Environmental Geology of Halifax Harbour, Nova Scotia

Gordon B. J. Fader
Dale E. Buckley
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2

SUMMARY

This paper demonstrates the importance of integrated studies of marine geology and geochemistry in the environmental management of an urbanized coastal inlet, using Halifax Harbour, Nova Scotia, as an example. The harbour receives 170 million litres of raw sewage per day; other sources of contamination include landfills, industrial activity, surface runoff and dredging. The level of contamination by metals in surficial sediments in Halifax Harbour is among the highest anywhere recorded in marine harbours, and is a result of sediment trapping and lack of flushing. Geological and oceanographic conditions strongly influence the present environmental quality of the harbour; assessment of environmental quality, and the design of waste-water management systems in urban harbours, are fundamentally dependant on detailed knowledge of sediment transport, deposition and erosion.

RÉSUMÉ

En prenant pour exemple le cas du Port de Halifax, le présent article montre l'importance de l'intégration d'études de géologie et de géochimie dans la gestion environnementale des bras de mer urbanisée. Quotidiennement, 170 millions de litres d'eaux d'égout sont déversés dans le port. Les décharges, les activités industrielles, les eaux de ruissellement et le dragage constituent d'autres sources de contamination. Le niveau de contamination des métaux des dépôts sédimentaires superficiels du Port de Halifax est parmi les plus élevés des ports marins étudiés dans le monde, et cela est la conséquence de la rétention des sédiments et du manque de chasse d'eau. Les conditions géologiques et océanographiques sont des facteurs lourds de la qualité actuelle de l'environnement du port; l'évaluation de la qualité de l'environnement et la conception de systèmes de gestion des eaux usées en port urbains dépendent d'abord des connaissances détaillées des modes de transport, de sédimentation et d'érosion des sédiments.

INTRODUCTION

Halifax Harbour is the largest port along the Atlantic seaboard of Canada, the east coast home of the Canadian Navy, and a major trans-shipment facility for large quantities of bulk and container materials (Fig. 1). The harbour is a significant lobster and finfish resource, and a major recreational facility for the surrounding communities. However, it also receives approximately 170 million litres of raw sewage per day from about 50 outfalls from the cities of Halifax and Dartmouth. Other sources of contamination are industrial activity related to shipbuilding and repair, surface drainage, old landfill sites, and dredge spoils and debris on the harbour bottom.

In 1977, the Metropolitan Area Planning Commission proposed that a single regional primary sewage treatment facility be constructed in the outer part of Halifax Harbour, with an outfall of treated effluent extending seaward into the approaches to Halifax Harbour. A federal-provincial agreement was signed in 1988 to develop this facility. In

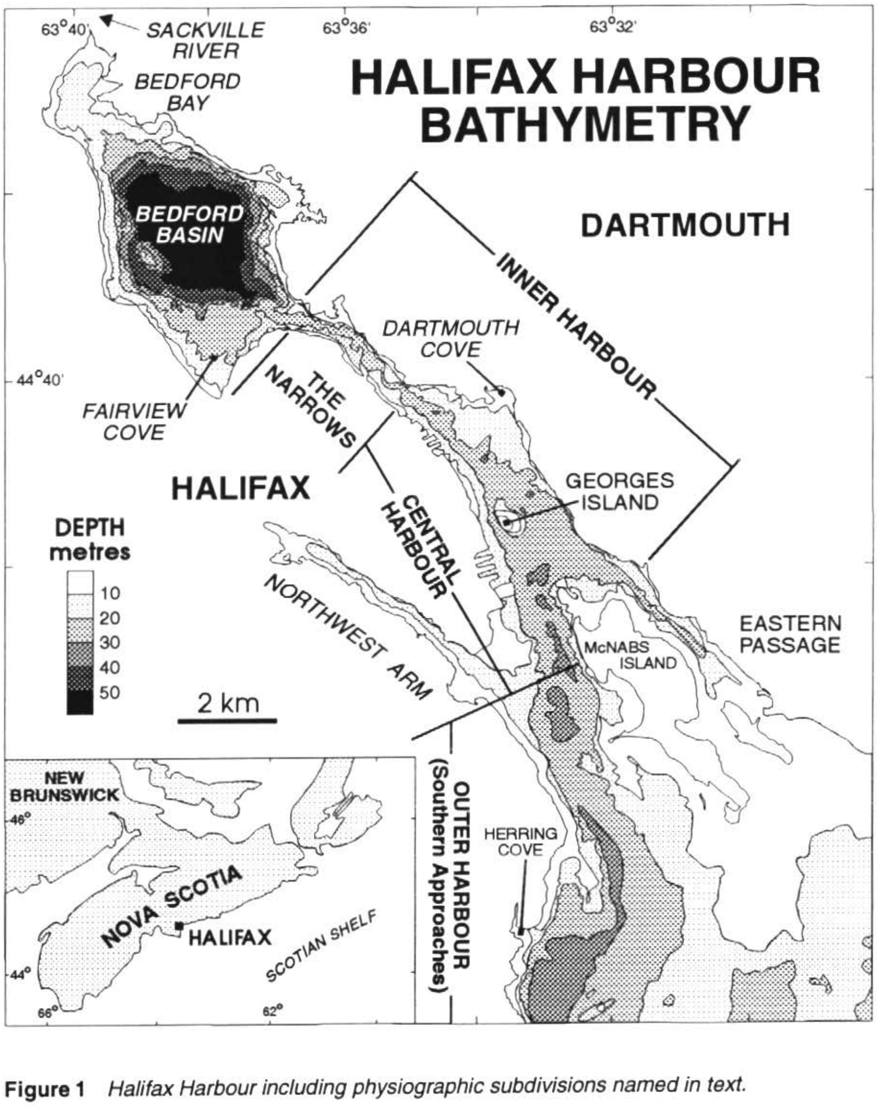


Figure 1 *Halifax Harbour including physiographic subdivisions named in text.*

1989, a report by the Nova Scotia Environmental Control Council identified major information gaps concerning the location of the plant and outfall, and the associated marine data base. As a result of this report, the Province of Nova Scotia commissioned the Halifax Harbour Task Force (Fournier, 1990), and together with a Federal Science Advisory Committee on Halifax Harbour (Nicholls, 1989), reviewed the proposed regional sewage treatment plan, focussing on the marine environment and related science and engineering issues. For further details of the assessment process itself, see C. Eyles, in press.

The Atlantic Geoscience Centre, Geological Survey of Canada, participated as an active member in assessing the marine environmental conditions and quality of the harbour, and conducted considerable additional research on the marine geology and geochemistry. These data, together with oceanographic and other environmental information, were used by the Halifax Harbour Task Force to recommend an alternate location for the consolidated sewage outfall in the inner harbour, rather than the earlier proposal for discharge in the approaches to Halifax Harbour. This recommendation was supported by the subsequent Environmental Assessment Panel. This decision was considered unconventional to many accepted practices, where sewage outfalls are located as far at sea as possible. The philosophy adopted in the final choice was one of containment *versus* dispersion of wastes. Geological and geochemical data provided a basis for understanding the present distribution and transport pathways of sediments and contaminants, and a basis on which to assess various sewage management options.

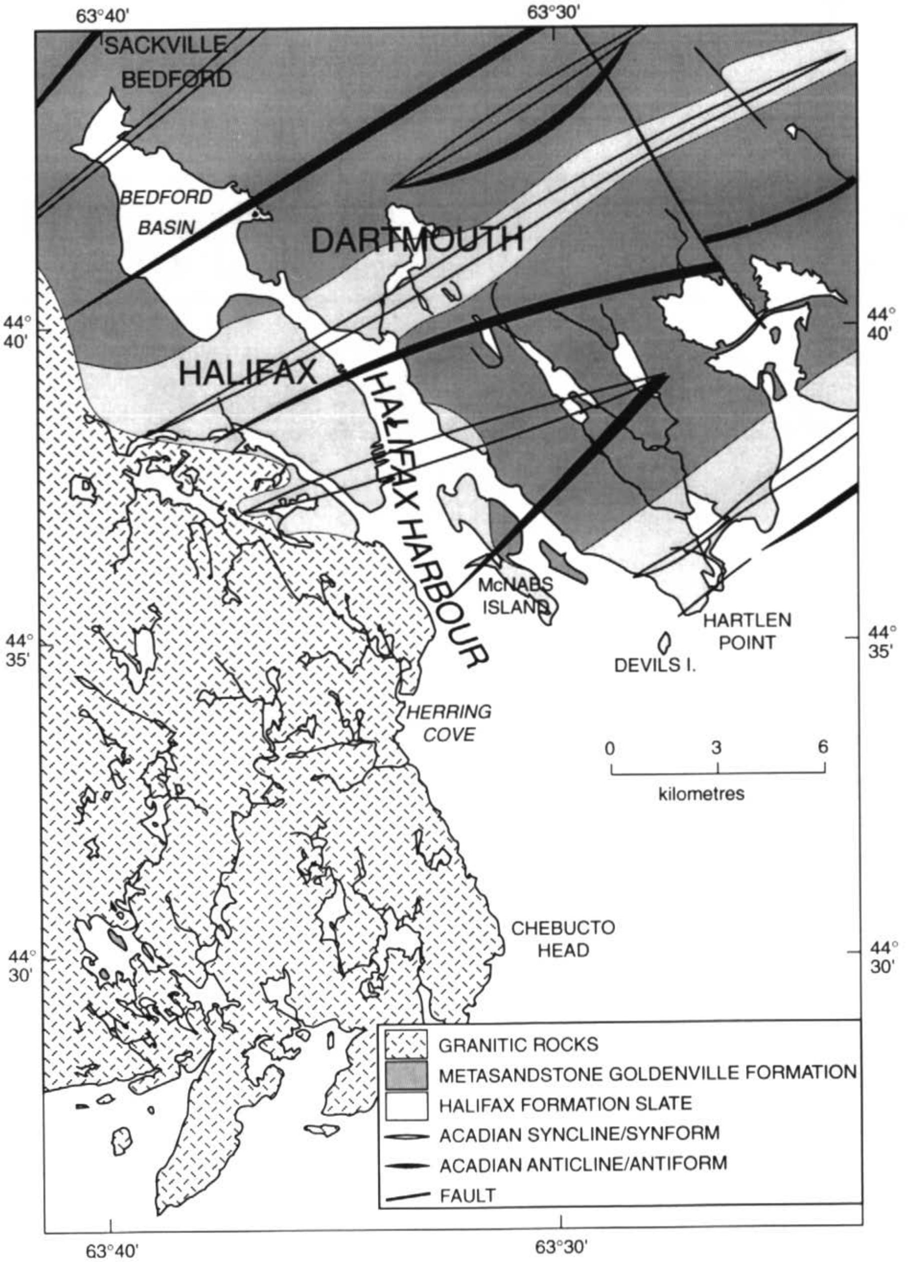


Figure 2 *Simplified bedrock geological map of the Halifax-Dartmouth area with the location of major structural elements (anticlines are solid slashes; synclines are open slashes; adapted from Keppie, 1982).*

The purpose of this article is to illustrate and summarize 1) the methodology used in the study of the harbour, 2) the importance and relative role of geological and geochemical studies, 3) the integration of the various disciplines, 4) the major scientific findings as they relate to waste-water management, and 5) recommendations for similar studies in other areas.

THE GEOLOGICAL FRAMEWORK OF HALIFAX HARBOUR

The data used in the geological framework interpretations were mainly collected during surveys in 1988, 1989, and 1990 (OceanChem Group Ltd., 1988; Buckley *et al.*, 1989; Miller and Fader, 1989; Nichols, 1989; Miller *et al.*, 1990; Fader *et al.*, 1991; Fader and Miller, 1992). The data base consists of a dense regional grid of echo sounder data, 100 and 500 khz side-scan sonograms, mid- to high-resolution seismic reflection profiles, cores, grab samples, epibenthic dredge hauls, bottom photographs and remotely operated vehicle (ROV) video information. A variety of seismic reflection systems were tested in the harbour to provide a combination of very high resolution with maximum penetration. Modifications were made to existing systems, and the final, most appropriate configuration for the harbour used a Huntec boomer and a surface towed IKB Seistec with line and cone array, together with a Datasonics Bubblepulser and an Elac 12 khz ship's echo sounder. Long piston cores and vibrocores of sediment were collected for subsurface stratigraphic information and geochemistry (Buckley, 1988; Fitzgerald *et al.*, 1989; Fader *et al.*, 1993).

Early reports on the formation of Halifax Harbour attributed its origin to the presence of suggested northwest-southeast structural lineaments or faults (Cameron, 1949). No evidence was found for structural offset and the presence of such interpreted faults in bedrock beneath the harbour. None of the major synclines and anticlines on either side of the harbour are horizontally displaced (Fig. 2). Aeromagnetic data also indicate continuity beneath the harbour.

An ancient Sackville River, and another drainage system originating from the northeast, flowed through Halifax Harbour. The second system existed in the location of a series of lakes in Dartmouth that presently empty into Dartmouth Cove. The term Ancient Sackville River, as defined by King (1970), is used for the entire system. Before Pleistocene glaciations, Bedford Basin likely did not exist. The Ancient Sackville River continued on its course across a gently dipping Cretaceous peneplain through the present area of Bedford Basin and out of the harbour. A major fractured bedrock anticline (Faribault, 1908) lies below the centre of Bedford Basin. With the onset of glaciation, the glaciers followed the course of the early fluvial drainage system, eroding the fractured rocks and excavating the present 70-m deep depression of Bedford Basin. The area now occupied by Halifax was left as a topographic high.

Widespread distribution of till beneath the harbour suggests that the area was occupied by glaciers several times during the Pleistocene. The last (late Wisconsin) glaciation covered the entire harbour area and extended across the Scotian Shelf to its edge (King and Fader, 1986).

Recent studies have identified a post-glacial low sea-level stand at 65-70 m water depth (Stea *et al.*, 1993; Fader *et al.*, 1993) at about 11.65 ka. Most of Halifax Harbour was subaerially exposed at this time, with the Ancient Sackville River draining through the harbour to Chebucto Head. A series of lakes existed in the inner harbour surrounding Georges Island, in the Eastern Passage, the Northwest Arm, adjacent to western McNabs Island, and in several areas of the western part of the outer harbour (Fig. 3).

