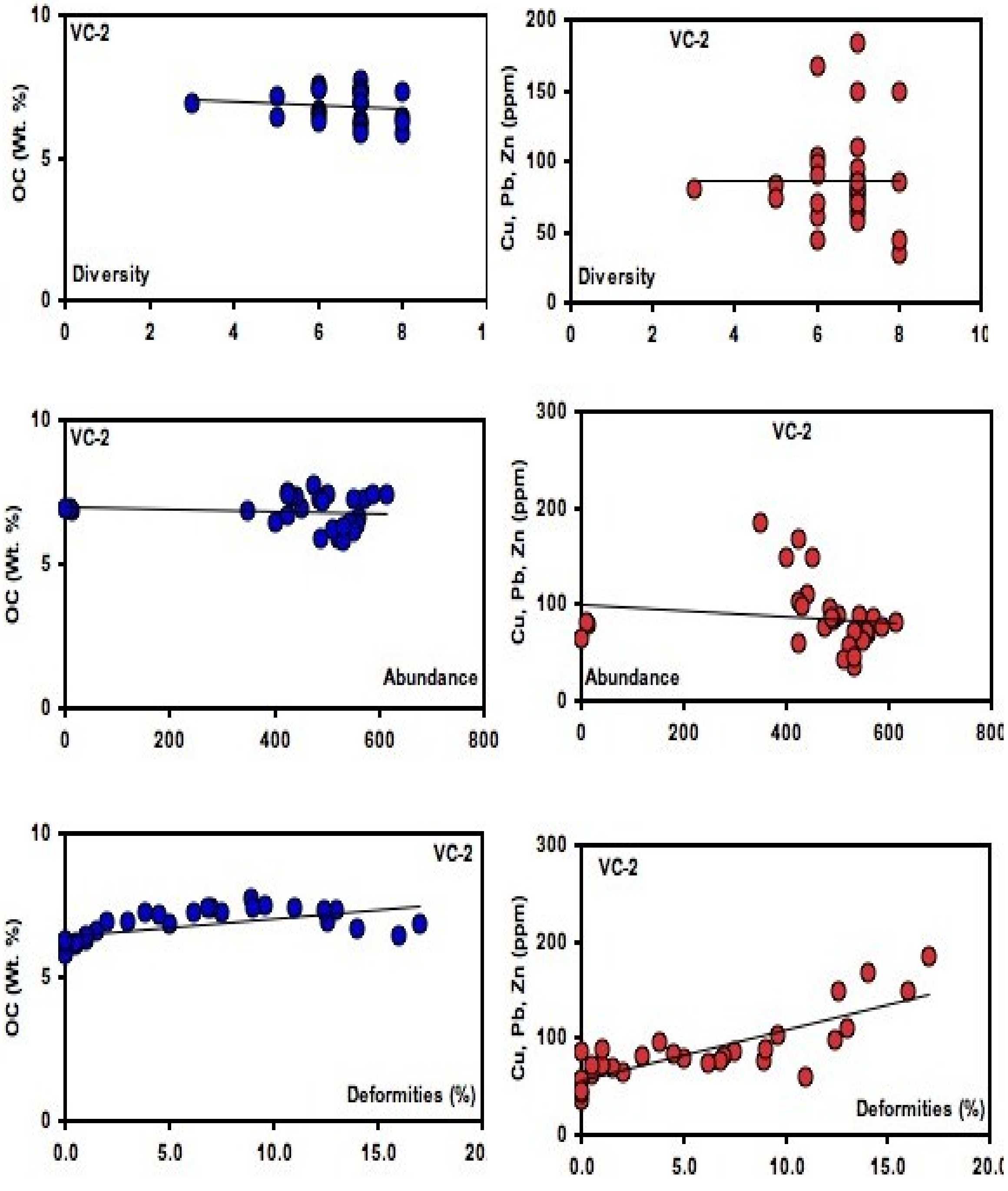

Figure 3. 5: Relationships between foraminiferal parameters and both OC (in blue) and total content of Cu, Pb, and Zn metals (ppm – in red) of vibracore 2 from Bedford Basin, Halifax Harbour. The chemical data are taken from Williams (2010).

3.5.3 Core 3 (near Mill Cove, Bedford Basin)

Of all the vibracores collected from Halifax Harbour, this core had the lowest numbers of foraminifera. Foraminifera were only observed in significant numbers in the upper 35 cm. Although benthonic foraminifera appeared at 71 cm, their numbers between 71 cm and 35 cm depths are negligible (75 individuals or less per 10 cc). This core is similar to core 2 in the absence of calcareous foraminifera (Fig. 3.6) and the presence of a thick (~201 cm) red to white sand layer at the bottom. In contrast to core 2, core 3 has no peat layer above the sand layer.

The foraminiferal diversity in this core ranges from 3 to 6 species per 10 cc, and the total abundance is less than 1,000 individuals, except for one peak value (~1900 individuals) at 10 cm depth (Fig. 3.6). The assemblage in this core is exclusively agglutinates and barren of calcareous species or their organic inner linings. The species *S. atlantica* dominates the assemblage with percentages that reach up to 95% (Figs. 3.6). After them, the agglutinated species *E. advena* and *C. crassimargo* co-dominate the assemblage with ratios reaching up to 40%. The opportunistic species *E. advena* reached its maximum percentage (~40%) in the core in the upper 15 cm (Fig. 3.6). Shell deformities in this core are rare (2-4%, Fig. 3.6).

3.5.4 Foraminiferal trends vs. OC and Hg in Core 3

The trends of foraminiferal proxies (diversity, abundance, and deformities) and the only available chemical data (OC, Hg from Williams, 2010) for vibracore 3 (Fig. 3.7) indicate that there is a slightly higher correlation between foraminifera and chemicals in core 3 compared to core 2. However, from the plots, it seems that both OC and Hg have comparable influence on benthonic foraminifera. This impact can be noticed in the positive relationship between shell deformities and chemical data, especially in the upper

11-12 cm (represented by the highlighted 4 dots above the trend line). On the other hand, there is also abnormally positive relationship between foraminiferal diversity and abundance with chemical data. This abnormal positive relationship can be understood in light of the fact that the increase in diversity and abundance was only in opportunistic species and only in the upper 11-12 cm (Fig. 3.6).

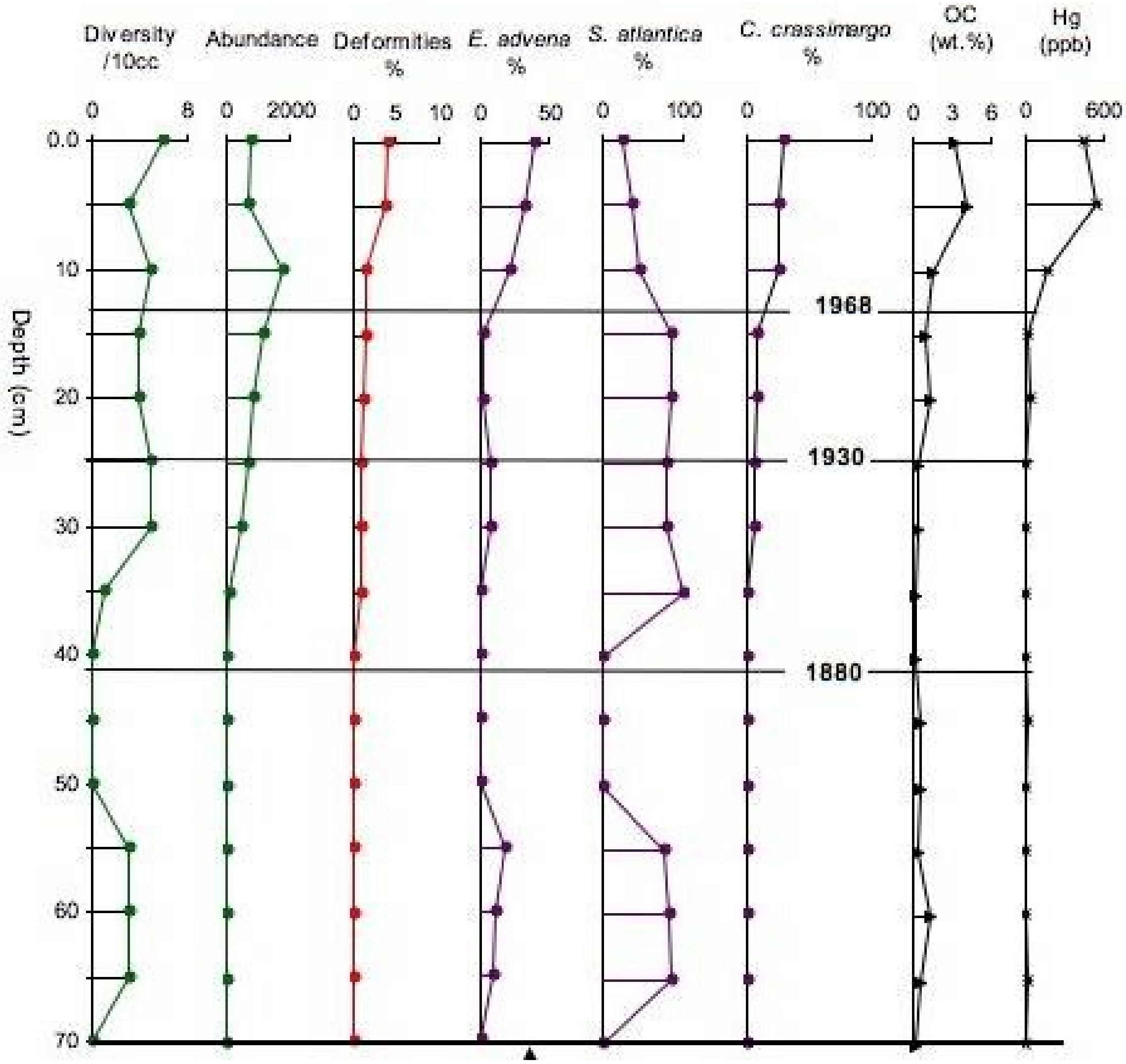

Figure 3.6: Assemblage characteristics and species distribution in core 3 (upper 70 cm only). Organic carbon and Hg data are taken from Williams (2010). The age lines are based on the sedimentation rate estimate (0.32 cm/yr) for nearby slow core 2 (Williams, 2010).

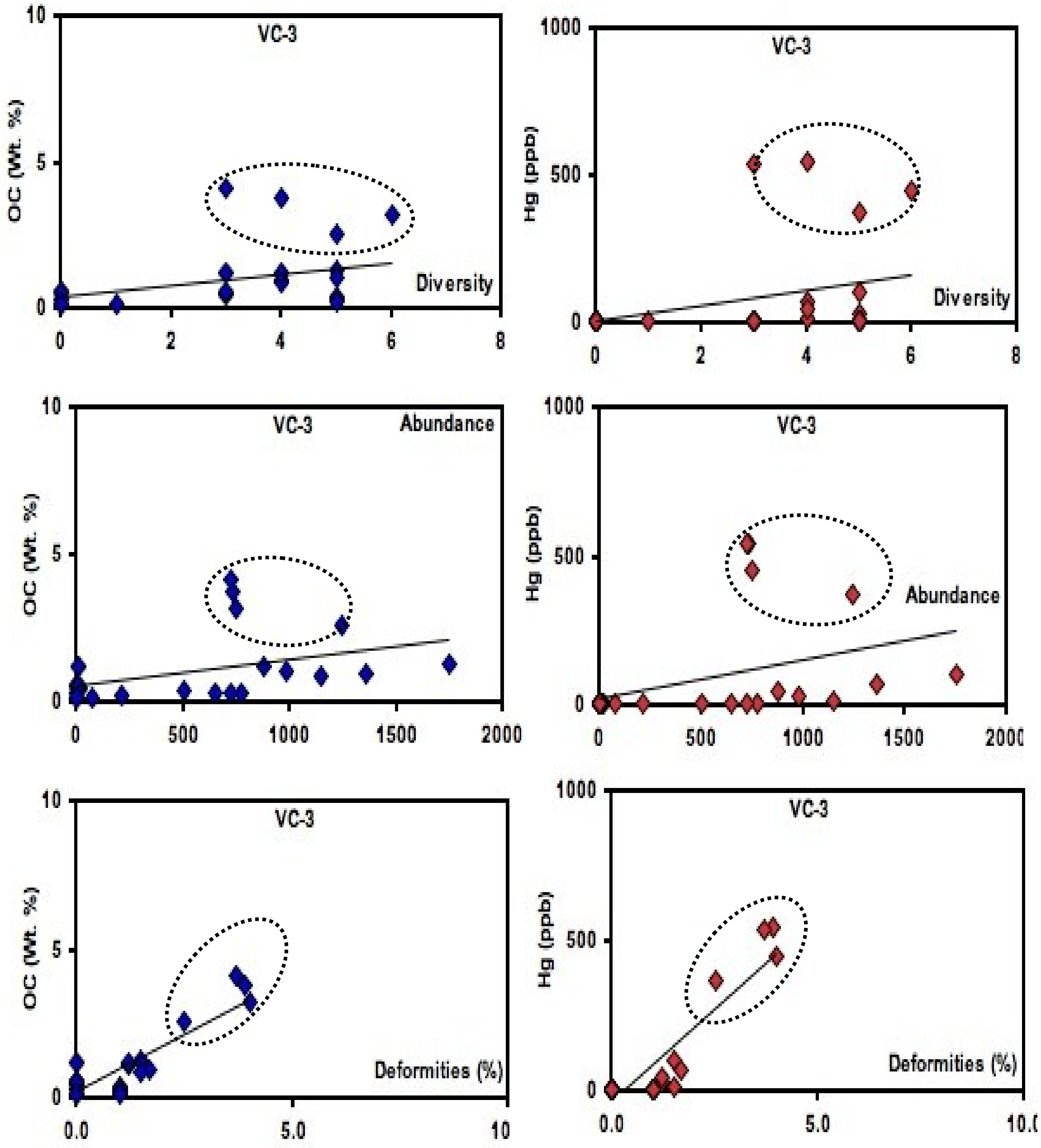

Figure 3.7: Relationships between foraminiferal proxies (diversity, abundance and deformities) and both OC (in blue) and Hg content (ppb – in red) of vibracore 3, Bedford Basin, Halifax Harbour. The chemical data are taken from Williams (2010).

3.5.5 Core 5 (Outer Harbour)

This core, 171 cm depth, was recovered from the outer harbour near Herring Cove (Fig. 3.1) in relatively unpolluted marine conditions. There are no significant changes in the foraminiferal assemblage at any depth throughout this core. Diversity and abundance values are high (27-33 species and 5,000 to 7,000 individuals per 10 cc, Fig. 3.8). Shell deformities are rare (1-2%) and remnant organic inner linings are absent. The assemblage is dominated by calcareous species with ratios that reach 90%. The most common species in the assemblage are the genus *Elphidium* that reach up to 60%. *Buccella frigida*, *Cibicides lobatulus*, *H. orbiculare*, *Quinqueloculina* spp., and *R. bulloides* morphotype *columbeinsis* together represent approximately 25% of the total abundance.

The calcareous species *H. orbiculare* shows elevated values at both ends of core 5 and lower values in the middle section of the core. Other calcareous species, such as *Cassidulina reniforme*, *Dentalina ittai*, *F. fusiformis*, and *Lagena apiopleura*, co-dominate with the aforementioned ones with limited percentages (totaling up to 10%). These species were not recorded anywhere in the cores of the inner parts of the harbour (Northwest Arm, inner harbour, and Bedford Basin) except in pre-impact sediments of core 8 in the inner harbour. The agglutinated forms reach up to 15% of the total abundance in some sections of core 5 (Fig. 3.8), where the most common species are *A. cassis*, *R. scottii*, *S. atlantica*, *S. biformis*, and *T. ochracea*. Some other species, such as *C. crassimargo* and *M. fusca*, are present in negligible percentages. Interestingly, the agglutinated species *E. advena*, which is widely recorded in Halifax Harbour, appears only between 50 and 70 cm depths and in very limited numbers (Fig. 3.8). Because chemicals have their lowest values in this core, there is no need to make comparisons between foraminifera and chemical data, as was done for other cores.

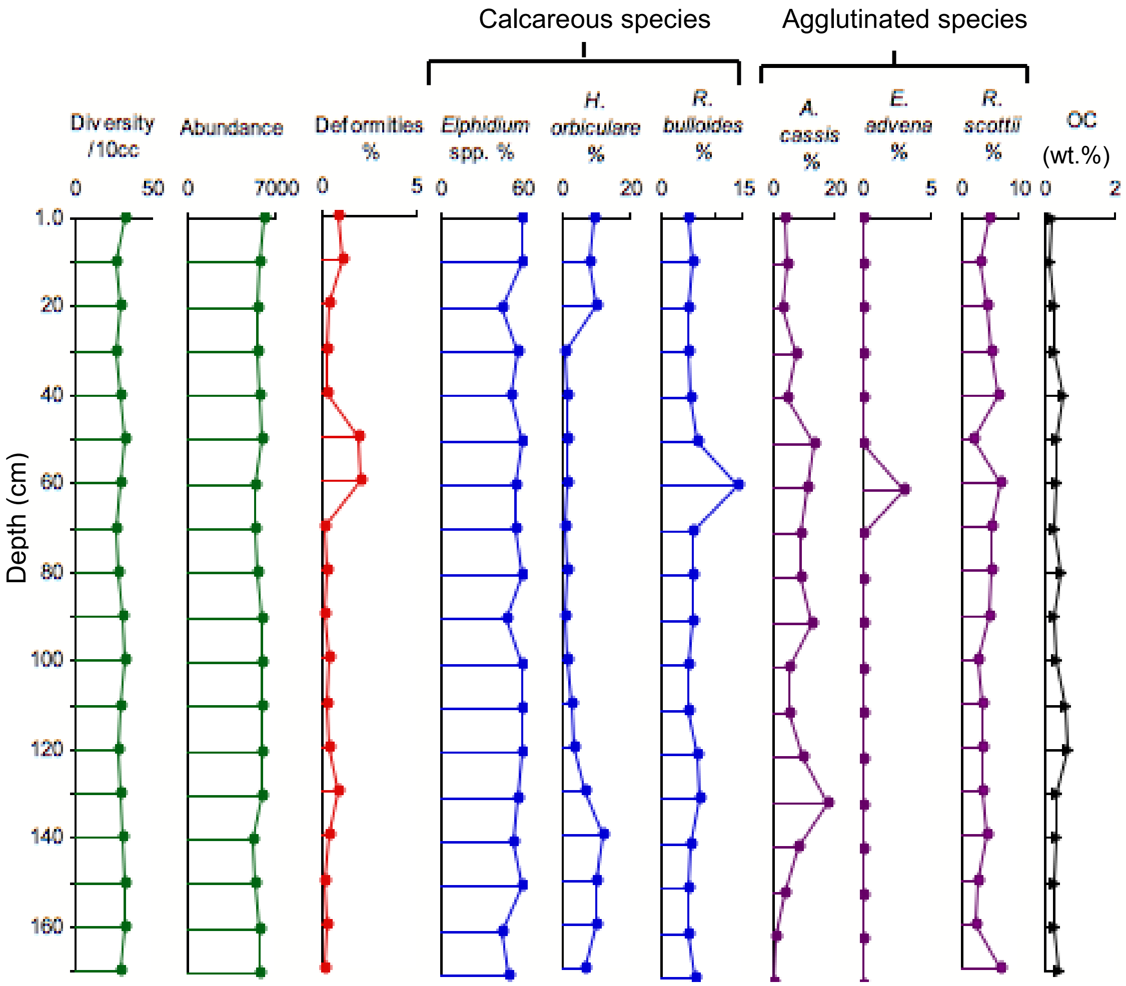

Figure 3.8: Assemblage characteristics and distribution of some species in core 5. Organic carbon data are taken from Williams (2010).

3.5.6 Core 6 (Outer Harbour, west of McNab's Island)

Similar to core 5, the foraminiferal assemblage of core 6, located west of McNabs Island (Fig. 3.1), shows high values of diversity, abundance and calcareous species, and low values of shell deformities and organic inner linings. The foraminiferal assemblage in the lower part of core 6, which extends from the base of the core to 70 cm depth, has high values in both diversity (>28 species) and abundance (>5000 individuals) and very low values in both shell deformities and organic inner linings (~4%, Fig. 3.9).

Calcareous species dominate the assemblage in that section with ratios up to ~75%. The species belonging to genus *Elphidium* dominate the calcareous assemblage with ratios ranging between 45 and 55% (Fig. 3.9). Other species, such as *H. orbiculare*, *Cassidulina reniforme*, *Cibicides lobatulus*, *Oolina borealis* and *Quinqueloculina arctica*, co-dominate the calcareous assemblage together with *Elphidium* spp. The calcareous species *R. bulloides*, morphotype *columbeinsis*, is less abundant in core 6 than in core 5. The most common agglutinated species in the assemblage are *A. cassis*, *E. advena*, *C. crassimargo*, *S. biformis*, *R. scottii*, and *T. ochracea* (Appendix 3-D).

In the upper part of the core, specifically from 70 cm to the surface, there was a slight gradual decline in the total abundance of the foraminiferal assemblage and of calcareous species. The diversity did not significantly change in this part of the core, where it ranged between 27 species at 130 cm depth to 23 species at the surface. The total abundance in this section of core 6 declined to 3,000 individuals at the surface (Fig. 3.9). Although the calcareous species still dominate the assemblage in the upper part of core 6, they become less abundant (~65 %). In addition, there is a gradual decrease to a complete absence of some calcareous species such as *Dentalina ittai*, *Lagena apiopleura*, *Oolina borealis*, and *Quinqueloculina arctica* after their last occurance at 40 cm depth (Appendix 3-D and Fig. 3.9). Shell deformities and organic inner linings, represented mainly by partially dissolved calcareous shells, increase gradually from ~4 % to reach 10 % at the surface of the core.

3.5.7 Foraminiferal trends vs. OC and Hg in Core 6

The comparisons between foraminiferal proxies (diversity, abundance, and deformities) and the chemical data (OC, Hg from Williams, 2010) show only a weak influence of these chemicals on benthonic foraminifera at this location (Fig. 3.11). The only noticeable trend is that presented by the positive relationship between shell deformities and both OC and Hg. However, this positive relationship appears in the plot in response to a minor increase in OC (from 1.69 to 2.81 Wt.%) and little noticeable increase in Hg (from 45 to 390 ppb) that appeared only in the upper 60 cm. Foraminiferal diversity and percentage of calcareous species also showed a slight inverse relation to the increase of chemicals in the upper part of this core.

Despite this slight decrease in number of both species and individuals in response to the minor increase in both OC and Hg, foraminiferal proxies are still in the high range. From the plot (Fig. 3.11), the diversity ranges between 20 and 30 while the calcareous species ranges between 50 and 80 % of the total abundance of the assemblage. Likewise, deformities that showed a positive relationship with chemicals were still restricted to the range of 8 to 12 %. The above-mentioned trends of foraminifera indicate a very limited impact of these chemicals on the environment in this location.

