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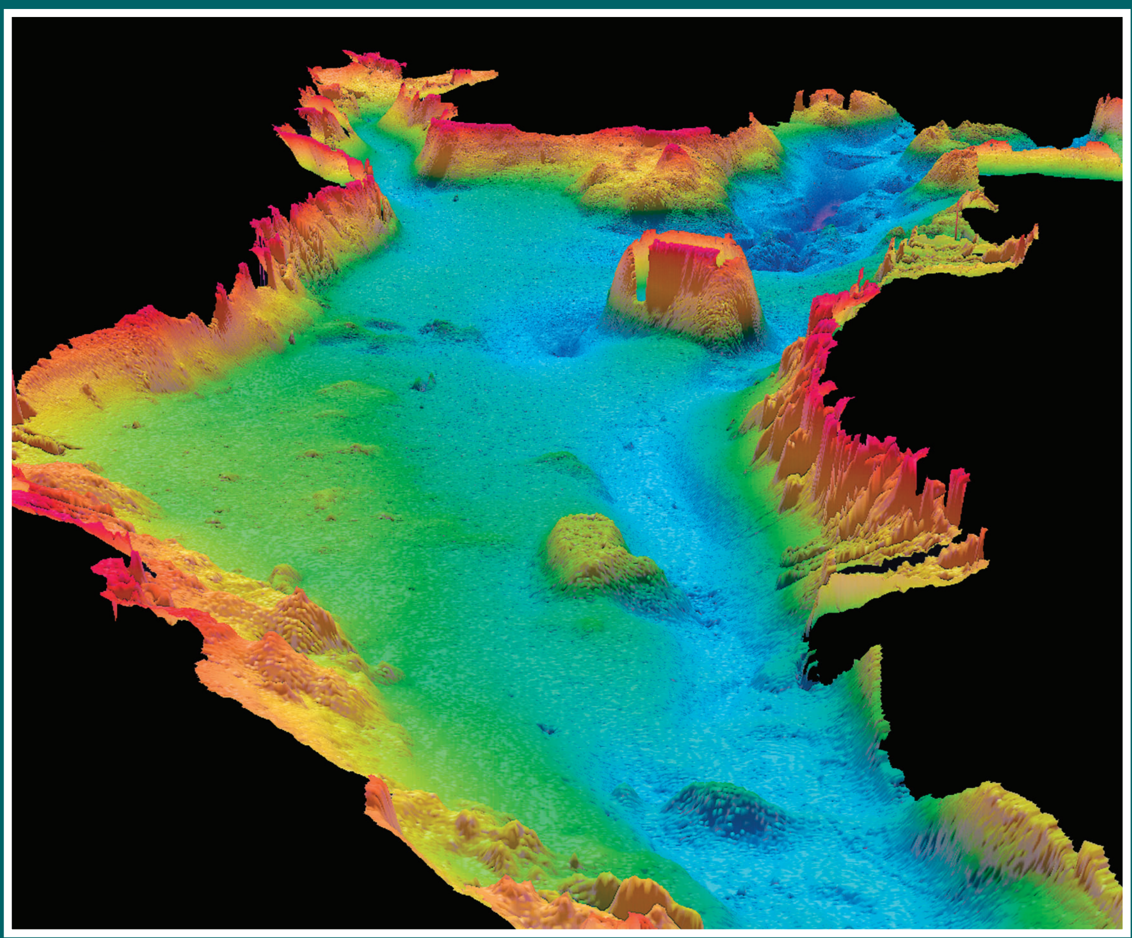
Surficial geology, Halifax Harbour, Nova Scotia

G.B.J. Fader and R.O. Miller



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Cover illustration
A multibeam-bathymetric, 3-D, colour depth-coded, shaded-relief image of inner Halifax Harbour looking from the north to the south. Halifax is on the left, Dartmouth on the right and McNabs Island in the distance. Shallow depths are in red and orange and the deepest depths (40 m) are in blue. Georges Island can be seen protruding from the floor of the harbour in the upper part of the image off Halifax. GSC 2008-127

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CONTENTS

Figures

Table caption

Surficial geology, Halifax Harbour, Nova Scotia

Abstract

The marine geology of Halifax Harbour, Nova Scotia, was studied using seismic-reflection profiles, sidescan-sonar systems, multibeam bathymetry, seabed samples, cores, and photographic observations. Dating of core material and information from seabed samples were correlated with the stratigraphic information from the seismic-reflection data and multibeam backscatter. Maps of detailed multibeam bathymetry, seabed slope, sediment distributions, and both natural and anthropogenic seabed features and processes are presented.

The surficial geology of Halifax Harbour results from glacial erosion and deposition during ice advance and retreat across a former fluvial drainage system, subsequent glaciomarine and lacustrine deposition, erosion by a marine transgression, and recent sedimentation. The outer harbour largely consists of coarse, well sorted sand and gravel with bedrock outcrop in many areas. Sand ribbons, megaripples, and gravel circles form in response to currents and waves. In contrast, the inner harbour consists of gas-charged Holocene mud and is covered with anchor marks, dredge spoils, shipwrecks, cables, and other debris. Natural features include sedimentary furrows, drumlins, moraines, pockmarks, and former shorelines. The inner harbour largely traps sediments and their associated contaminants and minimal amounts are transported out of the harbour.

Halifax Harbour is one of the first marine areas in Canada to have been studied with multibeam bathymetry. It provides a high-resolution portrayal of seabed morphology and features that are interpreted from a morphodynamic perspective. Net sediment transport is dominantly from south to north. The seabed sediment mapping and assessment of anthropogenic features provides a basis for management of Halifax Harbour including marine habitats.

Résumé

La géologie marine du port d'Halifax (Nouvelle-Écosse) a été étudiée à l'aide de profils de sismique-réflexion, avec des systèmes sonar à balayage latéral, par bathymétrie multifaisceaux ainsi que d'après des échantillons du fond marin, des carottes et des observations photographiques. Les données de datation de matériaux de carottes et l'information sur les échantillons du fond marin ont été mises en corrélation avec l'information stratigraphique extraite des données de sismique-réflexion et de rétrodiffusion multifaisceaux. Des cartes ont aussi été dressées pour illustrer la bathymétrie multifaisceaux détaillée, les pentes du fond marin, la distribution des sédiments, ainsi que les entités et les processus naturels et anthropiques du fond marin.

La géologie des matériaux superficiels du port d'Halifax témoigne de l'érosion et de la sédimentation glaciaires qui ont été actifs pendant l'avancée et le recul des glaces dans un ancien réseau fluvial de drainage, du dépôt subséquent de matériaux glaciomarins et lacustres, de l'érosion causée par une transgression marine et de la sédimentation récente. Le port extérieur renferme essentiellement des sédiments grossiers formés de sable et de gravier bien triés et d'affleurements du socle rocheux dans nombre de secteurs. Des rubans et des mégarides de sable ainsi que les plaques circulaires de gravier sont formés par l'action des courants et des vagues. Par contraste, le port intérieur est en grande partie occupé par de la boue de l'Holocène chargée de gaz, dont la surface est couverte de cicatrices d'ancres, de déblais de dragage, d'épaves, de câbles et d'autres débris. Les entités naturelles comprennent des sillons sédimentaires, des drumlins, des moraines, des petites dépressions circulaires et d'anciennes lignes de rivage. Le port intérieur piège en grande partie les sédiments et les contaminants qui leurs sont associés, et des quantités minimales de ceux-ci sont transportées à l'extérieur du port.

Le port d'Halifax est une des premières régions maritimes du Canada à faire l'objet d'une étude par bathymétrie multifaisceaux. Cette étude fournit une représentation haute résolution de la morphologie et des entités du fond marin, qui se prête à une interprétation employant une approche morphodynamique. Le transport net des sédiments s'effectue de façon prédominante du sud au nord. La cartographie des sédiments et une évaluation des entités anthropiques du fond marin fournissent des assises pour une gestion du port d'Halifax qui tienne compte, entre autres, des habitats marins.

SUMMARY

Halifax Harbour is a major inlet of the Atlantic Ocean within the province of Nova Scotia, midway along the southeastern provincial seaboard. It extends inland for over 28 km to the northwest and has a complex geography composed of outer and inner divisions; two projecting arms: Northwest Arm and Eastern Passage; and a very deep and large bowl-shaped basin at its head, Bedford Basin. It is the major port of Atlantic Canada and the location of large industrial, military, civilian, and tourism waterfront facilities. The harbour is surrounded by the major communities of Halifax and Dartmouth and smaller centres of Herring Cove, Bedford, and Eastern Passage, which all collectively occur in the area known as the Halifax Regional Municipality. The harbour was the seasonal home to native Canadians in early postglacial time beginning at 11 000 BP, was visited for hundreds of years by early explorers, and was finally formally settled by the British in 1749. The settlement was easily achieved largely because of the presence of many digable high hills (drumlins) that served as fortresses for security.

A systematic and comprehensive study of the marine geology of Halifax Harbour was initiated to provide geoscience advice to the siting and selection of waste-water treatment facilities for the region, which has been a continuing environmental problem. It was also conducted in response to new surficial mapping initiatives of the Geological Survey of Canada that shifted emphasis from the adjacent continental shelf in the offshore to the nearshore environment. A comprehensive set of marine geological and geophysical surveys extending from Bedford Bay to the inner Scotian Shelf, were conducted between 1987 and 1995.

Acoustic survey data were collected with sidescan sonars, a variety of high-resolution seismic-reflection profilers, and multibeam-bathymetric sonar systems. Multibeam-bathymetric data was collected beyond the mouth of the harbour on the adjacent inner Scotian Shelf between 1992 and 1994. Final collection and processing of multibeam-bathymetric data was completed in 2002 for Bedford Basin and Northwest Arm to provide coverage of all areas of the harbour.

Sediment samples were obtained with a variety of grab samplers, corers, and borehole-drilling equipment. Direct observations were conducted using submersibles, remotely operated vehicles, and seabed camera systems. The acoustic survey data were integrated with sample information that included radiocarbon dates from cores. Based on the interpretation of the seismic stratigraphy and sediment properties, maps of sediment distribution, bed forms, gas-charged sediments, sediment thicknesses, seabed anthropogenic and natural features, multibeam bathymetry, and seabed slope have

SOMMAIRE

Le port d'Halifax est une indentation majeure de la côte de l'Atlantique en Nouvelle-Écosse, qui se situe au milieu de la limite maritime sud-ouest de la province. Il s'enfonce dans les terres en direction du nord-ouest sur plus de 28 km; il présente une géographie complexe et comporte une partie intérieure et une partie extérieure, deux bras de mer, le bras Northwest et le passage Eastern, ainsi qu'un grand bassin très profond en forme de bol à sa partie intérieure, le bassin Bedford. C'est le principal port du Canada atlantique et il abrite de grandes installations industrielles, militaires, civiles et touristiques riveraines. Le port est entouré par les grandes agglomérations d'Halifax et de Dartmouth ainsi que par les centres plus petits de Herring Cove, Bedford et Eastern Passage, tous regroupés dans la région appelée « Municipalité régionale d'Halifax ». Lieu de résidence saisonnier d'autochtones canadiens au début de l'ère postglaciaire vers 11 000 ans BP, il a été fréquenté pendant des centaines d'années par les premiers explorateurs et des Britanniques s'y sont finalement établis en 1749. L'implantation fut relativement facile en grande partie en raison de la présence d'un grand nombre de hautes collines (drumlins) dont l'excavation permettait l'aménagement de forteresses à des fins de sécurité.

Une étude systématique et exhaustive de la géologie marine du port d'Halifax a été entreprise afin d'obtenir l'expertise géoscientifique nécessaire pour le choix de sites d'installations de traitement des eaux usées dans la région, un problème environnemental persistant. L'étude a également été entreprise en réponse à de nouvelles initiatives de cartographie des matériaux superficiels de la Commission géologique du Canada qui a déplacé son champ d'intérêt principal des secteurs éloignés des côtes de l'adjacente plate-forme continentale vers la région littorale. Un ensemble exhaustif de levés géologiques et géophysiques en mer couvrant la région qui s'étend de la baie Bedford à la plate-forme Néo-Écossaise interne ont été exécutés entre 1987 et 1995.

Des données de levés acoustiques ont été acquises avec des sonars à balayage latéral, avec toute une gamme de profileurs de sismique-réflexion haute résolution et avec des systèmes sonar bathymétriques multifaisceaux. Des données de bathymétrie multifaisceaux ont été recueillies au-delà de l'entrée du port sur l'adjacente plate-forme Néo-Écossaise interne entre 1992 et 1994. La collecte finale et le traitement des données bathymétriques multifaisceaux ont été complétés en 2002 dans le bassin Bedford et le bras Northwest afin de couvrir tous les secteurs du port.

Des échantillons de sédiments ont été prélevés avec divers échantillonneurs à benne, des carottiers et de l'équipement de forage. Des observations directes ont été effectuées à l'aide de submersibles, de véhicules télécommandés et de systèmes de prise de vues du fond marin. Les données de levés acoustiques ont été intégrées à l'information obtenue des échantillons qui englobait des âges radiocarbone tirés de carottes. D'après l'interprétation de la sismostratigraphie et des propriétés des sédiments, on a dressé des cartes de la distribution des sédiments, des figures sédimentaires du fond marin, des sédiments riches en gaz, de l'épaisseur des sédiments, des entités anthropiques et naturelles du fond marin, de la bathymétrie et des pentes du fond marin. Ces cartes fournissent un

been prepared. These provide a regional geological framework for an understanding of the geological history of the harbour from its earliest beginnings to its modern development in response to its role as a busy waterway for a variety of public, military, and industrial applications. The information has been applied to the design and assessment of engineering projects, especially proposed waste-water treatment facilities for the Halifax-Dartmouth area.

The four major factors dominating the evolution of the harbour were: 1) the formation of fluvial drainage systems beginning in the Cretaceous were controlled in location and degree of erosion by contrasting bedrock rock types and, to a lesser degree, structure; 2) the advance and retreat of Quaternary glaciers and their associated differential erosion of bedrock and deposition of surficial materials, together with their relationships with the adjacent Atlantic Ocean; 3) post-Wisconsinan glaciation sea-level lowstands and the formation of a series of lakes and connecting rivers; and 4) the rise of sea level to its preglacial position and marine transgression of areas above 65 m water depth including the progressive marine inundation of lakes. This geological history combined with present seabed processes has produced a complex stratigraphy and contrasting sediment distributions and characteristics between the inner and outer areas of the harbour.

Sediments within the harbour have been mapped following a formational classification system developed for the adjacent Scotian Shelf. Variations in harbour sediments occur where they have been transgressed in a low-energy protected inner-harbour environment with minor modification in contrast to the high-energy, open Atlantic Ocean conditions of the outer harbour and the adjacent inner Scotian Shelf. The presence of late glacial and early postglacial lakes are also unique features not commonly found on the adjacent continental shelf.

The morphology and location of the harbour is attributed to glacial overdeepening of pre-existing fluvial drainage systems that were first developed during the Cretaceous time. These early river systems flowed across a southeasterly dipping peneplain and were able to effectively erode the Meguma Group slate and quartzite more readily than the more resistant granite bodies that are largely confined to the western area of the harbour. As a result, the original locations of the first rivers that crossed the region were confined to areas east of the granite overlying the Halifax Formation slate and the Goldenville Formation quartzite in the present harbour area. Zones of structural weakness may have also contributed to the location.

cadre géologique qui nous permet de mieux comprendre l'histoire géologique du port depuis le tout début de sa formation jusqu'à son aménagement à l'époque contemporaine en réponse aux exigences de l'utilisation comme voie navigable très fréquentée et de toute une gamme d'applications publiques, militaires et industrielles. Cette information a été appliquée à la conception et à l'évaluation de projets d'ingénierie et en particulier des installations proposées de traitement des eaux usées dans la région d'Halifax-Dartmouth.

Les quatre principaux facteurs qui ont conditionné l'évolution du port sont les suivants : 1) la formation de réseaux fluviaux de drainage à compter du Crétacé dont la position et le degré d'encaissement par l'érosion ont été déterminés par les contrastes entre divers types de socle rocheux et dans une moindre mesure par la structure; 2) l'avancée et le recul des glaciers du Quaternaire ainsi que l'érosion différentielle du socle rocheux et le dépôt de matériaux superficiels qui leur sont associés, de même que les relations de ces phénomènes avec l'océan Atlantique adjacent; 3) les intervalles de bas niveau de la mer postérieurs à la glaciation du Wisconsinien et la formation d'une série de lacs et de cours d'eau les reliant; et 4) l'élévation du niveau de la mer jusqu'à sa position préglaciaire et la transgression marine sur les étendues de terrain reposant aujourd'hui jusqu'à une profondeur de 65 m, un phénomène qui a comporté, entre autres, l'ennoyage progressif des lacs par les eaux marines. Cette histoire géologique combinée aux processus actuels qui touchent le fond marin a engendré une stratigraphie complexe ainsi que des contrastes dans la distribution et les caractéristiques des sédiments entre les parties intérieure et extérieure du port.

Les sédiments à l'intérieur du port ont été cartographiés suivant un système de classification de formations élaboré pour l'adjacente plate-forme Néo-Écossaise. Des variations dans les sédiments du port s'observent aux endroits où ils n'ont subi que des modifications mineures par la transgression marine dans le milieu protégé à faible énergie du port intérieur qui contraste avec le milieu à haute énergie, ouvert aux conditions de l'océan Atlantique, du port extérieur et de l'adjacente plate-forme Néo-Écossaise interne. La présence de lacs tardiglaciaires et du début de la période postglaciaire constituent également une caractéristique unique qui ne se manifeste généralement pas sur l'adjacente plate-forme continentale.

La morphologie et l'emplacement du port sont attribués à un surcreusement par la glace des réseaux de drainage préexistants formés initialement au Crétacé. Ces réseaux fluviaux primitifs drainaient une pénéplaine inclinée vers le sud-est et ont érodé de manière efficace l'ardoise et le quartzite du Groupe de Meguma plus facilement que les massifs de granite plus résistants qui sont en grande partie confinés au secteur ouest du port. En conséquence, les emplacements d'origine des premiers cours d'eau qui sillonnaient la région ont été confinés aux secteurs situés à l'est du granite surmontant l'ardoise de la Formation d'Halifax et le quartzite de la Formation de Goldenville dans l'actuelle région du port. Des zones de faiblesse structurale pourraient aussi avoir contribué à la localisation des cours d'eau.

With the beginning of glaciation during the Quaternary, ice sheets and ice streams were focused in the pre-existing fluvial depressions and channels. Overdeepening by glaciers was confined to anticlines of the Goldenville Formation quartzite with minimal erosion of the Halifax Formation slate. This resulted from the thick bedding within the quartzite and the ability of the glaciers to pluck large boulders from the surface, especially within the anticlinal weakened structures. Wider areas of the present harbour and deep Bedford Basin are clearly attributed to this differential glacial erosion.

Glaciers repeatedly advanced throughout the harbour during the Pleistocene, and it is not clear which one is responsible for the extensive overdeepening of bedrock and the configuration of the harbour channel. Evidence from deep water, offshore eastern Canada indicates that the pre-Wisconsinan Illinoian glaciation may have been the most extensive and erosive; however, the bulk of the glacial sediment in the region results from the last glaciation, the Wisconsinan. The ice is interpreted to have been over 1 km thick during this event within the harbour region.

This phase of ice advance is referred to as the Escuminac phase of the Late Wisconsinan, which occurred from 22–18 ka BP. The ice was centred over the Gulf of St. Lawrence and it extended across Nova Scotia to the edge of the Scotian Shelf over 100 km to the southeast. Isolated drumlins, drumlin fields, and moraines were deposited by this ice. Three Wisconsinan tills occur in the harbour: the Hartlen, Lawrencetown, and Beaver River tills. Drumlins are located on the western side of Bedford Basin and in the inner harbour to the north of Georges Island. A large field of eroded and transgressed drumlins occurs southeast of Hartlen Point on the inner Scotian Shelf. They are oriented parallel to those found in Dartmouth on the east side of Halifax Harbour. A few north-south oriented drumlins occur south of Sambro on the inner continental shelf. Ribbed moraines lie on Middle Ground, in Bedford Bay, and south of Sambro on the inner Scotian Shelf.

Late Wisconsinan ice began to retreat back across the continental shelf by 18 ka BP. A major shift in ice centres developed as a result of ice-stream drawdown into areas surrounding Nova Scotia such as the Bay of Fundy and the Laurentian Channel. This resulted in the development of a Nova Scotia–centred ice cap termed the Scotian Ice Divide. The ice continued to retreat to the land from its terminus on the inner Scotian Shelf and reached the present coast of Halifax Harbour by approximately 13–12 ka BP.

As a result of the glacial overdeepening of many areas of the harbour, the pre-existing fluvial system was

Au début de la glaciation du Quaternaire, les nappes et les courants glaciaires ont été canalisés dans les dépressions et chenaux fluviaux préexistants. Le surcreusement par les glaciers a été confiné aux anticlinaux formés de quartzite de la Formation de Goldenville et n'a causé qu'une érosion minimale de l'ardoise de la Formation d'Halifax. Ceci résulte de la stratification du quartzite en couches épaisses et de l'aptitude des glaciers à détacher de gros blocs de la surface, surtout à l'intérieur des structures anticlinales affaiblies. Les secteurs les plus larges du port et le profond bassin Bedford sont nettement attribuables à cette érosion glaciaire différentielle.

Les glaciers se sont avancés à répétition sur l'ensemble du port pendant le Pléistocène et il n'est pas évident de déterminer à quelle avancée il faut attribuer l'important surcreusement du socle rocheux et la configuration du chenal du port. Des indications relevées en eau profonde au large de la côte Est du Canada révèlent que la glaciation pré-wisconsinienne de l'Illinoien peut avoir été la plus étendue et celle qui a produit la plus forte érosion; cependant, la plus grande partie des sédiments glaciaires dans la région provient de la dernière glaciation, celle du Wisconsinien. La glace aurait alors eu une épaisseur de 1 km dans la région du port.

Cette phase d'avancée glaciaire est appelée « phase d'Escuminac » du Wisconsinien supérieur et elle se serait déroulée de 22 à 18 ka BP. La glace était centrée sur le golfe du Saint-Laurent et s'avançait sur la Nouvelle-Écosse jusqu'au rebord de la plate-forme Néo-Écossaise, à plus de 100 km au sud-est. Des drumlins isolés, des champs de drumlins et des moraines ont été formés par cette glace. On trouve trois tills du Wisconsinien dans le port : les tills de Hartlen, de Lawrencetown et de Beaver River. Les drumlins sont situés du côté ouest du bassin Bedford et dans le port intérieur, au nord de l'île Georges. Un grand champ de drumlins, en partie érodés et portant les traces de la transgression, est présent sur la plate-forme Néo-Écossaise interne, au sud-est de la pointe Hartlen. Ces drumlins sont orientés parallèlement à ceux observés à Dartmouth du côté est du port d'Halifax. Il y a également quelques drumlins d'orientation nord-sud sur la plate-forme Néo-Écossaise interne, au sud de Sambro. Des moraines côtelées gisent sur le *Middle Ground*, dans la baie Bedford, et sur la plate-forme Néo-Écossaise interne, au sud de Sambro.

La glace du Wisconsinien supérieur a commencé à se retirer sur la plate-forme continentale à 18 ka BP. Il y a eu un déplacement majeur des centres glaciaires en réponse à la ponction exercée par les courants glaciaires dans les régions périphérique à la Nouvelle-Écosse comme la baie de Fundy et le chenal Laurentien, ce qui a engendré la formation d'une calotte glaciaire centrée sur la Nouvelle-Écosse dont la crête a été appelée la « ligne de partage glaciaire de Scotian ». La glace a continué à se retirer vers l'intérieur des terres depuis le front glaciaire sur la plate-forme Néo-Écossaise interne pour atteindre l'actuelle côte du port d'Halifax à 13-12 ka BP environ.

Le surcreusement glaciaire d'un grand nombre de secteurs du port a modifié le réseau fluvial préexistant en formant sur toute sa modified with the formation of many deep basins along its length. The Narrows exhibits an exposed curvilinear section of this river termed the 'ancient Sackville River'. Early postglacial lakes formed throughout the harbour in many of these overdeepened bedrock depressions and were connected by a river and stream system to the Atlantic Ocean. As many as 10 lakes existed in the present area of the harbour.

The lakes were progressively flooded by the sea during the marine transgression that began approximately 12 000 BP from a lowstand of -65 m off the mouth of the harbour. The transgression eroded and reworked previously deposited glacial materials, forming well sorted sand and gravel deposits, areas of bedrock outcrop, and eroded drumlins at the seabed. By 5500 BP, the ocean had progressed far enough up the harbour and was deep enough for deposition of LaHave Clay to begin in the inner harbour, sourced from eroding glacial, lacustrine, and estuarine materials. Bedford Basin, which was formerly a series of three lakes, was finally flooded by the rising sea at 5700 BP when the shallow sill of The Narrows was breached by the rising waters and a transition from a lacustrine to a marine environment occurred.

The former level of the lake in Bedford Basin is well defined by the presence of two continuous boulder berms that ring the basin at a present depth of 23 m. These formed when the basin was a lake, through the concentration of boulders in ice-push ridges at the former lake shoreline as the lake underwent seasonal freezing. Boulder berms also occur in other areas of the inner harbour and help define the location of former lakes. A series of exposed bedrock ridges of quartzite with a notch cut into the bedrock likely represents the site of a former waterfall as part of the early fluvial drainage system in northern Bedford Basin at the junction with Bedford Bay.

In the outer harbour the early marine incursion occurred in a narrow channel in the western part. A large area of present bedrock shoals in the east were emergent until 7000 BP and were likely covered with fields of drumlins similar to the McNabs Island area directly to the north. During the marine transgression these areas were subjected to large waves and strong currents that effectively eroded the previous till deposits down to the bedrock. In some areas linear boulder ridges oriented northwest-southeast remain as evidence of the previous location of drumlins. Large, fluted, linear bedrock depressions were exhumed during the transgression and attest to erosion beneath an ice stream that occupied the Halifax Harbour area. Sand-sized sediment liberated from the transgression was deposited in the deep western channel of the outer harbour, overlying previously deposited glaciomarine and lacustrine sediments. Fine-grained muds eroded from the outer harbour area were transported farther to the south to Emerald Basin.

longueur plusieurs bassins profonds. Le goulet appelé *The Narrows* constitue un segment curviligne exposé de ce cours d'eau appelé « ancienne rivière Sackville ». Des lacs postglaciaires se sont formés tôt après la glaciation tout au long du port dans ces dépressions de surcreusement glaciaire du socle rocheux et ils étaient reliés à l'océan Atlantique par un réseau de cours d'eau. Dans la région actuelle du port, jusqu'à 10 lacs ont existé.

Les lacs ont progressivement été ennoyés par la transgression marine qui a commencé à 12 000 ans BP environ depuis un bas niveau de - 65 m, à partir d'un point situé au large de l'entrée du port. Cette transgression a érodé et remanié des matériaux glaciaires antérieurement déposés pour former des dépôts de sable et de gravier bien triés, pour mettre à nu le socle rocheux et pour éroder des drumlins du fond marin. Vers 5 500 ans BP, l'océan s'était avancé assez loin dans le port pour que commence dans le port intérieur le dépôt de l'Argile de LaHave issue de l'érosion de matériaux glaciaires, lacustres et estuariens. Le bassin Bedford, qui auparavant formait une série de trois lacs, a finalement été ennoyé par l'élévation du niveau de la mer à 5 700 ans BP lorsque le seuil peu profond du goulet (*The Narrows*) a été entaillé sous l'effet de la montée des eaux, ce qui a entraîné une transition d'un milieu lacustre vers un milieu marin.

L'ancien niveau du lac qui occupait le bassin Bedford est bien marqué par la présence de deux bermes de blocs rocheux continues qui entourent le bassin à la profondeur actuelle de 23 m. Ces bermes se sont formées par la concentration des blocs en bourrelets de poussée glacielle à la ligne de rivage de l'ancien lac confiné par le bassin lors des gels saisonniers. Des bermes de blocs existent également dans d'autres parties du port intérieur et aident à définir les emplacements des anciens lacs. Dans la partie nord du bassin Bedford, à l'endroit où celui-ci rejoint la baie Bedford, une entaille dans une série de crêtes de quartzite du socle rocheux affleurant marque vraisemblablement l'emplacement d'une ancienne chute dans le réseau de drainage initial.

Dans le port extérieur, le début de l'incursion marine s'est produit dans un étroit chenal de la partie ouest. Des hauts-fonds actuels du socle s'étendant sur une vaste étendue à l'est émergeaient jusqu'à 7 000 ans BP et leur surface était vraisemblablement couverte de champs de drumlins similaires à ceux du secteur de l'île McNabs directement au nord. Pendant la transgression marine, ces secteurs ont été soumis à l'action de grosses vagues et de forts courants qui ont efficacement érodé les dépôts de till antérieurs jusqu'au socle rocheux. Dans certaines zones, des crêtes linéaires de blocs rocheux d'orientation nord-ouest–sud-est témoignent d'emplacements antérieurs de drumlins. De grandes dépressions linéaires du socle rocheux en forme de flûte ont été exhumées pendant la transgression et témoignent de l'érosion active à la base d'un courant glaciaire qui occupait la région du port d'Halifax. Des sédiments de la taille des sables, dégagés par la transgression, ont été déposés dans le profond chenal occidental du port extérieur et recouvrent des sédiments glaciomarins et lacustres déposés antérieurement. Des boues à grain fin produites par l'érosion dans le secteur du port extérieur ont été transportées plus loin au sud dans le bassin Emerald.

During the transgression, erosion was much less severe in the inner harbour. In many places till units were preserved overlying bedrock and only their surfaces were winnowed and slightly armoured with gravel lag. The gravel clasts in the inner harbour are angular to subangular compared to the well rounded gravel of the outer harbour. In The Narrows, beach processes were much more intense as a result of a long fetch and narrowing funnel-shaped channel. Curvilinear gravel-beach ridges were formed that remain at the seabed today.

The earliest deposition of Holocene LaHave Clay occurred in the inner harbour at approximately 5500 BP. Variations in depositional patterns, the formation of nondepositional moats, and deposits of fining-up sequences in the clay indicate higher energy conditions during the time of early deposition.

As the sea level returned to its former preglacial position, the harbour became deeper and fine-grained mud was deposited over larger areas of coarser grained sediment in the inner harbour. Modern conditions were established at approximately 3000 BP when sea level had returned to less than 5 m of its present position and estuarine circulation was established that was largely driven by discharge from the Sackville River at the head of Bedford Basin and a few smaller rivers and streams that entered the harbour. The area to the west of McNabs Island is a key transitional area for sediment deposition and erosion. The LaHave Clay of the inner harbour thins and overlies the Sable Island Sand and Gravel in a complex set of sedimentary furrows at the seabed. During large storms, coarse sediment from the outer harbour is transported to the north up the harbour, and in other more quiet times, fine-grained mud is deposited in the area. The presence of sedimentary furrows, sediment moats, and obstacle-induced scours attest to periodic deposition and erosion of fine-grained sediments.

Today the inner harbour north of McNabs Island is generally a depositional zone for muddy sediments. A few local areas of nondeposition or periodic deposition and erosion also occur in the inner harbour that result from high-velocity currents around topographically high features. The Narrows is a highly energetic region with a lack of fine-grained sediments and a hard bottom of gravel, former beach ridges, and mimicked bedrock ridges covered in gravel. Mud dominates the seabed of Northwest Arm; however, adjacent to The Dingle, a narrowing restriction increases the flow of water that results in a deeper region of nondeposition.

Contrary to earlier thinking that suggested that the harbour regularly transports silt and clay and their associate contaminants seaward, fine-grained sediments are generally trapped in the inner harbour. Particles introduced from rivers and sewage systems

Pendant la transgression, l'érosion était beaucoup moins intense dans le port intérieur. En nombre d'endroits, des unités de till recouvrant le socle ont été préservées et seules leurs surfaces ont été vannées et légèrement cuirassées de gravier de déflation. Les clastes qui composant les graviers du port intérieur sont anguleux à subanguleux comparativement à ceux bien arrondis des graviers du port extérieur. Dans le goulet (*The Narrows*), les processus agissant sur les plages étaient beaucoup plus intenses en raison d'un long fetch et de la forme en entonnoir du chenal. Des crêtes de plage graveleuses curvilignes se sont formées et persistent encore de nos jours sur le fond marin.

L'Argile de LaHave de l'Holocène a commencé à se déposer dans le port intérieur à 5 500 ans BP environ. Des variations de la configuration sédimentaire, la formation de fossés de non-sédimentation et le dépôt de séquences à granodécroissance ascendante dans l'argile témoignent de conditions de plus haute énergie au début du dépôt.

Alors que le niveau de la mer revenait à sa position d'avant la glaciation, le port est devenu plus profond et de la boue fine s'est déposée sur de plus grandes étendues de sédiments à grain plus grossier dans le port intérieur. Les conditions contemporaines se sont établies à environ 3 000 ans BP, lorsque le niveau de la mer est revenu à moins de 5 m du niveau actuel et que s'est établie une circulation estuarienne en grande partie régie par le débit de la rivière Sackville au fond du bassin Bedford et de celui de quelques cours d'eau plus petits se jetant dans le port. Le secteur situé à l'ouest de l'île McNabs est une zone de transition clé pour le dépôt et l'érosion des sédiments. L'Argile de LaHave dans le port intérieur s'amincit et recouvre les Sables et Graviers de Sable Island dans un ensemble complexe de sillons sédimentaires du fond marin. Pendant les grosses tempêtes, les sédiments grossiers du port extérieur sont transportés vers le nord et l'intérieur du port, alors que par temps plus calme, une vase fine se dépose dans ce secteur. La présence de sillons sédimentaires, de fossés de non-sédimentation et de cicatrices d'affouillement engendrés par la présence d'obstacles témoigne d'intervalles périodiques de dépôt et d'érosion des sédiments à grain fin.

De nos jours, le port intérieur au nord de l'île McNabs est généralement une zone de dépôt de sédiments boueux. Il y a quelques zones locales de non-sédimentation ou d'alternance périodique de dépôt et d'érosion dans le port intérieur en raison des courants à grande vitesse circulant autour de hauteurs topographiques. Le goulet (*The Narrows*) constitue une étendue à haute énergie dépourvue de sédiments à grain fin et à fond dur graveleux, où l'on observe d'anciennes crêtes de plages et des crêtes de gravier qui reproduisent par mimétisme la surface du socle rocheux. La vase est dominante dans le bras Northwest; cependant un rétrécissement à côté de *The Dingle* accélère l'écoulement de l'eau ce qui engendre une région de non-sédimentation plus profonde.

Contrairement à l'hypothèse antérieurement acceptée voulant que le silt et l'argile présents dans le port, ainsi que les contaminants qui leur sont associés, soient régulièrement transportés vers le large, les sédiments à grain fin sont généralement piégés dans le port intérieur. Les particules introduites par les cours d'eau et les flocculate as they enter the surface harbour waters and as they move seaward become heavier and eventually sink where they become entrenched in the incoming bottom waters and move to the north. In striking contrast, the outer harbour is a highly energetic environment of sand and gravel with a variety of bed forms and large expanses of exposed bedrock. The coarse character of the outer harbour, however, owes it existence more to erosion during the marine transgression than to modern processes that are only responsible for shifting local sand and preventing the accumulation of silt and clay.

The deep entrance channel of the harbour is on the western side in the area of the contact between the granite and the slate and quartzite. It is flanked by steep granite cliffs along the Chebucto Head western coastline. The eastern flank of the deep entrance channel is a series of shallow bedrock shoals surrounded by gravel that dominate the eastern part of the outer harbour. Often viewed as a deep and easily transited harbour, it does, however, contain a number of shallow bedrock and till shoals that must be carefully navigated.

The dynamics of the seabed of the harbour decreases from south to north. Little sediment deposition is presently taking place in the outer harbour with the exception of sand and gravel eroded from till and drumlins along the shoreline of the southeastern area of McNabs and Lawlor islands as well as the adjacent mainland. Bed forms such as sand ribbons and megaripples are common in the outer harbour. A grouping of 95, unusual, circular gravel patches occurs near Bear Cove Shoal. They are surrounded by sand and their origin is attributed to erosion by shedding vortices from the nearby steep bedrock shoals during large storms. Both the inner and outer areas of the harbour exhibit areas of seabed that are relict, resulting from glacial deposition and erosion followed by marine transgression with no modern alteration.

Large zones of LaHave Clay in the inner harbour, and buried estuarine and lacustrine mud in the outer harbour, are charged with biogenic methane gas. This gas leaks out of the seabed at the entrance to Northwest Arm and forms a large field of pockmarks. In the central area of Bedford Basin are two horseshoe-shaped depressions that are interpreted to be subsidence features associated with the venting of methane gas. The hazard potential of gas release in not well understood. Gas may also leak out of the buried lacustrine sediments in the outer harbour beneath sand and gravel, but there are no passage features at the seabed because of the coarseness of the sediments.

Dredging, propeller scouring, and anchoring are anthropogenic seabed disturbances that contribute to the release of the methane gas as well as erosion and deposition of seabed sediments. Large areas of the inner harbour and Bedford Basin are covered with

réseaux d'égouts floculent en pénétrant dans les eaux de surface du port et deviennent plus lourdes en cheminant vers le large pour éventuellement s'enfoncer jusque dans l'eau de fond pénétrant dans le port et se déplacer par entraînement dans cette eau vers le nord. Par un saisissant contraste, le port extérieur est un milieu à très haute énergie au fond couvert de sable et de gravier et présentant toute une gamme de figures sédimentaires de fond ainsi que de grandes étendues de socle rocheux mis à nu. La nature plus grossière des sédiments du port extérieur est cependant davantage attribuable à l'érosion pendant la transgression marine qu'aux processus contemporains qui ne font que déplacer le sable local et empêcher l'accumulation de silt et d'argile.

Le profond chenal d'entrée du port se trouve du côté ouest du contact entre le granite et une succession d'ardoise et de quartzite. Il est bordé d'abruptes falaises de granite le long de la ligne de rivage ouest du promontoire Chebucto. Le flanc est du profond chenal d'entrée est occupé par une succession de hauts-fonds du socle rocheux bordés de gravier qui dominent la partie orientale du port extérieur. Souvent perçu comme un port profond où le passage est facile, il présente néanmoins un certain nombre de hauts-fonds composés du socle rocheux et de till qui exigent une navigation prudente.

Du sud au nord, le fond marin du port devient un milieu moins dynamique. Il n'y a actuellement qu'une faible sédimentation dans le port extérieur, exception faite de celle du sable et du gravier érodés du till et des drumlins qui se produit le long de la ligne de rivage de la partie sud-est des îles McNabs et Lawlor ainsi que de la terre ferme adjacente. Des figures sédimentaires de fond marin comme les cordons et les mégarides de sable sont courantes dans le port extérieur. Un groupe de 95 plaques de gravier inusitées de forme circulaire sont présentes près du haut-fond Bear Cove. Ces plaques sont entourées de sable et leur origine est attribuée à l'érosion par des tourbillons qui détache des matériaux de proches hauts-fonds du socle rocheux aux parois abruptes pendant les grosses tempêtes. Les parties intérieure et extérieure du port présentent des étendues de fond marin reliques qui témoignent de la sédimentation et de l'érosion glaciaires, de la transgression marine subséquente ainsi que de l'absence de toute altération récente.

De grandes zones de l'Argile de LaHave, dans le port intérieur, et de boues estuarienne et lacustre enfouies, dans le port extérieur, sont chargées de méthane biogène. Ce gaz s'échappe du fond marin à l'entrée du bras Northwest et forme un grand champ de petites dépressions circulaires. Dans la partie centrale du bassin Bedford, il y a deux dépressions en forme de fer à cheval que l'on assimile à des entités d'affaissement associées à l'échappement de méthane. Le danger que pourrait poser un éventuel dégagement de gaz est mal compris. Du gaz peut également s'échapper des sédiments lacustres enfouis sous le sable et le gravier dans le port extérieur, mais aucune entité témoignant d'échappement n'est visible sur le fond marin en raison de la grossièreté des sédiments.

Le dragage et les cicatrices d'affouillement par les hélices et les ancres de navires sont des perturbations anthropiques du fond marin contribuant au dégagement de méthane ainsi qu'à l'érosion et au dépôt de sédiments du fond marin. De grandes étendues du port intérieur et du bassin Bedford sont couvertes de nombreuses many generations of anchor marks. These include drag marks, chain marks, and a variety of other features attributed to ship anchoring. They are formed by the deployment, dragging, and recovery of ships' anchors. Some of the largest anchor marks are over 3 km long, 2.5 m deep, and 5 m wide. In the most affected areas of Bedford Basin and the inner harbour, over 25% of the seabed sediment is disturbed. The term 'anchorturbation' is proposed to describe the process of anchor disturbance and resuspension of sediments. Their widespread presence attests to a strong influence of shipping-related activities on the seabed. Cores and seabed samples collected from these disturbed areas cannot be relied on to provide an intact and meaningful stratigraphy.

The thickest deposits of LaHave Clay, ranging to over 6 m, occur in depositional zones in the inner harbour north of McNabs Island, north of Georges Island, in Northwest Arm, Eastern Passage, and in Bedford Basin. The mud is very thin or absent in The Narrows and in most nearshore zones with less than 5 m water depth, as well as to the east and west of Georges Island, on Ives Knoll, and in the deepest part of the inner harbour between northwestern McNabs Island and south Halifax peninsula.

Anthropogenic features are widespread on the harbour floor and are largely confined to the area north and west of McNabs Island in the inner harbour. These include a dense network of anchor marks, dredge spoils, mining depressions, borrow pits, collapsed bridge remains, shipwrecks, propeller scours, dredged areas, cables, pipelines, outfalls and intakes, sewage banks, seabed moorings, automobiles, and unidentified debris. Based on the distribution of these seabed features and attributes it is apparent that the seabed of Halifax Harbour is heavily influenced by human activities. Studies of the harbour did not reveal some of the pre-existing myths that have persisted for a long time. There is no crater from the Halifax Explosion of 1917 and no tunnel to Georges Island under the harbour from Halifax Citadel National Historic Site of Canada (locally known as 'Citadel Hill'). Remains of the two original bridges that crossed the harbour in The Narrows are widespread and consist of cribwork, rail track, and scattered debris. The remains and erosional effects of antisubmarine nets designed to protect the harbour from invading submarines during World War I and II also remain on the seabed of the outer harbour.

Approximately 45 shipwrecks were discovered on the harbour floor, many of which were unknown or the positions of which were inaccurate. Those that ran aground in the outer harbour on the shallow shoals and against the rocky western headlands have been reduced to debris piles and attest to the high wave energy in the outer harbour generated during storms. Those that sunk

générations de cicatrices laissées par les ancres. Elles regroupent des cicatrices de dragage d'ancres, des marques laissées par les chaînes et toute une gamme d'autres entités attribuables à l'ancrage des navires. Elles se sont formées lors du mouillage, du dragage et de la récupération des ancres de navires. Certaines des plus grosses cicatrices d'ancres mesurent plus de 2,5 m de profondeur sur 5 m de largeur et s'étirent sur 3 km de longueur. Dans les parties les plus touchées du bassin Bedford et du port intérieur, plus de 25 % des sédiments du fond marin sont ainsi perturbés. Il est proposé d'utiliser le terme « ancroturbation » pour décrire le processus de la perturbation et de la remise en suspension des sédiments par les ancres de navires. L'omniprésence de ces cicatrices reflète l'intense influence des activités de navigation sur le fond marin. On ne peut se fier aux carottes et aux échantillons du fond marin prélevés dans ces secteurs perturbés pour obtenir des données sensées sur la stratigraphie intacte.

Les dépôts les plus épais de l'Argile de LaHave, qui peuvent atteindre plus de 6 m, se sont accumulés dans des zones du port intérieur au nord de l'île McNabs, au nord de l'île Georges, dans le bras Northwest, dans le passage Eastern et dans le bassin Bedford. La vase est très mince ou absente dans le goulet (*The Narrows*) et dans la plupart des zones près du rivage, où la profondeur de l'eau est inférieure à 5 m, ainsi qu'à l'est et à l'ouest de l'île Georges, sur le dôme Ives et dans la partie la plus profonde du port intérieur, entre le nord-ouest de l'île McNabs et le sud de la presqu'île d'Halifax.

Les entités anthropiques sont répandues sur le fond marin du port et en grande partie confinées au secteur au nord et à l'ouest de l'île McNabs ainsi que dans le port intérieur. Elles englobent un dense réseau de cicatrices d'ancres, des déblais de dragage, des dépressions d'exploitation minière, des bancs d'emprunt, des vestiges de ponts effondrés, des épaves, des cicatrices d'affouillement par les hélices de navires, des zones draguées, des câbles, des pipelines, des émissaires et des prises d'eau, des bancs d'égouts, des coffres d'amarrage, des carcasses de voitures et des débris non identifiés. La distribution de ces entités du fond marin démontre clairement que le port d'Halifax est fortement influencé par l'activité humaine. Les études du port n'ont pas permis de confirmer certains des mythes existants qui ont longtemps persisté. Il n'existe aucun cratère attribuable à l'explosion survenue à Halifax en 1917 et aucun tunnel ne relie l'île Georges au lieu historique national du Canada de la Citadelle-d'Halifax (appelé localement « la Citadelle ») en passant sous le port. Les vestiges des deux premiers ponts enjambant jadis le port au goulet (*The Narrows*) sont répandus et consistent en caissons à claire-voie, en rails de voies ferrées et en débris épars. Les restes et les effets érosifs de filets anti-sous-marins destinés à protéger le port des sous-marins pendant les deux guerres mondiales persistent également sur le fond marin du port extérieur.

Sur le fond marin du port, on a découvert environ 45 épaves dont plusieurs étaient inconnues ou localisées de manière inexacte. Les navires qui se sont échoués dans le port extérieur sur les hauts-fonds et contre les promontoires rocheux à l'ouest ont été réduits à l'état de tas de débris et témoignent de la grande énergie des vagues soulevées par les tempêtes dans le port extérieur. Les bâtiments qui ont coulé suite à des abordages en route se retrouvent en grande through collisions while under way and ended up on the deeper water seabed largely remain intact, offering a unique archaeological opportunity. Some of these vessels contained munitions and this material remains at the bottom of the harbour as unexploded ordnance.

partie intacts sur le fond marin en eau plus profonde et constituent d'uniques occasions en archéologie. Certains de ces navires renfermaient des munitions et ces matériaux persistent sur le fond du port sous forme de munitions explosives non explosées.

Sediment bed forms and other transport indicators occur both on cohesive and noncohesive sediments. Periodic strong oceanographic currents that result from large storms redistribute sand and gravel in the outer harbour. These events also resuspend fine-grained sediments in the inner harbour, developing sedimentary furrows, sediment moats, and scour depressions. The orientation and symmetry of the bed forms, together with geochemical anomalies, indicate net transport of material upharbour to the north.

On observe des figures sédimentaires sur le fond marin et d'autres indicateurs de transport tant dans les sédiments cohésifs que dans les sédiments non cohésifs. Les forts courants océaniques engendrés par les grosses tempêtes redistribuent le sable et le gravier dans le port extérieur. Ces événements remettent en outre en suspension des sédiments à grain fin dans le port intérieur pour y creuser des sillons sédimentaires, des fossés dans les sédiments et des dépressions d'affouillement. L'orientation et la symétrie des figures sédimentaires du fond marin, ainsi que les anomalies géochimiques, témoignent d'un transport net de matériaux vers le nord et l'extrémité intérieure du port.

Anthropogenic effects continue to be increasing in the inner harbour and are the dominant processes affecting the seabed today. Coastal segments are modified through infill, the construction of new docks, and other harbour infrastructure. Upon completion of the three proposed harbour waste-water treatment facilities, the quantity, quality, and location of discharges will vary considerably and this will result in changes to the sedimentation patterns. In contrast, the outer harbour area is a region where natural storm-driven processes dominate at the seabed along this exposed Atlantic Ocean inner shelf region.

Les effets anthropiques continuent de s'accroître dans le port intérieur et sont de nos jours les processus dominants sur le fond marin. Les segments littoraux sont modifiés par comblement et par la construction de nouveaux bassins et d'autres installations portuaires. À l'achèvement des trois installations proposées de traitement des eaux usées du port, la qualité, les quantités et les emplacements des déversements seront considérablement transformés ce qui entraînera des modifications des configurations sédimentaires. À l'opposé, dans la région du port extérieur, le fond marin est caractérisé par l'action prédominante des processus naturels entraînés par les tempêtes qui balaient cette étendue exposée de la plate-forme continentale interne de l'océan Atlantique.

INTRODUCTION

This Geological Survey of Canada bulletin summarizes research on the surficial sediments, seabed and subsurface features, seabed processes, shallow bedrock geology, and geological history of Halifax Harbour, Nova Scotia. The field component of the study was undertaken by the Geological Survey of Canada (Atlantic) at the Bedford Institute of Oceanography, mainly over a seven-year period extending from 1987 to 1995. It provides a regional overview of the stratigraphy and distribution of sediments, their sedimentological characteristics, and a history of erosional and depositional processes (including anthropogenic) that have and are presently affecting the seabed.

The marine geological study of Halifax Harbour was part of a new regional, Eastern Canadian, coastal marine geological program to study the distribution and characteristics of surficial sediments together with their glacial and postglacial history. It was also part of another program to evaluate the mineral and aggregate potential of the nearshore in a Canada-Nova Scotia Cooperation Agreement on Mineral Development (MDA). The study of the harbour was also driven by a need for an understanding of the geological environment as it applied to the discharge of sewage and the selection and design of a waste-water management system (sewage treatment facility) for the Halifax-Dartmouth area. The waste-water management component was commonly referred to as the 'Halifax Harbour Cleanup' and more recently as the 'Halifax Harbour Solutions Project'. In this regard, the geological research was conducted concurrently with geochemical, biological, engineering, and oceanographic studies by other government and industry groups focused on an assessment of the environmental characteristics of the harbour related to the design and siting of a waste-water treatment and disposal system.

While these geological studies were under way, early interpretations of the results (Fader et al., 1991) were fed directly into deliberations of the Halifax Harbour Task Force (Fournier, 1990), a government-sponsored group, the mandate of which was to determine the best method for treating the 180 million litres (40 million gallons) of raw sewage discharged into the harbour on a daily basis. In 1998 The Halifax Harbour Solutions Advisory Committee used results of the geoscience studies to revise and define waste-water siting criteria, water-quality objectives, and facility locations.

As a result of the integrated study by such a wide variety of disciplines and organizations, Halifax Harbour is now one of the best-studied harbours in the world (Fader and Buckley, 1997), and the interpretation of the marine geology has benefited from research in other fields. The marine geological information has, in turn, provided a framework in which physical oceanographic, biological, and geochemical studies can be placed: a relationship generally absent from previous studies (Nicholls, 1989). For example, in areas where oceanographic measurements were lacking, regional sediment characteristics and seabed dynamic features assisted in the extrapolation of movements of the water mass (Fader and Petrie, 1991). The methods, results, and applications presented here can be used as a model for study of other coastal inlets with similar environmental problems (Fader and Buckley, 1997).

An understanding of the geological environment is fundamental to present and future industrial, tourism, and other economic uses of the harbour, including the design of waste-water treatment facilities. From a sedimentation and sediment transport perspective, it is important to understand the present distribution of sediments, contaminants, and their transport pathways, as they can be altered by changes to existing discharge systems. From an engineering perspective, geological information is essential for design, siting, and construction of structures such as pipelines, electrical and telecommunication cables, outfall diffusers, tunnels, and other engineering facilities that will be built on and within seabed materials.

Setting

Halifax Harbour is the major coastal inlet midway along the southeastern coast of Nova Scotia and extends inland from the coastal headlands over 28 km to its head, where the Sackville River enters Bedford Bay (Fig. 1). Halifax was formally settled on June 21, 1749, as the sloop-of-war ship *Sphinx* entered the harbour with the soon-to-be-governor Edward Cornwallis (Wills, 1999). The harbour was first known to the native Mi'kmaq as Chebooktook, meaning 'great long harbour'. It had been previously visited by Basque fishermen attracted by the rich fishery for over a century before the first French explorers arrived and referred to the area as Acadia. Samuel de Champlain, along with Pierre de Gau and Sieur de Monts visited the area in 1604. They referred to the harbour as "une baie fort saine", but never established a settlement. The French used the harbour over the next 145 years and developed a series of names for regional features. The native name Chebooktook became Chibouctou or Chebucto, a name that is still used for the rocky granite headland at the western mouth of the harbour. The name Waeg-wol-teck-k for 'it runs down to an end' later became the Sandwich River and today is known as Northwest Arm. Bedford Basin was originally termed 'Torrington Bay'. Halifax was the first planned town of English origin to be constructed in Canada (Wills, 1999). Across the harbour to the east, the Mi'kmaq name of Boonamoogwaddy, meaning 'tomcod ground', was the site of the settlement of Dartmouth. The locations of relevant place names for the regional Halifax Harbour area used in this report are shown in Figure 2 and figures in the report are indexed in Figure 3.

The harbour is flanked by the major centres of Halifax and Dartmouth and smaller communities of Herring Cove, Bedford, and Eastern Passage, collectively referred to as the Halifax Regional Municipality (HRM), as of April 1, 1996.

The former cities of Halifax and Dartmouth are now referred to as metropolitan areas, and the town of Bedford has become an urban community.

With the exception of shallow shoreline areas, the water depths throughout most of the harbour are greater than 20 m, affording easy access for large vessels. Mainly as a result of its deep water, extension far inland, protection from large waves, and ice-free environment, it was first settled in 1749 as a military outpost. It is presently the major Eastern Canadian seaport offering shelter and services to large vessels from the North Atlantic, as a busy multi-use waterway for both freight and bulk cargo.

The harbour largely remains ice-free throughout the winter season and as such, is a major terminal for trade throughout North America, with container facilities and other shipping docks such as loading and offloading facilities for gypsum, automobiles, and petroleum products. It is also the east coast home of the Royal Canadian Navy, Department of National Defence. Ships and submarines are stationed here and frequently conduct exercises in Bedford Basin, the outer reaches of the harbour, and beyond the harbour mouth.

The entire harbour area played a major role in the early days of colonization with the construction of fortifications on the easily digable, high drumlin islands and mainland areas such as Halifax Citadel National Historic Site of Canada (locally known as ‘Citadel Hill’) and Georges Island. During World Wars I and II, the harbour was strongly influenced by the military presence with facilities constructed on the seabed and along the shoreline, and large convoys anchored throughout the harbour. Present military facilities include ship repair and seabed installations for acoustic studies, degaussing ranges, cables, and anchorages.

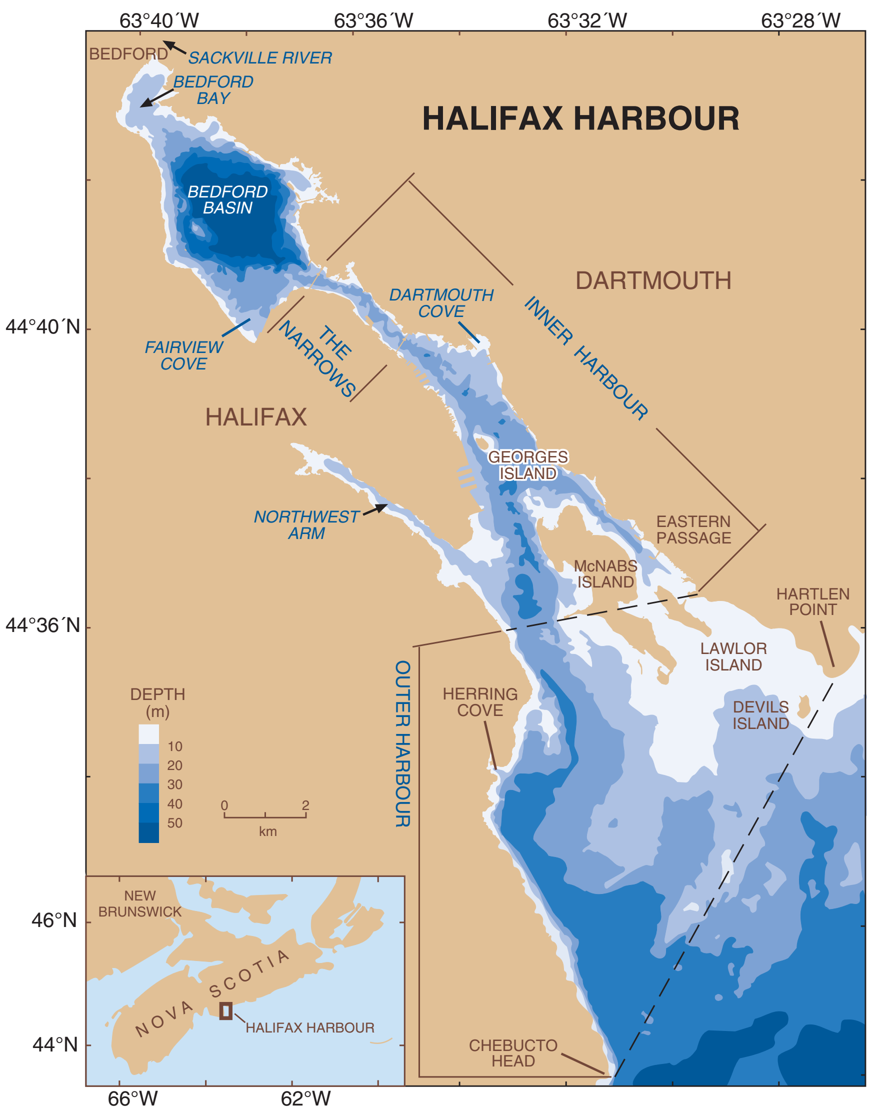


Figure 1. Geographic divisions of Halifax Harbour, Halifax Regional Municipality (HRM), Nova Scotia, showing the major communities of Halifax, Dartmouth, Bedford, Herring Cove, and Eastern Passage as well as generalized bathymetry and a regional index.

Many other groups regularly use the harbour (Fournier, 1990) and include yacht clubs, swimmers, divers, ecotourists, whale-watching charters, research establishments, and sport fishermen. The harbour supports an extensive fishery particularly for lobster and finfish, and lobster holding tanks recirculate seawater.

Historical changes

With the settling of Halifax in 1749, major changes took place on the surrounding land and in shoreline areas that also affected the seabed of the harbour. These were the cutting of large tracts of forest, the cultivation of crops, the infilling of shoreline areas, the construction of docking and ship-repair facilities, the discharge of waste water, and the channelling and rerouting of runoff into the harbour. For example, large areas of McNabs Island and south end Halifax (Point Pleasant Park) were deforested for military security reasons during the early years of settlement. In 2003 Hurricane Juan also deforested up to 70% of the Point Pleasant Park area and large tracts of McNabs Island.

As the urbanization of the surrounding area of the harbour continued at a rapid pace, so did the deposition of sediments. In addition to the natural glacial soils and bedrock that were eroded from the adjacent land, untreated sewage and associated domestic and industrial wastes were mixed with these materials and deposited through discharge outfalls at many locations. As the uses of the harbour continued to expand as a result of increased industrial and military development, the sediments on the harbour floor were further modified by direct disturbance. Dredges scoured and deepened many areas; shallow areas were blasted and dredged; docking facilities were built; large areas were infilled, decreasing the water area of the harbour; sand and gravel were mined; dredge spoils were dumped; ships' anchors were dragged; old ships and debris were scuttled; and bridge footings were

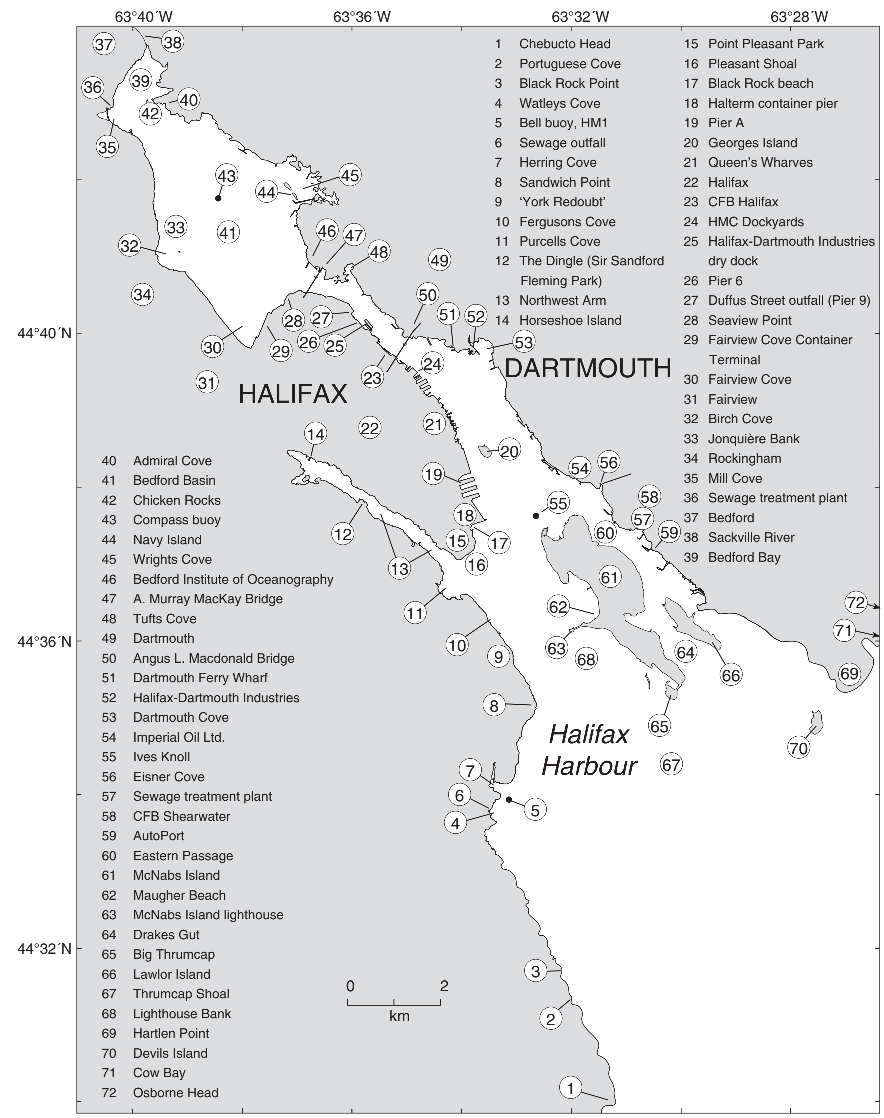


Figure 2. Index of place names and features for Halifax Harbour and vicinity used in this report.

constructed. These types of activities have all influenced the morphology of the seabed, sediment distributions, and transport pathways in different ways.

Concurrent with these anthropogenic uses of the harbour is its use by shellfish, finfish, and benthic invertebrates as a marine habitat. Changes in the rates and patterns of sedimentation and constituents of sewage and industrial wastes have affected this habitat. The biological community in the harbour presently reflects these new conditions established by the uses of the harbour over the past 250 years and is in a constant state of flux in response to variations in these inputs.

From this background, it is obvious that the materials on the floor of the harbour contain a history of natural environmental parameters and anthropogenic uses, and in particular they record the most recent history of harbour use as a repository for wastes. Sediments and their depositional patterns, therefore, not only provide a record of natural and anthropogenic changes, but can be a predictive tool to understand future changes to inputs to the system through the construction of waste-water treatment facilities, the industrial control of contaminants, and shipping-related construction.

One of the major issues involving the sediments is a concern for trace metals that occur in high concentration within certain areas of the harbour (Fitzgerald et al., 1989). Their stability within these sediments and their potential for release by natural or other processes largely remains an unknown. A future concern is the potential release of these metals under various waste-water treatment and -outfall scenarios. The consolidation and treatment of waste water will alter the amount, location, and type of materials discharged into the harbour.

Waste-water disposal systems

Halifax Harbour has been used as a repository for raw sewage for over 250 years with the first few consolidated sewage outfalls constructed in the 1850s. The present system

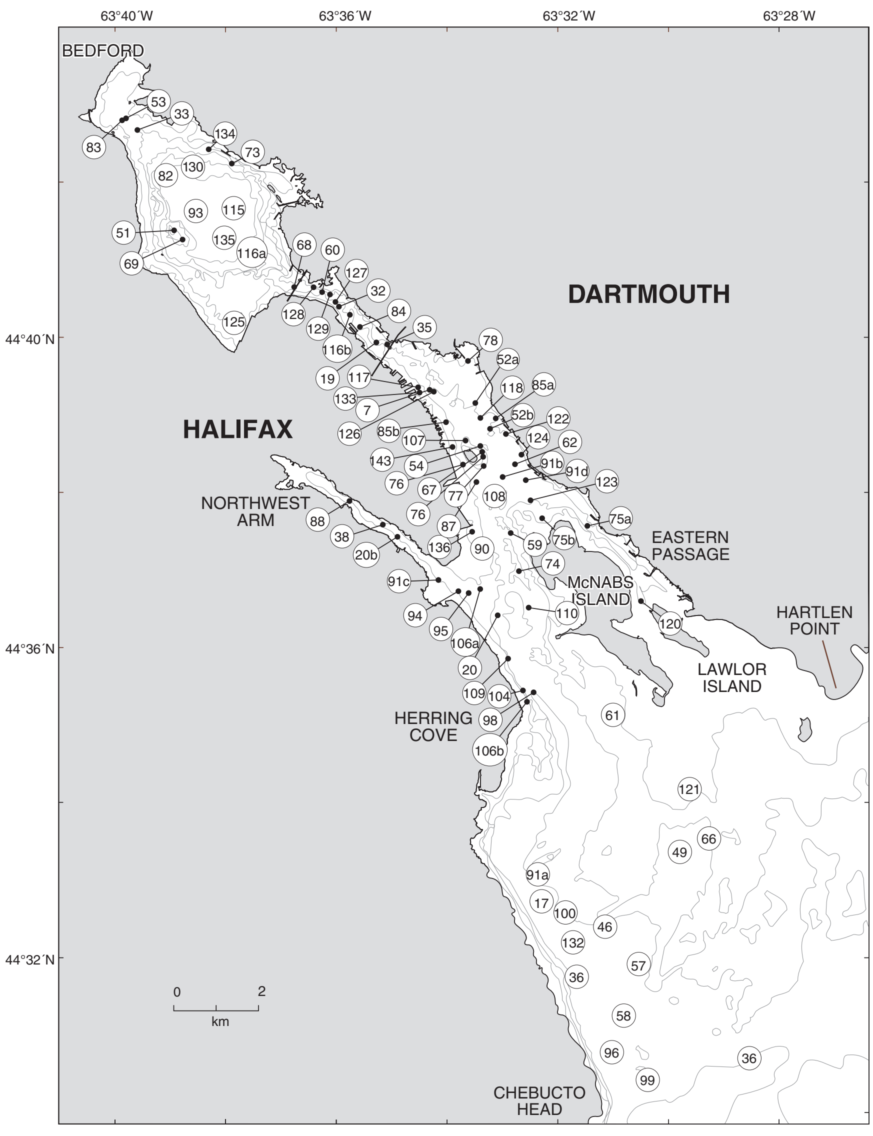


Figure 3. Index of figures used in this report.

(2006) largely consists of combined sewage and stormwater outfalls with only 20% of the effluent treated at two small facilities located in Bedford Bay and Eastern Passage. Approximately 43 large raw-sewage outfalls discharge untreated sewage into the harbour on a daily basis, mostly in the inner harbour area, adjacent to the downtown core of Halifax and Dartmouth, with one large outfall at Watleys Cove, south of Herring Cove discharging to the outer harbour.

In order to select an appropriate remedial action plan and management strategy to 'clean up' the harbour, it is essential to be able to predict the dispersion and fate of contaminated sediments under present conditions and following proposed remedial actions. Geological information on sedbed sediments, morphology, and depositional and erosional processes that have occurred in the harbour over the past several thousand years can be used as a guide to predict changes that are likely to occur with the construction of a waste-water treatment facility.

In addition to raw sewage, Halifax Harbour has been used as a repository for dredge spoils and other discarded debris and many areas of the seabed are littered with large volumes of material. Dredging to deepen shallow areas of the harbour, as well as to mine sediments for aggregate has been a common practice. Many areas have also been infilled to form shore platforms for the construction of transportation, transhipment, and ship-repair facilities. All of these types of anthropogenic activities have left an imprint on the sediments of the harbour in addition to the natural patterns of sedimentation and erosion. In some areas it has made the interpretation of natural geological processes and their history very difficult.

Report layout

This bulletin includes a series of seven oversized figures on CD-ROM. Three are regional maps delineating characteristics of the seabed of Halifax Harbour prepared at scales of 1:25 000: sun-illuminated seabed morphology, sun-illuminated seabed slope, and interpreted surficial geology. The surficial geology map is presented overlying a grey-scale multibeam-bathymetric base and includes an interpreted cross-section. Morphodynamic and feature interpretations are presented for three areas: Bedford Basin, Northwest Arm, and inner Halifax Harbour. A regional sun-illuminated multibeam-bathymetric image for the inner Scotian Shelf, including Halifax Harbour is also included at a scale of 1:50 000.

The report contains a discussion of the survey control and techniques, database, physiography, bedrock geology, surficial sediments, subsurface stratigraphy, seabed and subsurface features, anthropogenic features, sediment transport, sediment isopachs, and the distribution and depth of shallow gas. A synthesis of the geological history for the surficial sediments is presented. The majority of the report is focused on the distribution of surficial sediments, their sedimentological characteristics, modern depositional and erosional processes, morphology, and anthropogenic characteristics. A brief summary of sediment geochemistry and oceanography is also included.

DATABASE

Geological surveys

Prior to 1986, studies of Halifax Harbour included standard bathymetric mapping with echosounders, analyses of sparse physical oceanographic data, biological productivity, and stratigraphic analyses of a few sediment cores and seismic-reflection profiles. Most of these studies were site specific and not regional in nature, and were largely designed to address engineering problems or student theses. The data collected and interpreted for this report are regional in nature and were collected on scientific cruises of the C.C.G.S. *Navicula* in 1987, 1988 (Miller and Fader, 1989), 1989 (Miller and Fader, 1990), and 1990 (Fader and Miller, 1992). Data from the outer harbour and in the approaches to the harbour, were obtained during cruise *Dawson* 91-018, as part of a Nova Scotia-Canada Mineral Development Agreement project to assess the placer gold and aggregate potential of the inner shelf (Fader et al., 1993; Stea et al., 1994).

The database consists of a regional grid of echosounder data, sidescan sonograms, mid- to high-resolution seismic-reflection profiles (Fig. 4), and a variety of sediment cores, grab samples, boreholes, epibenthic dredge hauls, bottom photographs, submersible observations, and remotely operated vehicle (ROV) video information (Fig. 5). Box, Lehigh, and Eckman cores were collected for both geochemical and sedimentological analyses (Buckley and Hargrave, 1989; Buckley et al., 1991; Fader and Buckley, 1997) during concurrent integrated studies of the geology and geochemistry of harbour sediments. Surveys from C.C.G.S. *Hudson* and C.S.S. *Dawson* collected long piston cores and vibrocores of sediment for subsurface stratigraphic information and geochemistry. Marine programs conducted from the C.C.G.S. *Frederick G. Creed* obtained additional sidescan-sonar data in the nearshore and site-specific samples to ground truth the acoustic interpretations. Submersible dives were undertaken with the *Pisces IV* and SDL-1 submersibles in co-operation with the Department of National Defence from the HMCS *Cormorant* and the Department of Fisheries and Oceans from the MV *Pandora II*. These dives took place in Bedford Basin, in the outer harbour, and in the approaches to the harbour beyond Chebucto Head, and collected video, photographic data, and seabed samples (Fig. 5).

Sediment samples

Prior to the regional geophysical surveys of the harbour, Prouse and Hargrave (1987) collected 102 seabed samples, and the OceanChem Group Ltd. (1988) collected an additional 135 samples. Buckley et al. (1991), Winters et al. (1991), LeBlanc et al. (1991), and Fitzgerald et al. (1992) reported on the analyses of these and additional samples. These samples were collected for geochemical and textural information in a grid pattern without the aid of sidescan-sonar and seismic-reflection data to control the selection of sample sites. Subsequent samples were chosen to define characteristics of the sediments categorized on the basis of acoustic survey data. The existing sedimentological information database eliminated the need to collect a large number of additional samples. Those that were collected were targeted to both acoustic anomalies and representative areas, and to fill data gaps. In total, more than 300 samples of seabed sediments have been utilized in this study (Fig. 5).

Subsurface samples

Information on the characteristics and distribution of subsurface sediments is from a study of high-resolution seismic-reflection profiles and cores. Four types of coring systems were used during these surveys: vibro, piston, gravity, and Eckman corers. Subbottom data were also provided by boreholes drilled by The Department of National Defence and the Halifax Harbour Cleanup Corporation. These penetrated not only the soft Holocene muds, but also often the entire surficial section terminating in bedrock. Five Benthos™ piston cores were collected from the C.C.G.S. *Hudson* in Bedford Basin and Northwest Arm. Three vibrocores were collected by the C.S.S. *Dawson*, one near Georges Island, and the others in the vicinity of Lichfield

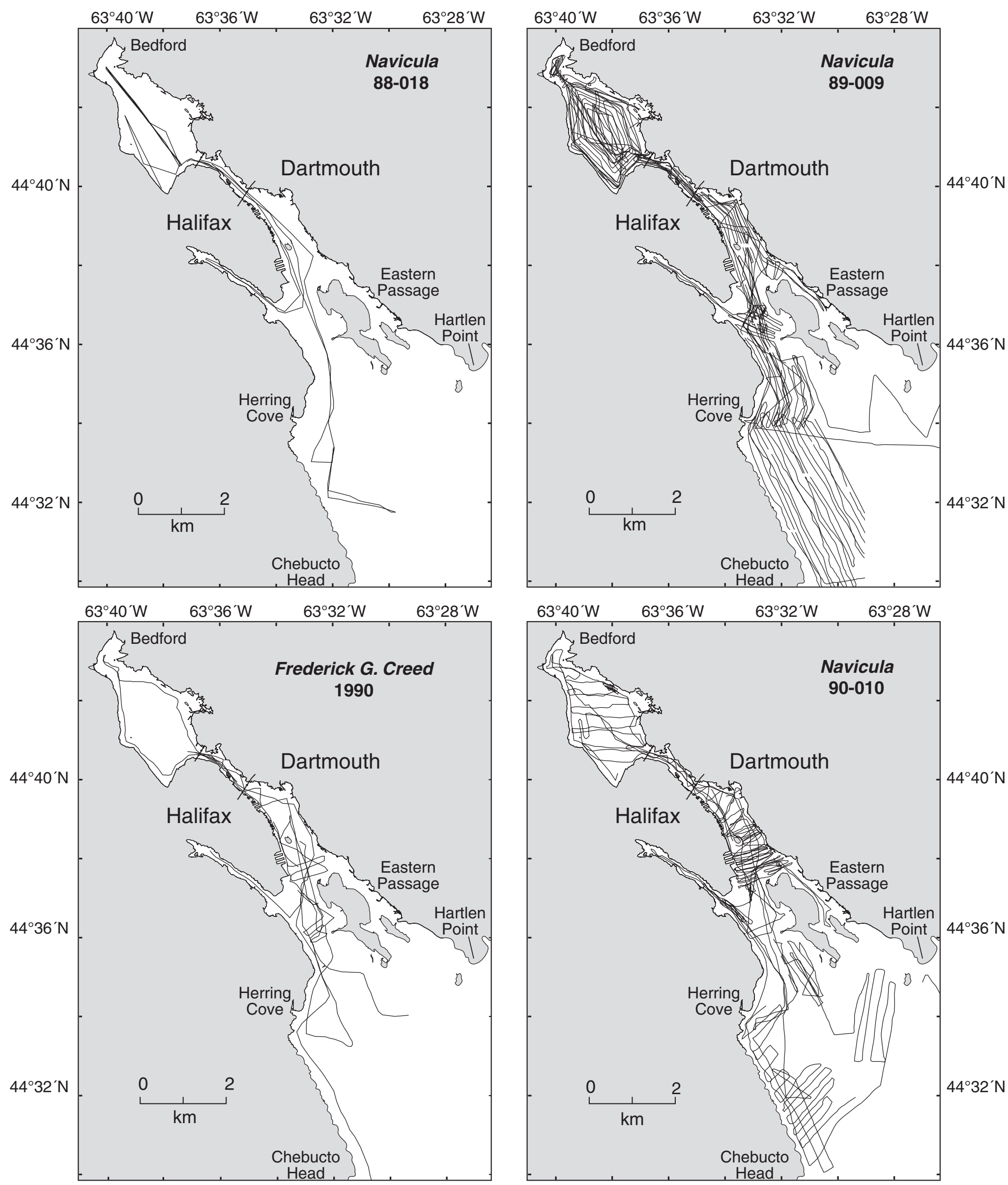


Figure 4. Ships' tracks of high-resolution seismic-reflection profiles, sidescan sonograms, and echosounder data collected during the four major cruises of this study.

Shoal (Fig. 6, on CD-ROM) in the outer harbour. Sixteen Eckman-style and twelve Leheigh cores were collected from the C.C.G.S. *Navicula* and C.C.G.S. *Frederick G. Creed* in the inner harbour. Shells and foraminiferal tests have been subsampled from the cores and dated to provide ^{14}C chronological control for sediment deposition and are uncorrected radiocarbon ages.

General methodology

Two principal techniques were employed to delineate and map the distribution of sediments at and below the seabed. Grid surveys were first conducted with seismic-reflection profilers, echosounders, and sidescan sonars. Data from these acoustic systems were interpreted to define seabed and subsurface seismostratigraphic units and sequences, and were followed by the collection of carefully positioned cores, seabed samples, and visual observations to provide ground truth for the acoustic signatures. Additional investigations of unusual sedimentological seabed attributes were then conducted.