The post-glacial marine transgression of the harbour reworked glacial and lacustrine sediments into lag gravel and sandy deposits. As sea level rose, small lakes in the harbour were inundated, forming a series of estuarine embayments (Edgecombe, 1994). The final breach of the Narrows sill, at 5.8 ka (Miller *et al.*, 1982), resulted in the modern configuration of the harbour. Many gravel areas of the inner harbour are

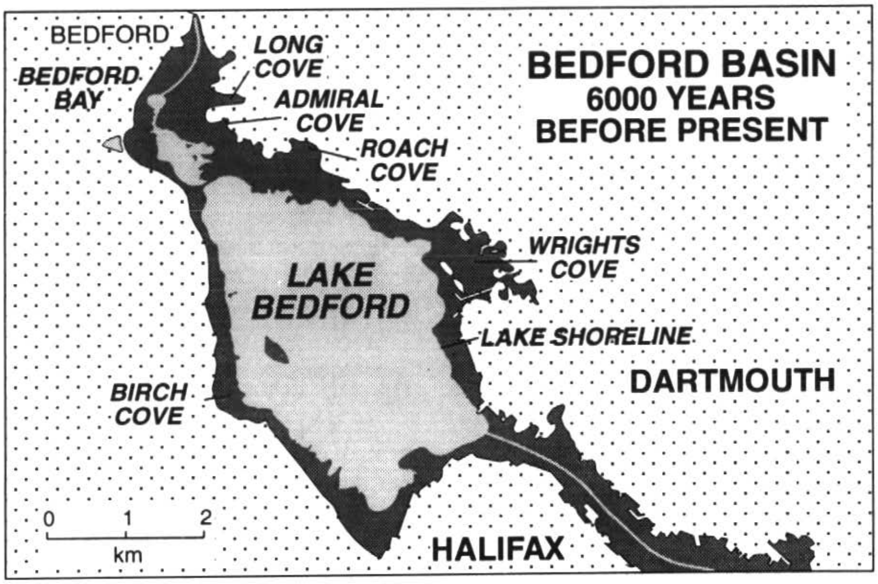


Figure 3 *Paleographic reconstruction of Bedford Basin just before the Holocene marine incursion. The location of the former shoreline is based on two basin-fringing boulder berms at a present depth of 23 m. See text for details.*

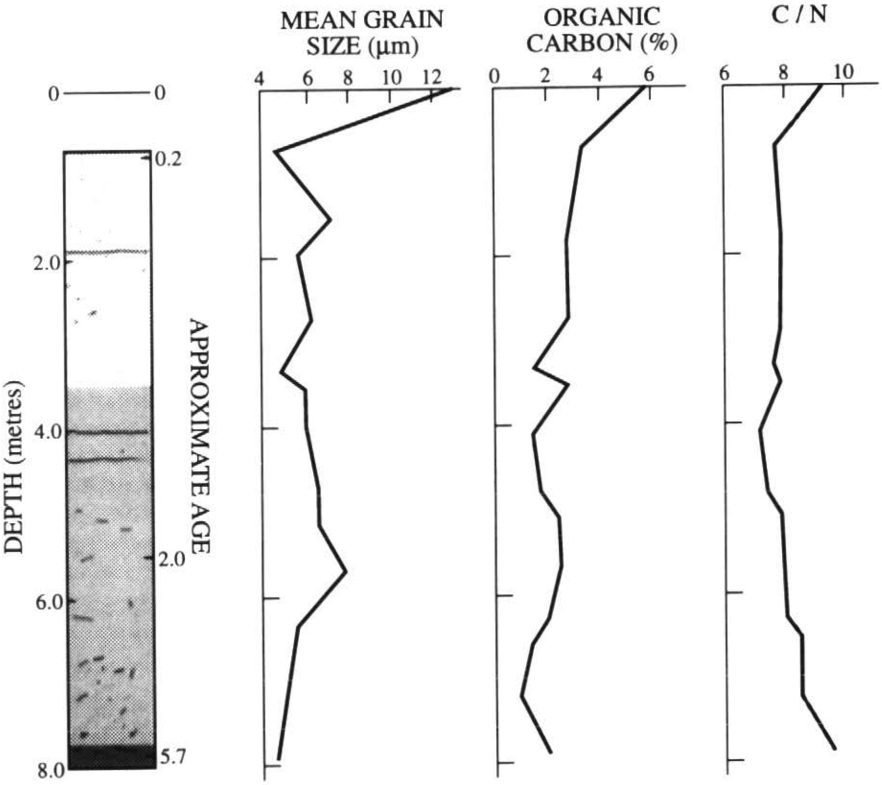


Figure 4 *Sediment core from Bedford Basin showing a sequence of sediments dating to 8 ka. The deepest sediments contain fresh-water brachiopods and marsh vegetation. The quantity of organic matter preserved increased during the past 5000 years as the basin became more marine; the carbon to nitrogen (C/N) ratio also reflects the transition from a terrestrial fresh-water or brackish environment, to a marine environment, up to about 200 years ago (0.2 ka). Recent changes probably reflect contamination.*

relict surfaces formed during the Holocene marine transgression, and remain exposed on the seabed in areas where high current energy has prevented deposition of fine-grained Holocene mud. A sediment core sample from Bedford Basin (Buckley, 1988: Fitzgerald *et al.*, 1989) provided evidence of the transition from lake conditions, through brackish marine conditions, to restricted marine conditions over the past 6000 years (Fig. 4).

The geological framework of Halifax Harbour, which has evolved over millions of years, establishes the geomorphological control for hydrodynamic and sedimentary processes that determine the present nature of the harbour. Old fluvial, lacustrine and glacial deposits, buried under more recent sediments, can continue to influence the geochemical nature of recent sediments.

PHYSIOGRAPHIC DIVISIONS AND CHARACTERISTICS

We have divided Halifax Harbour into three divisions from south to north termed: outer Halifax Harbour; inner Halifax Harbour including the central harbour, Northwest Arm and Eastern Passage, and Bedford Basin including Bedford Bay (Fig. 1). The entire harbour has sometimes been referred to as Halifax inlet (Nicholls, 1989); however, we propose to use the term Halifax Harbour for the body of water extending north of a headland line from Hartlen Point to Chebucto Head (Fig. 5). Areas seaward, to the southeast of this line are part of the inner Scotian Shelf.

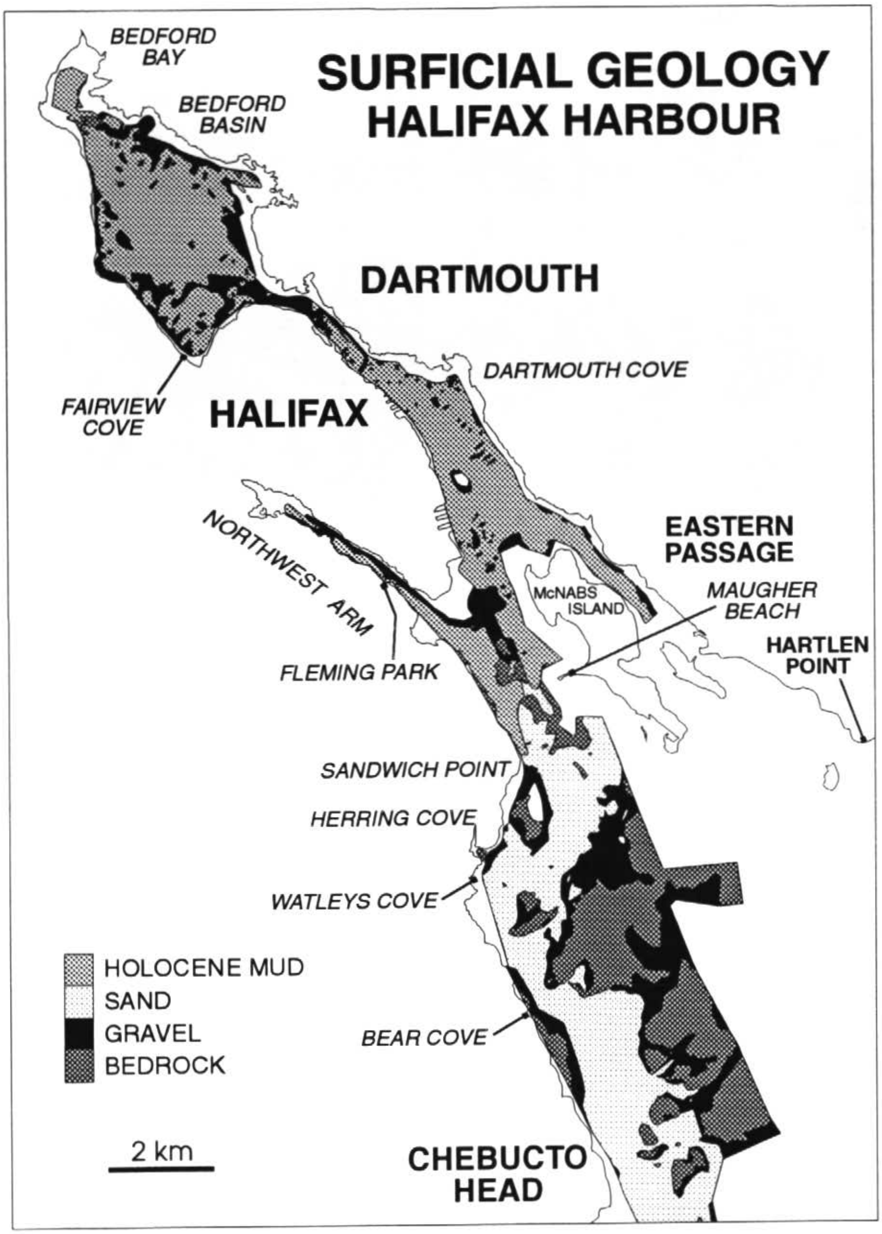


Figure 5 *Distribution of surficial sediment types in Halifax Harbour. Note the transition from inner harbour muddy sediments to outer harbour transgressive sands and gravels.*

Bedford Basin

Bedford Basin is a bowl-shaped depression at the head of the harbour with a maximum depth of 71 m (Fig. 1). It is joined in the north with Bedford Bay, a shallow embayment into which the Sackville River drains. This river is the major drainage conduit for areas to the north and east of Halifax Harbour. The basin is mostly mud covered in areas deeper than 20 m, but the shallow areas consist of gravel in the cobble and boulder range with a few areas of outcropping bedrock.

Three separate bodies of Holocene mud up to 10 m thick occur in Bedford Basin, in Fairview Cove, Bedford Bay and the main central area of the basin (Fig. 5). They are separated from one another by bedrock-controlled sills, sometimes covered with till and/or gravel. These modern depocentres also reveal a similar distribution of subsurface lacustrine sediments deposited in early post-glacial time. Bedrock crops out on the east side of the basin adjacent to Long Cove, Admiral Cove, Roach Cove, and Wrights Cove (Fig. 3). Other areas of hard seabed consist of transgressive sand and gravel deposits formed as lag gravel overlying till.

A parallel set of boulder berms, separated by 12-15 m horizontally, and 2 m in depth, surround the entire nearshore area of Bedford Basin at a present depth of 23 m. The boulder berms define the location of two paleo-shorelines of an ancient fresh-water lake which occupied the area of Bedford Basin in late glacial to early Holocene time (Fader *et al.*, 1994). Floating ice masses concentrated the boulders as push ridges.

Inner Halifax Harbour

A new technology for marine seabed mapping, multibeam bathymetry, was applied to the study of the inner (Courtney, 1993) and outer Halifax Harbour (Courtney and Fader, 1994; Fig. 6). These systems provide decimetre depth resolution and 100% coverage of seabed morphology, thus enabling correlation of morphologic features on conventional side-scan sonar or bottom profile records with greater accuracy (Courtney and Fader, 1994; Fader *et al.*, 1994).

The Narrows

The Narrows is a geographic junction between Bedford Basin and the central harbour, having a sill at a depth of approximately 20 m. The seabed of the Narrows is composed of gravel with boulders and some outcropping bedrock (Fader *et al.*, 1991) but with patches of a thin veneer of Holocene mud. A former channel of the Ancient Sackville River can be clearly identified (Courtney and Fader, 1994).

Central Harbour

This area of the harbour is adjacent to the downtown areas of the cities of Dartmouth and Halifax and is 20-30 m in depth. The main body of Holocene mud begins in the southern Narrows and continues southward to the Maugher Beach area on McNabs Island (Fig. 5). Although the seabed appears generally flat and featureless, several drumlins protrude through the mud floor (Fig. 6). To the northeast of Georges Island is a small submerged drumlin with a dredged upper surface. The most northern mud deposit, up to 7 m thick (Fig. 7), formed in the lee of Georges Island under flood-tide-dominated flow. Seismic reflection data indicate the presence of a thick sequence of estuarine/lacustrine sediments overlain unconformably by a thin layer of sand and thick Holocene mud (Fig. 8). The largest continuous body of Holocene mud in the harbour is found southeast of Georges Island. It is more than 9 m thick and is charged with methane gas.

A large area of the seabed, between Ives Knoll and Halifax City, consists of gravel-covered till. Holocene mud is patchy or absent (Fig. 7) as a result of stronger currents in this constricted part of the harbour. Ives Knoll is an area of coarse sediment consisting of transgressive (lag) gravel overlying till. Ives Knoll has been the preferred location proposed by Halifax Harbour Cleanup Incorporated for the construction of an artificial island for a sewage treatment facility (see below and C. Eyles, in press.)

The Northwest Arm is a northern extension of the central harbour west of Halifax, and is mostly a mud-bottomed narrow linear depression approximately 10 km in length (Fig. 5). Currents have been strong enough to prevent fine-grained sediment deposition, so that gravel and bedrock are exposed in the constricted area of the Arm. Eastern Passage is a southern extension of the central harbour to the east of McNabs Island; a small outlet connects Eastern Passage with the outer harbour.

Outer Halifax Harbour

To the north, in the inner harbour, the seabed is dominated by Holocene mud (Fig. 5). South of Sandwich Point, the outer harbour consists of exposed bedrock, gravel and sandy-silty sediment with little or no mud. The outer harbour is dominated by a deep sand-bottomed, western channel, 30-40 m in depth (see Fig. 1). On the eastern side of the outer harbour, the seabed is very shallow with large shoal areas of exposed bedrock and boulder gravel. The outer harbour is influenced by large storm-driven waves which move cobbles in 20 m water depth, thereby preventing the accumulation of fine sediment. The gravel is a nearshore equivalent of the Sable Island Sand and Gravel Formation (King, 1970; King and Fader, 1986) found on the inner shelf and bank areas of the Scotian Shelf.

The morphology of the outer harbour is dominated by a deep channel that hugs the western shoreline (see Fig. 1). The channel continues for more than 30 km further seaward beyond Chebucto Head, cutting across the inner Scotian Shelf (Loncarevic *et al.*, 1994).