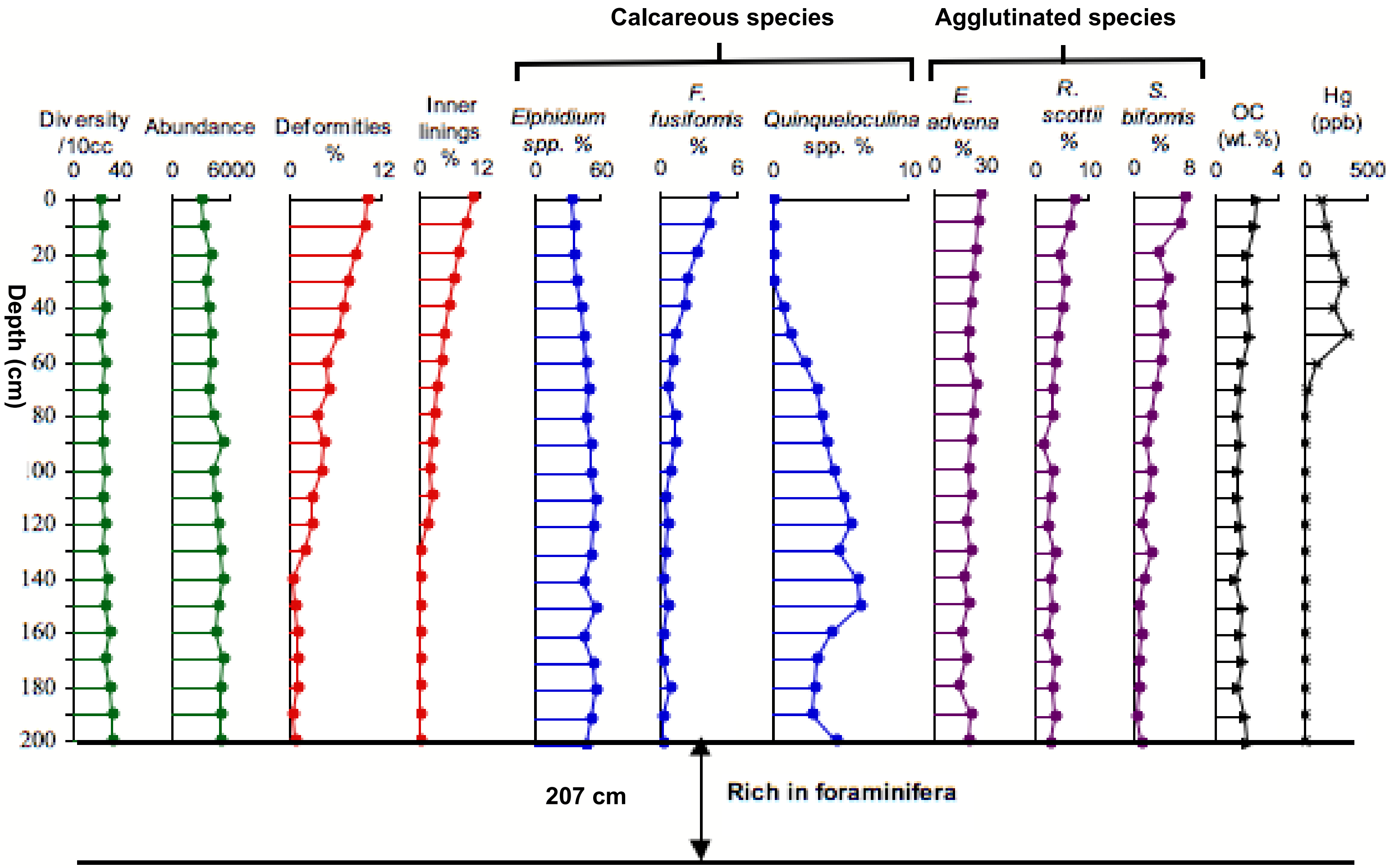

Figure 3.9: Assemblage characteristics and species distribution in Core 6 (the upper 200 cm only). Organic carbon and Hg data are taken from Williams (2010).

Figure 3.10: Photographs of vibracores 5 and 6 with some sedimentological characteristics.

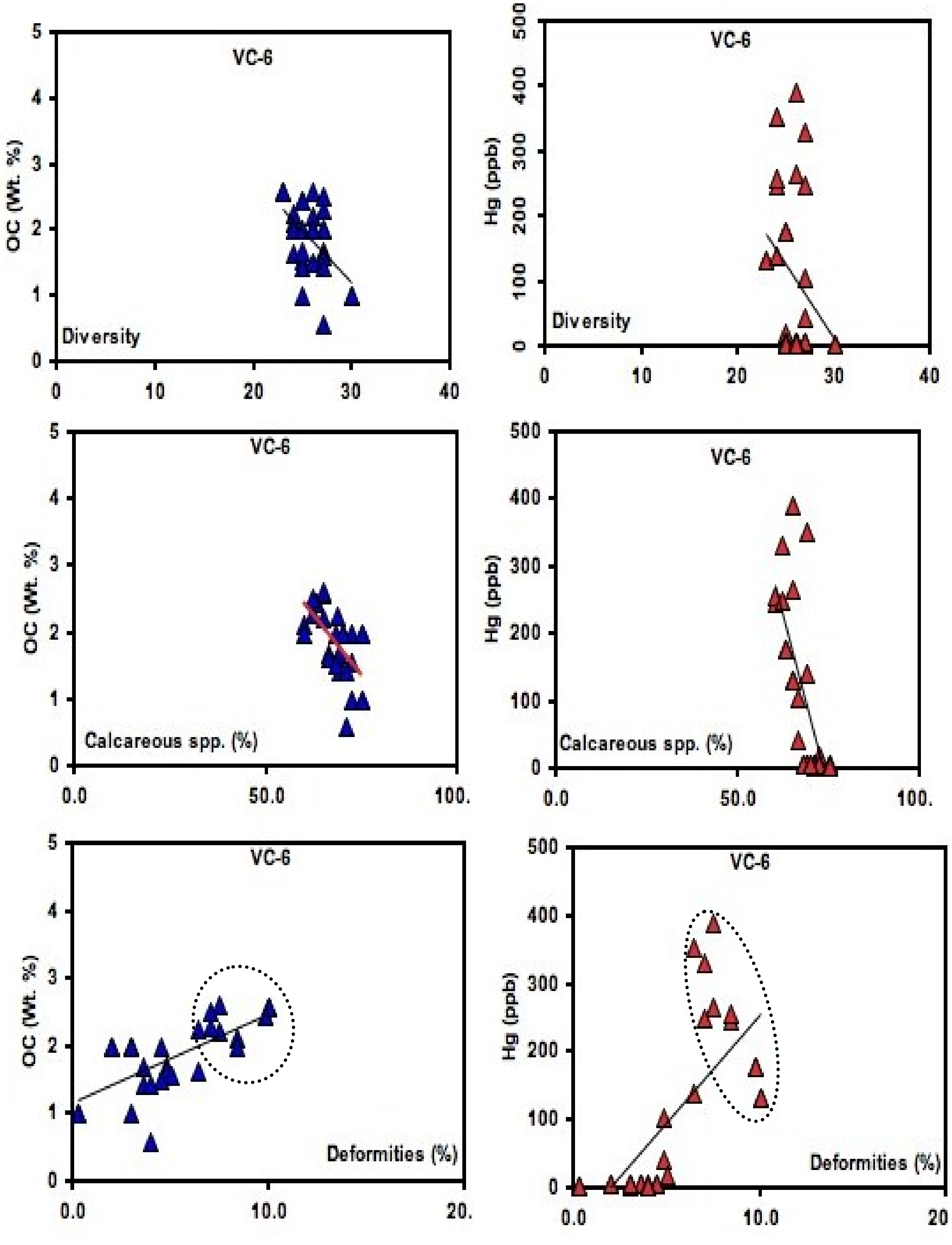

Figure 3.11: Relationships between foraminiferal parameters and both OC (in blue) and Hg (in red) of vibracore 6 from the outer harbour. The chemical data are taken from Williams (2010).

3.5.8. Core 7 (mouth of Northwest Arm)

This core was taken from a location at the mouth of the Northwest Arm where there was a large outfall that discharged around 12 ML of raw sewage per day until May 2010. The Northwest Arm is a narrow, shallow inlet where the currents coming from the ocean have little effect on the bottom sediments (Fader and Winters, 2008). In the lower part of this core (from the bottom of the core to 220 cm), where organic carbon is relatively scarce (Williams, 2010), the foraminiferal assemblage has a very low diversity (only 2 species) and abundance (< 350 individuals). The agglutinated species *T. ochracea* dominate the assemblage with relative abundance up to 70%, followed by *E. advena* with values that may reach up to 40% (Fig. 3.12). From 220 cm to the surface of core 7, the diversity was 8-10 species per 10 cc and total abundance was less than 1,000 individuals per 10 cc. Calcareous species are recorded only at three depths (200, 170-180, and 70 cm), with total ratios of 30% (Fig. 3.12). The percentage of *T. ochracea* decreased gradually from 58 % at the bottom to < 5% at the surface of this core. Likewise, *E. advena* decreased gradually to reach ~20% at 30 cm depth then increased to become the most dominant species in the upper 20 cm, with values up to 80% (Fig. 3.9). Shell deformities reached ~10-15% between 190 and 70 cm depths. Organic inner linings also increased gradually but did not reach such high values. In the upper 70 cm, there were many peaks of extreme ratios of shell deformities and inner linings (~37.5% for deformities and ~50% for inner linings), with a noticeable decrease at 40 cm depth (Fig. 3.12).

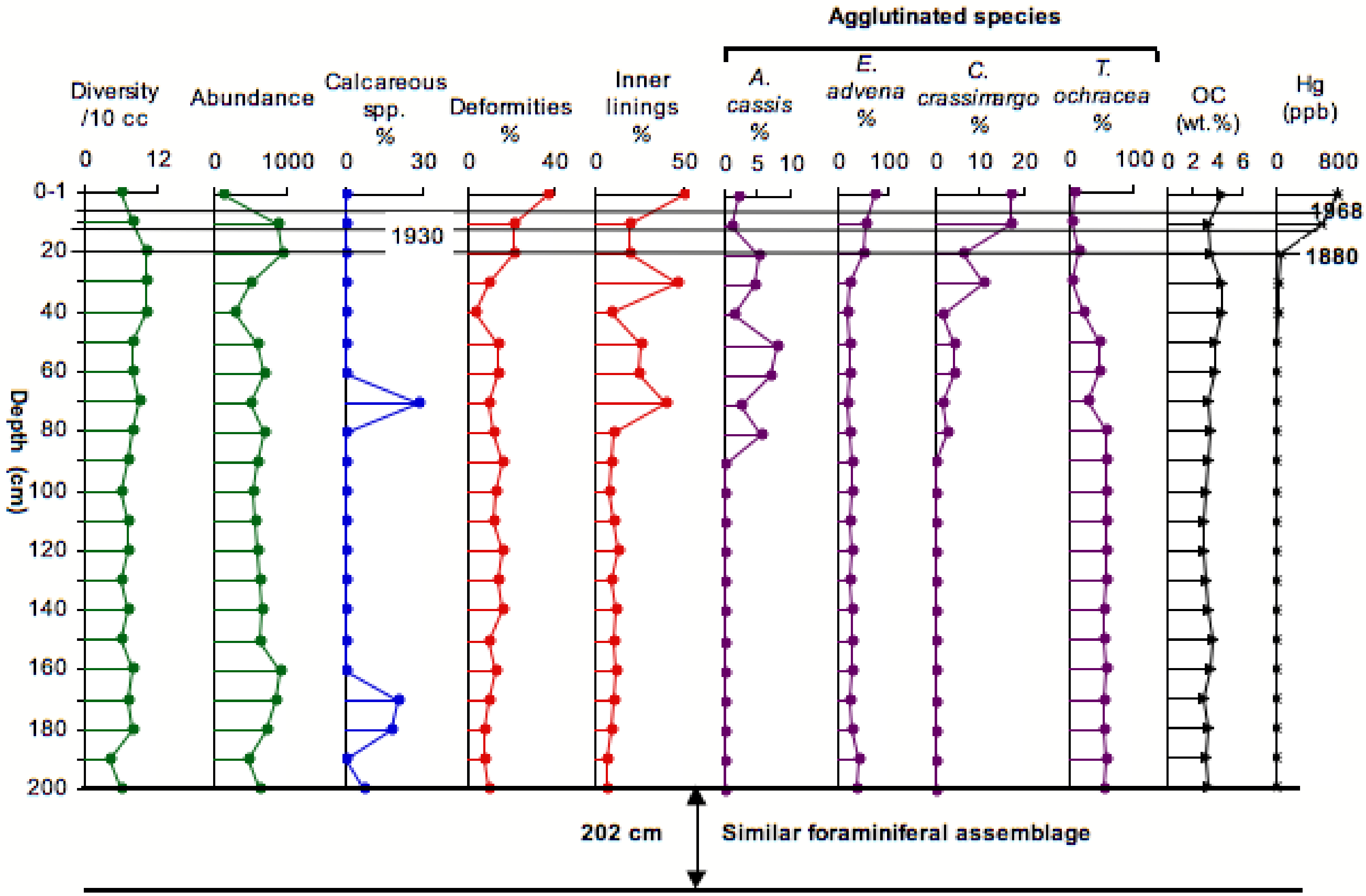

Figure 3.12: Assemblage characteristics and distribution of common species along Core 7. Organic carbon and Hg data are taken from Williams (2010). Age lines are based on the estimated sedimentation rate (<0.21 cm/yr. Table 3.1) of slow core 8 of Williams

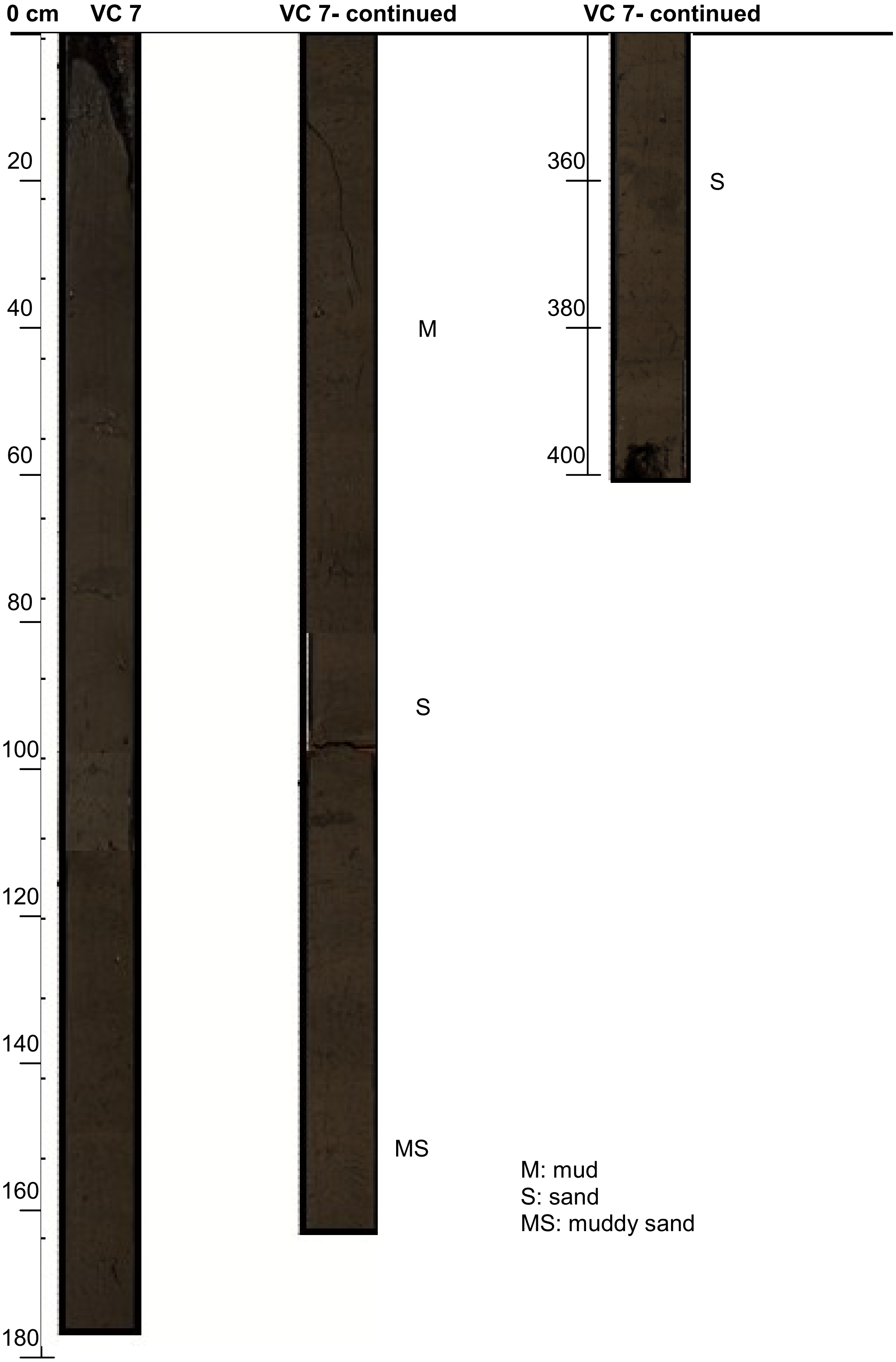
0 cm
VC 7
VC 7- continued
VC 7- continued
20
40
60
80
100
120
140
160
180
M
S
MS
360
380
400
S
M: mud
S: sand
MS: muddy sand

Figure 3.13: Photographs of vibracore 7 with some sedimentological characteristics.

3.5.9 Foraminiferal trends vs. OC and Hg in Core 7

Plots of foraminiferal proxies (diversity, abundance, and shell deformities) versus the available chemical data (OC, Hg-from Williams, 2010) for vibracore 7 (Fig. 3.14) indicate that benthonic foraminifera have no strong relationship with the amount of organic carbon (Fig. 3.14-blue coloured plots) in the sediments of that core. The relatively constant values of OC (~ 4 wt.%) throughout the core strongly suggest that other environmental parameters are controlling the observed variability in foraminiferal parameters. The increase in Hg from 340 to ~800 ppb throughout the upper 20 cm of the core seems to have only a small impact on benthonic foraminifera (Fig. 3.14 – the red-coloured plots). This impact appears in the inverse trend of diversity (the highlighted 4 dots in the plot) and the positive relationship of shell deformities with Hg. However, the trend of shell deformities is not obvious in uncontaminated sections of the core.

At some depths (between 90 and 145 cm), the deformities have high ratios (up to 16%) where Hg values are very low (<10 ppb). Such an increase of shell deformities where there is no noticeable increase in chemicals (Fig 3.14 – highlighted with a solid line) may be related to adverse natural environmental conditions. The general trends of foraminifera in this area indicate that metal contaminants have more influence than OC.

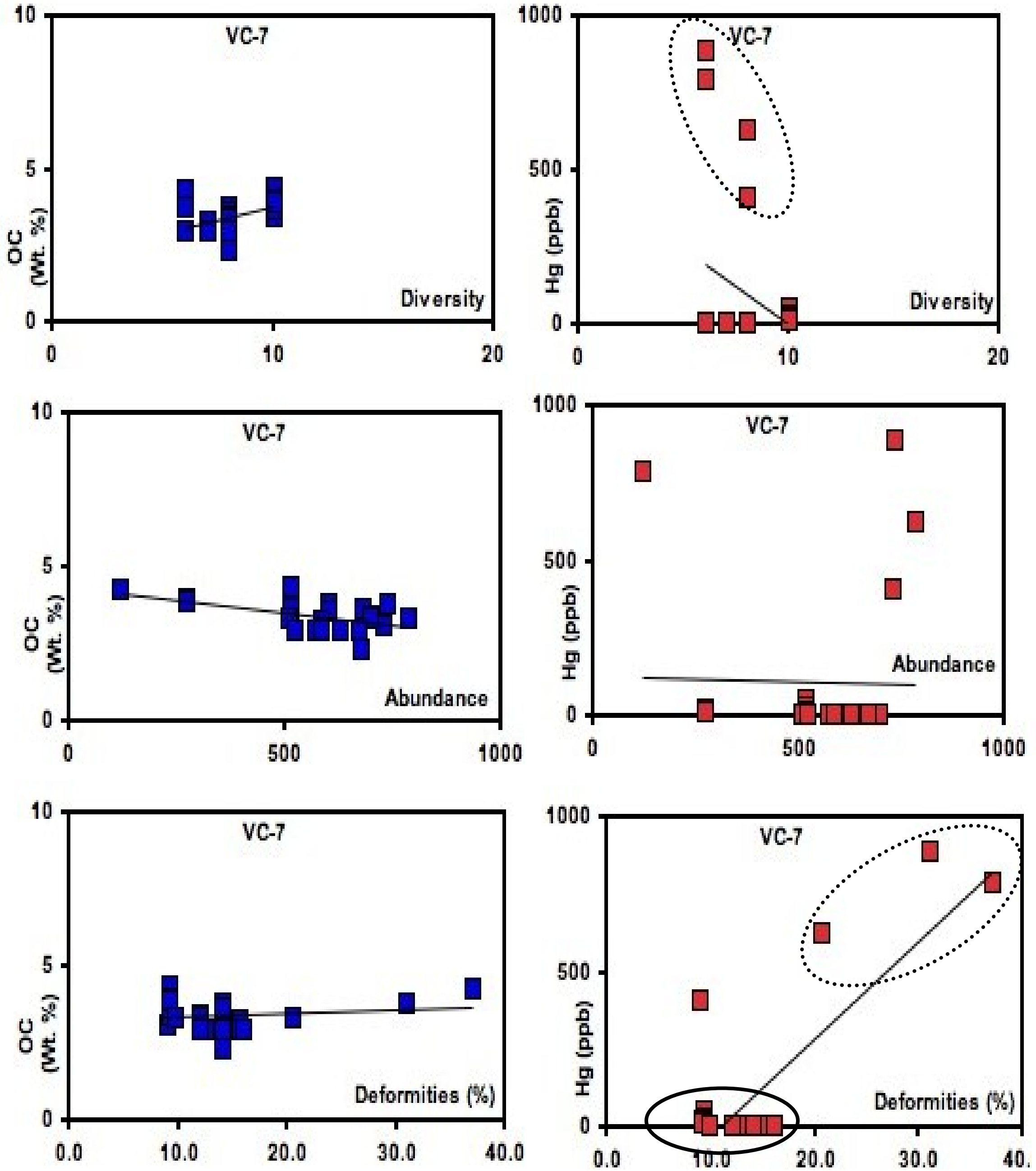

Figure 3.14: Relationships between foraminiferal parameters and both OC (in blue) and Hg (in red) of vibracore 7 from the Northwest Arm, Halifax Harbour. The chemical data are taken from Williams (2010). The dashed highlighted dots with dash lines show

correlations between foraminiferal proxies and Hg, while the dots highlighted with a solid line shows foraminiferal proxies that may be related to adverse natural conditions.

3.5.10 Core 8 (inner harbour, off of the Halifax waterfront)

Core 8 is located on the Halifax side of the central part of the harbour. This area is the most polluted part of HH because it represents the centre of both downtown Halifax and Dartmouth and previously received more than two-thirds of the waste materials that were discharged into the harbour. The analyzed part of core 8 for foraminiferal proxies is only 140 cm, whereas the total length of the core is 360 cm. The general trend of the foraminiferal assemblage in this core records a clear environmental change from normal marine conditions at 140 cm core depth to strongly polluted conditions at the surface.

The lower zone of the analyzed part, extending from 140 cm to 108 cm, is characterized by high diversity (25-30 species), total abundance (4,500 to 5,000 individuals), and dominance of calcareous species (~90%). The calcareous species, such as *Elphidium* spp., *Quinqueloculina* spp., *Cibicides lobatulus* and *Dentalina ittai*, dominate the assemblage, while the agglutinated ones, such as *A. cassis*, *E. advena*, *R. scottii* and *S. biformis*, are rarely observed (<10%). Both shell deformities and organic inner linings are absent in this zone (Fig. 3.15).