High-resolution seismic-reflection systems

Seismic-reflection systems use sound energy to penetrate sediments and resolve layering, internal structure, and relationships between units. The data present an acoustic cross-section of the seabed and subsurface. This allows the

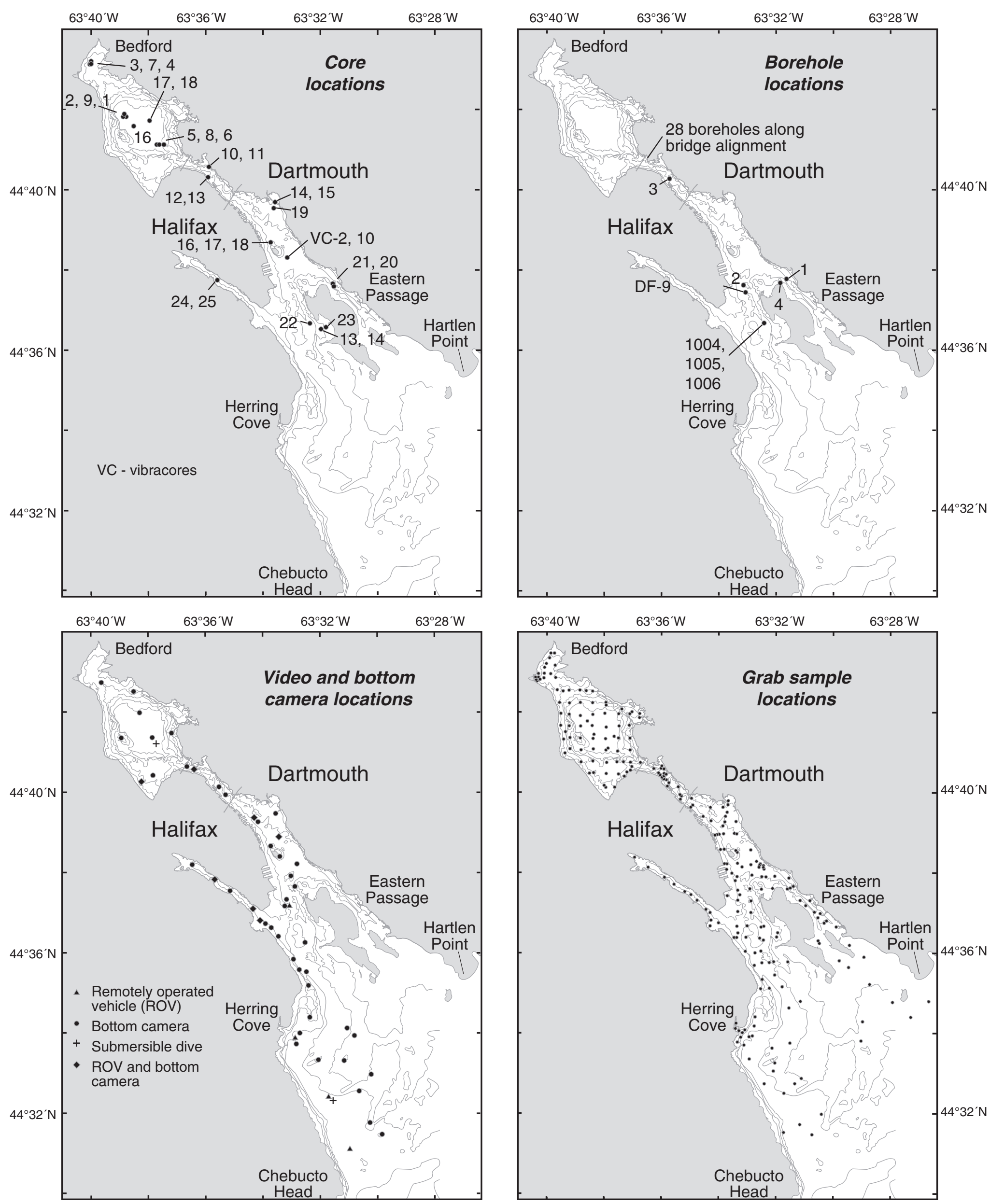


Figure 5. Locations of cores, boreholes, grab samples, bottom photographs, submersible dives, and remotely operated vehicle (ROV) video used in this study. The reader is referred to Fader et al. (1994) for detailed information and maps of individual station samples and observations.

construction of maps of sediment units, sediment thickness, boundary relationships, and internal structure upon which the selection of core locations is based. The seismic-reflection data also provides an understanding of unit lateral continuity and stratigraphic relationships.

The choice of seismic-reflection system involves trade-offs in penetration and resolution, whereby low-frequency systems provide increased penetration at the expense of resolution. For example, lower frequency sparker seismic-reflection systems provide penetration of over 50 m through hard soils such as till units and unconsolidated bedrock, but display low vertical resolutions of approximately 3–10 m. In contrast, high-frequency echosounders provide limited sediment penetration, but with vertical resolutions of often less than 1 m. The system choice for the study of Halifax Harbour was to utilize a variety of seismic systems with a range of resolutions and penetrations. Several systems were tested before final survey configurations were determined and equipment modifications were made for the surveys of Halifax Harbour. The systems used were:

1) a 280 joule, 20 tipped, surface-towed sparker that provided resolution of 5–10 m and penetration of 50 m through till;
2) a Datasonics Bubble Pulser© which consisted of a 20 joule vertically mounted, surfboard-towed boomer with a resolution of less than 10 m, but penetration through 20 m of till;
3) a prototype, Huntec Sea Lion©, shallow-tow boomer system with a resolution of less than 1 m and penetration of over 30 m in glacial till;
4) a ship-mounted echosounder, with no penetration of hard soils such as sand, gravel, till, and bedrock, but good penetration within mud; and
5) a Seistec boomer© and line-in-cone array receiver system, with a resolution of less than 1 m and penetration through 30 m of mud and sand.

Surveys were conducted in Bedford Basin with 40 cubic inch air guns in an attempt to penetrate the gas-charged sediments and define the thickness of sediment overlying bedrock. These attempts were only partially successful.

The Datasonics Bubble Pulser system easily penetrated through tills to the bedrock surface (Fig. 7a, b), but with low resolution of less that 3 m, whereas the Seistec system did not penetrate till, but provided 0.3 m resolution through overlying mud, sand, and gravel (Fig. 7c, d). The Narrows presented the most difficult area of the harbour in which to resolve subsurface stratigraphy overlying bedrock, because of the hardness and coarseness of sediment at the seabed (boulders and gravel berms) and the presence of overconsolidated tills. Echosounder systems were particularly good at discriminating between predominantly muddy and sandy sediments and helped in transitional areas between the inner and outer harbour. All systems were unable to penetrate and resolve the stratigraphy beneath areas of gas-charged sediments in Bedford Basin, Northwest Arm, Eastern Passage, and the inner harbour.

At the approaches to Halifax Harbour, seismic-reflection surveys were conducted from the C.S.S. *Dawson* (Fader et al., 1993) using a Huntec Deep Towed© boomer system and a Haliburton sleeve-gun system. Within the inner harbour, a digital Datasonics™ chirp system provided very high resolution of the upper LaHave Clay section.

Sidescan sonar

Sidescan sonars are deep-towed systems that emit narrow-beam, fan-shaped, high-frequency sound that does not penetrate the sediments, but sweeps across the seabed at low grazing angles presenting a plan-view image that resembles an aerial photograph. From these images, information can be extracted on sediment texture and distribution, as well as seabed morphology. These systems are particularly good at revealing anthropogenic features on the seabed such as the presence of shipwrecks, anchor marks, cables, and debris. Interpretation of these data, in conjunction with seismic-reflection and sample data, provides an understanding of erosional and depositional processes. Sidescan-sonar mosaics were compiled from the sidescan data collected in the inner harbour (Fader et al., 1991).

Sidescan sonograms also provide information on bedrock structural characteristics in outcrop areas such as bedding, joints, and lineations. The presence of unique bedrock surface characteristics sometimes can be used in conjunction with seismic-reflection and sample data to classify and map bedrock type and to understand glacial and sea-level transgressive processes that have affected the bedrock surface.

The sonar system used for most of the surveys in Halifax Harbour was a dual-frequency Klein 100 and 320 kHz towfish fitted with a K-wing depressor to stabilize the towfish and maintain desired towing depths. Data quality and sonar range are often degraded by water-property characteristics such as the presence of thermoclines, rip currents, wastewater discharge outfalls, and turbulence from ships' wakes, most of which were encountered in Halifax Harbour. Many repeat passes were conducted over specific areas of seabed in an attempt to obtain the highest quality data possible for interpretation. Sonar data can be collected in water depths as shallow as a few metres, but with limited range. A towfish distance of between 10–20 m above the seabed is an optimum height for sonar ranges of 100–150 m. Because of steep slopes and rapidly changing bathymetry encountered in bowl-shaped Bedford Basin, it was necessary to conduct the surveys along curvilinear tracks parallel to the bathymetry for optimum results. The sidescan-sonar towfish were not navigated with short baseline systems during this study and towfish layback (horizontal distance from ship) was manually calculated for interpretation and mosaic production.

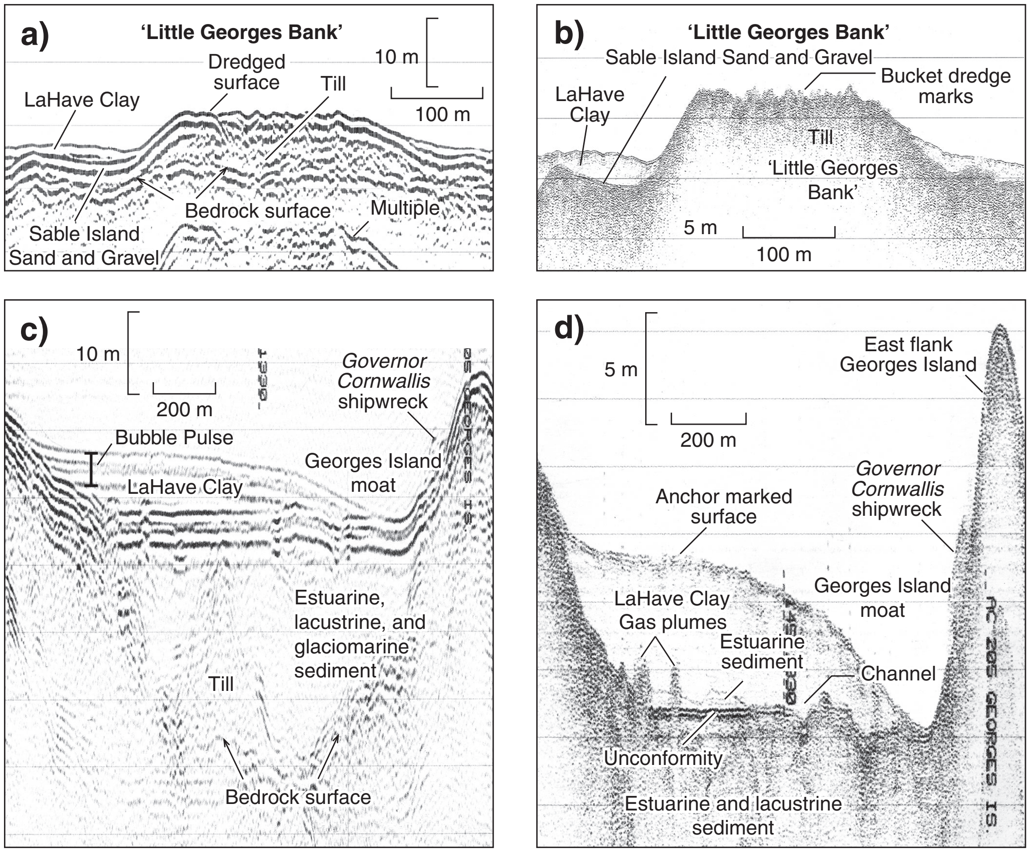


Figure 7. Seismic-reflection profiles for comparison of the two major systems used during the study over a small drumlin termed 'Little Georges Bank' north of Georges Island in the inner harbour, and in an area adjacent to Georges Island. **a), c)** Datasonics Bubble Pulser profiles that display low resolution of approximately 3 m, but easily penetrate till to the subsurface bedrock. **b), d)** Seistec line-in-cone seismic-reflection profiles over part of the same area. These do not penetrate the till, but provide resolution of 0.3 m through overlying sediments. Various other seismic-reflection systems (Huntec Sea Lion and Huntec Sea Otter, both boomers) were tested and modified for surveys in Halifax Harbour, but the Datasonics Bubble Pulser and Seistec systems were found to complement each other and provide optimum penetration and resolution. Echograms from ship sounders were also useful in differentiating hard and soft sediments and characterizing LaHave Clay. Beyond the mouth of the harbour on the inner Scotian Shelf, Huntec deep-towed boomer and air-gun seismic-reflection systems were used.

Data analyses

The pre-1988 sample data were reviewed before any of the detailed geological and geophysical surveys of the harbour were undertaken. A regional systematic grid pattern was established in order to completely insonify the harbour bottom with sidescan imagery and to integrate the seismic-reflection data with the sample information. Because of the large pre-existing grab-sample database, fewer additional samples were required. Vessel tracks were spaced for a minimum of 20% overlap on sidescan imagery, and in some areas, for example in The Narrows, approximately 20 passes were made, providing for 100% overlap on adjacent tracks and feature characterization from different angles. Areas of unique character or unusual geological features were repetitively surveyed to best characterize the features.

It was necessary to survey small sections of the harbour at a time, because of limitations of the short base-line navigation systems that were the primary navigation systems used throughout the surveys. Differential GPS was not available during the time frame of these surveys. Difficulties were also encountered working under high vessel traffic densities and some areas were missed during the first field season surveys. These problems were further increased because of the presence of anchored ships, speed-boat wakes, high volumes of pleasure craft, and dredging operations that limited manoeuvrability and degraded data quality. Limitations were also imposed by the 3 m draft of the survey vessel that restricted operations to depths no shallower than 5 m. In these areas the sidescan-sonar data provided information much closer to shore.

Preliminary interpretations of the surficial geology were undertaken during the surveys to locate suitable sampling sites. These were chosen to ground truth all of the seismic-reflection and sidescan-sonar signatures as well as to purposely sample seabed hazards and anthropogenic features such as dredge spoils, sewage banks, bed forms, anchor marks, etc.

After interpretation of the first field season's data, additional surveys were planned and undertaken to: 1) infill unsurveyed areas and to further delineate stratigraphic sections, 2) collect data on tie lines normal to the previous tracks, and 3) infill data gaps in nearshore shallow areas in as safe a manner as possible. During the final part of the survey, a remotely operated vehicle (Phantom HD2) was used to investigate individual targets or seabed features that were difficult to interpret from the acoustic data alone. Observations from manned submersibles were conducted in Bedford Basin, the outer harbour, and in the approaches to the harbour on the inner shelf. Bottom camera stations were occupied to provide photographic information on the surficial units and seabed features interpreted from the seismic-reflection and sidescan-sonar data.

During the regional geological mapping of Halifax Harbour, concurrent studies of the geochemistry (Buckley et al., 1991; Fader and Buckley, 1997) were also underway. Both of these activities were integrated and samples shared by co-workers for analysis.

The maps of sediment distribution include all of the available sample data. Isopach maps of the Holocene LaHave Clay are derived from the interpretation of the seismic-reflection data as well as echograms. Sidescan-sonar data provided relative backscatter information for the interpretation of sediment type and distributions as well as seabed features. The Nova Scotia Archives, Museum of the Atlantic, the Nova Scotia Museum of Natural History, the Department of National Defence, and local divers and diver associations provided valuable information to aid in the identification of shipwrecks and other anthropogenic features.

Multibeam bathymetry

Multibeam bathymetry provides for 100% seabed coverage enabling geological and geophysical interpretations of seismic-reflection and sample data to be improved by the confident correlation of features and characteristics observed from widely spaced survey tracks and sample locations. Additionally, the digital manipulation of shading and vertical exaggeration allows subtle aspects of deposition, erosion, and seabed features to be enhanced for improved characterization and interpretation. Multibeam-bathymetric technologies were not available during the initial geological surveys of Halifax Harbour. Their addition has helped immensely in the interpretation of sediment distributions, seabed features, and processes. Some of the sediment boundaries from the earlier GSC Open File maps (Fader et al., 1991) have been adjusted to conform with additional data provided by the multibeam-bathymetric information and the availability of more precise navigational positioning provided by GPS navigation systems during these later surveys.

During the summer of 1992, C.C.G.S. *F.C.G. Smith*, a Canadian Hydrographic Service vessel, conducted the first comprehensive multibeam-bathymetric survey of Halifax Harbour, extending from McNabs Island in the south to the entrance to Bedford Basin in the north. The survey utilized a series of 32 boom-mounted transducers on a dual-hulled vessel to determine the bathymetry along successive overlapping swaths, each approximately 30 m wide. Some areas such as Dartmouth Cove were not surveyed during these field operations. Sidescan sonars were also deployed during this survey concurrent with the collection of multibeam bathymetry.

In 1994, C.C.G.S. *Frederick. G. Creed* conducted a multibeam-bathymetric survey of the western part of the outer harbour extending

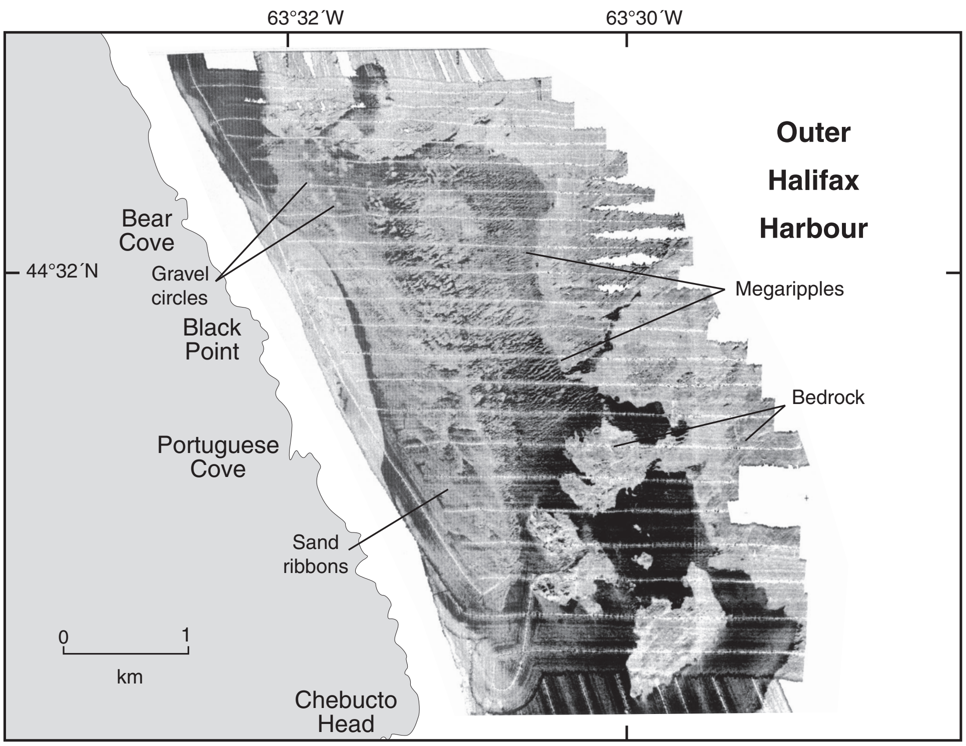


Figure 8. Backscatter map of a section of the outer harbour seabed extending from Bear Cove to Chebucto Head. This image was produced through processing of multibeam bathymetry collected from the C.C.G.S. *Frederick G. Creed* by the Ocean Mapping Group, University of New Brunswick. It has been calibrated with samples and video imagery and clearly differentiates sand and gravel deposits and a variety of bed forms. The pattern of distribution of the backscatter can be interpreted for an understanding of sediment-transport processes and pathways. On this image the lighter the grey scale, the harder the sediment, hence gravel and bedrock appear light-toned and sand dark-toned.

from McNabs Island to Chebucto Head. This survey employed a Simrad EM1000 multibeam-bathymetric mapping system. These data were processed by the Geological Survey of Canada, the Canadian Hydrographic Service, and the Ocean Mapping Group at the University of New Brunswick to produce multibeam-bathymetric sun-illuminated (Fig. 6) and seabed backscatter maps (Fig. 8). The multibeam bathymetry has not been processed for backscatter in other areas of the harbour. For the inner harbour the data are presented with a horizontal resolution of 5 m.

Similar multibeam-bathymetric surveys were conducted to the south of the harbour by the C.C.G.S. *Matthew* in 1992 (Loncarevic et al., 1994) using a Simrad EM100 multibeam system (Fig. 9) on CD-ROM).

The final collection of multibeam bathymetry in the harbour was conducted in Bedford Basin (Fig. 10) and Northwest Arm (Fig. 11) in 1998. The system used for these surveys was a Simrad EM3000 mounted on the *Plover*, a hydrographic survey launch. The system has a much higher horizontal resolution capability (10 cm) than either of the previous systems

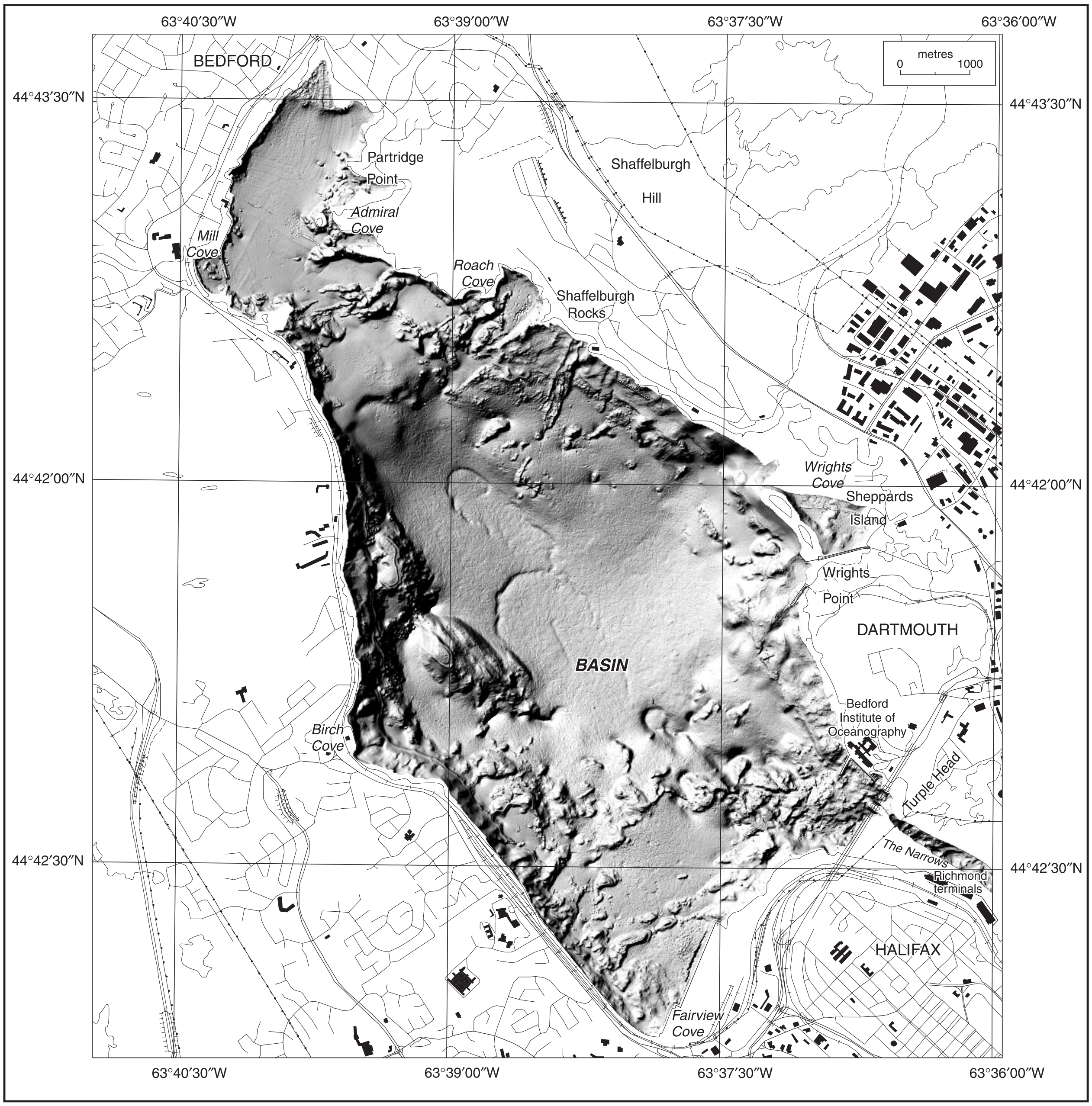


Figure 10. A Simrad EM3000 multibeam-bathymetric image from Bedford Basin, Halifax Harbour. Prominent features include boulder berms, shipwrecks, bedrock ridges, former islands, gas-escape depressions, anchor marks, and nondepositional moats. *See* Figure 18 (on CD-ROM) for interpretation of image. Multibeam-bathymetric data courtesy of Canadian Hydrographic Service. Figure is not to be used for navigation.

used for the earlier surveys in the inner harbour. The data has been processed at 1 m resolution and the images have been incorporated in the maps of the harbour on CD-ROM and throughout the bulletin. A simplified bathymetric map of Halifax Harbour based on the multibeam bathymetry and contoured at 5 m intervals is included in 'Multibeam bathymetry' section below (*see* Fig. 16).

The multibeam-bathymetric data from the harbour have also been processed for seabed slope information (Fig. 12, on CD-ROM). This map shows the slope of the seabed that ranges from flat areas to steep slopes of up to 30°. Sun-illuminated enhancement was added during processing to better portray slopes and dynamic processes. In general, the flat areas are depositional zones of both cohesive and noncohesive sediment. The steepest slopes occur on the flanks of bedrock shoals, in the nearshore adjacent to the drumlins of Georges and McNabs islands, in The Narrows, and in association with shipwrecks and other anthropogenic features.

PREVIOUS RESEARCH

Halifax Harbour has been the focus of study over many years since permanent settlement began in 1749. A bibliography by Hargrave and Lawrence (1988) summarizes the earlier research on physical, geological, chemical, and biological investigations within the marine environment of Halifax Harbour and adjacent areas. Because of the close proximity of government, university, and industry ocean-related research facilities, many research, equipment testing, and data collection surveys have been undertaken in the Halifax Harbour region, for example, *see* McKeown (1975). Research on the geochemistry of harbour sediments has also been extensive and integrated with the marine geological studies (Buckley and Hargrave, 1989; Winters et al., 1991; Fader and Buckley, 1997). This will be discussed in greater detail in later sections.

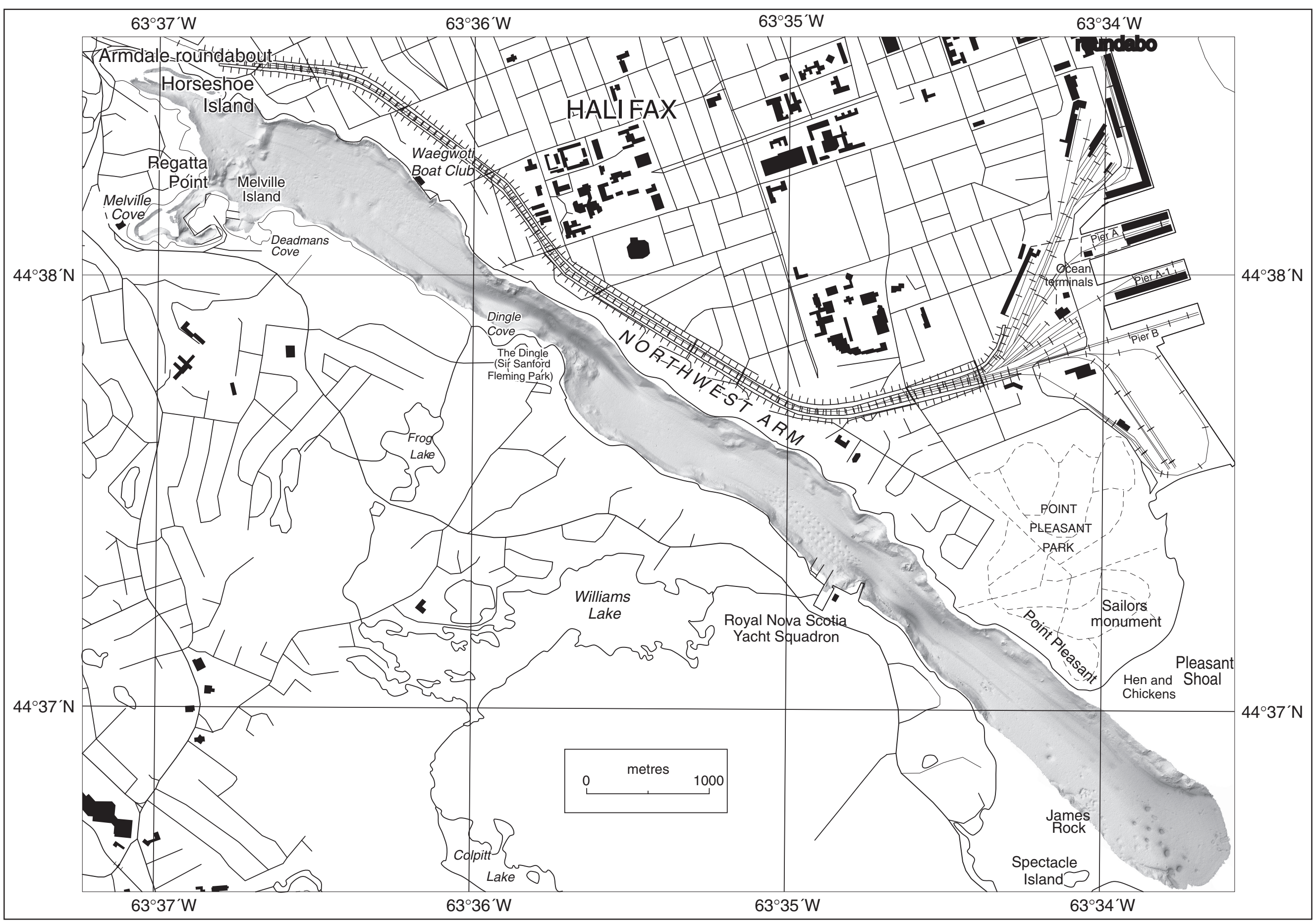


Figure 11. A Simrad EM3000 multibeam-bathymetric image of Northwest Arm, Halifax Harbour. Prominent features from southeast to northwest are: pockmarks, sedimentary furrows, toe-of-slope moats, boat moorings, shipwrecks, and an end moraine. *See* Figure 103 for interpretation. Multibeam-bathymetric data courtesy of Canadian Hydrographic Service. Figure is not to be used for navigation.

Grant (1967) conducted one of the first seismic-reflection profiling surveys in the inner harbour and identified a thick sequence of surficial sediments near Georges Island from a seismic-reflection profile. Stanley (1968) mapped sediments and assessed the role of reworking of glacial materials in Northwest Arm. During the 1970s and early 1980s a number of thesis studies were undertaken at Dalhousie University. The first regional assessment that included marine geology was that of Gregory (1970; M.R. Gregory, unpublished report 3-72, Nova Scotia Research Foundation, 1972), which focused on sediment micropaleontology. Regional maps of sediment distribution were prepared based on interpretation of seismic-reflection data, echosounder information, and seabed samples. Storm influence on sedimentation in the outer harbour was assessed by DeIure (1983). Gas charging within the inner harbour sediments was studied by Kepkay (1977) and Kepkay et al. (1980). Miller et al. (1982) studied cores from Bedford Basin and determined the depositional environment and timing of the marine breaching of a sill in The Narrows by postglacial sea-level rise. Stewart (1975) mapped specific areas of the harbour in an assessment of the aggregate and/or granular potential using sidescan sonar to delineate sediment distribution. More recently, Edgecombe (1994) and Edgecombe et al. (1999), studied vibrocores from estuarine sediments in the inner harbour to determine fluctuations in relative sea level during the mid-Holocene. These vibrocores were positioned based on seismic-reflection profiles from this study.

Much attention has focused on coastal processes of beach erosion in the eastern area of the outer harbour, particularly related to the removal of material for aggregate needs (Taylor et al., 1985, 1996; Forbes and Taylor, 1987). Forbes et al. (1990, 1991) conducted surveys of the inner shelf off Halifax Harbour to assess sea-level change and sedimentation in a transgressing beach zone.

A considerable amount of data have been collected for engineering activities in and around the harbour, such as the construction of two large harbour-crossing bridges, container piers, seabed and coastal military installations, and pipeline and cable placements. Some of this information was available for incorporation into the present study. The Halifax Harbour Task Force (Fournier, 1990) and a report of the Federal Science Advisory Committee on Halifax Harbour (Nicholls, 1989) provide a broad assessment of harbour environmental conditions and quality related to the design of a waste-water treatment facility. Geological maps and interpretations of processes from early stages of the present study were provided in those reports. Following the release of the Halifax Harbour Task Force report and appendix (Fournier, 1990), Halifax Harbour Cleanup Incorporated commissioned many additional studies as the basis for design of a proposed waste-water treatment facility and an associated environmental-impact assessment (Jacques Whitford Ltd., 1992). These included borehole information and environmental, archaeological, and oceanographic data, together with modelling of water flow and the fate of contaminants. Some of this information has been incorporated in the present study.

This study is the first harbour-wide regional assessment of the marine geology using a wide variety of modern marine geological technologies. During the early phase of this study a need existed to quickly release pertinent geological information and interpretations to support environmental and engineering aspects of the Halifax Harbour Cleanup Project. As a result, many reports and maps (Fader et al., 1991, 1994) were published as GSC Open Files. Two summary assessments of the environmental and engineering characteristics of the harbour (Fader and Buckley, 1997; Lewis et al., 1998) were also prepared. As part of the 75th anniversary of the Halifax Explosion of 1917, a symposium was held in 1992 sponsored by the Gorsebrook Research Institute to provide a modern scientific forensic assessment of the event. A summary publication titled *Ground Zero* (Ruffman and Howell, 1994) detailed geological conditions at the location of the explosion (Fader, 1994). A more comprehensive geological assessment was published as GSC Open File 3045 (Fader, 1995).

With the introduction of multibeam-bathymetric systems in 1992 by the Canadian Hydrographic Service, the first colour-depth-coded, shaded-relief image of seabed morphology for the harbour was produced (Courtney, 1993; Courtney and Fader, 1994). This provided a bathymetric database for morphological insight and an understanding of subtle aspects of sediment transport, deposition, and erosion (Fader et al., 1997). Following this survey, additional advanced techniques for the collection, processing, and presentation of multibeam bathymetry were developed and applied to areas of the outer harbour, the approaches to the harbour (Loncarevic et al., 1994), Northwest Arm, and Bedford Basin. This has resulted in the production of maps of multibeam bathymetry, seabed backscatter, seabed slope, and contoured bathymetry, and these data have been integrated with the conventional marine geological survey data. Multibeam images of Halifax Harbour and approaches are included as figures in this report. Interpretation of seabed features and processes integrated with the multibeam bathymetry for the inner harbour is provided in Miller and Fader (1995) and Fader et al. (1997) (Fig. 13, on CD-ROM).

Two workshops sponsored by the Department of Fisheries and Oceans and the Halifax Regional Municipality were conducted in 2000 and 2001 on aspects of preserving the environment of Halifax Harbour. These workshops assessed the state of knowledge on physical, chemical, and biological conditions in the harbour as well as the regulatory regimes with a view toward preservation and restoration of coastal and marine habitats. Summary papers on geoscience aspects of the harbour in these proceedings are by Buckley (2000, 2001), and Fader (2000, 2001).

PHYSIOGRAPHY

Physiographic setting

Halifax Harbour lies within the Southern Uplands of Nova Scotia and the Inner Scotian Shelf Subdivision of the Atlantic Uplands division of the Appalachian Region geomorphic province, (King, 1972; Williams et al., 1972) (Fig. 14). Both uplands and lowlands of the Appalachian Region developed together in response to a long erosional cycle that began in the Jurassic Period. The harbour is located within the submerged portion of the Southern Uplands, at its northern boundary on the central part of the inner Scotian Shelf. The Atlantic Uplands is a low-angle, southeastwardly sloping surface, developed across resistant granite, slate, quartzite, schist, gneiss, and volcanic rocks. It is interpreted to have been subjected to many cycles of deposition and erosion that have produced valleys and lowland areas throughout the terrain. Remnants of this complex history include extensive outliers of Cretaceous sediments in the Shubenacadie River valley (Stea et al., 1992a, b), which connects with Halifax Harbour through a series of lakes in Dartmouth (Fig. 15). This system is thought to have acted as a spillway to Halifax Harbour for large ice-dammed lakes in central Nova Scotia in the late Wisconsinan (Stea and Mott, 1989). The location of many of the rivers that cross the Atlantic Uplands is controlled by a series of northwest-striking faults in Paleozoic rocks of the Meguma Terrane.

The southeast coast of Nova Scotia is characterized by numerous irregular embayments consisting of shallow, flooded valley estuaries with glacially overdeepened depressions. The coast consists mainly of bedrock headlands and small islands as well as eroding drumlin fields. Postglacial sea-level flooding of former glacially modified river valleys and lake basins produced the present geomorphic configuration.

Halifax Harbour is one of the largest embayments along the south coast of Nova Scotia. The coastal region east of the harbour is dominated by drumlin headlands that provide

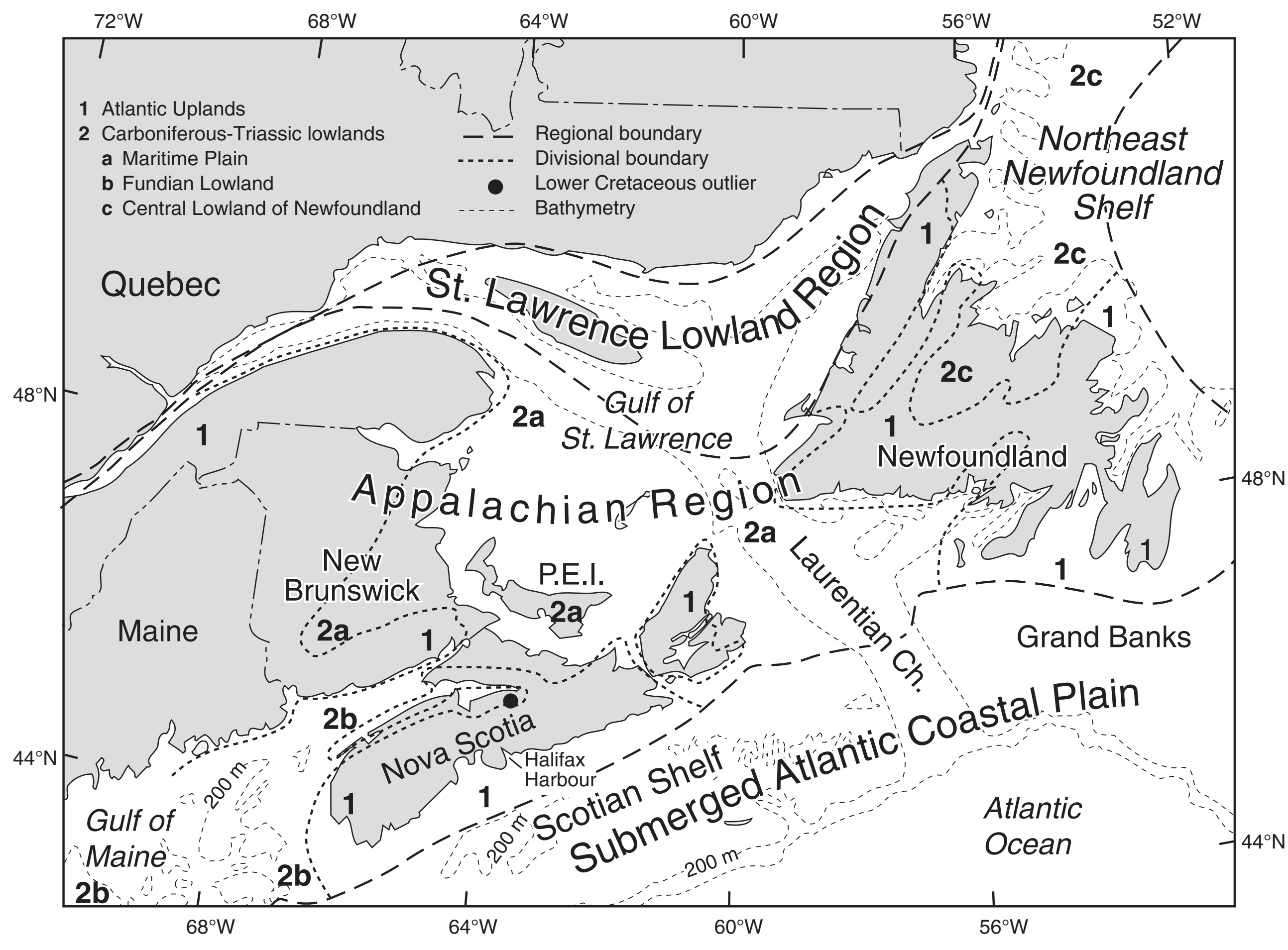


Figure 14. Major physiographic provinces of Atlantic Canada. Halifax Harbour occurs within the Southern Uplands of Nova Scotia and the inner Scotian Shelf Subdivision of the Atlantic Uplands physiographic province (*modified from* King, 1972).

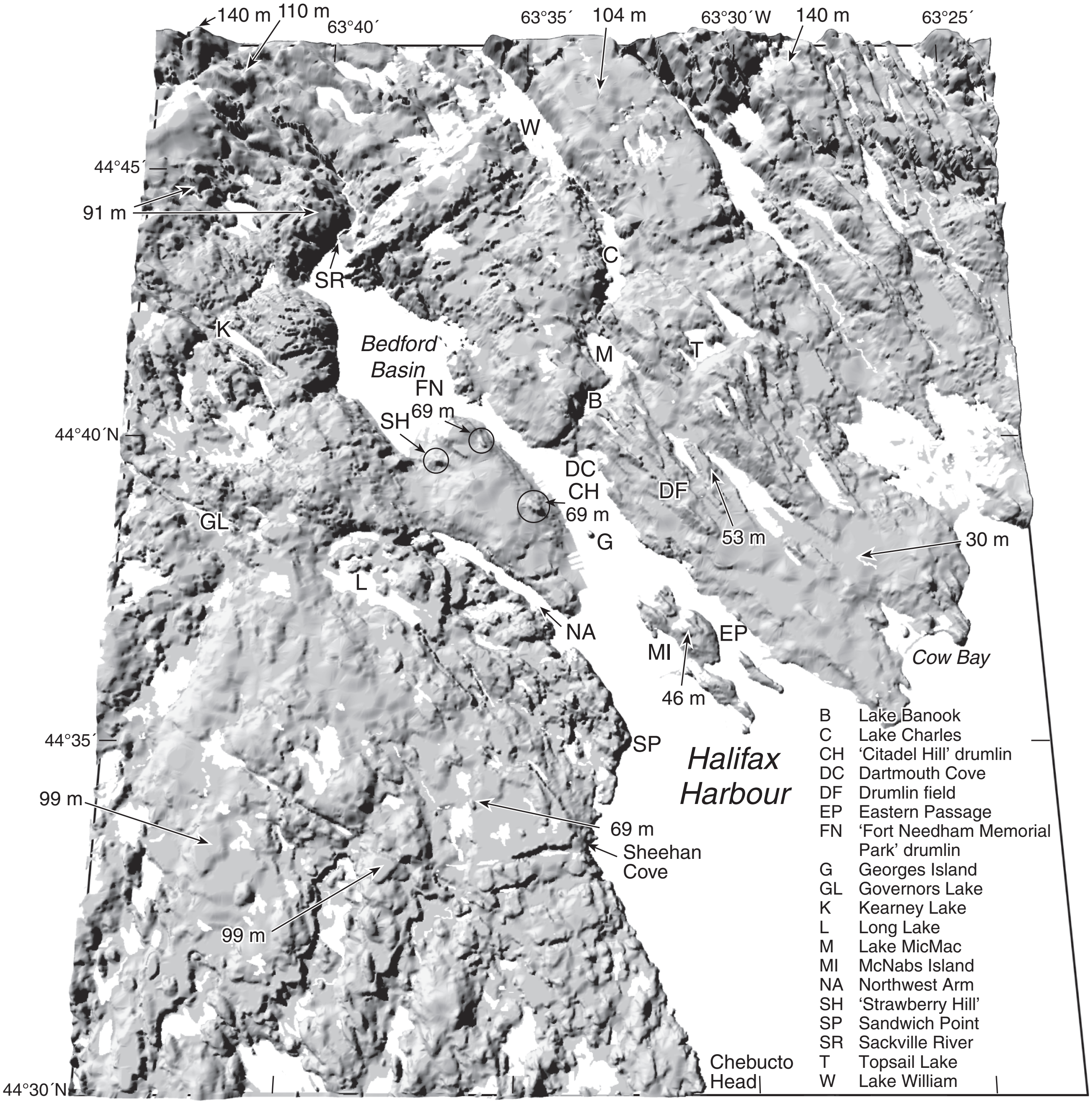


Figure 15. A regional grey-scale shaded-relief, topographic map of the Halifax Regional Municipality surrounding Halifax Harbour. The map is based on contour data from digital maps NTS 11 D/11, 11 D/12, 11 D/13, and 11 D/14 (1:50 000 scale). Artificial shading is from an azimuth of 315° and an altitude of 45°. Letter abbreviations are for key features and areas. The map has a horizontal resolution of approximately 20 m with 10x vertical exaggeration. It shows the major topographic elements, systems of lakes, and some bedrock structural features. Note the low-lying areas surrounding southeast and north peninsular Halifax that are flat, infilled areas of the harbour constructed for shipping-related facilities. Linear drumlin fields (DF) in Dartmouth and isolated drumlins (CH), (SH), and (FN) in Halifax are identified. The lakes in Dartmouth (B, M, C, and W) delineate a major drainage system connecting Halifax Harbour with the Bay of Fundy in the north. Image produced by A. Sherin, GSC (Atlantic). Selected elevations are shown in metres.

coarse sediment for a variety of beaches and back-barrier coastal sedimentary systems (Forbes et al., 1990). In contrast, the coast of the western outer harbour is dominated by granite bedrock outcrop with steep cliffs and a few gravel beaches.

Harbour geographic divisions

The geographic divisions of Halifax Harbour have previously not been well defined nor universally accepted. For example, the area adjacent to the downtown core of Halifax and Dartmouth is often referred to as the only legitimate 'Halifax Harbour' whereas in other cases this usage is extended to include the outer areas of the harbour to Chebucto Head.

The authors propose herein to define geographic divisions of Halifax Harbour and use this classification throughout the bulletin (Fig. 1). The divisional system is based on the location of major boundaries between morphology and surficial sediment types that are largely controlled by variations in the energy within the oceanographic regime. The harbour has sometimes been referred to as 'Halifax Inlet' (Nicholls, 1989) in place of Halifax Harbour, however, the present authors propose to retain the term 'Halifax Harbour' for that body of water extending north of a line between the headlands of Hartlen Point and Chebucto Head. It includes the subdivisions of inner and outer Halifax Harbour, Northwest Arm, Eastern Passage, The Narrows, Bedford Basin, and Bedford Bay, as well as many other smaller bays, coves, and inlets within these general boundaries. Areas seaward, to the southeast of this line, are designated as the approaches to Halifax Harbour, following the usage of the Canadian Hydrographic Service in their bathymetric charting and traffic-control lanes. This area is also sometimes referred to as the inner Scotian Shelf off Halifax Harbour.

The inner harbour includes the area extending from and including The Narrows in the north, to a line from Maugher Beach in the east on McNabs Island, across the harbour to York Redoubt National Historic Site of Canada (locally known as 'York Redoubt'). It also includes Northwest Arm and Eastern Passage. The outer harbour lies to the south of this area and extends to a line between Chebucto Head and Hartlen Point. This division is modified from the usage described in the Halifax Harbour Task Force report (Fournier, 1990; Fader and Buckley, 1997).

Bathymetry

The Canadian Hydrographic Service has published a series of nautical charts of Halifax Harbour at a scale of 1:10 000, which are contoured at 10 m intervals in depths greater than 10 m. The 2 m and 5 m contours are also depicted. This series of charts served as the primary base for the marine geological surveys and earlier data interpretations and compilations (Fader et al., 1991, 1994).

Multibeam bathymetry

Unlike conventional bathymetry, often contoured at 10 m or greater intervals, multibeam-bathymetric imagery has a vertical resolution of approximately 0.1 m and each measurement represents a small footprint (1–2 m^2) of seabed. The multibeam images presented in this report for the harbour have maximum resolutions of approximately 1 m, whereas newer systems (Simrad EM3000 utilized in Bedford Basin and Northwest Arm) have theoretical resolutions of decimetres in 20 m water depth. Contoured maps can be produced from the multibeam database with smaller contour intervals (Fig. 16). The multibeam data can also be processed to provide information on the relative reflective strength of the returning echoes from the seabed in the form of acoustic backscatter maps. These maps are similar to data displayed by sidescan-sonar systems providing information on seabed sediment texture and roughness and/or rugosity as a proxy for sediment type. Backscatter processing has only been applied to the multibeam data from the outer harbour and was undertaken by the University of New Brunswick Ocean Mapping Group (Fig. 8). The backscatter imagery complements the morphological information produced from the bathymetric processing of the multibeam imagery (Fig. 17).

Halifax Harbour was one of the first areas to have multibeam images produced (Courtney, 1993; Courtney and Fader, 1994). Not only did this new information enhance the earlier geological interpretations based on survey tracks separated by up to 100 m, but it provided an opportunity to assess the value of the multibeam technology in comparison to conventional surveys, bathymetry, and interpretations. Such an evaluation shows that multibeam technology greatly improves the correlation of data from conventional, widely spaced adjacent tracks. It also provides an ability to display and characterize the morphology of subtle seabed features resulting from a variety of processes of deposition and erosion (Courtney and Fader, 1994); however, the interpretation of morphological elements on multibeam data must be supported by conventional marine geological survey and sample information.

The following is a brief regional description of seabed morphology of the harbour based on the multibeam imagery and existing bathymetry. It provides a geomorphic framework for subsequent sections where many of the features are discussed in greater detail.

Bedford Basin

Until 1998, systematic multibeam-bathymetric data had only been collected for the southern Fairview Cove area of Bedford Basin. At the request of the Geological Survey of Canada, the Canadian Hydrographic Service conducted a systematic survey of all of Bedford Basin, including Bedford Bay, using a high-resolution Simrad EM3000 multibeam

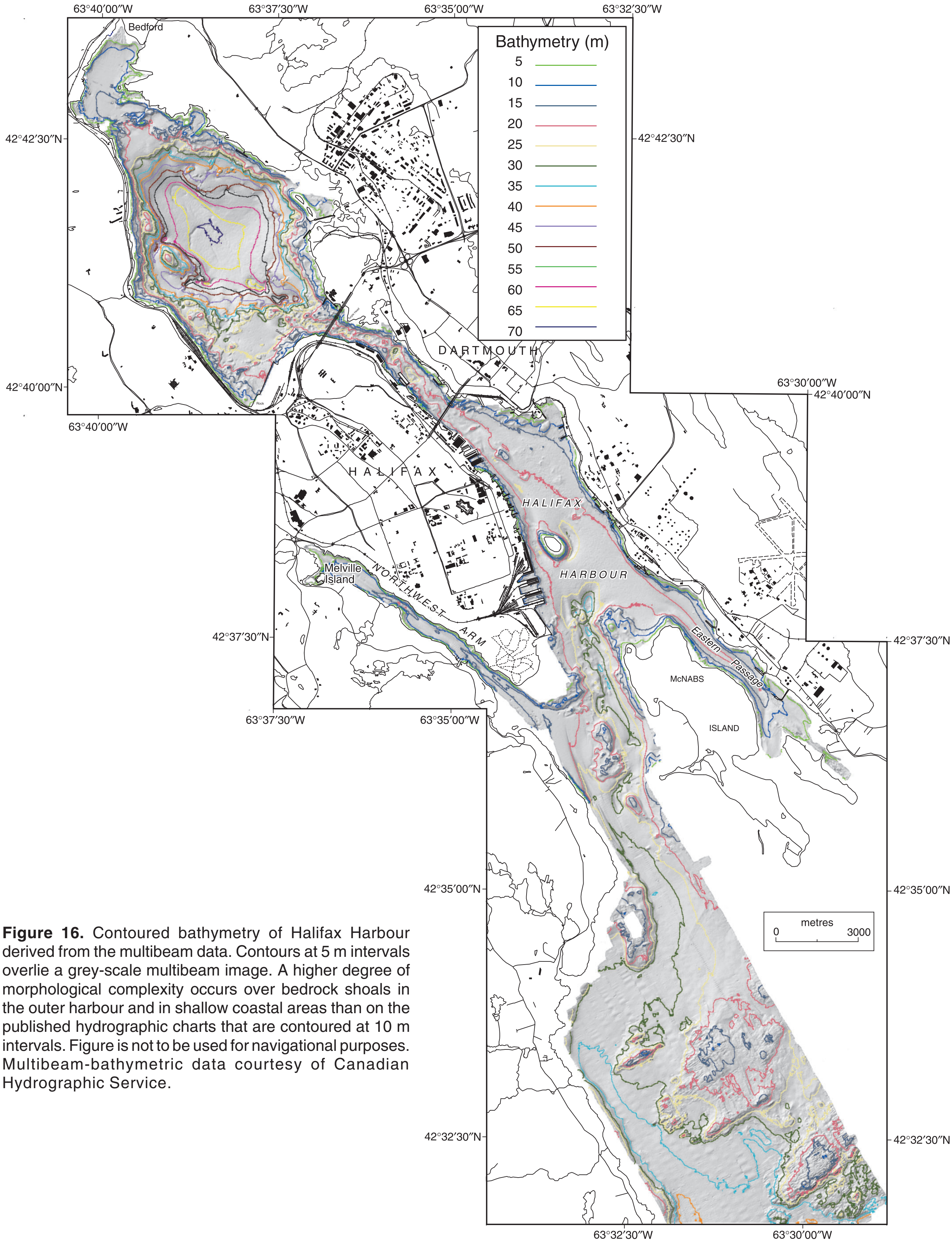


Figure 16. Contoured bathymetry of Halifax Harbour derived from the multibeam data. Contours at 5 m intervals overlie a grey-scale multibeam image. A higher degree of morphological complexity occurs over bedrock shoals in the outer harbour and in shallow coastal areas than on the published hydrographic charts that are contoured at 10 m intervals. Figure is not to be used for navigational purposes. Multibeam-bathymetric data courtesy of Canadian Hydrographic Service.

mapping system (Fig. 11). The following description is based on data collected from that survey and Canadian Hydrographic Service (1990a).

Bedford Basin is a large, bowl-shaped depression, approximately 5 km long and 3 km wide, oriented northwest-southeast, with a maximum water depth of 71 m near its geometric centre. A series of shallow banks occur along the western side of the basin, such as Parfait Bank and Jonquière Bank. The authors propose to name the large unnamed bank north of Jonquière Bank, 'Princes Lodge Bank', and the bank south of Jonquière Bank, 'Sherwood Bank' after adjacent onland locations (Fig. 18, on CD-ROM). The largest of the banks in Bedford Basin is 'Princes Lodge Bank'. Jonquière Bank is a gravel-covered drumlin.

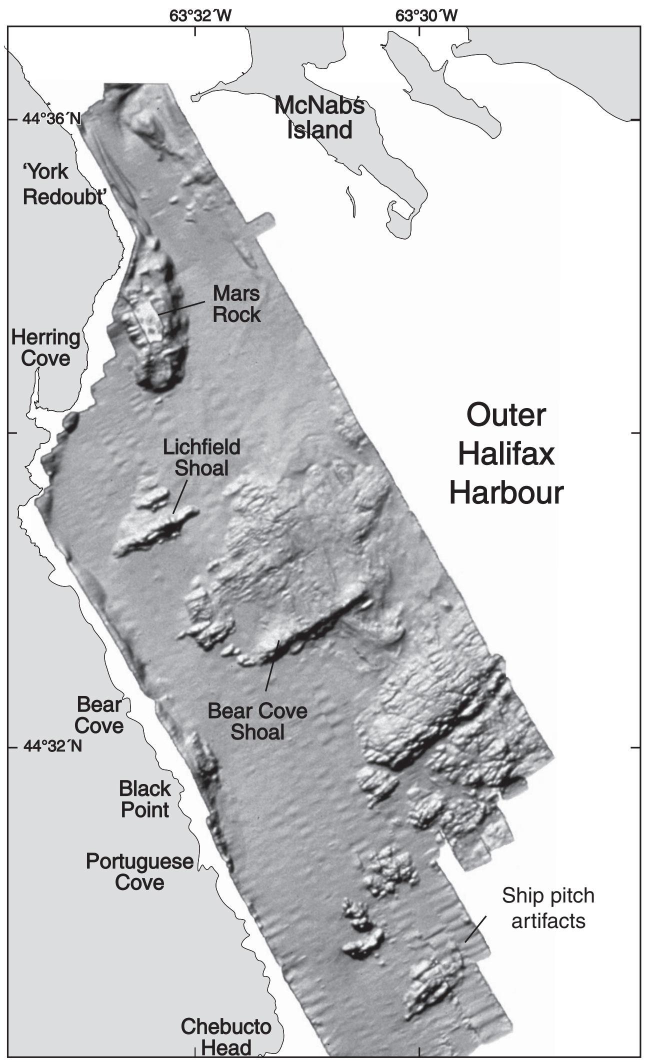


Figure 17. Multibeam-bathymetric shaded-relief map of outer Halifax Harbour extending from 'York Redoubt' to Chebucto Head. Note the flat-floored, deep western channel of the harbour in contrast to the shallow area with many bedrock shoals to the east. Undulations on the flat seabed are artifacts due to seaswell not removed from the data.

Two major, subparallel, bedrock-controlled ridges occur in the southern part of Bedford Basin that isolate two smaller basins from the main part of Bedford Basin (Fig. 18). The northernmost ridge trends easterly from Sherwood Point on the western side of the basin to The Narrows. The authors propose the name 'Sherwood Ridge' for this bedrock-controlled feature that contains Sherwood Bank as part of its structure. A similar, smaller bedrock-controlled ridge, for which the authors propose the name 'Rockingham Ridge', separates another smaller basin adjacent to the Fairview Cove Container Terminal, and extends to the southwest from the northeastern terminus of the container pier.

At the juncture with The Narrows, the seabed of Bedford Basin is rough with bedrock ridges, gravel including boulder-sized clasts, and dredge spoils. The deep channel that connects the basin to The Narrows is closer to the Halifax side, whereas the Dartmouth side is shallow with rough topography. A convoluted channel of an ancient Sackville River (King, 1970) can be traced through the rough topography near The Narrows (Fig. 18).

A conspicuous morphological characteristic of Bedford Basin presented on the EM3000 multibeam bathymetry is the presence of a shelf-like zone (unit 1 on Fig. 18) that rings most of the basin in depths generally above 20 m water depth. It is generally flatter and smoother than the adjacent deeper seabed. This is interpreted as a transgressed area that has been eroded and modified by a postglacial rise in sea level. The transition to the smoother topography in shallower water is marked by a continuous pair of boulder berms.

The deep seabed of Bedford Basin exhibits three unusual curvilinear morphological depressions or steps in the otherwise flat, muddy seabed (Fig. 18). The southernmost feature is circular. They are interpreted to represent depressions associated with the venting of biogenic methane gas and are discussed in detail in later sections.

Bedford Bay

Bedford Bay is an elongate northeast-trending feature, 2 km long and approximately 700 m wide at the northwestern head of Bedford Basin. It is separated from the main body of the basin by east-trending bedrock ridges that form a sill at Western Ledges and Wellesley Rock. The authors propose the name 'Wellesley Ridge' for this sill (Fig. 18). Shallow, exposed bedrock ledges and shoals also occur at the seabed north and south of Spruce Island on the east side of Bedford Bay. The maximum water depth in Bedford Bay is 16 m and occurs in the southern area. It is generally a flat, sandy-mud basin. The Sackville River empties into Bedford Bay in the northeast, and a large deposit of sandy mud to muddy sand occurs in a delta off the mouth of the river. Large quantities of this material have been dredged and transported by slurry for infill projects along the western shoreline of Bedford Bay.

Inner harbour

The Narrows

The inner harbour can be divided into three morphological zones: 1) The Narrows; 2) a north inner harbour zone extending from The Narrows to the Ives Knoll–south Halifax container pier area; and 3) a south inner harbour zone continuing to the Maugher Beach–'York Redoubt' area.

The Narrows zone is 2.7 km long and approximately 500 m wide, with the narrowest section of 320 m occurring 500 m south of the A. Murray MacKay Bridge. In contrast to the northern inner harbour zone to the south, which is generally flat and smooth, The Narrows consists of a rough and hummocky seabed with a series of ridges trending northeast (Fig. 6, 13). The ridges are prominent, with higher relief near the Dartmouth shore of the northern and southern areas of The Narrows. The overlying sediments (till and gravel) are thin and the seabed largely mimics the morphology of the underlying bedrock surface. Smaller curvilinear features in deeper water of the central channel of The Narrows are relict beach ridges. A series of isolated depressions, up to 27 m deep, occur throughout The Narrows and are interpreted as glacially overdeepened features. They are confined by bedrock ridges that suggest that waterfalls and plunge pools may have been characteristics of The Narrows in postglacial time prior to the marine transgression, when a precursor of the modern Sackville River flowed through this part of the harbour.

The remains of the two harbour-spanning bridges constructed in the late nineteenth century occur on the seabed at the north end of Pier 9 in the narrowest area of The Narrows (Fig. 13). The remains consist of cribwork, rock ballast, and railway track. A shallow bedrock ridge cuts across The Narrows from the southern end of Pier 9. The western part of this ridge was blasted and dredged in 1990 and 1999, in a harbour-maintenance program to remove the shallow bedrock shoal that was a navigational hazard to deep draught vessels in a critical area of the harbour. It is now a small, flat-topped, bank-like feature.

A channel segment of the ancient Sackville River is clearly evident in the southern part of The Narrows (Fig. 6, 13, 19). Its sinuous course meanders between bedrock ridges and isolated mounds. Sedimentation since the marine transgression of Halifax Harbour has also been very low in the southern part of The Narrows, and has helped preserve the seabed expression of the old river channel; i.e. it is only partially buried. The Angus L. Macdonald Bridge occurs near the southern boundary of The Narrows. The Dartmouth footing for the bridge is founded on the northernmost of a series of large bedrock ridges that project from the Dartmouth side of The Narrows at the juncture with the widening southern part of the inner harbour.

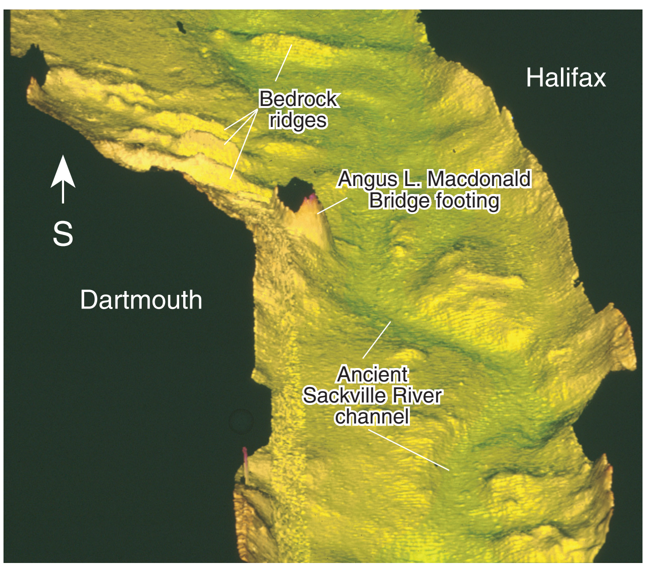


Figure 19. A perspective shaded-relief colour multibeam image of a section of The Narrows, Halifax Harbour, looking south, shows the sinuous, partially infilled channel of the 'ancient Sackville River' at the seabed. Bedrock ridges and till mounds flank the channel. The channel is cut into bedrock, and the overlying sediments in this area of the harbour are thin, allowing the channel to be observed at the seabed. The sinuosity of the channel suggests fluvial rather than glacial erosion for its formation. The eastern footing for the Angus L. Macdonald Bridge is founded on one of a series of bedrock ridges southeast of the channel. The width of The Narrows at the bridge footing is approximately 500 m.

Northern inner harbour

The morphology of the seabed of the northern part of the inner harbour zone is quite different from that of The Narrows to the north. In general, the northern zone is flatter and smoother, with depths over 20 m and an average width of 1.5 km (Fig. 6, 12). The lack of relief is attributed to the presence of thick deposits of Holocene mud and in some cases ponded lacustrine and estuarine mud in the subsurface overlying bedrock and till. Positive relief elements include drumlins, till ridges, and till mounds that protrude above the mud and occur to the northeast and north of Georges Island. Bedrock ridges extend from the Dartmouth shoreline in the area between the Angus L. Macdonald Bridge and Dartmouth Cove. Georges Island, the only island in this part of the harbour, is a drumlin. Four hundred metres to the northwest of Georges Island is a shallow bank in 13.4 m of water that is also a drumlin, but completely submerged (Fig. 13). The authors propose the name 'Little Georges Bank' for this seabed feature. It was once much shallower, but has been dredged, deepened, and flattened, as it was an obstruction to harbour navigation. Surrounding the south, eastern, and western flanks of Georges Island is an asymmetric moat-like depression, 31 m deep and 9 m deeper than the surrounding seabed that the authors term the 'Georges Island moat'. Directly north of Georges Island is a large depositional mound of Holocene mud, more than 6 m thick.

In the broad area surrounding Georges Island to the north and southeast, the seabed appears generally flat and featureless on the multibeam and bathymetric maps; however, sidescan sonograms indicate that it is criss-crossed with many generations of anchor marks that produce a small-scale roughness of up to 2 m. Only some of the largest anchor marks show on the multibeam data.

Anthropogenic features resulting from the grounding of ships and oil-rigs occur in this area. Large, 15 m diameter rimmed pits are interpreted as 'spud can' footprints of jack-up oil-rigs. The impression of the hull of the British steamship *Trongate*, which sank in the harbour, is a large linear depression, flanked by two asymmetrical mud mounds. The authors refer to this feature as the 'Trongate depression'.

East of the South End Container Terminal Pier C are two linear sediment ridges (Fig. 13) that previously have been termed "obstacle induced depositional features" or "sediment drifts" (Fader and Buckley, 1997). Their distribution north of two bedrock mounds was interpreted to result from strong northward-flowing bottom currents that prevented sediments from accumulating on the south side, favouring sedimentation on the north side (Fader et al., 1997). Scoured depressions associated with these features attain depths of 38 m ('fisherman hole', Fig. 13). The present authors now consider that the features are residual sediment deposits resulting from current scour in adjacent areas; they will be discussed in greater detail in section 'Sediment transport'.

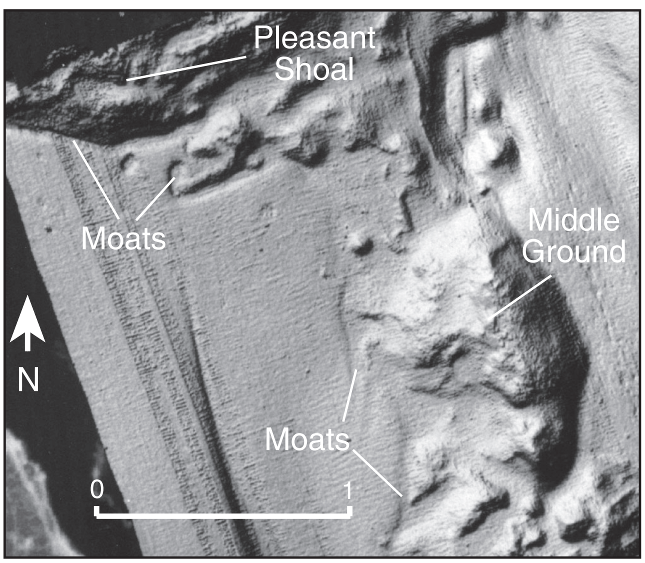


Figure 20. A multibeam-bathymetric map of the area of the harbour south of Halifax showing the location of moats in LaHave Clay surrounding bedrock outcrop and shoals (Pleasant Shoal) composed of gravel-covered till. This relationship is in contrast to areas of the inner harbour where the mud onlaps coarse, rough terrain without the formation of contact moats. They are interpreted to form in areas where stronger currents are focused by topography and accompanied by a lack of sediment deposition and some erosion.

Southern inner harbour

This area extending from Ives Knoll to 'York Redoubt' is morphologically and geologically complex, with both rugged relief and flat areas with isolated features (Fig. 6, 13). Some areas are depositional and/or erosional, some are relict from past environments, whereas others are periodically depositional, punctuated by erosion from strong, storm-generated currents. The area is characterized by two deep and narrow main channel areas in the east and west separated by a series of shallow shoals: Pleasant Shoal, Middle Ground, and Outer Middle Ground. Pleasant Shoal is a boulder-strewn outcrop of Halifax Formation slate bedrock, whereas the other shoals to the south are bedrock ridges and mounds partially covered with till and gravel.

The eastern channel extends southward from the area south of Georges Island with isolated basins up to 37 m deep. On the western side of the shoal area is the western channel, which is up to 30 m deep off 'York Redoubt'. It gradually shoals to the entrance to Northwest Arm in the northwest. Middle Ground and Outer Middle Ground are breached by a deep passage up to 29 m deep that was formed and occupied by the ancient Sackville River where it shifted position from the east to the west side of the shoals. Nondepositional or erosional moats are common characteristics in this area of the harbour around bedrock and other shallow shoals where mud deposition terminates (Fig. 13, 20).

A series of bifurcating, linear, erosional scours, known as sedimentary furrows (Flood, 1983) occur adjacent to Sandwich Point, 'York Redoubt', and Fergusons Cove (Fig. 2, 13) on the western side of the harbour. They were previously known from conventional seismic-reflection and sidescan-sonar surveys, but had been difficult to map because they are very shallow and narrow, and sediment textural differences are minor. A series of additional erosional scours is concentrated in the area between 'York Redoubt' and the Maugher Beach lighthouse breakwater on McNabs Island. Two parallel, subtle, shallow depressions in the seabed extend across the harbour, and are interpreted as scoured depressions resulting from the presence of antisubmarine nets during World War II. Other scoured depressions occur around large concrete antisubmarine net anchors that remain on the seabed.

The area between Sandwich Point, 'York Redoubt', and Maugher Beach is a significant sedimentological transition area for Halifax Harbour. The harbour muds of the north interdigitate in a complex fashion with the sand and gravel of the outer harbour in the sedimentary furrow zone (Fig. 21, on CD-ROM).

Northwest Arm

Northwest Arm is a northwest continuation of the western channel of the southern part of the inner harbour. The arm is 5 km long and averages 300 m wide. It has more or less parallel shorelines that are slightly sinuous. Narrow constrictions adjacent to the Royal Nova Scotia Yacht Squadron and off

The Dingle (in Sir Sandford Fleming Park) where the width narrows to less than 180 m. Average water depths are 12 m to 14 m with a depression of 17 m at the constriction off The Dingle. Deeper water depths occur in erosional furrows in the outer part of the arm. Mud dominates the deeper floor of Northwest Arm, with bedrock and gravel dominating on the sloping flanks and in some deep depressions. A prominent ridge, interpreted as a moraine, cuts across the head of the arm at Melville Cove.

Eastern Passage

Eastern Passage is similar to Northwest Arm in many respects, but has a more continuous cover of sediment without mid-channel exposure of hard ground. It is approximately 4 km long and 600 m wide and is a southeast extension of the southern inner harbour between McNabs Island, Dartmouth, and the community of Eastern Passage. It is a mud-floored linear depression with average depths of 20 m and a deepest depth of 22 m. In the south, it bifurcates with one arm extending between McNabs Island and Lawlor Island and the other between Eastern Passage and Lawlor Island. Water depths shallow in these bifurcations to several metres. Strong currents occur in the channel between Lawlor Island and the community of Eastern Passage with the generation of large, sandy bed forms and scour features on the seabed.

Outer harbour

During the summer of 1993, the C.C.G.S. *Frederick G. Creed*, outfitted with a Simrad EM1000 multibeam-bathymetric mapping system, was used to survey the western part of the outer harbour in an area extending from Maugher Beach to Chebucto Head.

Unlike the multibeam image of the inner harbour to the north, which shows many anthropogenic attributes and depositional and erosional features on the seabed, the image of the outer harbour predominantly indicates a flat, western, deep-channel area with a series of connected and isolated, shallow bedrock shoals to the east (Fig. 6).

Sedimentary furrows off 'York Redoubt' continue south-easterly to the Sandwich Point area where they and the inner harbour mud both terminate north of Mars Rock.

The flat, deep channel in the western area of the outer harbour contains mainly silty sand near Herring Cove, grading to sand and gravel, with a variety of bed forms farther seaward to the southeast. Depths range from 30 m off Herring Cove to more than 60 m southeast of Chebucto Head with a gentle, seaward-sloping profile (cross-section, Fig. 21c). Many small bedrock mounds and ridges protrude above this flat bottom.

The western flank of the outer harbour, extending from Herring Cove to Chebucto Head, consists of an approximately straight, fault-controlled, steep coast consisting of granite bedrock. An easterly broad projection of bedrock at Black Point extends out a short distance into the channel. Shoals on the eastern flank of the western outer harbour channel are largely boulder-strewn bedrock outcrops. The major shoals are Lichfield, Neverfail, Bear Cove, Portuguese, and Head Rock shoals. Additional, smaller bedrock outcrops that are not shallow enough to be identified and named for navigational purposes occur east and northeast of Chebucto Head.

The eastern area of the outer harbour is generally shallow. Maximum depths of 22 m occur in an isolated, sand-filled depression to the southeast of McNabs Island. South of McNabs Island, Thrumcap Shoal is a shallow bedrock feature with scattered boulders, and it is continuous to the north toward McNabs Island. Devils Island occurs southwest of Hartlen Point and is largely a bedrock island of low elevation (Fig. 9). Limited geological survey data and no multibeam bathymetry were collected in the area of the eastern outer harbour because of the shallow depths and difficulties in surveying in shallow shoal and boulder-strewn waters.

Approaches to Halifax Harbour

Beyond Chebucto Head, in the approaches to Halifax Harbour, multibeam bathymetry was collected by the Canadian Hydrographic Service and the Geological Survey of Canada (Loncarevic et al., 1994) (Fig. 9). Figure 22 is an interpretation of this multibeam bathymetry with an emphasis on glacial, bedrock, and former shoreline and associated features. It utilizes the multibeam bathymetry for feature continuity in conjunction with data from submersible dives, cores, samples, sidescan sonograms, and seismic-reflection profiles.

The multibeam bathymetry provides evidence for the recognition and definition of four major terrains. The shallowest and most northern terrain off Chebucto Head consists of areas of muted topography, gravel-lag surfaces, eroded drumlins, gravel barriers, and sea-level lowstand deltas. These features indicate a low sea-level stand of -65 m to -70 m at 11 600 BP (Stea et al., 1994) and a subsequent marine transgression. To the east and southeast, the second terrain is dominated by bedrock outcrop with structural elements such as folds, joints, and fractures in thickly bedded Goldenville Formation quartzite. This pattern continues to the southeast to approximately 150 m water depth where moraines of the Scotian Shelf moraine complex (King and Fader, 1986) dominate the terrain and overlie the bedrock. The orientation of the moraines is subparallel to adjacent bedrock structure.

The third terrain is represented by hummocky topography of the offshore triangular extension of the South Mountain granite batholith. Loncarevic et al. (1994) interpreted two different types of morphology within the granite terrain as representing different granite phases of biotite granodiorite and monzogranite (MacDonald and Horne, 1987, 1988); however, when the postglacial, low sea-level position is extrapolated through the area of granite (Fig. 9, 22), two regions of

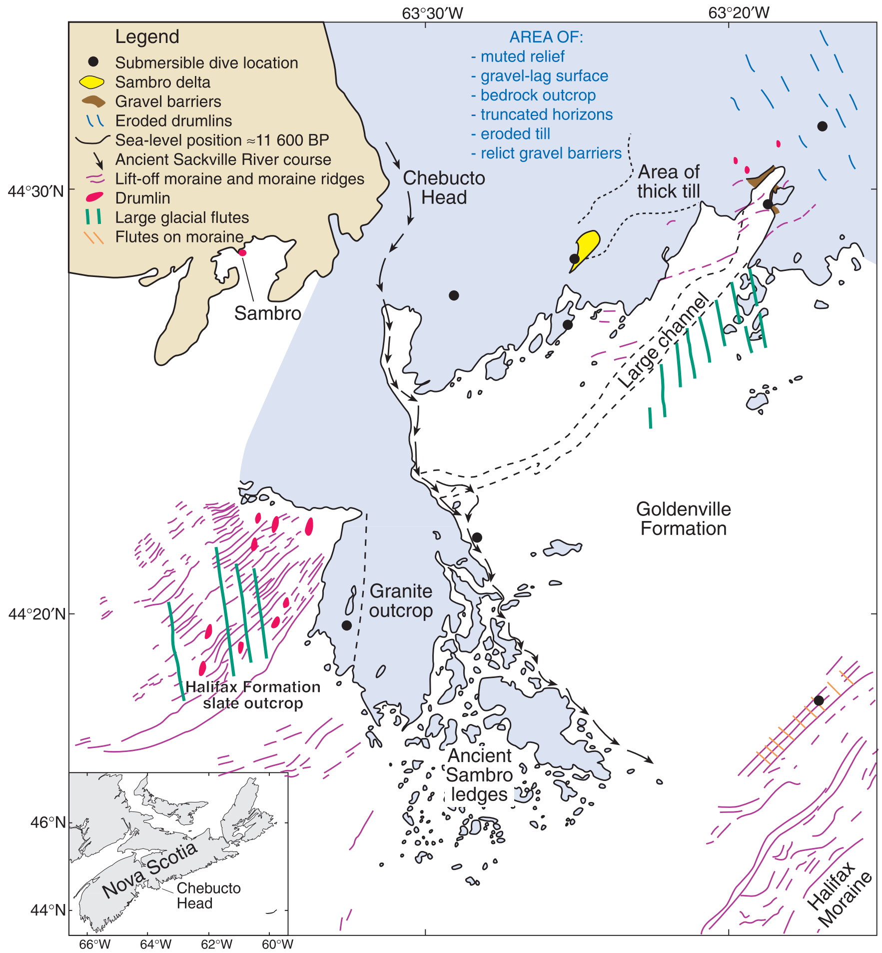


Figure 22. Interpretation of multibeam bathymetry (Fig. 9) at the approaches to Halifax Harbour. A low sea-level stand that occurred at approximately 11 600 BP, at a present depth of 65–70 m, clearly differentiates surficial sediments and terrains. Above the lowstand, the seabed morphology is muted, gravel-lag deposits and bedrock dominate, and glacial features such as drumlins have been severely eroded into linear boulder ridges. Sand is generally absent. Large glacial flutes trending northwest occur on the bedrock surface. Drumlin fields south of Sambro trend northeast. Eroded drumlins above the low sea-level stand in the northeast trend northwest, parallel to the alignment of drumlins on land in Dartmouth (Fig. 15). Small lift-off (ribbed) moraines south of Sambro are parallel to bedrock structure of Halifax Formation slate and were likely formed during ice retreat to the northwest. These varied glacial features attest to changing directions of ice movement.

differing morphological character appear and more likely result from the position of the sea-level lowstand and its subsequent transgression rather than lithological variability.