GAS-CHARGED SEDIMENTS

Both the Holocene mud and the older lacustrine/estuarine sediments of Halifax Harbour display large areas of gas-charging, where acoustic energy from

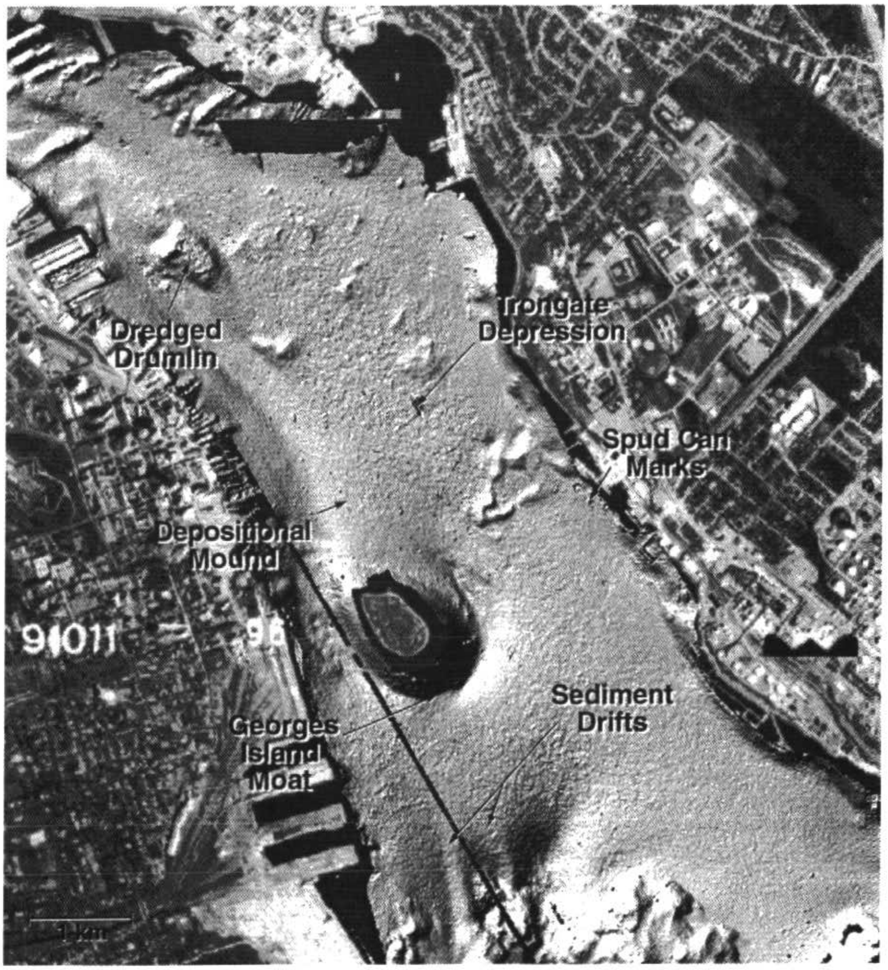


Figure 6 *A multibeam bathymetric image of a section of inner Halifax Harbour presented in a shadowgram format with artificial illumination from the northwest. Note the scour moat around Georges Island, the associated depositional mound and related sediment drifts recording principal current direction. See Figure 1 for location.*

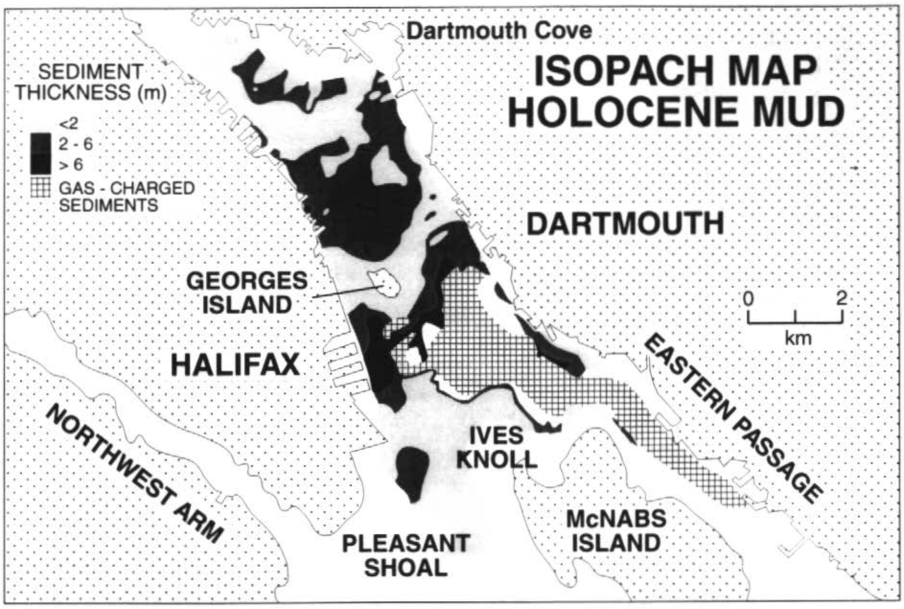


Figure 7 *Isopach map of Holocene mud in the inner harbour. Clearly defined depositional centres occur to the north and southeast of Georges Island. The thickness of the sediment southeast of Georges Island cannot be measured because of the presence of methane gas which prevents penetration of acoustic energy from the seismic reflection systems.*

the high-resolution seismic reflection systems will not penetrate and resolve subsurface stratigraphic reflections (Fig. 9). It occurs at a variety of depths, ranging from virtually at the seabed in Bedford Basin to 15 m below the seabed in the outer harbour. Gas is represented on the seismic reflection profiles as zones of incoherent reflections accompanied by a lack of acoustic penetration and the presence of discontinuous high-intensity reflections (Knebel and Scanlon, 1985; Keen and Piper, 1976; and Fader, 1991). This effect is referred to as acoustic masking or acoustic blanking, and is attributed to the presence of interstitial gas within the sediments (Hovland and Judd, 1988; see also Hart and Barrie, pages 172-183 this volume).

The gas most frequently associated with this characteristic is biogenic methane, which is formed during bacteriological decay of organic matter at shallow depth within anoxic unconsoli-

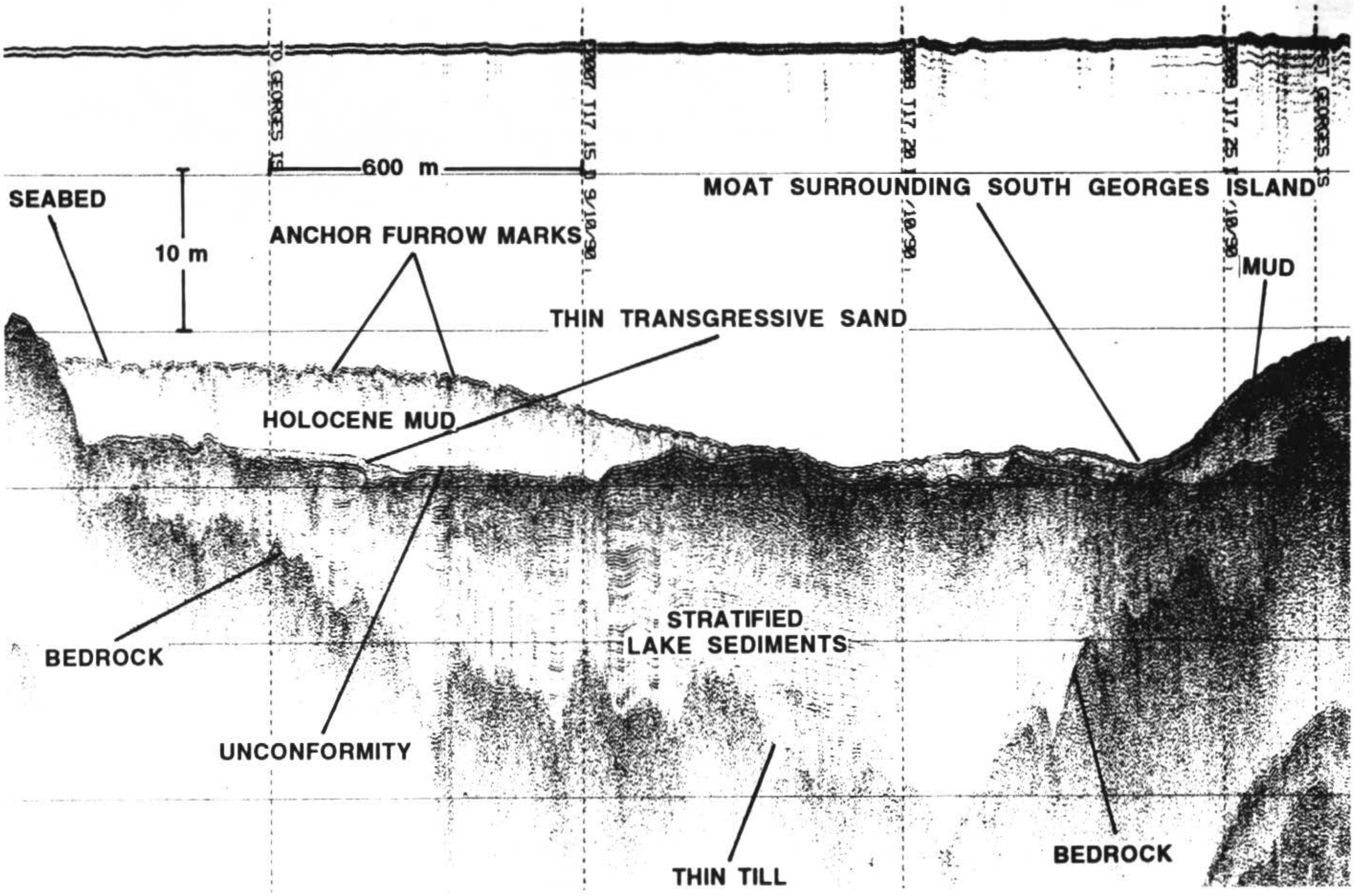


Figure 8 *High-resolution seismic reflection profile and interpretation from inner Halifax Harbour, to the east of Georges Island, showing the typical stratigraphic sequence. The basal sequence is a thin till overlying a rough bedrock surface. The basin infill of high-intensity continuous coherent reflections represent lacustrine/estuarine sediments. An unconformity on the surface of the basal sequence was formed during the Holocene marine transgression. Thin sands and gravels were deposited on this surface, overlain by Holocene mud as the harbour deepened. The roughness of the present seabed is mainly due to marks left from repeated ship anchoring (Fig. 12).*

dated sediments. The presence of shallow gas within sediments is often considered a nuisance during seismic reflection profiling, as the resolution of geological events beneath the area of gas is degraded. Lower frequency sound sources can better penetrate gas-charged sediments, but stratigraphic resolution is reduced. Reflection pull-downs, characterized by downward dipping reflections at the flanks of the gas zones, are frequently associated with acoustic masking. These arise from the reduction of the sound speed through the gassy sediments. The distribution of gas-charged sediment is shown in Figure 9.

Circular patches of high-intensity acoustic backscatter on side-scan sonograms occur on the muddy seabed of the northern flank of Bedford Basin, near the mouth of Bedford Bay (Fader *et al.*, 1994). They give the seabed a mottled character. The circular patches, up to 5 m in diameter and clustered, are interpreted to represent either localized effects of methane gas venting or the presence of concentrated benthic communities, also possibly associated with the venting of methane gas. The area occurs at the northern subsurface edge of gas-charged sediments in Bedford Basin (Fader *et al.*, 1991).

The largest zone of gas charging occurs in the Holocene mud in the inner harbour to the southeast of Georges Island, and continues to the south into Eastern Passage (Figs. 7 and 9). The upper gas-charged seismic reflector occurs at a consistent depth of between 2 m and 3 m. It is important to note that many anchor marks in the harbour (see below) penetrate the seabed to depths of between 1 m and 3 m, suggesting that the gas-charged layer is broken through in many areas, possibly liberating some of the gas.

Pockmarks

Pockmarks are crater-like depressions on the sea floor first discovered by King and MacLean (1970) on the Scotian Shelf. They are interpreted as gas or fluid-escape features and can range to hundreds of metres in diameter and tens of metres in depth (Fader, 1991). They generally occur in thick muds, where gasses or fluids venting to the water erode the seabed. Fine-grained sediments are put into suspension by this process, and ocean currents disperse the material away from the vent site.

Pockmarks exist in a dense distribution at the entrance to the Northwest Arm, and are approximately 3 m in diameter. Their depths into the seabed have not been measured. It is possible that these depressions could also be formed from current scour around objects. ROV surveys of these features (Fader and Miller, 1992) were inconclusive concerning the venting of methane gas as the process responsible for their formation.

HYDRODYNAMICS AND SEDIMENT DEPOSITIONAL FEATURES

Circulation Patterns in Halifax Habour

Oceanographic currents exchange water between the inner Scotian Shelf and Halifax Harbour. Early simplistic models suggested that the harbour was flushed regularly and sediments were removed by this process (ASA Consulting Ltd., 1986). Oceanographic data most recently collected, together with a knowledge of sediment and contaminant distributions on the sea floor (*e.g.*, Fader and Petrie, 1991), indicate that conditions are much more complex, and that most sediments discharged into the inner harbour remain in the inner harbour.

Halifax Harbour is an estuary, *i.e.*, a semi-enclosed body of water whose properties are influenced by fresh-water runoff from the land. The average annual fresh-water discharge into Halifax Harbour is 15.7 $m^3 \cdot s^{-1}$, of which 16% is through the sewer systems of the metropolitan areas. The largest river discharge comes from the Sackville River which contributes 5.41 $m^3 \cdot s^{-1}$ (Buckley and Winters, 1992). The near-surface watermass flows towards the ocean (286 $m^3 \cdot s^{-1}$), becoming saltier as it moves through the harbour. Salt is supplied through mixing with a water mass from the adjacent continental shelf which moves into the harbour below the outgoing near-surface flow (Petrie and Yeats, 1990). In turn, this shelf water becomes less salty as it moves into the harbour because of mixing with the shallower, fresher water.

With regard to current velocity in the surface layer, the weakest outflow (0.2 $cm \cdot s^{-1}$) is found in Bedford Basin and moves a parcel of water approximately 200 m in one day. The currents accelerate to their highest values of about 5 $cm \cdot s^{-1}$ in the Narrows, slow to about 2 $cm \cdot s^{-1}$ as the harbour widens adjacent to the downtown city areas, increase slightly with a narrowing off Sandwich Point, and finally slow to about 1 $cm \cdot s^{-1}$ before flowing out onto the shelf. The picture is much the same in the lower layer except in the opposite direction, *i.e.*, inflow instead of outflow.

In the harbour, currents change rapidly as a result of semi-diurnal tidal flows. Wind also can bring rapid, dramatic changes to the circulation by causing waterborne material to cross the harbour in about an hour (Lawrence, 1989), or by resuspending bottom sediments through wave action.

Sediment Transport

No direct measurement of sediment transport in Halifax Harbour has been undertaken. Such studies require the use of tracers together with subsequent

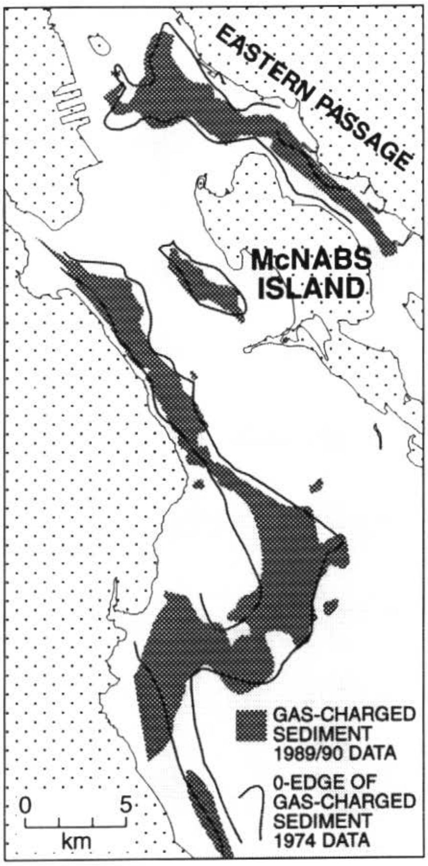


Figure 9 *Distribution of gas-charged sediments in a section of Halifax Harbour. Gas occurs at average depths of 2-3 m in mid-Holocene sediments in the inner harbour, and at depths up to 15 m in older lacustrine/estuarine sediments in the outer harbour that are buried beneath thick transgressive sands and gravels.*

monitoring programs; in this region, these studies have only been conducted on the adjacent Scotian Shelf (Amos, 1990). However, many other characteristics of seabed sediments can be used as qualitative indicators with respect to the responsible currents. These include distribution patterns of gravel, sand, silt and clay; bedforms in sand and gravel; scour or moats around seabed obstructions; the distribution of sewage banks; the distribution of geochemical anomalies relative to injection points; and the distribution of exposed bedrock. A complicating factor is that Halifax Harbour has been subjected to a series of varying geological processes that have produced relict seabed features that are not in equilibrium with present conditions.