The zone extending from 107 to 75 cm in core 8 has a gradual upward decrease in most of the parameters of the foraminiferal assemblage. The diversity decreased from ~27 species at the bottom (105 cm depth) to ~20 species at the top (75 cm depth) of this zone (Fig. 3.15). Likewise, the total abundance decreased from ~4000 to ~2000 individuals per 10 cc, and calcareous species from ~60% to <30% upwards throughout the zone (Fig. 3.15). On the other hand, the opportunistic species *E. advena*, *C. crassimargo*, *R. scottii* and *S. biformis* gradually increased to predominate the assemblage, with a total content of ~70% at the zone's top (Appendix 3-F, Fig. 3.15). Additionally, at the very top of this zone (at 75 cm depth), shell deformities reached values of ~8% and organic inner linings reached values of ~10% (Fig. 3.15).

In the zone extending between 75 cm and 55 cm there was a greater decrease in both diversity and total abundance and an increase in shell deformities, organic inner linings, and relative abundance of the opportunistic agglutinated species. The number of species decreased from 20 to 15 species per 10 cc, and the total abundance declined from ~2000 to ~1000 individuals per 10 cc upwards (Fig. 3.15). The relative amounts of calcareous species decline from ~25% at the bottom to <10% at the top of the zone.

The calcareous species belonging to the genus *Quiqueloculina* disappeared completely in this zone at a depth of 65 cm. In contrast, the agglutinated species continuously increase to dominate the assemblage, specifically in the upper 10 cm, where their ratios reach up to 65%. In addition, shell deformities increased from ~8% at the bottom (75 cm) to ~13% at the top (55 cm) of the zone. Similar findings occured with organic inner linings, which increased from ~4% at 75 cm depth to ~10% at 55 cm depth (Fig. 3.15).

In the upper zone in core 8, from 55 cm to the surface, the diversity continuously decreased to reach 12 species per 10 cc at the surface, whereas the total abundance did not change significantly. The calcareous species completely disappeared at a 45 cm depth, while the organic inner linings of their tests reached ~16% and the agglutinated species *C. crassimargo*, *E. advena*, *R. scottii*, and *S. biformis* dominated the assemblage in this zone (Figs. 3.15).

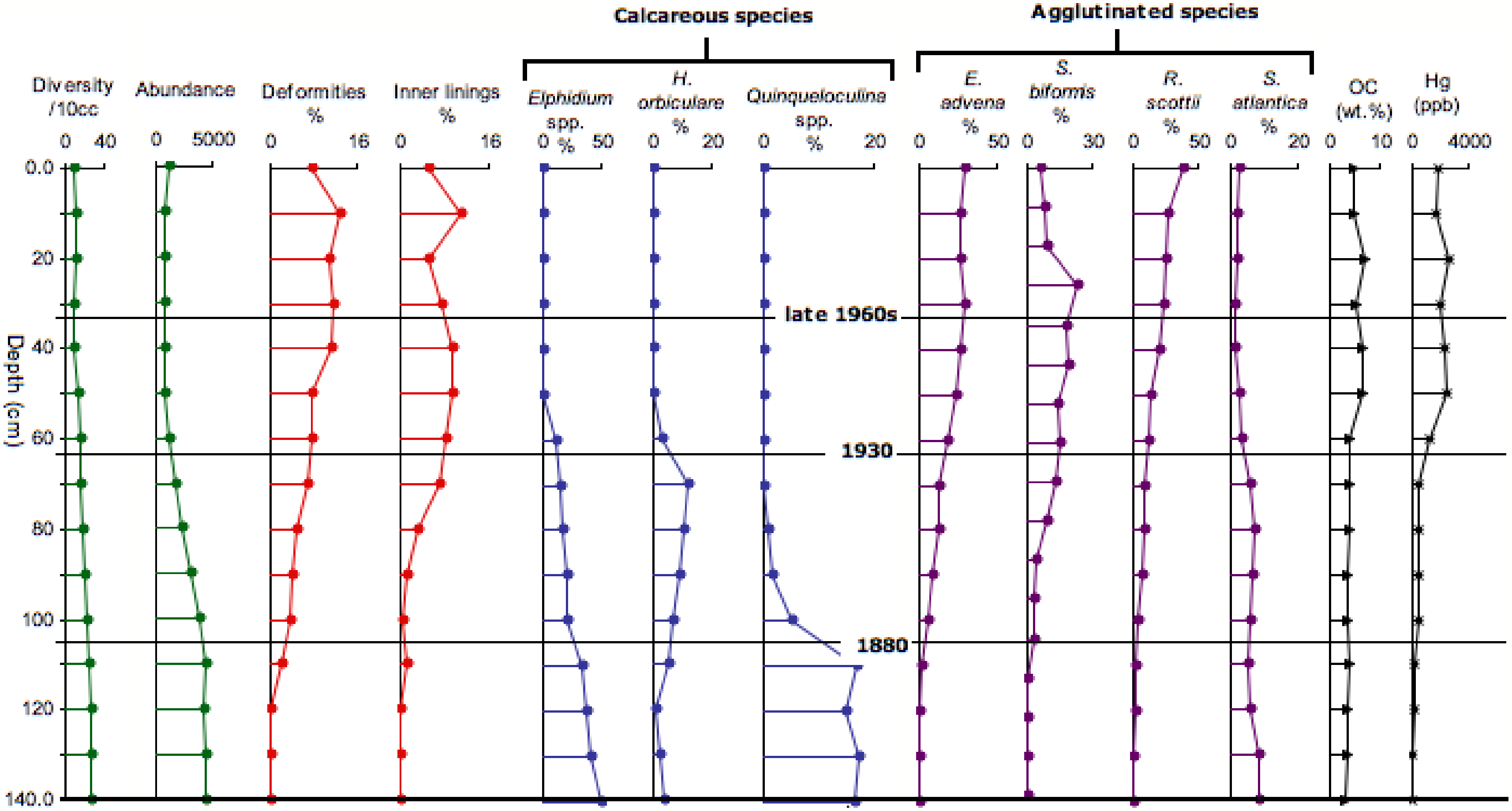

Figure 3.15: Assemblage characteristics and distribution of common species along Core 8 (the upper 140 cm only). Organic carbon and Hg data are taken from Williams (2010). Age lines are based on the mean sedimentation rate (0.82 cm/yr) for the estimated rates of cores 30 (0.90 cm/yr) and 32 (0.74 cm/yr) of Buckley et al.. (1995. Table 3.1).

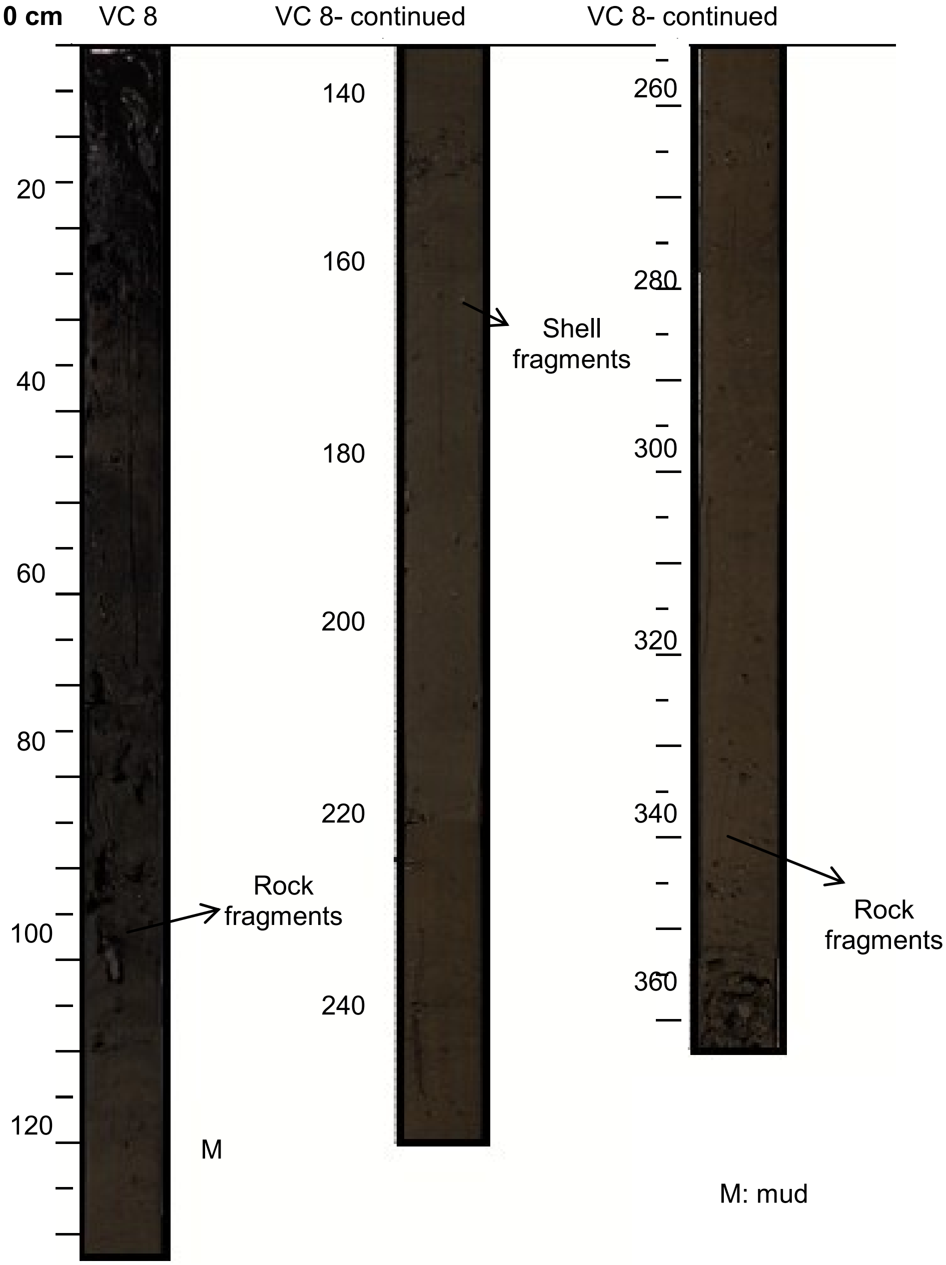

Figure 3.16: Photographs of vibracore 8 with some sedimentological characteristics.

3.5.11 Foraminiferal trends vs. OC and Cu, Pb, Zn metals in core 8

Comparisons between foraminiferal proxies (diversity, percentages of calcareous species, and shell deformities) and the available chemical data (OC, Cu, Pb, Zn-from Williams, 2010) for vibracore 8 (Fig. 3.17) indicate that benthonic foraminifera in that core have a strong correlation with both OC (Fig. 3.17 – blue-coloured plots) and metals (Fig. 3.17 – red-coloured plots) in the sediments. This correlation is represented by a positive relationship of deformities and an inverse relationship of both diversity and calcareous species with the OC and metal concentrations along core 8. The trends indicate the combined influence of both OC and metals on foraminiferal proxies. This coincides with the increase of values of both OC (from <5 to ~8 wt.%) and metals (from <300 to >700 ppm) in the upper 60 cm of the core.

Nothing in the trends supports one or more of the chemicals having a stronger influence on foraminifera than any other. In contrast, many signals indicate a comparable impact of both OC and metals on foraminifera. For example, samples that have the lowest values of both OC and metals have the highest foraminiferal diversity (Fig. 5.17 – dots highlighted with dashed lines) and the lowest percentage of calcareous species (Fig. 5.1 – dots highlighted with solid lines). It is important to note that this trend of foraminiferal proxies may not be the same in all proxies and at all depths. For example, there are three to four points in the deformities trend that have the highest values in chemicals (Fig. 5.17 – dots highlighted with solid green lines) while the deformities are slightly less than other samples of lower chemicals. These abnormalities in the trends may suggest that other environmental parameters (e.g., salinity, substrates, pH) could also have some impact on benthonic foraminifera in this area.

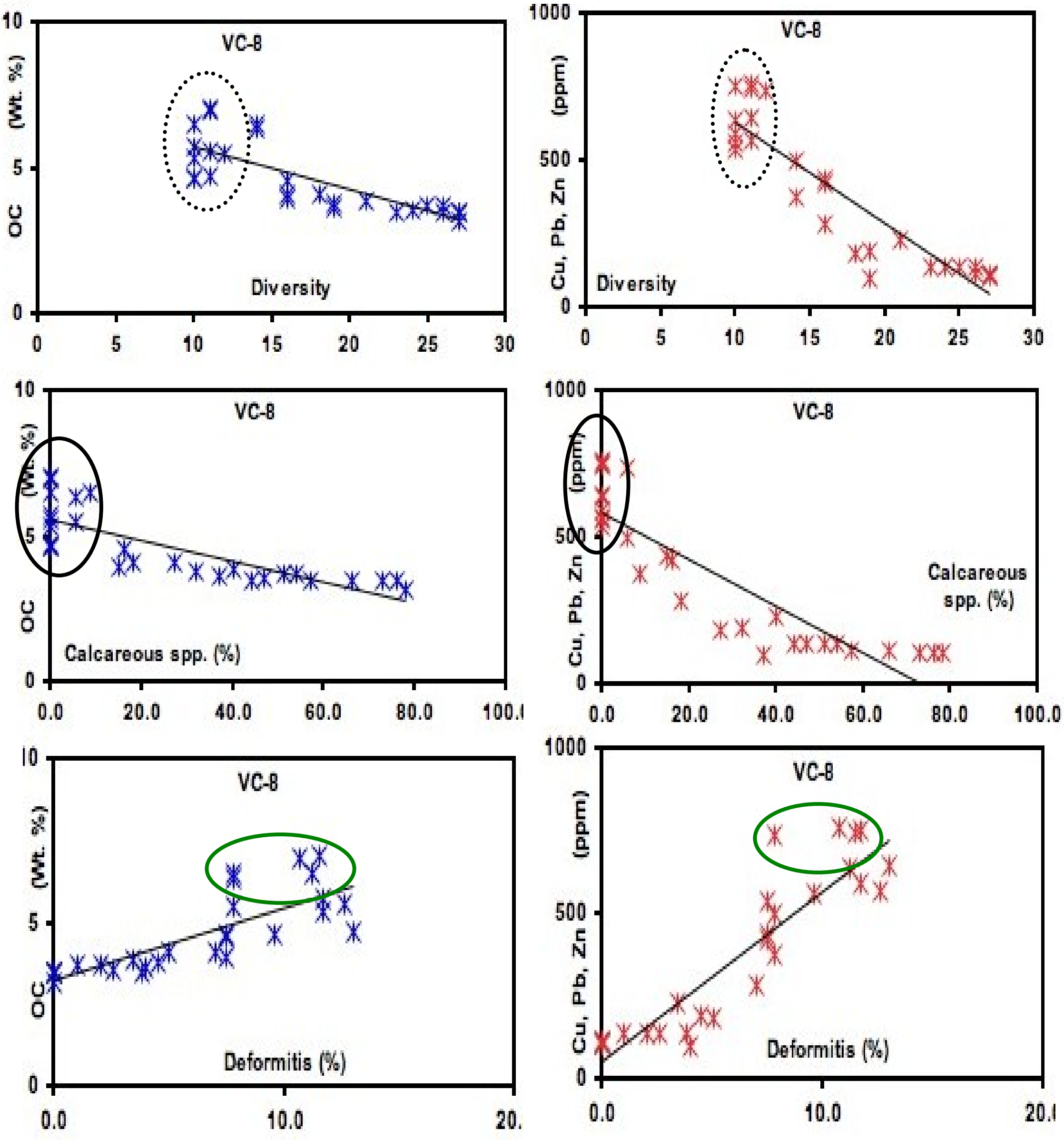

Figure 3.17: Relationships between foraminiferal parameters and both OC (in blue) and total Cu, Pb, and Zn content (in red) of vibracore 8. The chemical data are taken from Williams (2010).

3.6 Discussion

3.6.1 Core 2

The low diversity and abundance along with the rare presence or complete absence of calcareous foraminifera in vibracore 2 from Bedford Basin corroborate the results from surface grab samples that were examined over a two-year period for short-term monitoring purposes (Chapter 2). These low values of foraminiferal proxies may be due to dilution with very high amounts of silty and fine sandy sediments originating from the freshwater runoff from the Sackville River and other rivers that drain into the basin from its northern end and surrounding areas.

The presence of a thick (85 cm) yellow-to-white and fine-to-coarse sand layer barren of any foraminifera at the bottom of this core may indicate freshwater deposition. However, we did not notice any freshwater ciliates in the 45 μm fractions of the samples investigated from this layer. The presence of the sand layer below a 25 cm thick peat layer without any intercalations of sediments that have marine fauna may support the fresh water origin of this sand layer. Shaw et al. (1993) pointed out that fresh water and estuarine sediments that formed on the inner shelf of Nova Scotia were deposited during the early Holocene transgression along the Atlantic coastline of Nova Scotia, 8,000 to 6,000 years BP. Although we do not have age dates for the peat layer, it is most likely 5.5 to 6.0 thousand years old, if compared to other records of similar layers in the area. Miller et al. (1982a) dated a layer containing a brackish-to-freshwater faunal assemblage from a 5 m long piston core from Bedford Basin to be 5,830± 230 years BP. Shaw et al. (1993) indicated that the sea water overtopped the sill of Bedford Basin 5,830 BP. If the basin was invaded by the sea at 5,830± 230 years BP, the peat layer and the sediments below were deposited prior to that date. The appearance of benthonic foraminifera above the peat layer indicates a rise in sea level and a marine environment. The predominance of the agglutinates and near absence of calcareous species above the peat layer may be interpreted as shallower conditions that were not favorable for calcareous foraminifera.

Based on the estimated sedimentation rate (0.26 cm/yr) by Williams (2010) for her slow core 1, located 10 m apart from vibracore 2, the lost part (upper 22 cm) of vibracore 2 represents the last 85 years (from 1923 to 2008) of sedimentation in the area. Based on this, any strong contamination-related changes in foraminiferal assemblage (e.g., high ratios in deformities and inner linings) are not expected to be present in the recovered part of vibracore 2. However, the inner linings and shell deformities of foraminiferal assemblage increased substantially from 22 cm to ~62 cm corrected depths (Fig. 3.3). Mercury values (127-242 ppb) corroborate this in the upper 13 cm (from 23 cm to 35 cm corrected depth). The presence of these high values in both the foraminiferal deformities and Hg indicates that the sedimentation rate in this location is higher than the estimated one (0.26 cm/yr). This is likely because of the close proximity of this location to a main outfall affecting this area. Further evidence is provided by the presence of about 30-40 cm of black mud at the top of the core, which presents the severe organic enrichment in the area in the second half of the twentieth century. For that reason, if there were funds available, we would suggest making ^{14}C dates at 62 cm and 208 cm corrected depths in vibracore 2. The first depth point (62 cm) would be chosen because of the significant change of foraminiferal assemblage, and the second depth point (208 cm) because of the peat layer.

Scott et al. (2005) studied two short (22 and 60 cm) sediment cores close to our vibracore 2 from Mill Cove and pointed out that *A. cassis* and *R. scottii* dominate the assemblage and that the calcareous species are completely absent from the assemblage of the surface and near the surface of their cores. In addition, they recorded calcareous shells in the lower 10 cm of their longer (60 cm) core and suggested that the level containing calcareous species in their core is equivalent to Gregory's (1971) late 1960s samples. Furthermore, Scott et al. (2005) emphasized that the sedimentation rate in this area could be much greater than that estimated by Buckley et al. (1995) due to its proximity to the sewage outfall. The foraminiferal assemblage in our vibracore 2 is similar (agglutinated dominated, low diversity and abundance) to that of Scott et al. (2005), except for the absence of calcareous species in our core. That may be related to a stronger fresh water effect on our vibracore 2 site.

3.6.2 Core 3

The presence of sandy sediment that is completely barren of any foraminiferal content and similar to that at the bottom of core 2 but in greater thickness (~201-cm-thick) suggests that freshwater conditions persisted for a longer duration or that more sediment accumulation near core 3. The limited representation of benthonic foraminifera in core 3 can be related to a strong freshwater runoff rather than pollution effects. The complete absence of calcareous foraminifera and their organic inner linings from the fossil record of core 3 indicates unfavorable conditions for calcareous species to survive. The assemblage can be described as the *S. atlantica* assemblage because of the great abundance (~95 %) of this species in the assemblage. Gregory (1971) pointed out that *S. atlantica* attains its highest ratios (~23%) throughout Halifax Harbour in Bedford Basin. He also mentioned that the distribution of *S. atlantica* forms a near-shore girdle around the central deeper parts of the basin.

The gradual decrease of diversity and the gradual increase of both shell deformities and the ratios of the opportunistic species *E. advena* in the upper 13 cm may indicate impact conditions in the area. The analyses of Williams (2010) indicated a significant increase in OC and mercury concentrations in this part of vibracore 3 (Fig. 3.5). According to the sedimentation rate of 0.32 cm/yr, estimated by Williams (2010) for nearby slow core 2, the upper 13 cm represent the last 40 years. In this part (upper 13 cm) of vibracore 3, changes in the foraminiferal assemblage correlate with the results of OC and Hg data of Williams (2010).

3.6.3 Core 5

The foraminiferal assemblage in core 5, located near Herring Cove in the outer harbour, reflects the open ocean nature of this part of the harbour. This setting can be inferred from the consistently high values of diversity (25 to 35 species per 10 cc) and abundance (~7000 individuals per 10 cc), and the apparent predominance of calcareous taxa (~90%) in the foraminiferal assemblage throughout the core. Foraminifera in surface grab samples, collected close to the location of core 5, indicate normal marine conditions for this section of HH (Chapter 2). Gregory (1971) recorded very high diversity (25-40 species) and abundance (>7500 individuals) in surface samples in the outer harbour and highlighted that these high values are restricted only to this part of HH. Gregory (1971) interpreted these results as the preference of these species to offshore deeper waters.

3.6.4 Core 6

Although core 6 is located to the west of McNabs Island in the inner part of the outer harbour and receives much less pollution compared to the inner parts of HH, the foraminiferal assemblage clearly outlines an environmental change from no pollution to a low pollution rate along the core (Fig. 3.7). The diverse number of foraminiferal species

(>29) and the abundant number of individuals (~5000) in the lower 325 cm of the core are indicative of an unpolluted marine environment. The similarity between the faunal content of the lower part of core 6 and that of core 5 indicate similar environmental conditions.

Although the decline in foraminiferal assemblage in the upper part of core 6, from 70 cm to the surface, is not as dramatic as noted in cores further inside the harbour, it indicates a gradual slight enrichment of organic material in the area. This coincides with the increase of both shell deformities and organic inner linings from <5% to ~10 % in this section of the core. That may also explain the gradual decline to complete disappearance of some calcareous species that tolerate only normal marine conditions, such as *Dentalina ittai*, *Lagena apiopleura* and *Quinqueloculina arctica*. Gregory (1971) recorded very high diversity (25-30 species) and abundance (>3500-4000 individuals) in surface samples close to the location of this core. We have correlated his results to our foraminiferal records and put a line marking the late 1960s at 40 cm depth in core 6.

Buckley et al. (1995) studied 27 short gravity and box cores throughout Halifax Harbour to reconstruct the metal contamination history in the area. Although they did not date the cores that are located close to our vibracore 6, east of McNabs Island, they pointed out that these cores are relatively uncontaminated compared to other areas throughout the Harbour. This is consistent with our observation that there was only a slight decline in the foraminiferal assemblage of the upper 70 cm in this core. Williams (2010) recorded a slight increase in the OC and a dramatic increase in mercury in this part of the core (Fig. 3.7).

3.6.5 Core 7

The limited numbers in species (2/10 cc) and individuals (<350/10 cc) throughout the lower part of this core (from 390 cm to 220 cm) may be related to the shallow depths that characterize the Northwest Arm (Fig. 3.9). The dominance of *T. ochracea* in this part of the core (~ 70%) indicates a transitional marsh environment (Tobin et al., 2005). Additionally, the three records of calcareous species (at 190, 160-170 and 70 cm depths) may indicate periods of increased water depth and more favorable conditions for the preservation of calcareous shells, while the high percentages of shell deformities (20-40%) and inner linings (~50%) towards the surface of the core may reflect increased contaminant input to the environment. This may also explain the increase in the relative abundance of agglutinated species *E. advena* that is known to be common in areas affected by high amounts of waste discharge (Watkins, 1961; Clark, 1971; Schafer and Cole, 1974; Bates and Spencer, 1979; Alve and Nagy, 1986; McGann et al., 2003; Scott et al., 2005).