West of the granite batholith, the fourth zone is dominated by bedrock outcrop and a series of low-relief till ridges superimposed on a drumlin field (Fader et al., 1997). The bedrock consists of thinly bedded, concentric ridges of an eroded dome of Halifax Formation slate. The orientation of the drumlins is northeast-southwest, indicating ice movement from the northeast. Small, overlying ribbed moraines trend northeast, indicating formation by a retreating ice margin oriented northeast-southwest. The orientation of the small moraines is also parallel to the adjacent bedrock ridges, suggesting bedrock structural control on their formation, that is ice-margin grounded positions on bedrock.

The channel of the ancient Sackville River (King, 1970) occurs at the contact between the Goldenville Formation and the offshore extension of the Devonian South Mountain granite batholith. Several other large channels trend northeast, to the east of the contact near the sea-level lowstand. They also connect with the ancient Sackville River channel. It is not clear if these large channels have been excavated by glacial ice or subglacial meltwater. Their orientation is subparallel to bedrock structure.

REGIONAL SETTING

Onshore bedrock geology

Two major terranes dominate Nova Scotia: the Meguma Terrane in the south and the Avalon Terrane in the north (Keppie, 1982, 1979) (Fig. 23). The southern Meguma Terrane consists of a conformable sequence of Cambrian to Devonian metasedimentary and metavolcanic rocks. It is dominated by the Cambrian-Ordovician Meguma Group and Devonian-Carboniferous granitoid rocks. The Avalon Terrane is separated from the Meguma Terrane by the Chedabucto-Cobequid fault system that continues offshore to the east on the Scotian Shelf and to the west in the Bay of Fundy as part of the regional Glooscap fault system (King and MacLean, 1976). Carboniferous and Mesozoic rocks occur in the northern part of the Meguma Terrane and in the adjacent Avalon Terrane. Devonian deformation and metamorphism within the Meguma Terrane produced northeast-trending folds, and compression of the region developed northwest-trending joints, veins, and dykes and east-west strike-slip faults. These structures controlled the later emplacement of granitoid rocks such as the South Mountain Batholith. Northwest-trending transcurrent faults have been interpreted from Mesozoic rifting (Williams et al., 1995).

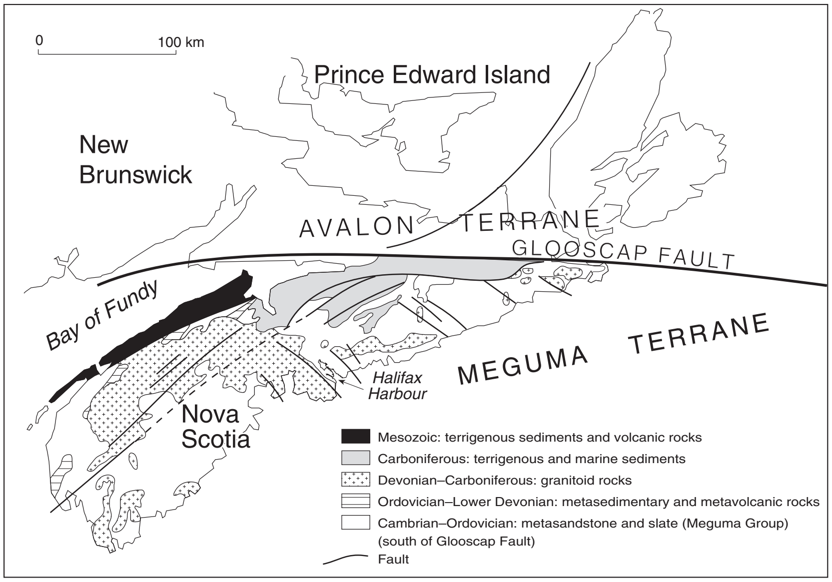


Figure 23. Major terranes of Nova Scotia and their dominant bedrock types. Halifax Harbour is located within the Meguma Terrane between Devonian granitic batholiths. The harbour and its offshore extension continue to the southeast within the same Meguma Terrane setting.

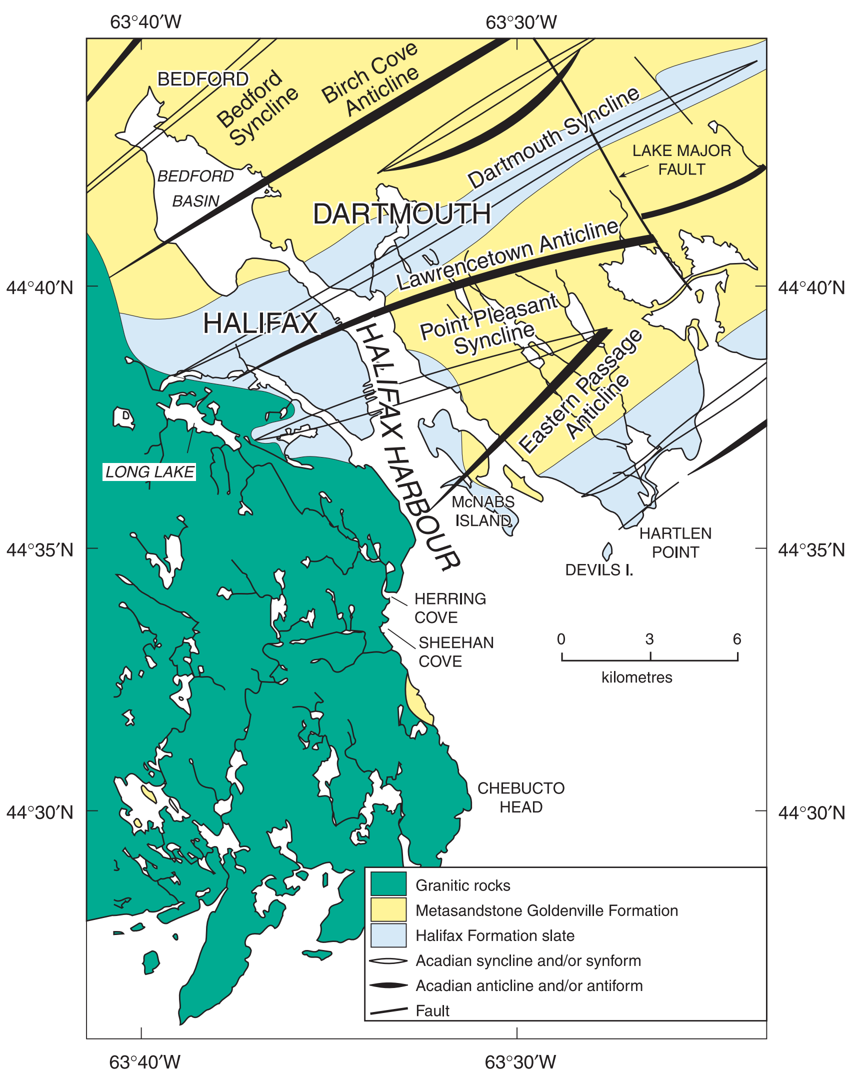


Figure 24. Map of major anticlines and synclines mapped on both sides of the harbour by Fairbault (1908) and the regional bedrock distribution. Note that the deepest water in the centre of Bedford Basin, 71 m, occurs on the axis of the Birch Cove Anticline as it crosses the basin. In general the harbour narrows in association with synclines.

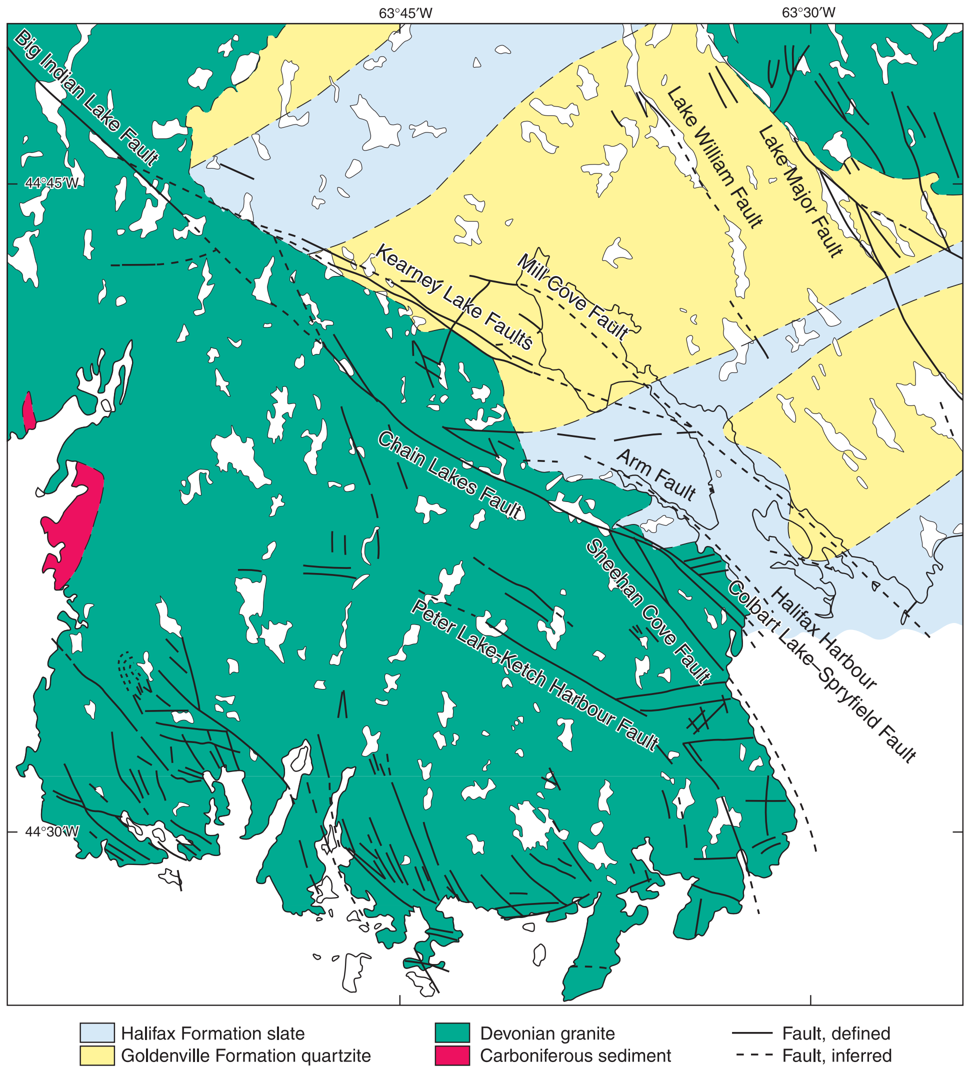


Figure 25. A map of an early interpretation of faulting in the harbour region (*after* Cameron, 1949, Fig. 1) largely based on airphotos. The location of faults extrapolated to occur beneath the harbour was not based on marine information and marine data does not support their offshore extension. The major fault system in the harbour is the Sheehan Cove Fault on the western flank of the outer harbour and its extension to the northwest through the Chain Lakes and Big Indian Lake faults. The digital terrain model (*see* Fig. 30) indicates that this structure continues a considerable distance farther to the northwest across Nova Scotia.

Halifax Harbour is largely underlain by the Meguma Group, the slate and quartzite of which are folded into a series of well defined, southwest-trending anticlines and synclines (Fig. 24, 25). These structures were projected to continue uninterrupted beneath the harbour in the first published map of Halifax Harbour bedrock geology by Fairbault (1908). The South Mountain granite batholith truncates the rocks and structures of the Meguma Group along the outer western flank of the harbour (Fig. 24) with a narrow contact aureole of cordierite, andalusite, and sillimanite porphyroblasts.

The most recent bedrock geology assessment of the land area is presented in Nova Scotia Department of Mines and Energy Map 87-6 (MacDonald and Horne, 1987). This study focused mainly on the granitic rocks that occur along the western margins of the study area. Based on Schenk (1982), the country rocks of the Meguma Group are described as metagreywacke units of the Goldenville Formation and metapelite units of the overlying Halifax Formation. The granitic rocks show no effect of regional Acadian deformation. The contacts of the granite with the Meguma Group are sharp and discordant and the regional structural trends in the Meguma Group are abruptly truncated.

Offshore bedrock geology

The offshore regional bedrock geology of the Scotian Shelf was first mapped and described by King and MacLean (1976). The inner shelf off Halifax consists of a zone of

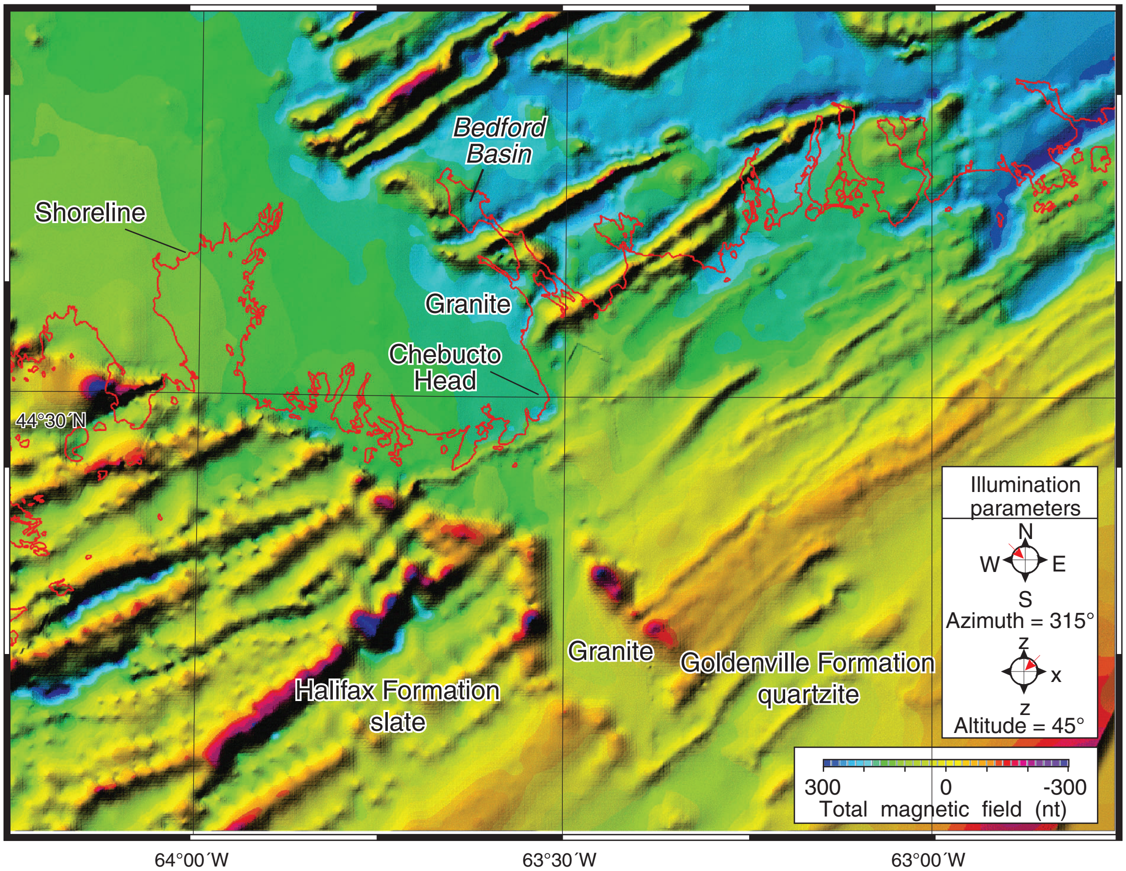


Figure 26. A shaded total-magnetic-field compilation of the Halifax Harbour area including the adjacent inner Scotian Shelf (*modified from* Courtney et al., 1993). Note the absence of magnetic linear signatures overlying the Devonian granite both onland and offshore. The regional structural trend of the magnetic anomalies is southwest-northeast. There is no offset of these anomalies resulting from faulting within the harbour.

acoustical basement composed of Lower Paleozoic and older rocks. These rocks have a high surface reflectivity and are highly metamorphosed, hence internal subsurface reflections are not observed on seismic-reflection data. Differentiation of the inner shelf bedrock must be based on samples and gravity, magnetic, and refraction techniques. King and MacLean (1976) interpreted that the bedrock off Halifax Harbour was a continuation of the Meguma Group on land, but did not define subdivisions within that group.

Courtney et al. (1993) and Loncarevic et al. (1994) integrated multibeam bathymetry (Fig. 9), total-magnetic-field data (Fig. 26), and onshore bedrock geology in an assessment of the offshore bedrock geology (Fig. 27) of the inner Scotian Shelf off Halifax Harbour. A seaward continuation of the granite batholith can easily be correlated based on its low magnetic signature and unique massive and hummocky relief (Fig. 9). Northeast-southwest linear zones of Halifax Formation rocks crossing the harbour clearly correlate with high-intensity, linear magnetic anomalies. In the outer harbour and beyond Chebucto Head the magnetic data become subdued with zones of weak signature. This area of the outer harbour was interpreted as Halifax Formation (Loncarevic et al., 1994). At the time of the interpretation, multibeam bathymetry did not exist for the outer harbour area. Based on video and photographs of the seafloor collected during this study, the present authors suggest that some of these areas may represent Goldenville Formation. The bedrock distribution in the outer harbour is more complex and should be considered as undifferentiated Meguma Group until bedrock samples are collected and identified.

Onshore surficial geology

The regional surficial geology of the land area adjacent to Halifax Harbour has been mapped and described by Stea et al. (1992a) and Finck et al. (1992), and is summarized in Figure 28, (Lewis et al., 1998) and in the following discussion. The dominant terrain occurring to the northeast and west of Bedford Basin and extending along the western side of Northwest Arm to Chebucto Head is largely exposed bedrock with isolated basins and knolls shaped by glacial erosion and overlain by thin discontinuous till. Throughout this area bedrock structure and large-scale glacial features can clearly be identified on airphotos. The topography of the terrain consists of

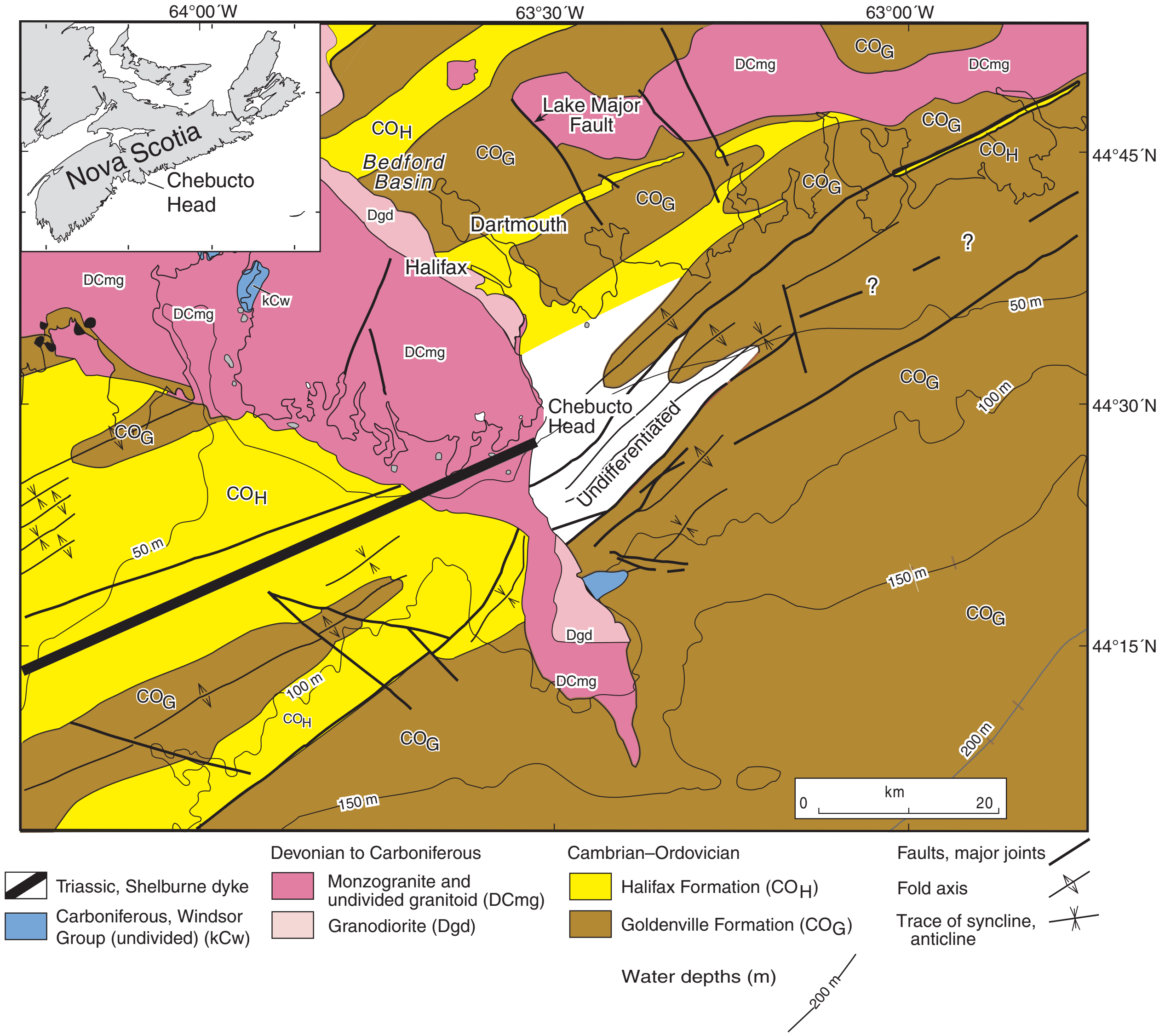


Figure 27. A bedrock map of Halifax Harbour and the adjacent inner Scotian Shelf showing interpreted structural features largely based on multibeam bathymetry (*modified from* Loncarevic et al., 1994, Fig. 2). The differentiation of the offshore granite batholith south of Chebucto Head into granodiorite may be incorrect, representing only transgressed versus nontransgressed monzogranite.

flat to highly rolling surfaces with common exposed ridges of bedrock with roches moutonnées. The till varies in thickness to 4 m. This area is generally underlain by Devonian granite and Goldenville Formation quartzite.

The dominant unit in the area occupied by the Halifax peninsula and extending to the northeast across the harbour in Dartmouth, including the southeastern side of Bedford Basin and McNabs Island, is a very stony Wisconsinan till plain with drumlins. The till has a sandy matrix and rock types are derived from local bedrock sources: that is, Halifax Formation slate beneath Halifax, and Goldenville Formation quartzite beneath the Dartmouth area adjacent to The Narrows and the southeastern side of Bedford Basin. The drumlins are generally silty as a result of incorporation of older till units by Wisconsinan glaciers. The terrain of these deposits is generally flat to rolling with many exposed surface boulders. The drumlins are elongate, oval hills composed of multiple till layers and are veneered with stony till. The thickness of the till plain reaches 20 m and the drumlins reach 30 m thick.

The unit underlying the eastern area of the harbour, extending from Dartmouth Cove to Hartlen Point, is a silty till plain with drumlins in the northwestern area. Drumlins are common to the area north of Bedford Basin in the Sackville River valley, but their greatest concentration surrounding Halifax Harbour is on the Dartmouth side including McNabs Island. The till is compact, with material derived from both local and distant sources. The drumlin facies is siltier, with a high percentage of distant source materials and red clay. The

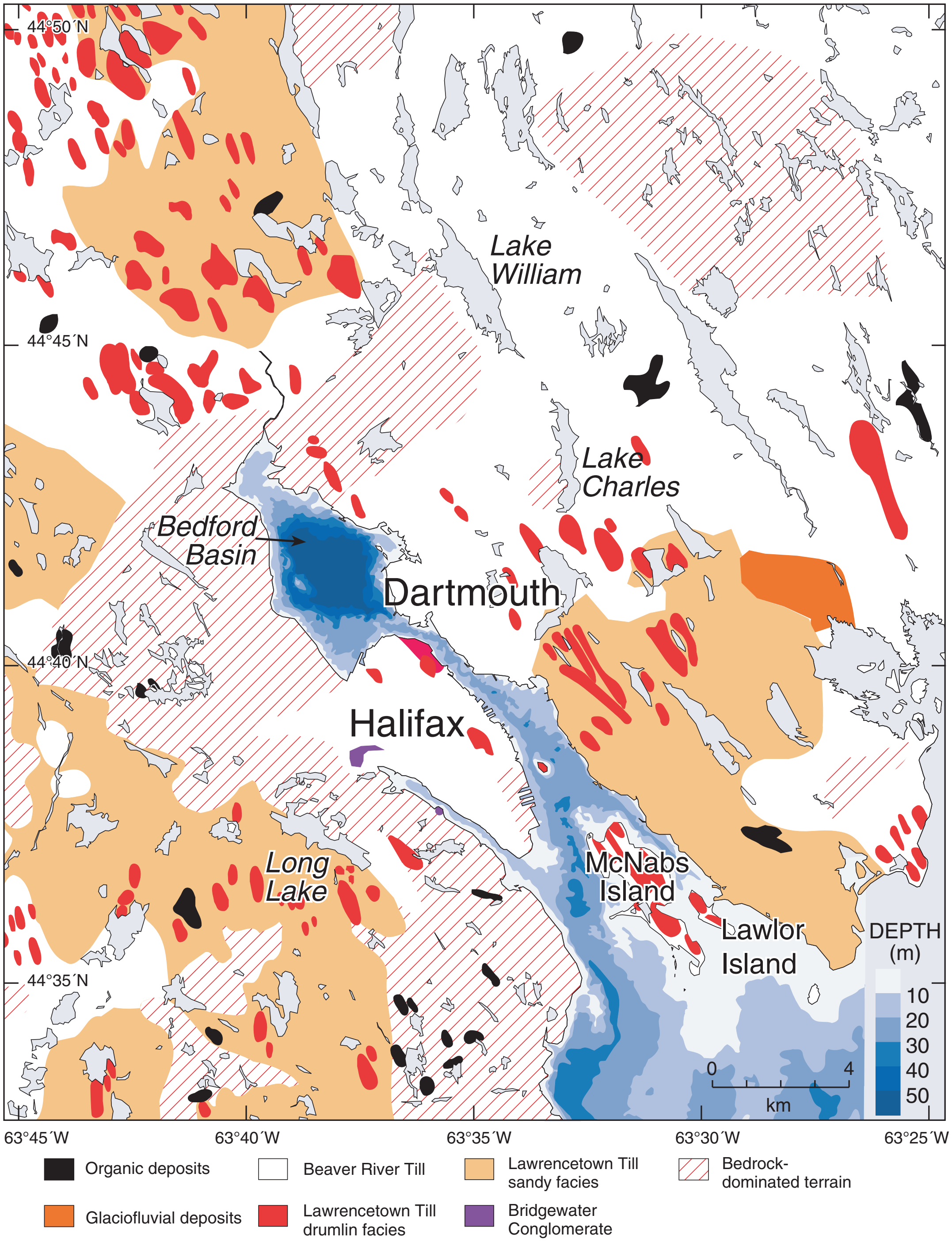


Figure 28. Surficial geology and bathymetry of the Halifax Harbour area (*modified from* Lewis et al., 1998, Fig. 7). Drumlins are clustered in southeast Dartmouth and on McNabs Island. The southeastern side of the harbour is dominated by Lawrencetown Till terrain, whereas the western side is mainly a bedrock-dominated terrain. Hartlen Till occurs in the subsurface beneath many drumlins and outcrops at the shoreline in the eastern outer harbour.

terrain is flat to rolling and the till is sufficiently thick to mask undulations on the bedrock surface. The drumlins consist of multiple stacked units. Both the till plain and the drumlins reach 40 m thick. These tills are generally thought to have been deposited by ice sheets centred west and northwest of Nova Scotia (Stea et al., 1992a).

McNabs and Lawlor islands are primarily a series of overlapping drumlins, whereas Georges Island in the inner harbour consists of an isolated drumlin. Peninsular Halifax has three large drumlins along its northern and eastern flanks. Because of their unique morphology and military applications, all have been given local names: ‘Strawberry Hill’, ‘Fort Needham Memorial Park’, and ‘Citadel Hill’.

Ice-flow directions interpreted from the orientation of drumlins and large and small glacial striae on bedrock, generally indicate a northwest to southeast flow direction. An older set of striae in the area north of Bedford Basin indicates a more northerly to southerly ice-flow direction. This is similar to the orientation of drumlins on the inner shelf west of the granite batholith (Fig. 9).

Stea et al. (1992a, 1998) interpreted the glacial history of Nova Scotia based on the distribution and characteristics of Quaternary glacial and other surficial deposits. Highly oxidized, iron-cemented, orange deposits referred to as the Bridgewater Conglomerate may predate the earliest glaciation and the Sagamonian interglacial period (75 000–128 000 BP) that is represented in Nova Scotia by marine and terrestrial deposits underlying Wisconsinan tills. These sediments are widespread along the western shores of Northwest Arm.

The timing of the formation of the first glaciers during the Wisconsinan is not well known, but a continuous ice cover of mainland Nova Scotia punctuated by short intervals of ice retreat is interpreted to have occurred in the early Wisconsinan. Striations indicate that the earliest ice flows were eastward, later changing to southeastward. In the area around Halifax Harbour, the Hartlen Till was likely deposited by these flows. It generally forms the cores of drumlins at the base of the surficial succession. A later ice flow shifted more to the south and southwestward from a centre located near Prince Edward Island. This is referred to as the Escuminac Ice Center and occurred at 22 000–19 000 BP. The Lawrencetown Till, with its characteristic red colour and muddy to sandy texture derived from a source to the north, was deposited by this ice.

A major change in ice direction followed, resulting from the development of a southwest to northeast local ice divide located over southern Nova Scotia that transported material to both the north and south. This ice extended across the inner Scotian Shelf between 17 000–15 000 BP to at least the Scotian Shelf moraine complex on the inner Scotian Shelf (King, 1970; Stea et al., 1998). The final regional phase of ice flow was from a series of remnant ice caps along the Scotian Ice Divide. These flows cut across the trend of features previously formed, and were largely restricted to low-lying areas.

A final episode of local ice advance, largely confined to eastern Nova Scotia, occurred between 11 000 BP and 10 000 BP (Younger Dryas Oscillation). This advance extended over previously deposited till and organic deposits on land. In the offshore this climatic oscillation resulted in increased storminess, the generation of sea ice and possibly small icebergs with erosion of fine-grained glaciomarine sediments, and deposition of coarser grained sequences in isolated basins and depressions.

Offshore surficial geology

The inner shelf off Halifax Harbour gradually deepens to 100 m water depth over a distance of 30 km. The surficial geology of the inner Scotian Shelf off Halifax Harbour was mapped and described by King (1970). This was the first in a series of surficial mapping projects on the Scotian Shelf (King and Fader, 1986). Interpretation of sediment texture, morphology, and distribution was based on Kelvin Hughes 26B, 14.25 kHz echosounder profiles collected along closely spaced tracks by the Canadian Hydrographic Service during systematic bathymetric charting of the Scotian Shelf. These were supplemented with data from a large number of grab samples, seabed photographs, low-resolution (air-gun single-channel) seismic-reflection profiles, and additional echograms.

The inner shelf off Halifax Harbour was depicted as a zone in which sediments exposed at the seabed consisted predominantly of gravel. A sand-floored ancestral channel of the Sackville River was identified to cross the inner shelf to approximately 110 m water depth. Beyond this area the seabed was interpreted to consist of till overlain by many small isolated basins of LaHave Clay and Emerald Silt (Fig. 29). A large and prominent moraine, the Halifax Moraine, was identified as a linear ridge, deposited parallel to the coastline at the northern flank of Emerald Basin as the most northern of a series of moraines that includes the Sambro, South Shore, and Pennant Point moraines (King, 1969; King et al., 1972; King and Fader, 1986) (Fig. 29). The moraines are part of the Scotian Shelf end-moraine complex, a series of parallel large linear moraines that are widespread on the inner Scotian Shelf. King (1996) suggested that the Halifax Moraine was formed at an ice-marginal, floating-front position at approximately 14 000 BP based on analyses of cores collected in the Emerald Silt, which interdigitates with the moraine. These moraines formed as glacial ice retreated in a stepwise fashion from the shelf edge across the large shelf basins toward the shoreline. Till tongues are common attributes of the moraines of the Scotian Shelf and represent distal interdigitization of the till (Scotian Shelf Drift) and glaciomarine Emerald Silt (King and Fader, 1986)

Subsequent surveys on the inner Scotian Shelf (Hall, 1985; Forbes et al., 1991; Fader et al., 1993) largely confirmed the earlier interpretation of King (1970) that the inner shelf off Halifax Harbour represents a transgressed surface consisting largely of gravel, but also provided details of sediment distributions, bedrock geology, and glacial stratigraphy unresolved by the earlier studies. Forbes et al. (1991) identified a northeast-southwest tributary to the ancient Sackville River and termed the entire system the Halifax valley complex, suggesting a subglacial meltwater origin. They defined a three-part zonation of the inner shelf consisting of an inner zone of transgressed estuarine sediments, a middle zone of truncated till and outwash, and an outer zone of mainly bedrock outcrop. They also questioned the interpreted low sea-level position of 110 m (King, 1970; Fader, 1989), suggesting a maximum lowering of approximately 50 m.

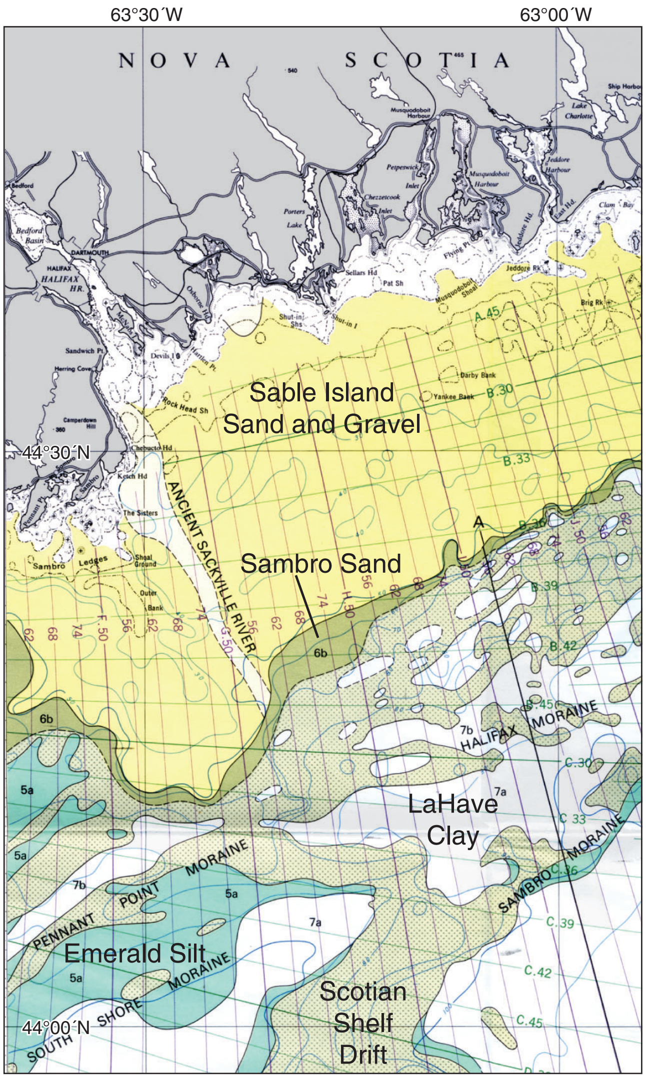


Figure 29. A map of the surficial geology of the inner Scotian Shelf off Halifax Harbour (*after* King, 1970). The Halifax Moraine to the southeast of the harbour is a lobate, regional, floating ice-front moraine. The Sambro Moraine occurs south of the Halifax Moraine in northern Emerald Basin. This early mapping of the continental shelf characterized the seabed off Halifax Harbour as dominantly consisting of transgressed gravel of the Sable Island Sand and Gravel above water depths of 90 m (50 fathoms). A channel of the 'ancient Sackville River' was found to be sand-floored, cutting across the inner shelf connecting to the harbour, but the authors now know it is much narrower than originally envisioned. The new multibeam-bathymetric imagery across this inner shelf area (Fig. 9) has revealed detailed information on seabed features and sediment distributions that have been interpreted for an understanding of relict and modern processes (Fig. 22).

The collection and presentation of multibeam bathymetry provided the next major advance in the study of the seabed off Halifax Harbour. Loncarevic et al. (1994) interpreted the imagery, identifying some of the surficial sediment features and the bedrock geology. High-resolution magnetometer data collected during the multibeam surveys show regional trends of Halifax Formation structure and 52 isolated anomalies that likely represent shipwrecks.

Recognition of truncated drumlins, former shorelines, and major unconformities, together with dated sea-level lowstands permitted refinement of the postglacial history of the area, and interpretation of a sea-level lowstand of -65 m at 11 600 BP (Stea et al., 1992a, b). Followup submersible programs across this area collected additional data that support the interpretation of the sea-level lowstand (Fig. 22). These include the identification of features such as relict gravel barriers, eroded drumlin fields, truncated lift-off moraines, muted topography, and eroded bedrock surfaces. Anthropogenic material largely consists of shipwrecks and scattered debris.

A seismic-reflection, sidescan-sonar, and sample survey of the inner shelf area was conducted to assess the placer gold and aggregate potential (Fader et al., 1993; Fader and Miller, 1994). Several gold anomalies were found in the till and sand and gravel off Halifax with values over 77 ppb (Stea et al., 1993). Large areas of sand and gravel that could be used for marine aggregate applications occur on the inner Scotian Shelf off Halifax Harbour (Fader and Miller, 1994). Multiple till units lie beneath the thin gravel-lag deposits off Hartlen Point and suggest a tripartite glacial stratigraphy similar to the tills found on the adjacent land (Fader et al., 1993).

Regional onshore terrain

A digital terrain model of the central area of Nova Scotia (Fig. 30) shows regional topographic aspects of the setting of Halifax Harbour and the immediate surrounding landscape. The resolution of the image is approximately 20 m and is low compared to multibeam-bathymetric images offshore, but does depict glacial features such as drumlins. One prominent characteristic is the connection of Halifax Harbour through the lakes in the Dartmouth area to a large basinal area of the Shubenacadie River and the Bay of Fundy in the northeast. This series of connected lakes is a major breach in the Atlantic Uplands physiographic province connecting the Hants-Colchester Lowlands to Halifax Harbour and suggests that differential bedrock erosion is partly responsible for the breach and hence the location of Halifax Harbour.

Another conspicuous aspect of the terrain image near Halifax Harbour is a series of northeast-trending, broad, linear, parallel depressions on the South Mountain Batholith west of Halifax Harbour (Fig. 30). These linear features are the present location of a series of small lakes and drainage systems as well as sites of urban development (Lewis et al., 1998). They may relate to earlier periods of glacial erosion from ice centres located to the northeast that crossed the harbour from northeast to southwest. Similar linear erosional patterns occur in other areas of the granite batholith to the west as well as the Cobequid Highlands to the north.

A digital terrain model for the regional Halifax area is shown in Figure 15. Resolution on the image is less than 20 m and drumlins and other features are depicted. The railway cut through Halifax Formation slate in southwest Halifax is an anthropogenic feature also shown on the image. Most of peninsular Halifax is a gentle mound with several high drumlins: 'Citadel Hill', 'Fort Needham Memorial Park', and 'Strawberry Hill'. In addition to the drumlins, the highest areas occur in the approximate geographic centre of peninsular Halifax and in the north end, both representing bedrock highs with thin till. Areas of coastal infill are depicted by flat, low, featureless terrain along the shoreline bordering the docks of southeast peninsular Halifax.

Overlapping drumlins in Dartmouth and on McNabs and Lawlor islands are numerous. The drumlins are steep-sided, linear, ridge-like glacial features. In contrast, Bedford Basin is surrounded to the west, north, and northeast by high, bedrock-controlled topography. The Sackville River occupies a relatively short and narrow channel and the drainage area is small. In contrast, the series of lakes in the Dartmouth area that drain into Dartmouth Cove are large, linear, well connected, and lie adjacent to very steep bedrock slopes and drumlins. Several well defined lineaments in the area to the west of the harbour correspond to fault zones such as the Sheehan Cove Fault (Fig. 25).

OCEANOGRAPHY

An early understanding of the ocean circulation of Halifax Harbour extends back to the research of Huntsman (1924) and Hachey (1934), based on temperature and salinity data. Temperature and salinity measurements made monthly for two years, at eight cross-sections from the head to the mouth of the harbour, provided the most comprehensive set of hydrographic data that allowed seasonal circulation to be derived from the salinity distribution information (Jordan, 1972). More recent additional information has come from current meter measurements from Bedford Basin, The Narrows, and the inner and outer harbour with records extending in time from a few weeks to about seven months.

The first models of water movement suggested that the harbour was flushed regularly and that sediments were also transported out by this process (ASA Consulting Ltd., 1986). Oceanographic data collected as part of a program to determine appropriate locations for marine outfalls from a waste-water treatment plant suggest that conditions are more complex, and that much of the sediment discharged to the

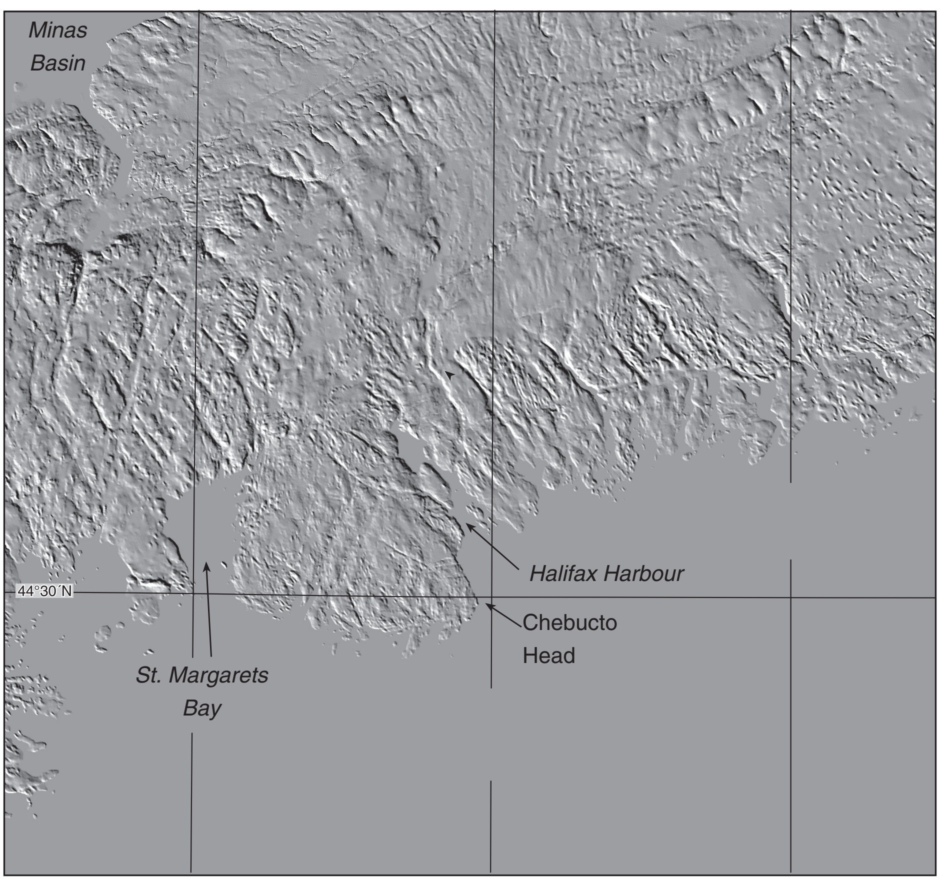


Figure 30. A shaded-relief digital terrain model for an area of central Nova Scotia including Halifax Harbour extending across the province to Minas Basin in the Bay of Fundy. It is extracted from a terrain model for the Province of Nova Scotia prepared by Tim Webster, College of Geographic Sciences. Note the broad northeast-trending bedrock depressions in the South Mountain granite batholith west of the outer area of Halifax Harbour. These linear troughs are interpreted as glacial erosional features from ice centred to the northeast. Individual drumlins and fields of drumlins occur across the image. Note the extension of the Sheehan Cove, Chain Lakes, and Big Indian Lake faults (Fig. 25) more than half-way across Nova Scotia.

inner harbour is contained within the system and not exported. Additionally, aspects of the distribution of sediments and seabed features from geological mapping provide information to further understand details of circulation not provided by minimal, direct-current measurements (Fader and Petrie, 1991) and large-scale models.

The following is a brief summary of the history of sea-level and present oceanographic conditions in the harbour, together with their relationship to sediment transport, erosion, and deposition, the generation and preservation of sediment bed forms, and contaminant distributions.

Relative sea-level history

Tide-gauge data from Atlantic Canada extend back over 100 years and indicate a rising mean sea level. Shaw and Forbes (1990) calculated the sea-level rise in Halifax Harbour and suggested a rate of change for the period of 1896–1988 of +31.8 cm/century. If data for 1920 onwards is only used, the trend increases to +36.3 cm/century. Mean sea level appears to stabilize from ca. 1970 onwards when smoothed with an 11 year running mean.

Harbour circulation

Halifax Harbour is a semienclosed estuary the properties of which are strongly influenced by freshwater runoff from the adjacent land including sewage effluent. A simplified two- layered flow circulation model of the harbour is shown in Figure 31 (Fournier, 1990; Fader and Petrie, 1991). The average freshwater discharge is 15.7 m^3/s and the sewer system provides approximately 16% of this amount on average, but can equal the flow of the Sackville River during the summer months. The Sackville River provides an average flow of 5.41 m^3/s (Buckley and Winters, 1992) that ranges from 9 m^3/s in the spring to 2 m^3/s during the drier July to September period (Fournier, 1990). The two-layered flow is also reinforced by thermal stratification in the summer and winds that generally result in surface outflow and deep-water return flow.

The fresher waters near the surface tend to flow toward the ocean, becoming saltier as they move through the harbour. The salt is supplied through mixing with waters from the shelf that move into the harbour below the outgoing near-surface flow (Petrie and Yeats, 1990). The shelf waters become less salty as they move into the harbour because of mixing with the shallower, fresher waters. Salinity measurements confirm this picture of average circulation and can be used in models that predict horizontal current strength and the rate of vertical mixing.

The weakest mean outflow of the surface layer, 0.2 cm/s, is found in Bedford Basin and moves a parcel of water approximately 200 m/day. The mean currents reach their highest values of about 5 cm/s in The Narrows, slowing to about 2 cm/s where the harbour widens in the inner harbour area. They increase slightly with a narrowing of the harbour off Sandwich Point, and finally slow to about 1 cm/s before flowing out to the inner Scotian Shelf off Chebucto Head. The picture is similar in the lower layer except in the opposite direction, that is, inflow toward the north instead of outflow.

The current meter data support the salinity-derived picture of the circulation in the harbour (Fig. 31). In The Narrows, the instruments indicated the strongest inflows near the bottom of the eastern (Dartmouth) side of the harbour as well as the most vigorous vertical mixing. The current measurements from 1991 in the inner harbour, and those from the outer harbour in 1989, indicate that the mean circulation is estuarine, but the magnitude is uncertain (ASA Consulting Ltd., 1990, 1991).

Current variability

Currents can change rapidly with the most common variation being the tidal flows. Wind also can result in rapid changes to circulation by causing surface water to cross the harbour (Lawrence, 1989). This may stir up the bottom sediments through wave action particularly in the shallow nearshore areas.

Currents are weakest in Bedford Basin and average 3.5 cm/s. Deposition of fine-grained silt and clay should occur in this low-energy environment. The highest values, ranging from 15 cm/s to 35 cm/s, are found in The Narrows and are largely due to the tides. This is one area in the inner harbour that should not have fine-grained sediments and indeed fine-grained sediments are generally absent. From Sandwich Point to the harbour mouth at Chebucto Head, the time-varying flows have amplitudes of 5–15 cm/s, with the lowest values occurring off Herring Cove. These areas,

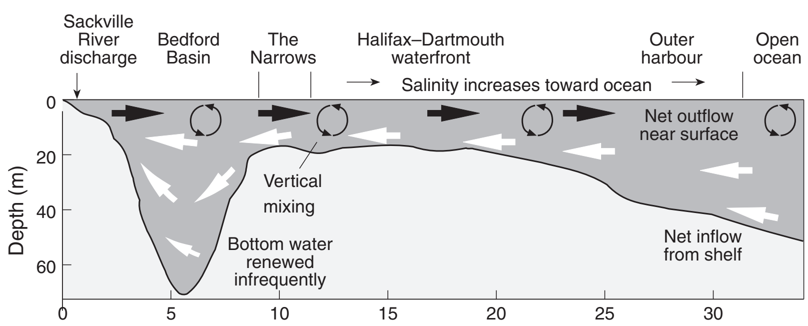


Figure 31. A simplified cross-sectional model of water circulation in Halifax Harbour from Bedford Basin to the harbour mouth. The dominant movement of water in the harbour is estuarine circulation with water in on the bottom and out on the top driven by input from the Sackville River and waste-water discharge. At times during large storms this circulation pattern has been observed to reverse, with flow in on the surface and out at the bottom (*modified from* Fournier (1990) Fader and Petrie (1991)).

though having lower current variability than The Narrows, are more exposed to ocean waves that can significantly affect sediment transport and deposition. The dominant deposition of fine-grained LaHave Clay in Northwest Arm, with the exception of the narrow area off Sir Sandford Fleming Park, attests to weaker flows.

Observations in the outer harbour during 1991, using an acoustic doppler current profiler, indicate that reversed estuarine flow can dominate for a time period of up to several weeks with flow in on the top and out on the bottom. This reversal resulted from the passage of large storms moving from southwest to northeast along the Scotian Shelf. Measurements made in the deep moat to the east of Georges Island indicate that currents do not always change direction with the ebb and flow of the tide, but can persist in the same direction over several tidal cycles.

Tides

The tides in Halifax Harbour are mesotidal. Mean and maximum ranges are 1.3 m and 2.1 m, respectively (MacLaren Plansearch Ltd., unpub. report, 1991). The semidiurnal M_2 (principal lunar semidiurnal constituent) component is the largest tidal constituent in the harbour producing 15–35 cm/s currents in The Narrows and 5–15 cm/s currents extending from Sandwich Point to Chebucto Head in the outer harbour.

Currents and particle transport

The inferences for sediment distribution and transport suggest a general tendency for fine-grained particles on or near the bottom to move towards the head of the harbour, that is, towards Bedford Basin. Sewage and run-off particles, which enter the harbour waters in the surface layer, would initially be carried seaward; however, as these particles floculate and sink, they would be, on average, caught up in the deeper inflow and move back up the harbour. Sewage-derived sediments, therefore, should be largely confined to the inner harbour and Bedford Basin, areas where the major sewage outfalls are located. This is indeed the case. There may be a tendency for greater sediment transport into the basin on the eastern side of The Narrows because of the stronger currents.

Sediment history and oceanography

From a study of sediment distributions, seabed characteristics, and features it is possible to determine the direction of net sediment transport; areas where sediments are being eroded or deposited; areas of temporary deposition; and areas of nondeposition. This information can be compared with the physical oceanographic data and used to fill in gaps where oceanographic measurements do not exist (Fader and Petrie, 1991). Inferences can also be made regarding paleo-oceanographic conditions in an early Holocene Halifax Harbour when sea level was lower.

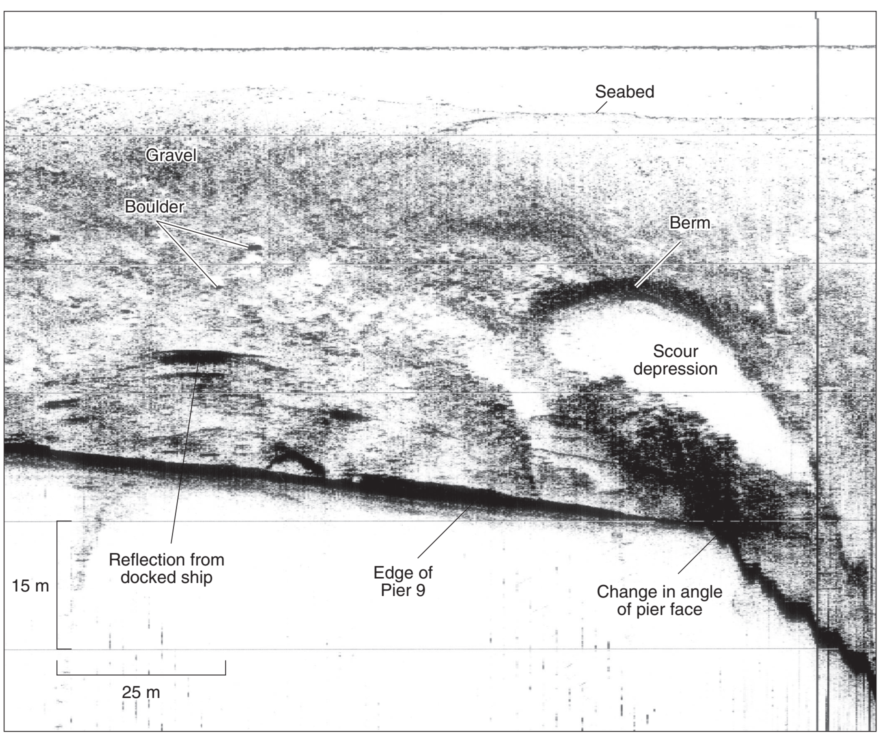


Figure 32. Sidescan sonogram from the west side of The Narrows showing a large scoured depression in coarse-grained sediment at the seabed near Pier 9. It formed as a result of erosion by strong currents along this side of the harbour at an abrupt change in the angle of the dock face. The sidescan image indicates that material from the scoured depression has been transported as bedload upharbour toward Bedford Basin, to the left on the image.

With the exception of the shallow transgressed coastal areas, the most extensive area of coarse-grained sediment occurs in The Narrows (Fig. 21), corresponding to the region with the highest current variability in the inner harbour. A similar area of coarse sediment occurs in a small zone of Northwest Arm adjacent to The Dingle in Sir Sandford Fleming Park. The seabed there consists of a gravel-floored depression flanked by thick mud to the northwest and southeast; fine-grained silt and clay are absent in the depression. As both of these areas occur at narrowing restrictions within the harbour, stronger currents are interpreted as the responsible mechanism for preventing sediment accumulation.

Sidescan sonograms from The Narrows were closely evaluated for sediment transport directional indicators in a high-current regime such as obstacle-induced scours and comet marks (boulder-induced scours), but few could be found. Most features such as gravel ridges and boulder fields are relict, resulting from high-energy beach conditions developed during the marine transgression. The features persist today with little modern modification. A large scour depression occurs along the Halifax side of The Narrows at the base of Pier 9 where the angle of the face of the dock changes abruptly (Fig. 32). The seabed is scoured in an oblong depression and the dock has been undermined over time, resulting in extensive repairs being required to the structure. Sediments from this scoured depression appear to be transported to the north. The seabed of The Narrows consists of coarse gravel with limited exposure of bedrock; silt- and clay-sized sediment are rare. Flow velocities are high enough to prevent deposition of most silt and clay sediments, indicating a bed shear stress of greater that 1 Pa. Currents exceeding this strength have been measured in The Narrows (Fournier, 1990).

Other areas of the harbour are also devoid of fine-grained sediments: the sill at the entrance to Bedford Bay, Ives Knoll, shallow coastal areas to a depth of 10 m along the Dartmouth shore and Bedford Basin, many bedrock shoals in the outer harbour, and large expanses of the outer harbour to the southeast of McNabs Island. Wave action may account for the absence of sediment in the shallow areas of the outer harbour and in other shallow coastal areas. In the inner harbour, to the north of McNabs Island, many small deposits of coarse sediment protrude through the muddy seabed. The present distribution of coarse seabed areas thus has arisen from a complex combination of relict glacial and postglacial processes, together with modern conditions of high energy. The geological assessment has identified these high-energy areas and provided an understanding of the link between the oceanographic conditions that formed and maintained them.

Much of the deeper seabed in Bedford Basin and Bedford Bay is covered with muddy sediments (Fig. 21). To the south of the hard gravel seabed of The Narrows, mud dominates the inner harbour and generally extends seaward to the Sandwich Point area. Mud also occurs at the seabed of Northwest Arm and Eastern Passage, again in agreement with conditions of weak current flow.

Seaward of Sandwich Point, however, the character of the seabed changes dramatically and resembles that of the inner Scotian Shelf with coarse sediment, bedrock outcrop, and little or no silt and clay deposition. In addition, gravel is well sorted and rounded to subrounded, suggesting that it was subjected to a high-energy environment. A variety of bed forms occur in sand, and ripples in gravel are common. Bedrock outcrops on the many shoals, and the seabed to the south of McNabs Island is characterized by vast expanses of exposed bedrock strewn with boulders. This is an area where wave action has a significant effect.

The morphology of the outer harbour is dominated by a large, deep, sand-floored channel that borders the western side of the outer harbour from Sandwich Point to beyond Chebucto Head. The northern limit of bed forms (megaripples) occurs in the deep 30 m channel off Sandwich Point in a field of sedimentary furrows. The sedimentary furrows suggest a zone of complex conditions where periodic deposition and erosion occurs. Large areas of megaripples lie to the south of Lichfield Shoal and continue farther out the harbour in the deep western channel. The area north of Lichfield Shoal is a silty sandy seabed without megaripples. This suggests that bottom current velocities are less in the area off Herring Cove. This area has also been identified as having the lowest current-energy environment in the outer harbour, which may result from topographic sheltering effects of bedrock-controlled Lichfield Shoal to the south.

Many of the bed forms in the outer harbour are usually generated under strong turbulent flow and their shape and distribution indicates bottom sediment transport up the harbour to the north, that is, in the direction of the mean current flow. In many areas, in shallow water adjacent to the sand megaripples, large areas of gravel ripples occur. These often flank the outcropping bedrock shoals between the bedrock and the sand megaripples. They are formed more or less in situ by oscillatory motions associated with large waves. The areas of gravel ripples and megaripples in the outer harbour indicate that fine-grained silt and clay sediments are not deposited in these areas. Silt- and clay-sized sediments discharged there by drainage systems and sewage outfalls are transported either farther offshore to the inner Scotian Shelf or up the harbour to the north.

A geochemical characterization of the sediments (Buckley and Hargrave, 1989) identified seabed contaminant distributions throughout the harbour that can be sourced to the many sewage outfalls. These can also be used to determine areas of nondeposition and/or erosion and transport pathways. The distributions suggest dispersion and settlement of material from the sewage discharge locations, situated along the shores of the harbour, in a northerly direction (upharbour) in agreement with directions of mean current flow. Anomalies of mercury concentrations suggest that material discharged from the Duffus Street and Tufts Cove areas is transported through The Narrows and deposited on the southeast side of Bedford Basin. In a similar fashion, the Pier A sewage outfalls can be traced up the harbour to a depositional area north of Georges Island.

In summary, both oceanographic and geological data are in agreement indicating that bottom currents dominantly move up the harbour to the north. The distribution of active bed forms in the outer harbour suggests that currents are strongest to the south of Lichfield Shoal. This has prevented the deposition of fine-grained silt and clay sediments. North of Lichfield Shoal, and adjacent to Herring Cove, an area of seabed with no bed forms in sandy sediments is consistent with oceanographic data, suggesting lower velocity bottom currents resulting from topographic sheltering by Lichfield Shoal. Coarse sediments in The Narrows are predicted from the oceanographic data and the geological information confirms this prediction, but the origin of the coarse-grained sediment was the marine transgression from the Holocene sea-level rise in the harbour and not from present conditions. Present conditions merely prevent further deposition of fine-grained sediments. In Northwest Arm adjacent to Sir Sandford Fleming Park, a similar lack of fine-grained sediments in a constricting channel suggests the presence of strong currents in an area where no current measurements have been made. The eastern part of the outer harbour to the south and southeast of McNabs Island is dominated by bedrock and rippled gravel at the seabed and indicates that significant wave energy reaches the seabed in water over 20 m deep. The presence of muddy sediments in the area north of Sandwich Point, in the inner harbour, Eastern Passage, and Northwest Arm reflects lower current velocities. Sediment geochemical anomalies indicate sediment transport upharbour even in these areas of lower current velocities.

BEDROCK GEOLOGY

Bedrock lithology, structure, and surface morphology control the location of sediment depositional zones in most areas of the harbour. Bedrock in the inner harbour is largely buried beneath thick surficial sediments, but outcrops at several areas in Bedford Basin and Northwest Arm. In contrast, it outcrops over 50% of the seabed in the eastern outer harbour. In southern Bedford Bay at Wellesley Rock, a series of prominent bedrock ridges forms a morphological trap for fine-grained surficial sediments from the Sackville River, confining most of the deposition to the area north of the bedrock sill at the juncture between Bedford Basin and Bedford Bay.

In the outer harbour, shallow and steep bedrock shoals affect the dissipation of wave and current energy. This controls depositional processes in adjacent deeper areas and the presence and location of active bed forms on the seabed. The slope map (Fig. 12) shows that the steepest slopes, up to 30°, are associated with bedrock exposure along the western flank of the outer harbour, at Bear Cove and Lichfield Shoals, and at unnamed bedrock outcrops east of Chebucto Head.

Seismostratigraphy

The Halifax Formation slate and Goldenville Formation quartzite are highly metamorphosed sediments, and together with the Devonian granite units appear as acoustic basement to the various seismic-reflection systems used throughout the study. Internal structures and stratigraphic characteristics cannot be assessed using these acoustic techniques. The seismic-reflection systems do, however, delineate bedrock surface morphology, and this information, in conjunction with data from adjacent on-shore areas and multibeam bathymetry, can be used to differentiate rock units as well as to understand processes that have affected the bedrock surface. This information can be used as a bedrock discriminating criteria, as varying rock types have responded in different ways to fluvial, glacial, and marine erosional processes.

The Goldenville Formation (Fig. 33, 34a) appears thickly bedded with widely spaced ridges on sidescan sonograms and multibeam bathymetry (Fig. 9) in contrast to thin bedding and closely spaced ridges of the Halifax Formation (Fig. 9, 34b, 35). Folds are tight in the Halifax Formation compared with the Goldenville Formation. The Halifax Formation generally displays less relief across its surface than the Goldenville Formation, whereas faults and major fractures cut both of these units. Glacial fluting also occurs on both bedrock units in fields of broad linear depressions oriented northwest-southeast on Jonquière Bank in Bedford Basin, on Neverfail Shoal in the outer harbour (Fig. 6), and beyond the mouth of the harbour in several areas on the inner Scotian Shelf (Fig. 9, 22).

On sidescan sonograms and multibeam bathymetry the Devonian granite displays a contrasting morphological expression to the Meguma Group (Fig. 9, 36). It is characterized by a massive hummocky terrain with joints and irregular channels and small isolated basins. Submersible observations of the granite batholith off Chebucto Head revealed terraced and blocky surfaces with dense biogenic growth (Fig. 34c). The contact of the Meguma Group with the eastern margin of the granite, which coincides with the location of the ancient Sackville River, is irregular and rough. This suggests that the contact is not fault controlled.

Bedrock distribution

Figures 24 and 27 illustrate the bedrock geology of Halifax Harbour and adjacent areas. The area of Bedford Basin including Bedford Bay and the surrounding adjacent land is underlain by Meguma Group Goldenville Formation. The Birch Cove Anticline runs southwest-northeast through the centre of the basin and coincides with the deepest depth, 71 m. Bedrock outcrops at the juncture between Bedford Basin and Bedford Bay at the Chicken Rocks, Western Ledges, and Wellesley Rocks and is characterized by continuous massive beds on sidescan sonograms (Fig. 33). Bedrock also outcrops at the seabed of the eastern side of Bedford Bay, extending from Spruce Island to Partridge Point and on the western side in a few small, isolated areas northeast of Mill Cove (Fig. 21). It also outcrops in Roach Cove and Wrights Cove on the east side of Bedford Basin. The sidescan-sonar data from the bedrock sill of Bedford Bay show no evidence of structural offset or the presence of the Mill Cove Fault (Fig. 25) as suggested by Cameron (1949). In fact, the sidescan-sonar and multibeam data suggest that the east-trending bedrock sill separating Bedford Basin from Bedford Bay is continuous.

The contact between the Goldenville Formation quartzite and the Halifax Formation slate occurs in the northern area of The Narrows near its juncture with Bedford Basin (Fig. 24). The Halifax Formation continues throughout The Narrows and underlies most of the harbour to the south (Fig. 24, 27). Parallel, southwest-trending ridges are common (Fig. 37). The bedrock surface morphology is mimicked through overlying till and gravel to the seabed. Despite the ridged morphology of The Narrows, bedrock outcrops in only a few areas. In an area adjacent to Pier 9 the seabed has been blasted and dredged to remove sediments and a shallow bedrock obstruction to ship navigation (Fig. 13).

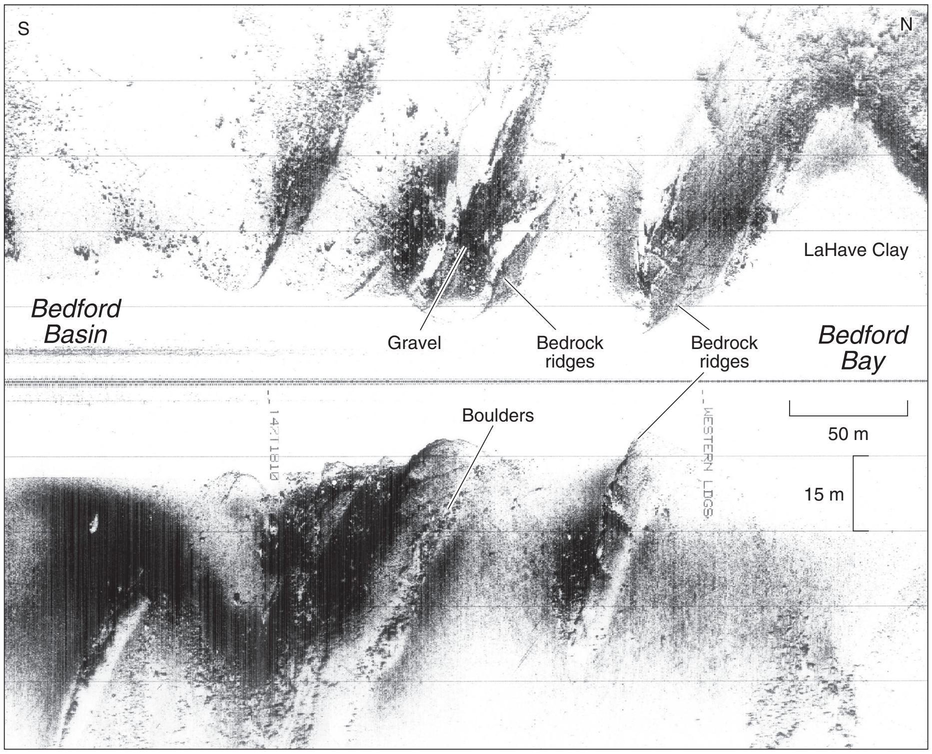
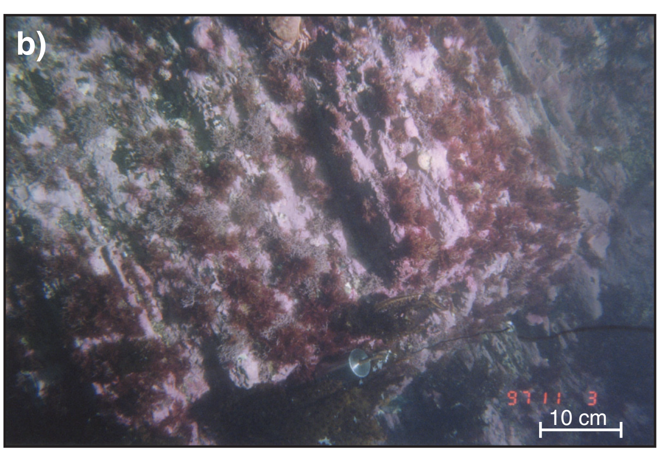
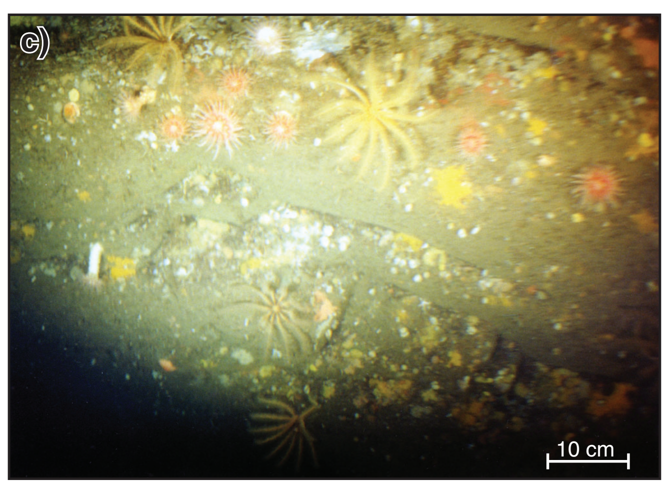


Figure 33. A sidescan sonogram of the seabed at the juncture between Bedford Bay and Bedford Basin. Bedrock ridges protrude from muddy sediment; the bedrock is massive, thickly bedded Goldenville Formation quartzite that appears to be continuous, separating the bay and the basin. LaHave Clay onlaps the bedrock outcrop in places and the bedrock is overlain with gravel and boulders. A small breach occurs in a bedrock ridge that was likely occupied by a waterfall of the ancestral Sackville River when sea level was lower. *See* Figure 18 for multibeam-bathymetric interpretation.

Figure 34. Bottom photographs of: **a)** Goldenville Formation quartzite at the Chicken Rocks in Bedford Bay. Photograph by R.O. Miller. GSC 2006-201. **b)** Halifax Formation slate on Neverfail Shoal, outer harbour east of Halibut Bay. Photograph by R.O. Miller. GSC 2006-202. **c)** Granite at the seabed south of Chebucto Head along the western flank of the 'ancient Sackville River' collected from the submersible SDL-1. Photograph by G.B.J. Fader. GSC 2006-203. Both the slate and quartzite are covered with purple concretionary algae, lithothamnion. Sea urchins are also common and are 5 cm in diameter.





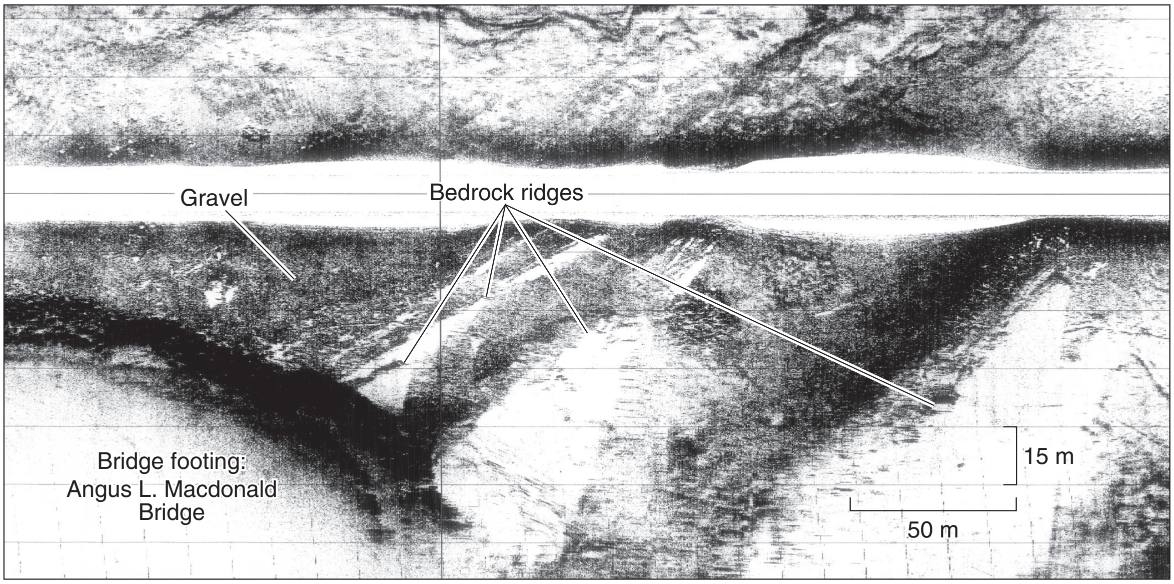


Figure 35. A sidescan sonogram from the inner harbour near the Dartmouth shore over Halifax Formation slate bedrock ridges. The outcrop of the slate consists of a series of ridges that have been smoothed by glacial erosion. One of the bedrock ridges forms the foundation for the eastern footing of the main tower of the Angus L. Macdonald Bridge and can be seen protruding from beneath the bridge footing.

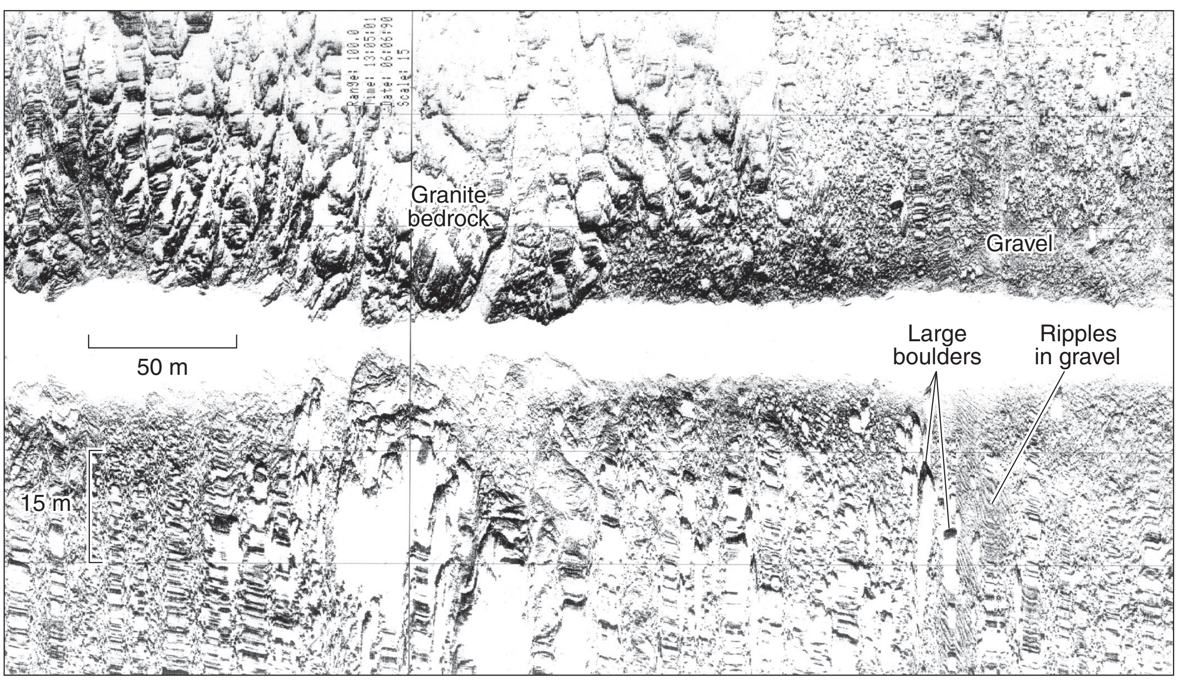


Figure 36. A sidescan sonogram across granite bedrock outcrop and gravel in the western area of the outer harbour. Unlike the quartzite and slate of the inner harbour, the granite displays a hummocky, nonlinear, rough terrain with joints, fractures, and terraces. It has a similar appearance on multibeam bathymetry. The granite outcrop is flanked with large boulders and ripples in gravel. Some of the boulders are 5 m in diameter.

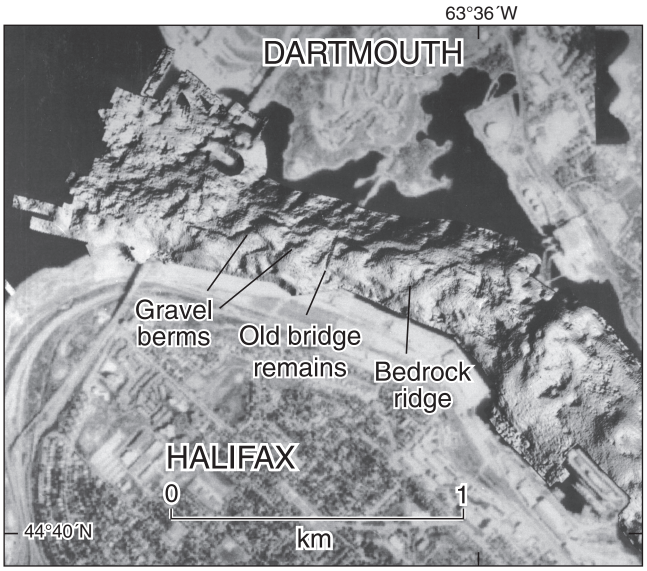


Figure 37. Detailed multibeam-bathymetric image from The Narrows showing the roughness of the seabed and the location of bedrock ridges mimicked through the overlying till. The bedrock ridges are subparallel and relict gravel-beach berms are evident (*see* Fig. 13).