Sedimentary features indicative of current patterns in the inner harbour are rare, in part either because bottom currents are weak in areas of sediment accumulation, or currents have been strong enough to sweep away most sediment (*e.g.*, the Narrows). South of Georges Island are sedimentary features, termed obstacle-induced sediment drifts, developed in the lee (north) side of bedrock highs (Courtney and Fader, 1994; Fig. 6). The only other features indicative of current patterns in the inner harbour are gravel ripples near the Dartmouth side of the harbour, resulting from wave action under strong westerly winds.

Sedimentary Furrows

A series of linear erosional scours occurs in Holocene mud at the boundary between the inner and outer harbour adjacent to Sandwich Point (Fig. 10). These features parallel the adjacent shoreline and show higher acoustical reflectivity than the surrounding seabed, suggesting the presence of sand, debris or shells. They are up to 2 m in depth, and extend over 3.5 km. The furrows bifurcate, opening to the south, or seaward. Toward the north, they gradually shallow and merge with the flat mud seabed. Similar erosional features have been found in diverse sedimentary environments, such as the deep sea, lakes and estuaries (Dyer, 1970; Hollister *et al.*, 1974; Flood, 1980, 1981). Furrows that exhibit tuning-fork junctions, where a single furrow opens into the direction of dominant current flow, can be used as current and sediment transport pathway indicators. Sedimentary furrows adjacent to Sandwich Point indicate that the currents that formed them move from the south to the north toward the inner harbour. Extensive data do not exist on the flow regimes necessary to create sedimentary furrows, but in estuaries where measurements have been made, and where the flow is tidal, currents range from 50 cm·s^{-1} to much greater than 100 cm·s^{-1}. Dyer (1970) and Hollister *et al.*, (1974) postulated that helical secondary flows operating close to the sea floor are responsible for formation of furrows; in addition, Flood (1981) suggested that abrasion by coarse sediment plays an important role in the initiation of furrows. Their presence indicates that the harbour is subjected to periodic, strong, directionally stable currents.

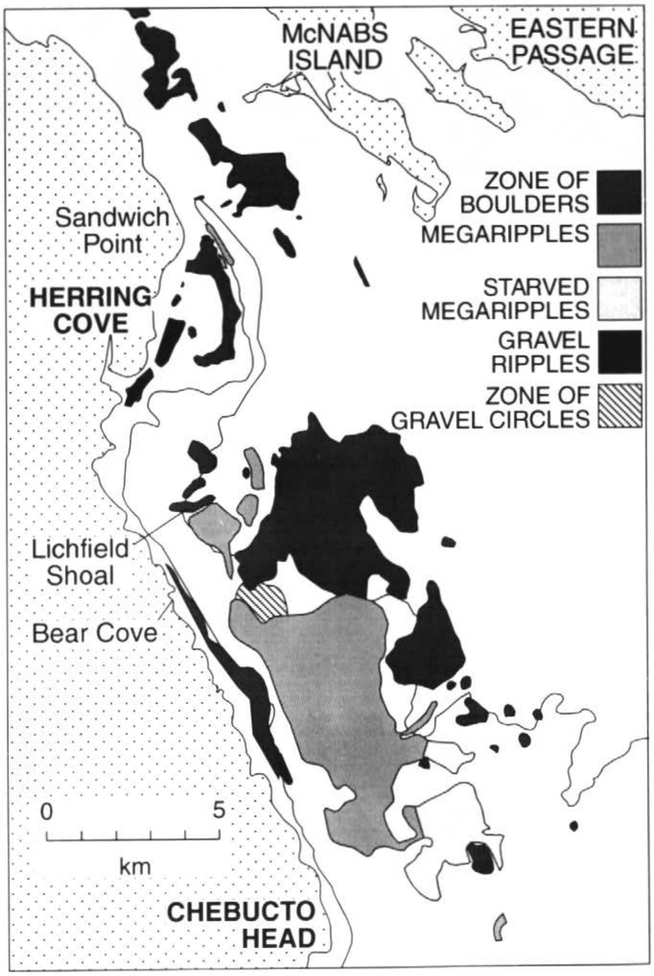


Figure 10 *Bedforms and boulders in outer Halifax Harbour.*

Sand Megaripples

The innermost bedforms in the harbour are subdued sand megaripples which occur in the deep narrow channel defined by the 30-m contour adjacent to Sandwich Point (Fig. 10). They are straight-crested, flow-transverse bedforms with a ripple-like profile. They are formed by currents with a near bedflow velocity of between 40-60 cm·s^{-1} (Amos and King, 1984) moving from south to north. The major zone of megaripples occurs south of Lichfield Shoal, and continues south to Chebucto Head (Fig. 10).

Gravel Ripples

Large areas of gravel ripples are present in many areas of the outer harbour between 10 m and 20 m water depth (Fig. 10). These often flank the outcropping bedrock shoals in areas between the bedrock and sand megaripples. The ripples are characterized by a wave length of between 1 m and 2 m and heights of less than 0.3 m, and are formed by oscillatory motions associated with large waves. Areas of gravel ripples and megaripples in the outer harbour indicate that fine-grained silt and clay-sized sediments are not deposited.

Gravel Circles

Approximately 90 gravel circles, each 25 m in diameter, occur in the outer harbour (Fig. 10). The circles are slight depressions, less than 0.2 m in depth from the surrounding sandy seabed, in about 30 m of water depth. Most occur in groups and many are aligned; in some cases, they are connected by narrow gravel deposits, giving them a beaded appearance on side-scan sonar imagery. In a few areas, the circles are singular isolated features. Small patches of sand occur in the centre of many of the circles. Initially, it was thought that they may represent dredge spoils dumped at the seabed of the outer harbour, but this is not a dumping ground for dredge spoils. Circles may have formed through the action of vortices which scoured the thin overlying sand in a circular pattern and exposed the underlying lag gravel. The steep bedrock topography of Bear Cove Shoal and the narrowing of the channel in this area may have generated a localized circulation in intense storms to form vortices, thereby attesting to periodic high-energy conditions at the seabed of the outer harbour.

ANTHROPOGENIC IMPRINTS AND ARTIFACTS

The impact of human activity on the character of Halifax Harbour has been profound (Figs. 6, 11, 12, 13, 14). The first significant anthropogenic impact on Halifax Harbour was the scuttling of a French fleet of 14 ships in Bedford Basin in 1746 (Raddall, 1965). Indeed, a very old shipwreck found in western Bedford Basin may be the remains of one of these vessels (Fader *et al.*, 1994). After the founding of Halifax in 1749, the construction of fortifications and wharfs would have had some impact. With in-

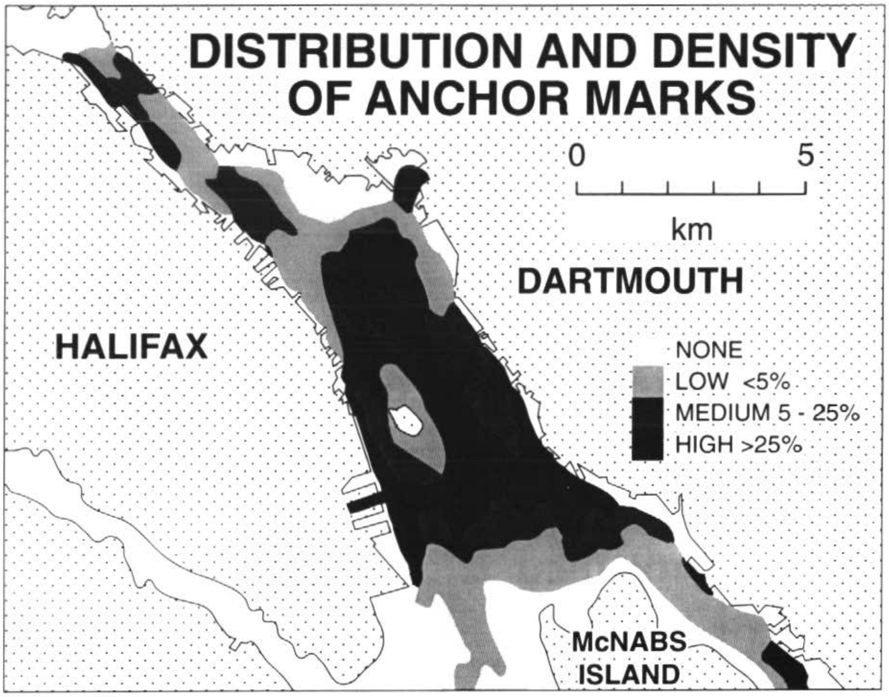


Figure 11 *Distribution and density of anchor marks in the inner harbour. Anchor marks include drag marks, pit marks, and chain marks (see text).*

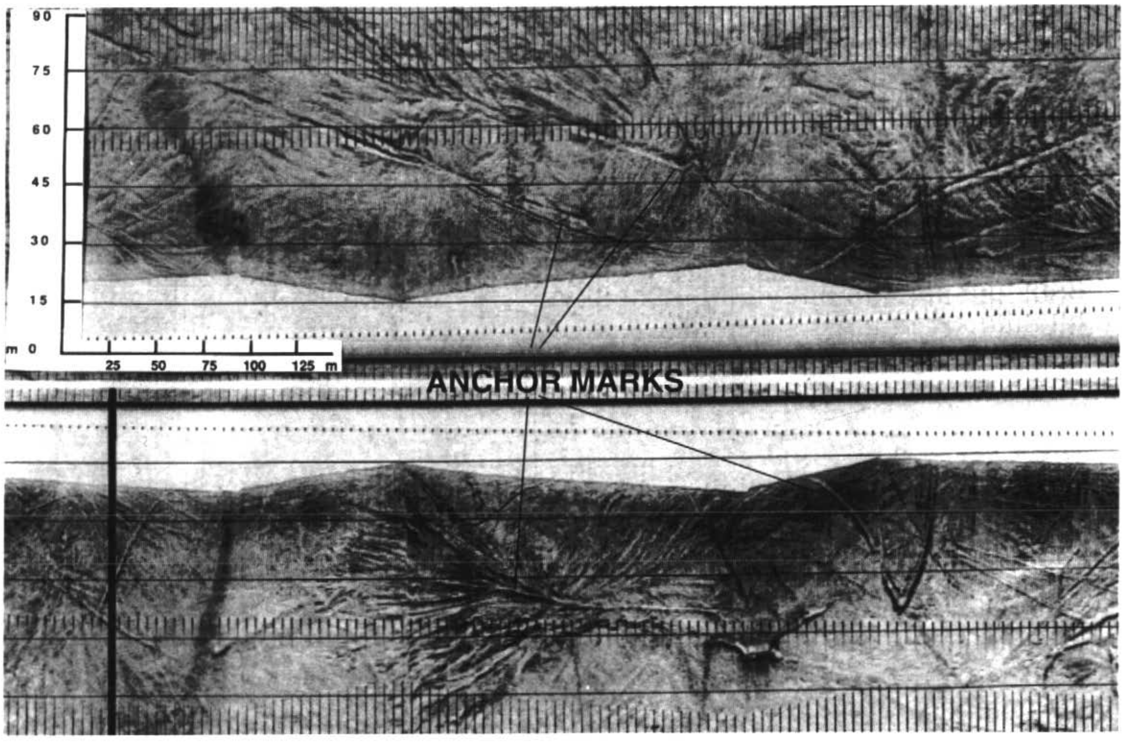


Figure 12 *Side-scan sonogram from the inner harbour showing typical distribution and shapes of anchor marks.*

creasing urban growth in the 19th and 20th centuries, waste from domestic and industrial sources has significantly influenced water quality in the harbour. Dredging of the seafloor for aggregate material or for improved shipping access, dumping of spoils from construction projects, and construction of footings for bridges have all had an impact. Anthropogenic features on the seabed include anchor marks, shipwrecks, dredge spoils, borrow pits, cables, propeller scours, dredged areas, and unidentified debris at the seabed, on both the Holocene mud and the transgressive gravels.

Anchor Marks

Marks on the seabed attributed to the process of ship anchoring are widespread, especially in Bedford Basin and the inner harbour (Figs. 11, 12). These features give the seabed a morphology similar to areas of offshore northern Canada, where ice berg and sea ice scours are common.

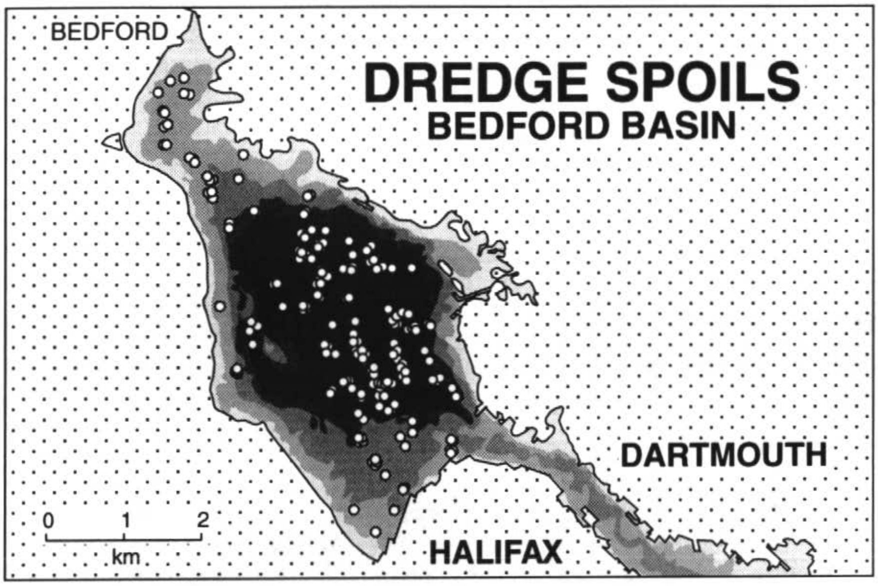


Figure 13 *Distribution of dredge spoils in Bedford Basin indicated by circles. Spoils are up to 45 m in diameter.*

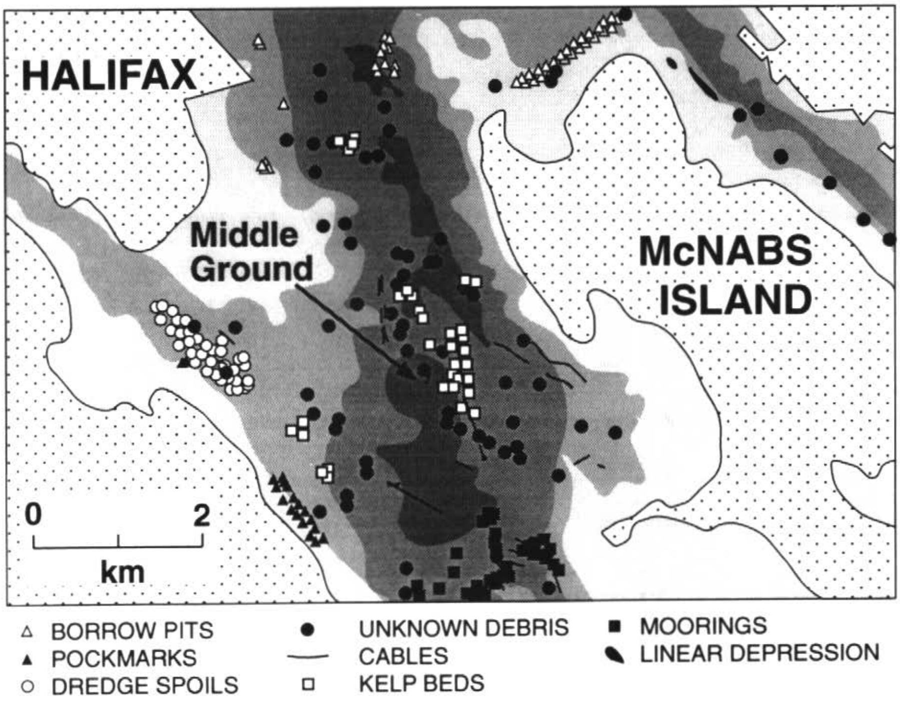


Figure 14 *Distribution of various anthropogenic and natural features in an area of inner Halifax Harbour.*

This process is a widespread and significant sediment turbator, and the term anchorturbation has been proposed for this process (Fader *et al.*, 1991). Sediment cores must be collected away from areas where anchor marks are found, in order to sample an intact and meaningful stratigraphy. The interpretation of results from sediment samples must also be carefully evaluated in areas of high density of anchor marks, especially where the anchors penetrate several metres into the seabed and older sediments are exposed and overturned. The widespread distribution of anchoring throughout the inner harbour suggests that sediments and their associated contaminants are continually being exhumed, resuspended and redeposited.