Gearing et al. (1991) estimated an accumulation rate of about 0.2-0.3 cm yr^{-1} for a core midway down the Northwest Arm. Buckley et al. (1995) estimated a similar accumulation rate (0.21 cm yr^{-1}) for one sediment core from the central part of the Arm. On the other hand, Williams (2010) estimated a sedimentation rate of about (<0.2 cm yr^{-}) for a slow core (slow core 8) in the same location as the vibracore 7 at the mouth of Northwest Arm. Based on Williams (2010), the upper 20 cm represent a record of the contamination in the area since the late nineteenth century. The Hg results of Williams (2010, Fig. 3.9) show that concentrations increased rapidly during this time, from 58 ppb at 21 cm to 794 ppb at the surface. However, the OC values remained consistent (~3.3-4.3 wt.%) throughout the upper 200 cm of the core.

The high percentage of both deformities and inner linings (~20%) in depths below 20 cm is an anomaly that may be related to sediment disturbance that took place in this area. Gearing et al. (1991) emphasized that sampling of sediment cores for reconstruction purposes is more recommended in the central part of the Arm, which has either no or at least much less sediment disturbance than the mouth of the Arm, the latter which has significant ship traffic and bioturbation. Williams (2010) mentioned that the ^{210}Pb profile of the slow core that she dated from the mouth of the Northwest Arm indicated sediment disturbance and mixing in this area. She attributed this to Hurricane Juan, which struck Halifax in September 2003. This interpretation may be applicable to explain disturbances in the surface or near-surface sediments but not at 20 cm depth. The estimated age dates make it is very difficult to relate these high ratios in both deformities and inner linings at 20 cm (~ 200 years ago) to contamination. So, the presence of shell deformities and organic inner linings in deep parts of the core could be related to any variation of other natural environmental parameters. It is important to notice that comparing the Hg and OC data of the vibracore 7 and the nearby slow core 8 of Williams (2010) showing a significant difference in the values of Hg in the top 10 cm of both cores. The very short distance (few meters) between the two cores (VC7, slow core 8-Williams, 2010) make the understanding of this difference very difficult and could be arged that there was a sediment loss at the top of core 7. Furher examination of these cores should take this discrepancy into account to verify if there was any loss in VC 7 during the vibracoring process or not.

3.6.6 Core 8

The faunal content of core 8 (Fig. 3.11) shows an environmental zonation ranging from a natural (un-impacted) environment at the bottom to a strongly sewage-impacted environment at the top. Natural marine conditions are clearly evident from a 140 to 108 cm depth in the core because of its high diversity (25-30 species), total abundance (4500-5000 individuals), and abundance of calcareous species (80-90%). The presence of some calcareous species that prefer open ocean environmental conditions with sandy substrates rather muddy organic ones (such as *Cassidulina reniforme*, *Cibicides lobatulus*, *Dentalina ittai* and *Quinqueloculina arctica*) strongly correlates the above-mentioned interpretation. The parameters of the foraminiferal assemblage in this zone are, to a degree, similar to those recorded in the surface samples in the outer harbour in the two-year period between October 2007 and July 2009 (Chapter 2). Thes characterestics allow us to confidently consider this zone as the pre-impact environment for this part of the harbour.

The foraminiferal assemblage between 107-75 cm in core 8 shows a gradual upward decrease in diversity (from ~27 to ~20 species), total abundance (from ~4000 to ~2000 individuals), and percentages of calcareous species (from ~60% to <30%). In contrast, the assemblage in this part of the core witnessed a gradual increase in values of agglutinated species, shell deformities (~7%), and organic inner linings (~10%). The foraminiferal assemblage throughout this part of core 8 marks the beginning of pollution in the area and suggests a gradual increase of organic matter in the environment.

The continuous decline of diversity (from ~20 to ~12), total abundance (from ~2000 to ~1000 individuals), and percentages of calcareous species (from <29% to <10%) between 75-55 cm depths in the core indicates a continuous increase of organic flux in the area. That can be inferred also by the continuity of increase in the calcareous inner linings (from ~4% to ~10%), shell deformities (from ~8% to ~13%), and relative abundance of the opportunistic species (>30%). The pollution causes a development of agglutinated species in the assemblage throughout sediment cores (Alve, 1995b; Nagy and Alve, 1987; Scott et al., 2001, 2005). The disappearance of calcareous species belonging to the genera *Quinquloculina*, *Lagena*, *Pyrgo*, *Fissurina*, *Oolina* and *Cibicides* recorded in the lower sections of the core (leaving only other calcareous species such as *E. excavatum*, *B. frigida*, *H. orbiculare* and *F. fusiformis* that can tolerate the presence of organic matter/pollution at a certain level) indicates a dramatic environmental change from normal marine to an organic-rich environment. *Elphidium excavatum*, *B. frigida*, *H. orbiculare* and *F. fusiformis* can tolerate only low to medium levels of organic pollution, indicating that this zone of core 8 is a moderately polluted environment.

The changes that characterized the foraminiferal assemblage in the previous part of core 8 continued throughout the rest of core 8 (50 cm to the surface) to develop an absolute agglutinated assemblage with low ratios of both diversity (~8 species) and abundance (~800 individuals) with high ratios of shell deformities (12-16%) and organic inner linings (~16%). According to the mean (0.82 cm yr^{-1}) of the estimated sedimentation rates (0.74 and 0.9 cm yr^{-1}) of Buckley et al. (1995) for two nearby sediment cores (cores 30 and 32 – Table 3.1), the upper 50 cm of core 8 represent the contamination record of this area over the last 60 years.

Because of the absence of any evidence of disturbance for the top part of this core, the surface (0-1 cm) is considered to represent the 2008 sediments. The presence of calcareous foraminifera in the grab samples that were collected from the same area (Inner Harbour) during the same year of collection (2008) makes their complete absence from the surface of this core unexpected and unexplained. However, we cannot propose a specific reason for this absence because this site was not sampled using grab samples.

The Hg results of (Williams, 2010) are in good agreement with the foraminiferal assemblage throughout the core (Fig. 3.11). Below 110 cm depth, Hg concentrations were less than 100 ppb and started to increase from 110 cm upwards in the core. Between 110 cm and 75 cm, the mercury increased from 95 to 460 ppb. From 75 cm to the surface of the core, mercury values increased rapidly to reach highly contaminated values of about 2000 ppb at the surface (Fig. 3.11).

3.6.7 Foraminiferal trends vs. OC and metals in the core sediments

The comparisons between foraminiferal proxies and the available chemical data for the studied vibracores indicate that benthonic foraminifera correlate with these chemicals through many of the core sediments. This correlation is represented by a positive relationship of deformities and inverse relationship of both diversity and calcareous species. However, some foraminiferal proxies seem to be sensitive to one contaminant more than the other. The results of these comparisons indicated that there are some locations where the chemicals (OC, Hg, Cu, Pb, and Zn) have no significant influence of benthonic foraminifera, as in core 2 in Mill Cove. In cases such as these, any declination in foraminiferal proxies is most likely a result of adverse natural environmental conditions.

In addition, these comparisons showed that foraminiferal proxies in some other locations (e.g., core 8 in the inner harbour) have strong relationships with both OC and metals specifically within the contaminated sediments. Although this relationship may vary from one foraminiferal parameter to another, shell deformities can be an indicator for each kind of contamination. The trend indicates a combination of comparable influence of OC and metals on benthonic foraminifera in this area and also coincides with the fact that both elements (OC and metals) increase parallel-wisethroughout the core. Conversely, metals in other cores (e.g., core 7 in the Northwest Arm) seem to show more influence on foraminifera than OC.

It is important to note that these chemical elements are not the only factor that impact benthonic foraminifera in the sediment cores. It was found that foraminiferal proxies have positive trends while chemicals are very low in the sediments. This can indicate a variation of some natural environmental parameters (e.g., salinity, dissolved oxgyne, pH) rather than contamination. Because of this, changes in foraminiferal parameters should be interpreted carefully and in light of other factors that may affect the environment.

3.7 Conclusions

The characteristics of the foraminiferal assemblages in the vibracore sediments from Halifax Harbour reflect the impacts of pollution over the last hundred or more years and provide an environmental baseline that can be used to assess the effectiveness of the ongoing wastewater treatment program. The pre-impact foraminiferal assemblages in core sediments of Bedford Basin are characterized by their low diversity (<7) and abundance (<1000 individuals), with dominance of agglutinated species and absence or near absence of calcareous ones. The freshwater runoff from Sackville River and other rivers that discharge into the Bedford Bay are inferred to be the main reason for the limitations in diversity, abundance and calcareous species.

In the confined inner parts of the harbour, where core 8 was collected, the foraminiferal assemblage presents a sharp environmental zonation and is considered a typical model for foraminiferal response to increased pollution discharge over time. We were able to differentiate pre-impact, low impact, moderate impact and high impact zones in this core. The assemblage of the pre-impact zone, considered to represent the baseline environment in this area, is similar to that of the surface samples in the unpolluted marine environment of the outer harbour. The total number of species in this zone is >30 and the total number of individuals reaches numbers >5000. Additionally, the assemblage in this zone is dominated by calcareous species *Elphidium* spp., *H. orbiculare*, and *F. fusiformis*. The gradual input of organic matter in the area with time caused dramatic changes in foraminiferal assemblages, including the development of an agglutinated dominated assemblage, the disappearance of calcareous species, and significant increases in both shell deformities and organic inner linings.

In the Northwest Arm, the general character of the assemblage is similar to that in Bedford Basin with respect to diversity (<10 species), abundance (<900 individuals except a few peaks), and dominance of agglutinated species throughout the core. However, the assemblage shows a strong transition from brackish to normal marine conditions without any pollution effect at the bottom related to strongly domestic pollution conditions at the surface. The background levels for the foraminiferal assemblage in this area were 7-10 species for diversity, 750-900 individuals for abundance, and <3% to both organic inner linings and shell deformities.

The highest recorded values of foraminiferal parameters throughout the area are those in core sediments from the outer harbour. The number of species reaches levels as high as 30 species/10 cc, with abundance reaching as high as 6000 individuals/10 cc with general dominance of calcareous species. These high values are characterestic of an open marine conditions with no or low pollution for this part of the harbour. These results are similar to those obtained from surface grab samples collected from the same area during a two-year period in 2008 and 2009 (Dabbous and Scott, 2012 – Chapter 2).

Comparisons of foraminiferal proxies with chemical data indicate that several factors could affect the distribution of benthonic foraminifera in the area. In Bedford Basin, it appears that natural environmental variables exert a greater impact on foraminifera than do contaminants (OC and metals). Conversely, in the inner harbour, both OC and metals significantly influence the foraminiferal assemblage, while in the Northwest Arm, metals along with core sediments have more impact on benthonic foraminifera than OC. Thus, all environmental elements (natural or artificial) have to be assessed and caution has to be considered in the interpretation of benthonic foraminifera as bioindicators.

This study indicates that shell deformities have more sensitivity to increases of metals in the sediments and thus shell deformities are among the most useful parameters for pollution monitoring. Likewise, organic inner linings are of great importance among the foraminiferal parameters that strongly indicate the evolution of domestic pollution with high OC in the environment. In addition, this research documents the use of benthonic foraminifera as proxies for baseline reconstruction for treatment programs. Figures 3.13 to 3.15 summarize the results of the foraminiferal assemblage in sediment cores. The time intervals used in these figures (prior to1890, 1890-1930, 1930-1960s, and 2008) were determined using sedimentation rate estimates from previous studies (Table 3.1). These chronological intervals were chosen based on the fact that, prior to 1890, contamination impacts were minimal (Buckely et al., 1995). In addition, the age-dating techniques employed (^{210}Pb and ^{137}Cs) in previous studies are applicable only to the last 100-120 years. Because the sediment loss in vibracore 2, the foraminiferal data used in the following figures for Bedford Basin are based only on vibracore 3.

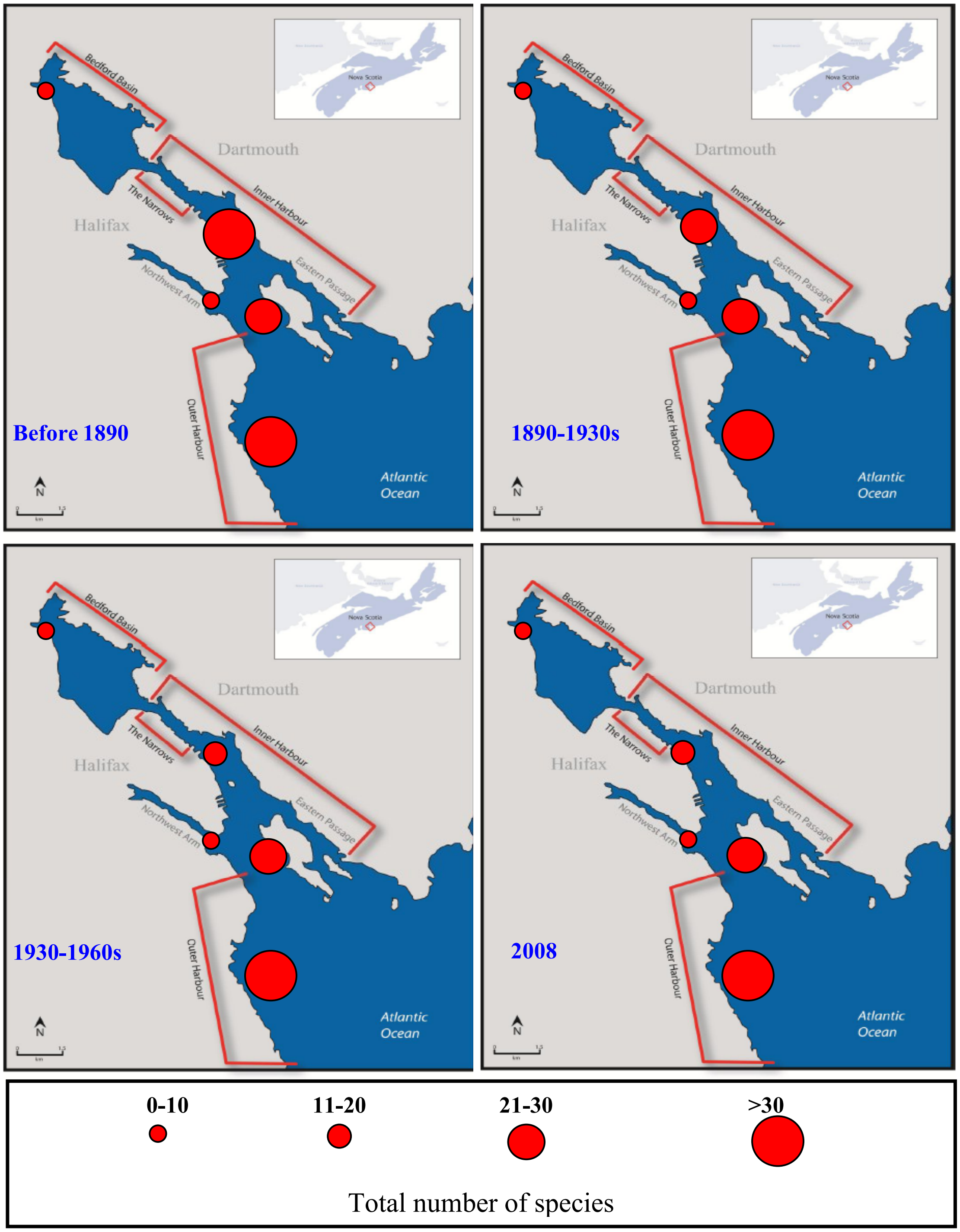

Figure 3.18: The foraminiferal diversity throughout Halifax Harbour over chronological intervals. The larger the circle is, the higher the diversity. The time intervals are based on sedimentation rates estimated by previous works in Table 3.1. The data in Bedford Bay are based on vibracore 3. Based on maps from Weston (2010).

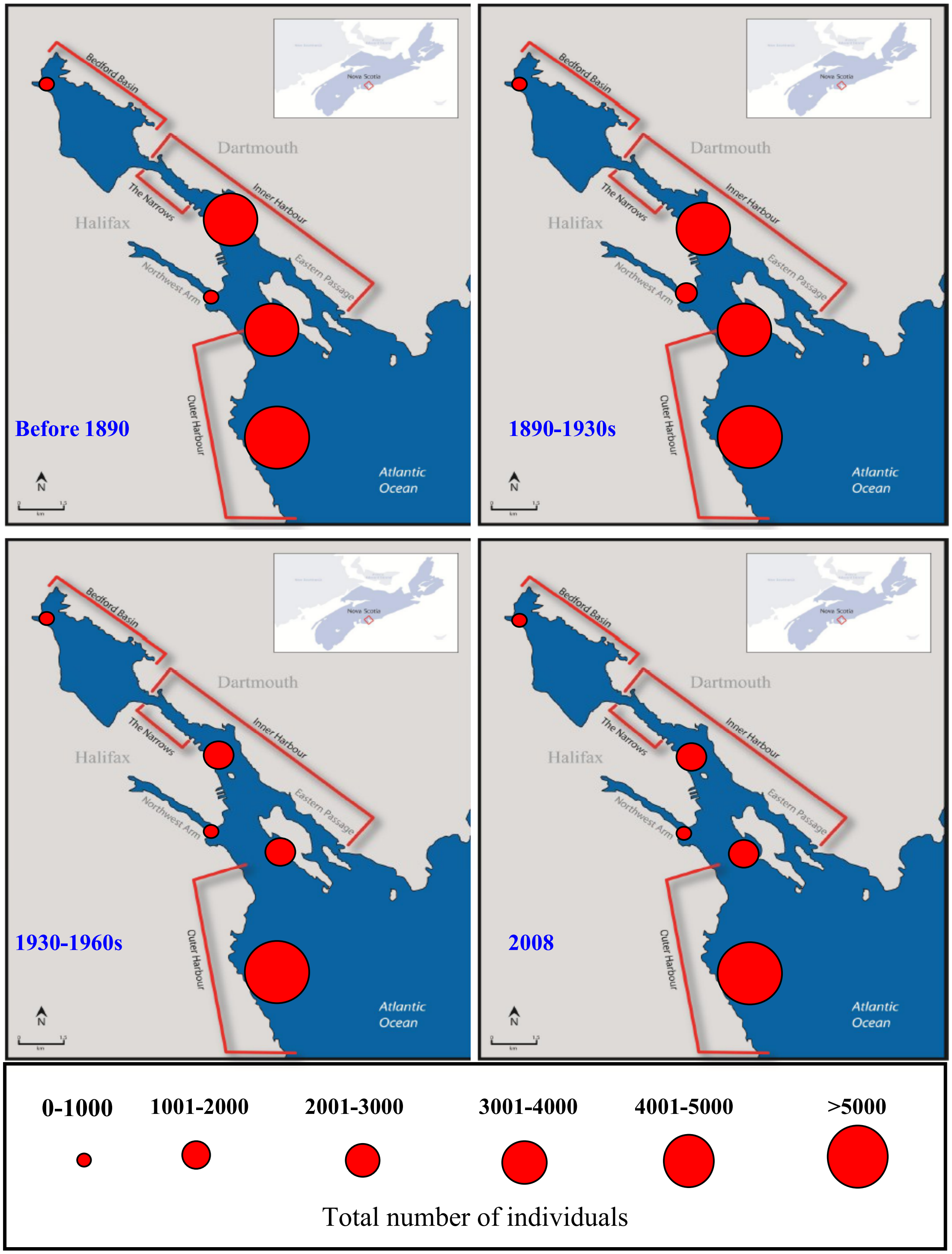

Figure 3.19: The total foraminiferal abundance throughout Halifax Harbour over chronological intervals. The larger the circle is, the higher the abundance. The time intervals are based on sedimentation rates estimated by previous works in Table 3.1. The data in Bedford Bay are based on vibracore 3. Based on maps from Weston (2010).

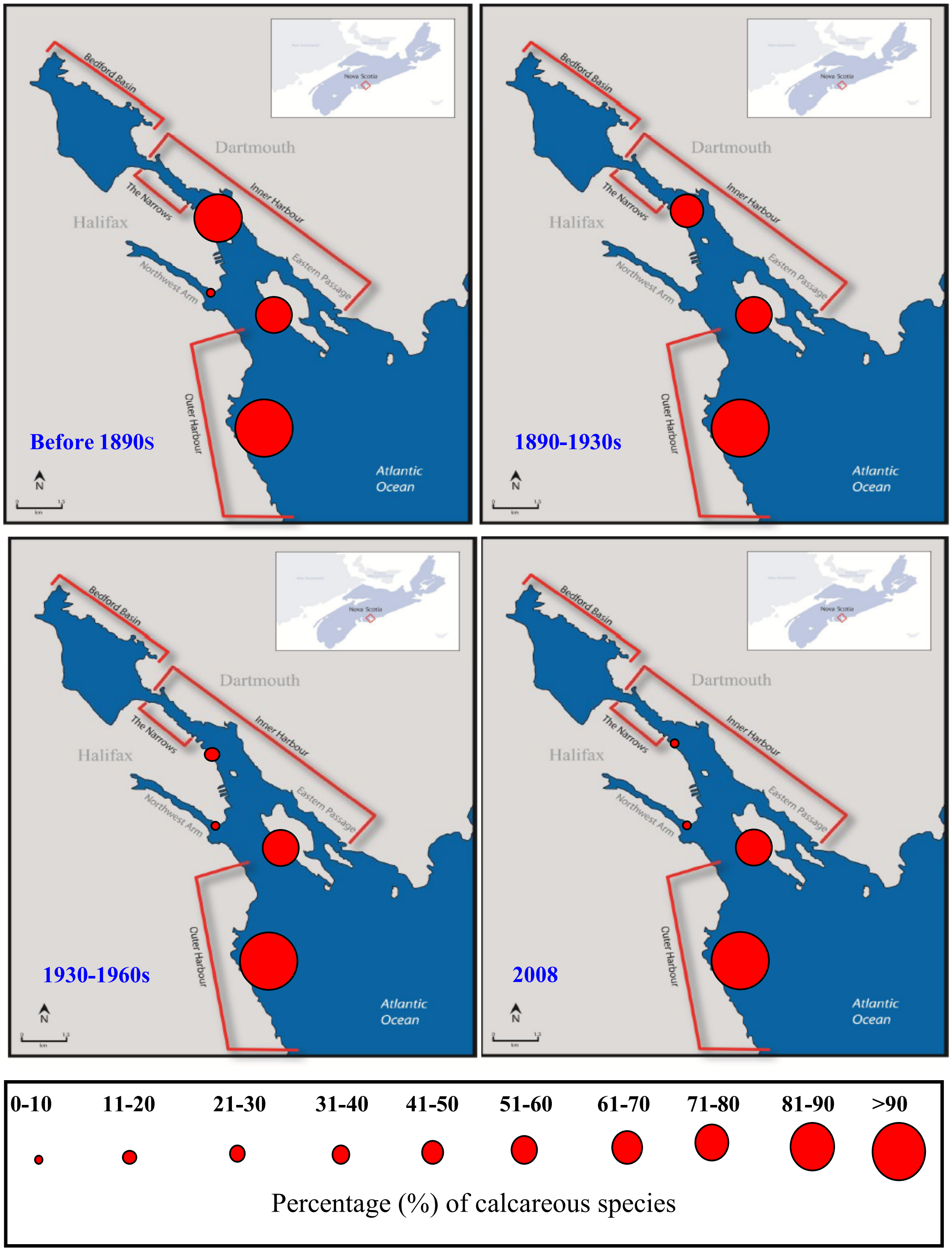

Figure 3.20: The percentage of calcareous species throughout Halifax Harbour over chronological intervals. The larger the circle is, the higher the percentage. The time intervals are based on sedimentation rates estimated by previous works in Table 3.1. Based on maps from Weston (2010).