Four bedrock outcropping ridges occur near the Dartmouth shoreline, southeast of the Dartmouth footing of the Angus L. Macdonald Bridge (Fig. 35). The bridge footing is located on the most northern of the exposed ridges (Fig. 6, 13).

Bedrock does not outcrop at the seabed throughout most other areas of the inner harbour. It is buried by thick till, glaciomarine, lacustrine, estuarine, and LaHave Clay sediments. Gas charging in the LaHave Clay prevents the penetration of acoustic energy from the seismic-reflection systems so little is known about the bedrock and its surface in some of these areas. In the area adjacent to Dartmouth Cove and Eastern Passage, the Goldenville Formation occurs beneath the harbour as plunging anticlines, known as the Lawrencetown and Eastern Passage anticlines (Fig. 24). The width of the inner harbour broadens at the location of the Lawrencetown Anticline and like Bedford Basin, the widening in this part of the inner harbour south of The Narrows is interpreted to result from greater differential glacial erosion of the Goldenville Formation versus the Halifax Formation.

Bedrock does not outcrop in Eastern Passage and the extensive presence of methane gas in the overlying sediments prevents acoustic imaging of the bedrdock. Bedrock is interpreted to outcrop in selected areas of Northwest Arm, especially on the east flanks of the main channel. These flanks are steep sided (Fig. 38), parallel, and form a sinuous channel.

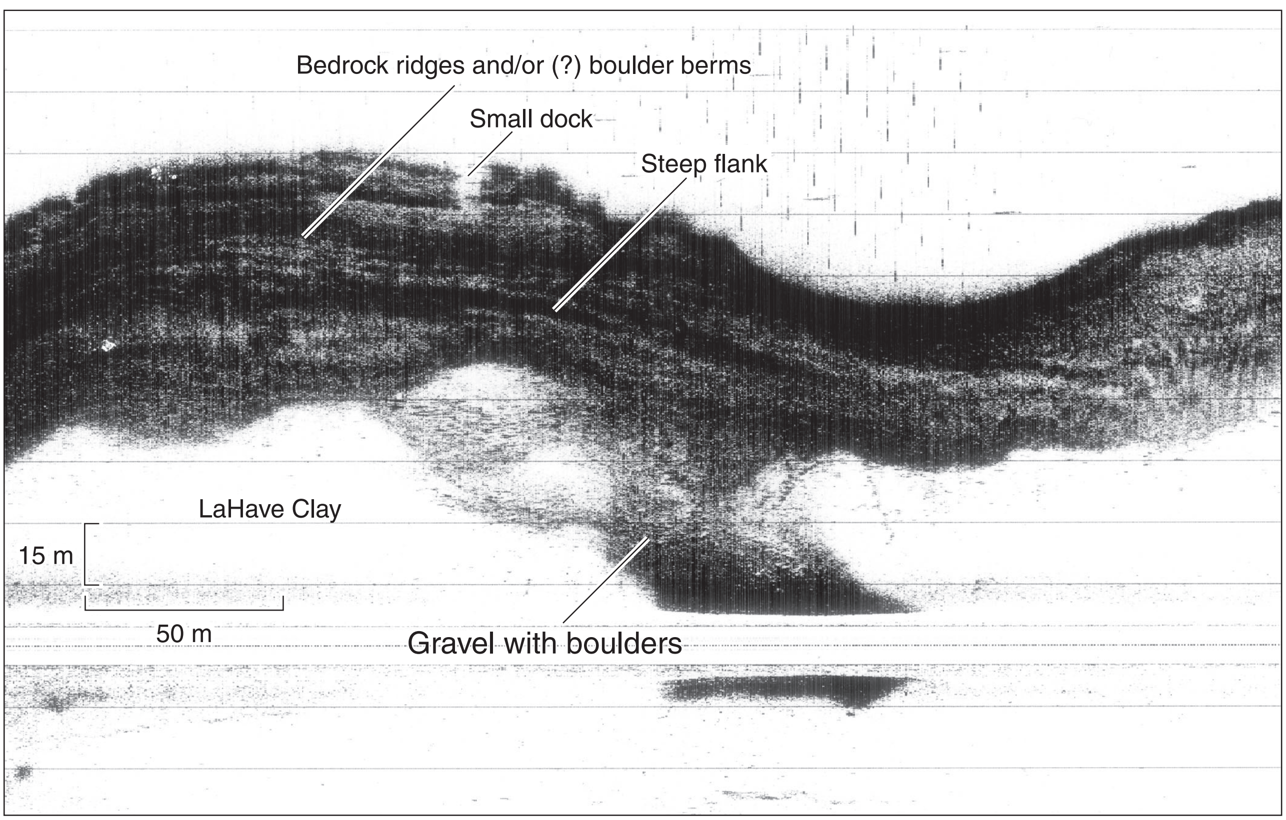


Figure 38. Sidescan sonogram from Northwest Arm showing the sinuous morphology of the highly reflective flank of the channel with continuous linear elements suggesting outcropping bedrock. They likely represent bedrock terraces rather than bedrock structure and were formed by glacial erosion.

Sidescan sonograms (Fig. 38) show parallel to subparallel ridges along the channel flanks that may represent outcropping bedrock or the presence of boulder berms formed during lower sea-level stands.

Bedrock is extensive at the seabed south of peninsular Halifax and outcrops on Pleasant Shoal, Mars Rock, Lichfield Shoal, Bear Cove Shoal, Neverfail Shoal, Portuguese Shoal, a series of deep shoals south of Portuguese Shoal, and in the nearshore extending from Sandwich Point to Chebucto Head (Fig. 6, 9). It is not clear if bedrock outcrops on Middle Ground southeast of Pleasant Shoal. Many other small and unnamed shoals in the outer harbour are outcropping bedrock partially covered with coarse gravel and boulders. Despite displaying a hummocky morphology of discontinuous ridges unlike areas of slate and quartzite with more continuous ridges, Mars Rock consists of a hornfels facies of the Halifax Formation slate (T. Kenchington, pers. comm., 2002). Lichfield Shoal, southeast of Herring Cove, is a large, high-relief ridge with smaller parallel ridges to the north and south (Fig. 6). Bedrock outcrop is extensive on Lichfield Shoal.

It is difficult to differentiate the Goldenville Formation from the Halifax Formation across the shoals of the outer harbour. Most bedrock surfaces are highly eroded and covered with macrophytes and lithothamnia encrustation. Total-magnetic-field signatures are weak and nonlinear south of Lichfield Shoal (Fig. 26), suggesting Goldenville Formation quartzite. Loncarevic et al. (1994) indicated that the outer harbour was underlain dominantly by the Halifax Formation; however, because of the weak magnetic signatures and lack of sample data, the present authors characterize the bedrock of the outer harbour as undifferentiated Meguma Group.

Borehole results

Boreholes drilled for the Halifax Harbour Solutions Project to evaluate the potential for bedrock tunnelling penetrated bedrock in the inner harbour and provided information on bedrock weathering, structure, and lithology. Borehole 3 (Fig. 39) from the central area of The Narrows penetrated 12 m of bedrock before termination. The upper 6 m was weathered, severely fractured, dark grey slate with interbedded metasiltstone. Sulphide mineralization was common. Three joint sets with dips of 80° to 90° occurred with well developed cleavage. The joints appeared smooth, planar, and un- weathered, and bedding was 45° with slightly irregular, rough, and weathered surfaces. At 6 m bedrock depth, the rock was more massive.

In the area between Ives Point and southern peninsular Halifax, severely fractured dark grey slate was encountered near the seabed beneath a thin 0.2 m layer of organic silt in borehole 2 (Fig. 40). At 5 m below the seabed the rock becomes very sound and is a dark grey slate with interbedded metasiltstone and common sulphide mineralization. The joint surfaces are unweathered at this depth. Below 7 m the rock becomes more massive to the bottom of the borehole, which terminated at 12.8 m below seabed.

Borehole 4 (Fig. 41) at the entrance to Eastern Passage encountered bedrock at a depth of 30.5 m. The rock consisted of severely fractured dark grey to grey slate with interbedded metasiltstone and common sulphide mineralization. Joint surfaces were frequently slickensided. Seven metres of bedrock were penetrated in this borehole. Nearby, borehole 1 (Fig. 42) encountered bedrock at a depth of 27.7 m below the seabed. It consisted of dark grey to grey, fractured slate with common interbedded metasiltstone and abundant sulphide mineralization. The rock was severely fractured at the bottom of the borehole at a depth of 32.7 m below seabed.

Boreholes (DF-1, DF-2, and DF-8) (Fig. 43, 44, 45) were collected at the site proposed by the Halifax Harbour Cleanup Incorported for a waste-water diffuser west of Ives Knoll. They sampled very severely to severely fractured slate between 3.5 m and 4.3 m below the seabed with beds dipping 45°. Only one borehole (1005) of a suite of boreholes collected by Department of National Defence to establish a degaussing range west of MacNabs Island adjacent to Middle Ground (Fig. 5) penetrated bedrock and recovered severely fractured grey slate at a depth of 16 m below seabed. All of these boreholes are interpreted to have sampled the Halifax Formation and confirm the bedrock distribution in the inner harbour extending from The Narrows to Maughers Beach. They are also in general agreement that the Halifax Formation is weathered to a depth of 6 m below the bedrock surface.

A suite of cores was collected in 1972, on behalf of the National Harbours Board, in Fairview Cove of Bedford Basin, near Navy Island, and Crosby Island in the area of juncture between Bedford Bay and Bedford Basin. They were intended to assess the seabed for possible location of future marine container terminal facilities. All of these boreholes encountered badly fractured quartzite at the base of the surficial succession and confirmed the dominant presence of the Goldenville Formation beneath Bedford Basin.

Faulting

Cameron (1949) assessed bedrock faulting in the vicinity of Halifax, largely based on an interpretation of aerial photographs. He proposed a large number of faults both in the granite and the Meguma Group. Many of these faults were projected beneath the harbour (Fig. 25) and this has influenced subsequent workers (Stanley, 1968; Gregory, 1970) to consider bedrock faulting as the main control on the shape, orientation, and actual location of Halifax Harbour.

The major fault interpreted to occur beneath the harbour (Cameron, 1949) is the Mill Cove Fault, which cuts across Bedford Bay and extends beneath Bedford Basin, The Narrows, and the inner harbour through Eastern Passage to Devils Island at the harbour mouth. This fault is further interpreted to connect with the Kearney Lake Fault which extends

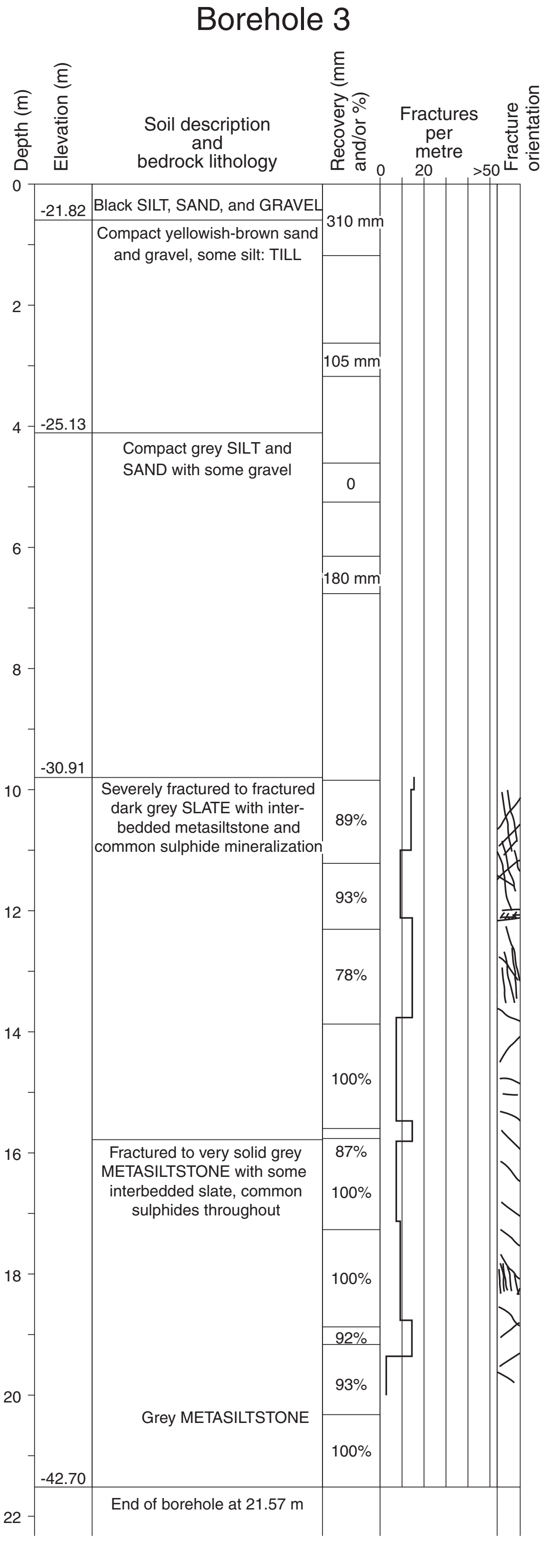


Figure 39. Borehole 3 log from The Narrows.

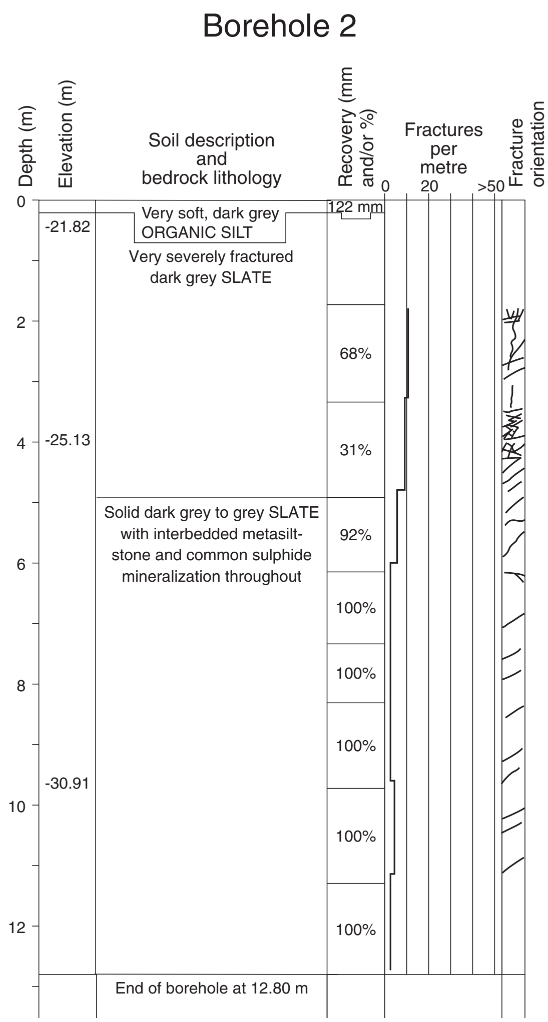


Figure 40. Borehole 2 log in an area between Ives Point and Halifax.

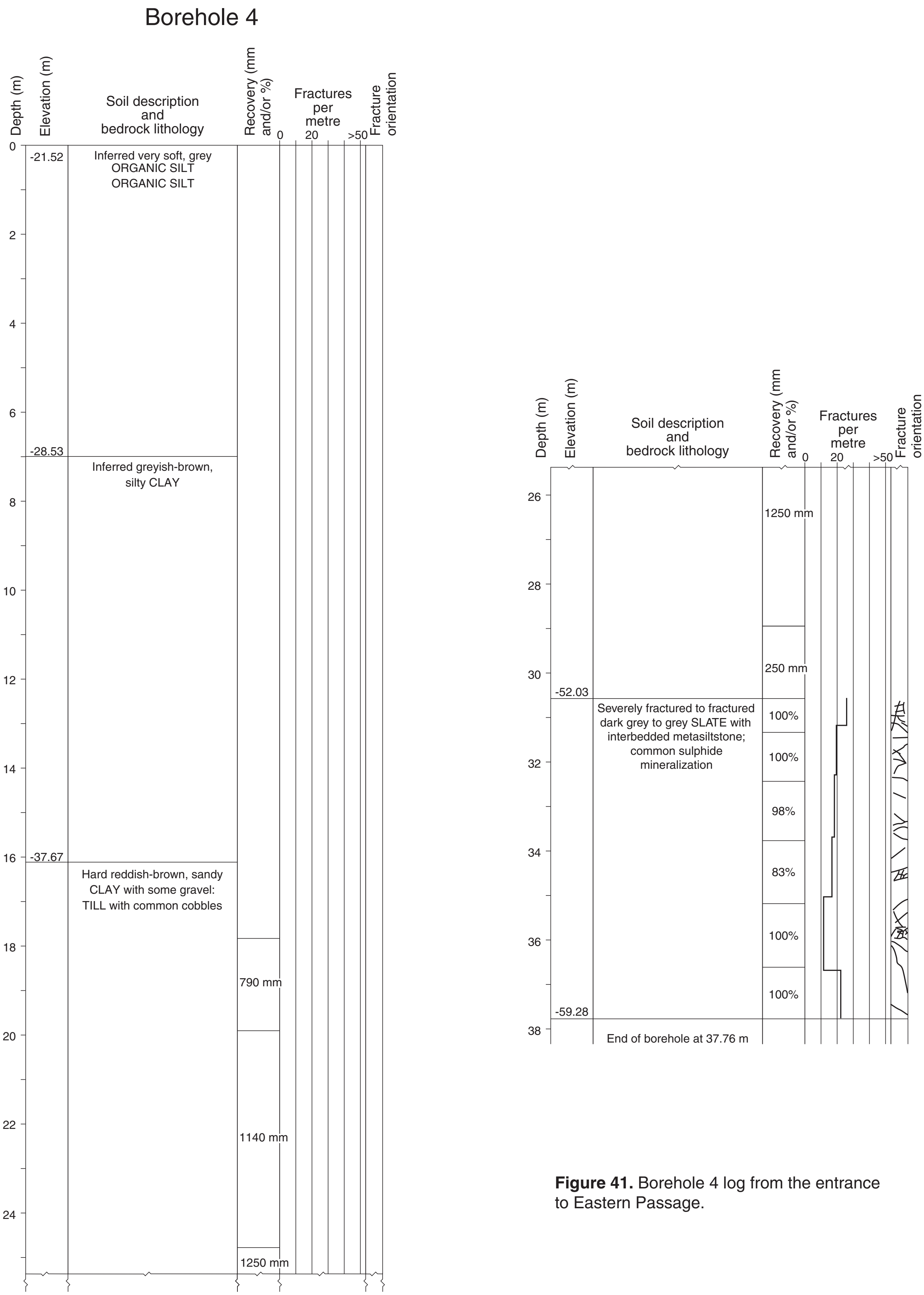


Figure 41. Borehole 4 log from the entrance to Eastern Passage.

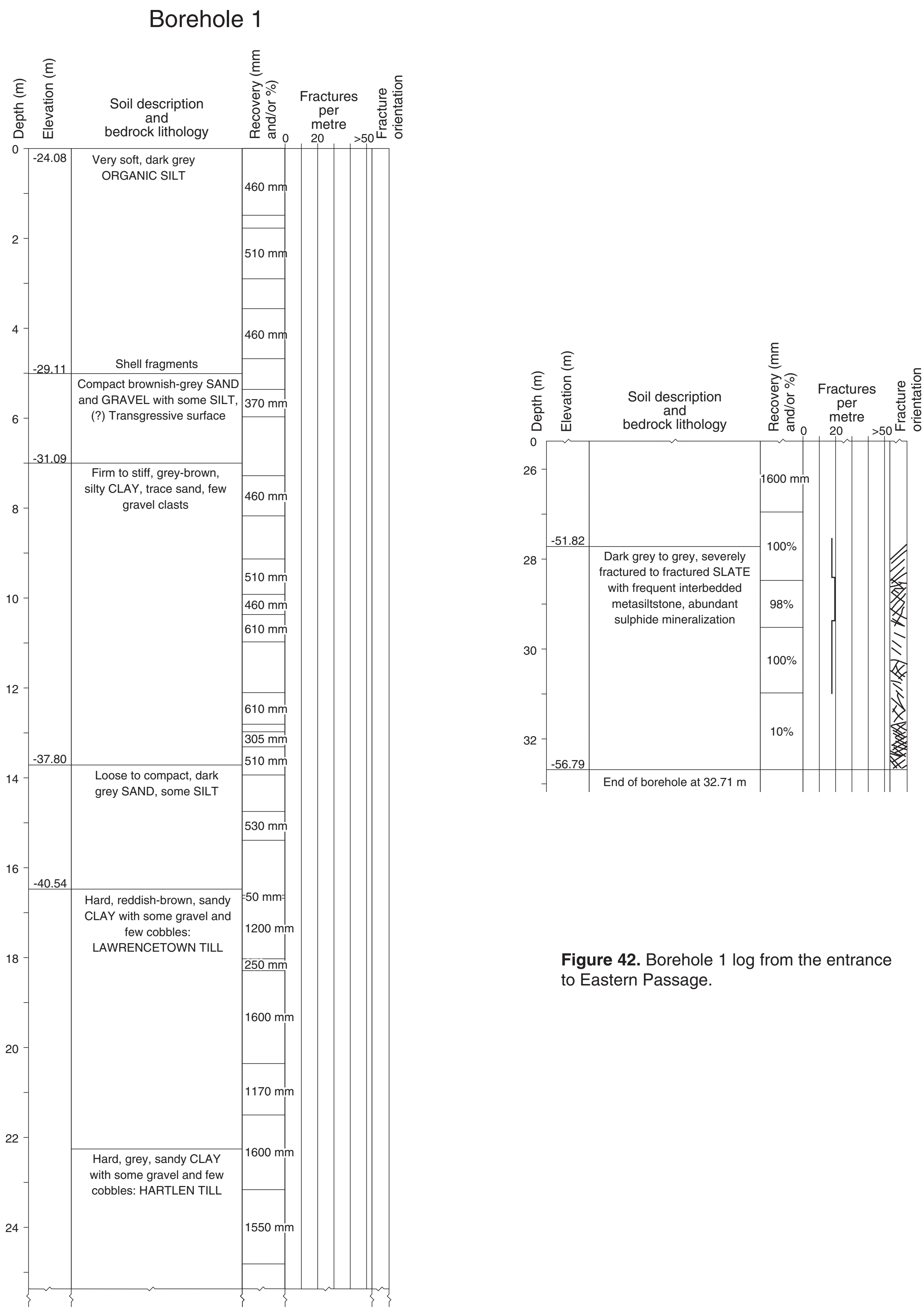


Figure 42. Borehole 1 log from the entrance to Eastern Passage.

beneath the Halifax peninsula and joins with the Mill Cove Fault in the vicinity of Georges Island. A fault Cameron (1949) termed the Arm Fault, is interpreted to follow the axis of Northwest Arm. The largest fault of the area is the Chain Lakes–Sheehan Cove Fault that extends from Maple Lake in the north to Sheenan Cove in the southeast, where it reaches the coast and is interpreted to continue parallel and near the shoreline to Chebucto Head. It has a confirmed length of 32 km with possible extension to over 48 km. These faults are interpreted to be part of a larger system of northwest-southeast faults that occur in Meguma Group rocks east of Halifax.

M.R. Gregory (M.R. Gregory, unpublished report 3-72, Nova Scotia Research Foundation, 1972) conducted a regional survey of the harbour with seismic-reflection systems and a sediment-sampling program to study the benthonic foraminifera distribution. He reiterated the earlier work on fault control to explain the trend of the harbour, although he presented no bedrock evidence on which to base such an interpretation. Low-resolution seismic-reflection profiles resulted in the misinterpretation of gas-charged sediments as bedrock.

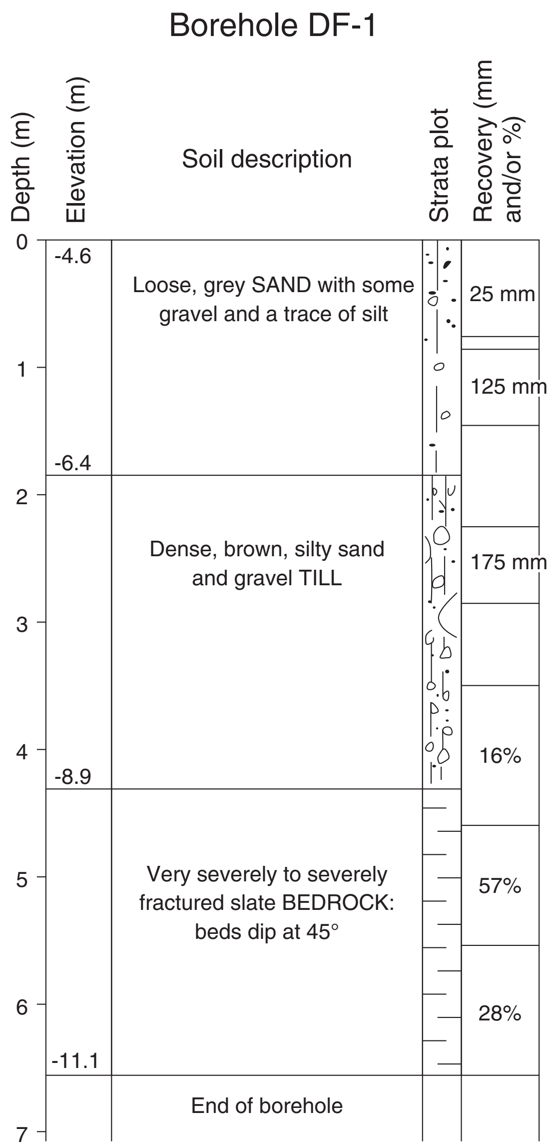


Figure 43. Borehole DF-1 log at a proposed diffuser location in Halifax Harbour west of McNabs Island.

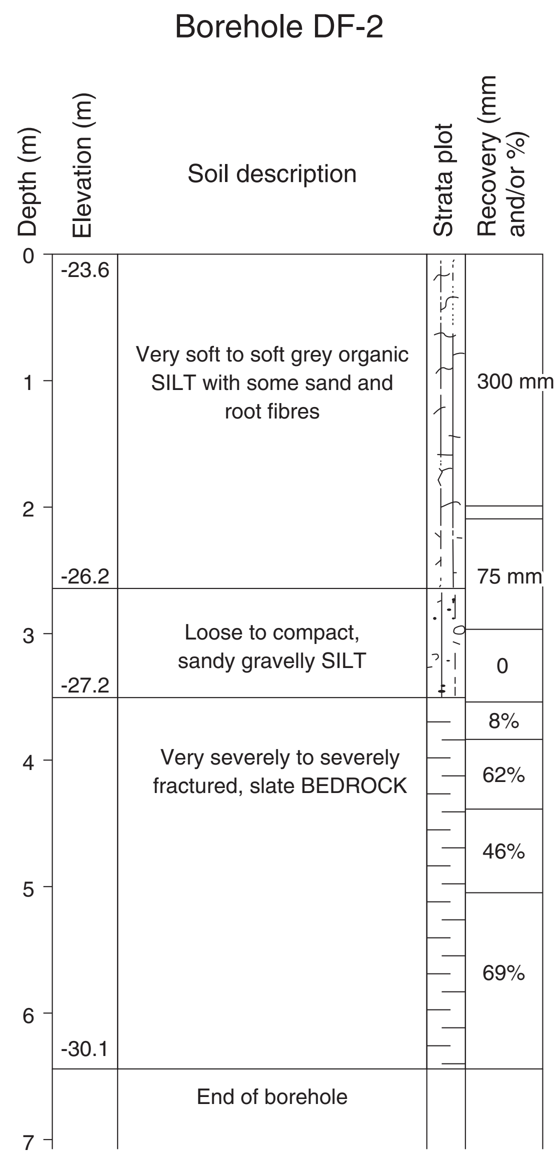


Figure 44. Borehole DF-2 log at a proposed diffuser location in Halifax Harbour west of McNabs Island.

Near Hammonds Plains, northwest of Halifax, Fairbault (1908) mapped peculiar structures termed the 'transverse anticline' and the 'transverse syncline'. These structures are parallel to the granite-metasedimentary contact and are perpendicular to the regional fold structures of Meguma Group rocks. MacDonald and Horne (1987) interpreted these structures to result from granite emplacement and deformation of the country rocks. These transverse structures occur in the same locations as the 'Kearney Lake Faults' of Cameron (1949) (Fig. 25). If the transverse structures relate to the contact with the granite, then it is highly unlikely that they continue beneath the harbour to the east, away from the contact as earlier interpreted. The granitic rocks of the area are normally massive and nonfoliated. Local faults are indicative of brittle shear. One major fault, termed the Herring Cove Fault, extends from Fraser Lake to Sheehan Cove, outer Halifax Harbour, where cataclastic rocks of the fault zone occur on the shoreline. This fault is the Sheehan Cove Fault of Cameron (1949). The orientation of joints, dykes, quartz veins, and greisen bodies have a very strong northwest orientation throughout the area.

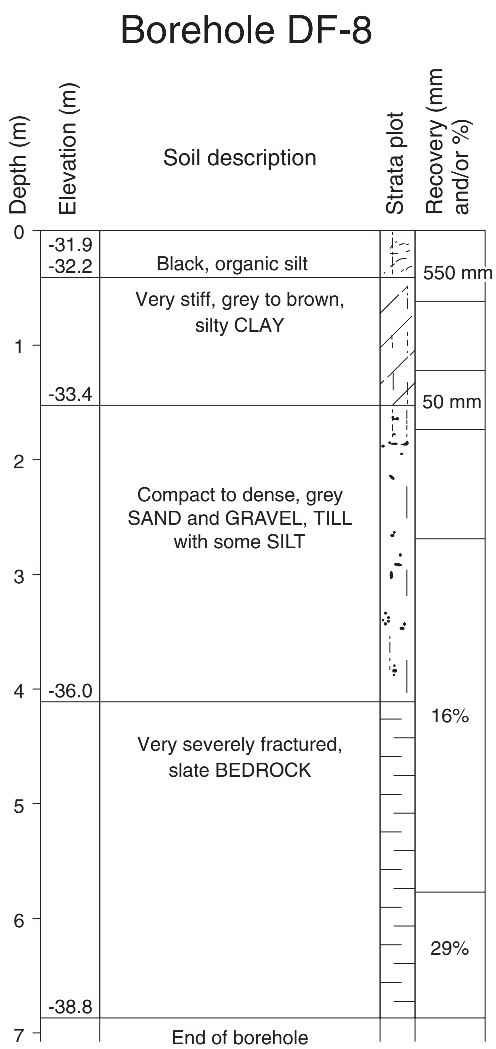


Figure 45. Borehole DF-8 log at a proposed diffuser location in Halifax Harbour west of McNabs Island.

In all of the bedrock structural assessments on both sides of the harbour, the major anticlinal and synclinal features are clearly identified and can be extrapolated without offset beneath the harbour. Fairbault (1908) identified six structural elements extending from Bedford Bay to Sandwich Point. These include the Bedford Syncline of Bedford Bay, the Birch Cove Anticline beneath the central deep area of Bedford Basin, the Dartmouth Syncline and the Lawrencetown Anticline beneath central Halifax, the Point Pleasant Syncline north of McNabs Island, and the Eastern Passage Anticline beneath McNabs Island (Fig. 24). Faults have not been identified beneath the harbour, nor have offsets of structures from adjacent sides. This is in contrast to the interpretation of Cameron (1949) who suggested that the presence of major faults beneath the harbour would be expected to result in structural offset as is the case along many of the faults farther to the east in Nova Scotia such as the Porters Lake Fault, the Sheet Harbour Fault, and the Country Harbour Fault. Aeromagnetic data from Halifax Harbour collected in 1958, by the Department of Energy, Mines and Resources, and magnetic compilations by Courtney et al. (1993) (Fig. 26) show a series of anomalies associated with the Halifax Formation slate trending southwest across the harbour. None of the anomalies appears to be broken or offset by northwest-trending lineaments that could be interpreted as faults. The sidescan sonograms and the multibeam bathymetry from Halifax Harbour and beyond the entrance to the harbour on the inner Scotian Shelf were carefully examined to determine if structural offsets associated with faulting were present. No offsets could be found; however, slickensides in borehole 4 at the entrance to Eastern Passage suggest faulting in that area.

SURFICIAL GEOLOGY

Introduction

Some of the surficial sediment units are buried and not exposed at the seabed. These units have been identified from cores and their distribution has been extrapolated using seismic-reflection data. In some areas, samples could not be collected because of depth of burial, thickness, and hardness of overlying sediments, or the presence of debris at the seabed. In these areas interpretation is based solely on comparative seismostratigraphy with nearby similar-sampled sections. Table 1 is a Table of Formations for the bedrock and surficial sediments in the harbour. The cross-section on Figure 21 illustrates stratigraphic relationships among the surficial sediments overlying bedrock.

Table 1. Table of formations for the bedrock and surficial sediments in Halifax Harbour.

Table of Formations			
Quaternary	Holocene	Anthropogenic layer	Dredge spoil, fill, shipwrecks, cables, debris, raw sewage
		LaHave Clay	Silty to sandy clay, sandy to clayey silt Some dropstones, shells
		Sable Island Sand and Gravel	Well sorted sand and gravel with boulders Generally a veneer deposit Can attain thicknesses over 5 m Inner harbour facies is angular gravel veneer with mud Gravel consists of slate, metasandstone, granite *Lithothamnia* cover on clasts
		Estuarine sediments	Peat, mud, sand, organic silt layers
	Wisconsinan	Glaciolacustrine, lacustrine, possible glaciomarine	Muddy sediment, sandy layers, some gravel, laminated, Grey to brown
		Scotian Shelf Drift	Beaver River Till Stony till plain with granite, metasandstone, and slate till facies
			Lawrencetown Till Sandy facies, reddish-brown, sandy, muddy till in drumlins
			Hartlen Till Grey, silty, sandy compact till, generally in drumlin cores
	Sangomanian	Interglacial beds	Peat and clay
	(?) Tertiary	Bridgewater Conglomerate	Indurated, iron-cemented diamicton
	Devonian	South Mountain Batholith	Granitoid rocks
	Cambrian-Ordovician	Meguma Group Halifax Formation Goldenville Formation	 Slate Metasandstone

Surficial formations

The authors have classified the surficial sediments of Halifax Harbour using the formational stratigraphic framework of King (1970) and King and Fader (1986) that has been developed for the entire Scotian Shelf (Williams et al., 1985). Several new units are proposed and others are modified to reflect unique conditions of the harbour coastal setting. In particular, problems arise regarding the distinction between the Scotian Shelf Drift and the Sable Island Sand and Gravel. The dominant sediment on the adjacent inner Scotian Shelf, extending from the present shoreline beyond the headlands to approximately 70 m water depth is the Sable Island Sand and Gravel. This unit developed as a result of postglacial marine transgression of pre-existing till and glaciomarine sediments through erosion, sorting, and deposition in the high-energy beach zone. These deposits can range from thin veneers of sand and gravel to thicknesses of up to 20 m. Unmodified till deposits on the shelf generally are exposed only in depths greater than 110 m water depth on the flanks and bottoms of shelf basins. Outer Halifax Harbour contains well sorted and thick Sable Island Sand and Gravel similar to areas on the inner Scotian Shelf and is a continuation from the inner shelf.

In inner Halifax Harbour to the north of McNabs Island, areas of till have also been transgressed, but the transgression only slightly modified the till surface. The clasts remain angular and a fine-grained matrix of silt and clay can be present. Gravel-lag surfaces are thin and discontinuous. This lesser degree of reworking has resulted from low-energy conditions during the Holocene transgression within the harbour that protected the till from significant reworking as occurs on the adjacent Scotian Shelf. Samples display characteristics of till found in deeper water that have not been transgressed and modified. The modification of the till in the harbour also varies considerably. In some areas, particularly on the eastern side of the harbour and in The Narrows, the till surface has been highly modified and thick, depositional transgressive bed forms such as gravel beach ridges and megaripples have formed. It is difficult to separate and map the varying degrees of till modification based on acoustic and sample information. For this reason and stratigraphic consistency, the authors have mapped all modified till areas of seabed north of McNabs Island as a nearshore, muddy, angular gravel facies of the Sable Island Sand and Gravel.

During the summer months when oceanographic energy conditions are at their lowest and biological productivity is high, fine-grained, mostly organic material sometimes is deposited as thin, discontinuous material over coarser gravel surfaces including boulders in the nearshore and shallow areas. These are only temporary deposits that become mobilized during higher energy conditions in the spring and winter. These thin sediment coatings are difficult to sample and are therefore not reflected in the grain-size analysis of seabed samples, although they have been observed on seabed photographs, underwater ROV video, and during submersible operations.

The emphasis of this study was to characterize the regional nature of sediment distribution and seabed processes throughout the harbour using modern geological and geophysical techniques. The approximately 300 samples previously collected for geochemical research on seabed sediments (Fig. 5) were initially used for ground truthing the acoustic data; however, certain shortcomings existed with the early sample database that required a re-evaluation and additional sampling. For example, for some samples only the fine-grained, sand-silt-clay matrix was subsampled for analyses and the gravel fraction was not included. Very small subsamples were taken that were not representative of the seabed sediment texture in areas of coarse gravelly material. Early maps of sediment texture were also contoured on a statistical basis without the advantage of acoustical backscatter information for correlation and extrapolation (Buckley and Hargrave, 1989). Some of these shortcomings were later corrected and new maps of texture and geochemical anomalies were recontoured (Winters et al., 1991).

For this study, maps of surficial sediment units based on acoustic backscatter and seismostratigraphy were prepared. These were integrated with the existing sample database and additional sample locations were chosen to obtain data on deposits not sampled, unique anomalies, and in areas where acoustic and existing sample data were in disagreement. Most of these problems occurred over hard, coarse seabed in the inner harbour.

Previous research on sediment distributions

Earlier maps of the distribution of sediments at the seabed of Halifax Harbour were largely based on analysis of surficial grab samples, the locations of which were chosen on a grid basis (Gregory, 1970; M.R. Gregory, unpublished report 3-72, Nova Scotia Research Foundation, 1972). The majority of samples collected by Gregory (1970) were in the outer harbour adjacent to McNabs Island and beyond. These samples, together with echosounder and sparker seismic-reflection profiles were interpreted to produce a generalized map of the distribution of sediments (Gregory, 1970). Because of the low resolution of the sparker system, details of the subsurface stratigraphy were not resolved.

Geomarine Associates Ltd. (1975), on contract to the Nova Scotia Department of Development, conducted a more comprehensive seismic-reflection and sidescan-sonar survey of Halifax Harbour to assess the aggregate potential. Again, lower resolution sparker systems were deployed and the first assessment of the seabed with sidescan sonar was undertaken. These early sidescan-sonar systems were in developmental stages and the resolution was low compared to modern systems, however, the images clearly differentiated gravel bottoms from mud, identified large anchor marks, and provided some information on outcropping bedrock in the outer harbour.

The most recent sample surveys conducted by Prouse and Hargrave (1987) and the OceanChem Group Ltd. (1988) were designed in a grid pattern without the aid of geophysical and sidescan-sonar data to assist in the selection of sample sites. These samples have been used in the present study to define regional textural characteristics. An additional 50 seabed samples were collected during the cruises of the C.C.G.S. *Navicula* and C.C.G.S. *Frederick G. Creed* for the present study. The locations of these samples were selected on the basis of the acoustic characteristics of the seismic-reflection and sidescan-sonar data and the samples were precisely located with reference to this information. In this way small targets and varied acoustic signatures were accurately sampled.

The classification system for sediment texture used in this report is the Wentworth Scale (Wentworth, 1922) in which the sediments are classified according to relative amounts of gravel, sand, silt, and clay. The fine-grained sediments of silt and clay contain minor trace elements and more organic matter than do coarser sand and gravel sediments. These organically rich sediments also contain higher concentrations of most metals. The first regional map of sediment texture for the inner harbour, based only on sample data, was published in 1989 (Buckley et al., 1989). It presented the distribution of mud (silt and clay). This interpretation did not have the advantage of sidescan-sonar or seismic-reflection data to measure the thickness of the mud or to interpolate distributions between sample locations. For many samples, only the upper 2 cm were analyzed. The sidescan-sonar data collected during the present study indicate that the mud covers less area of the seabed than indicated by an assessment based on samples alone.

Scotian Shelf Drift

Seismostratigraphy

The till (Scotian Shelf Drift) is characterized internally by incoherent reflections on seismic-reflection profiles (Fig. 7). In several areas in the outer harbour coherent reflections appear within the till that likely represent interfaces between multiple till sequences, or represent differing till properties that manifest as internal acoustic volume-scattering contrasts (Fig. 46). Multiple tills may be separated by gravel layers or the interface may represent differences in acoustic impedance between tills of differing lithology, geotechnical strength, or textural composition. The till in The Narrows differs from that throughout the remainder of the harbour in that it is very difficult to acoustically penetrate. This may result from the hardness and roughness of the seabed of The Narrows that consists of gravel with scattered boulders and thick, relict, gravel beach ridges. The till in The Narrows could also be more consolidated.

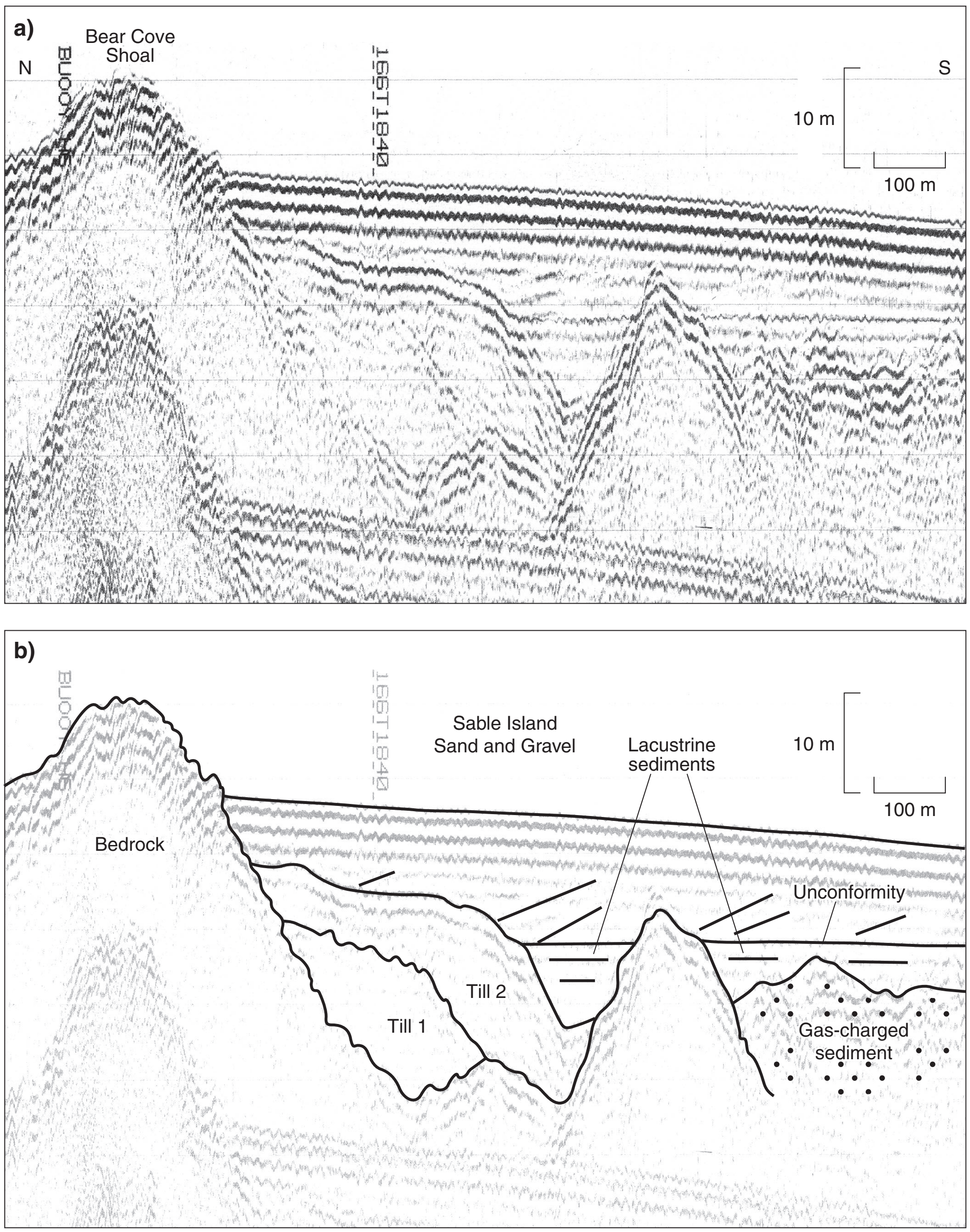


Figure 46. a) Seismic-reflection profile and **b)** interpretation in an area of multiple till sequences in the outer harbour, south of Bear Cove Shoal. Gas-charged lacustrine sediments in part overlie the tills that in turn are overlain by northward-prograding sand deposits of Sable Island Sand and Gravel. Bear Cove Shoal is exposed bedrock at the seabed.

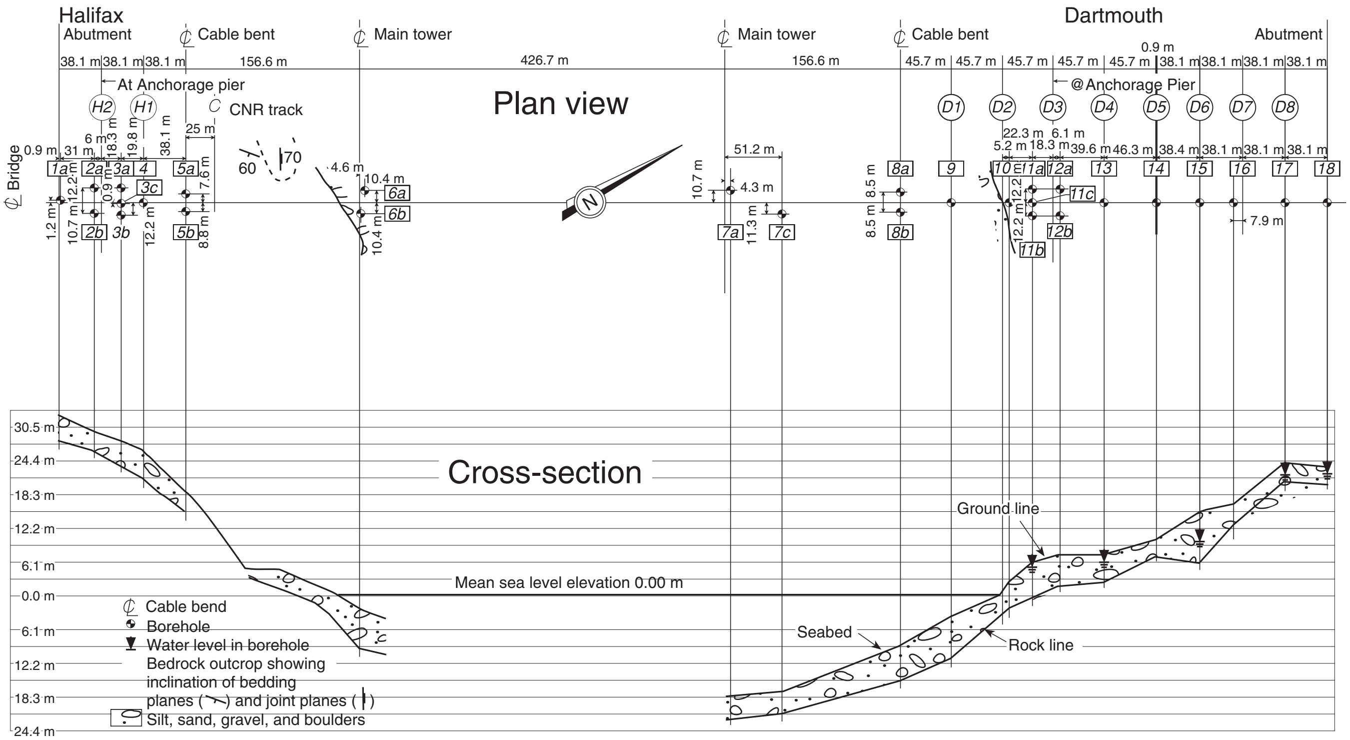


Figure 47. Interpreted cross-section and plan view from southwest to northeast across The Narrows at the location of the A. Murray MacKay Bridge, based on a suite of boreholes 1–18 collected for bridge foundation assessment. Note the continuous deposit and thickness of till locally more than 9 m at borehole location number 15. Terms 1a, 2a, etc. are borehole numbers for the original report. Figure courtesy of the Halifax-Dartmouth Bridge Commission; source is Pratley and Dorton Dwg. No. 103 Borehole Location and Stratigraphy form the original design of the A. Murray MacKay Bridge. Units have been converted to metric.

Lithology

As part of a preliminary assessment of the foundation character of the harbour for the construction of a waste-water collection system, several boreholes were completed in the harbour that penetrated and sampled till (Fig. 5). Borehole 1, collected at the northern entrance to Eastern Passage (Fig. 42) encountered till at a depth below the seabed of 16.4 m. It was immediately overlain by 2.7 m of loose to compact, dark grey sand with some silt. The till consisted of two units, the upper approximately 6 m thick, and the lower unit 5.6 m thick. The upper till consisted of very hard, reddish-brown, sandy clay with gravel including cobbles. Its reddish colour suggests it is Lawrencetown Till (Stea et al., 1992a). The lower unit was a very hard, grey, sandy, clayey till with gravel and cobbles. This unit likely represents Hartlen Till. These two lithological types are similar to the till stratigraphy found in the drumlins of adjacent Dartmouth and McNabs Island. Unfortunately, seismic-reflection profiles could not image the buried tills in this area because of the presence of interstitial methane gas in the overlying Holocene mud. A second borehole, borehole 4, collected nearby (Fig. 41), at the northern entrance to Eastern Passage, encountered a 14.5 m thickness of till at a depth of 16 m below the seabed, overlain by greyish-brown, silty clay and very soft, grey organic silt. The till was reddish-brown and sandy with gravel and common cobbles, and is likely Lawrencetown Till.

A suite of boreholes, 1004, 1005, and 1006 (Fig. 5), collected to the west of McNabs Island by the Department of National Defence, encountered a maximum thickness of 2.5 m of dense, dark, grey, sandy-gravelly till at the base of the section, likely Hartlen Till.

In The Narrows, 28 boreholes were collected spanning the harbour, as part of a foundation study for the construction of the A. Murray MacKay Bridge in 1967 (Fig. 47). The borehole information indicates that bedrock is not exposed at the seabed in that area of The Narrows and is buried beneath silt, sand, gravel, and boulders varying in thickness from 1.5 m to 10 m. Sidescan sonograms and seabed photographs indicate that the seabed is gravel with many clasts in the cobble to boulder range. The seismic-reflection profiles collected throughout The Narrows indicate that only one till occurs and reaches a maximum thickness of 16 m.

To investigate the possibility of constructing a sewage collection tunnel, crossing the harbour, under the mid-section of The Narrows, borehole 3 was drilled (Fig. 39). It penetrated a 6 m section of grey, silty and clayey till with some gravel.

A series of boreholes collected at a proposed diffuser location west of Ives Knoll (borehole DF-9) at the entrance to the inner harbour (Fig. 5) penetrated a 3 m thick compact to dense, grey, sandy gravel with minor silt, suggestive of the Hartlen Till. Other boreholes from the same area indicated that till was absent or very thin overlying bedrock. Borehole 2 collected between Ives Knoll and the container pier to the west indicated no trace of till. Bedrock was overlain only by thin, grey organic silt and the bedrock surface was weathered to a depth of 5 m.

The lithology of the till in the boreholes and of seabed samples largely reflects the lithology of the bedrock over which it lies. For example, in The Narrows, over 90% of the clasts in seabed samples consisted of Halifax Formation slate. A detailed regional analysis of the till lithology was not undertaken because of a lack of subsurface samples of unmodified till.

Distribution and thickness

Seismic-reflection profiles indicate that till blankets the bedrock in most areas of Halifax Harbour. The till is approximately 5 m thick in Bedford Bay. The presence of gas-

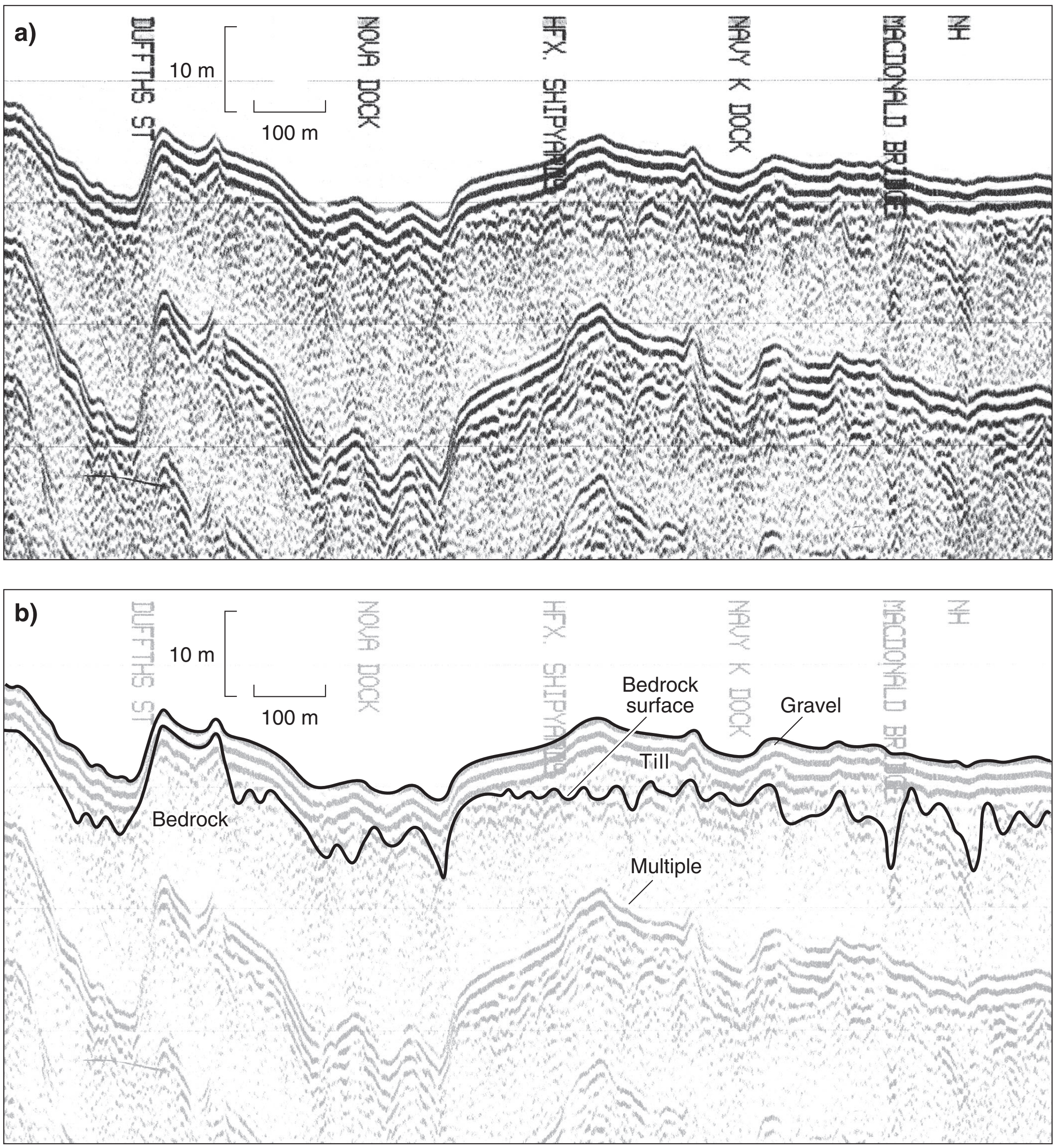


Figure 48. a) A Datasonics Bubble Pulser seismic-reflection profile and **b)** interpretation of area extending from Pier 9 at the foot of Duffus Street to the Angus L. Macdonald Bridge in the southern portion of The Narrows showing the bedrock surface beneath till and Sable Island Sand and Gravel. The till ranges up to 13 m thick on this profile and the bedrock surface is irregular. Some of the bedrock morphology is mimicked through the till to the seabed. The Narrows is a difficult area in which to define the bedrock surface with seismic-profiling systems, as the till and the overlying bouldery sediment prevent penetration and resolution of subsurface events. Boreholes at the location of the A. Murray MacKay Bridge penetrated till with a maximum thickness of 16 m.

charged mud in Bedford Basin prevents the measurement of till thickness. Till attains thicknesses of up to 16 m in The Narrows lying on bedrock, the surface relief of which is in the order of 8 m (Fig. 48). The till averages 5 m thick in the inner harbour. It is thickest in the outer harbour, reaching 22 m in large channels. It is also less continuous in the outer harbour, as bedrock outcrops over large areas of the eastern part of that region. Most of the shoals in the outer harbour, such as Bear Cove Shoal, Lichfield Shoal, and Mars Rock are devoid of till whereas Middle Ground is overlain by 3 m of till. Seaward of McNabs Island till is continuous, and thick where it infills channels (Fig. 49). Although transgressed in this area, and to a water depth of 70 m to the south, preservation of the till resulted from protection from erosion by the location of bedrock sills and bedrock topographic highs farther seaward (Fig. 50).

Morphology

In addition to its regional occurrence as a blanket deposit throughout most of the harbour, till occurs as distinct mounds and ridges in several areas. On land in the Halifax Regional Municipality, drumlins are a common landscape attribute. Several drumlins also occur within the harbour, both emergent as islands and at the seabed. The most well known drumlin of Halifax Harbour is Georges Island, used as a military fortification following the founding of Halifax in 1749. Georges Island and its onland military counterpart, 'Citadel Hill', were both developed as fortifications because of their prominent height, isolation, and diggability. Three other large drumlins have been found on the bottom of the harbour: Jonquière Bank (Fig. 51) on the west side of Bedford Basin, an unnamed drumlin northwest of Georges Island in the inner

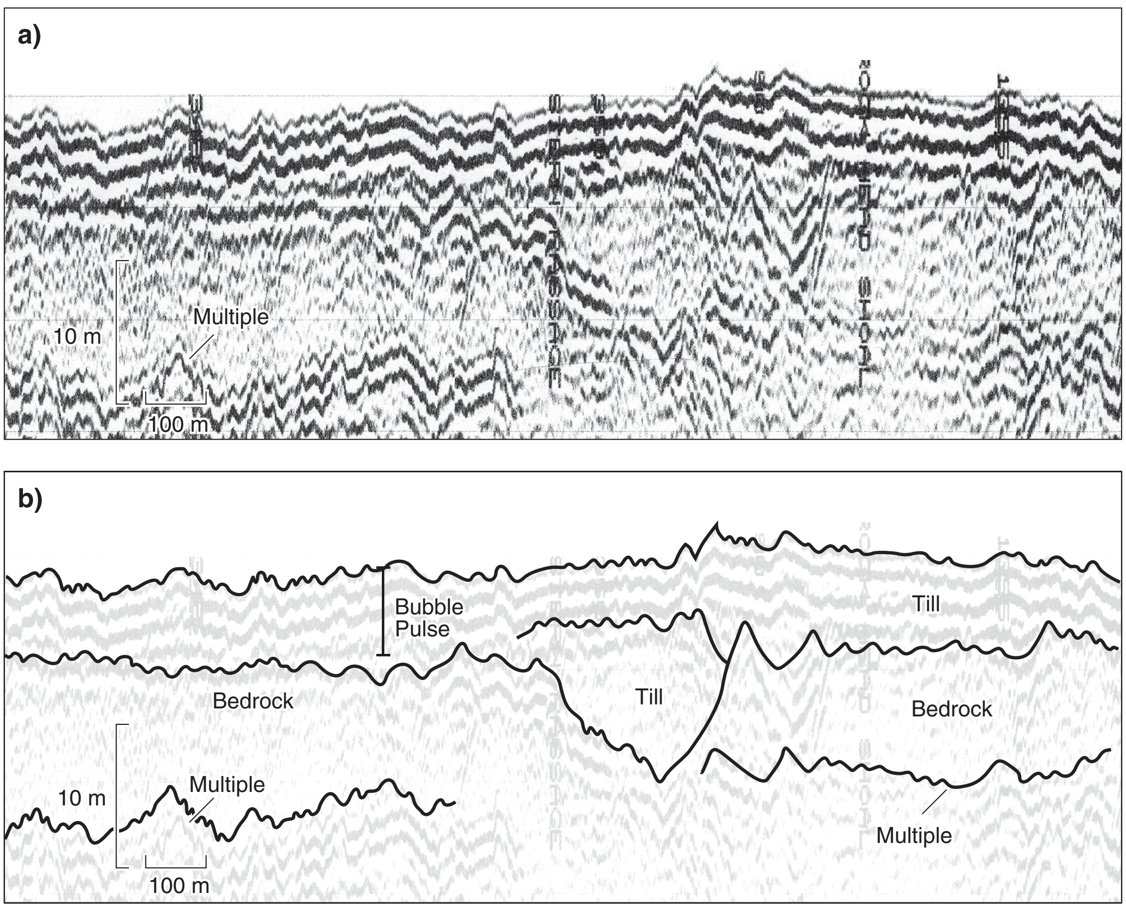


Figure 49. a) A Bubble Pulser seismic-reflection profile and **b)** interpretation of area south of McNabs Island showing thick till overlying bedrock. The thickest till occurs in a buried channel. These areas have been transgressed, but the till has survived erosion with the development of the Sable Island Sand and Gravel on its surface.

harbour (Fig. 7a, c, 13, 18), and a small gravel-covered mound ('Little Georges Bank') in the northern area of The Narrows. Its surface has been dredged to remove the top several metres as it was a hazard to navigation. The till in this drumlin is 12 m thick. As a result of the removal of a cover of Sable Island Sand and Gravel and several metres of till through dredging, it is the only exposed area of true till on the seabed of the harbour. Other areas of till have been transgressed and their surfaces have been eroded and armoured with gravel.

Till occurs on Middle Ground as a series of ridges, 2 m high and 200 m long that trend northeast (Fig. 6, 13, 21). They are gravel-covered ridges that overlie bedrock. The ridges may represent De Geer or lift-off moraines (King and Fader, 1986) that formed during glacial ice recession in Halifax Harbour and survived the marine transgression in postglacial time. Till ridges also outcrop in the inner harbour northeast of Georges Island on the Dartmouth side of the harbour (Fig. 52). A series of till ridges occurs in the subsurface of Bedford Bay that resemble lift-off moraines found on the Scotian Shelf. The overlying stratified material is conformably draped and ponded within the till ridges (Fig. 21, 53). The overlying sediment has not been sampled because of its depth of burial beneath thick LaHave Clay. It may represent glaciomarine or glaciolacustrine sediment ponded in Bedford Bay behind the bedrock sill of Western Ledges, Chicken Rocks, and Wellesley Ridge. These till ridges may have formed as the glaciers lifted off from the bedrock in Bedford Bay during ice recession.

Depositional processes

Regionally, the Scotian Shelf Drift of the harbour is interpreted to have been formed subglacially as primary lodgment till under Wisconsinan glaciers. These glaciers covered the entire area of the harbour and advanced across the Scotian

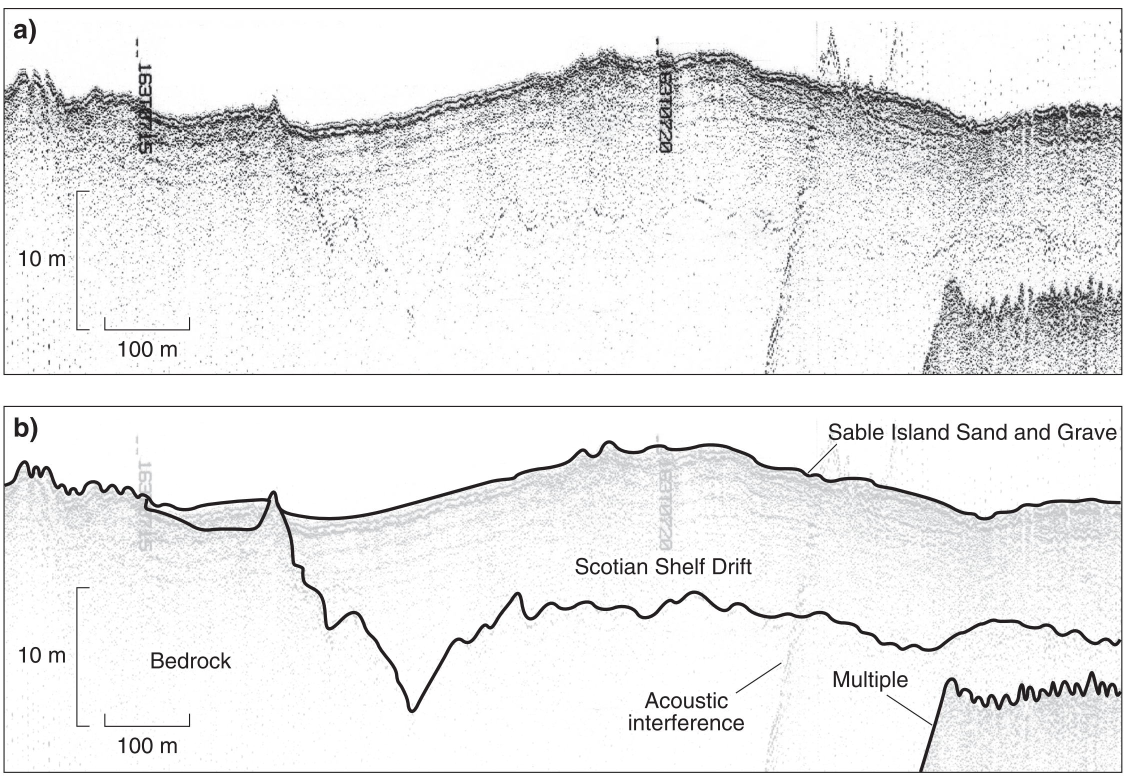


Figure 50. a) A Huntec deep-towed, external hydrophone, seismic-reflection profile and **b)** interpretation of area southeast of Chebucto Head off the entrance to Halifax Harbour, showing bedrock covered by up to 12 m of till overlain by a thin veneer of Sable Island Sand and Gravel. Despite being transgressed during the Holocene, areas of till have survived on the inner shelf where protected from erosion by bedrock ridges, local topography, and deposition in local basins. Bedrock outcrops on the left of the profile toward the west and dominates the seabed south of Halifax Harbour on the inner Scotian Shelf. Sand is rare off the mouth of the harbour.

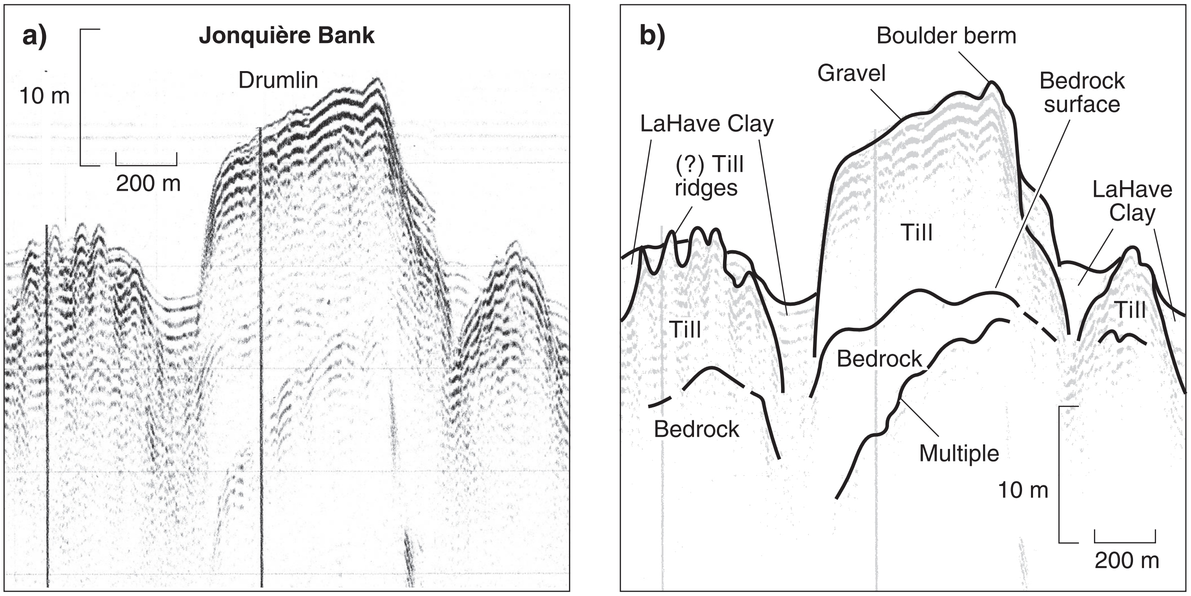


Figure 51. a) Seismic-reflection profile and **b)** interpretation of area over Jonquière Bank in western Bedford Basin. The bank is a drumlin formed of till and the bedrock surface can clearly be imaged at a depth of 20 m. The surface of the bank is ringed with two boulder berms.

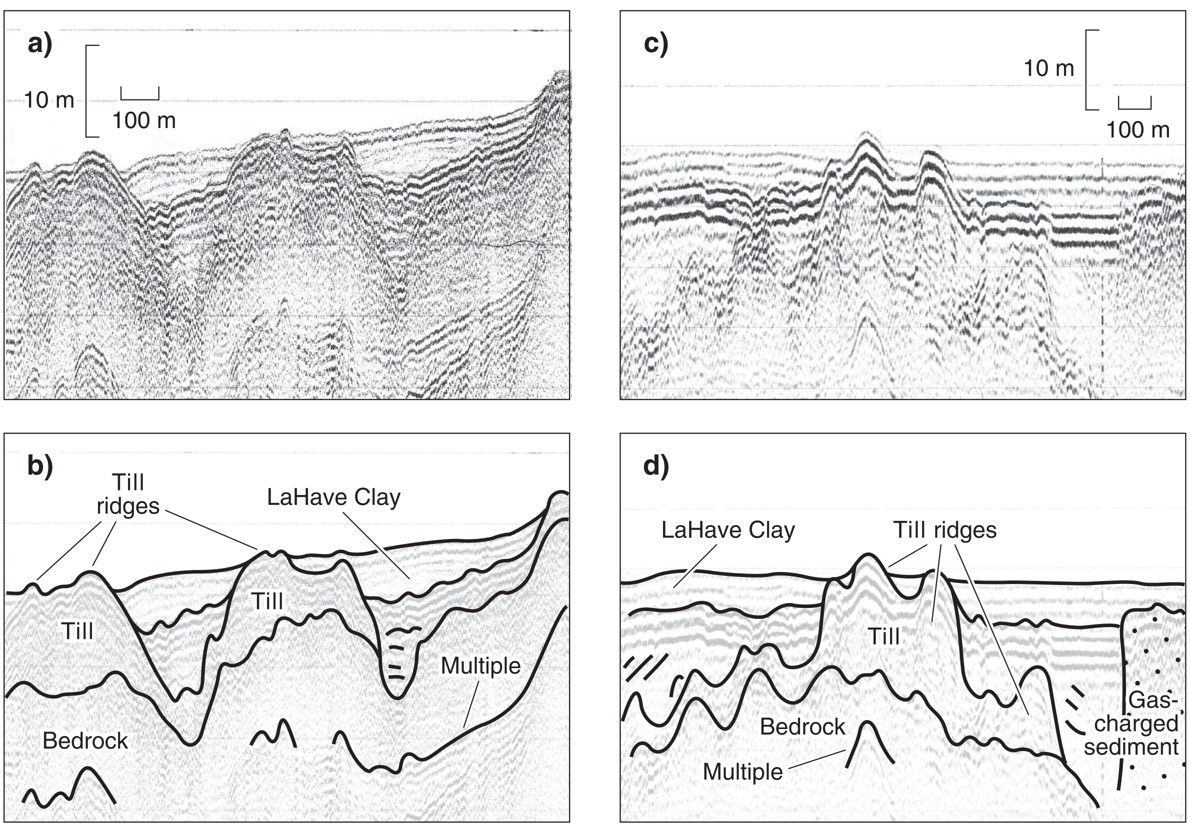


Figure 52. a) A Huntec Sea Otter boomer-reflection profile, **b)** interpretation, **c)** a Datasonics Bubble Pulser seismic-reflection profile, and **d)** interpretation from the eastern side of the inner harbour, northeast of Georges Island. Ridges exposed at the seabed protruding through LaHave Clay are composed of gravel-covered till overlying bedrock. These ridges, which are mostly buried, are likely transverse moraines deposited during ice retreat and are similar to moraines on the east side of Middle Ground and south of Sambro on the inner shelf.

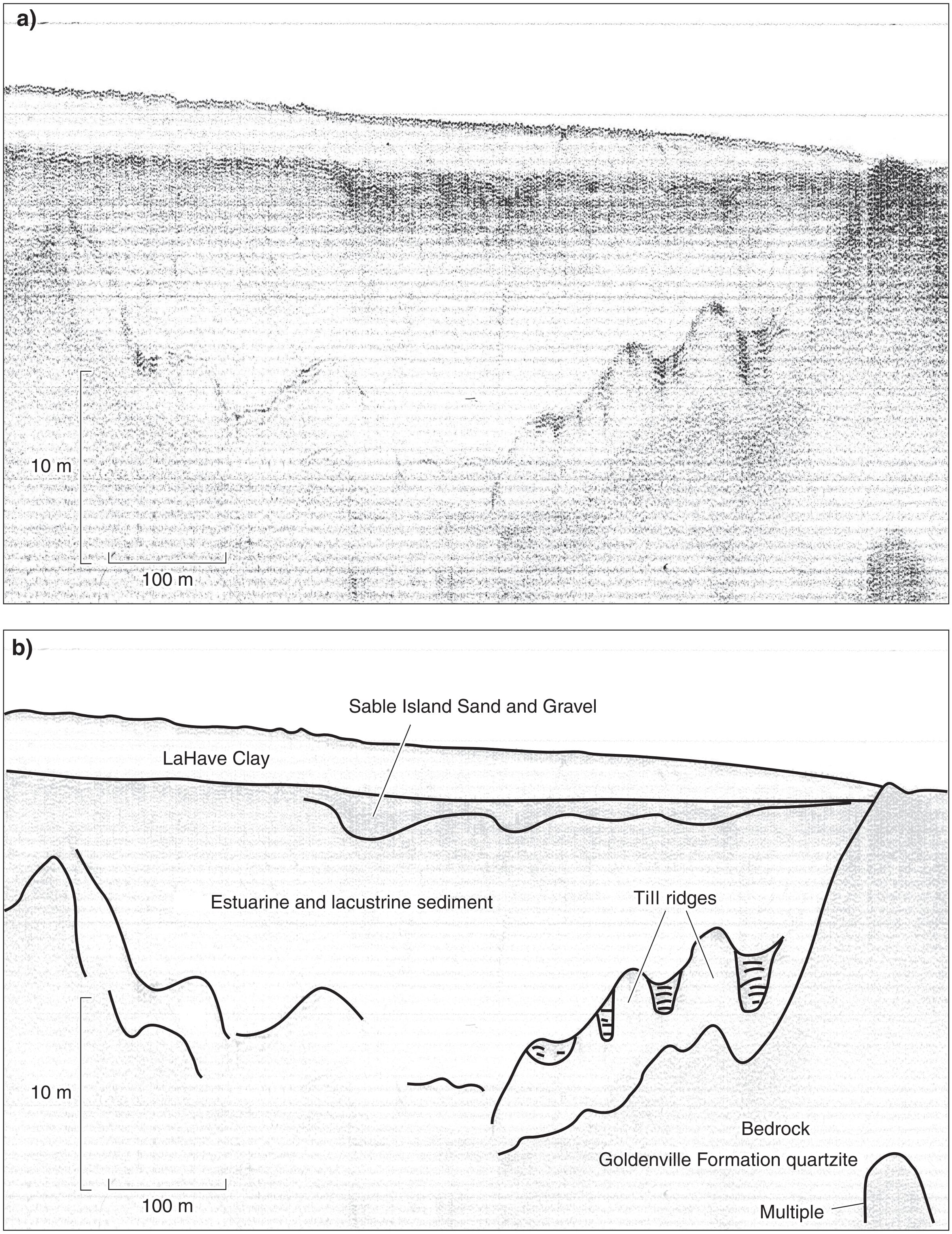


Figure 53. a) A Seistec seismic-reflection profile and **b)** interpretation from Bedford Bay, Bedford Basin, north of a bedrock sill separating the basin from the bay, shows a series of till ridges at the base of the section. The ridges resemble lift-off moraines (ribbed moraines), features that are widespread in the basins and on the inner Scotian Shelf. They are interpreted to form in fields in crevasses at the glacier base as the glaciers began to first float in the confined basins. The moraines are linear ridges and formed in recessional environments. Samples were not collected because of their deep burial. Similar-shaped ridges on Middle Ground are boulder-covered till. The estuarine and lacustrine sediments display a lack of continuous coherent reflectors and the overlying LaHave Clay is acoustically transparent.

Shelf to the shelf edge (King and Fader, 1986). Despite presently occurring under water, the till of the harbour was essentially deposited by terrestrial glaciers and not at an ice-marginal floating front location. Sea level was much lower during this time.