Anchor marks have been classified into three types: anchor pits, anchor drag marks, and anchor chain marks (Fader *et al.*, 1994). The initial impact of the anchor on the seabed often produces an amphitheatre-shaped, deep, circular depression (anchor pit). If the anchor has been dragged across the seabed in the process of setting the flukes or digging in and providing a hold, or in the process of being retrieved, long linear features termed anchor drag marks are formed. These can be kilometres in length and may also result from the dragging of anchors in response to the movement of ships under high winds. Anchor pit marks are often found at the beginning or termination of anchor drag marks.

Anchor chain marks form as the result of repeated touching down upon the seabed of anchor chains in response to winds and tides, as ships weathervane about their anchors. Such marks appear as a radial pattern of linear depressions, giving the seabed an imprint similar to a large feather. Some of these features can resemble other features termed plumose structures (Fader *et al.*, 1994), which are interpreted as dewatering structures in fine-grained sediments, formed in response to seismic activity. However, in Halifax Harbour the features are interpreted as resulting from anchoring.

Anchor marks occur in a variety of

sizes and shapes. The deepest ones are up to 2.5 m in depth and 5 m in width. The depth of some of these features may be increased by the release of methane gas from the seabed in areas where gas-charged sediments occur at shallow depth and anchors penetrate through to the gas-charged layer, facilitating its release. Anchor marks on gravelly hard seabeds are shallow, most often less than 1 m in depth. Some have been traced for over 2 km along the seabed of the harbour. Many of the large harbour docks have radiating patterns of anchor marks along them, suggesting that the deployment of anchors as a ship's speed/direction control mechanism is a common occurrence.

The densest distribution of anchor marks in the inner harbour, where greater than 25% of the seabed is disrupted, occurs to the north, east and southeast of Georges Island, in the area where present designated anchorages are located (Fig. 11). In Bedford Basin, more than 80% of the muddy seabed is crisscrossed with anchor marks. Several generations of anchor marks have been defined on the floor of Bedford Basin. Some appear fresher than others, having clearly defined berms and sharp contrasts in reflectivity, while others have gradational changes suggesting erosion and degradation of the original features. Because sedimentation since the founding of Halifax in 1749 is generally insufficient to fill the anchor marks (about 41 cm; Buckley *et al.*, 1995), it is possible that the entire population of anchor marks is still visible on the basin floor. The majority of the marks were likely made during the First and Second World Wars, when large convoys of cargo and warships assembled in Bedford Basin prior to embarking for Europe.

Borrow Pits

Borrow pits are seabed depressions formed by the removal of aggregate. The largest area of borrow pits in the harbour occurs north of McNabs Island, where there are many circular pits at the seabed, averaging 15 m in diameter and ranging up to 3 m in depth. A series of very large linear pits that were formed by dredging for aggregates occurs along the eastern side of McNabs Island. Some are over 200 m in length, 30 m in width and 3 m in depth.

Dredge Spoils

Dredge spoils are circular-shaped deposits of material discharged to the seabed, generally by barges. They range in diameter up to 40 m, and may exist as positive features several metres in height above the surrounding seabed, or as coarse debris in depressions several metres in depth. At the entrance to the Northwest Arm, dredge spoils have been dumped on Holocene mud, compressing and displacing the mud into features that resemble pockmarks on the side-scan sonar and seismic reflection records. In this area, the dredge spoils have resulted in the venting of gas from a zone directly beneath the spoil, as evidenced by the absence of gas-charged horizons on the seismic reflection profiles. Linear areas of high acoustic backscatter, connected with much larger circular features of the same acoustic signature, represent sporadic barge discharge of spoil while underway. These features appear concentrated near the Naval Dockyard in Halifax and are widespread in other areas of the inner harbour. Dredge spoils consist of a wide variety of materials such as construction debris, old wooden docks, gravel, boulders, muddy sediments, garbage and unidentified debris. Their presence on the harbour bottom makes it difficult to sample the naturally occurring sediments. Side-scan sonar data is essential for their recognition and accurate sampling. In Bedford Basin, dredge spoil covers approximately 5% of the basin floor (Fig. 13). The practice of dumping dredge spoils in the harbour is presently discontinued.

Shipwrecks

Shipwrecks normally exhibit unique characteristics on side-scan sonar data, primarily resulting from the hard nature of the material, the presence of large expanses of flat metal or wooden surfaces, high and unusual angles between structural elements, and the presence of diagnostic-shaped features such as railings, smokestacks, funnels, bows, anchors and chains, hatches and openings in the superstructure. Even when ships are badly broken, large fragments can be identified by the presence of unusual sonar characteristics, which are much different from natural geological signatures of sediments and bedrock. The most famous shipping accident in Halifax Harbour was the explosion of the munitions ship *Mont Blanc* in 1917 that resulted in the destruction of much of the north end of the city of Halifax. Marine geological studies have been conducted to identify the exact location of the explosion and any evidence of a crater that may have been made by the explosion (Fader, 1994).

Approximately 30 shipwrecks or large pieces of shipwrecks have been located on the seabed of Halifax Harbour (Fader *et al.*, 1994). Some are well-known wrecks, such as the ferry Governor Cornwallis, located on the southeast flank of Georges Island, while others remain unknown and require visual identification. Some of the vessels have recently been identified, such as the *Havana*, a schooner that sank in 1906 while attempting a salvage operation in the inner harbour. To the north of the Havana, off the south end of Halifax, lies another schooner which has been determined to be the *Gertrude de Costa*. It was involved in a collision in the harbour in 1951, and was never located until our recent survey. Seven seamen went down with the vessel after collision with an oil tanker. Both of these vessels lie in an area planned for the diffuser from the proposed sewage treatment plant and where considerable excavation of the seabed was planned for the placement of the diffuser. Of particular significance to this construction is not only the potential for disturbance of the wreck with human remains, but the presence of unexploded ordinance, discovered on the deck of the *Gertrude de Costa*, which may represent an engineering hazard.

One of the most difficult-to-interpret features found on the seabed of Halifax Harbour was a feature eventually recognized as the Trongate Depression (Fader *et al.*, 1991; Fig. 6), which is a linear depression 125 m in length, 3 m deep (deeper at one end), with flanking, asymmetrical berms of mud up to 2 m above the surrounding seabed. The feature was formed by the sinking of the Norwegian vessel, the *S.S. Trongate*, a seven thousand tonne merchant ship, which was purposely sunk in 1942 because of an on-board fire and an explosive cargo. The hull of the vessel was later salvaged, but an impression of the hull remained in the mud at the location of anchorage number 4, near the centre of the central harbour. ROV observations in the vicinity of the depression showed the presence of rolls of newsprint, wooden planks, boots and much debris at the location including unex-

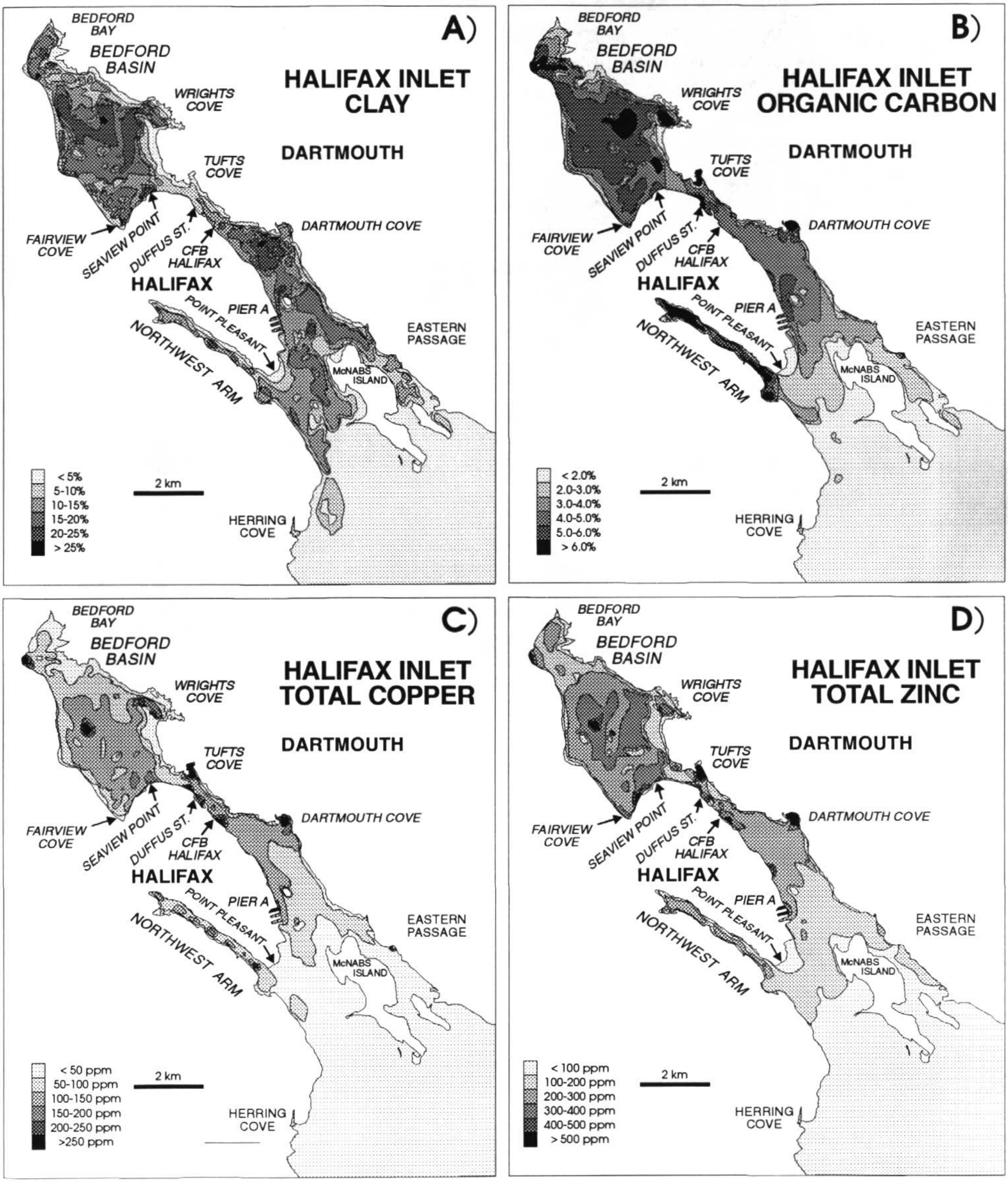


Figure 15 *Sedimentary and geochemical characteristics of surficial sediments (upper 2 cm) in Halifax Harbour.* (**A**) *Clay content (particles <4 μm diameter);* (**B**) *organic carbon derived from land and marine plants and animals and waste from sewage in sediment;* (**C**) *and* (**D**) *distribution of total copper and total zinc metal (after Buckley and Winters, 1992).*

ploded ordinance such as primed 4-inch shells, .303-calibre rifle ammunition, and scattered cordite.

The most recently formed large anthropogenic features of the seabed of Halifax Harbour were formed by the container ship *Atlantic Conveyor*, which grounded on June 1991, while entering the Dartmouth side of the harbour in 5-m water depth. The grounding produced a 200-m-long gash on the seabed, cutting several metres through a gravel lag and into underlying till.

Dredged and Blasted Excavations

Many areas of the harbour bottom have been dredged to provide deeper draft for the large vessels which use Halifax Harbour. Some of these are long linear bucket-dragged zones, while others were deepened by vertical clam-shell dredging. The Dartmouth nearshore has been extensively dredged and used as a dump site for dredge spoils. The top of a drumlin in the inner harbour has been dredged with a clam shell bucket (Fig. 6).

Propeller Scours

The seabed appears to have been eroded to a maximum depth of 2 m directly adjacent to many of the docks along the harbour waterfront. The eroded areas appear on the sonograms as a series of scallop-shaped depressions. This unique morphology is interpreted to result from propeller wash associated with large vessels.

Remains of Narrows Bridges

The remains of the first two bridges that spanned the harbour, connecting Halifax and Dartmouth, lie in the Narrows, approximately 500 m to the south of the existing A. Murray MacKay Bridge (Fader *et al.*, 1991). They were constructed in 1886 and 1892. The first bridge collapsed in a violent hurricane, on September 7, 1891, which destroyed many of the docks along the waterfront. A new piled bridge was unstable, and chains and granite blocks were attached for increased stability in 1892; geophysical data indicate that outcropping bedrock and gravel covers the majority of the seabed in the area and may have prevented the proper penetration of the bridge piles. The seabed is covered with cribwork, steel rail, and large timbers. Large carved rectangular granite blocks that may have been used to stabilize the second bridge also remain at the seabed.

Other Anthropogenic Features

Other anthropogenic features on the seabed of Halifax Harbour include large circular bermed pits, attributed to jack-up oil rig spud-can depressions (Fig. 6). These features are up to 3 m in depth and 15 m in diameter. Long linear parallel depressions record the grounding of the pontoons of a semi-submersible oil drilling rig (Fig. 14). Other scours have resulted from the presence of submarine nets that spanned the harbour during the Second World War (Fader *et al.*, 1994). Slight movements of the bottom of the nets in response to tides and currents eroded the parallel depressions.

CHEMICAL CONTAMINATION IN SEDIMENTS

The quality of water and sediments in a marine harbour reflects the anthropogenic influences of waste disposal, accidental and incidental losses of chemicals, and residues from domestic and industrial energy production.