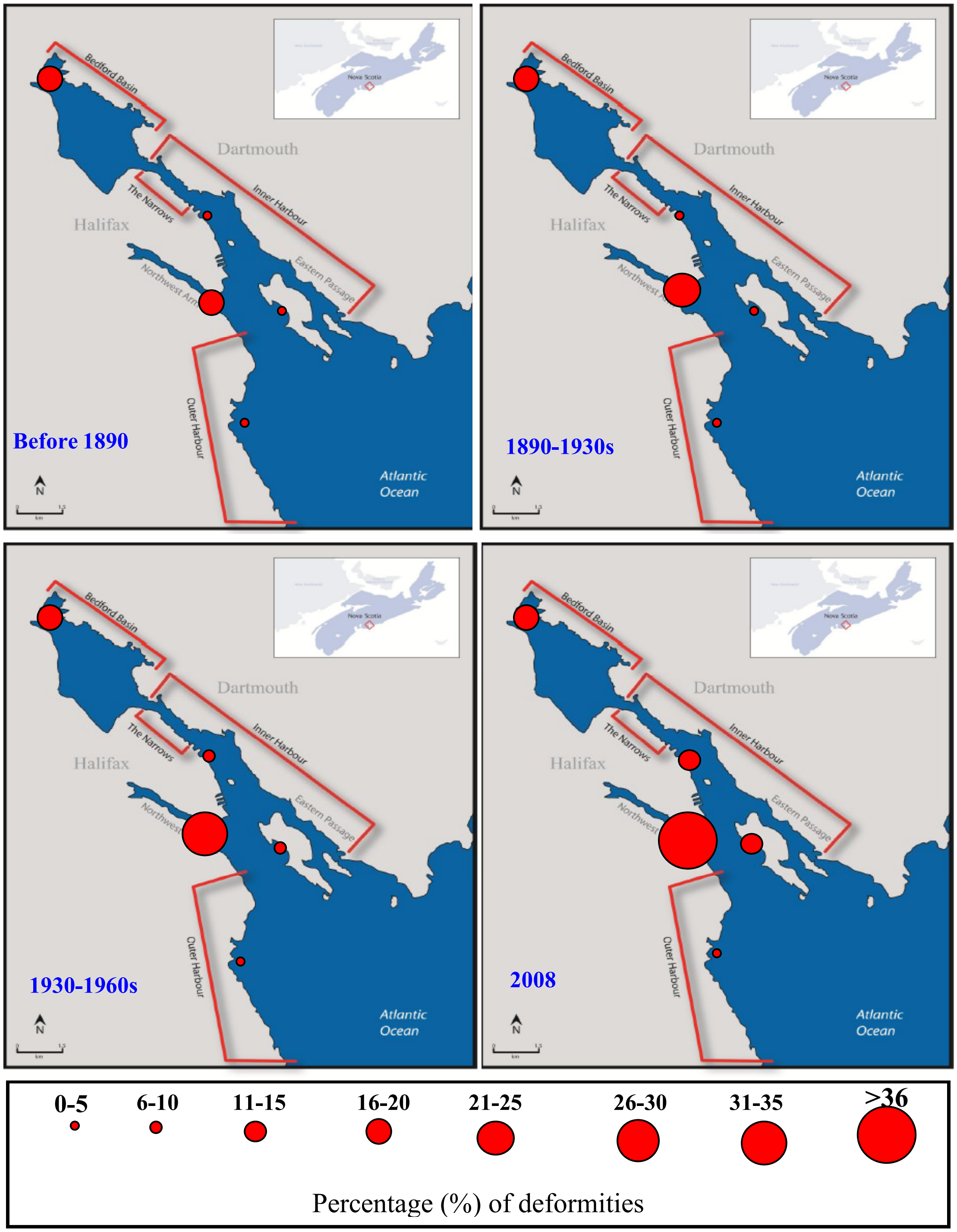

Figure 3.21: The percentage of shell deformities throughout Halifax Harbour over chronological intervals. The larger the circle is, the higher the percentage. The time intervals are based on sedimentation rates estimated by previous works in Table 3.1. The data in the Bedford Bay are based on vibracore 3. Based on maps from Weston (2010).

Chapter 4: Historical Reconstruction of Two Estuaries in Atlantic Canada Impacted with Two Kinds of Pollution: Domestic (Halifax Harbour) vs. Industrial (Sydney Harbour) Using Foraminiferal Proxies

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4.1 Abstract

Benthonic foraminiferal assemblages were examined in sediment cores from two environments in Nova Scotia, Canada, which have been impacted by two different types of pollution. Halifax Harbour (predominately domestic waste) and Sydney Harbour (predominately industrial waste) were studied to reconstruct environmental conditions pre- and post-impact. After many years of intensive and untreated pollution, both areas have recently seen clean-up efforts; however, full characterization of the pre-impact environmental conditions has never been completed.

The characteristics of the foraminiferal assemblages (e.g., diversity, abundance, deformities and inner linings) provide evidence of the intensity and impact of pollution in both harbours. In Halifax Harbour, the major foraminiferal species were agglutinated because the high organic carbon content has lowered the pH in the sediments and inhibited the preservation of calcareous tests. However, in Sydney Harbour, many calcareous species were found, among them *Ammonia beccarii*, which has not been previously observed in the cold water environments of the mid-latitude western North Atlantic.

The high diversity and dominantly calcareous assemblage, along with the presence of other fossil groups (e.g., Ostracods, Pelecypods) within the cores of South Arm-Sydney Harbour, are interpreted to reflect the type (i.e., industrial), and rate (i.e., low) of pollution in this area as compared to Halifax Harbour. The present study is the first one to examine benthic foraminifera in Sydney Harbour, and provides a target environment for the current remediation program and/or any future long-term monitoring efforts in this area.

4.2 Introduction

The 20th century witnessed tremendous growth in human population, which was associated with a worldwide increase in urbanization and industrialization. With the expanding population came extensive input of domestic and industrial pollutants to coastal marine environments. Emissions of a wide range of pollutants into coastal environments have caused substantial damage to sediment and water quality all over the world (Brown et al., 2006). Because of this, extensive research has been carried out since the 1970s to document and assess the level and rate of pollution in coastal environments.

There are many monitoring programs for marine environments that are based on the examination of community parameters of hard-shelled organisms such as macrofossils, benthonic foraminifera, ostracods, and thecamoebians. Among these various hard-shelled marine organisms, benthonic foraminifera are the most widely used (Scott et al., 2001; Frontalini and Coccioni, 2008). Many reviews summarize the previous literature on foraminiferal proxies either worldwide (e.g., Alve, 1991; Schafer, 2000, Scott et al., 2001, Tarasova, 2006, Nigam et al., 2006, Schönfeld, 2012) or in certain geographic locations like France (Armynot du Châtelet and Debenay, 2010) and Italy (Frontalini and Coccioni, 2011). The use of benthonic foraminifera as pollution bio-indicators is described in detail in Chapter 1.

Although a vast amount of work has been carried out using benthonic foraminifera as monitoring proxies, only a few studies have used these organisms in sediment cores to compare different types of pollution and to reconstruct pre-impact conditions (e.g., Alve, 2000; Scott et al., 2005). The present work uses foraminifera as proxies to reconstruct the history and rate of industrial and domestic pollution in Halifax and Sydney Harbour, two important ports in Canada's Maritime provinces. This study is the first to examine the assemblage characteristics and composition of benthonic foraminifera in Sydney Harbour.

4.3 Study areas

The environmental setting and pollution history of Halifax Harbour are discussed in detail in Chapter 1. Sampling methods and core results from Halifax Harbour are described in Chapter 3. This chapter discusses only the methods and results from Sydney Harbour, and compares these results with those of Halifax Harbour.

4.3.1 Sydney Harbour

Sydney Harbour is an Atlantic inlet located on the northeastern coast of Cape Breton Island, Nova Scotia. The 2.2 km wide and inverted "Y" shaped estuary consists of the main ocean-pointing Seaward Arm, and divides landwards into the Northwest Arm and the South Arm (Fig. 4.1). The Northwest Arm has an axial length of 6.5 km, a width of 2.6 km, and a maximum depth of 12 m, while the South Arm has a length of about 10 km, a width of 1 km and a maximum depth of 20 m. Current frequency throughout the harbour is usually weak during the year with current speeds of less than 10 cm/s (Petrie et al., 2001). Mean circulation patterns determine and control the sediment transport direction, which is towards the head of the harbour (Petrie et al., 2001).

There is a significant freshwater discharge (~17 m^3/s yearly average) flow into the harbour from Sydney River, Muggah Creek, Balls Creek, and Leitches Creek (CBCL, 2009). The former two sources, Sydney River and Muggah Creek, flow into the South Arm while the latter ones, Balls Creek and Leitches Creek, flow into the Northwest Arm.

The Sydney River empties into the head of the South Arm and represents the largest freshwater inflow to Sydney Harbour, with maximum inflow (21 m^3/s) in April and minimum inflow (5 m^3/s) in July and August (Gregory et al., 1993, Table 4.1).

The temperature of Sydney Harbour ranges from 19 ^oC at the surface to 14 ^oC at the bottom during the summer and from -1.5 ^oC at the surface to -0.5 ^oC at the bottom during the winter (Lane, 1988, Petri et al., 2001- Fig. 4.2). These significant temperature variations have a strong influence (at least in the summertime), causing thermal stratification in the harbour (Petri et al., 2001). Salinity ranges from 27 at the surface to 29.2 at the bottom during the summer and from 25 at the surface to 27 at the bottom during the winter (Lane, 1988, Petri et al., 2001-Fig. 4.2).

	Northwest Arm	Sydney River	Muggah Creek
January	6.8	10.9	1.2
February	5.3	8.5	1.0
March	7.5	12.0	1.4
April	11.7	18.8	2.1
May	7.2	11.6	1.3
June	3.9	6.3	0.7
July	2.6	4.2	0.5
August	2.7	4.4	0.5
September	3.3	5.3	0.6
October	6	9.6	1.1
November	9.5	15.2	1.7
December	9.2	15.2	1.7
Yearly average	6.3	10.2	1.2

Table 4.1 Estimated freshwater inflows (m^3/s) into Sydney Harbour for one year (from Gregory et al., 1993).

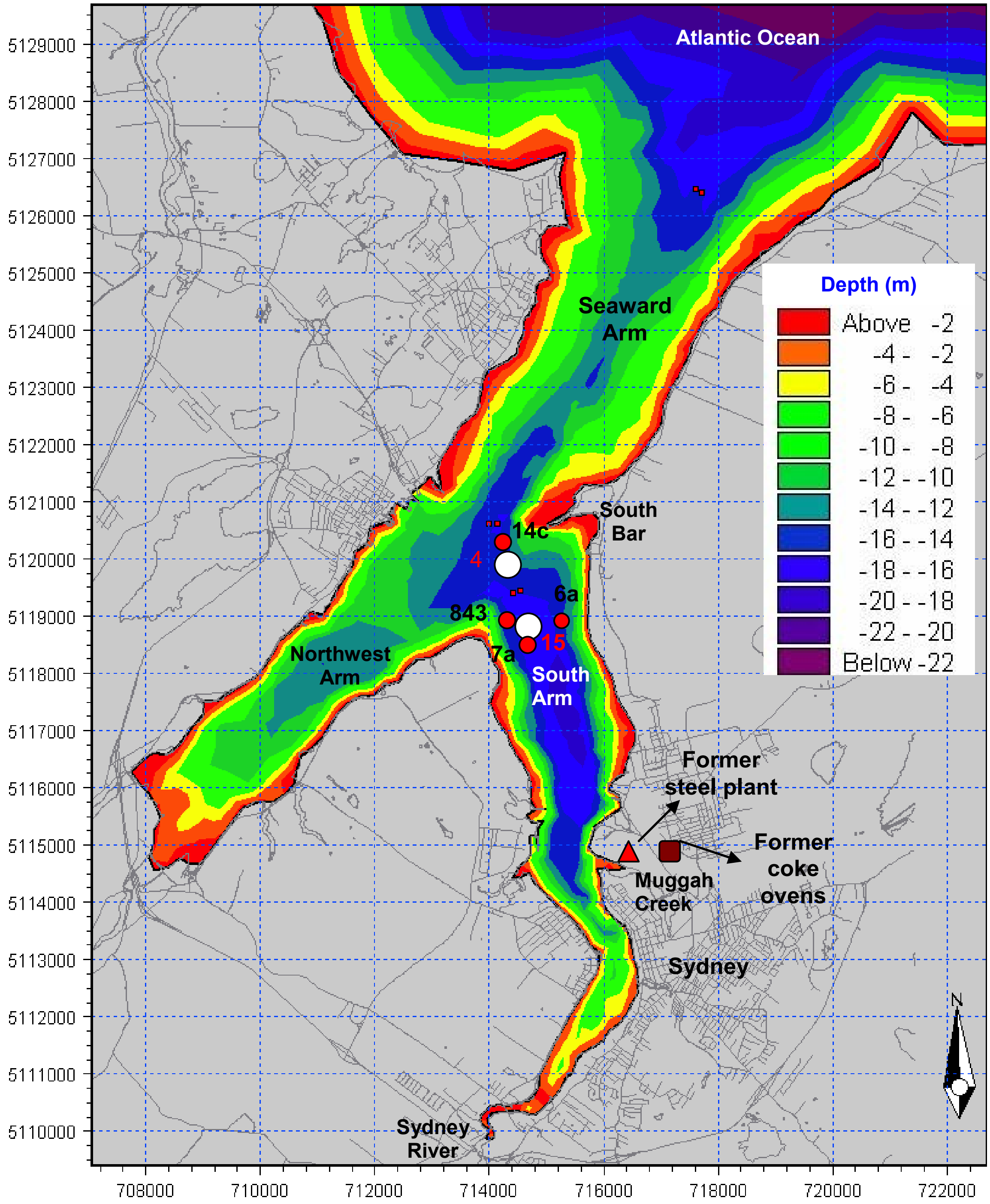

Figure 4.1: Bathymetry and location of vibracore stations (4 and 15 – large white circles), and reference cores (7a, 843, 14c – smaller coloured circles) for sedimentation rates in Sydney Harbour (after CBCL, 2009).

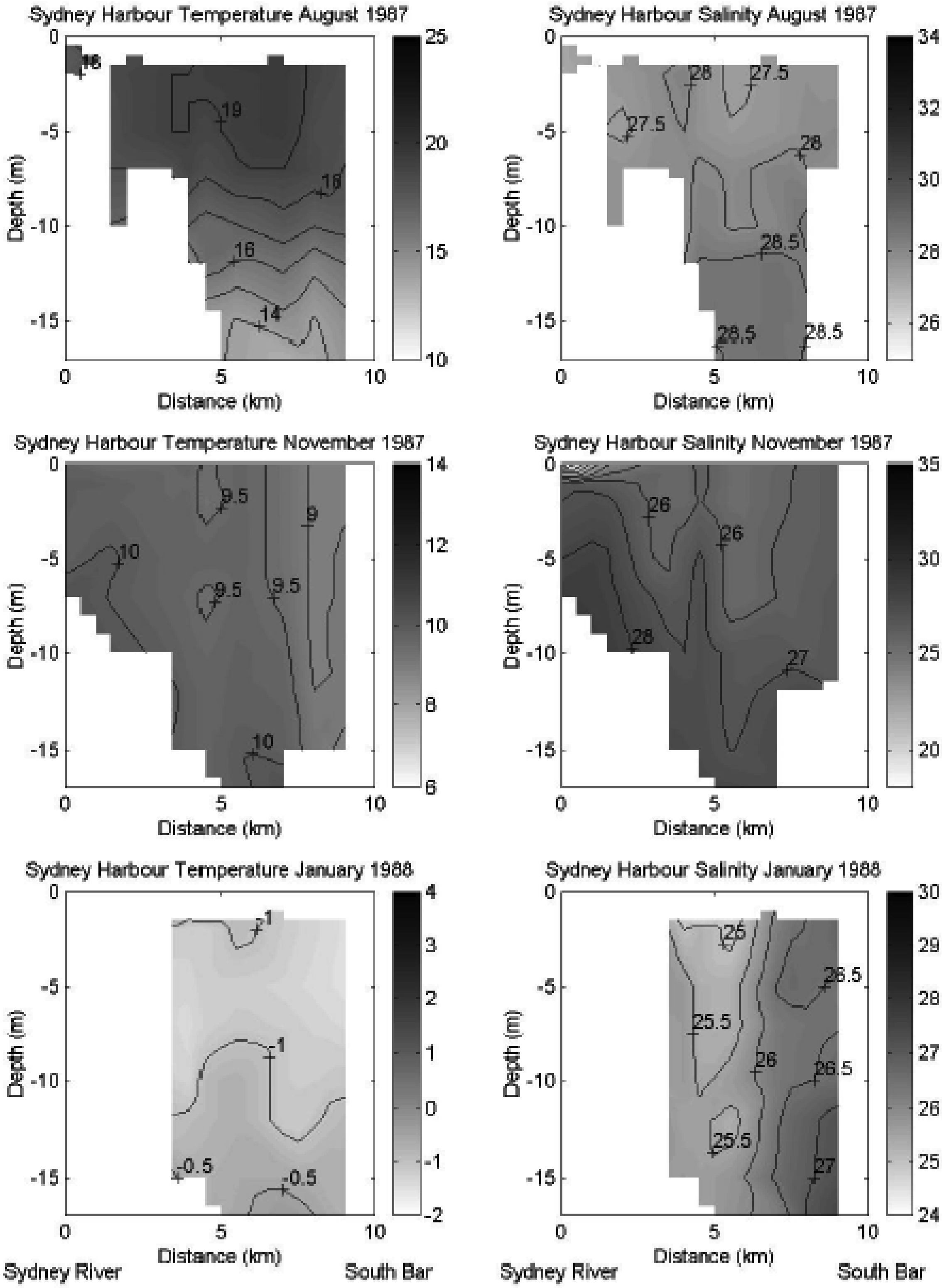

Figure 4.2: Temperature and salinity sections along the South Arm of Sydney Harbour (Petrie et al., 2001, redrawn from Lane, 1988).

Sydney Harbour has served as a depository for a wide range of industrial and domestic contaminants during the last century. The presence of diverse contamination sources is evident from the distribution pattern of contaminants in the harbour sediments (Lee et al., 2002). In addition to industrial contaminants, about 42 municipal sewage outfalls coming from Sydney, Sydney Mines, North Sydney and Sydney River were found to be among the major sources of contaminants in the area (UMA et al., 1994; Lee, 2001). Many contaminants (e.g., Hg, Cu, PAH) in these sewers exceed the CCME environmental guidelines (Lee et al., 2002) and flowed freely into Sydney Harbour until the recent construction of an advanced primary sewage treatment plant near Muggah Creek.

Although Sydney Harbour has many contamination problems that are typical of industrial ports (e.g., organic loading, metallic and organic contaminants, bacterial contamination) industrial contaminants released from the Sydney Steel Plant and Coke Ovens on the eastern bank of the South Arm of Sydney Harbour have had the most severe impact on the area (Stewart et al., 2002). The industrial activity associated with this facility discharged metals (Cd, Hg, Pb, and Zn), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and many other pollutants directly into the Muggah Creek Estuary from 1901 to 2001 (Furinsky, 2002, Lambert et al., 2006, Smith et al., 2009).

The contaminated sediments of the “tar ponds” along Muggah Creek were estimated to contain 700,000 tonnes of coal tar, including 3,500 tonnes of PAHs, plus metals (Lambert et al., 2006, Smith et al., 2009). Because of this, Muggah Creek is considered to be one of the most contaminated sites in Canada (Lambert et al., 2006).

Contaminants from Muggah Creek were transported to the South Arm of Sydney Harbour by tidal flushing and fluvial erosion (Fig.4.1). At some sites in the harbour, PAHs were found to be more than 70 times and PCBs more than 40 times over the limit set by the Canadian Environmental Quality Guidelines (Lee et al., 2002). Lead and Zn were about 2-4 times higher than the guidelines (Lee et al., 2002).

Concern over environmental conditions in Sydney Harbour grew when high PAH levels in the digestive glands of lobsters were first observed in the early 1980s (Uthe and Musial, 1986). High rates of cardiovascular and cancer-related diseases among the residents of the Sydney area also caused concern about the effect of these contaminants on public health (Tay et al., 2003). These findings caused the permanent closure of fisheries, coal coking and the steel industry in the South Arm of Sydney Harbour between 1988 and 2001. Currently, there is an ongoing remediation program using in situ stabilization techniques with a total cost of $400 million. As of March 2012, approximately $207.5 million of this budget has been spent (Cleanup Times, 2012).

Numerous environmental studies have discussed the pollution in Sydney Harbour in the context of risk- and site-assessments and human health. In addition, there have been countless public meetings and extensive media coverage. However, only a few studies have dealt with benthic communities in Sydney Harbour (e.g., Wendland, 1979; Zajdlik et al., 2000; Lee et al., 2002; Stewart et al., 2002; Tay et al., 2003). Wendland (1979) focused on the benthonic communities in South Arm only while other studies dealt with benthonic communities in the whole of Sydney Harbour. The results of these studies show that benthonic communities in Sydney Harbour are similar to those in other coastal areas of Nova Scotia but that their distribution is strongly influenced by pollution sources (Fig. 4.3-Lee et al., 2002; Stewart et al., 2002). However, none of these studies have examined the benthonic foraminifera, which have become known globally as bio-indicators for pollutants in coastal areas.