Lacustrine sediments

Lacustrine sediments would be expected to occur in Halifax Harbour given the maximum depth (71 m) and the length (28 km) of this coastal re-entrant as well as the timing of ice retreat from the region and the depth of the low postglacial sea-level stand on the inner Scotian Shelf (65–70 m). The lacustrine unit is difficult to sample and to delineate because it is buried deeply in the subsurface of the harbour within isolated basins and the presence of anthropogenic debris at the seabed has hampered sampling. Despite numerous attempts, it has only been sampled in a few areas in Bedford Basin and the inner harbour where only the upper part has been sampled. It is interpreted to occur in other areas on the basis of seismostratigraphic character, regional considerations of morphological setting, bounding relationships, and association with features such as boulder berms.

Seismostratigraphy

The lacustrine unit displays a variety of reflection characteristics. High-intensity, continuous coherent reflections that are highly conformable to the surface of the underlying till or bedrock occur at the base of the section (Fig. 54). The reflections become more ponded and grade to medium-intensity reflections in the upper part of the section. Some reflections are grouped together in bands of higher intensity separated by zones of weaker reflections, suggesting layers of coarser material within the unit. At the top of the section in the inner harbour, the reflections grade to discontinuous and some become incoherent. A major unconformity is developed across the surface of the unit in Bedford Bay and the inner harbour. Reflections are truncated at the unconformity and up to 5 m of section has been eroded in areas of the inner harbour near Georges Island. The upper part of the unit is channellized in places. In the inner harbour overlying this unconformity are two thin units of contrasting acoustic character. One unit, interpreted as estuarine sediment, is thin and acoustically transparent and deposited in a ponded style in slight depressions on the unconformity (Fig. 54). The other is mounded and constructional in depositional style and consists of high-intensity coherent reflections. This unit is interpreted as Sable Island Sand and Gravel.

The acoustic stratification and mantling geometry of the base of the lacustrine unit is very similar to the character of glaciomarine sediments (Emerald Silt) found widespread on the adjacent Scotian Shelf (King and Fader, 1986). Only the upper sections were sampled during this study and it is possible that much of the deeper section is glaciomarine sediment. For this reason the present authors consider the lacustrine unit to also represent undifferentiated glaciomarine sediment.

In Bedford Basin the lacustrine unit is also characterized by conformable, basal, high-intensity, coherent reflections overlying till ridges. These ridges are similar to lift-off moraines (King and Fader, 1986) found on the adjacent Scotian Shelf. In the outer harbour, the lacustrine unit is buried by thick Sable Island Sand and Gravel.

Lithology

Lacustrine sediments were sampled in Bedford Basin by several cores (Miller et al., 1982). The upper material consisted of laminated brown mud with zones of dark brown mud. Slightly sandier layers alternate with thicker, poorly sorted, brown to reddish mud with 3–5% sand. The sediment becomes greyish brown with scattered gravel and silty black laminae with depth. The upper part of the lacustrine sediment near the transition zone to marine sediment has a ^{14}C age of 5830 ± 230 BP. Patches of manganese-bearing vivianite were found and interpreted to have formed under reducing conditions common to postglacial lakes. Fader and Buckley (1997) also reported on a long piston core from Bedford Basin that penetrated lacustrine sediments at a downcore depth of 7.8 m below seafloor that were dated at 5700 BP. The lake sediments contained fresh-water brachiopods and marsh vegetation.

Boreholes 1004, 1005, and 1006 collected to the west of McNabs Island penetrated up to 3 m of soft, grey, silty clay, interpreted as lacustrine sediments. This area is bounded by boulder berms, similar to those that occur in Bedford Basin, at a present depth of approximately 30 m. They are interpreted to define the position of a pre-existing lake between McNabs Island and Middle Ground. Boreholes 1 and 4 penetrated up to 9 m of stiff, greyish-brown, silty clay with a trace of sand at the entrance to Eastern Passage. These sediments overlie till and in turn are overlain by transgressive sand and gravel of the Sable Island Sand and Gravel and/or LaHave Clay, a dark grey, organic silt. Boreholes 104 and 107 (provided by Halifax Harbour Cleanup Incorporated) penetrated peaty organic silt ranging in thickness from 0.6 m to 0.8 m overlying till east of Ives Point and north of McNabs Island. These materials are interpreted as estuarine sediments.

Depositional environment

Edgecombe (1994) and Edgecombe et al. (1999) studied two vibrocores in the inner harbour near Georges Island that were collected in an attempt to penetrate the LaHave Clay and the lacustrine ponded sediment (Fig. 5, 55). Core VC-10 penetrated a thin peaty and soil horizon underlying the LaHave Clay, but did not reach the underlying unit, interpreted to have been deposited in a lacustrine environment. Core VC-2 collected in 20.5 m water depth appeared to penetrate 66 cm of the upper section of the lacustrine unit, which consisted of

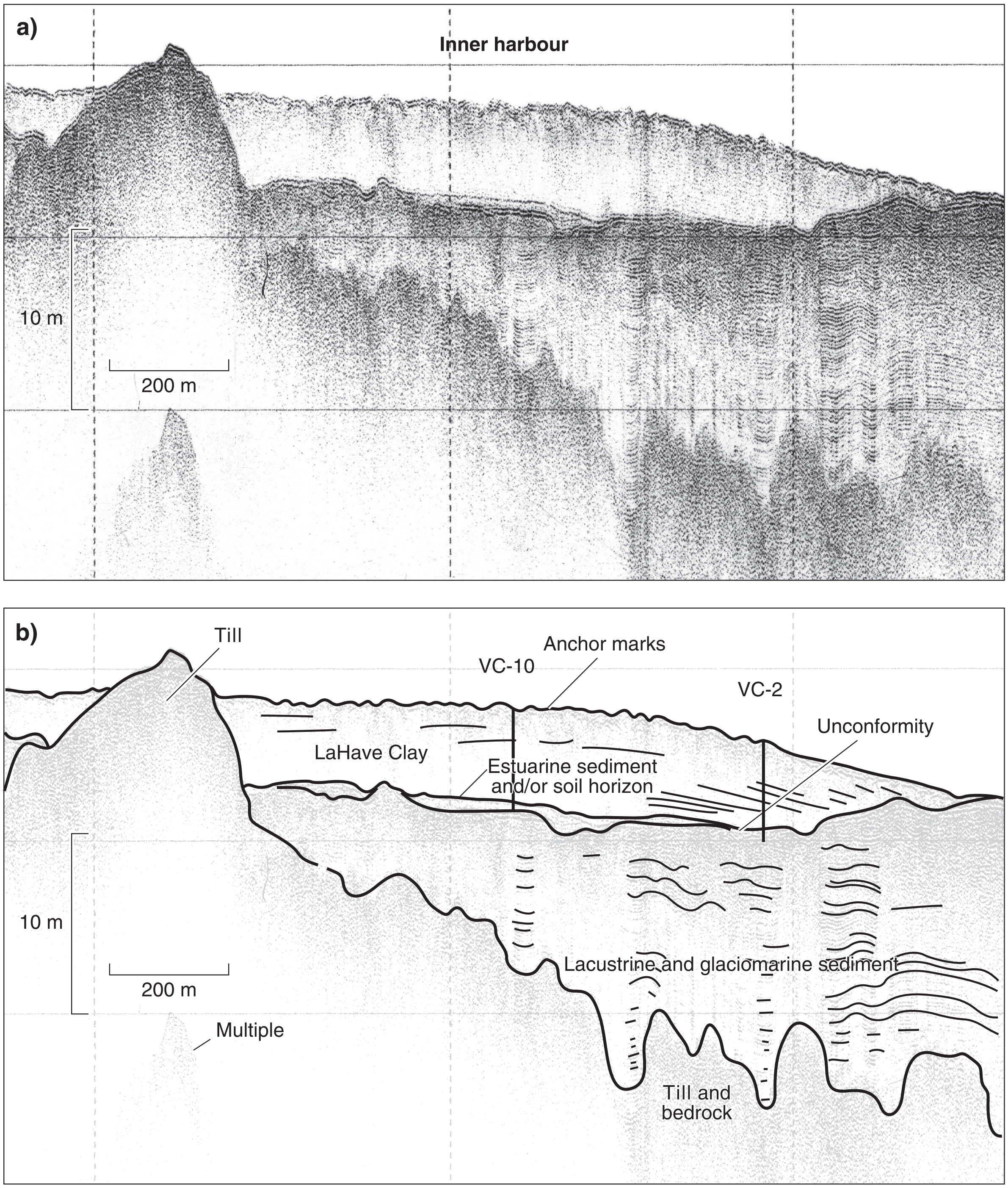


Figure 54. **a)** Seismic-reflection profile and **b)** interpretation from the inner harbour northeast of Georges Island showing a subsurface basin filled with conformable stratified sediments overlying till and bedrock. Note the thin, acoustically transparent ponded unit overlying the unconformity on the stratified sediments and underlying the acoustically transparent Holocene LaHave Clay. This unit represents the soil and/or estuarine material sampled at the base of vibrocores VC-2 and VC-10 (*see* Fig. 3 for location).

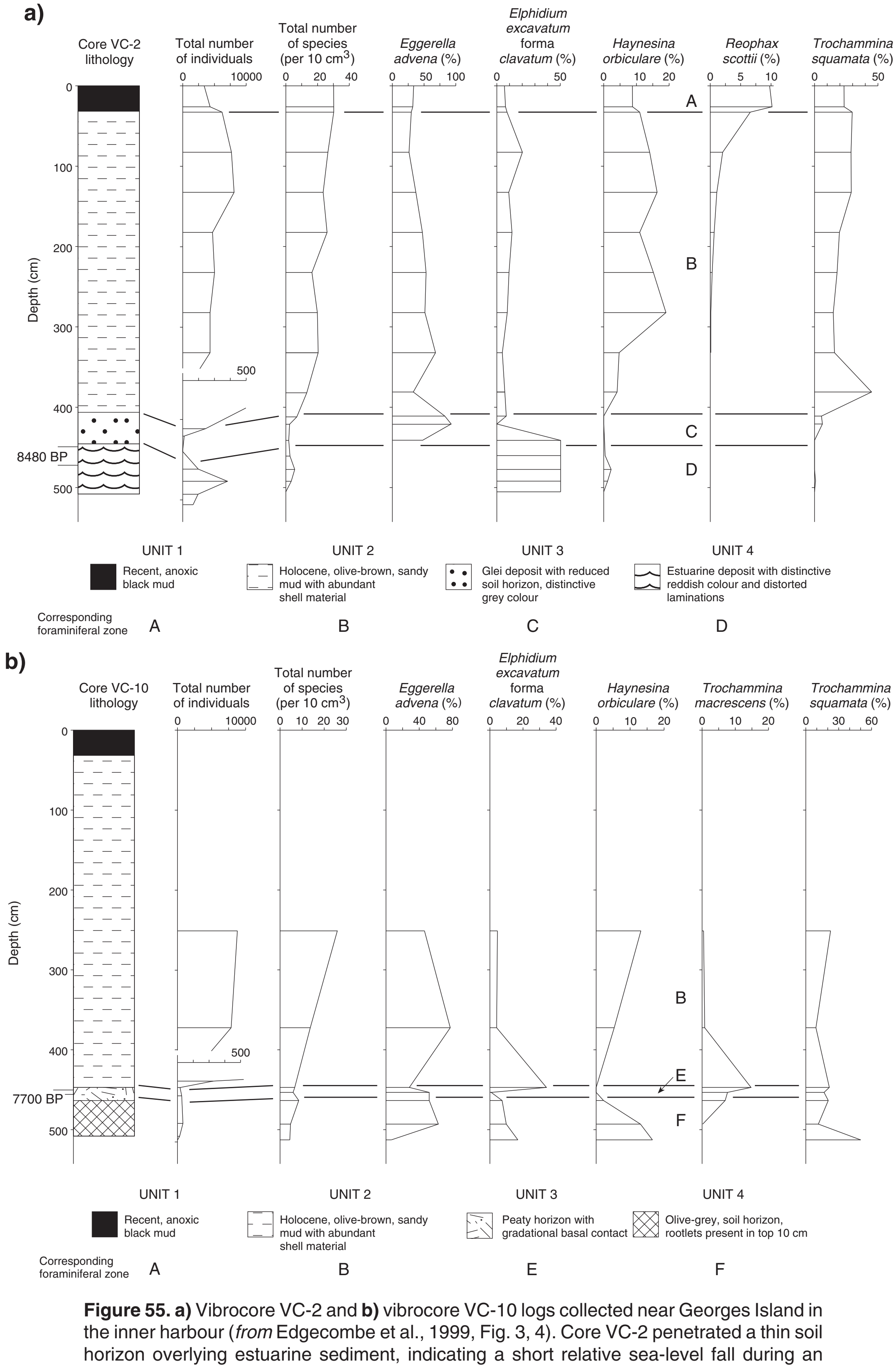


Figure 55. a) Vibrocore VC-2 and **b)** vibrocore VC-10 logs collected near Georges Island in the inner harbour (*from* Edgecombe et al., 1999, Fig. 3, 4). Core VC-2 penetrated a thin soil horizon overlying estuarine sediment, indicating a short relative sea-level fall during an overall period of sea-level rise. Core VC-10 penetrated a peaty horizon overlying an olive-grey soil horizon at the base of the core. The LaHave Clay is over 4 m thick at the core locations. Foraminiferal abundances are also shown.

red mud with contorted laminae. More than 10 m of unsampled section remained beneath the core location and the total thickness of the unit reaches 25 m in adjacent areas of the same basin. Detailed examination of the seismic-reflection data show that in this part of the harbour the surface of the lacustrine unit is not well defined and the acoustic stratigraphy is complex in the upper section. Reflections are discontinuous to incoherent and of higher intensity. Edgecomb et al. (1999) proposed that the remainder of the thick basin fill may also be estuarine sediment based on the core results. It is difficult to explain 25 m of estuarine deposition in these enclosed basins as this would suggest a prolonged time of slowly rising sea level for deposition. The conformable character of the beds of the lacustrine unit and a lack of channels and local erosional features suggests that it was deposited under quiet depositional conditions. The lacustrine sediments are acoustically similar throughout the inner harbour and in Bedford Basin and also occur in similar morphological settings. The present authors therefore interpret that the unit filling the large harbour subsurface basins represents lacustrine deposition and possibly glaciomarine sedimentation at the base. Glaciomarine sedimentation (Emerald Silt) may have occurred in a large glacial re-entrant that extended partially up the outer part of Halifax Harbour from the inner shelf.

Distribution

Lacustrine sediments in Bedford Basin occur in the central deep area of the basin, in Bedford Bay, and in Fairview Cove (Fig. 56; cross-section, Fig. 21). The presence of two boulder berms that ring Bedford Basin at a depth of 23 m are interpreted as indicators of the presence of a former lake and are thought to have developed as ice-push ridges during seasonal freeze over. A large lake also was present in the inner harbour to the north, east, and south of Georges Island extending southward in Eastern Passage. The presence of methane gas charging within the overlying LaHave Clay sediments makes the acoustic recognition of the subsurface lacustrine sediments very difficult. Other evidence can be used to support their presence in the subsurface, such as continuous boulder berms and the regional morphology of closed bathymetric depressions. Lacustrine sediments are interpreted to occur in Northwest Arm in several isolated basins separated by the narrow area adjacent to Sir Sandford Fleming Park. The lacustrine sediments in outer Northwest Arm likely extend farther seaward to the area off Sandwich Point. Another lacustrine basin occurs in the deep entrance channel of the inner harbour to the west of McNabs Island and, like the setting of Bedford Basin, is surrounded by the presence of continuous boulder berms (Fig. 13).

In the outer harbour, large sediment-filled, isolated basins occur off Herring Cove and in an area extending from Halibut Bay to Chebucto Head (Fig. 56). These subsurface deposits, however, have not been sampled because of the 3 m and greater thickness of the overlying sand and gravel and associated difficulties in coring. They could also represent glaciomarine Emerald Silt.

Estuarine sediments

The estuarine unit occurs in the subsurface of the harbour and has only been sampled in vibrocore VC-2, collected near Georges Island in the inner harbour (Fig. 5, 54, 55a). Only 66 cm of estuarine section has been penetrated by coring (446–512 cm). The vibrocores collected near Georges Island, VC-2 and VC-10 (Edgecombe et al., 1999), not only provide detailed information on the depositional environment, but also identified an unexpected overlying soil horizon that suggests a short interval of emergence during the overall marine submergence of the harbour during the Holocene.

The soil horizon overlying the estuarine unit in vibrocore VC-2 (414–446 cm) (Fig. 55a) is a unique 32 cm grey glei deposit with pebbles (Edgecombe et al., 1999). Glei deposits occur in Nova Scotia below modern bogs and marshes and are interpreted to form as sea level drops in coastal settings (R. Stea, pers. comm., 1996). Vibrocore VC-10 (Fig. 55b), from an adjacent location near Georges Island, encountered

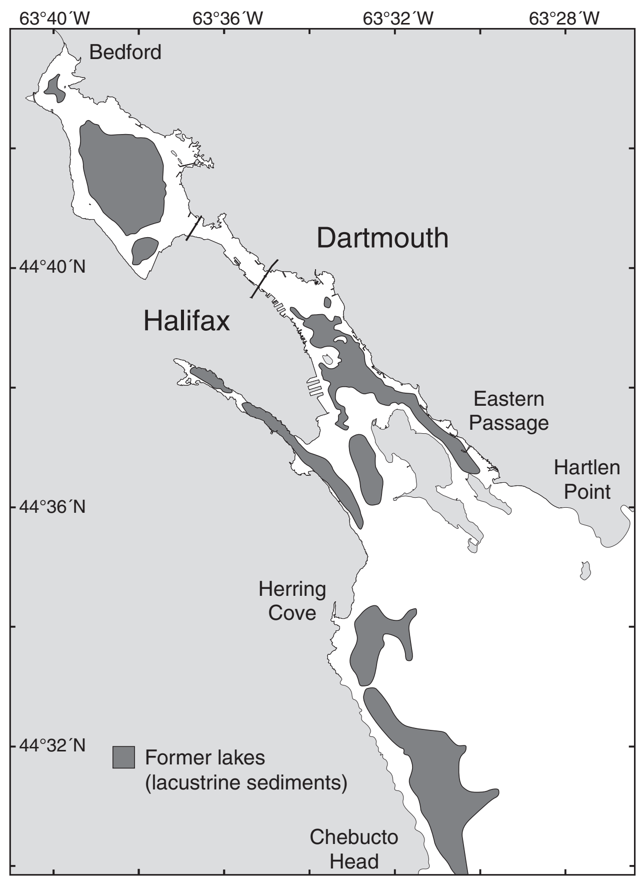


Figure 56. Interpreted distribution of lacustrine sediments buried in isolated basins throughout Halifax Harbour. Samples have not been collected from all of these areas in the harbour. Some of these basins could also contain glaciomarine sediments, particularly in the outer harbour.

peat dated at 7770 ± 260 BP, underlain by a similar grey sandy mud with rootlet traces. These two core samples confirm the existence of a thin soil horizon beneath the LaHave Clay in the inner harbour. The units are very thin and patchy and do not resolve on the seismic-reflection data, but their presence is critical to an understanding of the postglacial history of sea-level change in the harbour.

Seismostratigraphy

The estuarine unit overlies the lacustrine unit in the inner harbour and possibly Bedford Bay and it in turn is overlain by LaHave Clay. Reflections in the underlying lacustrine unit are truncated at the unconformity and up to 5 m of section has been eroded in places. In the inner harbour two thin units of contrasting acoustic character overlie this unconformity. The estuarine unit is thin and acoustically transparent and deposited in a ponded style on slight depressions on the unconformity (Fig. 54). The other unit is mounded and constructional in depositional style and consists of high-intensity, coherent reflections. This unit is interpreted as thin Sable Island Sand and Gravel. The acoustically transparent unit is interpreted to represent the thin soil horizon with peat as well as the estuarine unit. The upper part of the lacustrine unit is channellized up to 4 m in places.

Lithology

The estuarine unit in the inner harbour consists of reddish-brown mud characterized by contorted laminae. Two boreholes, 104 and 107, penetrated peaty organic silt ranging in thickness from 0.6 m to 0.8 m overlying till east of Ives Point and north of McNabs Island. These materials may also be estuarine sediments and were sampled to assess their settlement potential for construction of a proposed waste-water facility.

Depositional environment and discussion

An environmental interpretation of the estuarine sediment is based on the two vibrocores collected near Georges Island (Edgecombe, 1994; Edgecombe et al., 1999). The dominant fauna is *Elphidium excavatum f. clavatum*. A lack of an *E. excavatum–Cassidulina reniforme* assemblage indicates that it is not representative of a warm ice-margin glaciomarine environment (Scott et al., 1984). The assemblage is similar to one found by G.A. Bartlett (unpub. internal manuscript 66-2, Bedford Institute of Oceanography, 1966) and Scott et al. (1977) in the modern Miramichi River estuary of New Brunswick. This suggests that the unit was deposited in an estuarine depositional environment. An accelerator mass spectrometer analysis was undertaken on foraminifera tests and provided a radiocarbon age of 8480 ± 60 BP for the time of deposition.

Edgecombe et al. (1999) considered that the thick basin-fill material beneath the sampled estuarine sequence may also be estuarine sediment. The seismic-reflection profiles (Fig. 54), however, indicate complexity and discontinuities below the sampled unit at the top of the underlying sequence. The acoustic stratification, depositional structural style over underlying units, and contained fauna suggest that these sediments may also be glaciomarine in origin at depth below virbrocores VC-2 and VC-10 and appear on the section illustrated in Figure 54.

Sable Island Sand and Gravel

Seismostratigraphy

The Sable Island Sand and Gravel is generally very thin as a veneer deposit, but in areas where it is greater than 1 m thick it is represented on the seismic-reflection profiles by medium-intensity, incoherent reflections interspersed with zones of discontinuous coherent reflections (Fig. 57). The high-resolution, seismic-reflection systems have difficulty penetrating the unit as it increases in thickness. In a few areas, weak, continuous, coherent reflections are observed at the base. In some areas the coherent reflections prograde in an upharbour direction, suggesting dominant transport from south to north during deposition (Fig. 58). In areas of the outer harbour where the unit overlies interpreted lacustrine muddy sediments, the contact can be marked by a gas-charged reflection at the top of the lacustrine unit (Fig. 58). To the echosounder used in this study, the Sable Island Sand and Gravel is nonpenetrable and the seabed is portrayed as a high-intensity backscatter return.

The gravel facies of the formation consists largely of a veneer deposit a few tens of centimetres thick, which is beyond the resolution ability of the seismic-reflection systems used in this study. Where older estuarine and lacustrine sediments have been transgressed and a thin veneer of gravel has been deposited, its acoustic character consists of a single, high-intensity, continuous coherent reflection at the top of the underlying unit. Former gravel barriers appear as mounded structures with few internal coherent reflections (Fig. 59).

Sidescan sonograms provide the most important source of acoustic information for differentiation of the gravel from the sand facies at the seabed. The horizontal resolution of the sidescan-sonar systems is approximately 0.25 m which allows for the detection of individual boulders lying on gravel-lag surfaces and bedrock. The gravel occurs in flat areas of high backscatter (Fig. 60). Gravel can occur in ripples where the size of the material is granules, pebbles, and cobbles (Fig. 61). These ripples occur near the shoreline and in shallow areas of less that 20 m water depth. They are interpreted to form by oscillatory waves generated by storms.

Where the Sable Island Sand and Gravel lies beneath the LaHave Clay in the inner harbour, it is characterized as a channellized surface in places (Fig. 62). These channels are

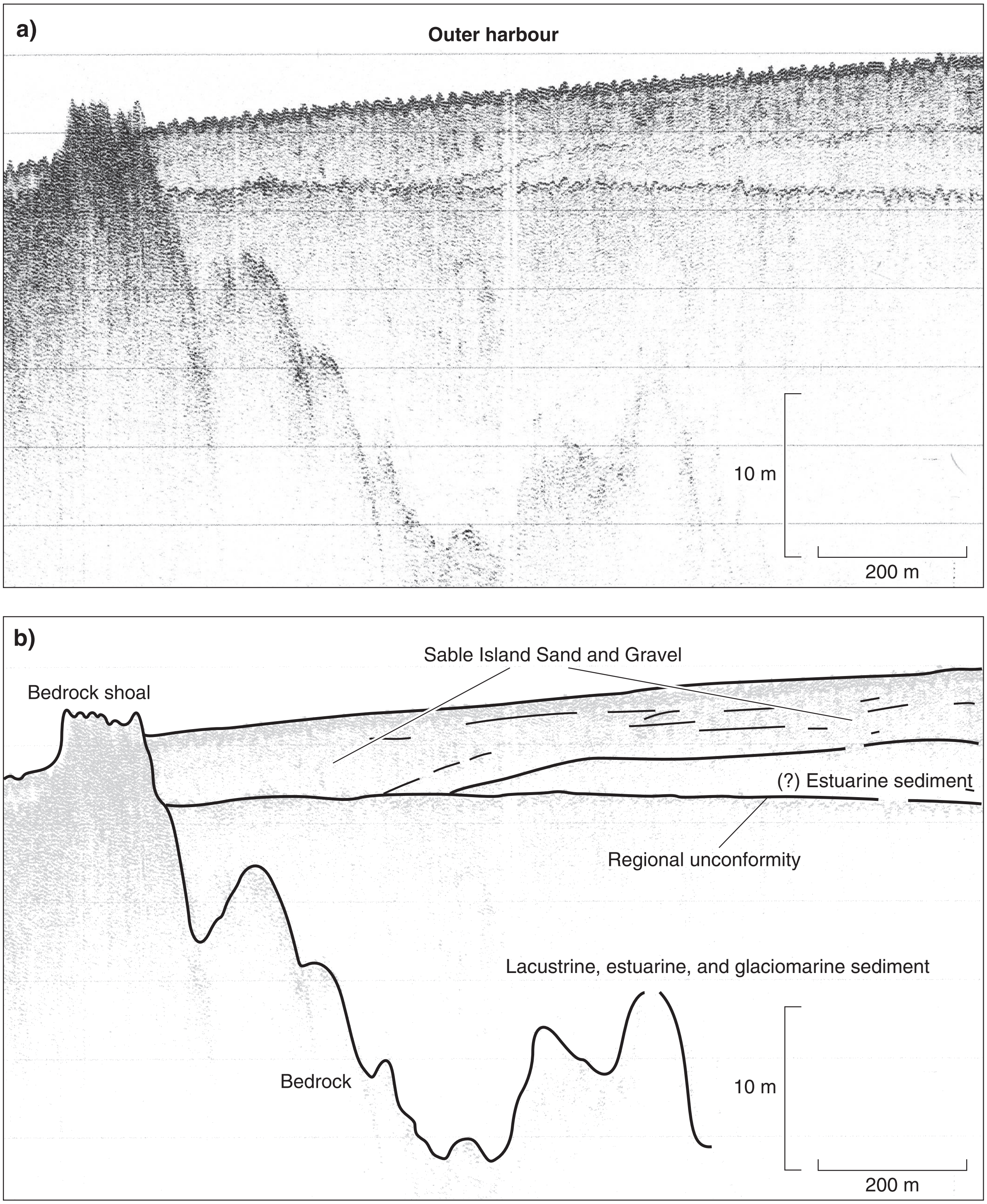


Figure 57. a) Seismic-reflection profile and **b)** interpretation from the outer harbour east of Black Point illustrating the acoustic character of the Sable Island Sand and Gravel. Here it overlies three units: bedrock and lacustrine and estuarine sediments. The subsurface lacustrine-estuarine-glaciomarine unit was not sampled because of its depth of burial in this area (*see* Fig. 3 for location).

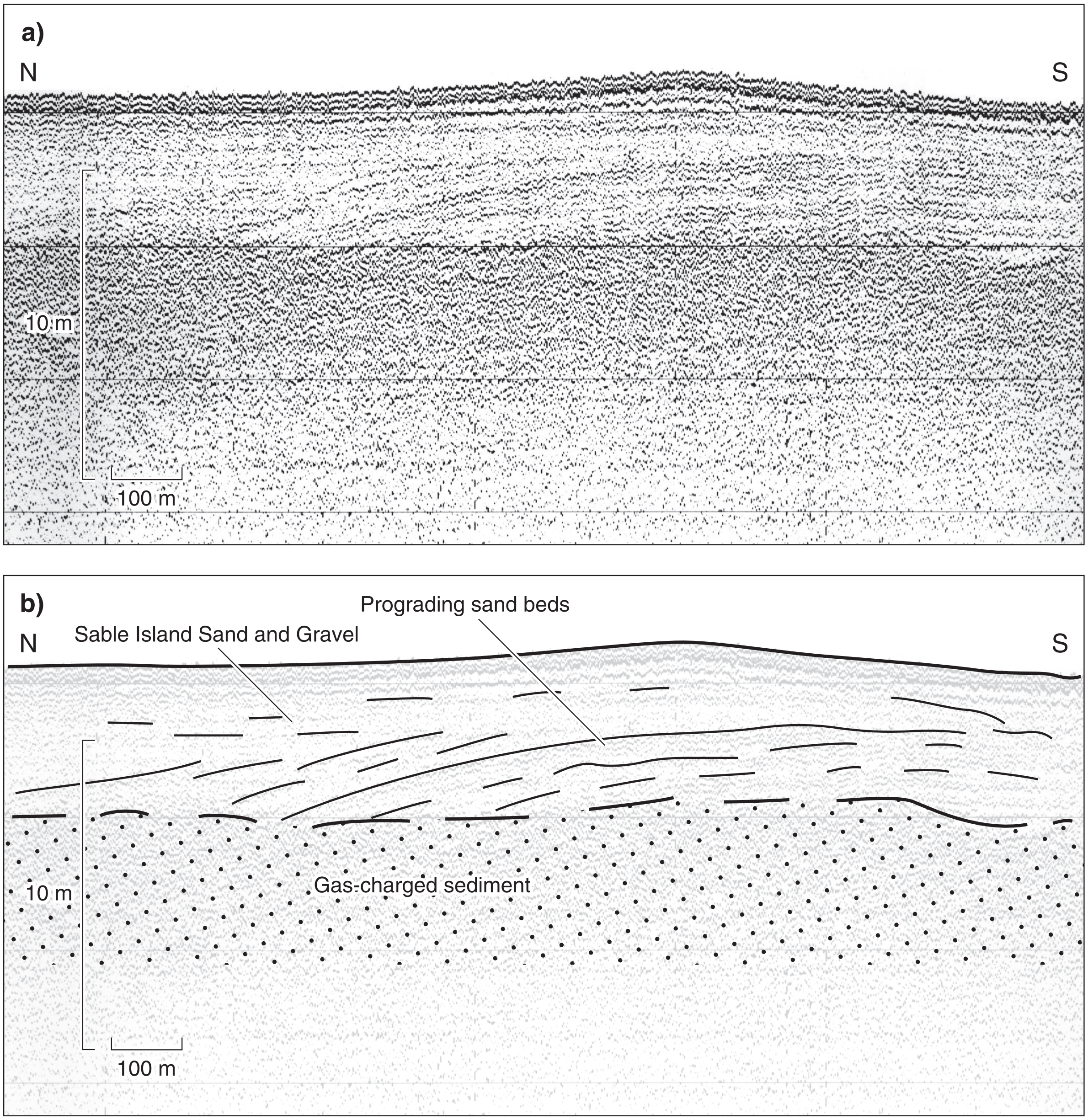


Figure 58. a) Seistec seismic-reflection profile and **b)** interpertation from the outer harbour northeast of Chebucto Head showing a prograding sequence of reflectors within the Sable Island Sand and Gravel . These indicate transport from south to north upharbour during deposition. The gas-charged reflection below the sand represents the top of the estuarine-lacustrine-glaciomarine unit.

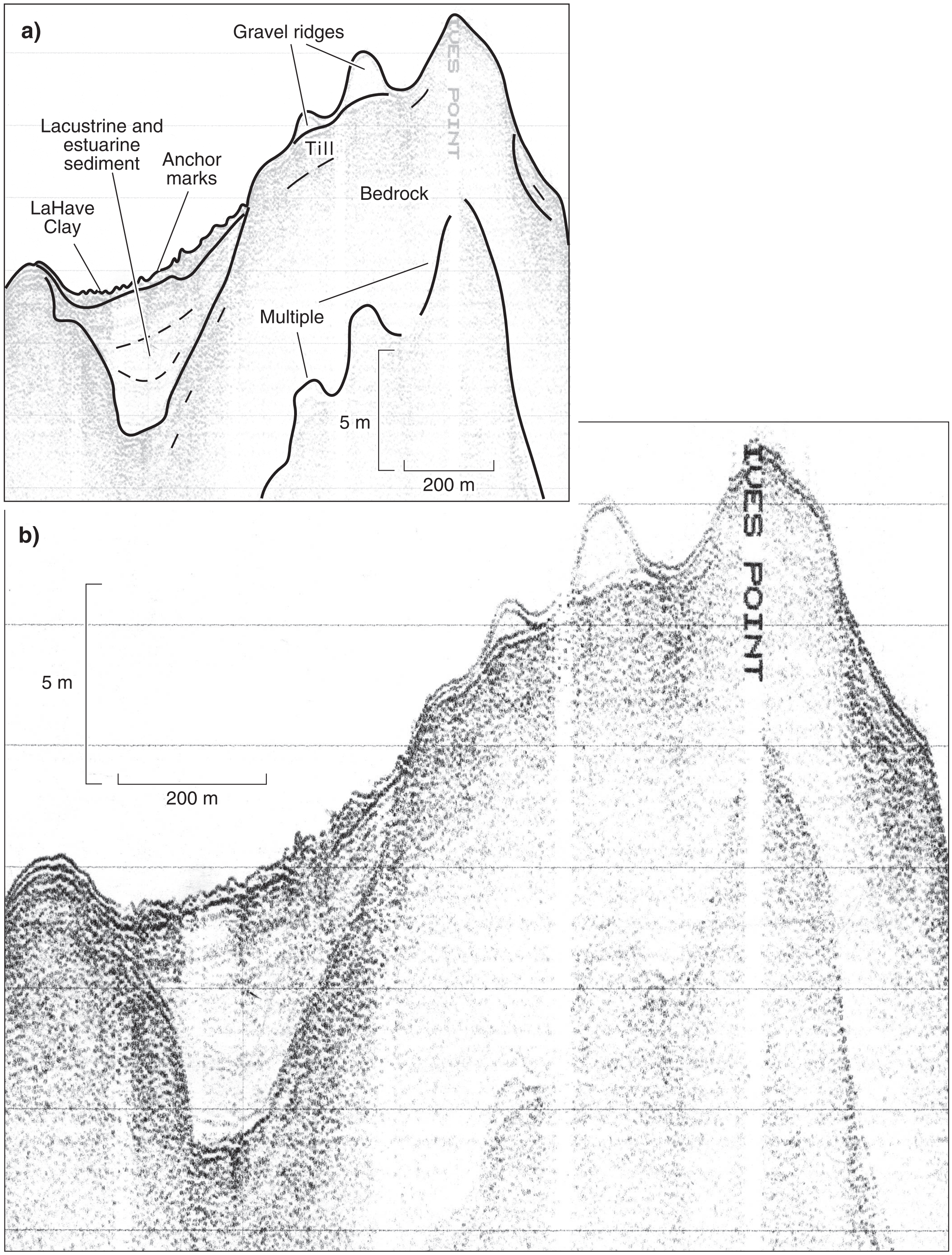


Figure 59. a) A Seistec seismic-reflection profile and **b)** interpretation north of McNabs Island off Ives Point showing relict gravel ridges overlying till. These are interpreted to have formed as ice-push ridges of a former lake.

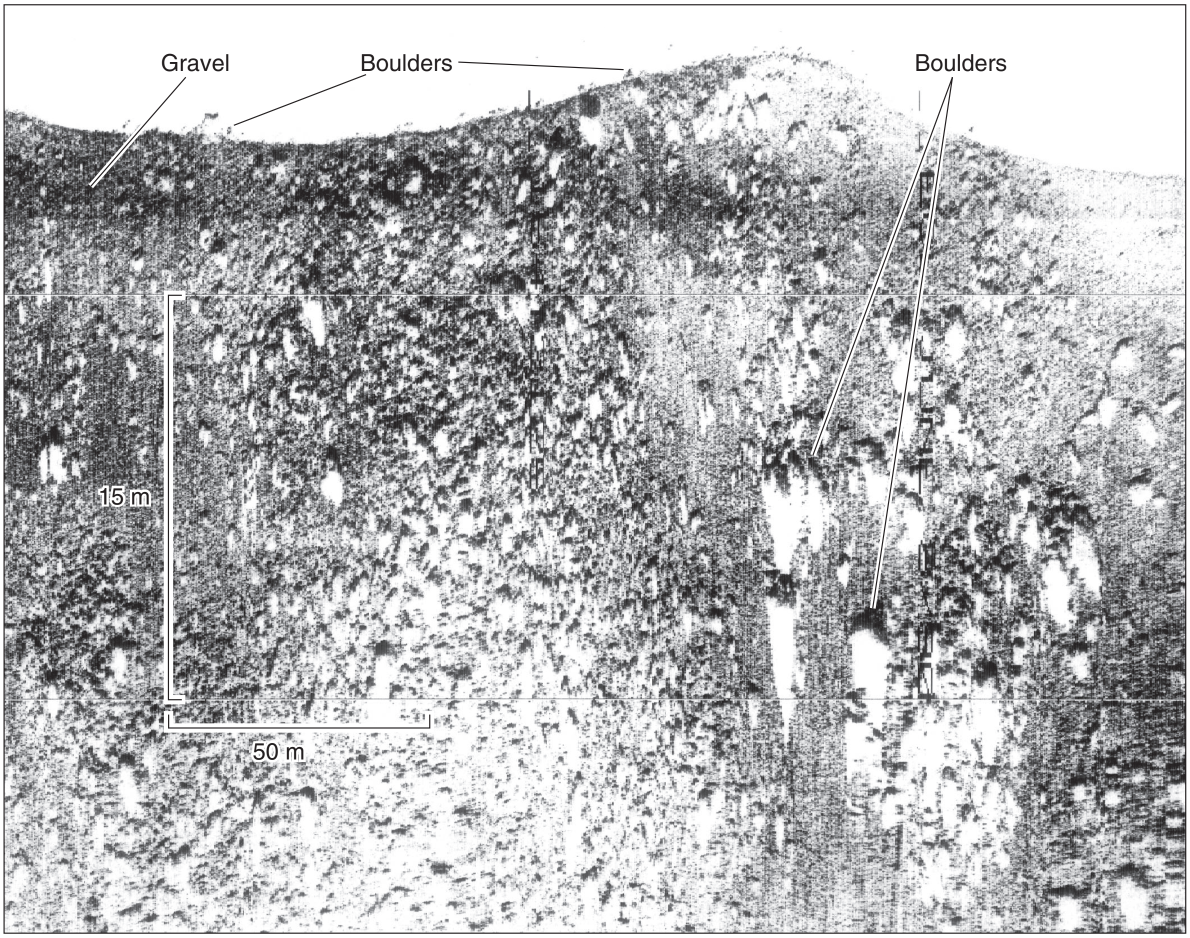


Figure 60. A 330 kHz sidescan sonogram of Sable Island Sand and Gravel from The Narrows. The seabed consists entirely of gravel with most clasts in the cobble to boulder range. Boulders extend to over 2 m in diameter. On sidescan sonograms, anthropogenic debris of similar size cannot be differentiated from boulders unless it exhibits unique identifying acoustic characteristics.

up to 3 m deep and 20 m wide. They likely represent small drainage systems that crossed the beach face during the transgression.

Lithology

The Sable Island Sand and Gravel ranges from silty sand to gravel (Fig. 63). The coarse gravel fraction is representative of the lithology of the underlying bedrock. In The Narrows, over 90% of the clasts are Halifax Formation slate, whereas in the outer harbour on the western side of the entrance channel, the dominant lithology is granite, reflecting the close proximity to the granitic batholith. Anthropogenic debris is common within the unit especially in the inner harbour and consists of fragments of metal, glass, wood, concrete, clinkers, bottles, cans, plastics, coal, and other discarded items. Broken and whole shells are common. In The Narrows, samples contained fragments of wood and broken shards of glass, and the video imagery indicated clusters of cans, bottles, and other unidentified debris that may have been concentrated by strong currents. The gravel fraction is often coated with pink coralline algae *Lithothamnion* that normally covers only the upper surface of immobile clasts in deep water. In water depths of less than 20 m, many of the clasts appear to have recently been overturned based on the distribution of *Lithothamnion* cover. Samples of Sable Island Sand and Gravel also contain large quantities of organic material including broken and whole shells. Sea urchin spines and broken shells are commonly found in the gravel ripples in the outer harbour.

Most areas of bedrock outcrop are partially covered by gravel with boulders (Fig. 64). They occur on Middle Ground, Outer Middle Ground, Lighthouse Bank, Lichfield Shoal, Neverfail Shoal, Bear Cove Shoal, Portuguese Shoal, in the nearshore between Crawley Head and Portuguese Cove, and in many small isolated clusters south of Portuguese

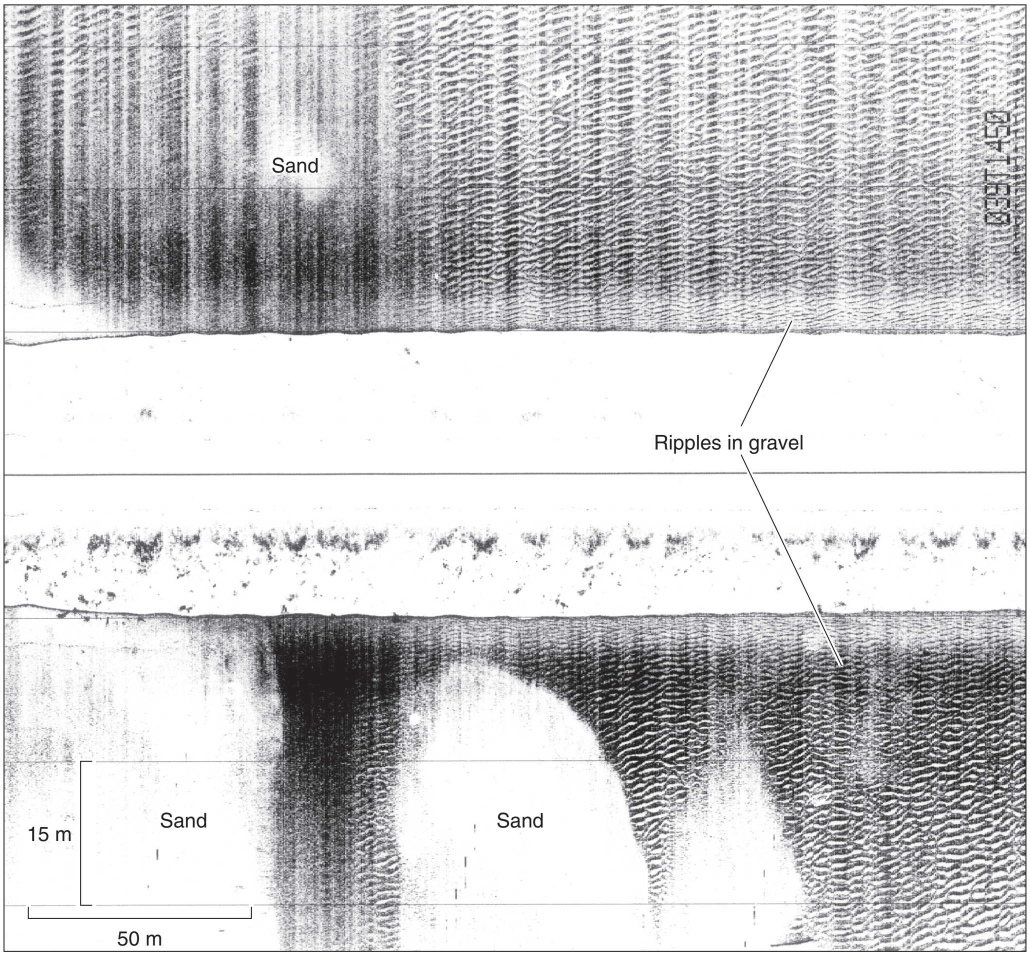


Figure 61. A 330 kHz sidescan sonogram of ripples in gravel and sand patches in the outer harbour west of McNabs Island. The gravel in these ripples consists of gravel-sized particles in the granule, pebble, and cobble range, with minor amounts of sand. The ripples in gravel are formed by large oscillatory waves during storm events and are therefore intermittently active.

Shoal. The boulders range up to 5 m in diameter. In the area to the southwest of Hartlen Point the seabed consists almost entirely of a boulder pavement.

As part of harbour cleanup studies, a suite of boreholes was collected on Ives Knoll that penetrated the Sable Island Sand and Gravel to the underlying till and provided information on grain size, sorting, and stratigraphy (Jacques Whitford Ltd., 1992). Three of the boreholes were located on a subaerial gravel spit and five were located in the nearshore. All the boreholes terminated in till at depths ranging from 4 m to 8.5 m, indicating that the sand and gravel directly overlies the till. Sand and gravelly sand contained layers of sandy gravel, gravel, cobbles, and boulders. The density of the materials indicates that they ranged from very loose to densely packed, but were generally in the loose to compact range. Trace amounts of organic materials were found. Most often sandy gravel was overlain by rounded cobbles and boulders with minor sand. The sandy gravel was dense and grey with minor silt. In two cores the unit overlaid peaty organic silt up to 0.8 m thick.

In the outer harbour, samples and ROV observations indicate that the sand areas consist of medium- to fine-grained sand with broken and whole shells. The sand becomes coarser adjacent to the gravel and bedrock areas and forms ripples in coarse sand with granules and broken shell debris. A silty facies of the sand occurs in the area off Herring Cove with values of silt as high as 35%. This silt component decreases both seaward to the southeast out of the harbour and to the east across the harbour away from the western shore. Samples collected off Chebucto Head contained up to 3% mud. South of Lichfield Shoal the sandy seabed is covered with a variety of bed forms with modern attributes that continue to Chebucto Head and attest to disturbance from large waves and strong currents.

In Bedford Basin the samples indicate that the unit is a silty-sandy gravel ranging to a gravelly-silty sand. The gravel content ranges up to 58%. These grain-size values must be placed in the context that the unit is only one cobble thick in many areas and the sampler sometimes penetrates beneath the gravel lag, collecting finer grained subsurface material. The grain size of these samples is similar to unmodified till. This

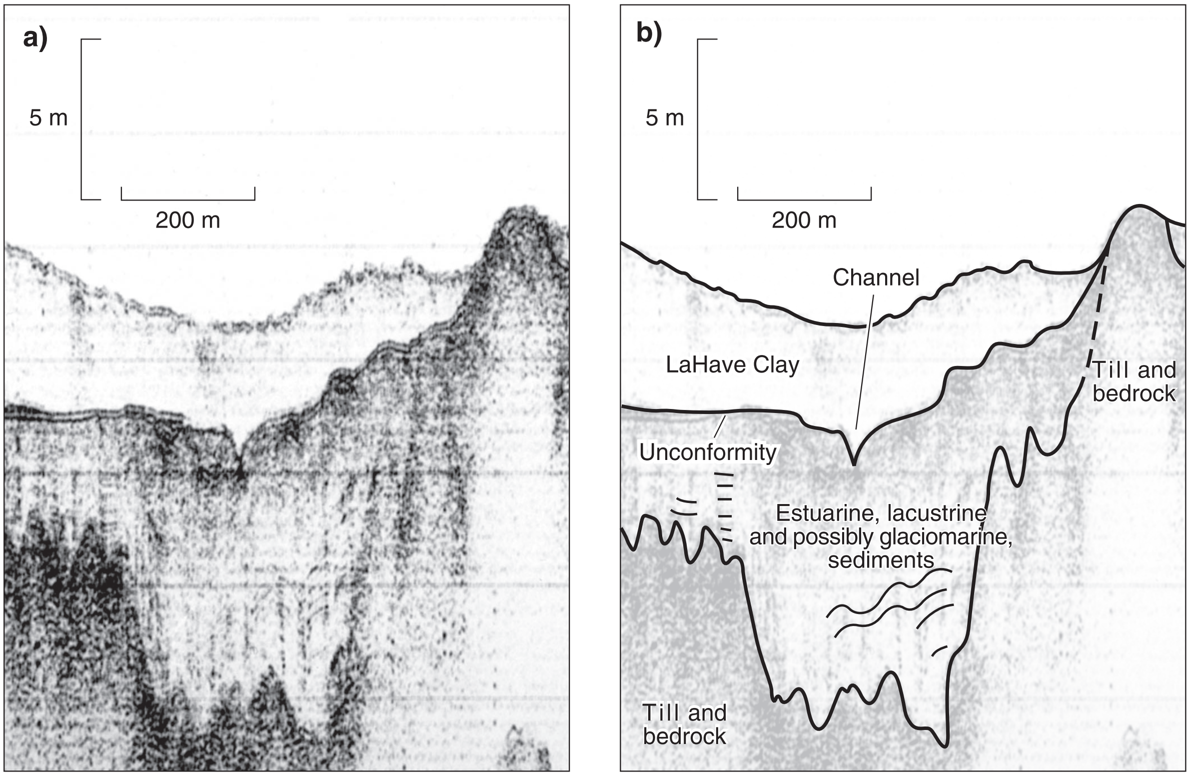


Figure 62. a) A Seistec seismic-reflection profile and **b)** interpretation from the inner harbour east of Georges Island showing a small, buried channel cut into the lacustrine and estuarine sediments formed during a phase of subaerial exposure. The Sable Island Sand and Gravel is a thin veneer overlying this surface (*see* Fig. 3 for location)

supports the concept that in the inner harbour, including Bedford Basin, the marine transgression was not as powerful an erosional agent as in the outer harbour, and only modified the surface of the till, producing a thin, discontinuous gravel lag of angular clasts.

Distribution

Sable Island Sand and Gravel is the dominant unit of the outer harbour, extending from the Maugher Beach area of McNabs Island to Chebucto Head and beyond. It extends to approximately 70 m water depth on the inner Scotian Shelf. Large areas are mapped as outcropping bedrock (Fig. 21, unit 1), but these have varying amounts of gravel cover in the cobble and boulder size range. Acoustically, it is difficult to differentiate small areas of gravel overlying bedrock, but where the boulders are large, they can be distinguished on sidescan sonograms. Aprons of gravel lag fringe most of the bedrock outcrop areas, which in most areas are topographic highs (Fig. 65). These aprons are generally flat areas that consist of gravel in the cobble to boulder range with some pebbles and granules. Close to the areas of bedrock on the western side of the outer harbour, gravel in the aprons is often formed into large ripples that contain pebbles and granules with broken shell fragments. Seaward, toward deeper water, the gravel underlies the sand that is the dominant sediment in the deep channel of the western part of the outer harbour. An area of large, isolated sand patches occurs south of Lawlor Island (Fig. 66), but that region is dominantly gravel with clasts ranging up to boulder size.

Sable Island Sand and Gravel in the inner harbour occurs both in the subsurface underlying LaHave Clay and exposed at the seabed over bedrock, till, and sometimes LaHave Clay. Where it occurs in the subsurface, it is interpreted to overlie till, estuarine and lacustrine sediments, and possibly glaciomarine sediments on an unconformity developed on their surfaces (Fig. 67). Where exposed at the seabed, it is generally a thin gravel veneer. Thick deposits of sand occur in the nearshore around McNabs Island (Fig. 13), some of which have been mined for aggregate for construction purposes. In The Narrows, the unit is a coarse gravel lag over till and bedrock, but it also occurs as constructional features in relict beach ridges and beach deposits (Fig. 6, 13, 68). These are curvilinear ridges of gravel formed at successively shallower depths as the Holocene sea flooded up The Narrows. Individual boulders in The Narrows are very large and range up to 4 m in diameter.

In Bedford Basin the unit is widespread, generally occurring in water depths of less than 20 m. The sill (‘Sherwood Ridge’, Fig. 18) separating Fairview Cove from the main body of Bedford Basin, extends between The Narrows and Birch Cove and is also gravel covered. Jonquière Bank (Fig. 69), a large drumlin topographic high, adjacent to Birch

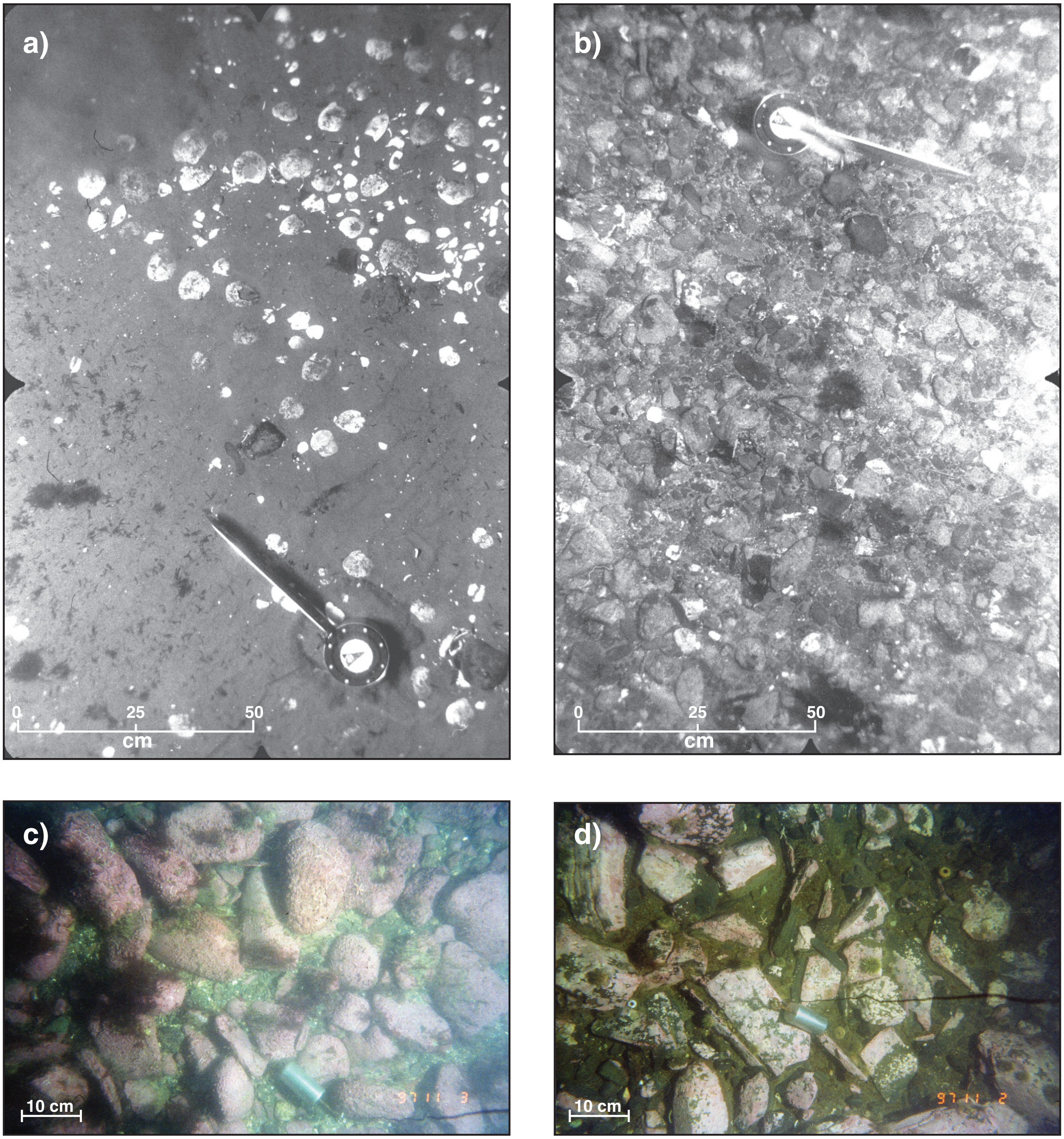


Figure 63. Bottom photographs of the Sable Island Sand and Gravel from the inner and outer harbour showing variations in clast shape and sorting: **a)** from the deep sandy channel of the western part of the outer harbour near Chebucto Head showing sand with broken and whole disarticulated shells (Photograph by G.B.J. Fader. GSC 2006-204); **b)** from farther east in the outer harbour area showing a gravel-lag seabed of subrounded pebble to cobble clasts (Photograph by G.B.J. Fader. GSC 2006-205); **c)** from Lichfield Shoal south of Herring Cove, outer harbour, showing lithothamnia-covered, rounded cobbles and boulders (Photograph by R.O. Miller. GSC 2006-206); **d)** from Ives Knoll in the inner harbour showing angular cobbles and boulders in a matrix of muddy sand (Photograph by R.O. Miller. GSC 2006-207).

Cove, is also covered with gravel and boulder berms. Sable Island Sand and Gravel does not occur beneath the LaHave Clay in the deeper water of Bedford Basin as it does in areas of the inner harbour because the transgressed area in Bedford Basin is limited to water depths above the 20 m sill at The Narrows.

Two conspicuous boulder ridges, which are part of the Sable Island Sand and Gravel, ring the entire nearshore area of Bedford Basin at a depth of between 20 m and 23 m (Fig. 70, 71). They also occur on isolated shallow areas on the western side of the basin. The presence of the boulder berms defines the location of approximately seven former islands in this area. Two have been previously named and are Parfait Bank and Jonquière Bank after a vessel and an officer of the doomed French fleet that sought protection and refuge before the founding of Halifax, respectively. The largest island in the group that existed when the basin was a lake occurs to the northwest of Jonquière Bank. The authors propose the name 'Princes Lodge Bank' for this feature after a historical landmark on the adjacent shore. It is 300 m long and less than 100 m wide. The authors also propose to name the bank that lies between Parfait and Jonquière banks as 'Sherwood Bank' for the name of the adjacent land community. The remaining former islands in the group occur to the southeast adjacent to the shoreline of Bedford Basin and in Fairview Cove. As these islands existed for a period of approximately five thousand years during the early Holocene they could represent submerged areas with significant archaeological potential. The boulder ridges were formed by seasonal freezing of a former lake that concentrated large boulders in push ridges (Fig. 72). They are up to 2 m high and are partially surrounded by LaHave Clay (Fig. 73). Remotely operated vehicle observations of large boulders in the ridges show that thin deposits of LaHave Clay occur on their surface and that biogenic growth is generally absent.

The two boulder berms, separated by 10 m to 20 m horizontally, and 3 m vertically, are interpreted to have resulted from changes in lake level associated with minor elevational changes in drainage depths across the sill at The Narrows, or changes in lake level due to fluctuating environmental conditions. A possible scenario is that a major flooding event of the early Sackville River into Bedford Basin resulted in erosion and deepening of the sill outlet in The Narrows, lowering the level of the lake, so that the deeper boulder berm represents the youngest event. It is also possible that changes in the lake level may have resulted from anthropogenic excavation activities of early peoples living in the area of The Narrows.

A large number of isolated sidescan-sonar acoustic targets occur adjacent to Navy Dock N at the naval magazine in Bedford Basin in the area of the boulder berms (Fig. 73). It has been speculated that some represent unexploded ordnance jettisoned into the basin during the 1945 explosion of the magazine (M.R. Gregory, unpublished report 3-72, Nova Scotia Research Foundation, 1972).

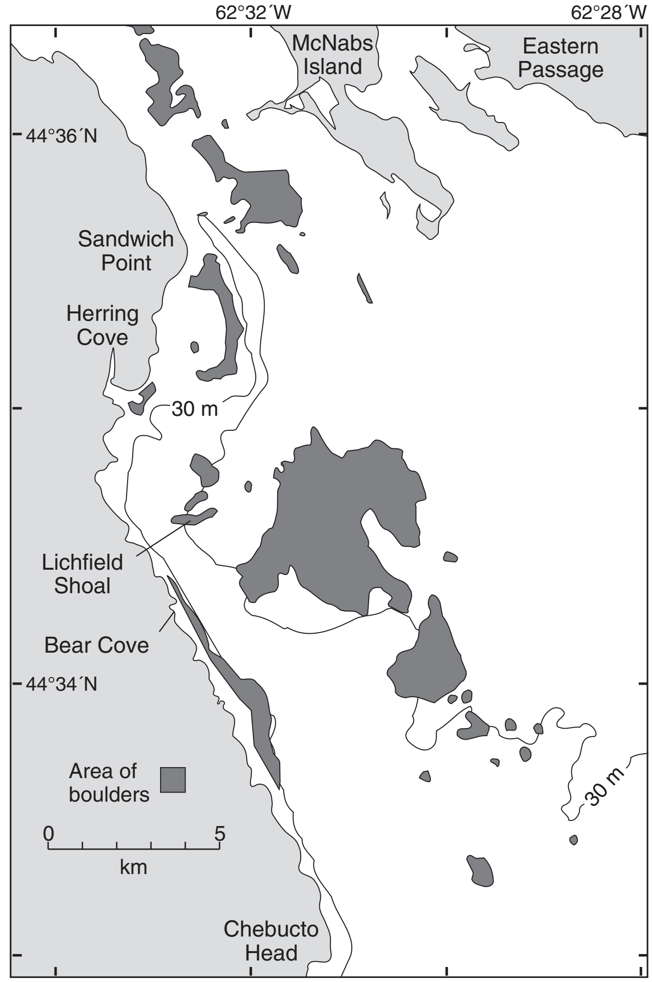


Figure 64. Map showing the distribution of boulders larger than 0.3 m in diameter in the outer harbour interpreted from sidescan sonograms. Most of the boulders overlie bedrock.

Boulder ridges also occur in the inner harbour on the flanks of Pleasant Shoal, Middle Ground, Ives Knoll, and western McNabs Island (Fig. 74). It is not clear if these boulder ridges were formed by a similar mechanism as those in Bedford Basin or whether they represent relict gravel barriers formed at some stage of the marine transgression; however, their continuous distribution, occurrence at one consistent depth, and sinuosity suggest that they are true push ridges formed by the presence of periodic ice cover of a lake in this area of the harbour (Fig. 56). In contrast, the relict boulder beach berms in The Narrows are discontinuous, parallel curvilinear features at varying elevations.

In the inner harbour, Sable Island Sand and Gravel occurs at the seabed in The Narrows; as ridges and isolated occurrences to the north and northeast of Georges Island; over Ives Knoll; in the nearshore of the Dartmouth coastline; in the nearshore of Northwest Arm and Eastern Passage; and on Pleasant Shoal, Middle Ground, and associated shoals at the southern boundary of the inner harbour (Fig. 13, 21).

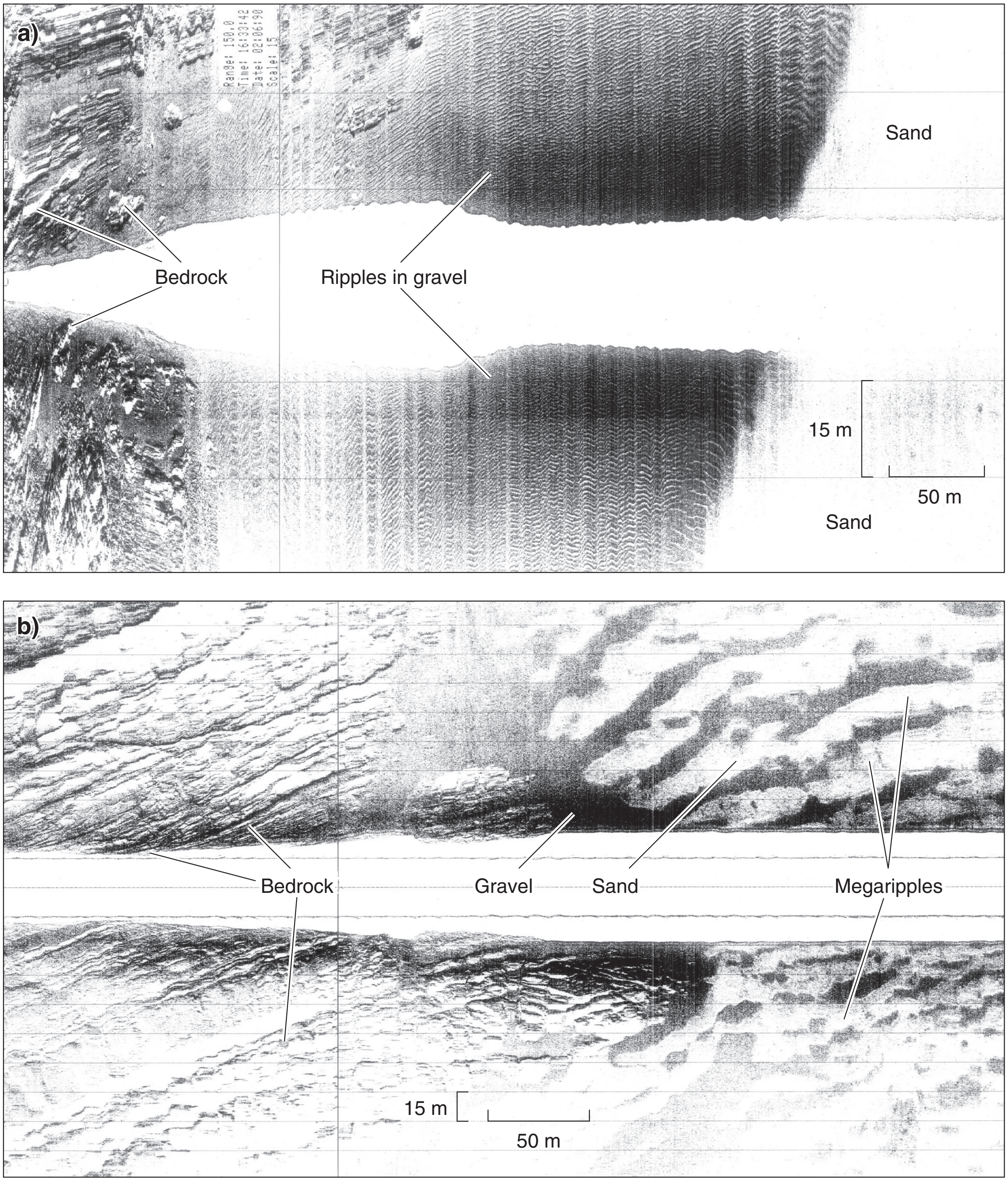


Figure 65. a), b) Sidescan sonograms from the western area of the outer harbour between Herring Cove and Chebucto Head showing the typical transition from shallow water with exposed bedrock in the west, through gravel apron (sometimes with ripples in gravel), to flat sand with megaripple bed forms in adjacent deeper water.

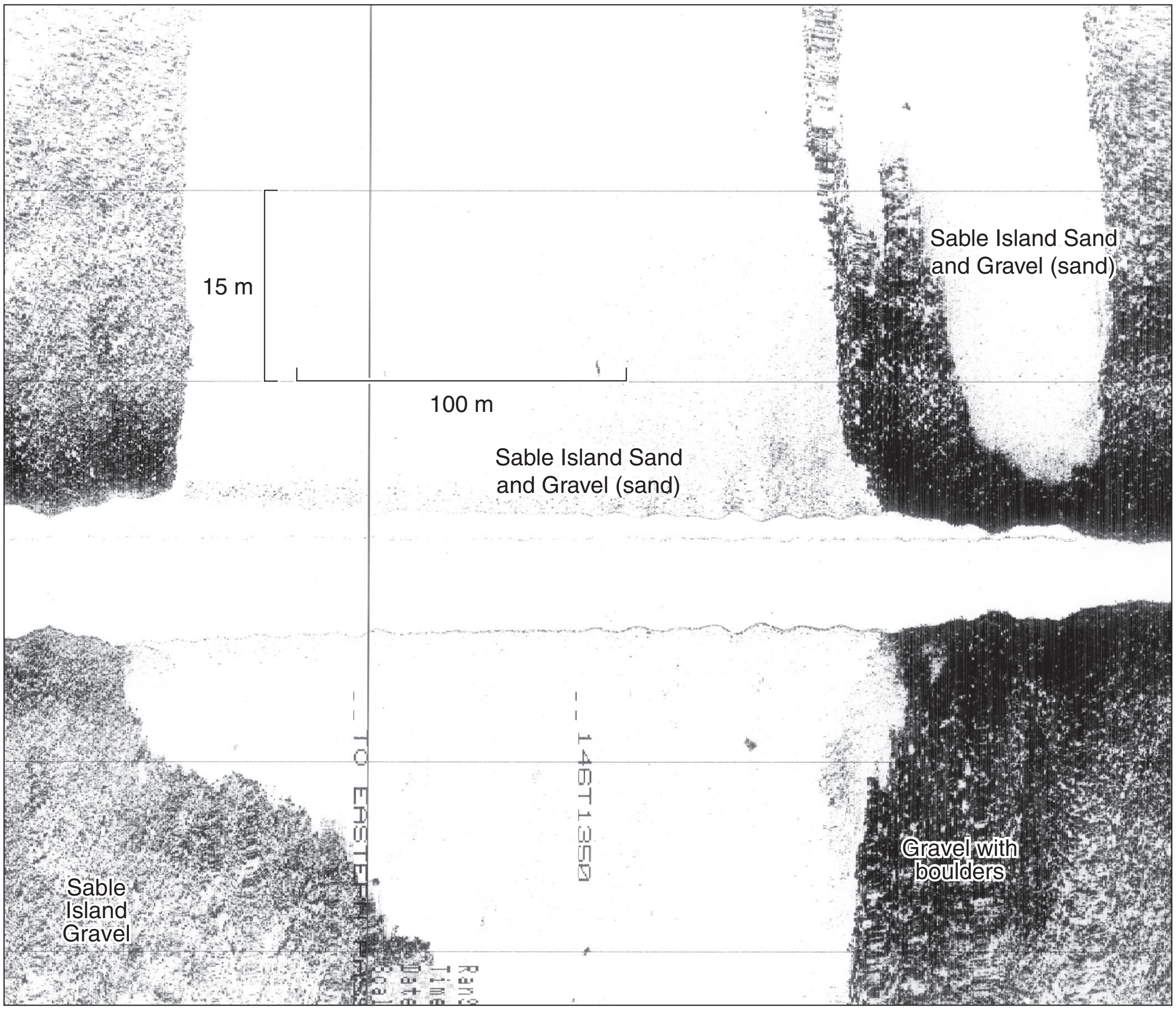


Figure 66. A 330 kHz sidescan sonogram showing large featureless sand patches covering gravel of Sable Island Sand and Gravel southwest of Lawlors Island, outer Halifax Harbour. The eastern area of the outer harbour is largely a gravel-covered seabed with many boulders and sand patches are localized in slight depressions between bedrock-controlled topographic highs. A lack of protruding boulders in the sand patch suggests that the sand is over 0.5 m thick.

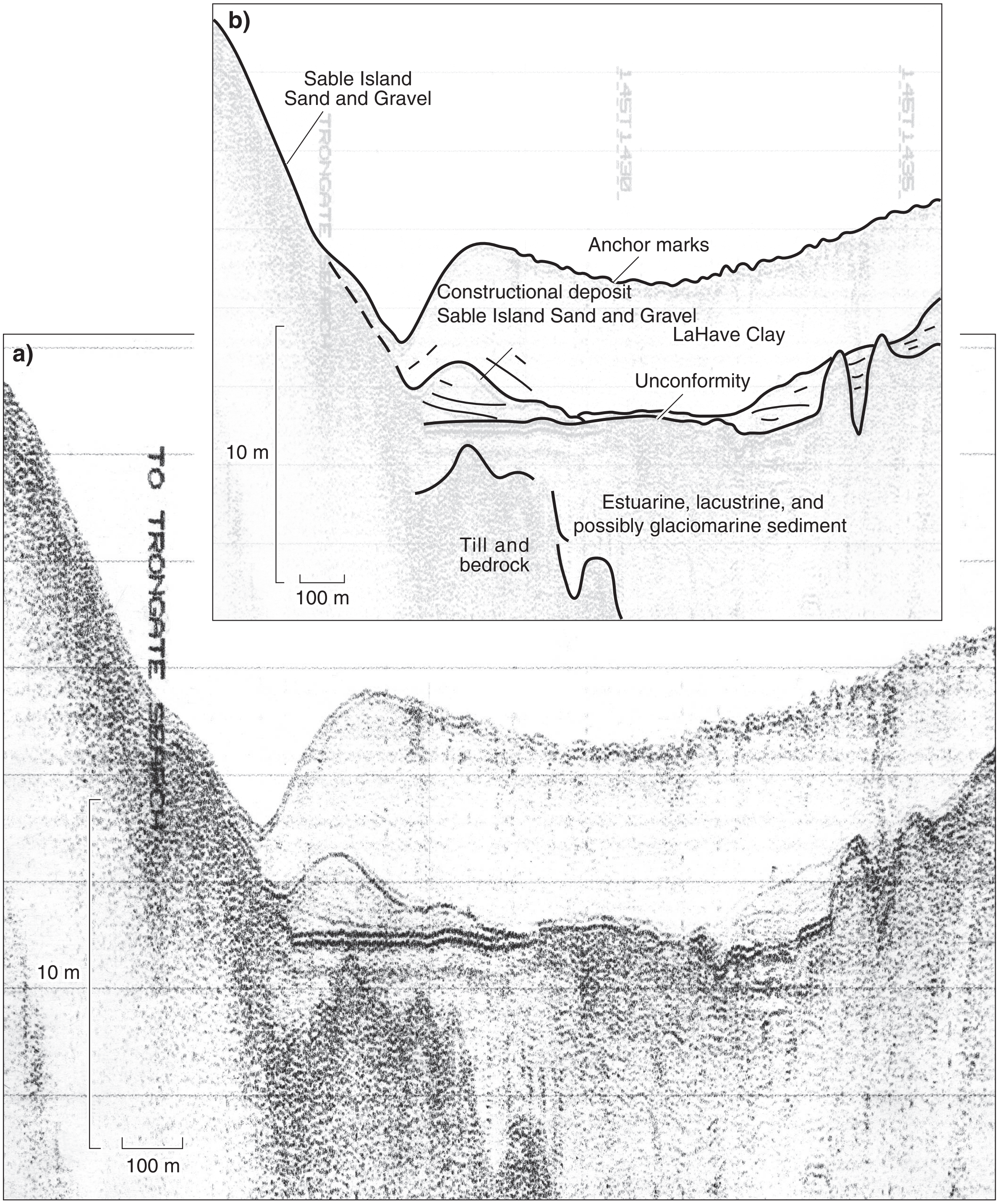


Figure 67. a) A Seistec seismic-reflection profile and **b)** interpretation from inner Halifax Harbour showing the stratigraphy adjacent to Georges Island. Note the constructional deposit of Sable Island Sand and Gravel beneath the LaHave Clay overlying the unconformity on the estuarine, lacustrine, and possibly glaciomarine sediments.

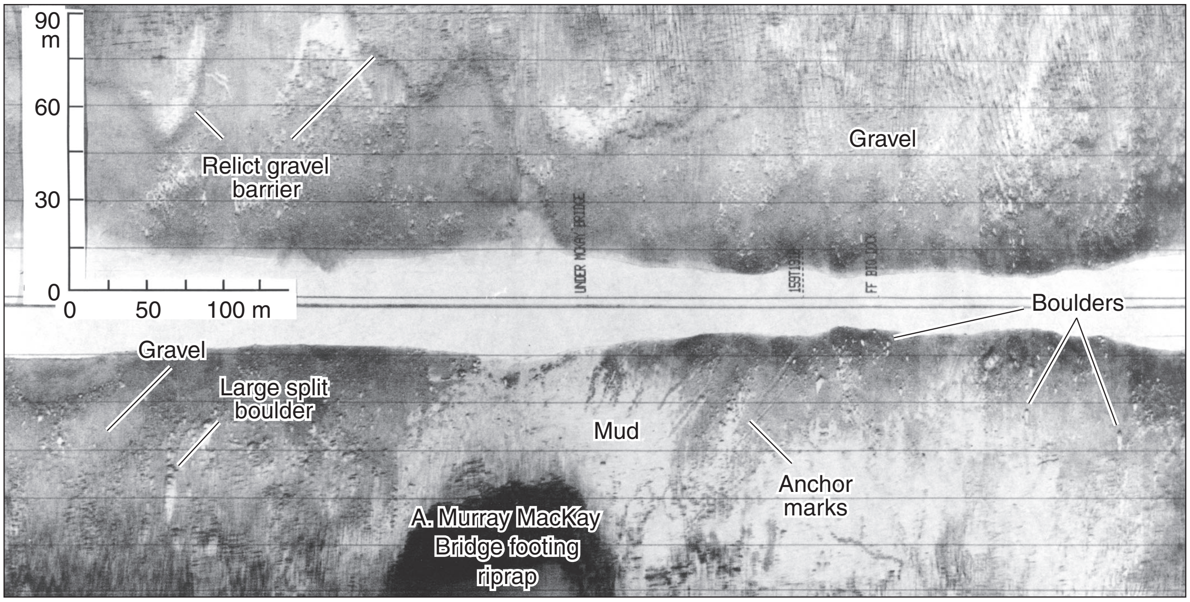


Figure 68. A sidescan sonogram from The Narrows beneath the A. Murray Mackay Bridge showing the distribution of relict, curvilinear, beach-boulder ridges and isolated boulders on a gravel seabed. A thin veneer of muddy sediment has accumulated in a slight depression adjacent to the riprap placed at the bridge footing for ship collision protection. A few anchor marks are evident. Several large boulders are up to 3 m in diameter.

To the north and east of McNabs Island, a sand facies overlies the LaHave Clay. This results from depositional changes that occurred as sea level rose in the inner harbour. As progressively higher sea levels were reached, the drumlins of McNabs Island were subjected to increased erosion and sand was deposited in the nearshore overlying the previously deposited clay. Some of these deposits of sand have been mined for use as marine construction aggregate and isolated pits and linear trenches remain on the north and east nearshore areas of McNabs Island (Fig. 13, 75).