Surficial Sediments

Systematic geochemical studies of the surficial sediments in Halifax began with the reports by Prouse and Hargrave (1987) and OceanChem Group

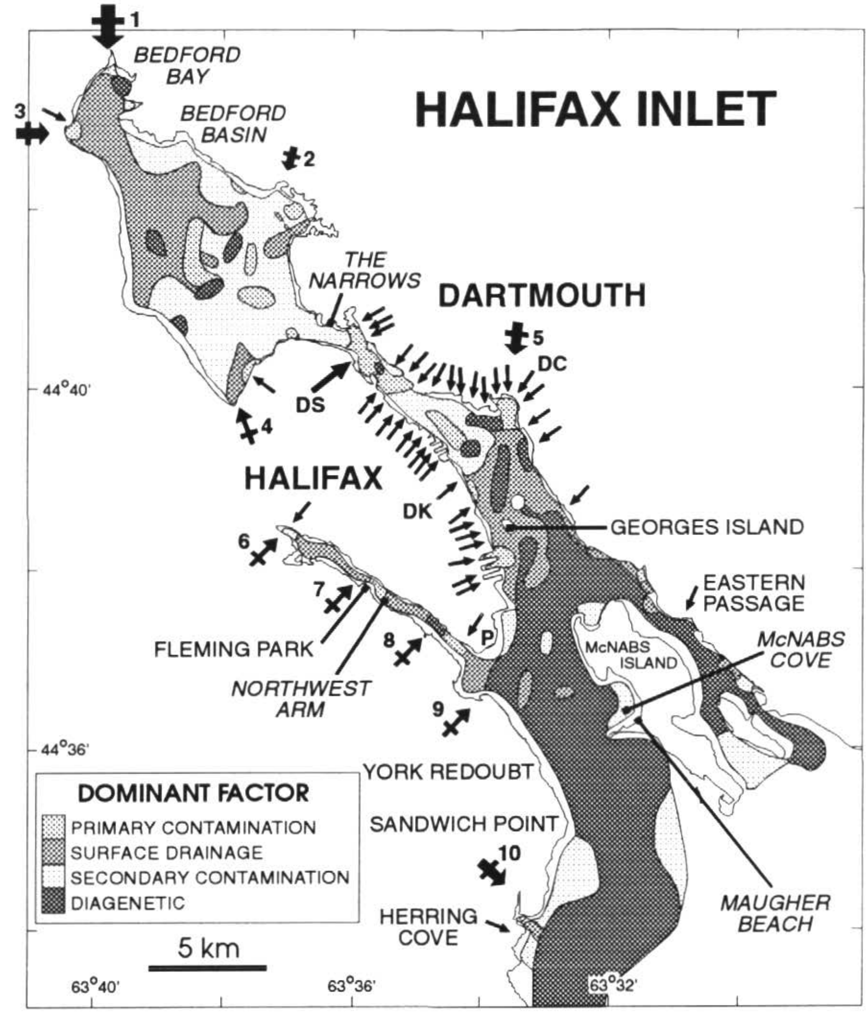
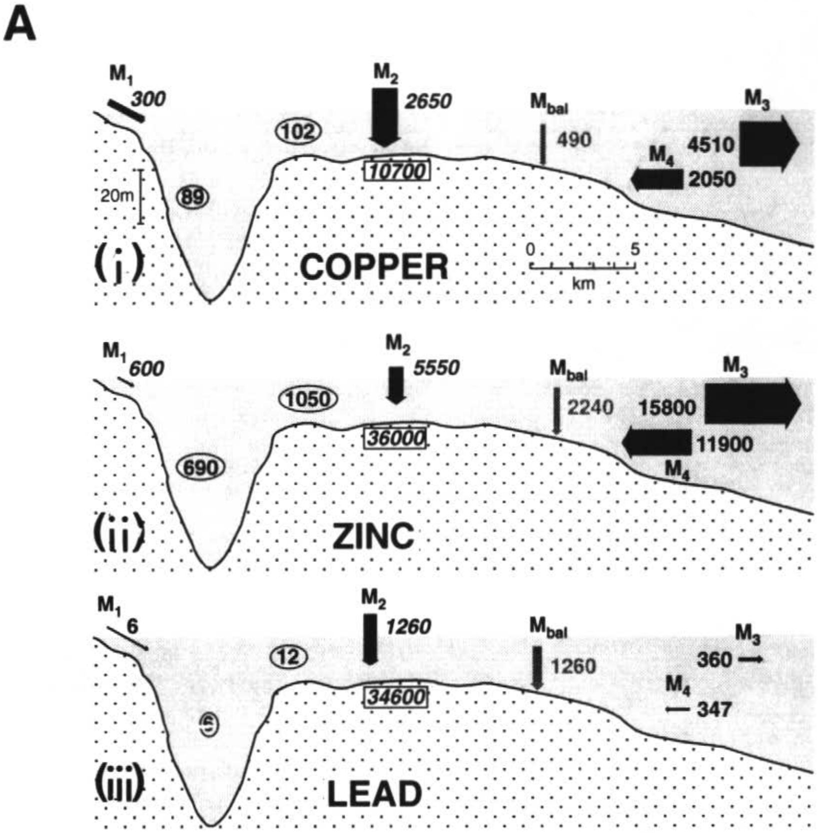


Figure 16 *Distribution of dominant factor type sediments, based on highest statistical factor loadings for individual samples. Sewage outfalls are identified by arrows with major designated outfalls being Duffus Street (DS), Duke Street (DK), Dartmouth Cove (DC), and Point Pleasant (P). Surface drainage and fluvial inputs are represented by numbered and scaled "t" vectors: 1 Sackville River; 2 Wrights Brook; 3 Paper Mill Lake flume; 4 Fairview Cove drainage; 5 Banook Lake flume; 6 Chocolate Lake brook; 7 Frog Lake brook; 8 Williams Lake brook; 9 Purcells Lake brook; 10 Powers Pond flume (after Buckley and Winters, 1992).*

Ltd. (1988). Samples were analyzed for total content of major and trace elements Si, Al, Fe, Ca, Mg, K, Ti, Mn, Cu, Zn, Ni, Pb, Hg and Li, total and organic carbon, water content, and sediment textural characteristics (see Buckley *et al.*, 1989; Buckley and Hargrave, 1989).

Maps illustrating the distribution of some sedimentological and geochemical characteristics of harbour sediments (Fig. 15) indicate a great deal about the sources and dispersion of contaminants. Fine-grained sediments, indicated by higher percentages of clay, are confined almost entirely to the inner harbour, especially in the central harbour and in Bedford Basin. Similarly, sediments containing a high content of organic carbon, indicative of high organic matter content, originate mainly from the major sewer outfall areas and are dispersed in the inner parts of the harbour, especially in the Northwest Arm and in Bedford Basin. Specific contaminant metals such as Cu and Zn are seen to be associated with point sources at Pier A, Dartmouth Cove, CFB Halifax, Tufts Cove, and in Bedford Bay. The indicated sources in the central harbour are at the location of major untreated sewer outfalls. The Bedford



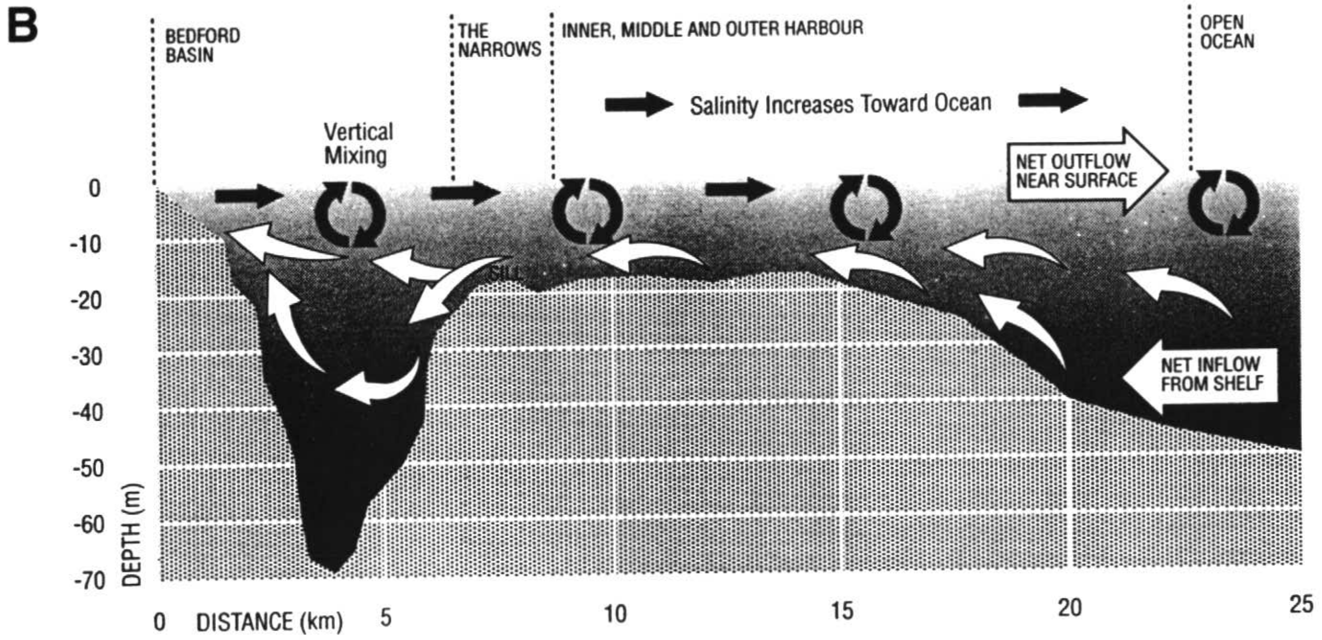


Figure 17 (**A**) *Representation of longitudinal section through Halifax Harbour illustrating geochemical flux models for (i) copper, (ii) zinc, and (iii) lead. All flux quantities are in kilograms per year. Numbers in ovals in the water column represent the average metal mass (kg) contained in the upper and lower water layers. Numbers in boxes below the sediment surface represent the mass (kg) of potentially reactive metal deposited in sediments in the year 1990. Inputs of dissolved metals from surface drainage and fluvial sources are written beside the arrow designated as M1; dissolved inputs from the sewers are noted beside the vertical arrows designated as M2. Exchanges of dissolved metal between the harbour and the Approaches are designated by M3 and M4. Estimates of dissolved metal scavenged from the water column and added to the bottom sediments are indicated by Mbal, (after Buckley and Winters, 1992).* (**B**) *Estuarine circulation of Halifax Harbour. Dense ocean water flows in to the harbour at depth; outflow water is less dense because of the addition of urban runoff, sewage and fresh water from the Sackville River.*

Bay anomaly is near the outfall from the sewage treatment plant for the town of Bedford, indicating the discharge of contaminant metals. The anomaly in the centre of Bedford Basin is associated with the dumping of contaminated dredge spoils from the central harbour (Lay *et al.*, 1993; Fader *et al.*, 1994; Buckley *et al.*, 1995). The anomalous zinc concentration near Seaview Point indicates that this metal is being leached from the site of the former Halifax City waste landfill.

In order to assist in the interpretation of a complex matrix of geochemical data, a factor analysis technique was employed to identify spatial variability across the harbour and source areas (Buckley and Winters, 1992; Winters and Buckley, 1992). Five factors were identified that could be used to characterize the surficial sediments. The first and most significant factor (41% of the variance in all geochemical variables), included four forms of Zn, two forms of Cu, three forms of Pb, Ni and Cr, as well as total Cd, and organic carbon. These variables characterize contaminants that are associated with sewage discharges and contamination from industrial sites.

A second factor (8% of the total variance) included Si, Al, Mg, K, Fe, as well as organically bound Fe and Mn. This factor also included the minor element Li, which can be used as an indicator of clay minerals that are often concentrated in the finest sediment grain sizes (Buckley and Cranston, 1991). The second factor has been designated as representing sediments derived from surface drainage systems from urban areas, including the Sackville River and several other smaller systems.

The third factor group (6% of the total variance), included acid labile or reducible forms of Zn, Pb, and Cu that are the product of some post-depositional secondary modification of metals originally associated with sewage or surface drainage sources.

A fourth factor group (5% of variance) associated several labile forms of Mn with Pb and Cu as well as Ti. These associations, and the location of samples with these characteristics, suggested that the labile metals were the product of diagenetic remobilization from subsurface layers into the surficial sediments, where the metals adsorbed to particle surfaces. A fifth, and least significant factor ($CaCO_3$ factor; 4% of variance), was one in which three forms of Ca were associated and is restricted to small areas of the outer harbour.

A map illustrating the distribution of factors 1 to 4 is shown in Figure 16, which readily identifies areas in the harbour that are dominated by a particular contamination process. It is evident that several areas in the central harbour adjacent to the many sewer outfalls are dominated by primary contamination (factor 1). Contamination from surface drainage (factor 2) from the Sackville River dominates the northwestern part of Bedford Basin and part of the central harbour. The presence of Zn, Pb and Cu contamination (factor 3) in the areas surrounding Seaview Point (site of old Halifax landfill) and adjacent to the industrial sites in the central harbour is an indication that secondary leaching of metal contaminants is taking place in these areas. The diagenetic factor (factor 4) indicates migration of metals from subsurface sediment layers, and domi-

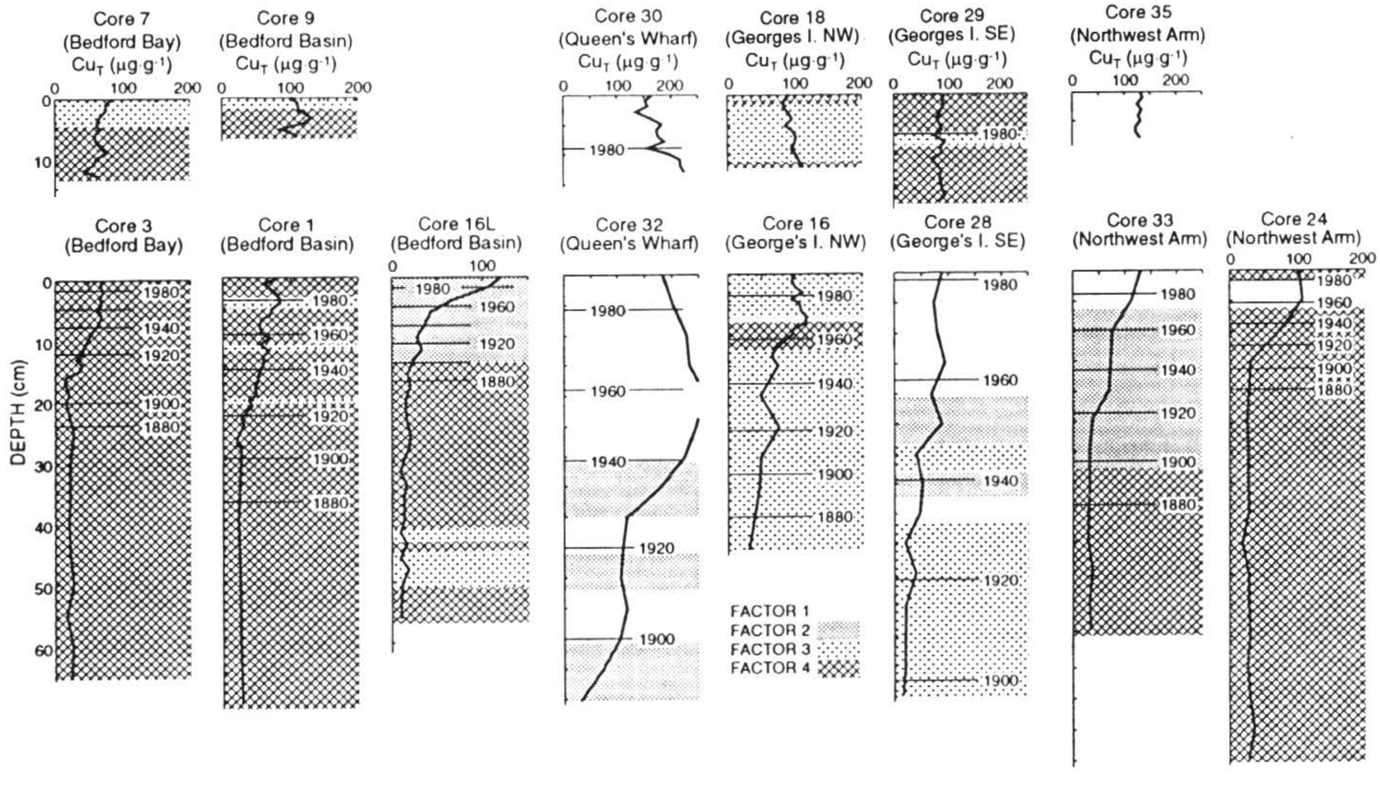


Figure 18 *Profiles of sediment cores illustrating the concentration of total copper with depth in dated sediments. Dominant geochemical factors representing dominant contamination processes are identified for depth zones in each core. Factor 1 is primary contamination from sewage; factor 2 is post-depositional, secondary contamination from urban drainage and storm runoff; factor 3 represents diagenetic alteration of metals from sewage and surface drainage; factor 4 is associated with diagenetic remobilization of metals from subsurface layers and is associated with areas of methane (see also Fig. 16).*

nates areas where subsurface methane has been found. This association may indicate that highly reduced sediments, in which organic matter is decomposing, may be a source for these metals.