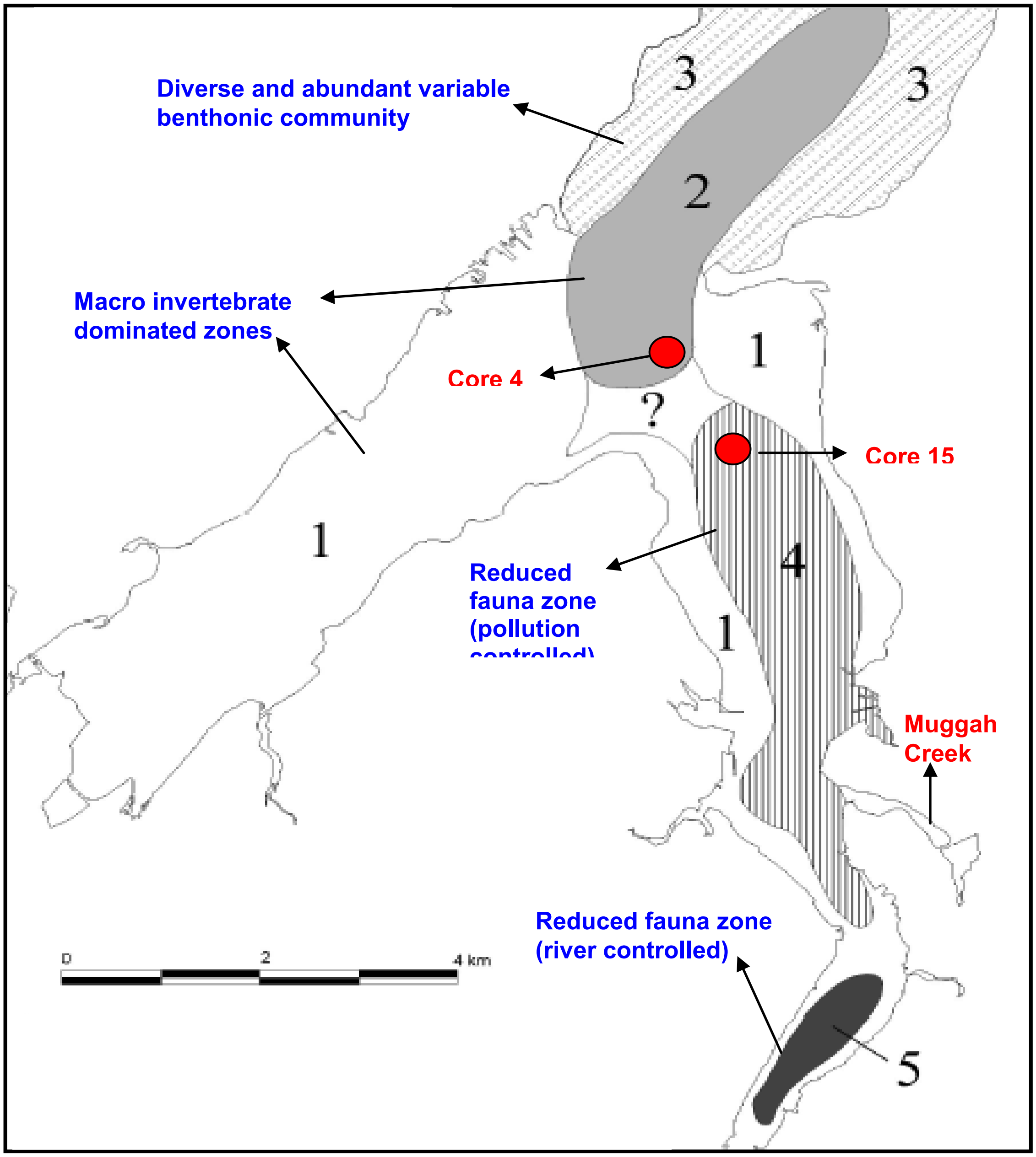

Figure 4.3: Benthonic communities in Sydney Harbour (from Lee et al., 2002).

4.4 Materials and methods

4.4.1 Sample Collection

McGregor GeoScience Limited conducted a survey of Sydney Harbour in January 2008 for CBCL Limited in preparation for a large-scale dredging operation. This survey included the collection of 15 long (2.0-3.5 m) cores at 16.5-19.5 m water depth throughout the area, starting from the mouth of the Seaward Arm and ending by the Muggah Creek in the South Arm, using a Rossfelder P-5 Vibracorer. McGregor GeoScience Limited kindly allowed Dr. Scott to sub-sample two of these vibracores (core 4 and core 15, Fig. 4.1, Table 4.2) for foraminiferal examination. Because of the way the cores are numbered in this survey, we thought that they were distributed in Sydney Harbour according to their numbering order. Accordingly, we picked two cores thinking that they will be fairly distributed through out the harbour. However, later on we realized that the cores are not distributed in the surevy transect based on their order of numbering and that the cores we picked are from almost the same location. Soon after collection, the cores were sub-sampled at 10 cm intervals, and 10 cc sub-samples were stored at 4 ^{o}C in the Dalhousie University Core Laboratory for later processing.

4.4.2 Laboratory techniques

Ten-cc samples were taken from each sampled interval and gently washed using tap water through a set of nested sieves ranging from 500 to 63 μm. The smaller sieve retained many of the small foraminifera while the larger-sized sieves remove undesired particles (e.g., leaves, rock fragments) and helped with the counting of the oversized individuals. All samples were suspended, examined, and kept in a liquid suspension for future analyses. Although some authors prefer to count dry residues, counting foraminifera in liquid suspension prevents the destruction of fragile agglutinated forms such as *Ammotium cassis* and *Reophax scottii*, and provides better visibility of organic inner linings that are left after the dissolution of their original calcareous tests (Scott et al., 2001; Murray, 2006). All processing techniques used in this study are described in detail in Scott et al. (2001).

Station	Latitude °N	Longitude °W	Water-Depth (m)	Core length (cm)	Sedimentation rate (cm yr^{-1})
4	46.1146	-60.1313	16.5	276	NA
***14c**	46.1943	-60.2170	NA	NA	0.556
15	46.1104	-60.1259	19.25	261	NA
***7a**	46.1822	-60.2143	NA	NA	0.423
***843**	46.1846	-60.2201	NA	NA	0.475

Table 4.2: Sampling stations, geographic coordinates and water depth for cores from Sydney Harbour. *: Reference cores for sedimentation rates taken from Smith et al., (2009). Core 14c is a reference for our vibracore 4 and cores 7a and 843 are references for our vibracore 15.

4.4.3 Sedimentation rate and chronological dating

Stewart et al. (2001) studied 94 surficial bottom sediment samples across Sydney Harbour for analyses of grain size and concentrations of trace metals. They concluded that the harbour is a depositional area with flocculation playing an important role in the deposition mechanism throughout the area. Lee et al. (2002) carried out chemical analyses of some sediment cores throughout the harbour and estimated sedimentation rates in Sydney Harbour to be between 0.2 and 2 cm/year. They pointed out that the highest sedimentation rates are present in the regions closest to Muggah Creek, whereas the lowest rates are present in the outer parts of the harbour.

On the other hand, Smith et al. (2009) carried out an extensive analysis for metal (e.g., Pb, Ag) and organic contaminants (e.g., PAHs, PCBs) for 41 dated (using ^{210}Pb and ^{137}Cs) sediment cores throughout the harbour. They estimated the sedimentation rates to be 0.10 to 5.4 cm/yr for the harbour, with the highest values near Muggah Creek and the lowest values for the outer reaches of the harbour (Fig.4.4). As there were no age dates available for vibracores 4 and 15 from Sydney Harbour, we applied the age estimations of Smith et al. (2009) for their cores 7a, 843, and 14c that are located close to our cores (Fig. 4.1; Table 4.2).

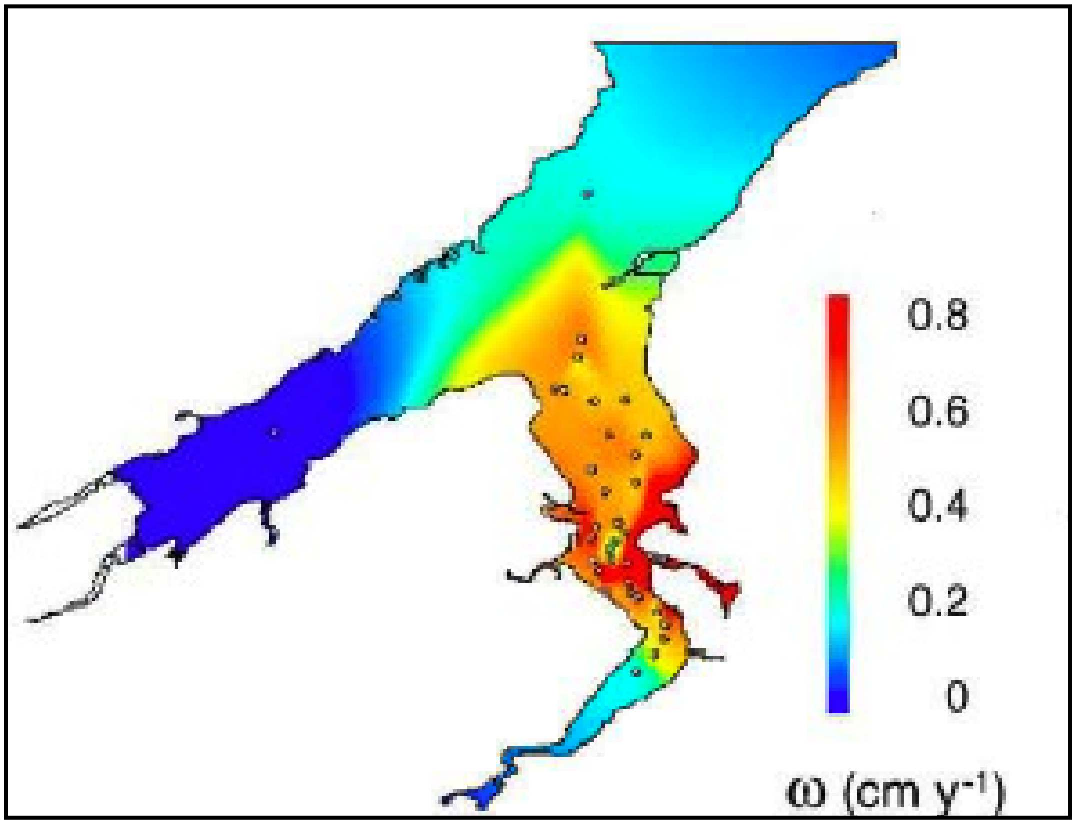

Figure 4.4: Distribution of sedimentation rates (ω) for Sydney Harbour showing the highest values in Muggah Creek and central harbour regions (from Smith et al., 2009).

4.5 Results

The results of foraminiferal analyses of sediment cores from Halifax Harbour are presented and discussed in detail in Chapter 3. The following sections will discuss the results from Sydney Harbour and then compare them to results from Halifax Harbour.

4.5.1 Core 4

The foraminiferal assemblage in core 4 from Sydney Harbour is characterized by its high diversity (~38 species per 10 cc) and total abundance (~ 5000, with peaks that reach up to ~ 9000 individuals per 10 cc; Fig. 4.5, Appendix 4A). The calcareous species dominate the foraminiferal assemblage at this location, with ratios that reach up to 60% The most common calcareous species are *Elphidium* spp. (~35%), *Haynesia orbiculare* (0-18%), and *Rosalina bulloides* morphtype *columbiensis* (1-23%, Fig.4.5, Appendix 4A).

In addition, there are other calcareous taxa of less abundance, such as *Ammonia beccarii*, *Cibicides lobatulus*, *Lagena mollis*, *Nonionellina labradorica*, *Quinqueloculina agglutinatus*, and *Q. seminulum*. Very few shells of the calcareous species *H. orbiculare* have an arenaceous cover, termed “sheath”, which surrounds the calcareous test, presumably for protection purposes (Scott et al., 1977). Surprisingly, the calcareous species *A. beccarii*, which has never been documented this far north in the cold waters of the Northwest Atlantic, is present in the lower half of core 4, with percentages reaching up to 8% (Fig. 4.5).

The dominant agglutinated species in the assemblage are *Eggerella advena* (18-61%), *Ammotium cassis* (6-35%), *Trochammina* spp. (4.5-20%), and *Reophax* spp. (2-8% (Fig. 4.5, Appendix 4A). Although foraminifera are well preserved in core 4, there are some deformations in their morphologies, and some degree of decalcification is apparent from residual inner linings. Abnormal morphologies were recorded (up to 14%, Fig.4.5) in both calcareous (mainly *Elphidium* spp., *H. orbiculare*, and *R. bulloides* morph type *columbiensis*) and agglutinated (mainly *E. advena*, *S. biformis*) species. Organic inner linings were recorded in core 4 with high percentages (~20%) with an anomalously high peak (~35%) at 230 cm depth (Fig. 4.5).

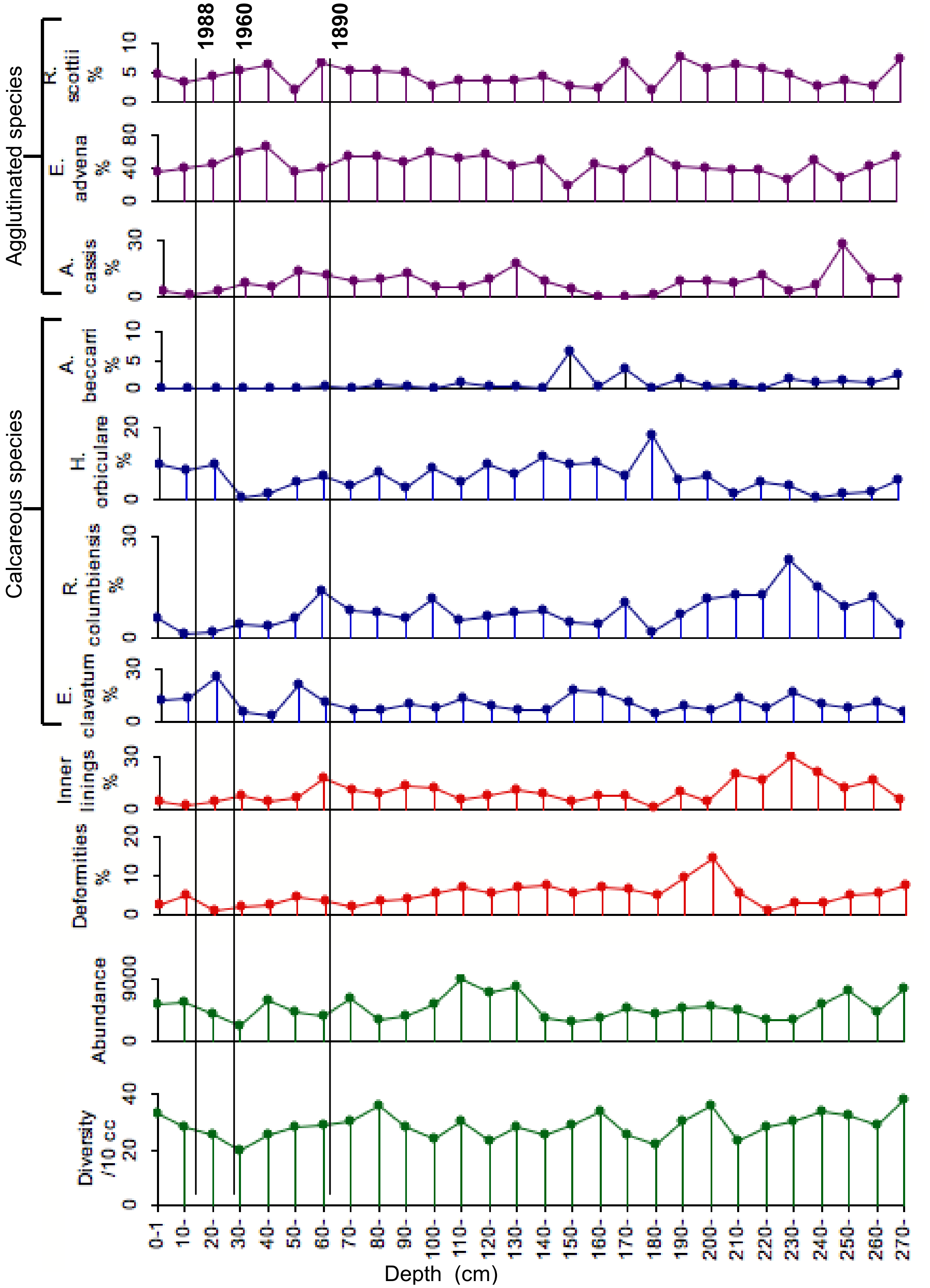

Figure 4.5: Assemblage characteristics and distribution of common species in core 4, Sydney Harbour. Age lines are based on sedimentation rates (0.556 cm/yr) estimated by Smith et al. (2009) in nearby core 14c (Table 4.2).

4.5.2 Core **15**

The foraminiferal assemblage in core 15 strongly resembles that of nearby core 4 (Fig.4.1) with respect to diversity, abundance and, to some extent, assemblage composition. Diversity and abundance range from 30 to 40 species and from 6,000 to 7,800 individuals per 10cc, respectively. This assemblage is dominated by calcareous species with ratios reaching up to 60 % (Fig. 4.6). The most common calcareous species are *Elphidium* spp., *B. frigida*, *H. orbiculare* and *R. bulloides* morphtype *columbiensis*. Other species are present at lower abundances (20-24%- Appendix 4B) (e.g., *L. merdionalis*, *Q. agglutinatus, Patellina currogata*, *N. labradorica*, and *Pyrgo wiliamsoni*). The main agglutinated species are *A. cassis* (10-30%), *E. advena* (40-60%), *S. biformis*, *Reophax* spp. (8-20%), and *Trochammina* spp. (<7%; Fig. 4.6). Shell deformities and organic inner linings range from 3-18% throughout the core. Other fossil groups (e.g., ostracods, pelecypods, and gastropods) are also found in significant numbers (Appendix 4B).

In contrast to core 4, the foraminiferal assemblage in core 15 can help to trace environmental change throughout the core. There is a slight gradual decline in most parameters of the foraminiferal assemblage between 50 cm and 10 cm core depths. Throughout this part of the core, diversity decreased from 28 to 19 species per 10 cc and abundance decreased from >6000 to ~2550 individuals per 10 cc (Fig. 4.6). At the same time, the total abundance of calcareous species decreased significantly to reach amounts of 17.5% at 10 cm depth, and many calcareous species (such as *L. merdionalis*, *Q. agglutinanus*, *P. corrugata*, and *N. labradorica*) disappear in the 50-10 cm interval (Fig.

4.6, Appendix 4B). Ostracods also decrease gradually from 225 individuals (at 50 cm) until they disappear at 10 cm depth (Appendix 4B).

In contrast, there was a gradual increase in agglutinated species, specifically the opportunistic ones such as *E. advena* (from 43% to 56%), *A. cassis* (from 9.2% to 16%), and *R. scottii* (from 9.2% to 16%-Fig. 4.6). Other agglutinated species, such as *S. biformis* and *S. atlantica*, increased in this part (50-10 cm) of the core but with percentages lesser than the former ones (Fig. 4.6). Additionally, shell deformities and organic inner linings increased from < 3.5% at 60 cm to 15 % for deformities and 10% for inner linings at 10 cm depth (Fig. 4.6).

In the upper 10 cm of core 15, diversity and total abundance increased again toward the core top. In addition, some of the calcareous species that completely disappeared between 60 and 10 cm (e.g., *N. labradorica*) reappear. Opportunistic species, shell deformities, and inner linings also decrease towards the core top (Fig. 4.6).

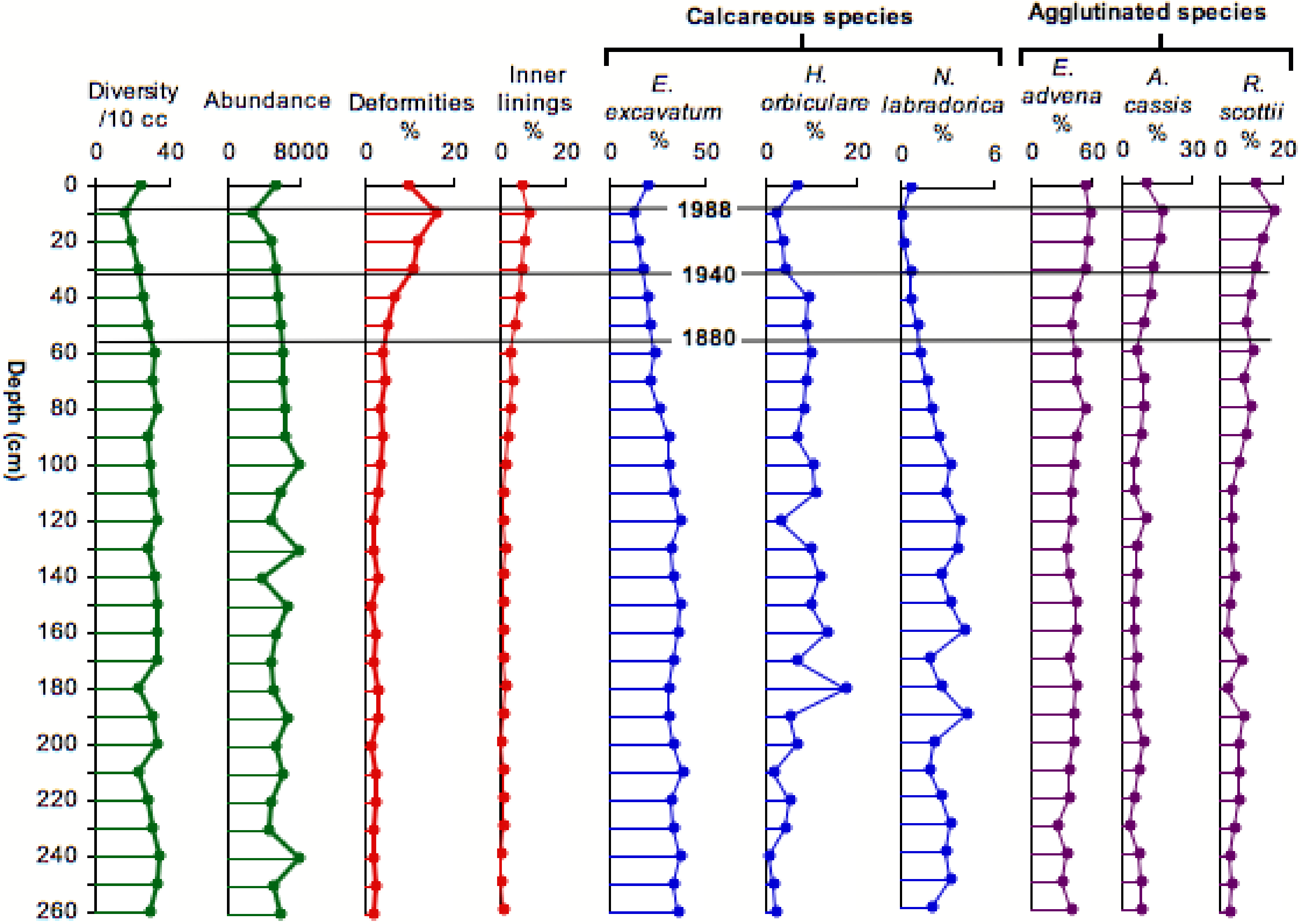

Figure 4.6: Assemblage characteristics and distribution of common species in core 15, Sydney Harbour. Age lines are based on the estimated sedimentation rates (0.423, 0.475 cm/yr) by Smith et al. (2009) for nearby cores 7a, and 843 (Table 4.2).

4.6 Discussion

4.6.1 Foraminiferal assemblages in Sydney Harbour

Both cores from Sydney Harbour indicate high diversity (up to 40 species per 10 cc), high abundance (up to 9,000 individuals per 10 cc) and the dominance of calcareous taxa (up to 60%) in the foraminiferal assemblages. The dominance of the *Elphidium* / *Haynesina* group in the assemblage may indicate low organic carbon content in the sediments, as these species cannot tolerate high organic carbon (it causes dissolution of their calcareous shells). On the other hand, these species were common in shallow areas with more chemical substances than organic carbon content (e.g., Long Island Sound-Buzas, 1965; New Bedford Harbor-Scott et al., 2005). The elphidiids, specifically *Elphidium excavatum*, are generally found in the colder waters of the North Atlantic high latitudes (Feyling-Hanssen, 1972; Scott et al., 2001; Filipsson and Nordberg, 2004) and have a strong tolerance to a wide range of environmental conditions, including excess pollution (Alve, 1995a; Bergeston et al., 1996; Scott et al., 2011). Surprisingly, the calcareous species *A*. *beccarii* is present in significant quantities (up to 8%) in the lower part (80-270 cm) of core 4, but disappears in the upper section (80 cm to the surface). This species, known to prefer shallow water depths with warmer temperatures, has never been recorded this far north in the West Atlantic, which historically has colder waters (Scott et al., 2005).

There are no contamination-related changes in the foraminiferal assemblage in core 4 that we can correlate to the pollution history of the area. The maximum pollution impact on Sydney Harbour was between 1960 and the late 1980s, which corresponds to the estimated sedimentation rate for this part of the harbour (0.556 cm yr^{-1}-Smith et al., 2009; core 14c), to depths between ~27 and 11.5 cm in core 4. At these depths we did not find any significant changes in diversity, abundance, shell deformities, or inner linings compared to deeper sections of the core. In addition, the reconstruction of pollutant history for a nearby core (14c; Smith et al., 2009) indicates that there was no significant metal increase at this location during the period of most industrial activity in Sydney Harbour (Fig. 4.7). This is also cosistent with the results of Lee et al. (2002), which indicate that the site of this core (i.e., vibracore 4) is located in a relatively unpolluted area.