Benthic biology

Systematic regional observations of the benthos have not been conducted for Halifax Harbour, but selective observations have been undertaken in the outer harbour (Hargrave et al., 1989), and during the collection of samples, and from submersible and ROV studies of the seabed during this study. Most of the studies have been confined to areas containing Sable Island Sand and Gravel. The common understanding, as a result of the continued discharge of raw sewage in the inner harbour, is that it contains a sparse distribution and density of benthic organisms. Hargrave et al. (1989) observed dense beds of brown and red macrophytes covering rocky slopes at depths from 7 m to 17 m near Herring Cove. Large boulders of the outer harbour are covered with bryozoans and seaweeds. In the deeper water of the outer harbour, the sand facies contains molluscs, whole and broken shell fragments, and polychaete worm tubes often in the troughs of sand bed forms. In The Narrows, large areas of gravel including boulders are covered with numerous sea anenomies and sea urchins, and large horse mussels occur on the flat gravel-lag surfaces. The gravel clasts are encrusted with coralline algae (*Lithothamnium*). In contrast, in Bedford Basin, large boulders in the nearshore and in the continuous boulder berms are largely devoid of attached organisms.

Depositional processes

Sable Island Sand and Gravel is the dominant surficial sediment unit in the outer harbour and its surface in many areas contains a variety of bed forms. These include megaripples, sand ribbons, gravel barriers, ripples in gravel, and gravel circles. They are largely modern bed forms, responding to present day, high-energy oceanographic conditions. Some aspects of the bed forms, however, are relict, having developed at the shoreface of the transgressing Holocene sea with little subsequent activity and include ice-formed boulder berms, barrier beaches, and gravel lags. The dominant textural characteristics of the unit, however, owe their origin to formation in the beach zone of the transgressing Holocene sea. In contrast to the unit in the outer harbour, which is dominantly a well sorted sand and gravel and largely devoid of fine-grained silt and clay, the unit in the inner harbour consists of thin, discontinuous gravel lag composed of angular clasts. It is poorly sorted and the angularity is attributed to a lack of high-energy environments in the inner harbour during formation of these sediments. Additionally, fine-grained silt and organic floc can periodically be deposited on the coarser sediment of the inner harbour during low-energy conditions. These sediments are subsequently mobilized and transported during stormier times of the year.

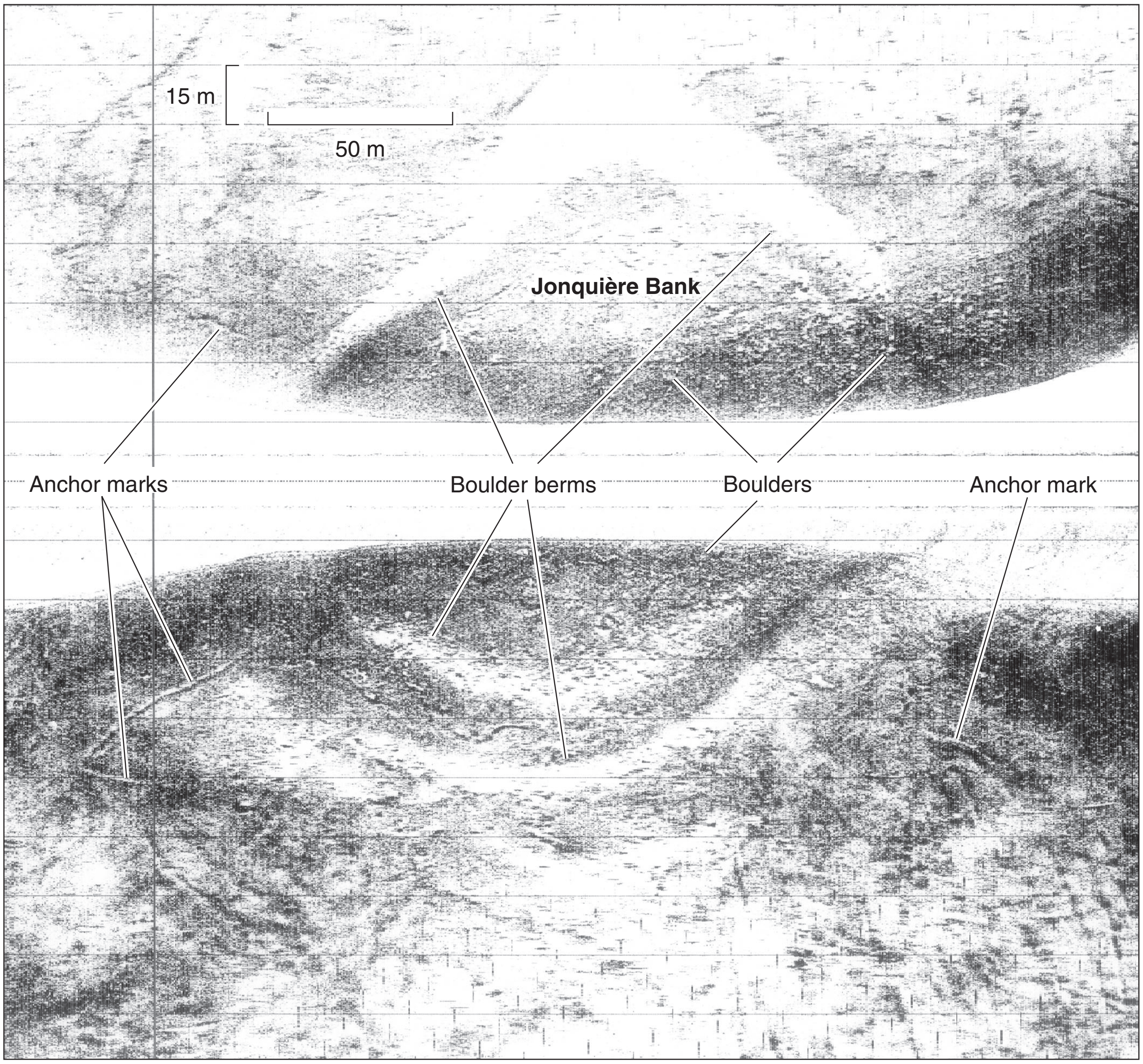


Figure 69. A sidescan sonogram across Jonquière Bank, a drumlin in Bedford Basin, showing the presence of two boulder berms ringing the bank. The boulder berms are separated horizontally by 15–20 m and are elevated 1–2 m above the surrounding seabed. Their presence indicates that the bank was a former island in a lake prior to the marine invasion of Bedford Basin approximately 5800 BP. Linear anchor-drag marks are widespread.

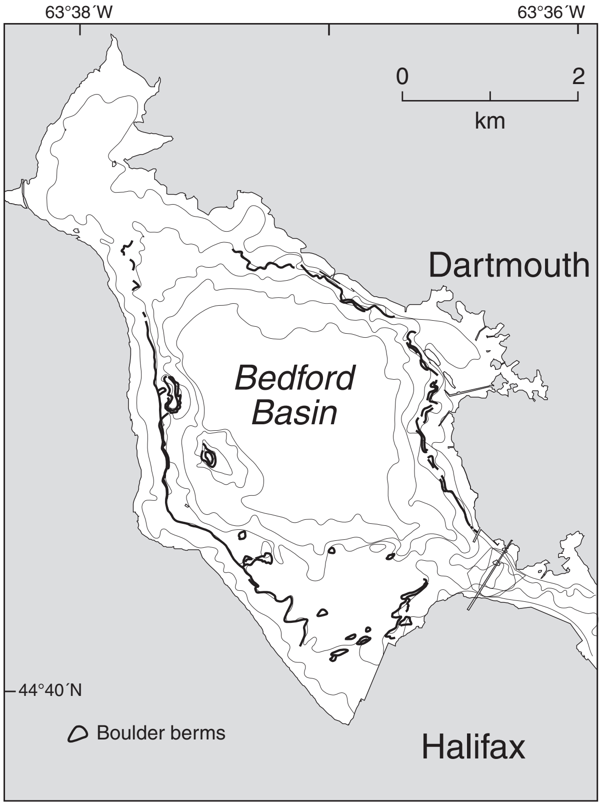


Figure 70. A map of boulder berms in Bedford Basin. These features are more or less continuous around the perimeter of the basin at a depth of 23 m. They define the location of former islands in the basin and the lower limit for transgressed surfaces. The boulder berms are buried by more recent sediment in a few areas.

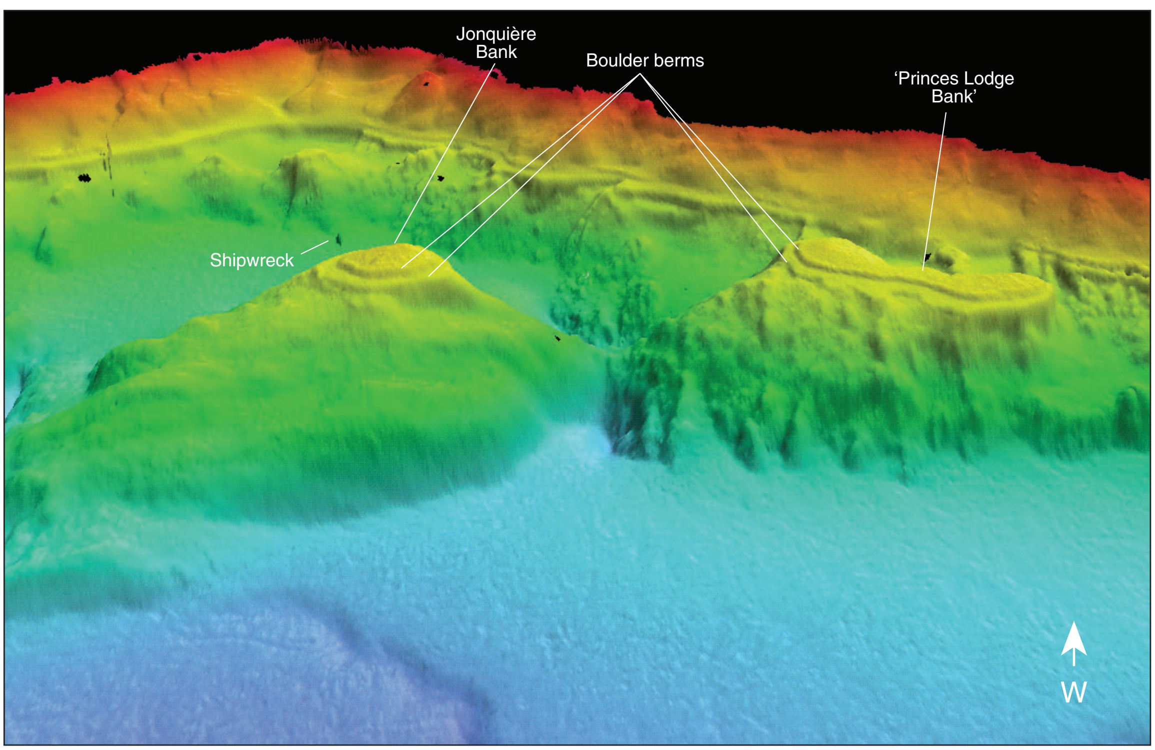


Figure 71. A 3-D perspective view of the western area of Bedford Basin based on multibeam bathymetry. Two prominent boulder berms ring the basin at a present water depth of 23 m and were formed as ice-push ridges when the basin was a lake. Areas in shallower water above the berms have been transgressed and the morphology of the seabed has been muted and smoothed by this process in contrast to deeper areas with more rugged relief. Closed boulder berms define the location of former islands within the basin: Jonquière Bank and 'Princes Lodge Bank'. For scale, the distance across Jonquière Bank is 180 m.

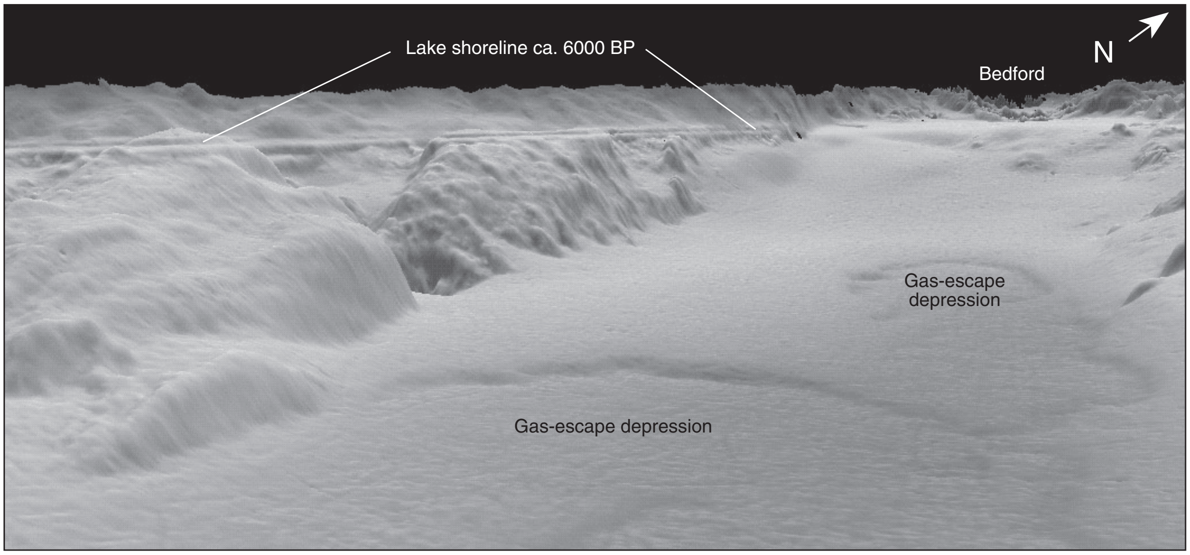


Figure 72. A 3-D perspective view of the northwestern area of Bedford Basin from multibeam bathymetry. This image clearly shows the former lake shoreline at approximately 6000 BP defined by boulder berms. The continuity and flatness of the berms suggests that they could only have been formed by a former water level. Two of the large methane-gas-escape depressions in the basin occur on the adjacent, deep basin floor.

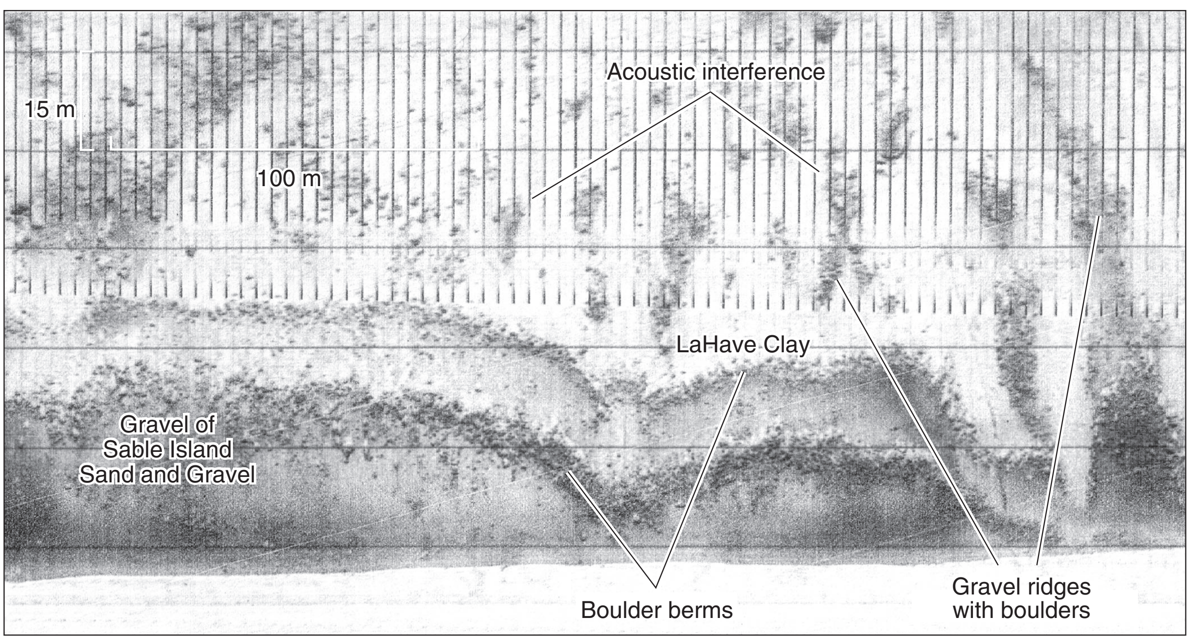


Figure 73. A sidescan sonogram from the northeastern side of Bedford Basin showing two boulder berms that ring Bedford Basin at a depth of 23 m surrounded by muddy sediment. Boulders in the berms range up to 3 m in diameter. The shallower boulder berm appears to be the larger of the two. In deeper water adjacent to the berms, the seabed consists of isolated and linear patches of gravel (eroded moraines) with boulders protruding through muddy sediment. Some of the isolated acoustic targets protruding from the LaHave Clay could represent unexploded ordnance ejected to the basin from the magazine explosion of 1945.

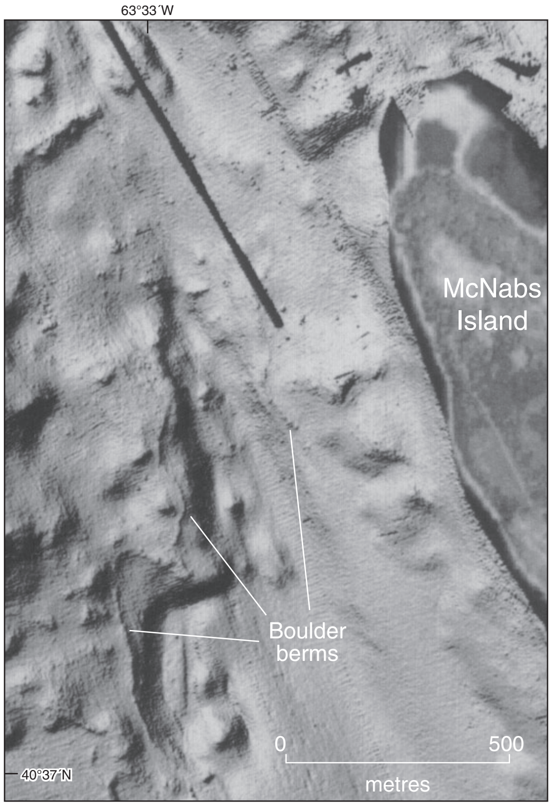


Figure 74. Multibeam bathymetric image showing the presence of continuous boulder berms between Pleasant Shoal and McNabs Island, suggesting the presence of a lake in this area of the harbour prior to the marine transgression (Fig. 13).

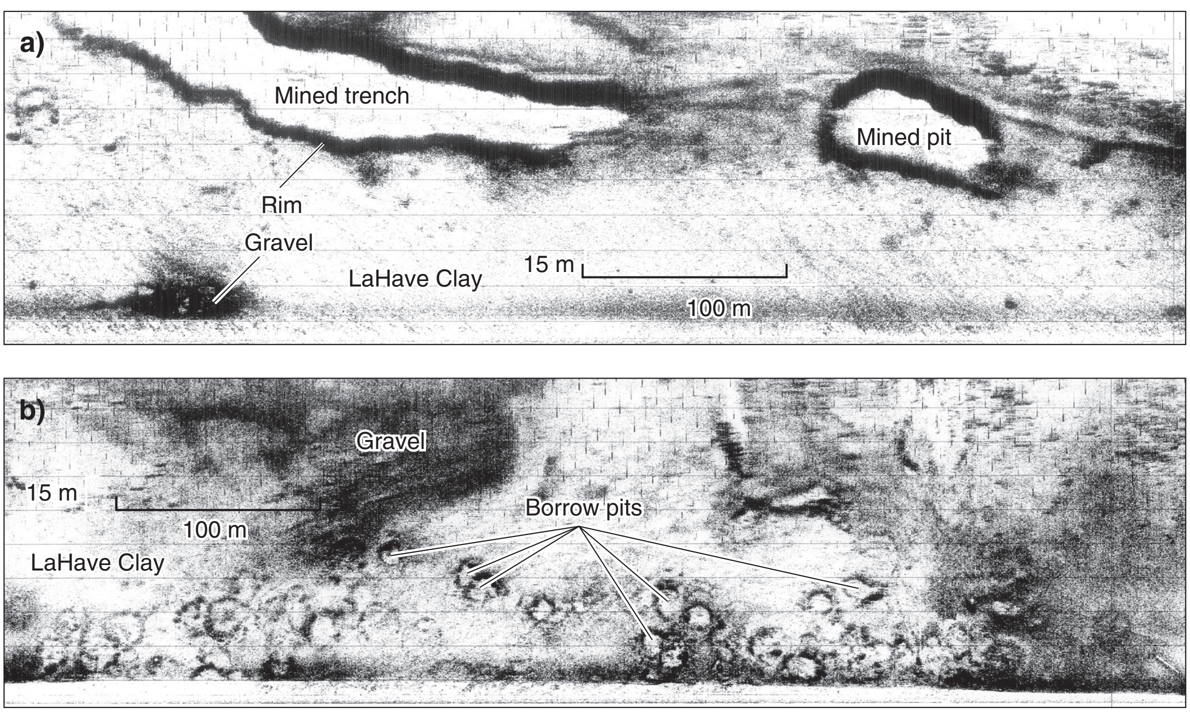


Figure 75. Sidescan sonogram of mined **a)** trenches and **b)** pits (borrow pits) along the eastern flank and north of McNabs Island. Aggregate was removed from these areas in the 1950s to supply construction projects in Halifax. They have not filled in since their formation over 40 years ago.

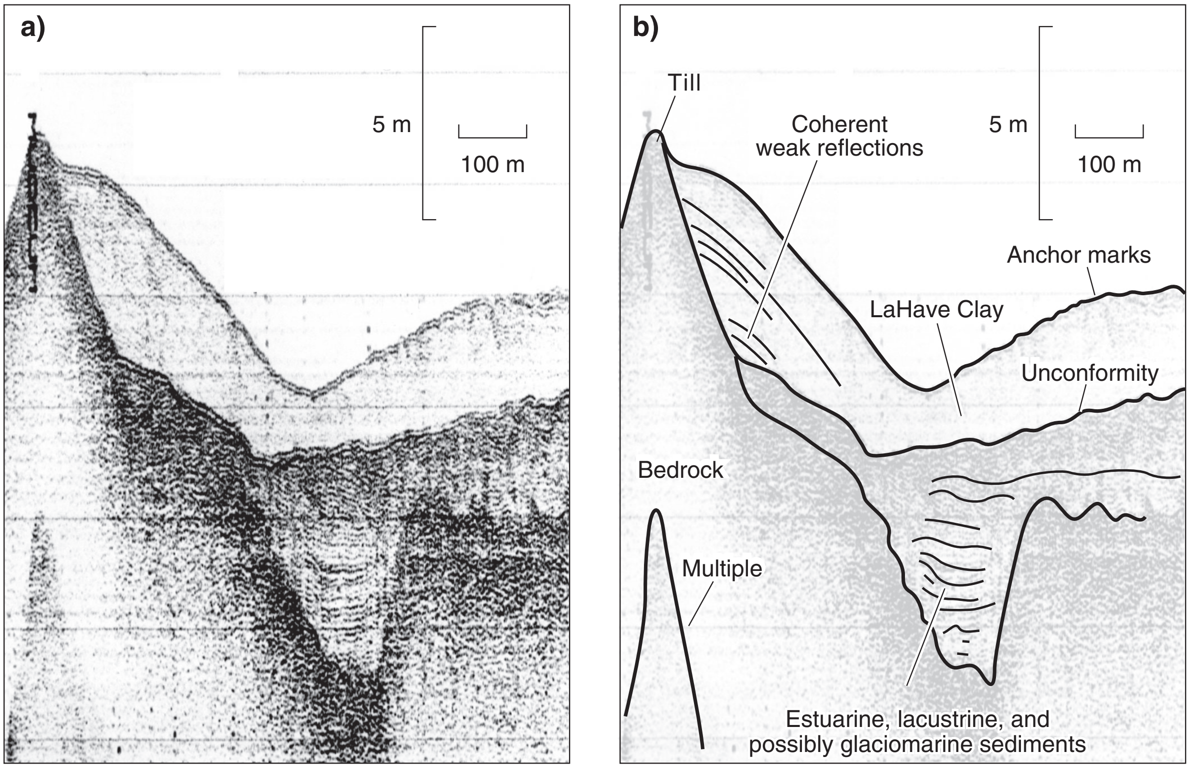


Figure 76. a) A Seistec seismic-reflection profile and **b)** interpretation of LaHave Clay onlapping till west of Georges Island in the inner harbour, showing its typical acoustic signature. It consists of weak, continuous coherent reflections locally at the base, grading to acoustically transparent sediments upsection. Most LaHave Clay surfaces in the harbour are rough and undulating from the presence of many generations of anchor marks and debris. It is gas charged in places.

LaHave Clay

Seismostratigraphy

The LaHave Clay is easily penetrated by all of the high-frequency, high-resolution seismic-reflection systems used in the study, including echosounders. The unit is normally acoustically transparent (Fig. 76), but can exhibit a wide variety of internal reflection characteristics. The basal section often contains weak to moderate, continuous coherent reflections (Fig. 77). These reflections decrease in intensity upsection and are interpreted to arise from a slightly coarser texture of the basal part of the section, which was deposited in an early post-transgression environment that was shallower and more energetic than at present. In some areas the continuous, coherent, low-intensity reflections persist throughout the section. The reflections at the base of the LaHave Clay near Georges Island (Fig. 77) show the persistence of a moat around the island continuing from the early deposition of LaHave Clay to the present. The moat has not formed as the result of recent erosion around the drumlin — an alternative interpretation based on morphology alone. Therefore, the moat is not an erosional feature, but a nondepositional feature.

A large sediment drift to the north of Georges Island is characterized by seismic reflections that indicate progressive infill of a moat that encircled Georges Island during early deposition of the unit, but has since been infilled and obliterated (Fig. 77). The infilling of the moat on the north side of the island indicates either that the strength of the bottom currents flowing in and out of the harbour have diminished over time, or that the currents have shifted in direction or orientation. It also supports an interpretation of current strength increasing from the south with time.

In Dartmouth Cove the reflections in the LaHave Clay are approximately flat lying and those in the upper section near the seabed have been truncated by an irregular unconformity representing the present seabed (Fig. 78). This is interpreted as modern erosion of the seabed, the result of dredging, anchoring, and other shipping-related activities. Nondepositional moats at LaHave Clay boundaries near steep surfaces such as bedrock shoals (Fig. 13, 20) are also common. The internal structure of downward-dipping reflectors in these areas indicates that many of the moats also formed during the early deposition of the LaHave Clay. In some areas the moats have persisted to the present time, suggesting little change to the current regime, whereas in other areas early moats have been infilled.

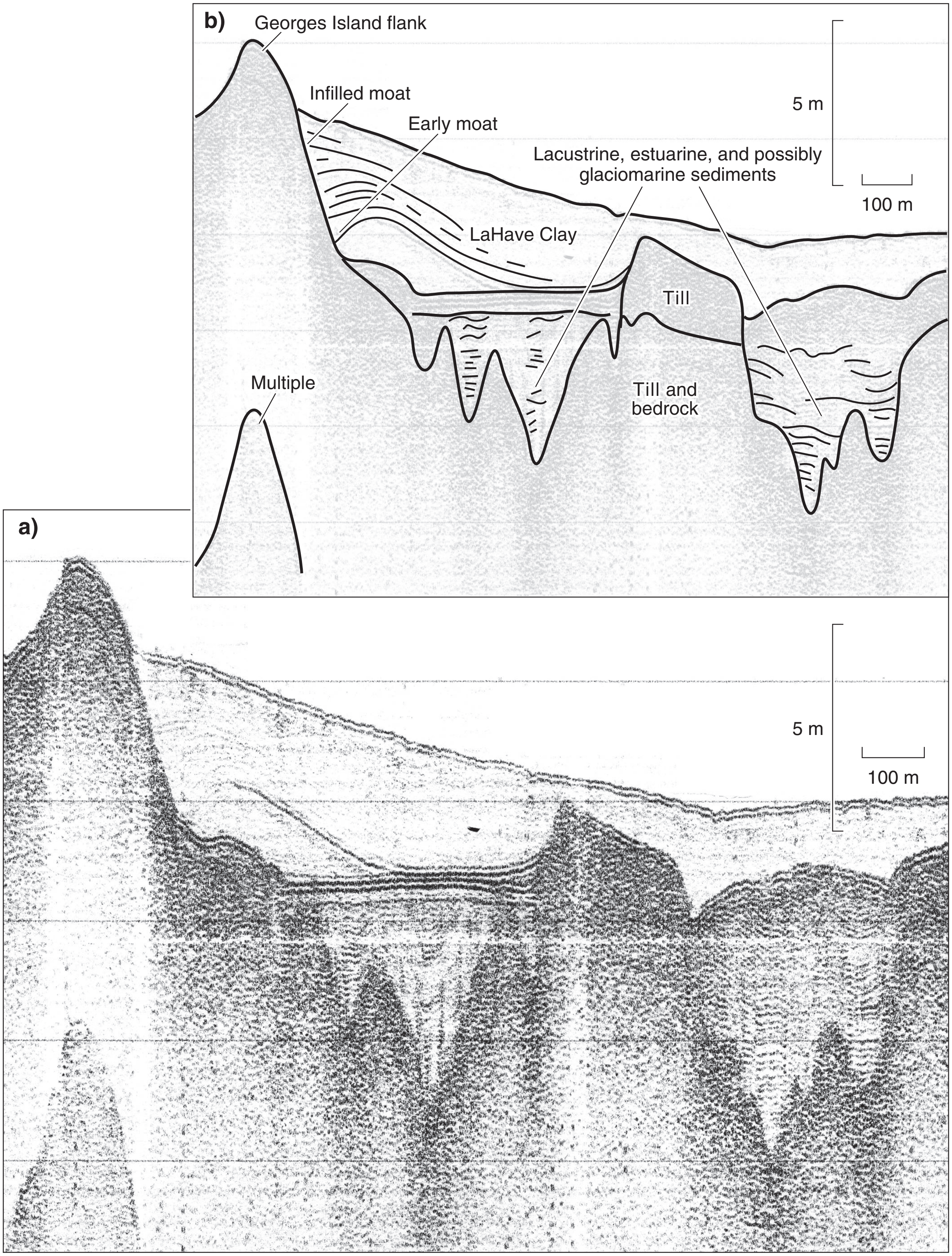
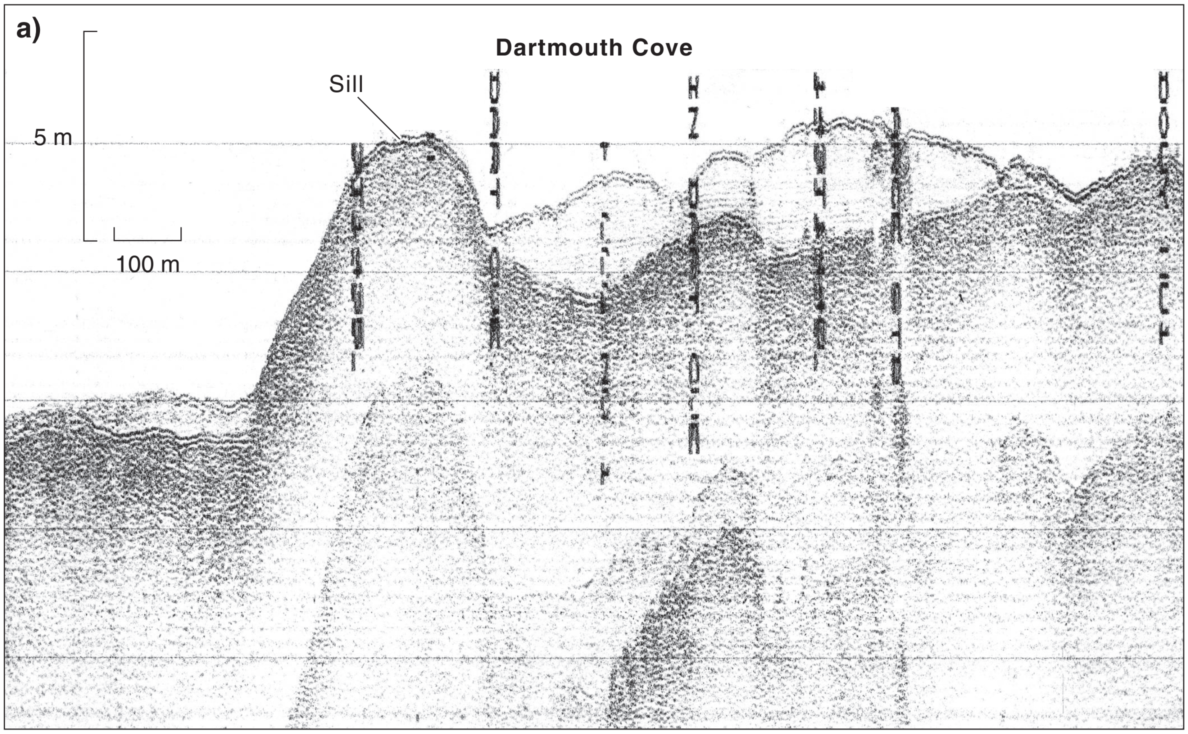


Figure 77. a) A Seistec seismic-reflection profile and **b)** interpretation from the area north of Georges Island showing continuous coherent reflections within the LaHave Clay. Reflections at the base of the LaHave Clay downlap on the flank of Georges Island and indicate the presence of an early moat. These reflections alter to onlap upsection. The shape and structure of these reflections indicate progressive infill of an early moat, suggesting changing depositional environments of decreasing energy in this area since early LaHave Clay deposition.



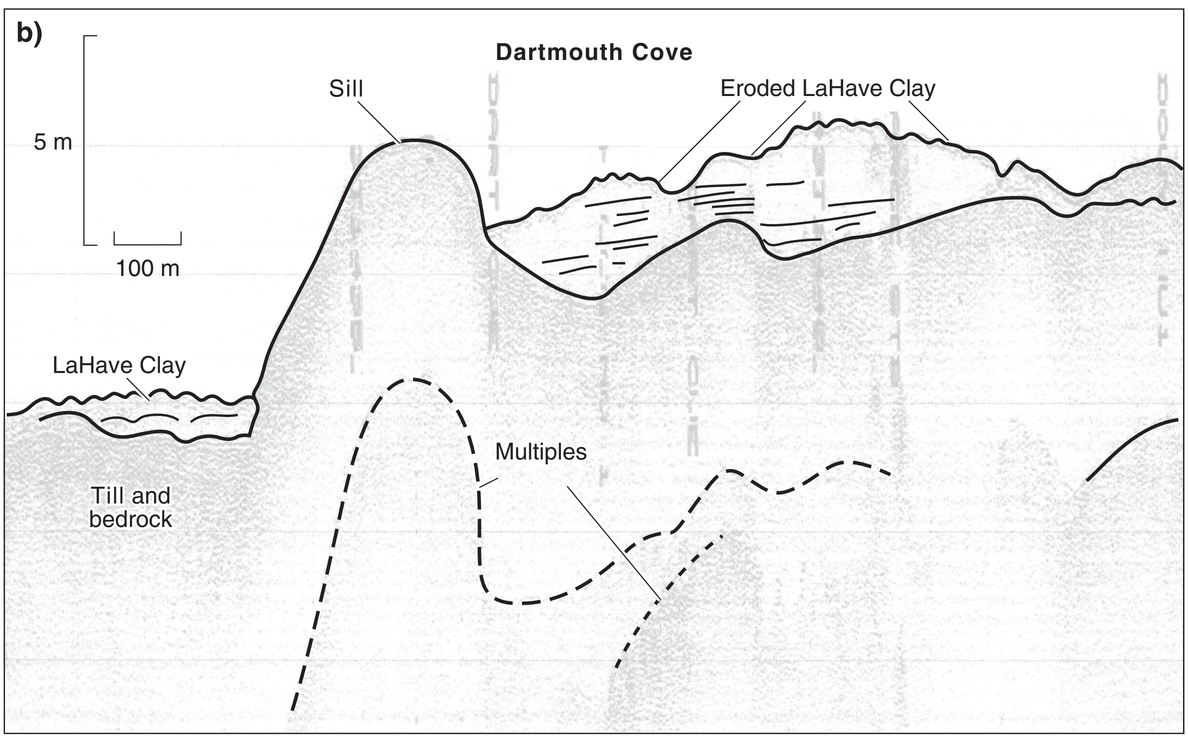


Figure 78. a) A Seistec seismic-reflection profile and **b)** interpretation from Dartmouth Cove showing flat-lying reflectors within the LaHave Clay that have been eroded and broken by erosional processes at the seabed. This erosion may have resulted from large, flood-discharge events within the Dartmouth lakes system that connects with Dartmouth Cove or may be the result of ship repair, dredging, and other anthropogenic activities.

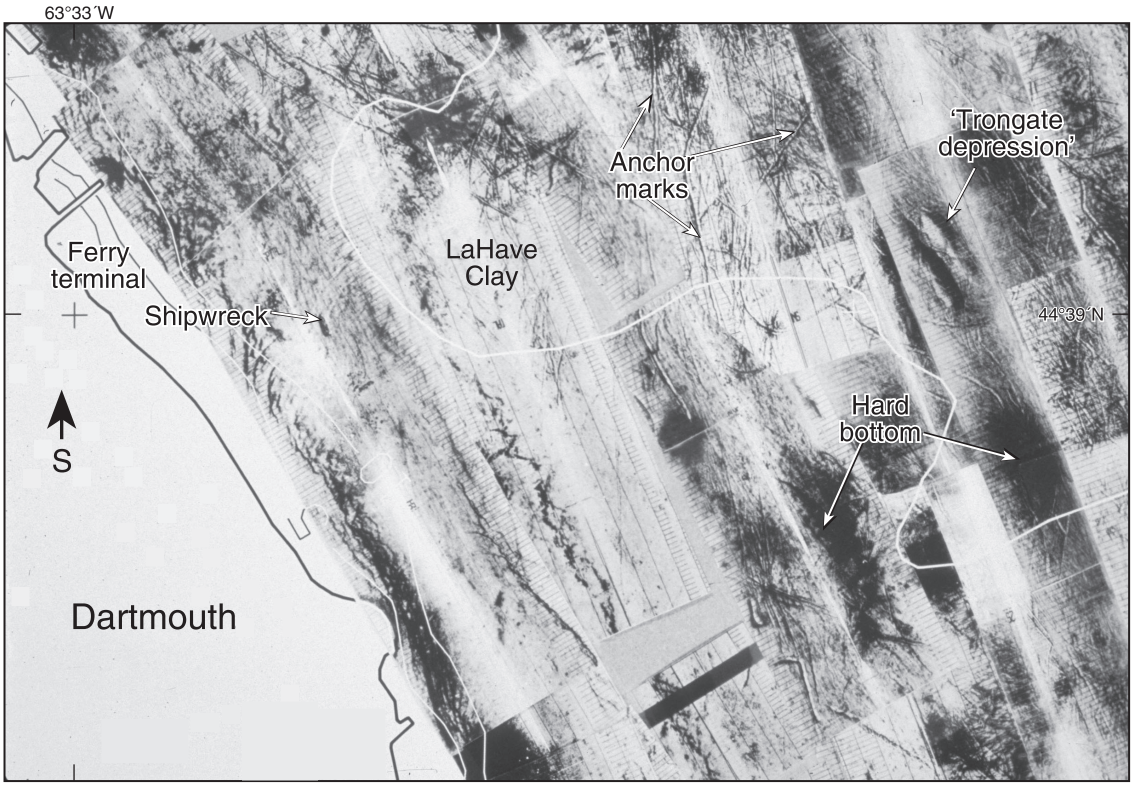


Figure 79. A section of a sidescan-sonar mosaic from the inner harbour northeast of Georges Island showing both sediment textural variation and seabed features (Fader et al., 1991). The light-toned low-reflectivity seabed represents LaHave Clay and the highly reflective seabed is gravel-covered till. Many generations of anchor marks cut into the seabed. Some appear fresher than others indicating varying ages of formation. The location of the sinking of the *Trongate* ('Trongate depression') and a small, unidentified shipwreck are also shown (Fig. 13).

In some areas of the inner harbour many parabolic reflections occur throughout the unit, suggesting the presence of point-source reflectors such as boulders, gas, buried cables, or debris; however, some of the shallow, parabolic reflections could also arise from side echoes generated by the complex criss-crossing pattern of deep and linear anchor marks.

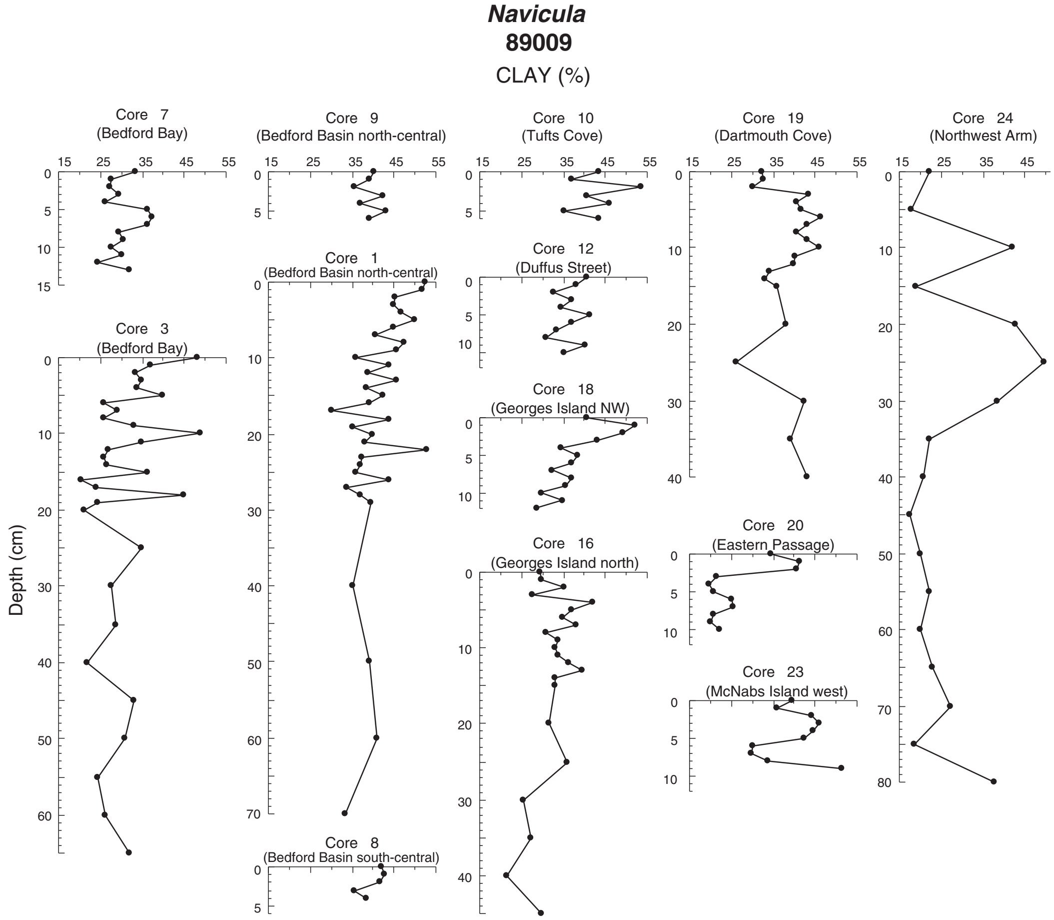
The surface of the LaHave Clay ranges from smooth and flat to very rough and hummocky. Most of the rough surface relief results from the presence of many generations of ship-anchor marks (Fig. 79). This has produced a characteristic rough and irregular morphology to the seabed and has eroded and mixed the sediment, a process for which the authors have used the Fader et al. (1991) term 'anchorturbation'. Other processes that have modified the surface of the LaHave Clay are the dumping of dredge spoils, propeller scouring, the venting of gas, and the development of pockmarks. *See* the discussion on anchor marks and anthropogenic debris in the 'Anthropogenic features' section for details.

Lithology

Many seabed samples and short cores have been collected to characterize the texture and geochemistry of the LaHave Clay in the harbour (Fader and Buckley, 1997). Approximately 30 piston, Eckman-style, and Lehigh gravity cores penetrated the LaHave Clay. Most were short cores approximately 1.5 m long. Textural analyses showing the silt and clay content from a selection of cores throughout the harbour is presented in Figure 80 (Buckley et al., 1991).

In Bedford Bay the LaHave Clay is a clayey-sandy silt ranging to a sandy-clayey silt. In the nearshore of Bedford Bay it is a coarser facies consisting of clayey-silty sand with some gravel, perhaps ice rafted. Cores indicate that it becomes siltier with depth. An average sample grain size of LaHave Clay from Bedford Bay consists of 4% sand, 76% silt, and 29% clay. In Bedford Basin the unit is a sandy-clayey silt ranging to a clayey-sandy silt, with the silt increasing from 46% at the seabed to 74% at 1 m depth. It also becomes coarser in the nearshore where it is represented by a clayey-silty sand with a small amount of gravel. A typical size distribution for LaHave Clay in Bedford Basin is 14% sand, 67% silt, and 17% clay.

Where it occurs in The Narrows, LaHave Clay is a clayey-sandy silt becoming siltier with depth. Cores from Tufts Cove are a consistent clayey silt with depth. For most of the inner harbour the unit is a clayey-sandy silt ranging to a sandy-clayey silt, increasing in silt content with depth. A typical size distribution from the inner harbour is 16% sand, 70% silt, and 14% clay. Samples collected in Northwest Arm indicate a clayey-sandy silt ranging to a sandy-clayey silt with a slight



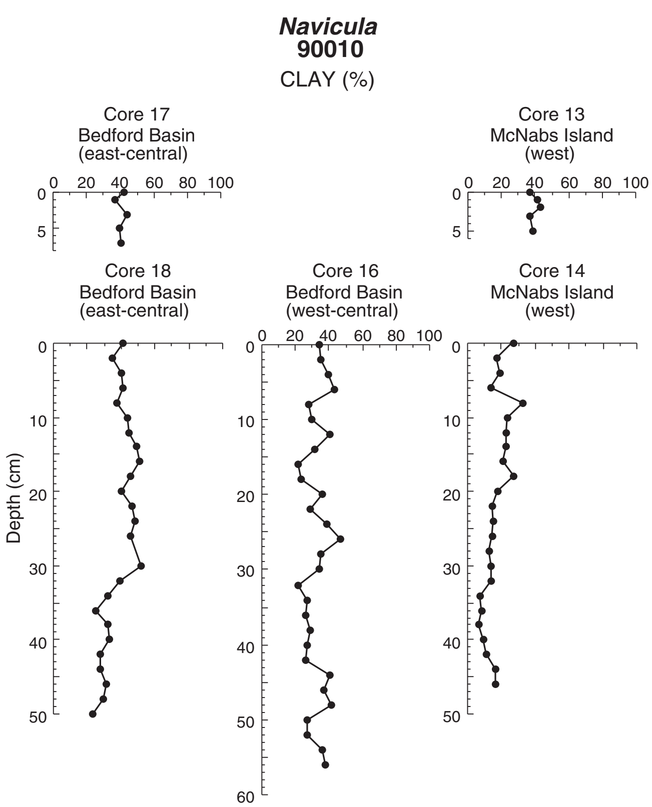


Figure 80. Core logs of silt and clay content through LaHave Clay in Bedford Bay, Bedford Basin, and the inner harbour including Eastern Passage and Northwest Arm (*modified from* Buckley et al., 1991). In most of the cores the clay content increases upcore with a concurrent decrease in silt. This is interpreted to be the result of a combination of increasing water depths and an associated drop in current velocities, increase and intensity of anthropogenic processes such as propeller scour, and changes in the textural composition of runoff from urban development.

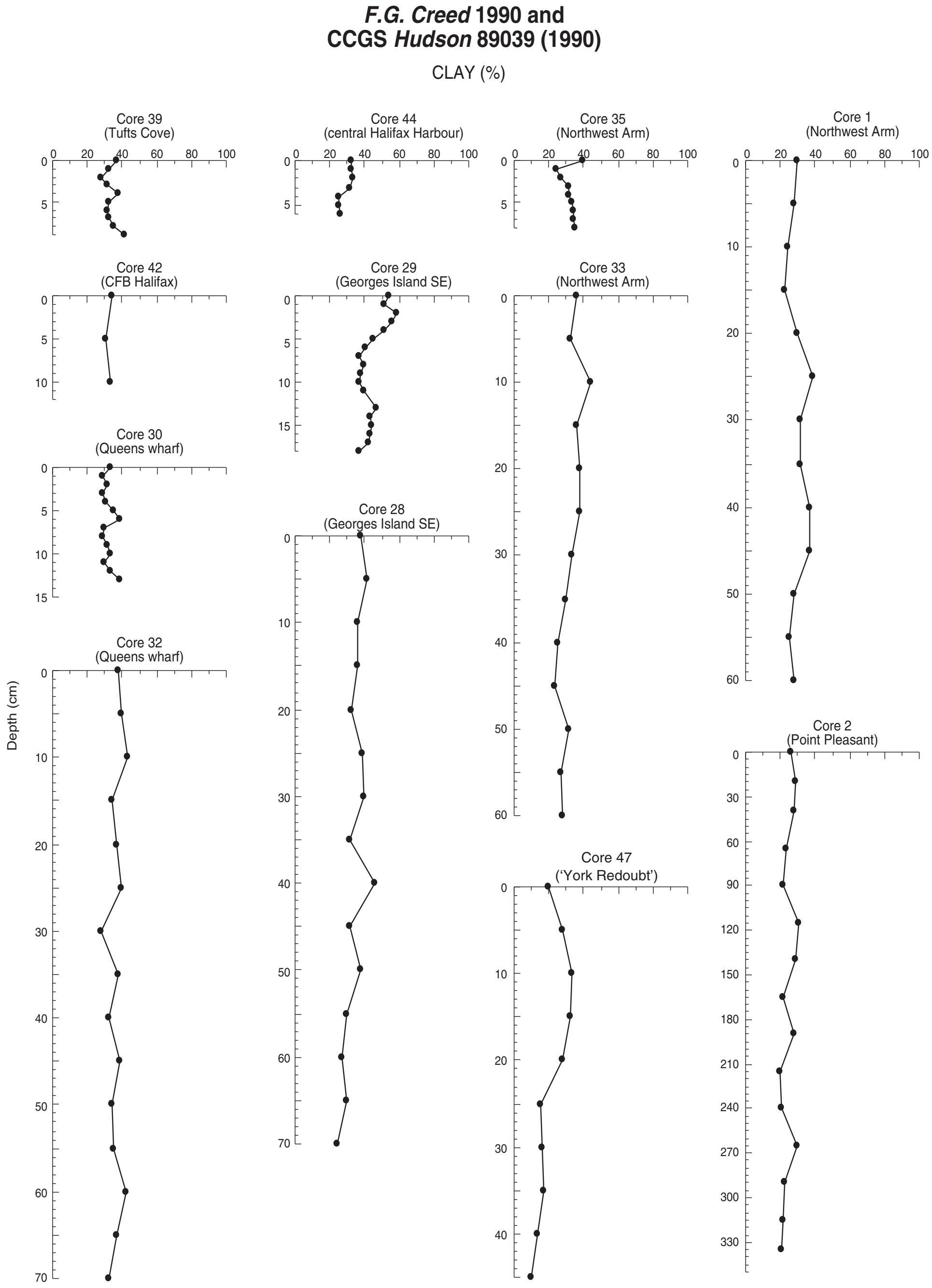
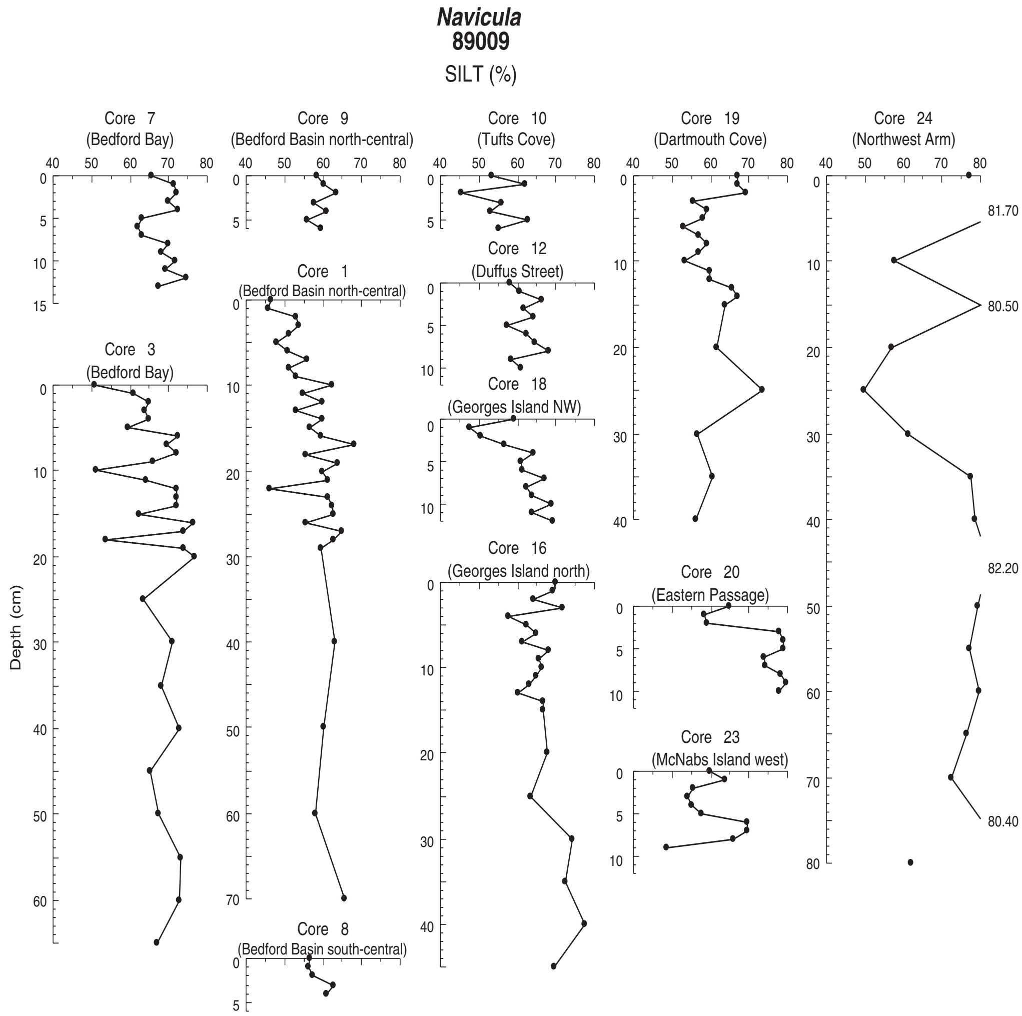


Figure 80 (continued)



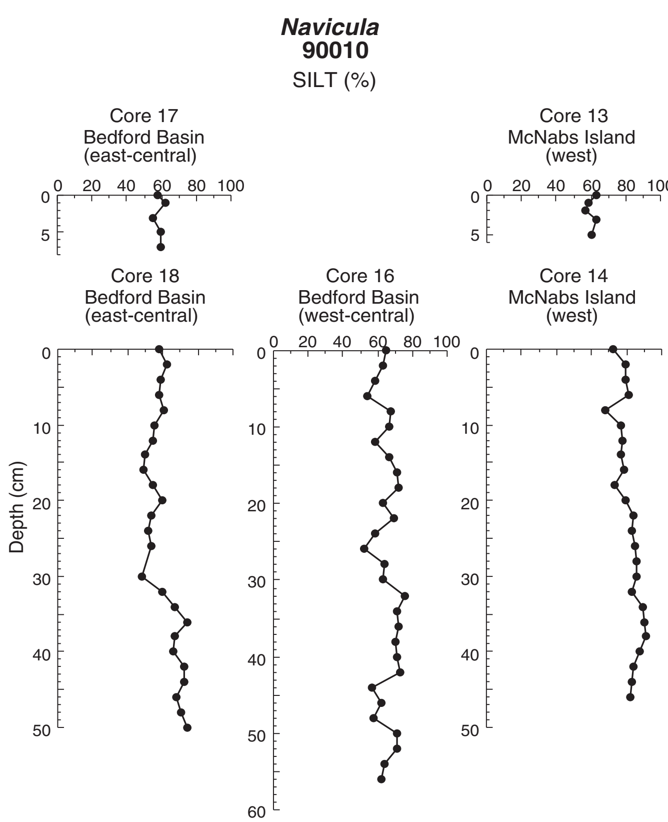


Figure 80 (continued)

F.G. Creed (1990) and
CCGS _Hudson_ 89039 (1990)

SILT (%)

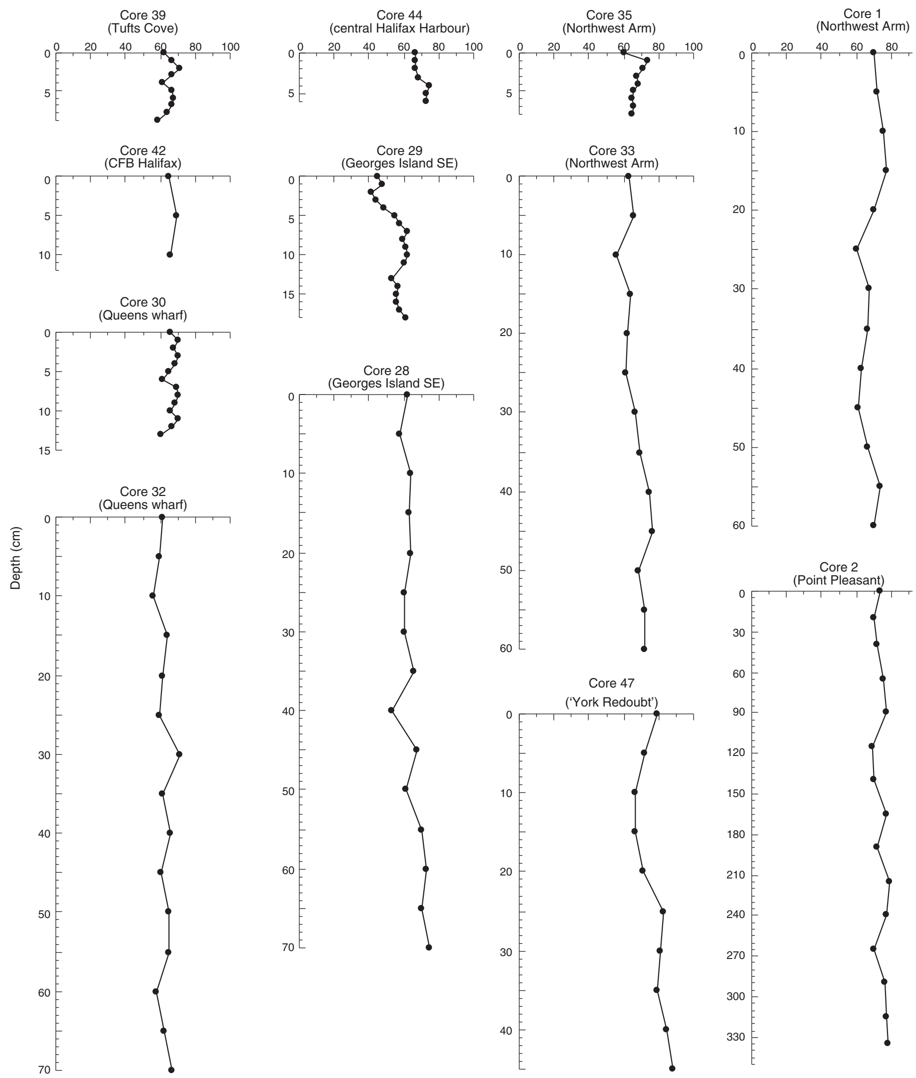


Figure 80 (continued)

coarsening with depth. A typical sediment texture from Northwest Arm is 31% sand, 56% silt, and 13% clay. A similar grain-size distribution is found in Eastern Passage. Cores from McNabs Cove and off Sandwich Point were clayey-sandy silt increasing in silt content with depth and with several sandy layers throughout the section. These textural variations are regionally consistent and indicate a coarsening of the LaHave Clay with depth. Boreholes collected through the LaHave Clay indicate that broken shells are common at depth and the sediment becomes more compact.

Samples of LaHave Clay and bottom observations from photographs and video images show that most areas of the LaHave Clay seabed of the harbour have a thin layer of brown oxidized sediments at the seabed immediately overlying an anoxic black layer up to 0.4 m thick. Vibrocores VC-2 and VC-10 (Edgecombe et al., 1999) collected near Georges Island in 20.5 m of water depth penetrated through the entire LaHave Clay section and revealed beneath an organic odoriferous anoxic layer, 3.5–4 m of olive-brown sediment with abundant shell material. Gas-induced cracking was present in the sediment and a large slate pebble was found at 200 cm depth.

The uppermost section of the LaHave Clay presently (2006) receives organic sediments derived from sewage and urban runoff largely discharged through a combined sewage and storm-water discharge system. Additionally, it is littered with anthropogenic debris such as dredge spoils, shipwrecks, cables, tires, bottles, cans, plastics, barrels, metal, and unidentified objects, and its upper surface is continually modified by ship anchoring, propeller scour, and other anthropogenic processes.

Benthic biology

Samples of LaHave Clay from Bedford Basin, Bedford Bay, and the west side of the inner harbour often contain tubes of the tubeworm *Spiochaetopterus*. The tubes protrude above the seabed up to 5 cm and penetrate over 15 cm in the sediment (Fig. 81). Many of the tubes do not contain living animals. Similar observations were made from samples collected by Hargrave et al. (1989). They also reported on macrofauna species diversity and indicated that it is the lowest in the harbour in central Bedford Basin over LaHave Clay where only two species of polychaetes were found at a depth of 70 m. The highest biomass of benthic macrofauna in Bedford Basin was sampled near the Mill Cove waste-water treatment facility in Bedford Bay. Submersible observations of the LaHave Clay seabed of Bedford Basin revealed the presence of white bacterial mats (e.g. *Beggiatoa*) in deep-water areas. Some of the mats were localized 30 cm patches, representing varying stages of decay of flatfish presumably trapped and dying in the deep anoxic water of the basin during the late summer.

Distribution

The dominant sediment at the seabed of the inner harbour including Bedford Basin is the LaHave Clay (Fig. 21). In Bedford Basin, most of the seabed deeper than 30 m water depth is covered with this fine-grained sediment. Its thickness is difficult to determine in the deepest part of the basin because of associated gas charging in the upper section that prevents acoustic penetration by the seismic-reflection systems. It appears to average 3–5 m in thickness where it is not gas charged and exceeds 10 m in the thickest acoustically resolvable zones (Fig. 82); however, the LaHave Clay in the deepest part of the basin could be considerably thicker.

Three separate depocentres of LaHave Clay occur in Bedford Basin: in Fairview Cove, Bedford Bay, and the main central area of Bedford Basin. They are separated from one another by bedrock-controlled sills, sometimes covered with till and/or gravel. These depocentres occur in the same areas as a subsurface distribution of interpreted lacustrine sediments deposited in early postglacial time. Bedford Bay is separated from Bedford Basin by a bedrock sill at a depth of 10 m (Fig. 18, 21, 33).

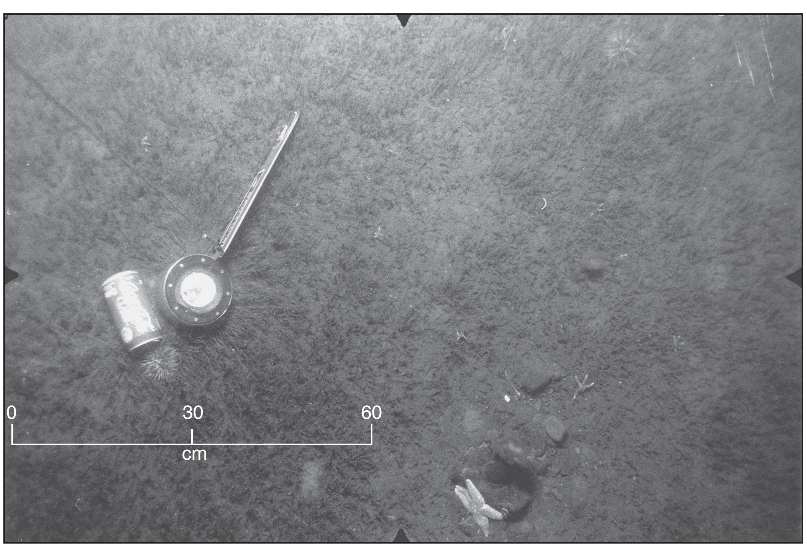


Figure 81. Bottom photograph of LaHave Clay from Bedford Bay showing worm tubes of *Spiochaetopterus* protruding from the seabed. Sea urchins and scattered debris are widespread. Photograph by R.O. Miller. GSC 2006-208

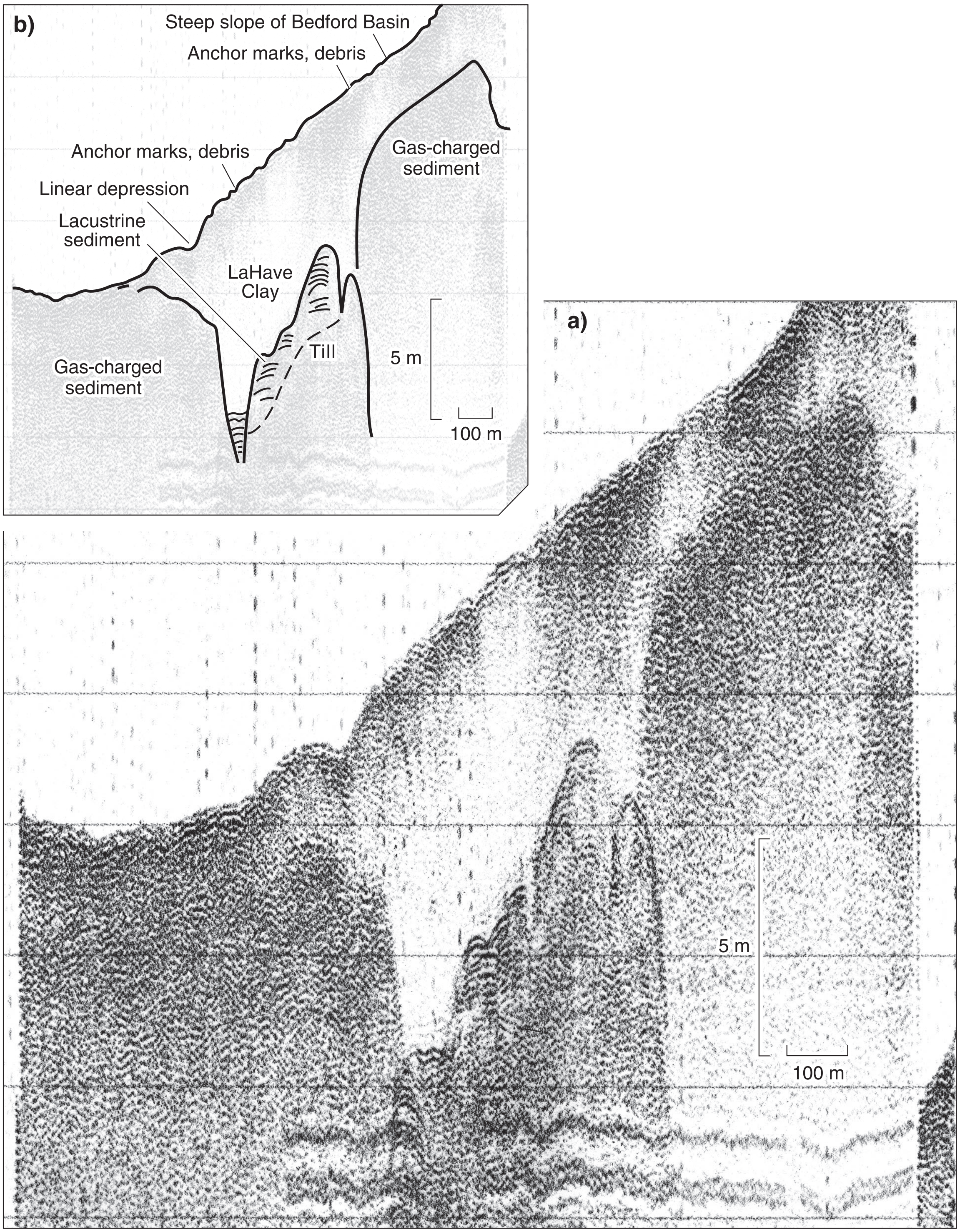


Figure 82. a) A Seistec seismic-reflection profile and **b)** interpretation from the northwestern flank of Bedford Basin showing typical LaHave Clay in an area absent of gas charging (acoustic window) where the entire section can be imaged. The basal till appears as ridges and is overlain by a unit of high-intensity, conformable, coherent reflections interpreted as lacustrine sediments. The LaHave Clay exceeds 12 m in thickness in the acoustically resolvable area. Areas of high-intensity seabed backscatter result from the presence of anchor marks and debris.

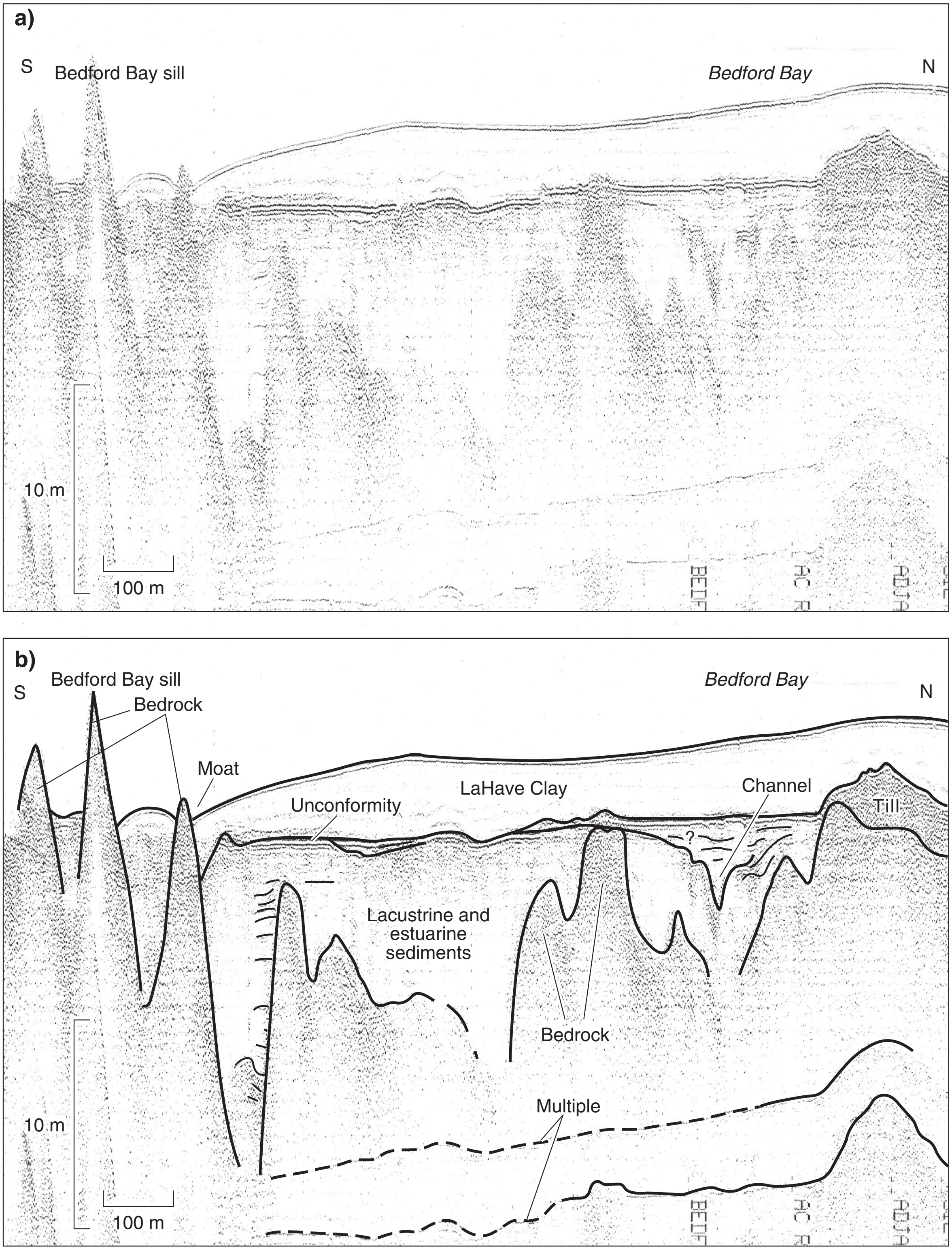


Figure 83. a) A Seistec seismic-reflection profile and **b)** interpretation from the southern area of Bedford Bay showing the wedging and thinning of the LaHave Clay from the north towards the bedrock sill between Bedford Bay and Bedford Basin. Beneath the LaHave Clay is a thick, ponded deposit of lacustrine and estuarine sediment with a flat, regional unconformity developed on its surface. Channels occur within the lacustrine and estuarine sediments. Shallow, nondepositional moats are formed around bedrock outcrop.

The LaHave Clay in Bedford Bay is a wedge-shaped deposit thinning to the southeast (Fig. 83). The upper part of the section is a recent deposit originating as sediment discharged from the Sackville River. Its surface is generally featureless with the exception of a few small anchor marks, boat moorings, and debris. Large volumes of this material were dredged in the 1980s near the mouth of the Sackville River in Bedford Bay and pumped in a slurry to fill in an area along the western shoreline as part of a land reclamation project.

The LaHave Clay is generally absent in The Narrows and only occurs as isolated, thin deposits in closed, deep depressions in Tufts Cove and near major sewage outfalls as sewage banks. At the south end of Pier 9, near the Duffus Street sewage outfall, a zone of fine-grained sediment covers the gravel seabed in a depression extending to the east across the harbour. Some of this sediment may originate from discharge at the Duffus Street sewage outfall. Tufts Cove is floored by soft, fine-grained sediment that continues out into the main channel of The Narrows where it terminates. Tufts Cove is also the location of major sewage outfalls, which are likely a source for some of the fine-grained material at the seabed.

The main body of LaHave Clay in Halifax Harbour begins adjacent to the Halifax Dartmouth Industries Drydock (Nova Dock, floating dry dock) in the southern part of The Narrows and continues to the south throughout the inner harbour to the Maugher Beach area of McNabs Island. From the Nova Dock to the Angus L. Macdonald Bridge the mud is patchy and thin and appears on the sonograms as infilling on a rough and irregular till-bedrock surface that protrudes through the mud in many areas. Anchor marks are widespread and they frequently cut through the thin mud, exposing the underlying coarser sediment as discontinuous gravel ridges (Fig. 84).

Where the inner harbour widens south of the Angus L. Macdonald Bridge, the LaHave Clay occurs in continuous large zones (Fig. 13, 21). The most northern deposit, up to 7 m thick, occurs directly north of Georges Island and trends to the north toward Dartmouth Cove. This deposit appears to have formed as a sediment drift in the lee of the island under flood-dominated flow. To the east and northeast of Georges Island, a large number of small, isolated, linear, ridge- and mound-like deposits of gravel-covered till protrude through the Holocene mud. The LaHave Clay is thick and deposited against the docks on the Halifax side of the harbour (Fig. 85), in contrast to the Dartmouth side where it occurs farther offshore and pinches out toward the gravelly shoreline. This likely results from higher energy storm conditions that occur along the Dartmouth side of the harbour, preventing deposition in shallow water. The large number of long-standing sewage outfalls along the docks of the Halifax shoreline may have provided more fine-grained material for local deposition and the presence of long, seaward-protruding docks on the Halifax side may also have helped to trap sediment. The shoreline of the Halifax peninsula inner harbour has been filled in considerably and the docks have been extended well out beyond the former shoreline into the main body of LaHave Clay.

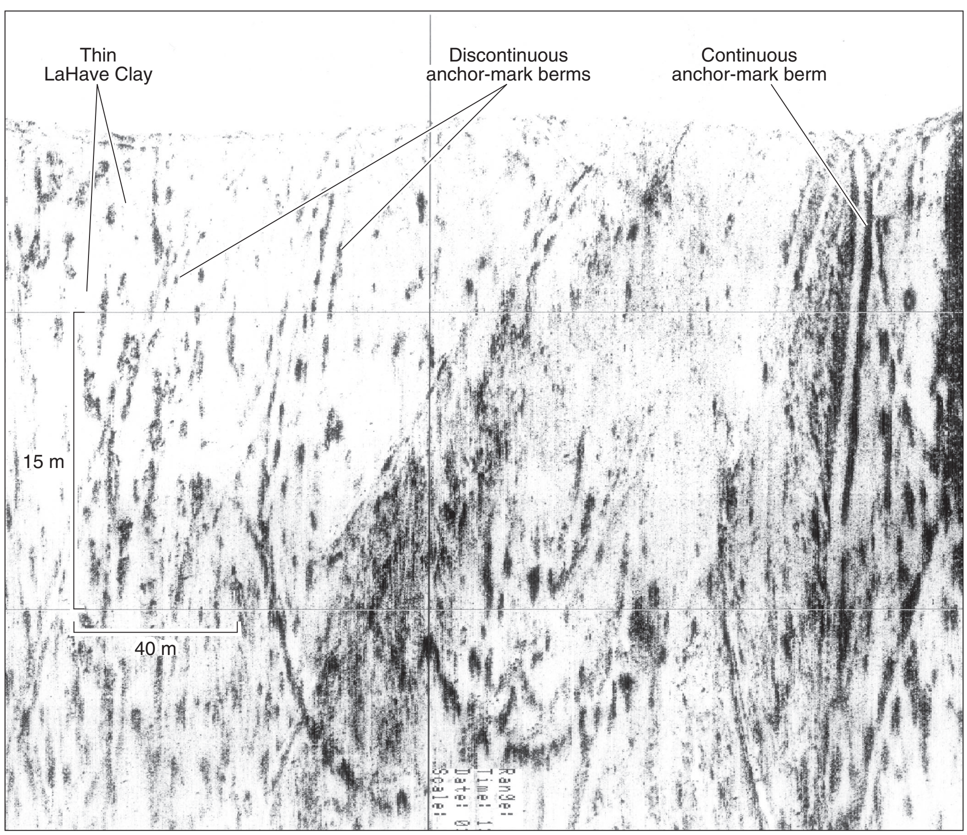


Figure 84. A 330 kHz sidescan sonogram of the southern area of The Narrows showing anchor marks in thin LaHave Clay. The dragged anchors have cut through the mud, exposing the subsurface Sable Island Sand and Gravel and till, forming discontinuous ridges flanking the anchor marks. This sonogram is typical of conditions in the southern part of The Narrows.