Metal Budget

A simple box model was used by Buckley and Winters (1992) to estimate budgets of metals contributed to the harbour from urban drainage and the sewer outfalls, accumulated in surface sediments, and exchanged with the Atlantic Ocean. This budget is depicted for three metals in Figure 17. The budget for Cu and Zn indicated that only about 10% of the dissolved metal enters the harbour from urban drainage systems, with 90% being contributed from the combined sewer outfalls. A small portion (17%) of the dissolved Cu is sequestered to the bottom sediments inside the harbour; however, about 36% of the dissolved Zn is sequestered to the bottom sediments. A much larger quantity of potentially labile particulate Cu and Zn is deposited in the bottom sediments each year (10.3 tonnes [t] Cu; 33.7 t Zn). The net export of dissolved Cu from the harbour each year is about 2.5 t, whereas the net export of dissolved Zn is about 3.9 t. There is about an order of magnitude more dissolved Zn as compared with dissolved Cu in the water column inside the harbour, with considerably more metal dissolved in the upper water layer as compared with the bottom layer. The budget model for Pb contrasts with that of Cu and Zn in that nearly all of the dissolved Pb injected into the harbour from the sewers and surface drainage is sequestered to the bottom sediments. The annual potentially labile particulate Pb accumulation in the sediments is much greater (27 times) than that from dissolved Pb sequestering. There is no significant net exchange of dissolved Pb with the Atlantic Ocean.

The level of contamination by metals in the surficial sediments of Halifax Harbour is among the highest recorded for marine harbours and estuaries in any developed country (Buckley and Winters, 1992). This may be surprising in view of the relatively small urban population and industrial base around Halifax Harbour as compared with many other harbours. The reason for the high level of contamination lies in the hydrodynamic characteristics of the harbour in comparison with other harbours and estuaries (Fig. 17B). Halifax Harbour is an estuary with a relatively small fresh-water inflow (17±8 $m^3 \cdot s^{-1}$) as compared with other systems with similar areas (*e.g.*, Miramichi, 332 ± 264 $m^3 \cdot s^{-1}$). The tidal to fresh-water volume ratio for Halifax Harbour is 373, as compared with the Miramichi estuary where this ratio is 73 (Buckley, 1994) and results in a much reduced flushing capacity. Moreover, the bathymetry of Halifax Harbour fosters the trapping of contaminants in the deep inner Bedford Basin. Partly as a result of these characteristics, about twice as much Zn and seven times as much Pb is deposited annually in sediments of Halifax Harbour as compared with the Miramichi estuary (Buckley, 1995).

Subsurface Sediments

An objective of the geochemical study of Halifax Harbour was to determine the history of contamination as well as the present state of environmental quality. A series of core samples was collected between 1989 and 1991 (LeBlanc *et al.*, 1991; Buckley *et al.*, 1991, 1994; Fitzgerald *et al.*, 1991). Sediment layers were dated by the use of ^{210}Pb and ^{137}Cs isotope analyses for determining high-resolution geochronology over the past 150 years. Hydrocarbon concentrations in the sediments increased 100-fold from about the year 1900 (depth 15-20 cm) to 1990 (Gearing *et al.*, 1991). Aromatic hydrocarbons reach peak concentrations in sediments deposited around the 1950s, coinciding with the conversion from use of coal as a domestic and industrial fuel to the use of petroleum. Metal contamination profiles in this core also indicated peak concentrations for Hg, Pb, Zn and some forms of Cu occurred in the 1970s.

With detailed chemical analyses and dating of a number of cores located at various places throughout the harbour, it was possible to reconstruct a contamination history for the entire harbour (Buckley *et al.*, 1995). Using the same factor analysis techniques as were applied in the study of the surficial sediments (Buckley and Winters, 1992; see above), four contamination factors were again identified, and represent the same processes as those that contributed to the contamination of the surficial sediments (see above). The value of this analysis in the study of the core samples was that it was possible to deduce when specific anthropogenic activities began to influence environmental quality of sediments.

Briefly, copper contamination began around 1900 in most of the harbour areas, but the extent of contamination was greatest in the central harbour (Fig. 18). Sediments in Bedford Basin have been dominated by contaminants sourced from urban drainage. Sediments from the central harbour were dominated by contamination derived from sewage and post-depositional diagenesis for most of the time since 1900. Sediments from the Northwest Arm show a transition from surface drainage dominance to that derived from sewage in most recent times. These historical trends reflect changing intensity of industrialization, urban growth influences, changes in the use of metals in paints and other chemicals, and in the nature of combustion fuels. Some changes can also be attributed to changes in the location and volume discharge of sewer outfalls.

Environmental Risks

The high concentration of contaminant metals and hydrocarbons in sediments in Halifax Harbour poses a risk to marine biological communities. Unfortunately, few studies of biological community distortions (decreased species diversity and/or biomass), biological uptake of contaminants, and toxicity reactions to contamination have been conducted in Halifax Harbour. Contamination of shellfish in Halifax Harbour by bacteria and other contaminants was considered a sufficient threat that this fishery was closed in the 1960s. Benthic ecological studies of a few areas in Bedford Basin and near Herring Cove revealed that overall the range of species was similar to other coastal areas in Atlantic Canada, but specific sites in Bedford Basin had low species numbers and low biomass (Hargrave *et al.*, 1989). Analyses for specific toxic chemical uptake in lobsters found that concentrations of Cd, Cu, Zn, Hg and Pb in the digestive glands and cooked meat were below levels judged to be hazardous to human health, although there was some elevation in some animals from certain areas of the harbour (Uthe *et al.*, 1989). These investigators also found elevated levels of PCBs and PAHs in digestive glands, suggesting that they should be avoided in human consumption. In a more systematic biological survey, Tay *et al.*, (1991), found significant biological damage to bottom-dwelling fish (flounder). All specimens had tissue deterioration commonly associated with severe contamination. They also demonstrated through experimental toxicity tests that the highly contaminated bottom sediments resulted in severe acute toxicity for bivalves. Cook (1995) demonstrated that surface sediments are marginally toxic, while subsurface sediments are considered to be toxic, based on Environment Canada guidelines.

The large inventory of contaminants in the surface and subsurface sediments of Halifax Harbour poses an environmental threat for many years in the future. Presently, most of the contaminated sediments are in a chemically reduced state because of the limited oxidation of the bottom sediments (Buckley *et al.*, 1995). The high content of organic matter in these sediments prevents penetration of oxygen from the overlying water column. Even secondary oxidants such as sulfate are reduced at relatively shallow depths in the sediments. As a result of reducing conditions, some of the contaminants are sequestered in insoluble forms that prevent them from being remobilized back into the overlying water and becoming available to most of the biological community. However, if these sediments were exposed to oxidizing conditions, such as may occur when the sediments are disturbed either by dragging of ships' anchors, or by dredging, then remobilization of contaminants is likely.

A WASTE-WATER TREATMENT FACILITY FOR HALIFAX HARBOUR

Many aspects of the geoscience investigations described above can be applied to the problem of developing a new waste-water treatment facility for the city of Halifax. In proposing and planning such facilities, environmental engineers and managers should be aware of information provided by the scientific investigations. On the basis of this knowledge, clearly stated objectives are required that can be understood and supported by the public. This was not done well in the case of Halifax Harbour. Establishment of Halifax Harbour Cleanup Incorporated (HHCI), to carry out design and environmental studies related to the waste-water facilities, created an expectation that the objective was to clean up the harbour. At best, the objective of the HHCI was to design a contamination abatement system by treating some of the raw sewage. It was never made clear to the public that the proposed sewage treatment facility would only address part of the public environmental concern for Halifax Harbour. These concerns can be classified as being: 1) aesthetics, 2) habitat restoration or preservation, and 3) public health. The proposed primary treatment facility would remove about 70% of the particulate matter, but less than 50% of contaminant metals. Such a facility would thus address mainly the concerns with aesthetics, in that particulates, especially the large floatables, could be removed during normal discharge conditions. The waste-water treatment facilities would do little to restore habitat conditions because these have been altered by many years of waste discharge in the harbour. Likewise, there would be little change in the human health risk because of continued discharge of contaminants, and because the large reservoir of contaminants in the harbour sediments would likely continue to release some contaminants.

Sewage Transport Paths

Problems regarding the siting of waste-water management facilities and outfalls often can be reduced essentially to predicting where sewage particulates, with their associated contaminants, will eventually be deposited. For Halifax Harbour, the majority of the evidence suggested that the harbour trapped sediments and only a small particulate fraction was transported seaward. There is a general tendency for the finer sedimentary particles on the bottom to move towards the head of the harbour, *i.e.*, towards Bedford Basin. Sewage particles, which enter the harbour waters in the surface layer, initially would be carried towards the shelf; however, as the sewage particles sink, they are caught up in the deeper inflow and move back up the harbour. Sewage-derived sediments are thus confined to the inner harbour, the Narrows and Bedford Basin. As a result, decisions regarding the location of effluent outfalls from waste-water treatment facilities in the sewage management system for Halifax Harbour were designed to enhance containment and deposition of effluent particles in the inner harbour (Halifax Harbour Task Force and Panel reports).

Given a containment philosophy for the choice of the outfall location, it became a rather easy task to locate the outfall in the inner harbour. Geotechnical characteristics required a suitable foundation for a marine outfall together with a location in an area of non-deposition so as not to bury the outfall. The preferred outfall location was chosen to the east of Georges Island, at the Georges Island moat area in the inner harbour where sewage would be contained and deposited. This area is the site of the largest and thickest deposit of mud recording deposition and non-erosion (see above).

The decision to site a sewage outfall in the inner harbour is unconventional as outfalls are often chosen as far out at sea as possible, as is the case for Boston Harbour and the city of Victoria. However, long outfalls at sea simply export the problems to distal fishing and recreational zones. Earlier recommendations for a sewage treatment plant location at Sandwich Point and an adjacent outfall were based on little or no marine data. From new information, it is clear that the Sandwich Point location is one of the worst possible areas for a marine outfall. The large sedimentary furrows found directly off this area indicate that sewage discharge would periodically result in storm-driven mass transport directly up the harbour to the entrance of the Northwest Arm, an important recreational zone. It would also directly impact Pleasant Shoal, a large lobster-fishing ground.

Current Status of the Waste-water Management Plan

On March 31, 1995, funding agreements for the Halifax Harbour Cleanup Project between the federal government and the Nova Scotia provincial government expired and the project has been terminated. The Cleanup Corporation is being dismantled and no agency representative of all government stakeholders will exist after this time. In the first few months of 1995, there was a flurry of proposals to move a number of the highly visible and odorous sewage outfalls a few hundred metres out into the central harbour. These measures were being proposed simply to satisfy aesthetic concerns.

The final chapter in the clean-up of Halifax Harbour has not been written, but it appears that an opportunity to control waste from sewers has been missed. However, a large scientific data base has been assembled on which to base future environmental management decisions.

DISCUSSION

It is clear from research in Halifax Harbour that future studies in other similar areas should first undertake geophysical remote-sensing surveys (seismic reflection and side-scan sonar). These data sets can be interpreted to produce a wide variety of geological and thematic maps, in order to determine where appropriate and representative samples should be collected to ground truth the acoustic signatures, to define anomalous sediment distributions and seabed features including hazards; and to have an initial assessment of dynamic processes indicative of sediment transport. Similar observations are made by Coakley and Mudroch (in press), Versteeg *et al.* (this volume), Nairn and Cowie (in press), and Hart and Barrie (this volume).

The most desirable primary tool for so-called first-look surveys is multibeam bathymetry. Shadowgrams produced from these data can greatly enhance the interpretation of subtle dynamic features to further refine the selection of sample locations. Subsurface seismic reflection data are essential to measure sediment thickness, to outline subsurface stratigraphy, and to choose core locations. Critical relationships often exist between subsurface features and seabed characteristics which can be enhanced by the integration of seismic reflection and side-scan sonar data. The seabed can provide important clues as to subsurface processes that must be further investigated. Core locations should be chosen away from areas where significant erosion and sediment mixing occur, such as produced by ship anchoring and propeller scouring.

When working near urban centres, the anthropogenic imprint can be overwhelming, making the interpretation and sampling of natural seabed materials and features very difficult. The widespread distribution of anchor marks limits areas where undisturbed sediments can be found and cored. Sample locations must be carefully selected taking this type of information into consideration. It is important to understand the historical aspects of waste discharge to harbours, and many archival agencies, museums, societies and special interest groups such as divers, industrial organizations and military associations can be valuable sources of information.

We lacked direct studies of sediment transport under conditions of waves and currents, and had to rely on other methods to assess the long-term transport pathways and locations of sediment sinks. Methods such as the use of grain size trends to define net sediment transport pathways are limited in areas like Halifax Harbour where relict sediments reflect glacial and post-glacial transgressive environments which are not in equilibrium with the present dynamics of the system. Geochemical anomaly distributions relative to input points greatly assisted in understanding transport directions. Other features, such as the location of sediment depocentres, scour moats, obstacle-induced sediment drifts, sedimentary furrows, sand bedforms, and regional distributions of hard seabeds, helped to infer the net direction of sediment transport.

ACKNOWLEDGEMENTS

We thank the captains and crews of the *C.S.S. Navicula, M.V. Frederick R. Creed, F.C.G. Smith, C.S.S. Hudson*, and the *C.S.S. Dawson* for their assistance in collection of samples and data. We thank Robert Miller for his assistance in field operations, map compilations and initial illustration designs. C. Schafer, C. Amos, D. Forbes, J. Syvitski and R. Cranston provided helpful advice in several geoscience interpretation aspects. We thank members of the Halifax Harbour Task Force and the Federal Scientific Advisory Committee for support and encouragement of the geoscience research program. Finally, we appreciate the reviews of an early draft version of the manuscript by Brian MacLean and Al Grant.

REFERENCES

Amos, C.L., 1990, Modern sedimentary processes, Chapter 11, *in* Keen, M.J. and Williams, G.L., eds., Geology of the Continental Margin of Eastern Canada: Geological Survey of Canada, n. 2, p. 609-673.