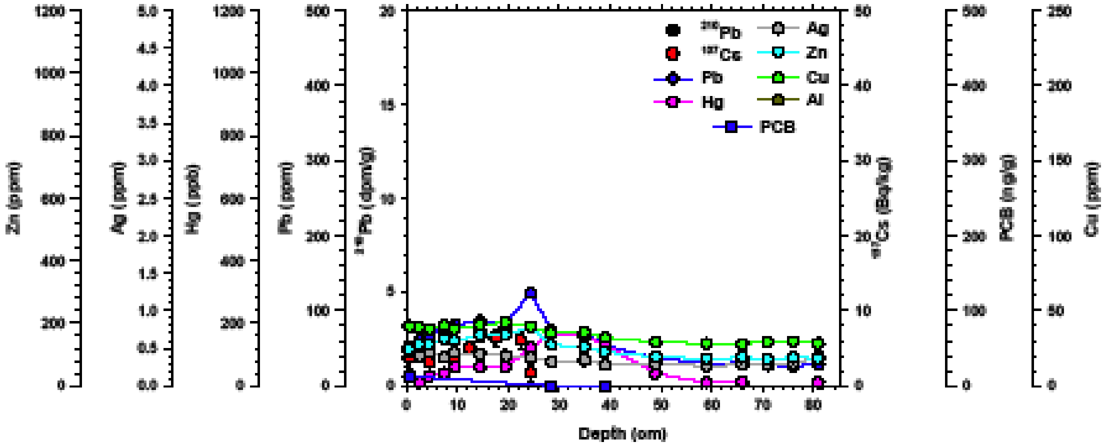

Figure 4.7 History and chronology of some contaminants in a sediment core (14c) near our vibracore 4 from the mouth of the South Arm-Sydney Harbour (Data courtesy of J. Smith, 2012).

Shell deformities and inner linings were recorded in anomalously high percentages (up to 30%) in sediments that were deposited centuries before any pollution impacts in this area at 200 to 250 cm depths. Shell deformities are considered to be a proxy for pollution impacts in more recent sediments if their ratios exceed 5% of the total assemblage (Scott et al., 2001). However, Geslin et al. (2002) recorded shell deformities from non-impacted areas in amounts (24% from the hypersaline lagoon Araruama, and

29% Rio Una estuary) higher than those recorded from another polluted area (12% from the polluted estuary, Baixada Santista) in Brazil. Likewise, the dissolution of calcareous tests, leaving only their organic inner linings, is a complicated process (Murray and Alve, 1999; Filipsson and Nordberg, 2004) and may be caused by variable factors such as the chemistry of the overlying water column, mineral constituents of the foraminifer's test, morphology of the test, and predation by other organisms (Mageau and Walker, 1976).

Based on the above discussion, the significance of anomalous values in both shell deformities and inner linings deep in core 4 related to aspects of contamination remains questionable. However, comparisons between foraminiferal proxies and chemical analyses of the core sediments in Halifax Harbour (Chapter 3 in this dissertation) indicated that these declinations in foraminiferal assemblage might result from the influence of either natural or artificial (conamination) factors. On the other hand, some physical activities such as dredging and ship anchors that may cause sediment disturbance and mixing of near-surface sediments with deep sediments could be the reason for such anomalies. However, without further studies of the changes in historical environmental conditions in this part of Sydney Harbour, it is not possible to offer a full interpretation of such discrepancies in both shell deformities and inner linings at deeper depths in core 4.

In contrast to core 4, the foraminiferal assemblage in core 15 can help to trace a slight contamination impact in this site. The lower part of the core, extending from 260 cm to 50 cm depth, represents natural marine conditions without evidence of any contamination (Fig. 4.6). This is inferred from the high foraminiferal diversity (~38 species), abundance (>7000 individuals), and the dominance of calcareous species

(>60%) through this part of the core. The absence and/or negligible percentages of both shell deformities and inner linings strongly support this interpretation.

Further up the core, between 50 cm and 10 cm depths, the foraminiferal assemblage shows a gradual decline in diversity (from 28 to 19), abundance (from >6000 to 2550 individuals) and calcareous species. At the same time there was an increase in deformities and opportunistic species (e.g., *E. advena*, *R. scottii*). Based on the estimated sedimentation rates (0.42-0.47 cm yr^{-1}-Smith et al., 2009; cores 7a, 843-Fig.4.4, Table 4.2), 50 cm depth in this core corresponds to the year 1880, which marks the beginning of industrial activity in the area. A depth of 9 cm corresponds the year 1988, which represents the period of highest industrial activity and greatest pollutant loading in the area. The foraminiferal assemblage above this depth seems to have recovered somewhat following the shutdown of the steel plant and coke ovens between 1988 and 2001. Based on this, the upper 9-10 cm of core 15 records the progressive improvement in marine environmental quality over the last two decades in Sydney Harbour.

Smith et al. (2009) showed that contaminant concentrations increased significantly in Sydney Harbour beginning in 1880 and reached maximum values in the late 1980s, before declining significantly following closure of the coke ovens in 1988. They pointed out that concentrations of Pb, PAHs, and PCBs are related to discharges from the steel and coke industries, whereas the concentrations of Ag are mainly related to urbanization and the area's population growth. Additionally, Smith et al. (2009) emphasized that the concentrations of contaminants are highest at the head of Muggah Creek and decrease with increasing distance from Muggah Creek.

Based on Lee et al. (2002, Fig. 4.4) and Smith et al. (2009, Figs.4.8-4.11), the site of our vibracore 15 is impacted by contamination, but to a lesser degree than more southern parts of the South Arm. Contamination near the mouth of South Arm is low and concentrated mainly from the central part towards the eastern side of the arm (John Smith – personal communication). The analysis of contaminants in core 843, the closest core to our vibracore 15 of Smith et al. (2009), shows an increase in the PAHs and PCBs during the period of industrial activity in the area (Table 4.3, Figs.4.8, 4.12, 4.13). The metal contaminants in this core do not show any significant increase during this period (Fig.4.8). However, metals (Ag, Cu, Hg, Pb) in core 7a of Smith et al. (2009), which is the other core located near to our vibracore 15, show some increase between the 1950s and the late 1980s (Fig. 4.9). The concentrations of Cu (40-60 ppm), Hg (160-200 ppb), Pb (80-150 ppm), and Zn (160-240 ppm) in this core during the second half of the twentieth century are similar to their concentrations in surface sediments collected from Halifax Harbour between 2008 and 2009 (Table 4.3). The chemistry of core 6a from Smith et al. (2009), which is located to the east of these cores (our vibracore 15, and the reference cores 7a and 843) indicates that the contamination is much more significant in the eastern part of the South Arm compared to the western part (Table 4.3, Figs.4.10, 4.12, 4.13). As mentioned above, the foraminiferal assemblage in core 15 indicates a relatively minor impact of metal contamination in this part of the harbour and environs. In areas affected by severe industrial impact (e.g., New Bedford Harbour – Scott et al. 2005) the diversity was as low as 10 species/10cc and the total abundance was less than 1000 individuals/10 cc. Thus, the foraminiferal assemblage in our vibracore 15 correlates well with the geochemical analysis of Smith et al. (2009).

	Sydney Harbour				Halifax Harbour			
	Core 843 Min-Max.	Core 6 a Min-Max	Core 7a Min-Max	Core 14c Min-Max	VC 3 Min-Max	VC 7 Min-Max	VC 8 Min-Max	(Surface samples (mean)
Ag	157-257	0.2-0.8	0.2-0.5	0.28-0.44	0.08-0.8	0.14-1	0.2-4.8	-
Cu	40-60	25-60	29-50	28-40	2-63	19-69	10-146	206[a]
Hg	20-392.3	10-190	10-160	10-30	<5-543	7-971	8-3273	155[b]
Pb	29.5-172.5	30-228	26-134.5	30-65	3-103	26-130	2-546	194[c]
Zn	106.9-284.9	90-388	92-196	86-190	28-166	55-168	65-401	384[d]
PAHs	0-40	0-100	0-45	0-35	-	-	0-147	13.4
PCBs	0-0.9	0-0.7	0-0.9	0-0.1	-	-	-	-
TOC	-	-	-	-	0.12-4.14	3.05-4.27	3.9-9.07	4.74

Table 4.3 Comparison between the concentrations of the main contaminants (Ag, Cu, Pb, Zn, PAHs, PCBs (ppm), Hg, (ppb), and Total Organic Carbon (TOC- wt. %) in both Sydney and Halifax harbours. The data from Sydney Harbour are based on the closest cores (843, 6a, 7a, 14c-Courtesy of J. Smith, 2012) to our vibracores 4 and 15. The data from Halifax Harbour are reported from Williams (2010) ([a]: Dartmouth Cove, [b]: Herring Cove, [c]: Tufts Cove, and [d]: Mill Cove). The minimum refers to the background (pre-impact; before 1880) values of these contaminants while the maximum refers to the highest value after the 1960s in both areas.

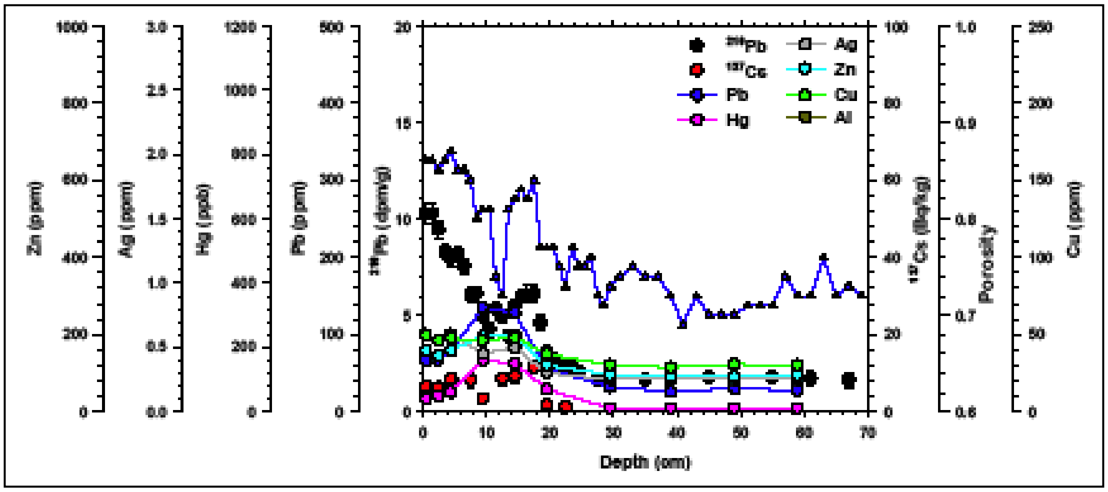

Figure 4.8: History and chronology of some metal contaminants in a nearby sediment core (7a) to our vibracore 15 from the mouth of the South Arm, Sydney Harbour (Data courtesy of J. Smith, 2012).

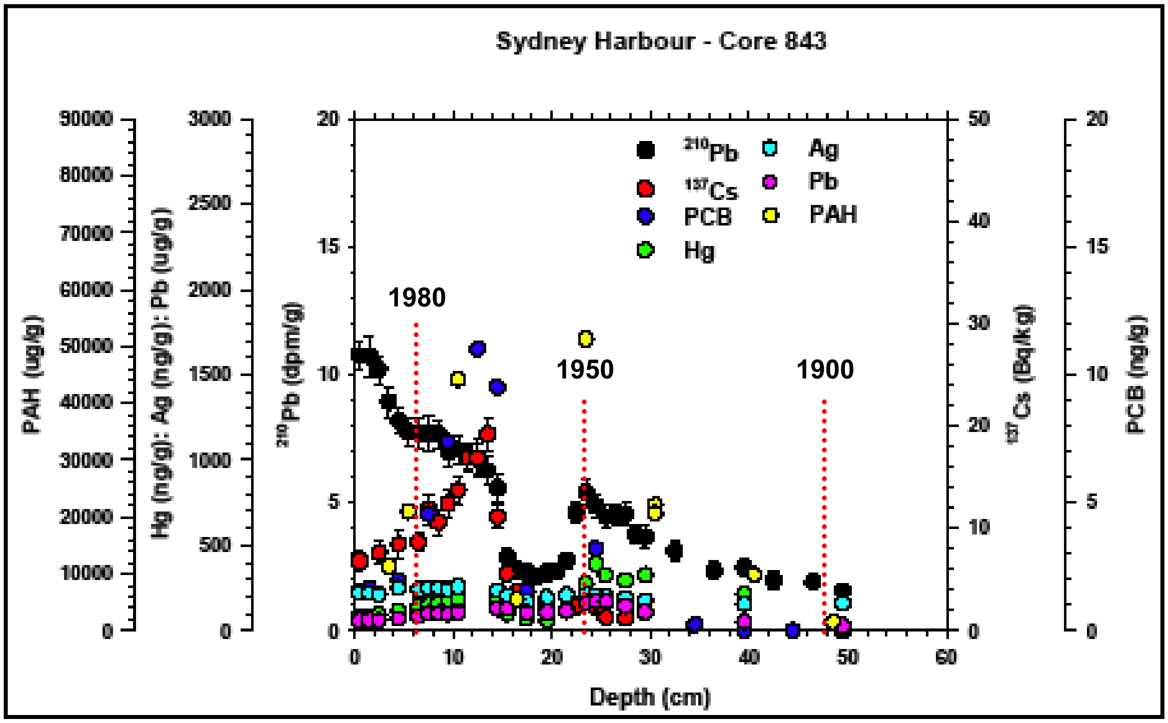

Figure 4.9 History and chronology of some contaminants in a nearby sediment core (843) to our vibracore 15 from the mouth of South Arm (Data courtesy of J. Smith, 2012).

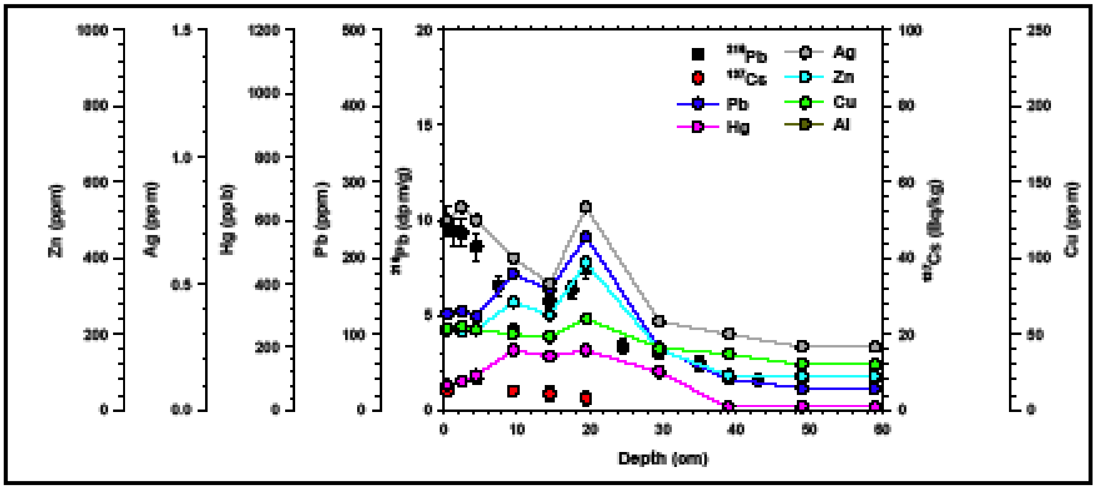

Figure 4.10: History and chronology of some metal contaminants in a sediment core (6a) from the eastern side from the mouth of the South Arm, Sydney Harbour (Data courtesy of J. Smith, 2012).

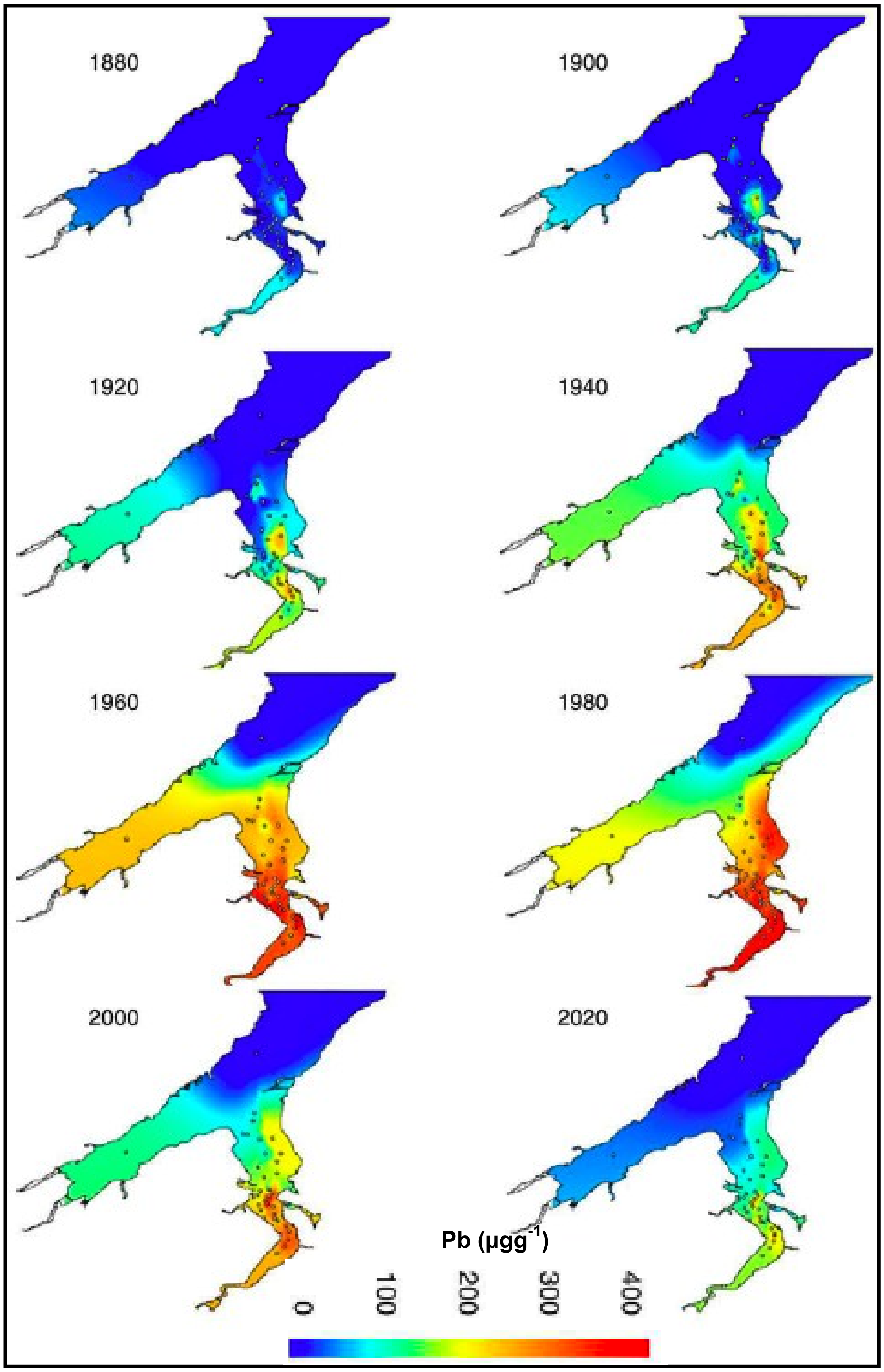

Figure 4.11 Historical reconstructions of Pb concentrations based on Pb geochronologies for sediment cores in Sydney Harbour. Extrapolation of Pb concentrations to 2020 was estimated from the model using a Pb time constant of 15 years (from Smith et al. 2009).

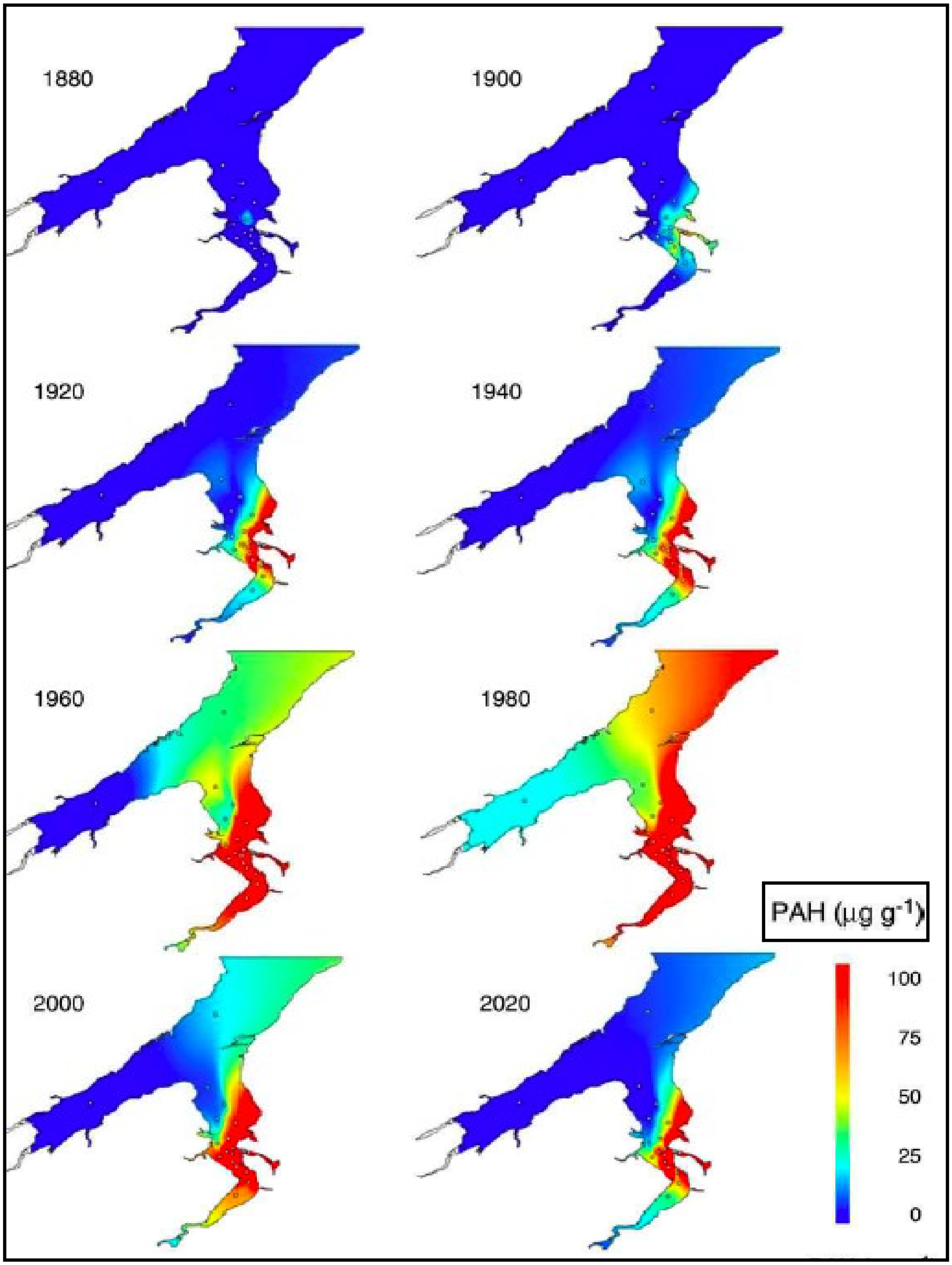

Figure 4.12-previous page: Historical reconstruction of PAH concentration based on sediment geochronologies in SH. Extrapolation of PAH concentrations to 2020 was estimated from the model using a time constant of 10 years (from Smith et al., 2009).