The largest and most continuous body of LaHave Clay in the harbour is found to the southeast of Georges Island and continues to the south into Eastern Passage (Fig. 7c). It exceeds 9 m in thickness and is gas charged over broad areas. In Eastern Passage the LaHave Clay is also gas charged and it covers most of the seabed. Coarse sediment only occurs in the shallow nearshore areas. The acoustic data show no evidence for a local buildup of sediment adjacent to the effluent outfall from the waste-water treatment facility in Eastern Passage (Fig. 86), unlike the sewage banks formed off many of the large untreated outfalls of the inner harbour.

On the western side of the inner harbour, in the narrow, restricted area between Ives Knoll and the ocean terminals, the LaHave Clay is patchy and thin and in some places is absent (Fig. 13, 21). This is interpreted to result from the presence of strong currents that arise from the narrowing of this part of the harbour between Ives Knoll and South End Container Terminal Pier C. Additionally, features first termed 'obstacle induced sediment drifts' are found in the LaHave Clay to the north of bedrock outcrops (Fader et al., 1997). They result from interaction of strong northward-flowing bottom currents that has produced the sheltered lee-side deposition of LaHave Clay on the north side of these obstacles. The present authors earlier attempted to

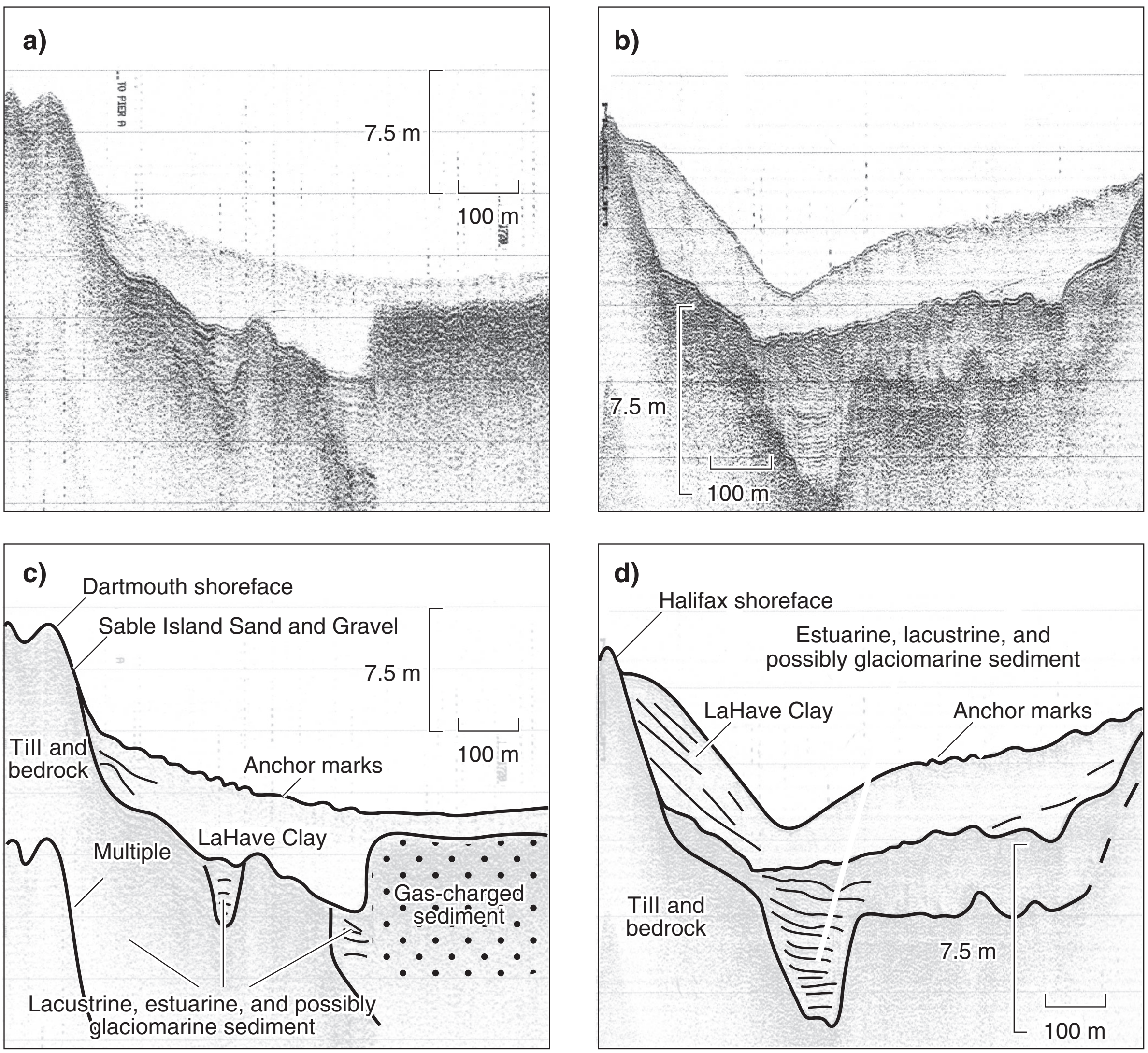


Figure 85. Seistec seismic-reflection profiles and interpretations comparing and contrasting the relationship between LaHave Clay and the Sable Island Sand and Gravel from the **a), c)** eastern and **b), d)** western sides of the harbour. The LaHave Clay onlaps the Sable Island Sand and Gravel several hundred metres offshore Dartmouth, but onlaps the Halifax shoreline as a thick deposit surrounding many of the wharves and docks (*see* Fig. 3 for location).

assess the role of the breakwater at the south side of the container pier in constricting the flow of water into the inner harbour, resulting in higher velocity flow and erosion and deposition of the LaHave Clay into sediment drifts; however, the LaHave Clay is gas charged and internal reflections indicative of changing depositional conditions could not be observed. The present authors interpret that the constriction of the passage in this area resulting from construction of the breakwater has increased erosion of the LaHave Clay seabed. Evidence to support this idea is the existence of a very thin, recent facies of the LaHave Clay overlying anchor-marked subsurface LaHave Clay south of Georges Island and immediately north of the sediment drifts (Fig. 87). This suggests that the original interpretation of the sediment drifts as

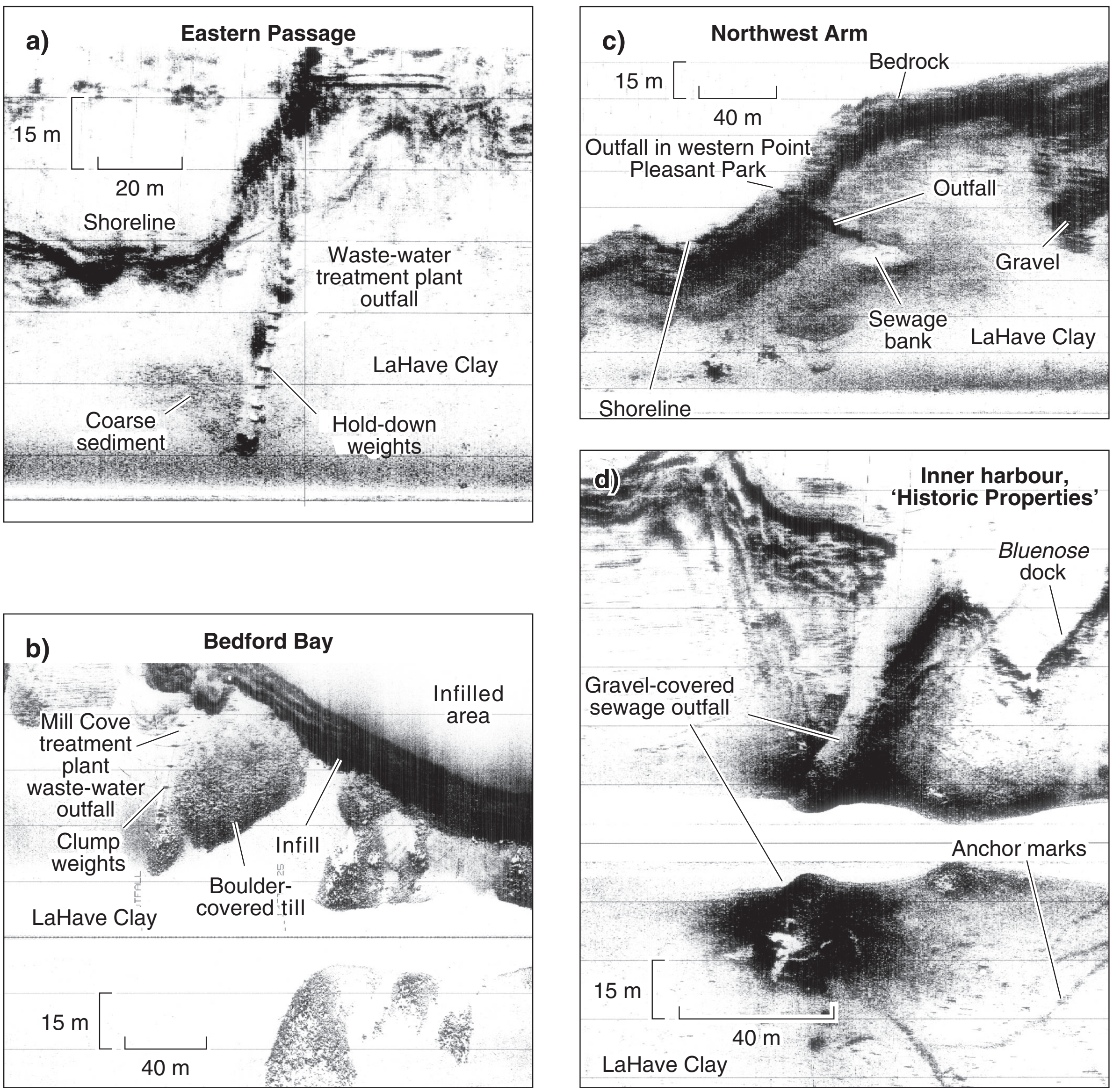


Figure 86. Sidescan sonograms of waste-water outfalls discharging treated waste-water in **a)** Eastern Passage and **b)** Bedford Bay, and **c)** untreated sewage in Northwest Arm and **d)** the inner harbour (as of 2004). The outfall at Point Pleasant Park in Northwest Arm has a small sewage bank deposited seaward of the discharge orifice. The outfall in Eastern Passage has no substantial buildup of material at the seabed; however, the texture of the seabed sediment is more highly reflective at the outer end of the outfall pipe and that deposit continues to the north. Hold-down weights are located on the outfall pipes in Bedford Bay and Eastern Passage. The pipe in Halifax Harbour adjacent to 'Historic Properties' is covered with coarse gravel fill.

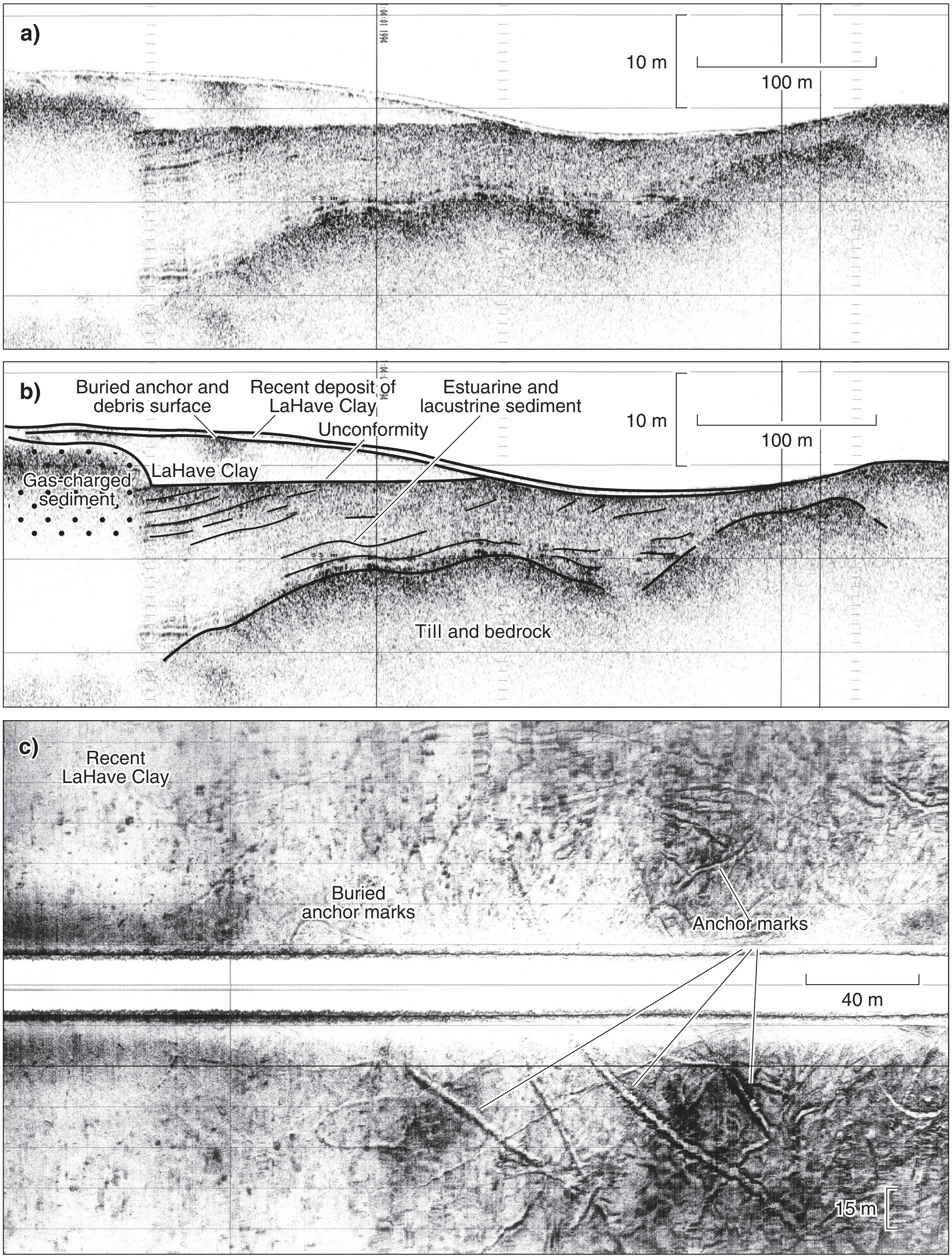


Figure 87. a) A Datasonics chirp™ seismic-reflection profile, **b)** interpretation, and **c)** a 100 kHz sidescan sonogram from south of Georges Island, showing burial of an anchor-marked surface beneath a recent deposit of LaHave Clay. The burial of the anchor marks may have resulted from local deposition of LaHave Clay eroded from the seabed to the south and transported to the north as a result of construction of a major inner harbour breakwater in 1913. This breakwater narrowed the passage by 25% into the inner harbour between McNabs Island and Halifax, increasing current velocities at the seabed and causing subsequent erosion.

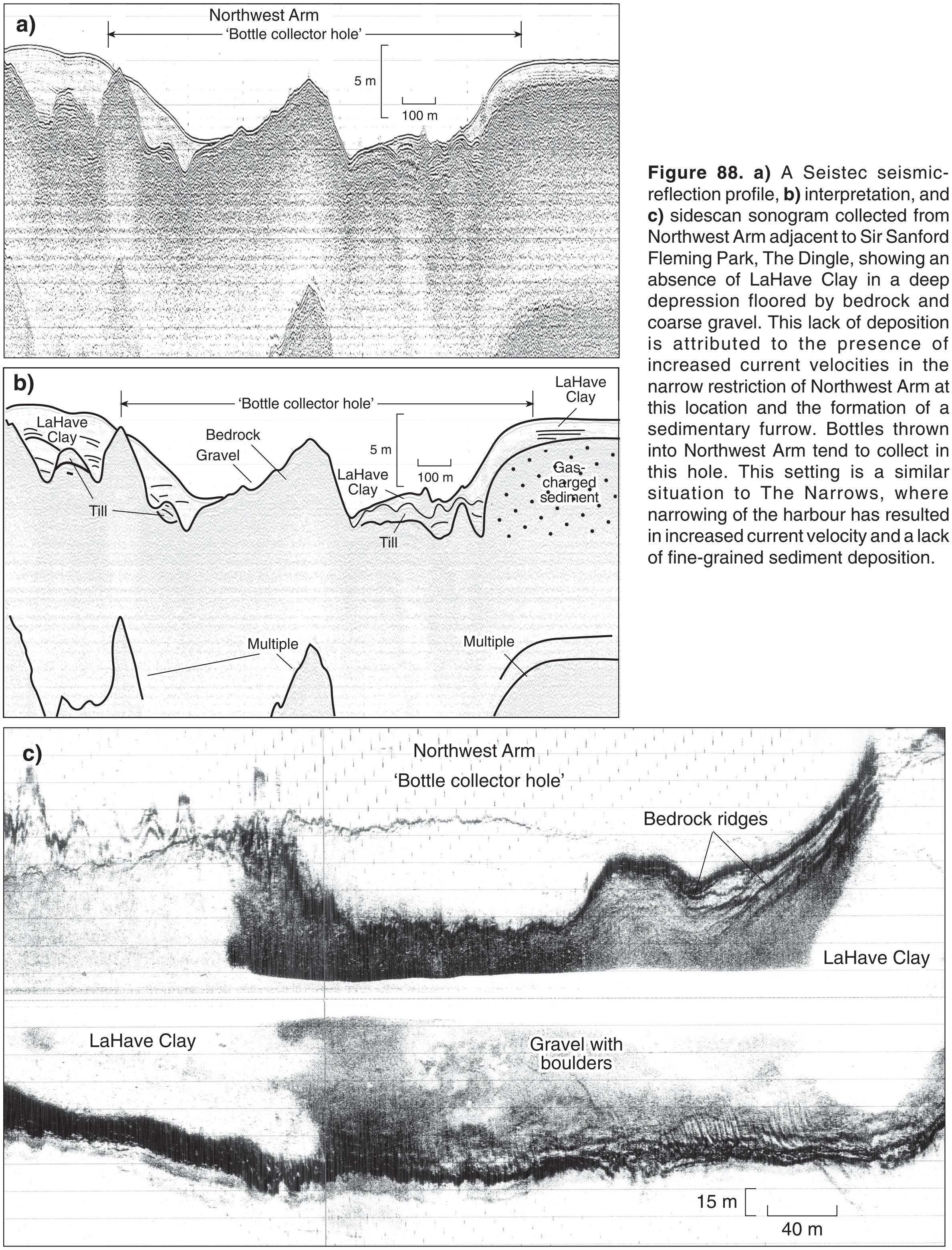


Figure 88. a) A Seistec seismic-reflection profile, **b)** interpretation, and **c)** sidescan sonogram collected from Northwest Arm adjacent to Sir Sanford Fleming Park, The Dingle, showing an absence of LaHave Clay in a deep depression floored by bedrock and coarse gravel. This lack of deposition is attributed to the presence of increased current velocities in the narrow restriction of Northwest Arm at this location and the formation of a sedimentary furrow. Bottles thrown into Northwest Arm tend to collect in this hole. This setting is a similar situation to The Narrows, where narrowing of the harbour has resulted in increased current velocity and a lack of fine-grained sediment deposition.

depositional features is likely incorrect, and that the deposits are more likely erosional remnants of pre-existing deposits of LaHave Clay.

The LaHave Clay occurs in Northwest Arm in two distinct zones separated by a deeper, bedrock-gravel–floored depression adjacent to The Dingle in Sir Sandford Fleming Park. The absence of fine-grained sediment in this mid-section is interpreted to result from a lack of deposition due to slightly stronger currents that occur where the arm narrows, in effect, producing a depositional setting similar to that in The Narrows (Fig. 88). Bottles discarded in Northwest Arm preferentially collect at the seabed in this depression. The LaHave Clay is absent where bedrock outcrops as rough and irregular positive topographic features, particularly on the flanks of the arm.

The LaHave Clay continues south of Northwest Arm to the Sandwich Point area where it terminates in a complex setting with sedimentary furrows, degraded megaripples, and interdigitation with the outer harbour Sable Island Sand and Gravel. The LaHave Clay is gas charged and over 8 m thick. This western harbour deposit of LaHave Clay is separated from one on the eastern side of the harbour to the north of Maugher Beach by a series of bedrock- and gravel-covered shoals, Pleasant Shoal, and Middle Ground (Fig. 13, 21). The deposit of LaHave Clay on the eastern side of the harbour north of Maugher Beach is also gas-charged mud and is over 8 m thick. Geochemical assessment of metals in the LaHave Clay from both areas suggests that material does not cross the shoal and is deposited locally in each of the depositional areas from different sources (Buckley and Hargrave, 1989).

Thickness

An isopach assessment of the LaHave Clay in the inner harbour south of The Narrows to Sandwich Point is based on an interpretation of echosounder and high-resolution seismic-reflection data (Fig. 89). The vertical resolution of the seismic systems is less than 0.3 m. Isopach assessments have not been prepared for areas of The Narrows because the mud is very patchy or absent, or for Bedford Basin where the LaHave Clay is gas charged and thicknesses cannot be assessed using seismic-reflection data. Isolated, thicker deposits occur as sewage banks in Tufts Cove and adjacent to the Duffus Street sewage outfall.

The thickest deposits of LaHave Clay occur in the inner harbour. Two large depocentres occur, one that extends northward from Georges Island, and another that lies south and southeast of Georges Island. The latter continues farther to the southeast toward the northern end of McNabs Island with an extension into Eastern Passage. This southeastern deposit is gas charged and the thickness beneath the gas has not been determined; however, the thickness of the LaHave Clay at the edge of the gas or in acoustic windows is over 7 m, suggesting that thickness is a control on the presence of gas charging and that at least this minimum thickness is likely maintained throughout the gas-charged areas.

Other depocentres of LaHave Clay in the harbour occur adjacent to the downtown Halifax docks south of the naval dockyard HMC Dockyards; adjacent to Ocean Terminals A, A-1, and B; and in an isolated area between Pleasant Shoal and the South End Container Terminal, Pier C in the south

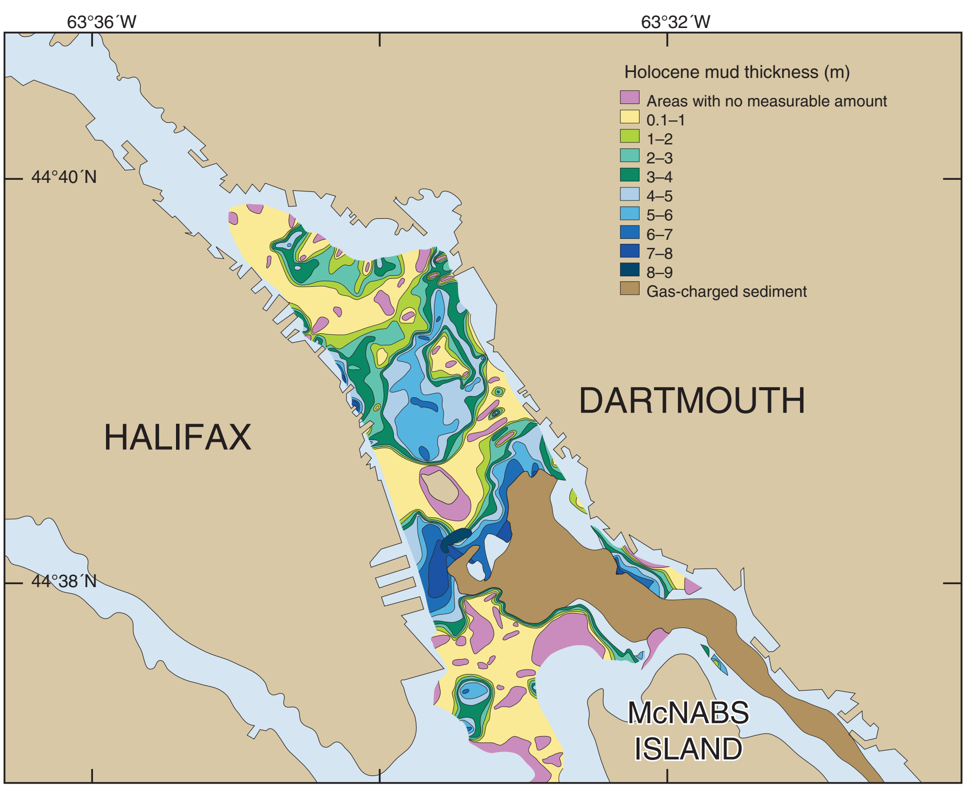


Figure 89. Isopach map of the LaHave Clay for the area south of The Narrows in the inner harbour extending to McNabs Island. Areas of gas charging do not have thicknesses determined. Note the thick sediment drift north of Georges Island and its extension to the north.

end of Halifax. An 8–9 m thick deposit of mud adjacent to the ocean terminals may have been partially deposited by a former stream called 'Freshwater Brook' which drained the central part of the old city of Halifax before it was founded and for many years after. The stream is no longer present but the limited drainage that remains is channelled in a storm-water overflow.

Within the inner harbour, large zones occur where the LaHave Clay is either absent or very thin: less than 1 m thick. Such a zone occurs directly to the east and west of Georges Island. This is interpreted to result from increased current velocities on either side of the island as a result of its obstruction to inward bottom flow. An area of thin or absent LaHave Clay to the northeast of Georges Island was chosen by the Halifax Harbour Task Force as the preferred location for a marine outfall from a proposed regional waste-water treatment facility because of a need for a suitable seabed foundation in a nondepositional area. Another large area of generally absent or thin Holocene mud occurs on Ives Knoll and between Ives Knoll, Pleasant Shoal, and South End Container Terminal, Pier C. Here again, strong ocean currents result from a narrowing of the inlet, which prevents the deposition of the fine-grained unit. A thick deposit of LaHave Clay adjacent to and north of Pleasant Shoal (Fig. 90) may have accumulated in a protected area of lower current velocities provided by the shoal.

The LaHave Clay in Northwest Arm, extending to Sandwich Point, is gas charged and thicknesses could not be determined; however, where the gas charging begins, the sediment is at least 8 m thick, and it is reasonable to assume that this is a minimum thickness over the deposit. A deposit across the harbour to the east, north of Maugher Beach, is of similar thickness.

Gas charging

Both the LaHave Clay and the older lacustrine and estuarine sediments of Halifax Harbour display large areas of gas charging. The acoustic energy of the high-resolution seismic-reflection systems does not penetrate and resolve subsurface stratigraphic reflections in areas of gas (Fig. 91). The upper reflector, which represents the gas on the seismic-reflection profiles, occurs at a variety of depths ranging from virtually at the seabed in areas of Bedford Basin and the inner harbour, to 15 m below the seabed (Fig. 92). The gas is represented on the seismic-reflection data as zones of incoherent reflections accompanied by a lack of acoustic penetration and commonly the presence of discontinuous high-intensity reflections (Keen and Piper, 1976; Knebel and Scanlon, 1985). 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; Fader, 1991; Fader and Buckley, 1997).

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 unconsolidated 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 or completely masked. Lower frequency sound sources can better penetrate through gas-charged sediments, but stratigraphic resolution is less. Reflection 'pull-downs', characterized by downward-dipping reflections at the flanks of the gas zones, are frequently associated with acoustic masking. These are acoustic artifacts that arise from the reduction of the sound speed through the gassy sediments.

Two assessments of the distribution of gas-charged sediment have been made in Halifax Harbour (Fig. 92). The first utilizes the database collected by the C.C.G.S. *Navicula* in the harbour during 1988, 1989, and 1990. The second is an unpublished interpretation by G.B.J. Fader in 1974 of survey data collected by Geomarine Associates Ltd. in a regional study of the aggregate potential of Halifax Harbour. A comparison of both compilations suggests that the general area of distribution of gas remains the same, but that in the most recent 1989 study, the distribution is diminished. Survey navigational problems can account for only a small part of the noted differences. One possible explanation for a decrease in the area of gas charging is that it could result from increased ship-related activities that impact the seabed and lead to release of the gas. These include propeller-generated turbulence, widespread anchoring with larger anchors, and the transit of larger vessels. Another possible explanation is that changes in bottom-water temperature and/or geochemistry within the sediments could result in increased gas venting. With the exception of the entrance to Northwest Arm, there are no apparent pockmarks in the sediments overlying the gas-charged areas, but it would be difficult to identify small pockmarks because of the widespread and intense distribution of anchor marks. The gas may vent from these areas without the formation of pockmarks.

For the distribution of the gas in areas other than Bedford Basin, Eastern Passage, and Northwest Arm, a contour map shows the depth to the uppermost reflection interpreted to represent the top of the gas-charged sediment zone (Fig. 92). In Bedford Basin the area of gas appears confined to a zone between the 50 m and 60 m bathymetric contours. An isolated outlier occurs in Fairview Cove in 25 m of water depth. The depth of burial of the gas-charged upper seismic reflector occurs at between 2 m and 3 m beneath the seabed with little variability across the occurrence. There are several areas in the central part of Bedford Basin where the gas is virtually at the seabed.

Associated with the shallow gas at the seabed of Bedford Basin are large depressed areas of seabed outlined by linear scarps (Fig. 93). These features were unknown before the collection of multibeam bathymetry and it indicates that the linear scarps are horseshoe-shaped depressions, convex to the north (Fig. 18). The flanking sides of the depressions that extend to the southeast consist of broken and en échelon scarps. The northernmost depressed area merges with the

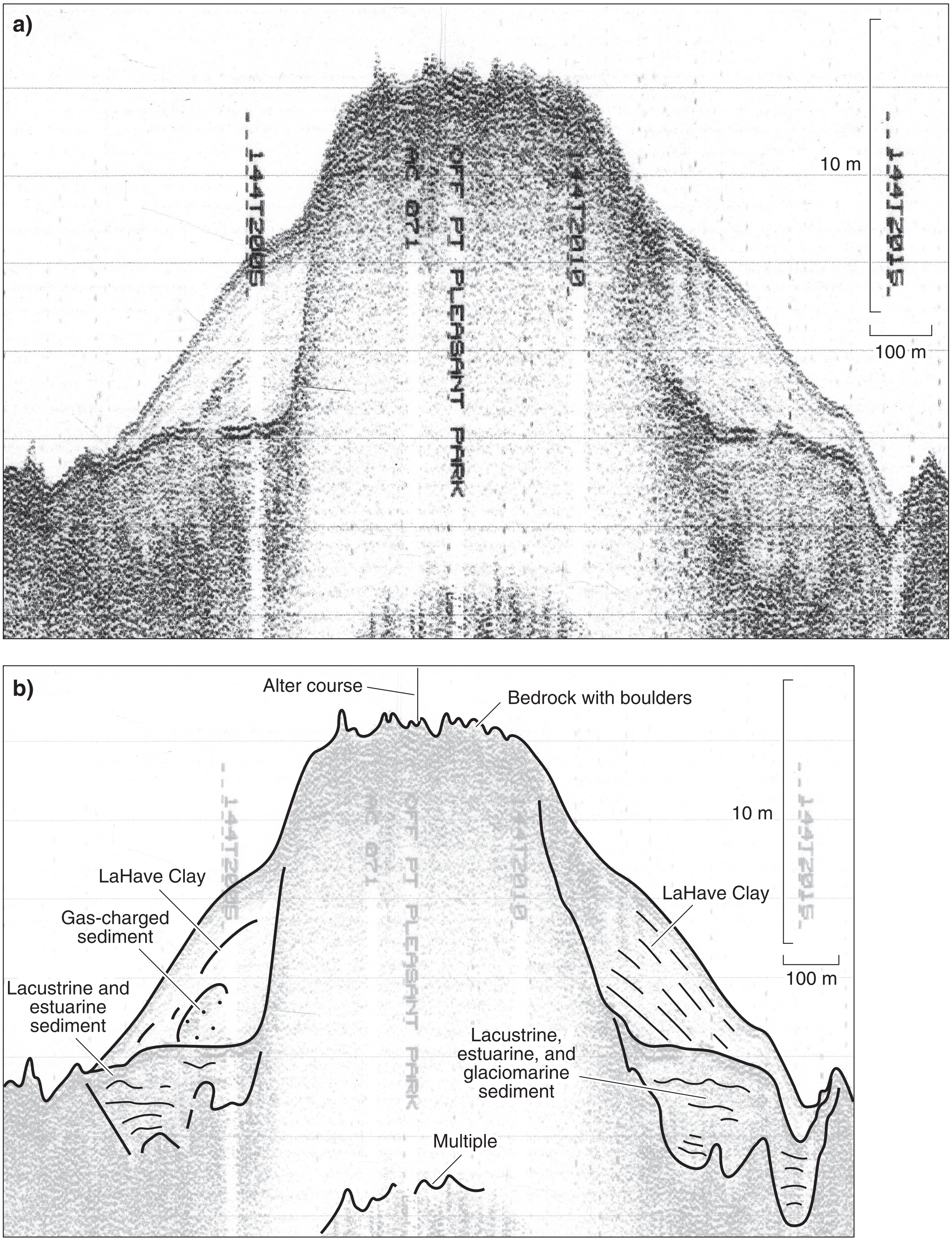


Figure 90. a) A Seistec seismic-reflection profile and **b)** interpretation of an isolated deposit of LaHave Clay north of eastern Pleasant Shoal, inner Halifax Harbour. The clayey silt appears to be preferentially deposited against a north-facing, steep-sloped bedrock surface as a result of topographic sheltering.

southern, large, depressed area and at the junction is the deepest depth of 71 m in the basin. These features have scarps that resemble those formed by slumped sediments or debris flows commonly found on the continental slope. In this case, there does not appear to be lateral movement of sediments, only vertical. In the central area of the southernmost, large, depressed area is a subtle linear depression (Fig. 6, 18). To the southeast of these large, depressed areas in the south-central area of the basin, is a circular depressed area flanked with a slightly deeper moat. This feature is identical to one identified in Bay of Islands, Newfoundland (Shaw et al., 2000) and termed a 'Horton' due to its resemblance to the product of a well known Canadian doughnut manufacturer. They determined the origin of the feature to be the result of gas venting. All of these gas-associated features in the basin are unusual characteristics for LaHave Clay. The origin of the scarps and broad depressions is not completely understood, but the relationship to the gas charging suggests that they may be the result of differential compaction, dewatering, or more likely, methane-gas venting. The thickest deposit of LaHave Clay in the harbour occurs in these areas. The hazard potential of the venting of gas from these features in the basin has not been assessed.

Gas charging occurs in the major deposit of LaHave Clay in the inner harbour to the southeast of Georges Island and continues to the south into Eastern Passage. The upper gas-charged seismic reflector occurs at a consistent depth of between 1 m and 3 m, with depths of occurrence beneath the seabed of 3 m to 5 m on the flanks of the gas-charged areas. It is important to note that many of the anchor marks in the harbour 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. A few very local areas of other parts of the inner harbour, particularly north of Georges Island, show the presence of small zones of gas charging (Fig. 91d). These have not been mapped. Gas charging is widespread in Northwest Arm. It is absent only where the mud is very thin, such as over bedrock highs. The gas also occurs at a consistent depth of 1 m to 3 m in Northwest Arm.

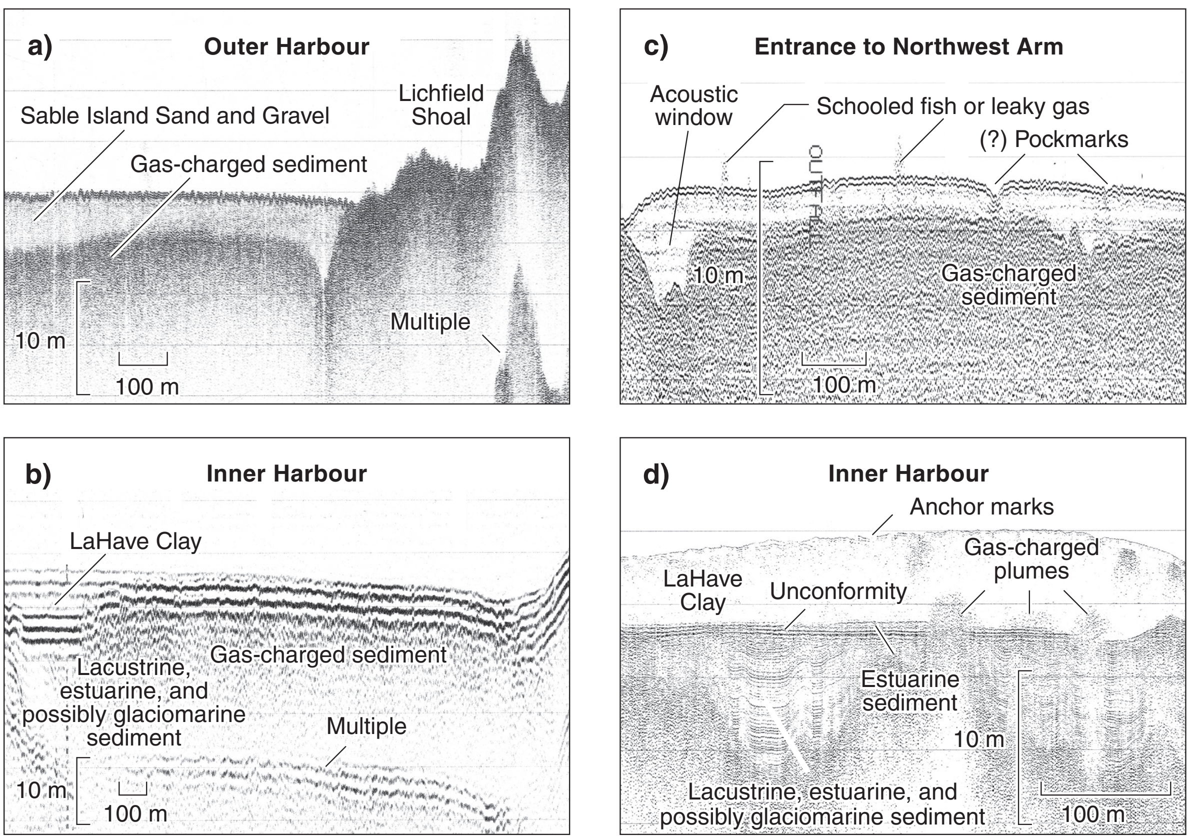
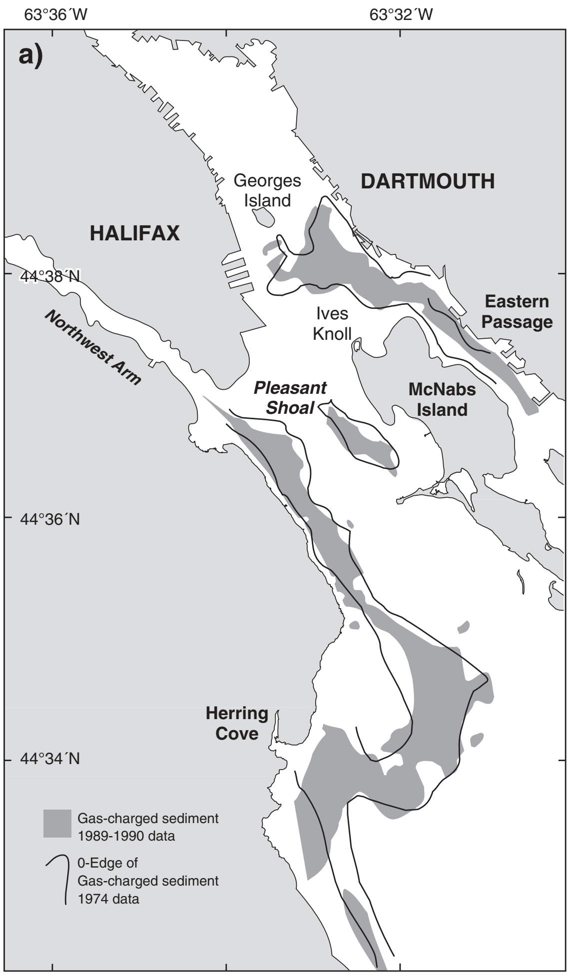


Figure 91. a), b), c), d) Seismic-reflection profiles from a variety of systems in areas of Halifax Harbour showing the presence and characteristics of gas-charged sediments in the subsurface. The presence of gas often prevents the penetration of acoustic energy of the seismic-reflection systems and resolution of subsurface events. In some areas the gas-charged sediments have been previously misinterpreted as bedrock. The gas-charged sediments can occur both over broad regional areas or isolated in small plume-like structures within the LaHave Clay. The gas may be leaking from the seabed at the entrance to Northwest Arm forming pockmarks, in Bedford Basin forming large subsidence depressions, and throughout all areas of the harbour from the use of ships' anchors. Plumes in the water column at the entrance to Northwest Arm are interpreted as gas venting.



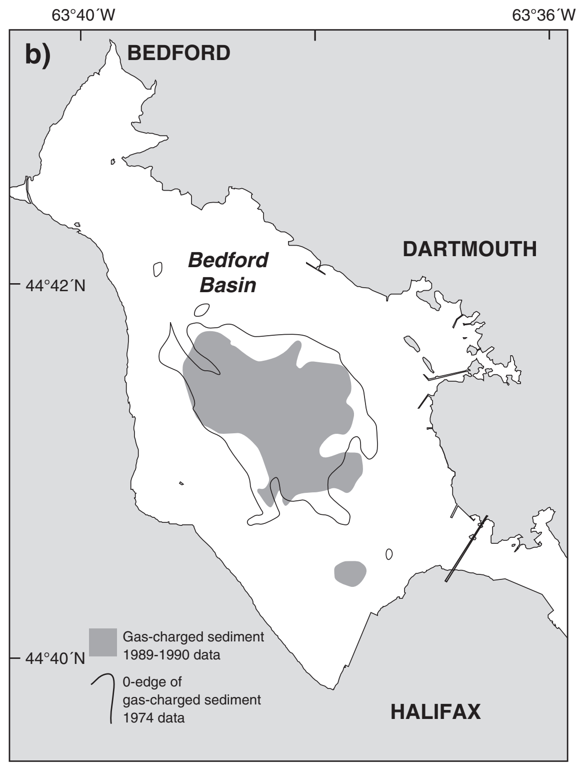


Figure 92. Distribution of gas-charged sediment in Halifax Harbour from **a)** the inner and outer harbour and **b)** Bedford Basin. Two seismic-reflection data sets were interpreted: 1974 and 1989–1990. The most recent data set suggests less gas charging within the sediments and the possibility of leakage. Variations in the precision of navigational systems and varying data quality cannot account for all the differences.

In the outer harbour (Fig. 92), gas charging is confined to the western side of that region. An isolated area occurs north of Maugher Beach off McNabs Cove and is separated by Pleasant Shoal and its southern extension, Middle Ground, from the major occurrence on the western side of the harbour. Extending out the harbour toward Herring Cove, the gas-charged sediments are found at increasing depths beneath the seabed. A major transition occurs at Sandwich Point where the LaHave Clay, with its gas charging, is overlain by Sable Island Sand and Gravel. The distribution of gas-charged sediment continues seaward, but in this area it is confined to lacustrine or estuarine sediments that are buried beneath Sable Island Sand and Gravel. As a result, to the northeast of Mars Rock, adjacent to Sandwich Point, the top of the gas reflection occurs at a depth of up to 11 m.

For the outer harbour, the distribution of the gas interpreted from the 1989 data also shows a smaller area of occurrence than interpreted from the 1974 data. This is similar to the relationship in the inner harbour to the north and in Bedford Basin. Gas-charged sediments do not appear to continue seaward within the outer harbour beyond the Bear Cove area; however, data collected 20 km beyond Chebucto Head indicate the presence of gas-charged sediments in the bedrock-controlled channel of the ancient Sackville River.

Pockmarks

A large number of circular depressions occur in the LaHave Clay at the entrance to Northwest Arm (Fig. 94). These are interpreted as pockmarks (gas-escape craters) similar to those first found in dense distributions in the basins of the adjacent Scotian Shelf (King and MacLean, 1970), and later studied by Josenhans et al. (1978) and Fader (1991). They display a variety of shapes from circular to ellipsoidal and range up to 3 m in depth and 45 m in diameter. They also have flat bottoms in contrast to the more typical cone shape of pockmarks in the basins of the Scotian Shelf. The sidescan sonograms show that some of the pockmarks have highly reflective rims and are also highly reflective at their base. The majority of the pockmarks are slightly elongated parallel to the northwest-southeast axis of Northwest Arm and some are asymmetrical with a steeper flank facing the northwest. This suggests that currents may play a role in elongating their dimensions similar to elongated pockmarks that occur in eastern Emerald Basin. The net current direction indicated by the asymmetric elongation is from the northwest, out of Northwest Arm, and is contrary to the overall pattern of sediment transport up the arm to the northwest indicated by other features of the seabed.

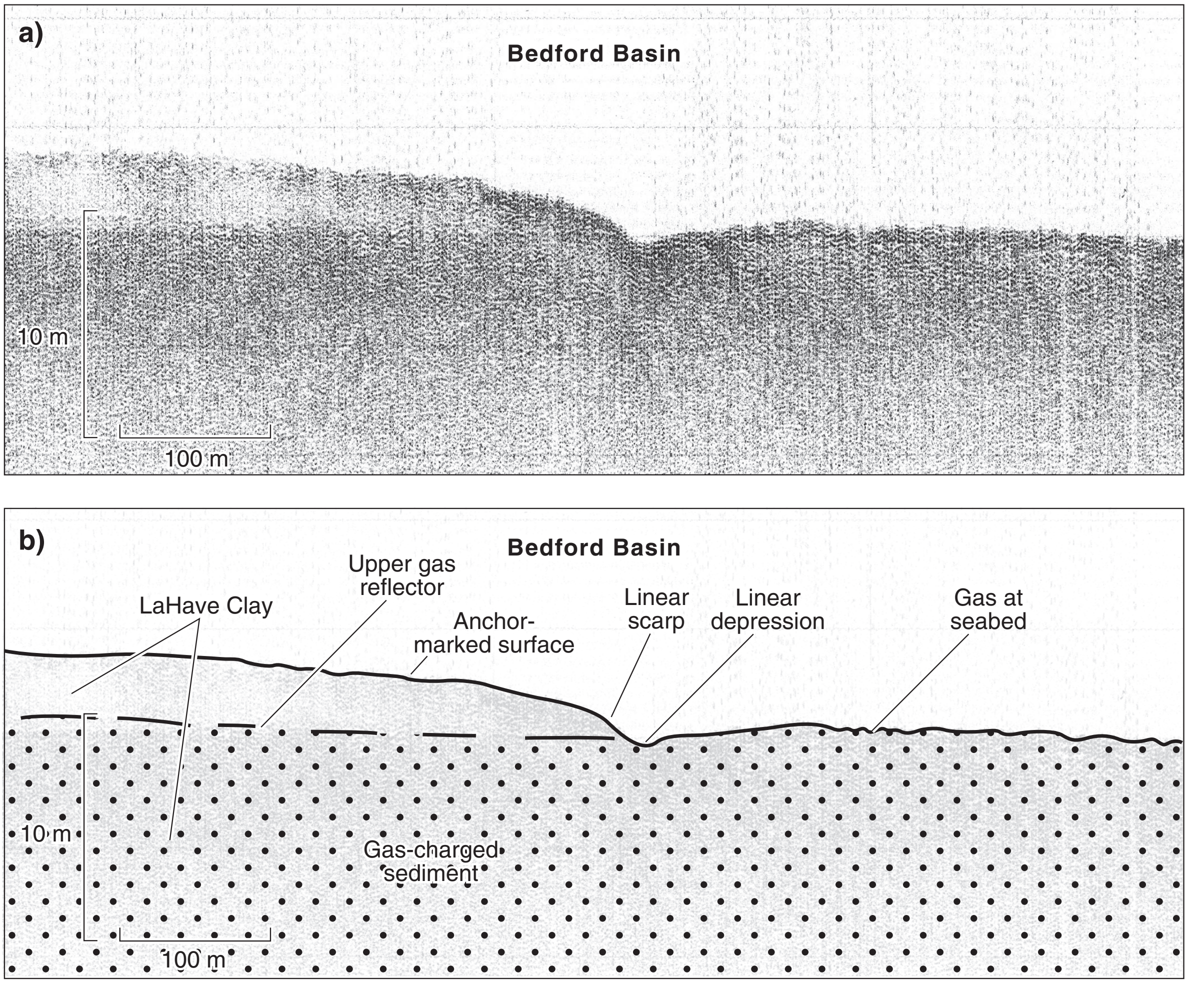


Figure 93. a) Seistec seismic-reflection profile and **b)** interpretation from Bedford Basin showing variation in the depth of the gas-charged reflector within LaHave Clay and its relationship to the linear depression and subsidence features. On the left of the image in the north, the gas is buried at a depth of 3 m. It is present at the seabed on the right of the image and where the gas reflector converges with the seabed, it is associated with a linear depression. Multibeam imagery shows that the linear depression is a large, horseshoe-shaped feature that defines a regional zone of depression. Within the depression, the gas reflector is at or very near the seabed.

In the same area as the pockmarks are several smaller depressions with a large number of acoustical scattering targets at their base as seen on sonograms (Fig. 95). These were investigated with an ROV and found to contain boulders and debris. A few are filled with living macroalgae (kelp) and their bottoms could not be visually observed. They are interpreted to represent depressions resulting from material dumped by barges (similar to dredge spoils). The presence of large bedrock quarries for building stone in adjacent Purcells Cove, and a transportation route directly over the pockmarked areas to Halifax, suggest that barge material may have inadvertently been dropped or lost to the seabed. The dumped material created depressions at the seabed as the coarse material compressed or displaced the LaHave Clay. In addition, this facilitated the venting of local gas as the depressions occur over areas of gas-charged sediments.

A series of four large depressions occurs in the inner area of Northwest Arm to the west of the Waegwoltic Club (Fig. 103). They are each over 50 m in diameter and less than 2 m in depth and were identified from the multibeam bathymetry. Their slopes are very low, unlike those of the pockmarks at the entrance to the arm. The authors suggest that they also formed as a result of gas venting from the LaHave Clay, but may have been partially infilled and are therefore interpreted as relict pockmarks.

Depositional history

The source of the material for the LaHave Clay is interpreted to be the till of the surrounding land and seabed of the harbour as well as previously deposited lacustrine and

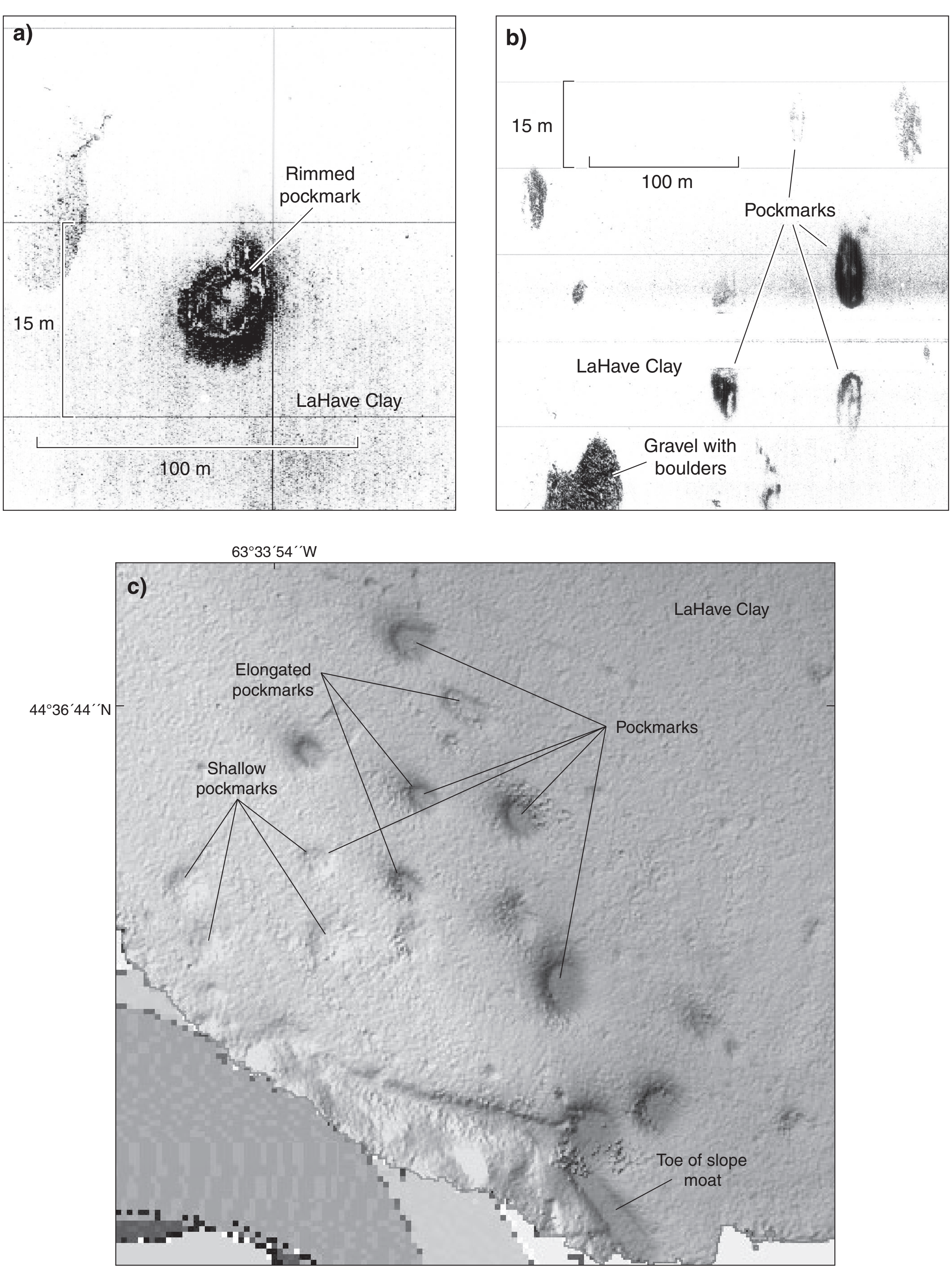


Figure 94. a), b) Sidescan sonograms and **c)** a Simrad EM3000 multibeam-bathymetric image of pockmarks at the entrance to Northwest Arm. In Figure 94a the pockmark appears as a high-backscatter-rimmed depression and in Figure 94b a group of pockmarks appear as elongated circular depressions with high backscatter rims and bottoms; Figure 94c shows that the pockmarks can be circular as well as ellipsoidal. They appear to have flat bottoms. Many smaller and shallower pockmarks also occur across the seabed.

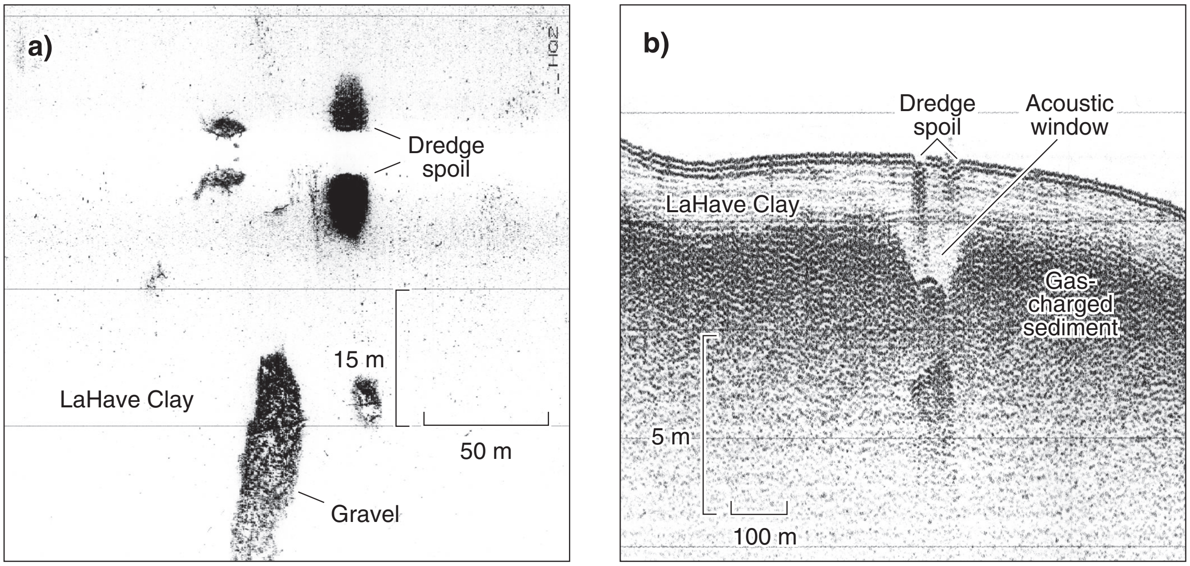


Figure 95. a) Sidescan sonogram and **b)** seismic-reflection profile from the entrance to Northwest Arm over a dredge spoil deposited on LaHave Clay. The seismic data show an absence of gas within the sediments directly beneath the spoil. The spoil has impacted, compressed, and displaced the sediment and vented the gas, creating a depression. Dredge spoils on mud can resemble pockmarks formed by the venting of gas. The material in the dredge spoil (Fig. 95a) was observed with an ROV and determined to consist of angular boulders.

estuarine sediments in the subsurface. Deposition of the LaHave Clay in the inner harbour began sometime after 7000 BP, based on a date from peat found directly below the base of the LaHave Clay, collected near Georges Island in vibrocore VC-10 (Fig. 55b). A reservoir-corrected date of 5330±60 BP was obtained from the base of the LaHave Clay in borehole 1005 west of McNabs Island, suggesting that deposition was under way at that time. This followed a period of subaerial exposure for large areas of the harbour and the marine transgression by rising sea level during the Holocene. From a study of foraminifers in core VC-2 (Fig. 55a), Edgecombe et al. (1999) noted a decrease in total abundance and species diversity with increasing depth in the core and two foraminiferal zones were identified. Zone B, extending from 30 cm to 414 cm, represents a typical Holocene open estuarine fauna. Core VC-10, collected northwest of Georges Island, is similar to core VC-2, but shows localized zones of distinct crosslaminae and three shelly layers. The shell content decreases at the base of the unit. The presence of cross- laminations and concentrated shell layers suggests that major storm events affected deposition during the past 5000 years. The presence of pebbles suggests ice rafting as a mechanism of coarse-sediment transport. With the exception of sewage banks where the sediment is up to 3 m thick and largely deposited over the past 100 years, in most areas of the harbour a maximum of 90 cm of deposition has occurred since approximately 1880 (Fader and Buckley, 1997).

An understanding of the depositional history of the LaHave Clay in Bedford Basin comes from cores reported by Miller et al. (1982), Fitzgerald et al. (1989), and Fader and Buckley (1997). Unit 1 of Miller et al. (1982) forms the base of the LaHave Clay and is an organic-rich, structureless, dark olive-grey, bioturbated, and gas-charged marine mud with a date of 5830 BP. A common characteristic of the microfossils in the upper zone is a decrease in abundance at the surface. Miller et al. (1982) determined a sedimentation rate of 10.8 cm/century since the founding of Halifax in 1749, compared to a lower rate of 5.3 cm/century at 310 cm downcore, and attributed this to a recent increase in sediment influx and effluent discharge. The estuarine foraminiferal fauna indicate a relatively stable depositional interval for the LaHave Clay in Bedford Basin, which is typical of deep-water Atlantic Canadian coastal inlets. Fader and Buckley (1997) reported on a long core from Bedford Basin that also penetrated through the marine sequence into a terrestrial fresh-water paleoenvironment and noted an increase in the quantity of organic matter over the past 5000 years.

Depositional style

For the most part, the LaHave Clay is a ponded sediment generally deposited under quiescent conditions. These sediments fill irregularities on the surface of the Sable Island Sand and Gravel, till, and bedrock over which they lie; however, continuous coherent seismic reflections within some areas of the unit, particularly at the base, indicate that dynamic conditions were variable during deposition. The present moat surrounding Georges Island has persisted since the deposition of basal LaHave Clay, whereas in other areas, early moats and depressions around obstructions have been infilled. The presence of Georges Island in the inner harbour has had a major effect on the deposition of LaHave Clay. Not only is there lack of deposition surrounding Georges Island in the moat, but the lack of deposition continues in the west to the Halifax shoreline.

Multibeam-bathymetric data provides important information on subtle details of seabed surface topography, and in the case of the LaHave Clay, indicates areas of nondeposition and areas of localized erosion (Fig. 6, 13, 21). Interpretation of these processes is based on characteristics of the multibeam portrayal of features such as moats, scoured depressions, sedimentary furrows, and sediment drifts. A detailed discussion of their distribution and significance is presented in the sections 'Bed forms'.

SEDIMENT TRANSPORT AND EROSION

Bed forms

A large variety of bed forms occur on the seabed of Halifax Harbour formed in both cohesive and noncohesive sediments. Most bed forms in noncohesive sand and gravel are modern features produced by currents and waves. Features formed in cohesive mud have both modern and relict aspects. The backscatter data from the outer harbour clearly shows a variety of flow-transverse and flow-parallel bed forms, as well as gravel circles and other features (Fig. 8).

The bed forms indicate great variability and complexity in the history of erosion, transport, and deposition of sediments in the harbour related to both natural and anthropogenic processes. An understanding of bed-form genesis is particularly important from an environmental perspective, as the bed forms indicate sediment-transport pathways and eventual sinks for contaminated sediments. The integration of seabed slope and shaded-relief multibeam imagery (Fig. 12) greatly enhances the portrayal of subtle, current-formed bed forms in cohesive sediments of the inner harbour.

Bed forms in noncohesive sediments largely occur in the outer harbour south of Sandwich Point, and include sand ribbons, megaripples, ripples formed in gravel, and gravel circles. They are rare in the inner harbour and Bedford Basin. Bed forms in cohesive sediments include sedimentary furrows, sediment drifts, scoured depressions, moats, erosional remnants, and obstacle-induced scours. Taken in their entirety, all of the bed forms in the harbour indicate a general pattern of decreasing energy from south to north that is overprinted by intermittent high-energy events that are likely storm related. The following is a more detailed discussion of the bed forms that are classified as occurring in cohesive and noncohesive sediments. The noncohesive sediments are presented in order of diminishing dynamic environments.

Noncohesive sediment bed forms

Sand ribbons

Sand ribbons are flow-parallel bed forms of low relief formed by strong currents. They are difficult to detect where they occur overlying sand, but are easily distinguished where the sand is thin overlying gravel lag (Fig. 96). In these areas the backscatter contrast on sidescan sonograms and multibeam data provide confirming evidence. Sand ribbons occur only in the outer harbour where they are confined to the western side near the steep granite bedrock flank (Fig. 97). They are well developed off Chebucto Head and are oriented subparallel to the shoreline, aligned in a northwest to southeast direction. The sand ribbons are well defined on the multibeam-backscatter imagery (Fig. 8). The field of sand ribbons continues to the north, terminating off Black Point. A zone of long-wavelength megaripples bound them to the east. The sand ribbons indicate the area of highest velocity bottom-water flows in the harbour where sediments occur. Higher flow conditions may occur on bedrock exposed areas, but cannot be determined from seabed information.

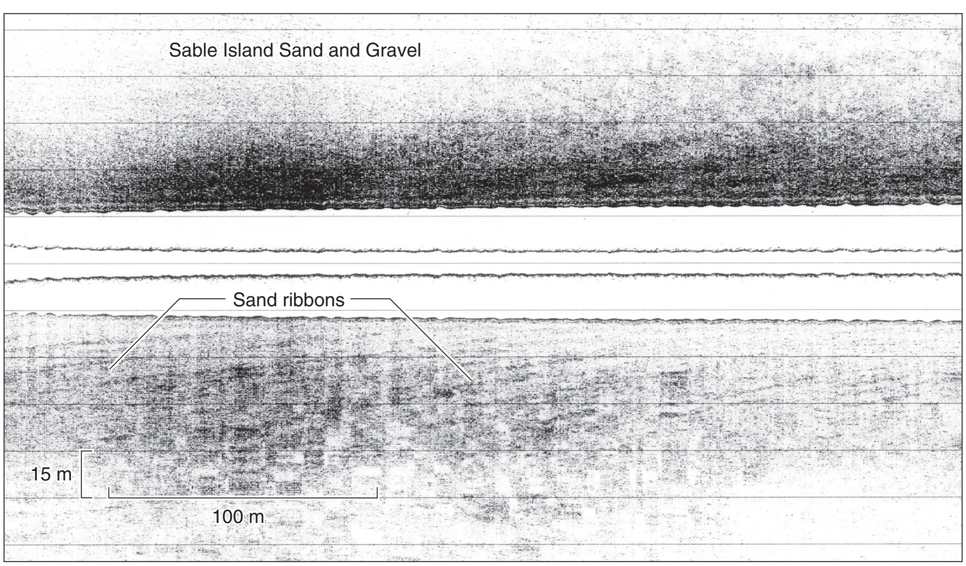


Figure 96. A 120 kHz sidescan sonogram illustrating sand ribbons on the seabed adjacent to Chebucto Head in the deep western channel of outer Halifax Harbour. They are thin, linear sand deposits overlying sand with broken and whole shells and gravel and indicate formation by strong bottom currents. They also appear on the multibeam-backscatter data (Fig. 8).

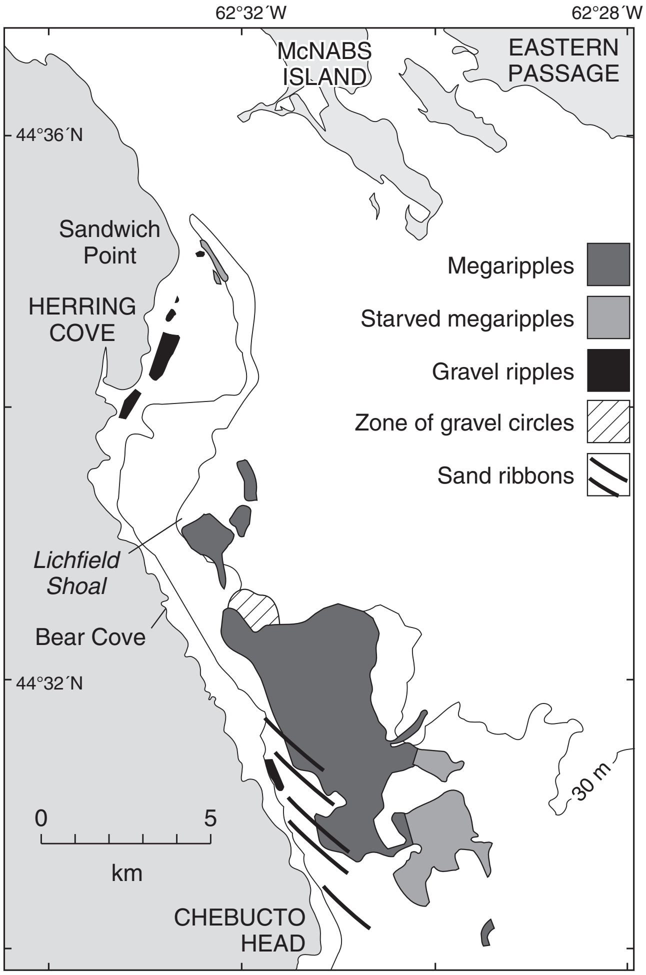


Figure 97. Classification and distribution of bed forms in the outer harbour extending from Sandwich Point to Chebucto Head. The most dynamic bed forms, sand ribbons, occur off Chebucto Head. The distribution, type, and orientation of bed forms suggest an upharbour decrease in current velocity from Chebucto Head to Sandwich Point.

Megaripples

Megaripples are straight, sharp-crested, flow-transverse bed forms with a ripple-like profile formed in medium- to fine-grained sand. They are formed by currents with a near-bed-flow velocity of 40–60 cm/s (Amos and King, 1984).

The most northerly occurrence of megaripples in the harbour is a field of subdued megaripples in a deep, narrow channel defined by the 30 m contour adjacent to Sandwich Point. These megaripples display broken and eroded crests on side-scan sonograms (Fig. 97, 98), suggesting that they may be in part relict, having formed months to years earlier. Their symmetry indicates transport and deposition upharbour, from south to north. They occur to the south of a field of sedimentary furrows in a sediment-transitional zone off Sandwich Point where LaHave Clay of the inner harbour interdigitates with Sable Island Sand and Gravel of the outer harbour.

The major zone of megaripples is confined to an area south of Lichfield Shoal, which continues out of the harbour to Chebucto Head, mainly on the eastern side of the deep, western outer harbour channel (Fig. 97). The megaripples overlie a gravel-lag surface. North of Lichfield Shoal, there is an absence of bed forms and the silty-sandy seabed is slightly rippled with only wave-formed ripples of 20 cm wavelength and 5 cm height. This suggests that Lichfield Shoal acts as a topographical barrier to strong inflowing bottom currents, resulting in their dissipation and deflection, thus protecting sediments directly off Herring Cove from high current velocity modification. This hypothesis is supported by oceanographic current measurements (ASA Consulting Ltd., 1990) and observations of lower flow velocities from the local fishing community. The seabed off Herring Cove is mainly sand to silty sand. A major raw sewage outfall discharges at Watleys Cove to the south of Herring Cove; however, evidence from ROV observations and sample analyses indicates no accumulation of sewage deposits or fine-grained sediments on the adjacent seabed. The tendency is for these particles to move to the north upharbour as was observed from ROV operations off Herring Cove.

The megaripples that occur closer to the large bedrock shoals of the outer harbour decrease in wavelength. A field of starved megaripples (Amos and King, 1984) occurs to the northeast of Chebucto Head (Fig. 97). They are discontinuous, the sand is thin and patchy, and they have limited heights of 0.1 m. The starved megaripples overlie lag-gravel surfaces on estuarine and lacustrine sediments that in some areas outcrop in the troughs of the bed forms.

Megaripple wavelengths range up to 15 m, but average 4 m and they are less than 0.3 m high (Fig. 99). Broken and whole shells are common in the bed-form troughs. Some of the crests of the megaripples are broken into isolated arcuate megaripples termed three-dimensional megaripples (Amos and King, 1984). These features are normally generated under strong turbulent flow. The shape and orientation of the 3-D megaripples in the outer harbour also indicate net bottom-sediment transport upharbour toward the north.

Ripples in gravel

In many areas of the outer harbour in water depths of between 10 m and 20 m, large areas of ripples formed in gravel are present (Fig. 97). They are more common along the Herring Cove shoreline, off Portuguese Cove, and in a few areas near southwest McNabs Island. They commonly occur flanking outcropping bedrock shoals between the bedrock and a zone of sand megaripples (Fig. 65). They are straight, crested bed forms formed in moderately sorted mixtures of coarse-grained sand and fine-grained gravel (granules, pebbles, and cobbles) with shells, and are characterized by wavelengths of between 1 m and 2 m and heights of less than 0.3 m. They do not indicate sediment transport, but are formed by oscillatory motions of water from large waves. Samples

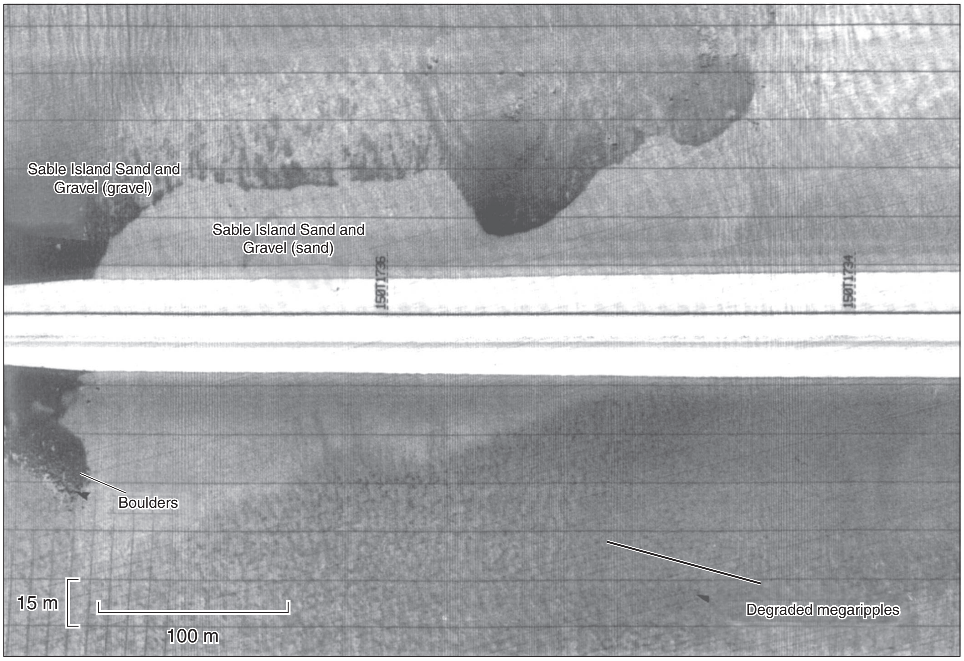


Figure 98. A 120 kHz sidescan sonogram of the northernmost occurrence of degraded megaripples in the harbour in the 30 m deep channel northeast of Mars Rock and Sandwich Point. These megaripples are located in the trough of a sedimentary furrow and attest to upharbour, northwest transport of sand during large storms and reactivation of the sedimentary furrows.

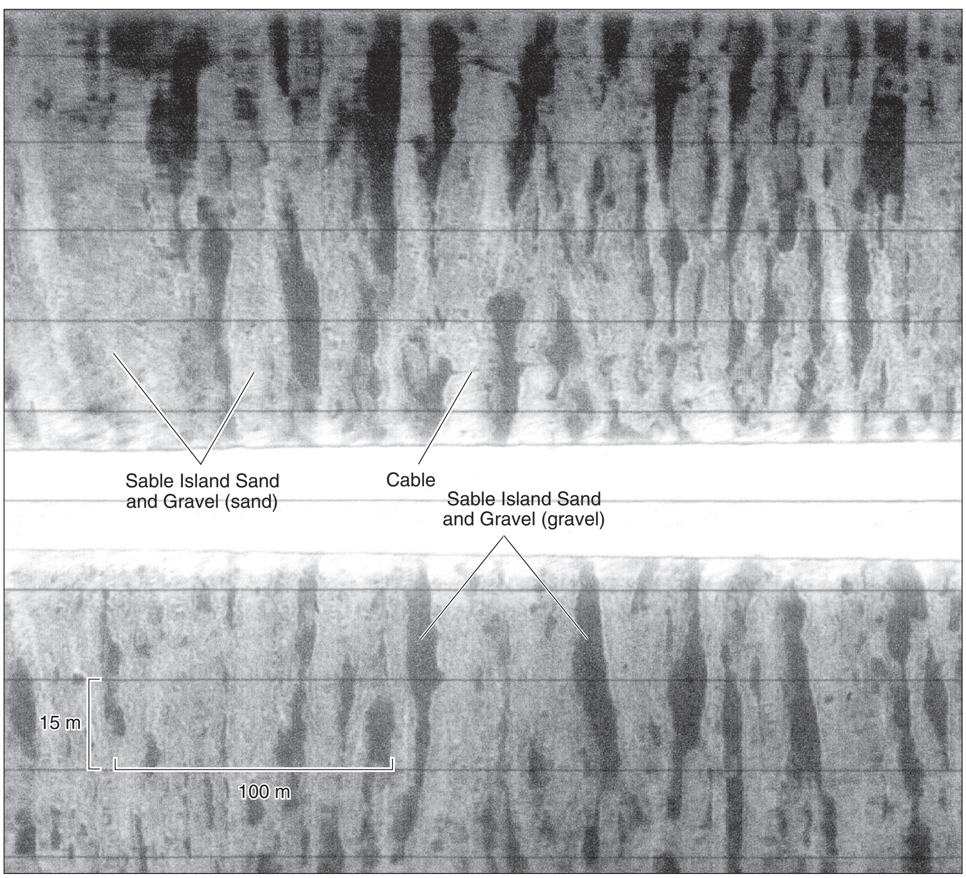


Figure 99. A 120 kHz sidescan sonogram illustrating megaripples in sand of the Sable Island Sand and Gravel in the outer harbour off Chebucto Head overlying gravel of the Sable Island Sand and Gravel. A partially buried cable also occurs across the seabed. The occurrence of gravel in the troughs of the bed forms indicates that the sand is thin, generally less than 1 m in thickness.

collected in the gravel waves in the outer harbour contained a biogenic component of over 70% broken shell debris and sea urchin spines.

The areas of exposed bedrock, gravel ripples, and megaripples in the outer harbour indicate that fine-grained, silt- and clay-sized sediments are not deposited there. Fine-grained sediments discharged to the outer harbour are transported either farther offshore to the inner Scotian Shelf basins, or up the harbour to the north. A small area of ripples in gravel occurs in the inner harbour, adjacent to the Dartmouth shore. These bed forms occur in 5 m water depth and likely formed by large waves generated during storm conditions.

Gravel circles

A field of approximately 95 unusual gravel circles, each up to 25 m in diameter (Fig. 8, 17, 97) occurs in the outer harbour adjacent to Bear Cove Shoal and a series of unnamed shoals to the northwest, on the eastern side of the deep outer harbour channel. The circles are slight depressions 20–40 cm lower than the surrounding sandy seabed and occur in 30 m of water. They lie in linear groups that are aligned (Fig. 100) with a northwest-southeast orientation. Sidescan sonograms show that in some groups, individual circles are connected by narrow, linear gravel deposits giving the circles a beaded appearance on the sonograms. They also occur as single, isolated circular features. Small patches of sand occur in the centre of many of the circles. In most areas the circles also occur in parallel to subparallel rows. The surrounding sand is generally featureless in the vicinity of the circles and between individual circles and the bedrock outcrop of Bear Cove Shoal. In deeper water, away from the circles to the south, the sand is formed into long-wavelength megaripples. The rows of circles are normal to the orientation of the megaripples.