Amos, C.L. and King, E.L., 1984, Bedforms of the Canadian eastern seaboard: A comparison with global occurrences: Marine Geology, v. 57, p. 167-208.

ASA, 1986, The Halifax Inlet water quality study, phase 2: ASA Consulting Ltd., Dartmouth, Nova Scotia, 136 p.

ASA, 1990, Residual circulation in Halifax inlet and its impact on water quality: Report for Nova Scotia Department of Environment, ASA Consulting Ltd. Dartmouth, Nova Scotia, 245 p.

Buckley, D.E., 1988, Geochemistry, *in* Piper, D.J.W., ed., Cruise report HUDSON 88-010: Atlantic Geoscience Centre, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, p. 45-49.

Buckley, D.E., 1991, Deposition and diagenetic alteration of sediment in Emerald Basin, the Scotian Shelf: Continental Shelf Research, v. 11, p. 1099-1122.

Buckley, D.E., 1994, 25 years of environmental assessment of coastal estuarine systems: lessons for environmental quality management, *in* Wells, P.G. and Ricketts, P.J., eds., Coastal Zone Canada '94, "Cooperation in the Coastal Zone": Coastal Zone Canada Association, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada, v. 3, p. 1304-1340.

Buckley, D.E., 1995, Sediments and environmental quality of the Miramichi Estuary: new perspectives, *in* Chadwick, E.M.P., ed., Water, Science, and the Public: The Miramichi Ecosystem: Fisheries and Aquatic Sciences, Canadian Special Publication, v. 123, p. 179-190.

Buckley, D.E. and Cranston, R.E., 1991, The use of grain size information in marine geochemistry, *in* Syvitski, J.P.M., ed., Principles, Methods, and Application of Particle Size Analysis: Cambridge University Press, New York, p. 311-331.

Buckley, D.E., Fitzgerald, R.A., Winters, G.V., LeBlanc, K.W.G. and Cranston, R.E., 1991, Geochemical data from analyses of sediments and pore waters obtained from cores collected in Halifax inlet, M. V. Fredrick Creed cruise '90 and Hudson cruise 89-039 ('90): Geological Survey of Canada, Open File Report 2410, 116 p.

Buckley, D.E. and Hargrave, B.T., 1989, Geochemical characteristics of surface sediments, *in* Nicholls, H.B., ed., Investigations of Marine Environmental Quality in Halifax Harbour: Fisheries and Aquatic Sciences, Canadian Technical Report 1693, p. 9-36.

Buckley, D.E., Hargrave, B.T., Mudroch, P., 1989, Geochemical data from analyses of surface sediments obtained from Halifax inlet: Geological Survey of Canada, Open File Report 2042, v. 1 and v. 2, 24 p.

Buckley, D.E., MacKinnon, W.G., Cranston, R.E. and Christian, H.A., 1994, Problems with piston core sampling: mechanical and geochemical diagnosis: Marine Geology, v. 117, p. 95-106.

Buckley, D.E., Smith, J.N. and Winters, G.V., 1995, Accumulation of contaminated metals in marine sediments of Halifax Harbour, Nova Scotia: environmental factors and historical trends: Applied Geochemistry, v. 10, p. 175-195.

Buckley, D.E. and Winters, G.V., 1992, Geochemical characteristics of contaminated surficial sediments in Halifax Harbour: impact of waste discharge: Canadian Journal of Earth Sciences, v. 29, p. 2617-2639.

Cameron, H.L., 1949, Faulting in the vicinity of Halifax, Nova Scotia: Proceedings of the Nova Scotia Institute of Science, v. XXII, Part 3, p. 1-15.

Coakley, J.P. and Mudroch, A., in press, Contaminated sediment in urban Great Lakes waterfronts, *in* Eyles, N., ed., Environmental Geology of Urban Areas: Geological Association of Canada, St. John's, NF, in press.

Cook, N.H., 1995, Toxicity of Halifax Harbour sediments: an evaluation of the Microtox R solid phase bioassay: unpublished M. Env. Sc. thesis, Dalhousie University, Halifax, Nova Scotia, 139 p.

Courtney, R., 1993, Halifax Harbour bathymetric morphology: Geological Survey of Canada, Open File Report 2637, colour map sheet.

Courtney, R. and Fader, G.B.J., 1994, A new understanding of the ocean floor through multibeam mapping: Science Review 1992 & '93, Bedford Institute of Oceanography, Halifax Fisheries Research Laboratory, St. Andrews Biological Station, Department of Fisheries and Oceans, Scotia-Fundy Region, p. 9-14.

Dyer, K.R., 1970, Linear erosional furrows in Southampton Water: Nature, v. 255, p. 56-58.

Edgecombe, R.B., 1994, Paleoenvironmental analysis of Halifax Harbour: sedimentology, paleoclimatology and Holocene sea level: unpublished B.Sc. Hons. thesis, Dalhousie University, Halifax, NS, 76 p.

Eyles, C., in press, Environmental law assessment, *in* Eyles, N., ed., Environmental Geology of Urban Areas: Geological Association of Canada, St. John's, NF, in press.

Fader, G.B.J., 1991, Gas-related sedimentary features from the eastern Canadian continental shelf: Continental Shelf Research, v. 11, p. 1123-1153.

Fader, G.B.J., 1994, The marine geological setting and seabed impact of the 1917 explosion of the Mont Blanc in Halifax Harbour: Proceedings of the 75th Conference on the 1917 Explosion in Halifax Harbour, Special Publication of the Goresbrook Institute, St. Mary's University, Halifax, NS, p. 345-364.

Fader, G.B.J. and Miller, R.O., 1992, Cruise report Navicula 1990-010, Halifax Harbour, May 22-June 8, 1990: Geological Survey of Canada, Open File Report 2445, 26 p.

Fader, G.B.J., Miller, R.O. and Pecore, S.S., 1991, The marine geology of Halifax Harbour and adjacent areas: Geological Survey of Canada, Open File Report 2384, v. 1 and v. 2, 23 p.

Fader, G.B.J., Miller, R.O. and Pecore, S.S., 1994, Sample control, anchor marks, anthropogenic features and lacustrine sediments of Halifax Harbour: Geological Survey of Canada, Open File Report 2958, 32 p.

Fader, G.B.J., Miller, R.O., Stea, R.R. and Pecore, S.S., 1993, Cruise report 91-018, C.S.S. Dawson: operations on the inner Scotian Shelf: Geological Survey of Canada, Open File Report 2633, 30 p.

Fader, G.B.J. and Petrie, B. 1991, Halifax Harbour — How the currents affect sediment distributions, *in* Smith, T.E., ed., Science Review, 1988 and 1989: Halifax Research Laboratory and St. Andrews Biological Station, Scotia Fundy Region, Department of Fisheries and Oceans, Bedford Institute of Oceanography, p. 31-35.

Faribault, E.R., 1908, Province of Nova Scotia, Halifax County (City of Halifax Sheet No. 68) Department of Mines, Geological Survey Branch, Map.

Fitzgerald, R.A., Winters, G.V., Buckley, D.E. and LeBlanc, K.W.G., 1989, Geochemical data from analyses of sediments and pore water obtained from piston cores and box cores taken from Bedford Basin, LaHave Basin, Emerald Basin and the slope of the southern Scotian Shelf, HUDSON cruise 88-010: Geological Survey of Canada, Open File Report 1984, 47 p.

Fitzgerald, R.A., Winters, G.V., LeBlanc, K.W.G., Buckley, D.E. and Cranston, R.E., 1991, Geochemical data from analyses of sediments and pore waters obtained from cores collected in Halifax inlet, C.S.S. Navicula cruise 90-010: Geological Survey of Canada, Open File Report 2449, 106 p.

Flood, R.D., 1980, Deep-sea sedimentary morphology: Modelling and interpretation of esho-sounding profiles: Marine Geology, v. 38, p. 77-92.

Flood, R.D., 1981, Distribution, morphology and origin of sedimentary furrows in cohesive sediments; Southampton Water: Sedimentology, v. 28, p. 511-529.

Flood, R.D., 1983, Classification of sedimentary furrows and a model of furrow initiation and evolution: Geological Society of America Bulletin, v. 94, p. 630-639.

Fournier R.O., 1990, Final report of the Halifax Harbour Task Force, submitted to the Minister of the Environment, The Honourable John Leefe, 84 p.

Gearing, J.N., Buckley, D.E. and Smith, J.N., 1991, Hydrocarbon and metal contents in a sediment core from Halifax Harbour: a chronology of contamination: Canadian Journal of Fisheries and Aquatic Sciences, v. 48, p. 2344-2354.

Geomarine Associates Ltd., 1975, Halifax Harbour bottom survey: Geological Survey of Canada, Open File Report 283, p. 1-100.

Hargrave B.T., Peer, D.L. and Wiele, H.F., 1989, Benthic biological observations, *in* Nicholls, H. B., ed., Investigations of Marine Environmental Quality in Halifax Harbour: Fisheries and Aquatic Sciences, Canadian Technical Report 1693, p. 37-45.

Hart, B.S. and Barrie, J.V., in press, Environmental geology of the Fraser Delta, Vancouver, *in* Eyles, N., ed., Environmental Geology of Urban Areas: Geological Association of Canada, St. John's, NF, in press.

Hollister, C.D., Flood, R.D., Johnson, D.A., Lonsdale, P.F. and Southard, J.B., 1974, Abyssal furrows and hyperbolic echo traces on the Bahama Outer Ridge: Geology, v. 2, p. 395-400.

Hovland, M. and Judd, A.G., 1988, Seabed Pockmarks and Seepages: Graham and Trotman Inc., Sterling House, London, 293 p.

Keen, M.J. and Piper, D.J.W., 1976, Kelp, methane, and an impenetrable reflector in a temperate bay: Canadian Journal of Earth Sciences, v. 13, p. 312-318.

Keppie, J.D., 1982, Tectonic map of the province of Nova Scotia, Department of Mines and Energy, Nova Scotia.

King, L.H., 1970, Surficial geology of the Halifax-Sable Island map area: Marine Science Paper 1, 16 p.

King, L.H. and Fader, G.B.J., 1986, Wisconsinan glaciation of the southeastern Canadian Continental Shelf: Geological Survey of Canada, Bulletin 363, 72 p.

King, L.H. and MacLean, B, 1970, Pockmarks on the Scotian Shelf: Geological Society of America Bulletin, v. 81, p. 3141-3148.

Knebel, H.J. and Scanlon, K.M., 1985, Sedimentary framework of Penobscot Bay, Maine: Marine Geology, v. 65, p. 305-324.

Lawrence, D.J., 1989, Physical oceanography and modelling in Halifax Harbour: a review: *in* Nicholls, H.B., ed., Investigations of Marine Environmental Quality in Halifax Harbour: Fisheries and Aquatic Sciences, Canadian Technical Report 1693, p. 54-63.

Lay, G.F.T., Fader, G.B.J. and Buckley, D.E., 1993, Environmental implications from disturbance of contaminated marine dredge spoils in Halifax Harbour, Nova Scotia: 1993 Canadian Coastal Conference, Coastal Zone Engineering Program, National Research Council, Ottawa, Canada, p. 253-269.

LeBlanc, K.W.G., Fitzgerald, R.A., Winters, G.V., Buckley, D.E. and Cranston, R.E., 1991, Geochemical data from analyses of sediments and pore waters obtained from cores collected in Halifax inlet: Geological Survey of Canada, Open File Report 2345, 116 p.

Loncarevic, B.D., Courtney, R.C., Fader, G.B.J., Giles, P.S., Piper, D.J.W., Costello, G. Hughes-Clark, J.E. and Stea, R.R., 1994, Sonography of a glaciated continental shelf: Geology, v. 22, p. 747-750.

Miller, A.A.L., Mudie, P.J. and Scott, D.B., 1982, Holocene history of Bedford Basin, Nova Scotia; foraminifera: Canadian Journal of Earth Sciences, v. 19, p. 2342-2367.

Miller, R.O. and Fader, G.B.J., 1989, Cruise report 88-018(A) Phase 1, F.R.V. Navicula, Halifax - Sambro, Nova Scotia, May 26-June 2, 1988: Geological Survey of Canada, Open File Report 2039, 22 p.

Miller R.O., Fader, G.B.J., Buckley, D.E., 1990, Cruise report 89-009, Phase A - Halifax Inlet, F.R.V. Navicula: Geological Survey of Canada, Open File Report 2242, 66 p.

Nairn, R.B. and Cowie, N.B., in press, Management of the Scarborough Bluffs shoreline of Lake Ontario, *in* Eyles, N., ed., Environmental Geology of Urban Areas: Geological Association of Canada, St. John's, NF, in press.

Nicholls, H.B., ed., 1989, Investigations of marine environmental quality in Halifax Harbour: Fisheries and Aquatic Sciences, Canadian Technical Report 1693, 83 p.

OceanChem Group Ltd., 1988, Halifax Harbour sediment quality study, Phase 1: sample collection: Environment Canada, Dartmouth, Nova Scotia, 26 p.

Petrie, B. and Yeats, P., 1990, Simple models of the circulation, dissolved metals, suspended solids and nutrients in Halifax Harbour: Water Pollution Research Journal of Canada, v. 25, p. 325-346.

Prouse, N.J. and Hargrave, B.T., 1987, Organic enrichment of sediments in Bedford Basin and Halifax Harbour: Fisheries and Aquatic Sciences, Canadian Technical Report 1571, 36 p.

Raddall, T.H., 1965, Halifax, Warden of the North: Doubleday, Garden City, New Jersey, 340 p.

Stea, R.R., Pecore, S.S. and Fader, G.B.J., 1993, Quaternary stratigraphy and placer gold potential of the inner Scotian Shelf, Nova Scotia: Department of Natural Resources, Mines and Energy Branches, Paper 93-2, 62 p.

Tay, K.L., Doe, K.G., Wade, S.J., Vaughan, J.D.A., Berigan, R.E. and Moore, M.J., 1991, Biological effects of contaminants in Halifax Harbour sediments: 17th Annual Aquatic Toxicity Workshop, Vancouver, B. C., Fisheries and Aquatic Sciences, Canadian Technical Report 1774, p. 383-426.

Uthe, J.F., Chou, C.L., Prouse, N.J. and Musial, C.J., 1989, Heavy metal, polycyclic aromatic hydrocarbon, and polychlorinated biphenyl concentrations in American lobsters (*Homarus Americanus*) from Halifax Harbour, *in* Nicholls, H.B., ed., 1989, Investigations of marine environmental quality in Halifax Harbour: Fisheries and Aquatic Sciences, Canadian Technical Report 1693, Appendix A, p. 64-68.

Versteeg, J.K., Morris, W.A. and Rukavina, N.A., in press, Mapping contaiminated sediment in Hamilton Harbour, Ontario, *in* Eyles, N., ed., Environmental Geology of Urban Areas: Geological Association of Canada, St. John's, NF, in press.

Winters, G.V. and Buckley, D.E., 1992, Factor analyses as a method of evaluating sediment environmental quality in Halifax Harbour, Nova Scotia: Geological Survey of Canada, Paper 92-1D, p. 165-171.

Winters, G.V., Buckley, D.E., Fitzgerald, R.A. and LeBlanc, K.W.G., 1991, Inorganic geochemical data for surface sediments from Halifax Inlet: Geological Survey of Canada, Open File Report 2389, 64 p.

Accepted, as revised, January 1996.