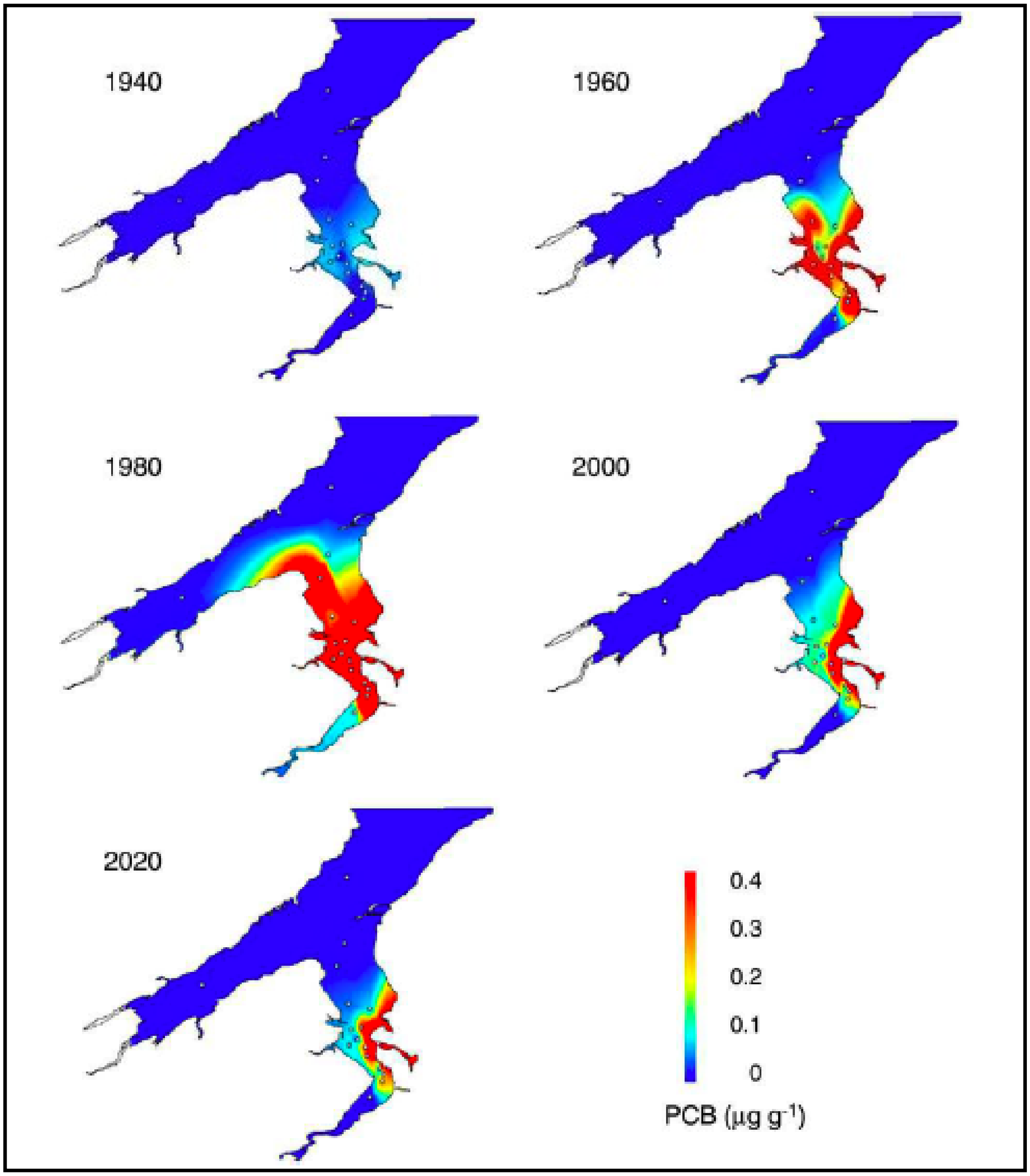

Figure 4.13: Historical reconstruction of PCB concentration based on sediment geochronologies in SH. Extrapolation of PCB concentrations to 2020 was estimated from the model using a time constant of 10 years (from Smith et al., 2009).

4.6.2 Comparison between Sydney Harbour and Halifax Harbour

Both Halifax Harbour (with the exception of Bedford Basin) and Sydney Harbour are estuarine systems with similar water depths and temperatures. They both have strong water circulation and receive fresh water runoff. The main difference between the two areas is the type of pollution affecting each area. Halifax Harbour has mainly been affected by untreated domestic pollution with high organic content over the past 100 years, whereas Sydney Harbour is mostly affected by industrial pollution caused from the steel and coking industry from 1901 to 2001. In contrast to Halifax Harbour, the pollution in Sydney Harbour is restricted mainly to the South Arm because of its connection to the tributary of Muggah Creek that served as a disposal site for the steel plant.

In both harbours, the foraminiferal assemblage in pre-impact times is dominated by calcareous species of *Elphidium* spp. and *H. orbiculare* associated with other species of less abundance. The agglutinated species in both areas are almost the same (e.g., the dominant components are *E. advena*, *A. cassis*, *S. biformis*, *Reophax* spp., and *Trochammina* spp). However, in Sydney Harbour, *Saccammina atlantica* is barely recorded and *Cribrostomoides crassimargo* is not recorded at all, even though they are both recorded in Halifax Harbour in relatively high numbers. Foraminifera in Sydney Harbour (specifically, pre-impact sediments) have more diversity (up to 38 species per 10 cc) and abundance (up to 9,000 individuals per 10cc) than in Halifax Harbour (~30 species and 6,000 individuals per 10cc).

Regarding the pollution impact, the predominantly domestic pollution in Halifax Harbour led to the development of a totally agglutinated assemblage with the complete disappearance of calcareous species resulting from continous enrichment of organic carbon in the sediments. The organic inner linings of the calcareous shells are recorded in very high percentages after the dissolution of the original shells, indicating their former presence. Their last appearance in sediments of Halifax Harbour was in the late 1960s, when Gregory (1971) recorded them in his surface samples. However, OC is not the only factor that affects the foraminiferal assemblage in Halifax Harbour, as indicated by the comparisons of foraminifera to chemical data.

In contrast, calcareous species are present throughout the pre- and post-impact sediments of Sydney Harbour. They declined somewhat in the most polluted sediments, (though not to the same level as in Halifax Harbour) as a result of their ability to tolerate metals and organic contaminants more than organic carbon-rich domestic pollution. This is supported by the presence of ostracods and other fossil groups (e.g., Pelecypods, Gastropods) that were barely noted in the highly polluted sites of Halifax Harbour. It is apparent that agglutinated species, specifically *E. advena*, *A. cassis*, *S. biformis*, and *Reophax scottii*, can tolerate both kinds of pollution. For that reason, they are recorded in significant numbers during the periods of high impact in both areas.

It is important to note that benthonic foraminifera in Sydney Harbour have flourished in the last 20 years (after the shutdown of the coking ovens in 1988 and the steel plant in 2001). This indicates that contaminated historical sediments throughout Sydney Harbour are being buried relatively quickly under cleaner sediment. Smith et al. (2009) studied the contaminant concentrations in sediment cores from Sydney Harbour and suggested 2080 as the date of complete recovery to the background levels in the harbour.

The organic-rich domestic wastes decompose relatively quickly compared to industrial wastes; thus, the benthonic foraminiferal community in Halifax Harbour is expected to recover sooner than Sydney Harbour. Benthonic foraminifera in surface sediments of Halifax Harbour recorded quick environmental recovery following advanced primary wastewater treatment for a one-year period (Chapter 2 of this dissertation). A one-year period is not sufficient to estimate a recovery rate in Halifax Harbour. However, indications are that the harbour will recover very quickly, as occured in the brief period when the treatment facility was operating. This can be assessed in the future by examining foraminifera every few years in surface samples from the same locations or close to the locations studied by Gregory (1971) and/or Dabbous and Scott (2012 – Chapter 2).

Scott et al. (2005) compared foraminifera (from short cores) in Halifax Harbour with those in New Bedford Harbor, Massachusetts that were exposed to severe industrial pollution. They reported the presence of zones in New Bedford Harbor that are totally barren of any foraminifera. They also found that the opportunistic species *E. advena* is completely absent in the New Bedford Harbor, even in pre-impact sediments. Shell deformities were found to be much more extreme in New Bedford Harbour than in Halifax Harbour. Scott et al. (2005) pointed out that pollution type is not the main factor controlling the foraminiferal assemblage in both areas but also other natural environmental factors (e.g., water depth, temperature and salinity) play important roles. For that reason, awareness of natural parameters is needed for comparison studies.

4.7 Conclusions

Foraminiferal assemblages in core sediments from Halifax Harbour and Sydney Harbour document the history and intensity of pollution in both areas. There was a decline in foraminiferal diversity and abundance throughout the time that pollutants were being discharged into the sediments. Concurrently, shell deformities and organic inner linings increased throughout the cores with the increase of pollution.

The foraminiferal records from Halifax Harbour (predominantly domestic pollution) and Sydney Harbour (predominantly industrial pollution) show a strong correlation with the kind (OC or metal) of pollution. The contamination-based changes in foraminifera in Halifax Harbour were more dramatic than those of Sydney Harbour. The domestic pollution in Halifax Harbour favoured an agglutinated assemblage and the calcareous ones completely disappeared because of their lack of tolerance to high content of OC. Organic inner linings are present in significant amounts following the dissolution of their calcareous tests because of the enrichment of organic matter in the sediment. In Sydney Harbour, both calcareous and agglutinated species are recorded in the assemblage because of the ability of calcareous species to tolerate industrial pollution better than organic-rich domestic waste.

The agglutinated species *E. advena*, *S. biformis*, *A. cassis*, and *R. scottii* are found to be opportunistic for both types of pollution, whereas the calcareous species *E. excavatum* and *H. orbiculare* can tolerate industrial pollution and to only some extent organic pollution. With severe domestic sewage, they disappear and their calcareous tests undergo a complete dissolution; however, they can survive in industrial pollution, but with an increase of deformities in their shells. It is important to note that pollutants are not the only factors that have controlled and shaped foraminiferal assemblages in both areas over the past 100 years.

Although the foraminiferal assemblages in HH and SH are similar, there are some variations in the assemblage composition of both areas. One of these variations is the complete absence of the agglutinated species *C. crassimargo* in Sydney Harbour, although it is well recorded in Halifax Harbour. Another significant variation in one of the Sydney Harbour cores is the presence of the calcareous species *A. beccarii*, which has never before been recorded in high North Atlantic latitudes with deep colder waters.

The foraminiferal assemblage in Sydney Harbour recorded an environmental recovery after the shutdown of the industrial facility in the late 1980s to 2001. This recovery is represented by an increase in diversity and abundance and a decrease in shell deformities. Since industrial contaminants are more persistent and do not degrade as quickly as organic-rich domestic sewage, we believe that the natural foraminiferal assemblages in Halifax Harbour will recover at a quicker rate than in Sydney Harbour.

Chapter 5: Conclusions

5.1 Foraminiferal distribution in surficial samples of Halifax Harbour

The monitoring of benthonic foraminifera in surface sediments in Halifax Harbour during the commissioning of new wastewater treatment plants between 2007 and 2009 provides evidence of relatively rapid environmental recovery in the treated areas of the harbour in response to the treatment process. Due to the high content of organic carbon in HH sediments, the presence or absence of calcareous shells is a key foraminiferal proxy of this recovery.

During the operation of the Halifax WWTF in 2008, there was a return of calcareous species such as *Elphidium* spp. in the treated area (inner harbour). Additionally, there was an increase in both diversity and abundance of the foraminiferal assemblage during the treatment period and a decline in both shell deformities and organic inner linings. These results are consistent with previous observations of the behavior of benthonic foraminifera in highly polluted areas, as discussed in detail in Chapter 1 and described in the literature (e.g., Alve, 1995a; Murray, 2000; Scott et al., 2001). These improvements in the assemblage highlight the resilience of foraminifera and show that they can respond very rapidly (i.e., within months or even weeks) to changes (either positive or negative) in environmental conditions, as indicated by previous authors (Tobin et al., 2005).

Although the observed recovery in calcareous species indicates that enrichment of organic carbon in the waste material plays an important role in the foraminiferal assemblage of Halifax Harbour, the spatial distribution of benthonic foraminifera throughout the area reflects variable (either natural or human-induced) conditions. This also coincides with comparisons between foraminiferal data and available chemical analyses. In the outer harbour, which has little pollution, the assemblage is highly diverse (27-33 species/10cc), dominated by calcareous species (~90 %), and has low levels of shell deformities and inner linings. Likewise, foraminifera in Bedford Bay, located to the north of Bedford Basin where the fresh water input is strong, are represented only by coarse-grained agglutinated species such as *A. cassis* and *S. atlantica* that tolerate turbid conditions with sandy mud sediments. In other geographic areas of the harbour there is a combined influence of both metals (Hg, Cu, Pb, Zn) and OC of the distribution and composition of foraminiferal assemblage. From the trends of benthonic of foraminifera with chemicals in the surface sediments, it can be inferred that OC have more influence on foraminifera than metals in most of the studied sites.

On the other hand, there are some locations (e.g., Tufts Cove) where metals play a more significant role in the shape and distribution of foraminifera than OC. It is important to note that other natural environmental variables (e.g., temperature, salinity, substrates) could affect the foraminiferal assemblage. Consequently, these environmental variables should be understood and caution should be considered before interpreting any change in foraminifera as a sign of the presence or absence of contamination.

This part of the study will serve as a baseline for any future long-term monitoring throughout the harbour. It also indicates that the present level of treatment will improve the water quality of Halifax Harbour. This coincides with the significant reduction in fecal coliform bacteria levels in water throughout the harbour over the two years following the construction of the new WWTFs as a signal of improvement in the overall quality of the harbour's environment after the treatment process (HRM, 2011). The improvement in water quality during this period allowed the opening of local beaches for swimming after three decades of closure. However, no specific date for complete environmental recovery can be provided because a two-year period of wastewater treatment is not sufficient to estimate a recovery rate.

In addition, this study documents the usefulness of periodic sampling in short-term studies to distinguish seasonal-derived from pollution-derived environmental changes. It is important to note that the treatment process that is currently taking place in Halifax Harbour does not include direct remediation (i.e., removal of historical contaminants from the sediments) but is instead reducing the ongoing input of contaminants. This means that any recovery due to the treatment process will be mainly in the water quality, not the sediments. The sediments need a certain period of natural sedimentation to cover the contaminated sediments with new sediments that have less or no contamination.

Furthermore, this study offers a cost effective and quick monitoring tool for remediation studies that can be applied worldwide. It also suggests a preference for a repeated sampling strategy instead of a one-time examination for short-term monitoring purposes for area under remediation or treatment. Additionally, this study issues a warning about the awareness of other environmental variables (either natural or human-induced) to render the interpretation of foraminiferal analysis more valid and reliable. Making comparisons either between polluted and unpolluted areas or between areas affected with different types of pollution or even between different variables in the same area gives more credence to study results.

5.2 Historical reconstruction of pollution in Halifax Harbour based on foraminifera in sediment cores

Analyses of the foraminiferal assemblages along six cores that penetrate sediments pre-dating European settlement starting in 1749 helped to document the pollution history in Halifax Harbour and thus construct a baseline environment for the current treatment process. In pre-impact core sediments of Bedford Basin, foraminifera are characterized by low diversity (<7 species/10cc) and abundance (<1000 individuals/ 10cc). In addition, the assemblage is mainly predominated by agglutinated species whereas the calcareous ones are rarely seen or are completely absent. Although this area has received effluent from a secondary wastewater treatment plant since 1970, the fresh water runoff from the Sackville River and other rivers that pour into the area seem to be the main reason for limited diversity and abundance in older sediments. This was clearly indicated by comparisons between foraminiferal proxies and chemicals along vibracore 2. However, based on the other vibracore that was collected from almost the same area, it appears that both OC and metals have an influence, to a certain degree, on benthonic foraminifera.

In the central part of the harbour, where core 8 was recovered, the benthonic foraminiferal assemblage helps to mark an environmental zonation similar to the model (Fig. 1.3b) described in Chapter 1. The assemblage of pre-impact conditions (our baseline environment) in core 8 has high diversity (~30 species/10 cc), abundance (>5000 individuals/10cc), and a negligible number of deformed shells. The calcareous species predominate the assemblage with values up to 90%. The gradual input of organic carbon-rich waste changed benthonic foraminifera dramatically and led to the development of an agglutinated assemblage. The extreme enrichment of contaminants (OC and Hg, Cu, Pb, Zn) associated with Halifax's expansion in the last 50 years caused the dissolution of calcareous shells, leaving their organic inner linings in very high percentages (>35%). Likewise, shell deformities increased gradually to reach similar high levels in the upper 40-50 cm of the core. The trends of foraminifera against the chemicals along this core indicated that both organic carbon and metal contaminants strongly influence the shape and composition of the foraminiferal assemblage. This can be inferred from the strong correlation between different foraminiferal parameters with these different contaminants.

The background levels for the foraminiferal assemblage in the Northwest Arm are 7-10 species for diversity, 750-900 individuals for abundance, and <3% for both organic inner linings and shell deformities. The comparisons between foraminiferal data and chemical analysis of this core indicated that the metals have a stronger influnce on foraminifera than organic carbon. This was presented by the strong correlations between foraminifera and the recorded high values of metals (from Williams, 2010) in the sediments from the past 90 to 100 years.

The foraminiferal assemblage in the outer harbour represents the highest recorded values of foraminiferal species richness and abundance throughout the area. The number of species reaches 30 species/10cc and the abundance is as high as 6,000 individuals/10cc, with great dominance of calcareous species. These high values indicate open marine conditions with no or low pollution for this part of the harbour. These characteristics are also present in surface samples collected from the same area during a two-year period (Chapter 2). Unfortunately, the vibracore sediments used for this study were not age-dated due to a lack of funding. However, the foraminiferal trends can be correlated (at least in the last century) to the chronological pollution history of the area established by previous workers (e.g., Buckley et al., 1995; Williams, 2010).

5.3 Comparison of Halifax Harbour (HH) to Sydney Harbour (SH)

Comparing different types of environments (e.g., polluted vs. unpolluted; domestically polluted vs. industrially polluted) helps to explain the foraminiferal response to variable environmental conditions. This approach is applied in the third part of this study, where foraminiferal assemblages in core sediments from Halifax Harbour (mainly domestic pollution) were compared to those from Sydney Harbour (mainly industrial pollution). It is interesting to note that degradation in the foraminiferal assemblages is correlated with the type and amount of pollution input in both areas. Generally, there was a decline in diversity and abundance throughout time in the sediment records of both areas as a result of pollutant discharge. In contrast, shell deformities and organic inner linings became more abundant throughout the cores with the increase of pollution to reach their highest values during the time of maximum pollution (after 1960s in HH, and from the 1950s to the late 1980s in SH).

In Halifax Harbour, the contamination-based changes in foraminifera were dramatic enough to develop an agglutinated assemblage after a complete disappearance of the calcareous species that are less tolerant of organic carbon enriched sediments. Thus, organic inner linings become abundant (up to 50%). In contrast, calcareous species are still abundant even in the sediments of Sydney Harbour. This is because the main contaminants in Sydney Harbour (mainly metals, PAHs, and PCBs, but much lower in total organic carbon) can be tolerated by calcareous foraminifera. The agglutinated species *E. advena*, *S. biformis*, *A. cassis*, and *R. scottii* are found to be opportunistic for both kinds of pollution. Although the calcareous species *E. excavatum* and *H. orbiculare* were found to be tolerant of both kinds of pollution, they undergo complete dissolution with severe enrichment of organic carbon.

The agglutinated species *C. crassimargo*, which was recorded in Halifax Harbour, was not recorded at all in Sydney Harbour. Interestingly, the calcareous species *A. beccarii* is present in core 4 of Sydney Harbour. To our knowledge, this species has not previously been recorded in cold waters at this latitude. Because of the absence of this species in the other core from Sydney Harbour and the wide sampling intervals, further research should be done on samples that cover different geographic locations in the harbour to clarify the presence and abundance of this species in the harbour.

This part of the study indicates that pollution type has had a major influence on foraminiferal populations for the past 100 years in both areas. Nevertheless, it is important to note that pollution is not the only factor that affects foraminiferal assemblage. The record of high shell deformities in deep sediments (older than 200 years) in both vibracore 7 in Halifax Harbour and vibra core 4 in Sydney Harbour support this point of view. It also indicates that pollution in Halifax Harbour has stronger effect on benthonic foraminifera and may be of longer duration than that of the studied part of Sydney Harbour. Foraminifera in core sediments in SH clearly document an ongoing environmental recovery (upper 10 cm) since the shutdown of the main source of industrial pollution between the late 1980s and 2001. Because of the persistence of the metals and organic contaminants relative to raw sewage rich in OC, it is possible that Halifax Harbour will recover at a faster rate than Sydney Harbour. The present author agrees with Tobin et al. (2005) that a 10 cm sampling interval does not provide sufficient temporal resolution for paleoenvironmental reconstructions of the past 200 years. Most coastal areas around the world have very low sedimentation rates (1-2mm), so a 10 cm sampling interval would only cover a period of approximately 50 years.

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Appendix 1—Copyright Permission Letters

Cushman Foundation for Foraminiferal Research
http://www.cushmanfoundation.org

June 26, 2012

Saad Dabbous
Earth Sciences Department,
Dalhousie University, Halifax
Nova Scotia B3H4J1, Canada
Tel. 902-494-3673

Dear Saad Dabbous, Permission is granted to include a manuscript version of your paper, "*Short-term Monitoring of Halifax Harbour (Nova Scotia, Canada) Pollution using Benthonic Foraminifra as Proxies*", Saad A. Dabbous and David B. Scott, Journal of Foraminiferal Research, 42, p. 187-206, 2012, as a chapter in your thesis. Permission is also granted for the material described above to be included in the copy of your thesis that is sent to the Library and Archives of Canada (formerly National Library of Canada) for reproduction and distribution.

Sincerely,

Jennifer Jett

Secretary/Treasure, Cushman Foundation
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Appendix 2 (A-F)—Foraminiferal data for Halifax Harbour grab samples

Counts of foraminifera from grab samples of Halifax Harbour for the six sampling cycles (October 2007, March 2008, July 2008, October 2008, April 2009, and August 2009) are to be permnantly archived as Electronic supplementary material at Dalhousie University. Each count of these counts includes for every site location:

1- Diversity (number of species per ten cm^3).
2- Total abundance (total number of individuals per ten cm^3).
3- Percentages of shell deformities and organic inner linings per ten cm^3.
4- Percentages of calcareous species per ten cm^3.
5- Realtive abundance for each individual species.

Appendix 3 (A-F)—Foraminiferal Data For Halifax Harbour Cores

Counts of foraminifera in Halifax Harbour six vibracores (VC2, 3,5,6,7, and 8) are to be permnantly archived as Electronic supplementary material at Dalhousie University. Each count of these counts includes for every core:

6- Diversity (number of species per ten cm^3).
7- Total abundance (total number of individuals per ten cm^3).
8- Percentages of shell deformities and organic inner linings per ten cm^3.
9- Percentages of calcareous species per ten cm^3.
10- Realtive abundance for each individual species.

Appendix 4 (A-B)—Foraminiferal Data For Sydney Harbour Cores

Counts of foraminifera in Sydney Harbour vibracore 4 and 15 are to be permnantly archived as Electronic supplementary material at Dalhousie University. Each count of these counts includes for every core:

11- Diversity (number of species per ten cm^3).
12- Total abundance (total number of individuals per ten cm^3).
13- Percentages of shell deformities and organic inner linings per ten cm^3.
14- Percentages of calcareous species per ten cm^3.
15- Realtive abundance for each individual species.