Remotely operated vehicle video, submersible observations, and seabed samples confirmed that the circles are depressions of well rounded, discoid, slate gravel clasts, in the cobble to boulder range, with broken and whole shells (Fig. 101). The sand is very thin in the adjacent area and gravel frequently outcrops in the troughs of the megaripples. The gravel circles do not exhibit any internal relief and the seabed is regionally flat. The adjacent bedrock shoals, however, shallow rapidly to 16 m over short distances of less than 50 m (Fig. 6, 12).

At first it was thought that they represented dredge spoils dumped at the seabed of the outer harbour; however, the unique geometric arrangement in parallel linear rows adjacent to the steep bedrock outcrop, the consistent orientation to the megaripples, and the fact that this is not a known dumping ground for dredge spoils, suggests that the features could not have formed by the random process of dredge-spoil dumping. Additionally, the material in the circles is not dredge spoil, occurs in slight depressions, and consists of rounded gravel lag.

Based on his research on macroturbulence in stream flow, Matthes (1947) proposed the term 'kolk' to describe a process of upward vortex action as the most important macroturbulance process in natural streams, often resulting in a surface boil. Such a process was modelled and observed to produce bed deepening by vortex suction, a phenomenon similar to tornadic action on land. The greatest erosion occurs at the upstream flank of boulders or steep bedrock cliffs. Negative pressures produced by vortex suction of the kolk type were determined to be the most powerful concentrated forms of energy applied to the bed by moving water.

The authors propose that the gravel circles periodically form under similar conditions in the outer harbour during storms with strong northward bottom flow. This part of the outer harbour occurs at the apex of a regional outer harbour narrowing and shoaling morphology that extends from Chebucto Head inward. Large vortices may develop as these strong, linear bottom flows are deflected vertically by the steep bedrock face of Bear Cove Shoal (Fig. 6, 12). Walls of shedding vortices scour the thin overlying sand in a circular pattern and expose the underlying gravel lag. The presence of small, centrally located circular sand patches in many of the gravel circles is an indication that this sand may have been protected from complete removal in the eye of the spinning vortex. The alignment and linear pattern of gravel circles suggests that a row of shedding vortices may have formed the circles as opposed to a single vortex intermittently touching down upon the seabed while travelling along a straight path. The area was surveyed repetitively over several years and no alteration was observed. This suggests that the flows necessary to generate the vortices may only develop during large storms and hurricanes.

Cohesive sediment bed forms

Sedimentary furrows

A series of linear erosional scours in LaHave Clay occur in two areas within Halifax Harbour: at the boundary between the inner and outer harbour between Sandwich Point and Fergusons Cove (Fig. 6, 12, 102), and within areas of Northwest Arm (Fig. 103, on CD-ROM). The features in the outer harbour are oriented subparallel to the adjacent western shoreline and are slightly curvilinear to the northeast, particularly in the northern area of furrow distribution. The sidescan-sonar imagery shows that the troughs of the furrows consist of more highly reflective material than the surrounding seabed, suggesting the presence of coarser sediment of sand, shell, or organic debris (Fig. 104). They range up to 2 m deep and 1.8 km long.

There are two distinct zones of furrow development in an area adjacent to Sandwich Point separated by an area with a lack of furrows off 'York Redoubt'. This may result from a seaward topographic protrusion of local bedrock into the harbour at 'York Redoubt', or the construction and operation of antisubmarine nets from former military activities. In the

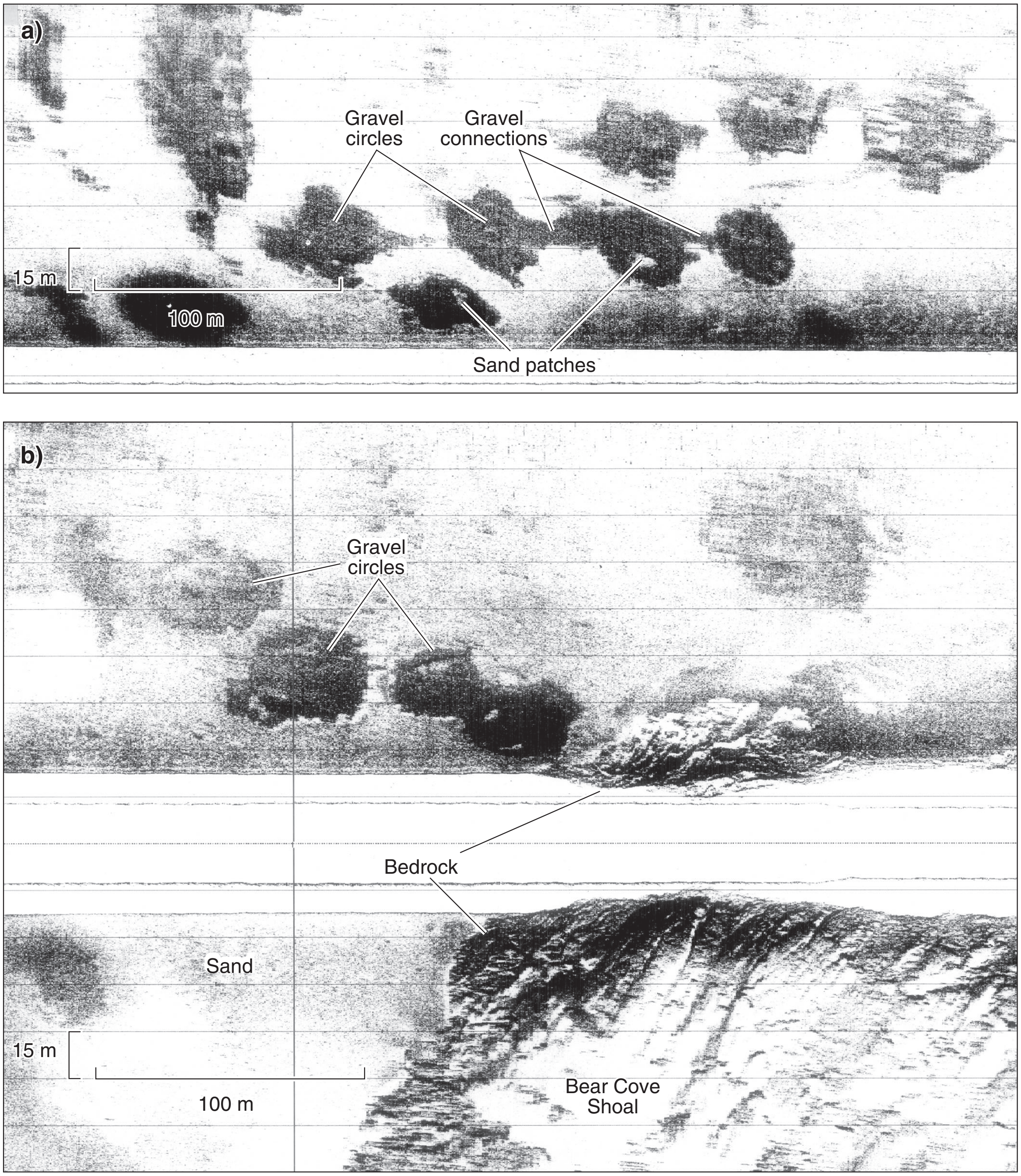


Figure 100. Two 120 kHz sidescan sonograms from an area of gravel circles to the **a)** west and **b)** south of Bear Cove Shoal in the western part of the outer harbour. The gravel circles are approximately 20 m to 30 m in diameter and 0.2 m in depth. Approximately 95 gravel circles were mapped in this area. Note the alignment of the circles sometimes connected by linear areas of high backscatter, the central patches of sand in some of the circles, and the parallelism of the circle rows. The surrounding seabed is sand.

southern area of the furrow distribution off Sandwich Point, the furrows bifurcate, opening to the south, or seaward. They gradually shallow, narrow, and merge with the flat, muddy seabed in the north. Seismic-reflection profiles across the area show weak clinoform reflections within the sediments prograding in a northerly direction. The furrows are both symmetric and asymmetrical in cross-section with the steepest slopes on their western flanks.

The sedimentary furrows that occur in Northwest Arm are adjacent to Sir Sandford Fleming Park midway up the arm, and in an area extending northwest from Point Pleasant Park at the entrance to the arm, to the Royal Nova Scotia Yacht Squadron (Fig. 6, 12, 13). A sedimentary furrow adjacent to Sir Sandford Fleming Park (The Dingle) is a northwest-southeast elongation of two deep, linear depressions floored with bedrock and gravel at the narrowest constriction in the arm. The northwest asymmetry of this sedimentary furrow suggests stronger currents affecting the seabed on the flooding tide with net sediment transport to the north up the arm.

Three sedimentary furrows occur in the outer part of the arm, with the longest one over 2 km long. Where the sedimentary furrows approach the shoreline they often merge with toe-of-slope moats. In this area the seaward starting point for the sedimentary furrows appears to coincide with shallow pockmarks. The pockmarks may have created sufficient bottom roughness to generate turbulence for furrow formation.

Furrow processes

Similar linear cohesive sediment erosional features have been found in many diverse sedimentary environments: the deep sea, lakes, and estuaries (Dyer, 1970; Hollister et al., 1974; Flood, 1980). Flood (1983) proposed a classification system for sedimentary furrow types using variations in furrow morphology and how these relate to the sedimentary environment. Furrows appear to develop in different sediment types, however most occur in fine-grained mud, as is the case in Halifax Harbour within LaHave Clay. Based on their cross-sectional shape, the harbour furrows are classified as type 1A, that is, they possess distinct troughs with steep walls, flat floors, and are generally symmetrical. Flood (1981) suggested that type 1A furrows appear to form in areas where sediment accumulation rates exceed erosion rates over long periods of time. Furrow spacing can vary widely from 2 m to over 200 m, but in a given field they usually maintain a consistent separation. The distances between the furrows in Halifax Harbour vary considerably.

Furrows can exhibit a joining pattern, whereby two parallel furrows come together to form one. These 'tuning fork' junctions open into the flow direction and can be used as current and sediment transport-pathway indicators. The distribution and geometry of the sedimentary furrows adjacent to Sandwich Point indicates that the currents that formed them dominantly moved from the south to 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 to much greater than 100 cm/s. Tidal flows are generally confined by the shape of the estuary in which they occur, and the deep, western, linear channel of Halifax Harbour likely exerts a controlling influence.

Dyer (1970) and Hollister et al. (1974) postulated that helical secondary-flow structure within the benthic boundary layer is responsible for formation of sedimentary furrows (Fig. 105). In addition, Flood (1981) suggested that coarse sediment plays an important role in the initiation of furrows. Coarse mobile sediments become concentrated in the convergent flow zone and abrade the seafloor. Directly seaward of the furrows in the harbour, the sediment consists largely of sand, a ready source of coarse-sediment supply. Megaripples occur on the sand in the deep 30 m bathymetric depression off Sandwich Point. It is possible that transport of the sand and coarse organic debris to the north across the Holocene mud has contributed to the

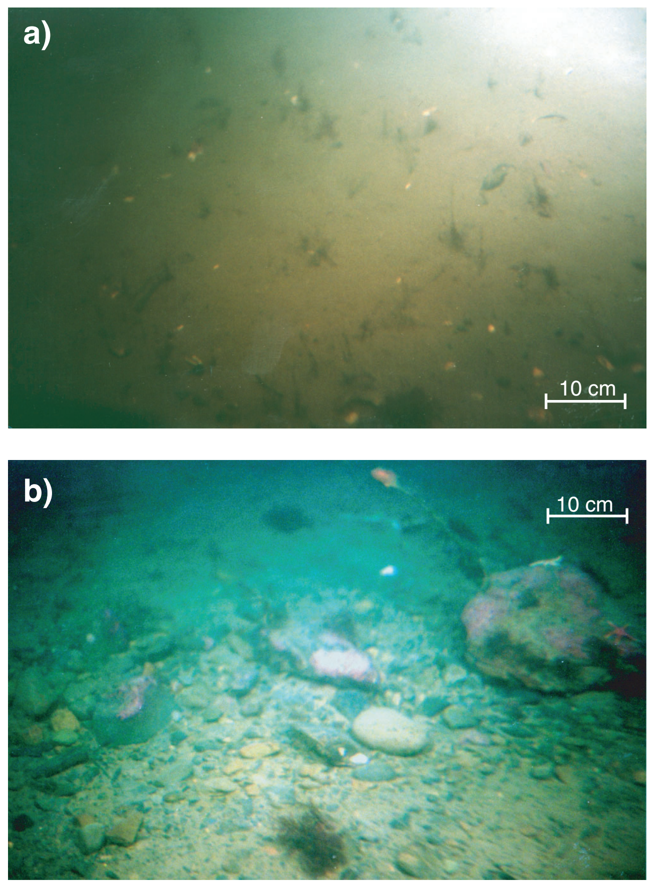


Figure 101. Bottom photographs **a)** outside and **b)** inside gravel circles adjacent to Bear Cove Shoal collected from the *Pisces IV* submersible. The gravel circles are unusual bed forms approximately 20–40 cm deeper than the surrounding seabed. It appears that sand has been eroded to expose a transgressed surface of gravel. The floor of the gravel circles is composed of pebbles, cobbles, and boulders, mostly rounded to subrounded. The large boulder in the right of the image is approximately 40 cm in diameter. Both photographs by G.B.J. Fader. GSC 2006-209 and GSC 2006-210, respectively.

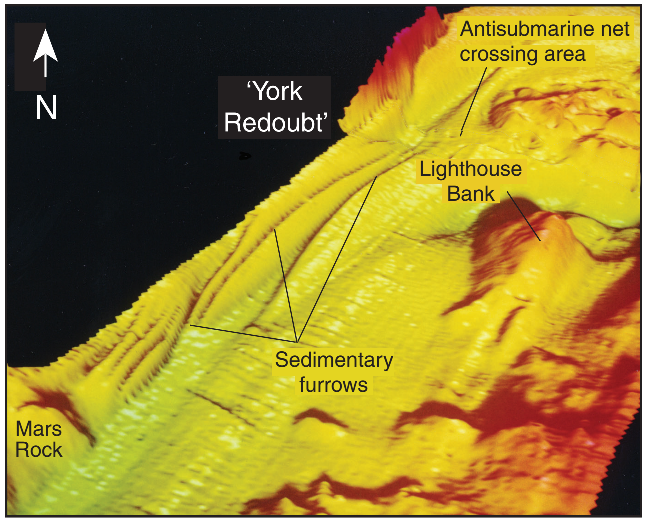


Figure 102. A multibeam-bathymetric perspective image of the sedimentary furrows off 'York Redoubt' in the outer harbour north of Mars Rock. They appear to be broken and partially interrupted off 'York Redoubt', at the former location of antisubmarine nets that spanned the harbour (Fig. 6, 13). From Mars Rock to end of data in east is approximately 1.25 km.

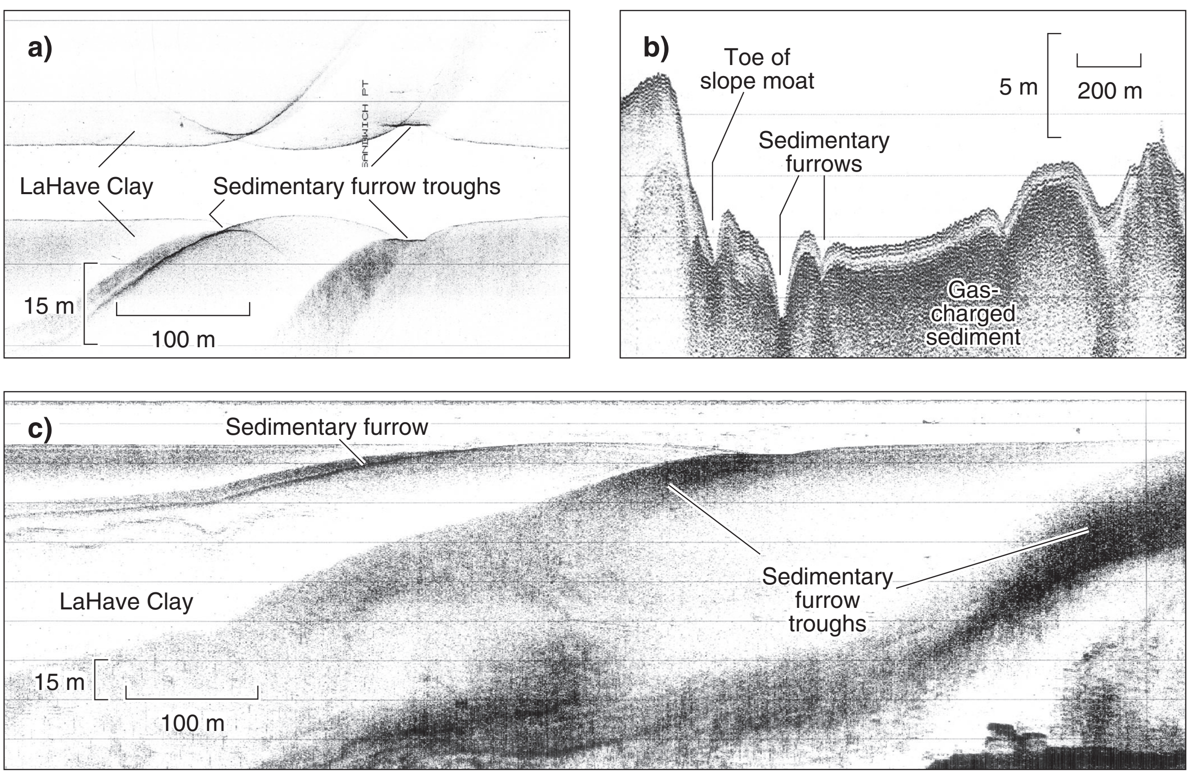


Figure 104. a), c) Two 330 kHz sidescan sonograms and **b)** a seismic-reflection profile of sedimentary furrows from the western side of the harbour extending from the entrance to Northwest Arm to Sandwich Point. The sidescan sonograms show that the floors of the furrows are high-backscatter surfaces composed of coarser material. The sedimentary furrows occur at the transition between inner harbour LaHave Clay and outer harbour Sable Island Sand and Gravel. They form as a result of erosion of LaHave Clay and transport of coarse sandy sediment from the outer harbour to the inner harbour by parallel, helical bottom flows generated during large storms.

formation of the furrows. It is not known if the features are continuously active or are filled in at intervals; however, they are present on the surveys conducted over a four-year period, suggesting some permanence. The sedimentary furrows indicate that this area of the harbour, although a general depositional zone, is likely subjected to periodic, strong, and directionally stable currents that erode the bed.

DeIure (1983) and Piper et al. (1983) studied the sediments off Sandwich Point to assess the role of storms in eroding coarse sediment from the nearshore with transport and deposition in deeper water. The sedimentology of cores collected in the area of the furrows identified sandy layers that were correlated with the historical record of major storms. On this basis, DeIure (1983) interpreted storm recurrence intervals and a source of sand from the adjacent nearshore.

Through interpretation of the multibeam bathymetry and seismic-reflection profiles, the authors suggest that the sandy intervals in the cores represent the troughs of buried sedimentary furrows that have shifted their location with time. If this is true, DeIure (1983) may have underestimated the frequency of storms over the past several hundred years as well as the source of the sand. The present authors' information on sediment transport directions suggests that the sand originates from areas to the south in the outer harbour and is transported northward in the troughs of the sedimentary furrows. There is little sand in the nearshore off Sandwich Point to be transported eastward to deeper water. Large hurricanes frequently pass offshore Halifax that do not severely affect local weather, but produce associated strong currents that could shift the location of sedimentary furrows as well as initiate northward movement of coarse material in the furrow troughs.

Moats: erosional and nondepositional

Moats are a common characteristic of the depositional style of the LaHave Clay in the inner harbour. They occur in a variety of sizes and shapes both associated with LaHave Clay occurrence near bedrock and glacial topographic features at the seabed. The most common type of moat occurs at the base of slopes (toe-of-slope moat) at the contact of the LaHave Clay with bedrock shoals and gravel-covered shallow areas. The moats are contact-following depressions up to 3 m deep (Fig. 20, 106, 107) and can continue for distances up to 2 km. The linear moats are confined to the area of the harbour between Pleasant Shoal and Sandwich Point and in nearshore areas of Northwest Arm.

In areas where isolated bedrock highs protrude above the surrounding muddy seabed, moats can take the form of circular, isolated depressions. Structural information on internal layering from seismic-reflection data indicate that most of the moats are not erosional features, but result from a lack of deposition, due to the presence of long-standing, contour-following currents or local turbulence developed adjacent to topographic highs. With the exception of Georges Island, moats are generally absent north of McNabs Island, likely as a result of decreased current strength. Some broad, shallow moats occur in Bedford Basin to the southeast of Jonquière Bank and are adjacent to steep bedrock and till features (Fig. 18). The contact of the LaHave Clay with the gravel-covered till along the Dartmouth shoreline in the inner harbour is an onlap relationship without the generation of a moat.

Georges Island moat

The Georges Island moat is a large horseshoe-shaped depression around the west, south, and east flanks of Georges Island (Fig. 6, 13). Maximum depths of 31 m occur in the feature on the east side and the seabed at the base consists of till and exposed estuarine and lacustrine sediments (Fig. 107). Seismic-reflection profiles show internal structural bedding horizons within the LaHave Clay that indicate that the moat is a nondepositional feature and not an erosional scour (Fig. 107). It has persisted since the early deposition of LaHave Clay over 5000 years ago. Its formation results from the presence of Georges Island in the inner harbour and its effect on local currents. As the water moves up the harbour, flow velocities increase around the island as a result of its obstruction preventing sediment deposition. In the lee of the island to the north, preferential deposition has resulted in the formation of an isolated mounded deposit (sediment drift) of LaHave Clay.

The Georges Island moat area was one of the chosen locations for a single waste-water treatment plant marine outfall by the Halifax Harbour Task Force (Fournier, 1990). Dispersion of effluent would be accomplished by the faster flowing water in the moat with deposition of particulate material in other areas to the north and south. This location followed a containment philosophy for outfall design. Lack of deposition in the moat area would sustain effluent dispersion and prevent outfall burial.

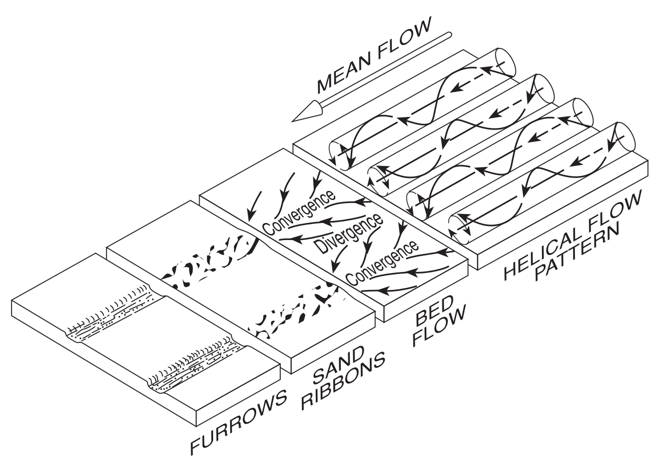
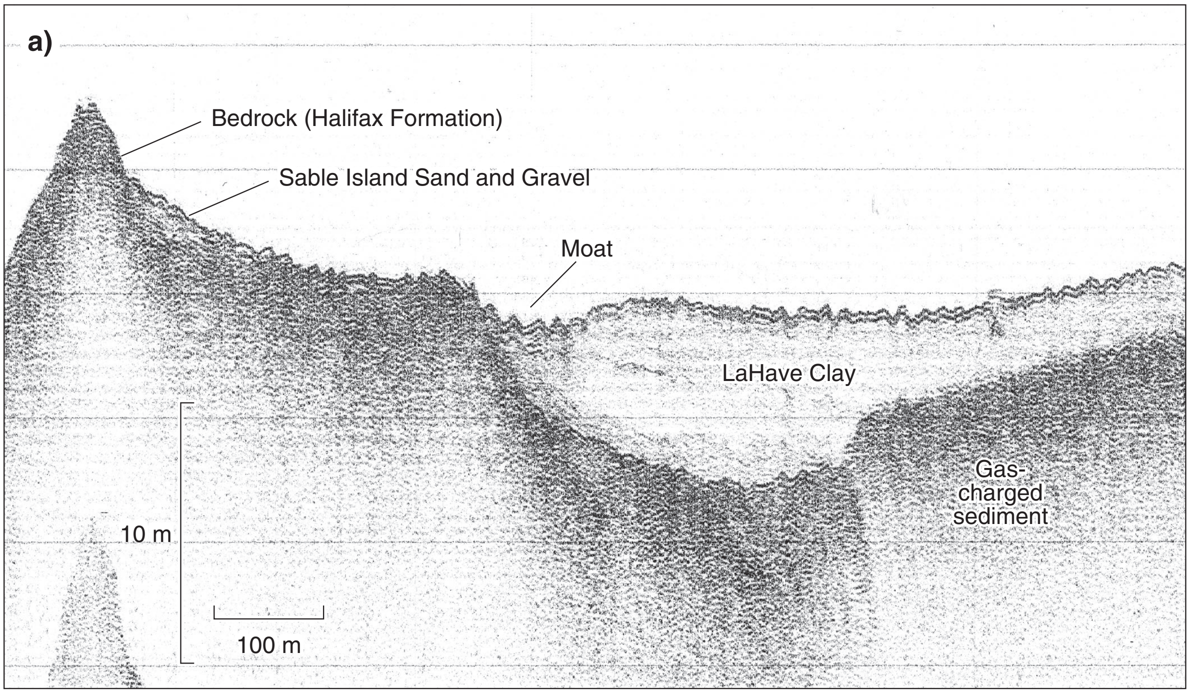


Figure 105. A diagrammatic model for the formation of sedimentary furrows proposed by Flood (1981) from studies of furrows in the Great Lakes and flume-tank experiments. Processes of flow convergence in sedimentary furrow troughs concentrate coarse sediment and debris.



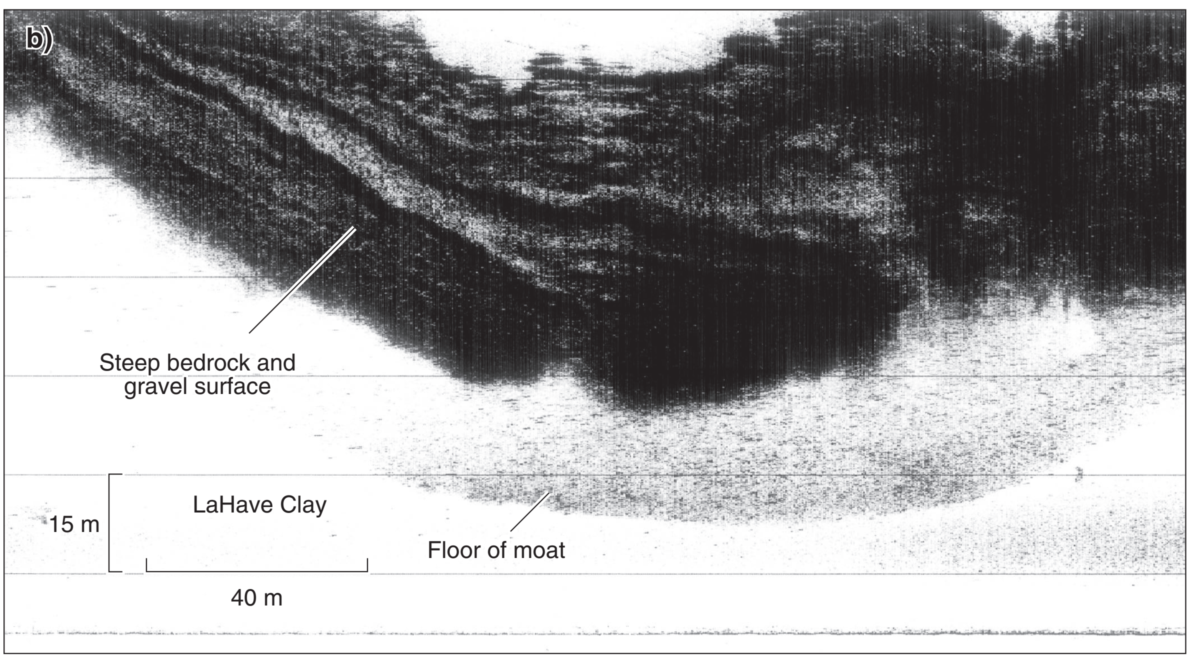


Figure 106. a) Seismic-reflection profile from the inner harbour adjacent to Pleasant Shoal showing a moat developed at the contact between LaHave Clay and bedrock, typical of the relationship between these units and for the area south of Pleasant Shoal to Sandwich Point. **b)** A sidescan sonogram of a moat along the western flank of the outer harbour adjacent to Sandwich Point, showing the coarser nature of the material at the base of the moat and its relationship to the steep gravel-bedrock flank. These moats, together with the sedimentary furrows, suggest that the area is one of sediment deposition, but is periodically subjected to strong currents that preferentially erode selected areas of LaHave Clay or prevent deposition adjacent to steep gravel-covered, bedrock-controlled slopes.

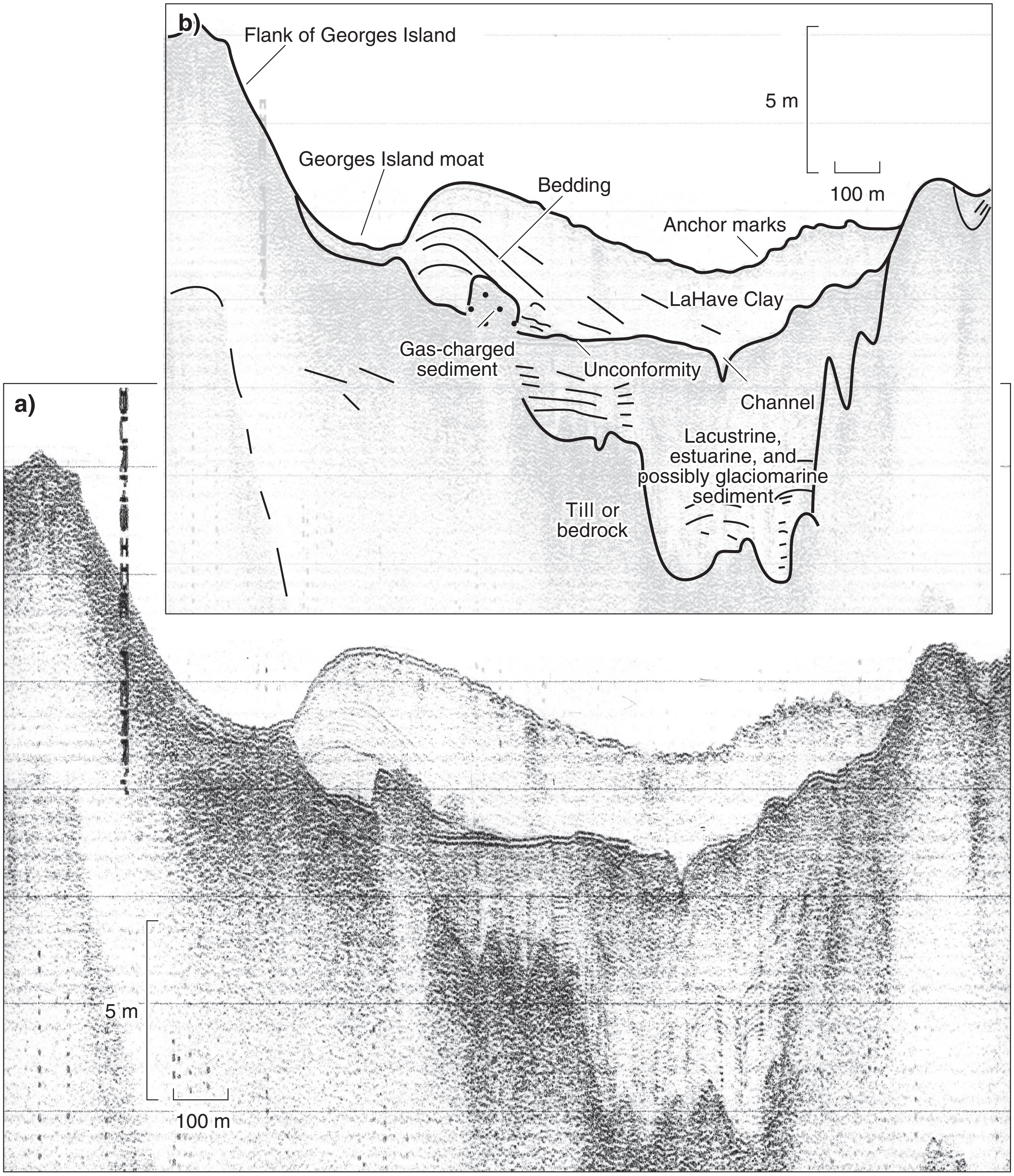


Figure 107. a) Seistec seismic-reflection profile and **b)** interpretation across the Georges Island moat, showing persistence of the moat from the time of early LaHave Clay deposition to the present, as evidenced by the structure of the internal reflections within the LaHave Clay. The reflectors representing bedding are curved downward near the moat and have maintained a conformable depositional style throughout the section.

Regional scoured depressions

In the inner harbour the multibeam-bathymetric data (Fig. 6, 12, 13) reveal the presence of broad, linear, subtle morphological depressions in LaHave Clay that are similar in morphology to sedimentary furrows, but are much broader with low-angle slopes. These occur at the deep channel between McNabs Island and Pleasant Shoal and Middle Ground, northwest of Georges Island along the Halifax shoreline, at the entrance to Eastern Passage, in Northwest Arm, and between Middle Ground and Outer Middle Ground. Their orientation, parallel to the regional axis of the harbour or distribution between confining shallow areas, suggests that they are formed by channellized, focused currents of slightly higher velocity than that of the surrounding areas. They are interpreted to represent areas of both periodic deposition and erosion of fine-grained sediment. As such, they represent preferred areas of the inner harbour for the placement of waste-water outfalls to achieve maximum effluent dilution. Their persistence over time suggests that erosional processes dominate and that the highest velocities of flow over LaHave Clay within the harbour are confined to these broad channel-like areas.

'Bottle collector hole'

The distribution and morphology of LaHave Clay deposits in Northwest Arm also indicate where high current velocities have affected the seabed. Mud is deposited in two major areas separated by an area of gravel and bedrock seabed adjacent to The Dingle (Sir Sandford Fleming Park) (Fig. 88, 103). Here the arm narrows and the currents increase in velocity, forming a large sedimentary furrow. This linear depression is not the result of previous deposition followed by erosion, but merely a continued lack of deposition resulting from stronger currents that have persisted in this area of the arm. The depression also acts as a trap for bottles thrown into Northwest Arm, hence the proposed term 'bottle collector hole'. Bottles thrown into the arm sink to the seabed in a neutral to slightly negative inverted position and move up and down the arm in response to currents and tides. Once in the depression off The Dingle, they become trapped. It is a popular dive location to retrieve bottles.

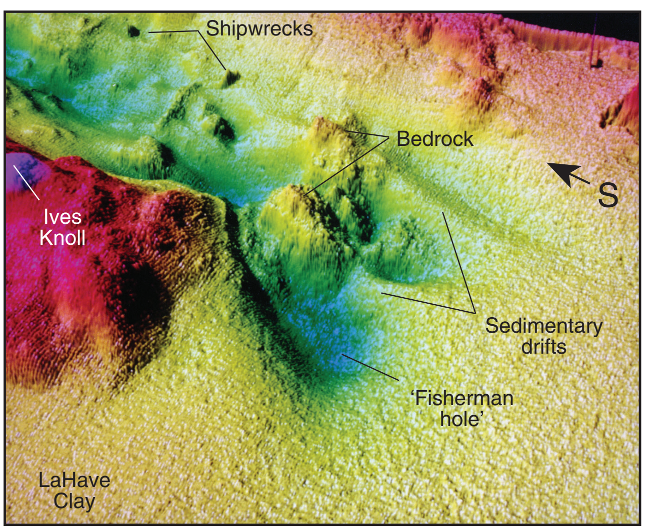


Figure 108. A multibeam-bathymetric perspective image looking southwest in Halifax Harbour in the area between Ives Knoll and Halifax, showing the presence of bedrock, current-scoured depressions, and erosional remnants of LaHave Clay referred to as sedimentary drifts. Strong currents moving from south to north have eroded the seabed on the south side of the bedrock outcrop and the bedrock mounds have prevented erosion on their northern lee-side flanks. The easternmost large scour is a deep depression locally referred to as the 'fisherman hole'. Distance between shipwrecks is approximately 400 m.

Anthropogenic scoured depressions

The scoured depressions discussed above are largely associated with localized strong currents resulting from seabed natural variations in the morphological shape of the harbour. Other scoured features relate to the presence of anthropogenic materials and features, and activities such as the construction of antisubmarine nets, sinking of ships and boats, and construction of wharves and docks.

Sediment drifts

Sediment drifts are localized deposits of fine-grained material with positive relief, usually associated with a drop in current velocity and in the lee of topographic elevations. The sediment mound to the north of Georges Island (Fig. 6, 13, 89) is a true sediment drift, that is, an accumulation of material on the current-sheltered lee side of the island. It is not a remnant of formerly deposited material that remains as a result of erosion in adjacent areas. Isopach information indicates that the sediment is more than 7 m thick. Its location to the north of Georges Island denotes long-term sediment depositional patterns and that this area has been an accumulation zone in the inner harbour since the deposition of early LaHave Clay.

The authors previously interpreted the occurrence of sediment drifts in the inner harbour between Ives Knoll and the Halterm South End Container Terminal (Fig. 108) (Courtney and Fader, 1994; Fader and Buckley, 1997). The evidence for such an interpretation was the positive relief of two linear mud deposits and their location to the north of bedrock highs on the seabed, suggesting deposition in a protected, lower current-velocity setting. Further evaluation of the seismic data suggests that the deposits most likely represent erosional remnants of a much broader and uniform deposit of LaHave Clay that once occurred to the east and south of Georges Island. On both sides of the deposits, scoured depressions are formed in the LaHave Clay. The present authors interpret the scouring of the mud to result from the construction of a large breakwater in 1913 east of Point Pleasant Park extending from the Halifax shoreline. This breakwater was intended to diminish the effects of ocean swell originating in the outer harbour from the inner harbour. It effectively reduced the width of the passageway between Ives Knoll and the Halifax shoreline by one-quarter of the previous distance. This resulted in increased current velocities in the restricted channel that induced erosion of the LaHave Clay, producing the scoured depressions and leaving the erosional remnants north of the bedrock outcrops. Directly north of these scoured depressions evidence exists to further support such an interpretation. Old generations of anchor marks are buried by more recent sediment cover (Fig. 87). The high-resolution seismic-reflection data also show a more recent layer of fine-grained sediment overlying the anchor-marked surface south of Georges Island, indicating a recent pulse of sedimentation.

Since the construction of the breakwater, the area to its north has been infilled for a container pier, but the constriction of the harbour entrance and initiation of seabed erosion likely commenced at the time of breakwater construction. The easternmost scoured depression is known locally as 'fisherman hole' for its abundance of fish and is a popular sport-fishing location. It recently has been used as a depositional area for dredge spoil.

Other sediment-transport indicators

No direct measurement of sediment transport in Halifax Harbour has been undertaken. Such studies require the use of tracers and sediment traps together with subsequent monitoring programs and have only regionally been conducted on Sable Island Bank on the Scotian Shelf (Amos and Nadeau, 1988); however, in addition to the presence of bed forms and scour features, many other characteristics of seabed sediments can be used as qualitative indicators of transport directions. These include distribution patterns of gravel, sand, silt, and clay; the distribution of sewage banks; and the distribution of geochemical anomalies relative to injection points (outfalls).

As discussed under 'Geochemistry', the distribution of geochemical anomalies in harbour sediments relative to injection points provides a clear indicator of sediment transport (Buckley and Hargrave, 1989). Many of these distributions indicate dispersion and settlement of material from the sewage-discharge locations along the shores of the harbour in a northerly direction upharbour in agreement with mean flow.

The presence of anchor marks on the seabed of the harbour is an important benchmark that can also be used to assess the history of sedimentation and sediment transport. Large areas of Bedford Basin and the inner harbour are covered with criss-crossing patterns of anchor marks. Some occur in the major shipping channels of the harbour where anchoring is presently prohibited, and are interpreted as being relict, that is, formed at some time in the past with little subsequent modification or burial. To the south of Georges Island, in an area where anchorages do not presently exist, is an anchor-scarred surface buried beneath recent sediment (Fig. 87). The source of the overlying sediment is to the south, indicating northward transport.

Discussion

An understanding of the direction of net sediment transport is essential for siting waste-water treatment plant outfalls, to predict the fate of discharged particles, and for other seabed engineering activities. The oceanographic, geological, and geochemical data are in good agreement that bottom currents generally move up the harbour to the north. The distribution of sand ribbons and geometry of megaripples in the outer harbour suggests that currents are strongest adjacent to Chebucto Head and decrease in intensity northward. Coarse sediments in The Narrows are predicted from the oceanographic data and a lack of fine-grained deposition confirms this prediction. In Northwest Arm adjacent to Sir Sandford Fleming Park, a similar lack of fine-grained sediments in a narrowing section suggests the presence of stronger currents where no measurements have been made.

The eastern part of the outer harbour is dominated by shallow bedrock and gravel at the seabed. The bedrock outcrops are flanked by rippled gravel deposits that indicate that wave energy is reaching the seabed and that they are zones of high energy. Cobble-sized clasts seen on bottom photographs indicate that some have been recently turned over, attesting to the effects of large waves in 20 m water depth. Muddy sediments in the outer harbour region are confined to the area north of Sandwich Point. Their presence in the inner harbour, Bedford Basin, Eastern Passage, and Northwest Arm reflects lower current velocities.

The multibeam bathymetry from the inner harbour, perhaps more clearly than other data sets, portrays net sediment transport pathways and associated local effects. The sedimentary furrows, obstacle-induced sediment drifts, nondepositional moats, current-scoured depressions, and lee-side depositional mounds indicate the net transport of materials to the north in the inner harbour. An exception occurs in the outer area of Northwest Arm where scours associated with buoy anchors and debris indicate net transport to the southeast, out of the arm. McLaren and Bowles (1985) and P. McLaren (unpub. report, 1991) attempted to determine sediment-transport pathways and areas of erosion, accretion, and dynamic equilibrium using spatial changes in grain-size parameters for sediments in the harbour. Their results were in general agreement with the directions from other studies that indicated landward direction of sediment transport in the outer harbour. The technique, however, is limited to areas away from seabeds formed by relict processes such as sea-level transgressions.

Previously proposed sewage-management systems for Halifax Harbour have recommended a containment approach whereby the deposition of effluent particles would be encouraged in the inner harbour (Halifax Harbour Task Force (Fournier, 1990) and Environmental Assessment Review Panel (1993) reports). For this reason, it was necessary to understand sediment-transport pathways and depositional centres in order to appropriately site facilities. Interpretation of the traditional geophysical data indicated the location of regional depositional centres, but the multibeam bathymetry clearly presented a better understanding of subtle details of erosion and deposition. For example, the extension of the sedimentary furrows is more clearly defined on the multibeam images. The scoured depressions south of Georges Island and subtle sedimentary furrows in Northwest Arm were previously unknown. Additionally, the ability to portray the multibeam-bathymetric data with varying vertical exaggerations and to shade the image from differing angles of illumination provides a major assistance to non-sedimentologists in understanding aspects of sediment transport and deposition and the application to waste-water facility design. This led the Environmental Assessment Review Panel (1993) to agree with the Halifax Harbour Task Force and to recommend a containment approach in the inner harbour for location of the outfalls from future waste-water treatment facilities.

ANTHROPOGENIC FEATURES

The seabed of Halifax Harbour contains a wide variety of anthropogenic features and materials (Fig. 13). The greatest density and variety of features occurs in the inner harbour, including Bedford Basin (Miller and Fader, 1995). They include anchor marks, obstacle-induced scours, dredge spoils, borrow pits, shipwrecks, ship-related features, oil-rig marks, dredged and blasted areas, bridge remains, antisubmarine net marks, cables, pipelines, trawl marks, sewage banks, and unidentified debris. The presence of these features on the harbour bottom has in many cases modified seabed morphology, sediment distributions, and subsurface stratigraphy, complicating the discrimination of anthropogenic from natural features and the collection of unmodified samples to characterize the surficial sediment units. Smaller anthropogenic debris includes bottles, cans, tires, barrels, metal objects, paper, timbers, and plastics. The following is a discussion of the anthropogenic features and attributes of the harbour seabed, including an assessment of the mechanisms responsible and their relationship with natural processes and geological history.

Antisubmarine net marks

Two parallel linear depressions occur in the outer harbour extending between Sandwich Point and Maugher Beach (Fig. 6, 13). They are interpreted to have formed beneath antisubmarine nets that spanned the harbour in this location during World War II. Current-induced and/or mechanical scouring of the seabed around the base of the nets is interpreted as the mechanism responsible for formation of these depressions.

A series of deeper scoured depressions at right angles to the antisubmarine net marks also occurs in the same area (Fig. 13). Sidescan sonograms (Fig. 109) show parallel groupings of large square objects, possible concrete blocks on the seabed, with scoured depressions to a depth of several metres between the blocks. The linear scoured depressions surround the blocks and the leading edge of erosion is an arrow-shaped feature pointing toward the south. The authors interpret that the concrete blocks remain as former anchors for the antisubmarine net gates that were left on the seabed after the nets and gates were removed. The scour is concentrated only around the blocks and the shape and alignment of the scoured depressions indicates that the currents that formed them were dominantly from the south.

Obstacle-induced scours

Localized scour occurs around boulders that protrude through thin LaHave Clay and around debris on the seabed. A large area of scour depressions around boulders occurs to the east of Middle Ground (Fig. 110). Diver observations at the location of the *Gertrude de Costa* shipwreck in this area suggest periodic deposition and erosion of silt-sized material (T. Dwyer, pers. comm., 1996). Repetitive dives to the wreck revealed over 1 m change in sediment thickness along the hull of the shipwreck over a two-year period. Multibeam images of the wreck confirm the presence of a local scoured depression. Scour in silty sand at the entrance to Herring Cove around the shipwreck *Deliverance* can also be clearly observed on the sidescan-sonar imagery (Fig. 111).

A large scour occurs on the seabed adjacent to Pier 9 in The Narrows (Fig. 32). This feature is a depression 30 m long and is interpreted to result from local turbulence generated by an abrupt change in angle of the dock face. This scour has undermined the adjacent dock foundation and has required major repairs to the dock. A plume of coarse sediment extending from the scoured depression projects to the north, suggesting that the depression is formed by northward-moving currents.

Anchor marks

Marks on the seabed formed by the process of ship anchoring are widespread, especially in Bedford Basin and the inner harbour. Their presence greatly affects the morphology of the seabed, creating a small-scale (0.2–3 m) roughness on fine-grained muddy sediments. Earlier surveys in Halifax Harbour conducted as trial operations to calibrate equipment, were often hampered by the roughness of the bottom. This roughness resulted in a lack of coherence from shot to shot on seismic-reflection profiles and echograms, and was often misinterpreted as arising from equipment problems, boulders, debris, recent faults, or the close proximity of subbottom undulating till or bedrock surfaces (M.R. Gregory, unpub. report 3-72, Nova Scotia Research Foundation, 1972; McKeown, 1975). The present authors now know that most of the roughness is caused by the widespread presence of anchor marks on the seabed. These features present a morphology and character similar to areas of offshore northern Canada where iceberg and sea-ice scours are common, and the seabed has been completely reworked by ice-keel scouring.

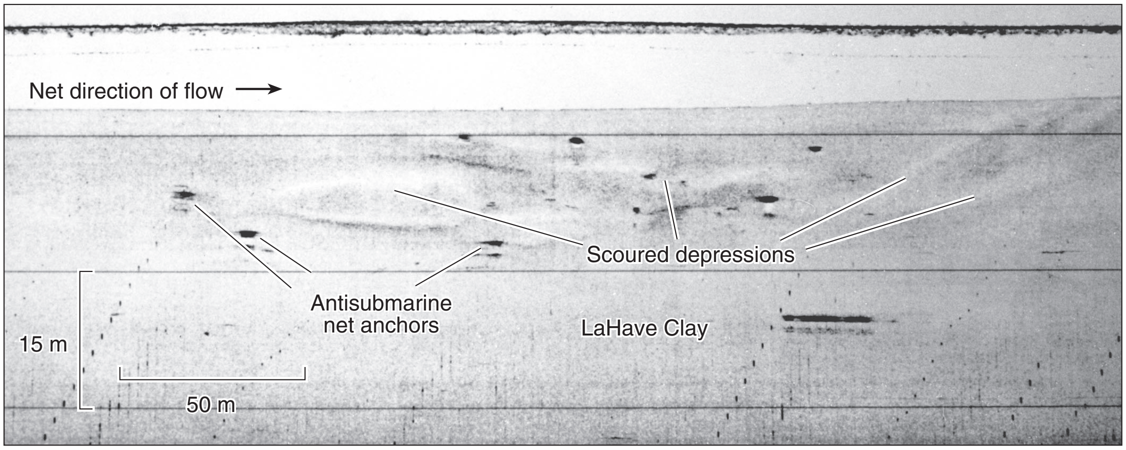


Figure 109. A 120 kHz sidescan sonogram of a scoured, 2 m deep, linear depression in LaHave Clay east of 'York Redoubt' formed around a series of large concrete blocks. The blocks were used to hold antisubmarine nets and associated gates in place during World War I and II. The scour orientation and arrow-like shape of the head, pointing to the south (left on image), suggests formation by strong bottom currents moving to the north that were obstructed by the net anchors on the seabed, generating sufficient turbulence for sediment erosion. Four similar-shaped linear scours occur in this area around antisubmarine net anchors (Fig. 13).

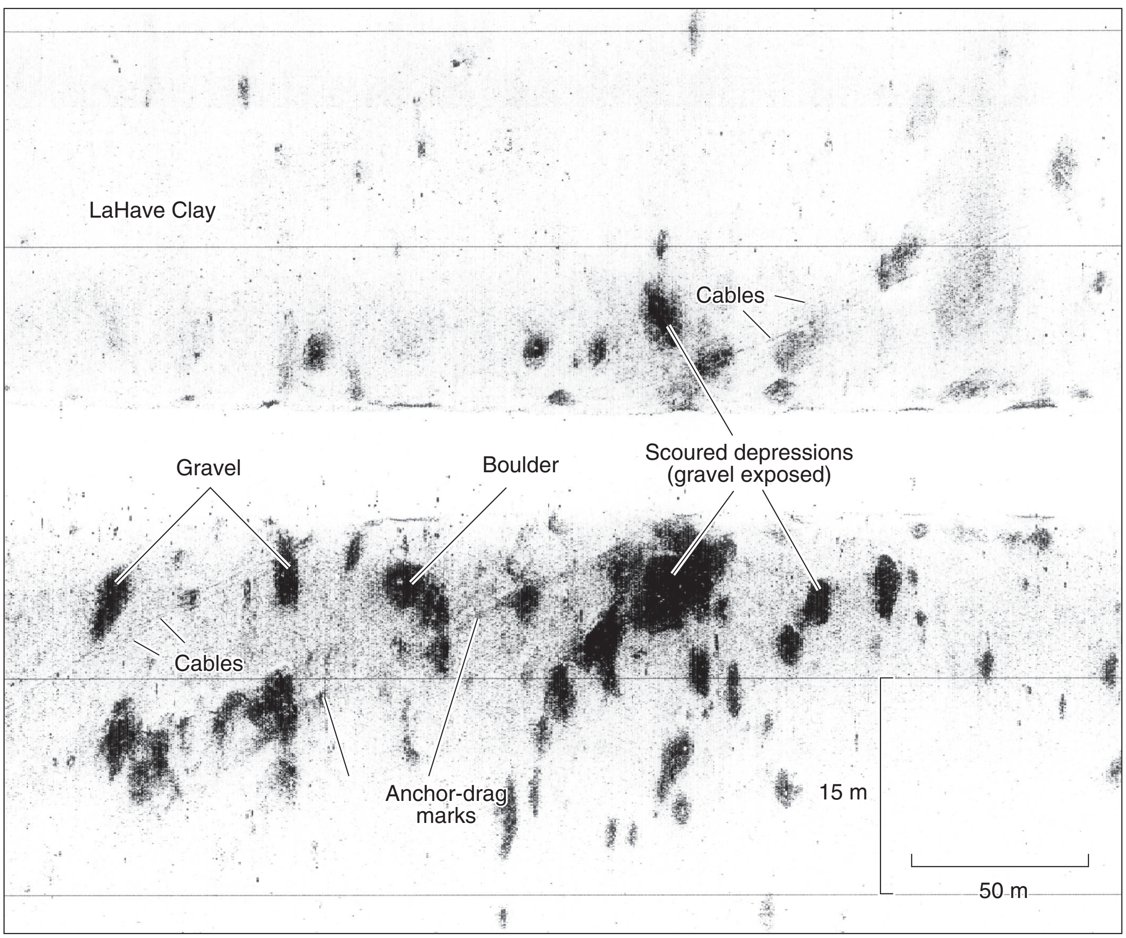


Figure 110. A 330 kHz sidescan sonogram east of Middle Ground, inner Halifax Harbour, showing an area of thin LaHave Clay with scouring around large boulders that protrude through the mud. The boulders are surrounded by circular patches of gravel (high acoustic backscatter). Strong currents in this area prevent deposition and/or induce erosion around the boulders. These features can also be observed on the multibeam bathymetry (Fig. 6).

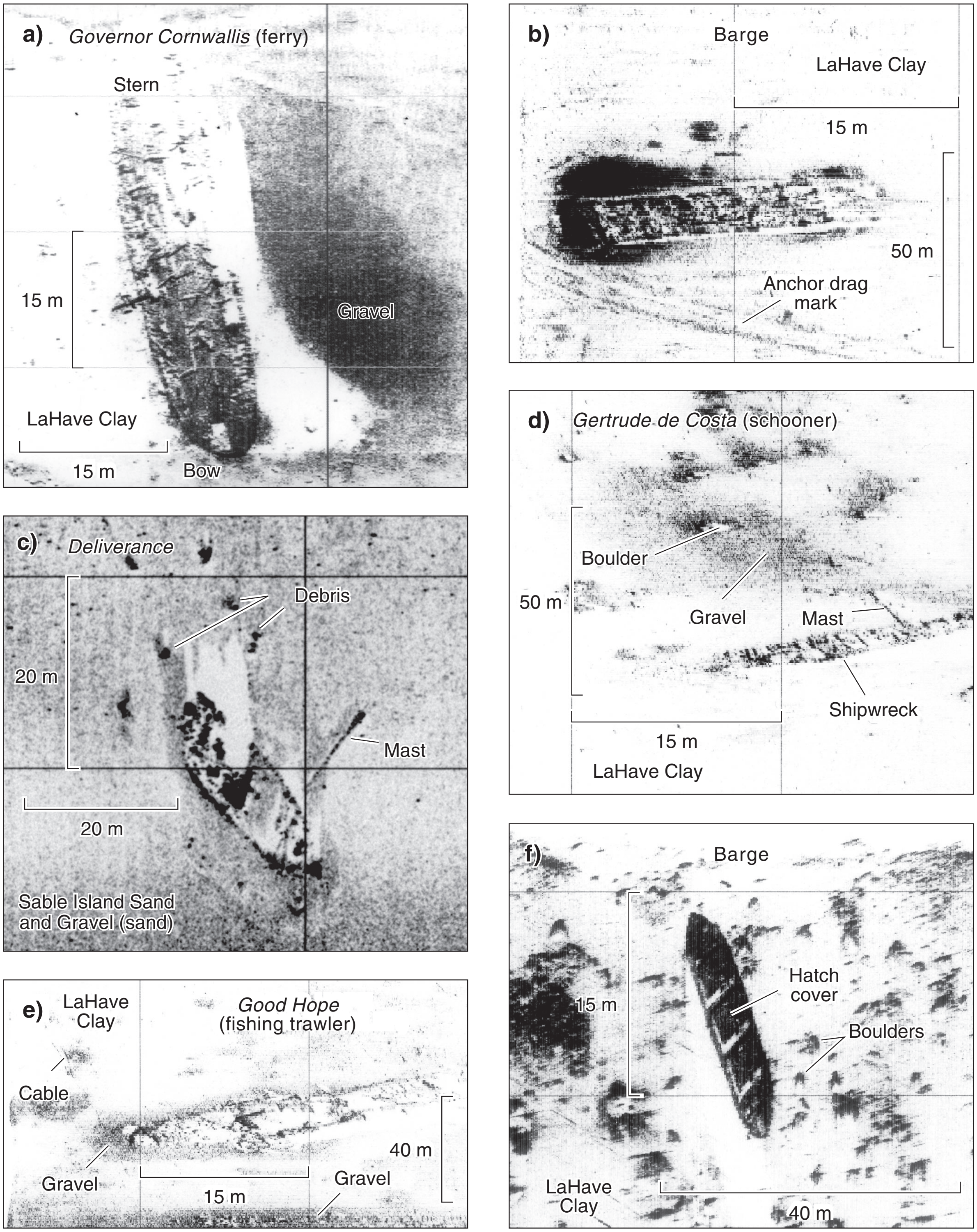


Figure 111. A composite of sidescan sonograms of several of the shipwrecks on the seabed of Halifax Harbour. Approximately 45 shipwrecks or large fragments of shipwrecks have been found in the harbour. Many have not been identified or verified with visual observations. These include **a)** the *Governor Cornwallis* ferry on the flank of Georges Island, **b)** a sand and gravel barge north of McNabs Island, **c)** the *Deliverance* off the entrance to Herring Cove, **d)** the *Gertrude de Costa* schooner off Point Pleasant Park, **e)** the *Good Hope* fishing trawler off McNabs Cove, and **f)** a barge (military) in northeast Bedford Basin.

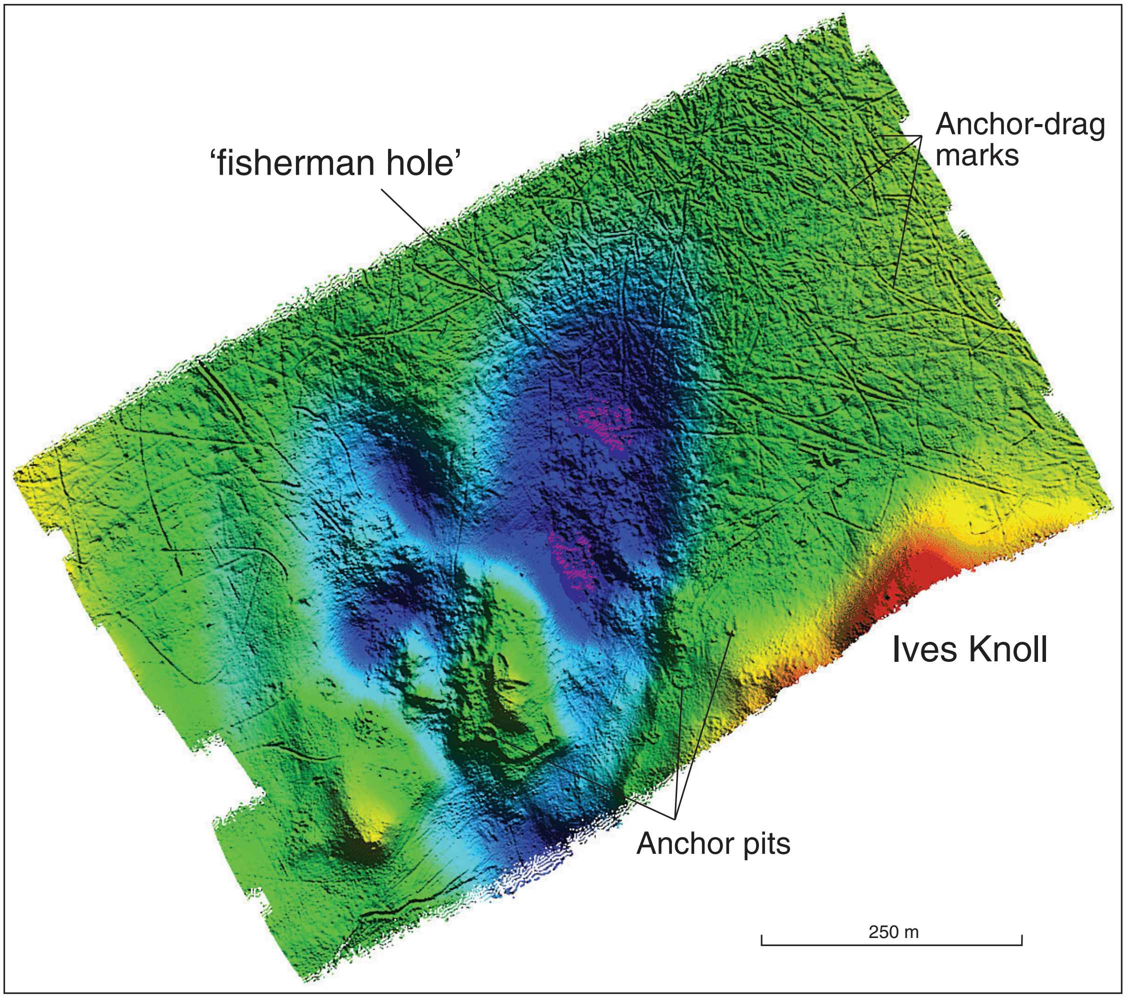
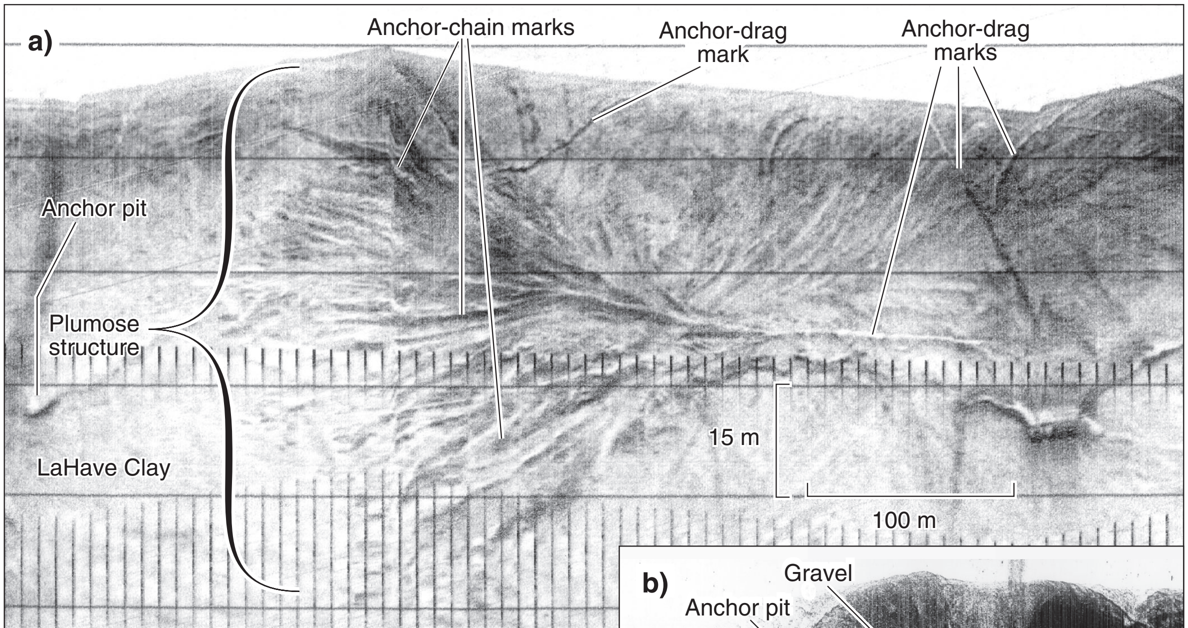


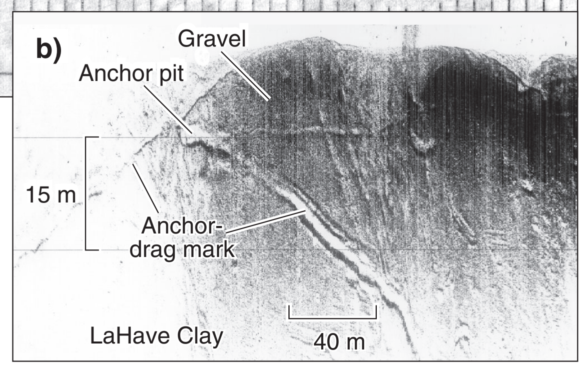
Figure 112. A Simrad EM3000 multibeam-bathymetric image collected in 2003 from the inner harbour to the northwest of McNabs Island adjacent to Ives Knoll over an area termed the 'fisherman hole' (Fig. 13). It clearly shows details of a seabed covered in many generations of large and small, straight and curvilinear anchor marks including pits and furrows. The greatest depth in the scoured depression (purple) is 38 m. Image courtesy of D.R. Parrott, GSC (Atlantic).

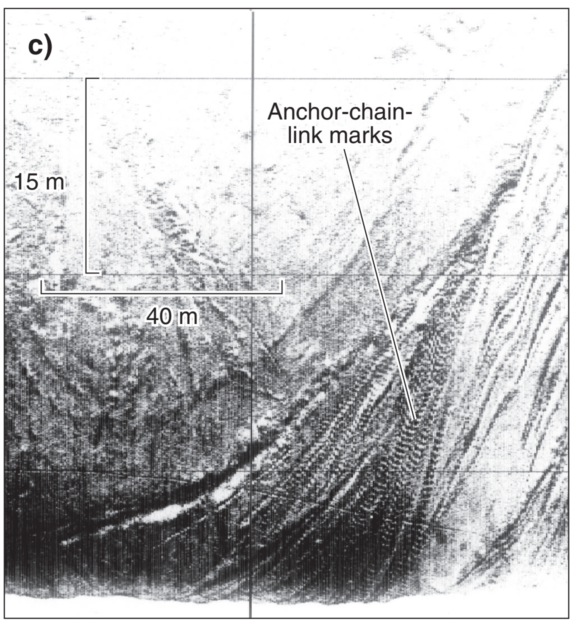
Sidescan sonograms provide the most detailed information on anchor-mark character and distribution, and mosaics have been constructed for the inner harbour (Fader et al., 1991) (Fig. 79). Depending on the multibeam systems used and the resolution of the processing, anchor marks are not generally well portrayed on that imagery. Only some of the larger anchor marks show on the multibeam image (Fig. 6) of the inner harbour derived from data collected by the C.C.G.S. *F.G.C. Smith*. Higher resolution multibeam systems, such as the Simrad EM3000, clearly show many generations of anchor marks and great variety in their size and shape in Bedford Basin (Fig. 18) and in a few areas of the inner harbour where recent surveys have been conducted (Fig. 112).

From a sedimentological and environmental perspective, one of the most important aspects of anchor marks is that the process is a widespread and significant sediment turbator. The authors have proposed the term 'anchorturbation' for this process (Fader et al., 1991). Additionally, in order to sample an intact, meaningful, and undisturbed stratigraphy, sediment cores must be collected away from anchor-marked areas. The interpretation of textural results from sediment samples must also be carefully evaluated in areas of high-density anchor marks especially where the anchors have penetrated several metres into the seabed and older and different sediments are exhumed and/or mixed with more recent sediment.

The widespread distribution of anchoring throughout the inner harbour and Bedford Basin suggests that sediments and their associated contaminants are also regularly being resuspended and redeposited. Anchor marks may also preferentially affect sedimentation with a local increase in deposition within the deeper central depression of the furrows. Anchor marks are classified into three major types: anchor pits, anchor-drag marks, and anchor-chain marks. Anchor-chain marks are further subdivided into anchor-chain-link marks (Fig. 113).







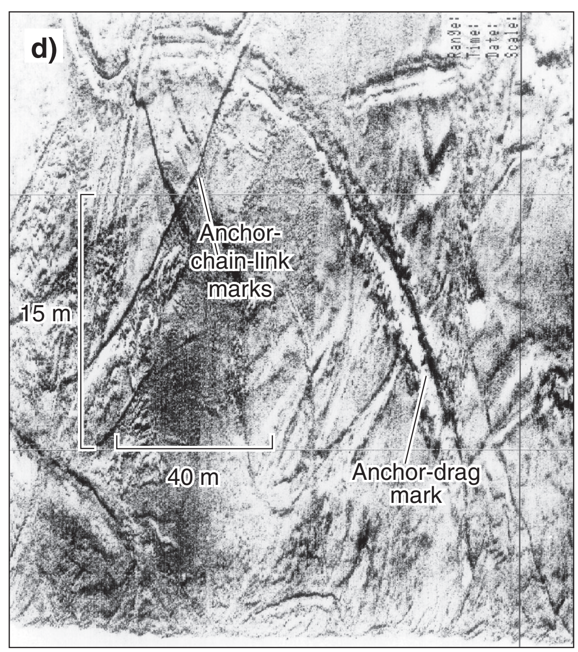


Figure 113. a), b), c), d) Sidescan sonograms illustrating the types of anchor-related marks on the seabed of Halifax Harbour. They are classified into anchor pits (Fig. 113a, b), anchor-drag marks (Fig. 113a, b, d), anchor-chain marks (Fig. 113a), and anchor-chain-link marks (Fig. 113c, d). Anchor pits are formed during the deployment and recovery of anchors, anchor-drag marks result from the dragging of anchors across the seabed, anchor-chain marks result from the repeated touching down on the seabed of anchor chains as ships weather-vane about their anchorages, and anchor-chain-link marks form through molding of sediment by small sideways movements of anchor chains. Collectively, fan-shaped anchor-chain marks are referred to as 'plumose structures'.

Anchor marks occur in a variety of depths, sizes, and shapes. The largest ones are up to 2.5 m deep and 5 m wide. The depth of some of these features may be increased by the subsequent 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 seabed tend to be shallow, most often less than 1 m deep, but are clearly defined because of the presence of gravel with boulders in the berms. Some have been traced for over 3 km along the seabed of the harbour. Many of the large harbour docks display radiating patterns of anchor marks, suggesting that the deployment of anchors as a ship's speed and/or direction control mechanism during docking is a common procedure, perhaps during times of high winds. Anchor marks located in the main transit corridors of the harbour, for example, between Ives Knoll and Pleasant Shoal, where anchoring is and has been prohibited, are interpreted to have formed as a result of deployment for collision avoidance or when shipboard power failures occur.

Anchor pits, anchor-drag marks, and anchor-chain and anchor-chain-link marks

The initial impact of an anchor dropped to the seabed often produces an amphitheater-shaped, deep, circular depression, which the authors refer to as an 'anchor pit' (Fig. 113). If the anchor has been dragged across the seabed in the process of setting the flukes and digging in to provide a hold or in the process of being retrieved, long linear features termed 'anchor-drag marks' are formed (Fig. 113). These can be straight or curvilinear and kilometres long. They may also result from the dragging of anchors when hold has been lost in response to the movement of ships under strong winds and currents. Anchor pits are often found at the beginning or termination of anchor-drag marks. They are slightly larger than the linear anchor-drag marks as a result of turning movements of the anchor as it is deployed and retrieved, producing a larger area of seabed disturbance. Depending on the sediment type and thickness, isolated mounds and ridges of overturned sediment can be deposited along the flanks of the anchor-drag marks. In some areas, particularly where the LaHave Clay is thin, the anchors penetrate through the mud to harder and coarser substrates, producing highly reflective discontinuous berms along the flanks of the anchor-drag mark and exposing subsurface sediments. This process occurs in the southern area of The Narrows (Fig. 84) where the LaHave Clay is thin, overlying till.

Another type of seabed mark associated with anchoring is termed 'anchor-chain mark'. These features form as the result of repeated touching down upon the seabed of anchor chains in response to winds and tides, as ships 'weather-vane' about their anchors and move up and down in response to tidal variations. Such marks appear as a radial pattern of linear depressions giving the seabed an imprint resembling a large feather (Fig. 113). Some of these features resemble features termed 'plumose structures' (Pecore and Fader, 1990) that are interpreted as dewatering structures in fine-grained sediments formed in response to active faulting in the subsurface; however, in Halifax Harbour the features are not interpreted to result from subsurface bedrock faulting or dewatering. On high-resolution sidescan sonograms, anchor-chain marks display another feature termed 'anchor-chain-link marks'. These are short, linear ridges normal to the linear chain marks (Fig. 113) representing the imprint of individual chain links on the seabed.

In most areas of the harbour where anchor marks occur, all of the characteristics of anchor marks can be seen, but in Bedford Basin there is preponderance for anchor-chain marks, possibly as a result of the deeper water and a greater scope of anchor chains.

Distribution of anchor marks

Most of the anchor marks occur in LaHave Clay sediments as both anchoring and sediment deposition generally take place in the deepest areas of the harbour. In the inner harbour, the densest distribution of anchor marks, where greater than 25% of the seabed is disrupted, occurs in the broad region to the north, east, and southeast of Georges Island (Fig. 114a). This is the area of the harbour where designated anchorages are located. Other areas with a similar density of distribution are found adjacent to the Imperial Oil wharves in Dartmouth, the Autoport in Eastern Passage, the ocean terminals in south Halifax, the naval dockyard, and Halifax-Dartmouth Industries docks in Halifax. The area of the inner harbour with the fewest anchor marks occurs immediately surrounding Georges Island and adjacent to the docks on the Halifax side of the harbour to the northwest of Georges Island. This may result from an absence of ship anchorages or the presence of zones of high sediment accumulation that has resulted in an infilling and obliteration of pre-existing anchor marks. The area adjacent to the Halifax docks and in The Narrows is also the major transportation corridor for the harbour and anchoring has not been permitted in those areas for a long time. The greatest density of sewage outfalls also occurs along this section of the harbour and may contribute to the infill of older, anchor-marked surfaces.

In Bedford Basin (Fig. 114b) over 80% of the muddy seabed is criss-crossed with anchor marks. The densest distribution occurs in the central deep-water area with water depths generally greater than 50 m. A shallower dense distribution also occurs in Fairview Cove in water depths of 20 m. Few anchor marks occur in the southeastern area of the basin where it joins The Narrows. Their absence likely results from the prohibition of anchoring in the major shipping entrance to Bedford Basin.

Submersible observations from the deep floor of Bedford Basin show that the seabed is a rough, hummocky surface with isolated mounds and depressions averaging 0.5 m deep resulting from anchoring. The sediment does not appear to slump and infill the depressions. Several generations of

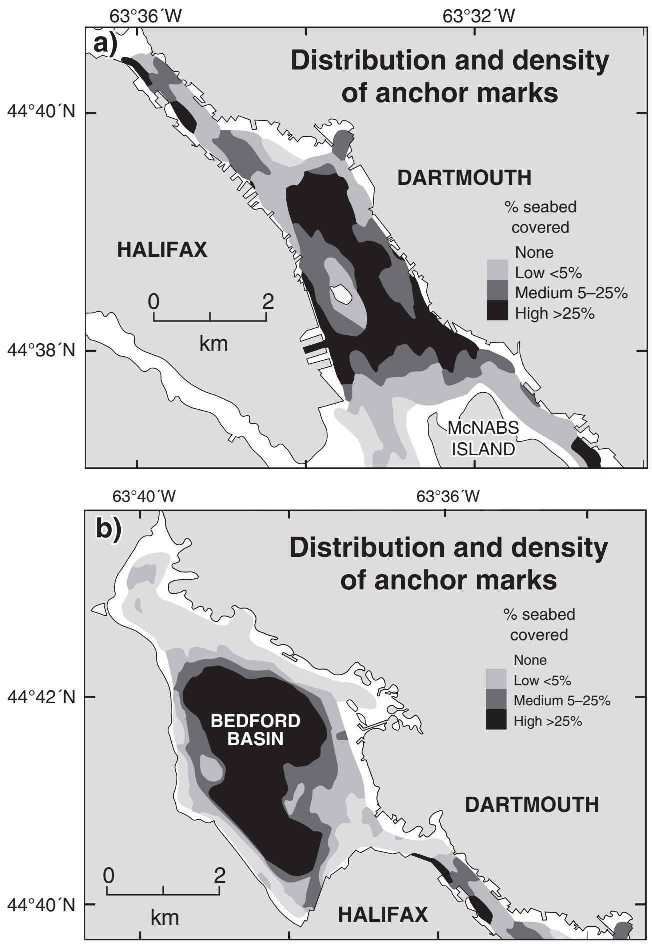


Figure 114. The distribution and density of anchor marks in **a)** the inner harbour and **b)** Bedford Basin. Some of the anchor marks occur in areas where anchoring is presently not permitted. Some of these may represent former anchorages and are thus relict, whereas others may represent anchoring as a speed, directional control, and safety or emergency operation.

anchor marks can be identified on the floor of Bedford Basin (Fig. 115). Some appear fresh, exhibiting clearly defined berms and sharp contrasts in acoustic reflectivity, whereas others have gradational changes, suggesting erosion and degradation of the original features. Because the sedimentation rates since the founding of Halifax are generally less than the depth of the anchor marks, 40 cm versus 1 m to 2 m, it is possible that the entire population of anchor marks is still visible on the basin floor on sidescan sonograms and multibeam bathymetry.

Anchor marks and sediment transport

The presence of anchor marks on the seabed is an important stratigraphic bench mark that can also be used to assess the history of sedimentation and sediment transport. The distribution of anchor marks, combined with knowledge of present anchoring practices, indicates that some of the anchor-mark populations likely are relict. Those in Bedford Basin are interpreted to have largely developed during World War I and II when large convoys of military and merchant ships assembled and anchored over broad areas of the basin, prior to sailing across the north Atlantic Ocean to Europe. A modern population also occurs in Bedford Basin, but is not as widespread. Those in inner Halifax Harbour, particularly in the present main navigational channel where anchoring is prohibited, are probably much older. South of Georges Island this population is covered with recent sediment and the old anchor-marked surface can be seen dipping beneath the recent sediments (Fig. 87). A similar relationship occurs in the northern part of Bedford Basin, south of the sill of Bedford Bay. The sediment, which covers the anchor-marked surface in this area, is material from the Sackville River, which has been transported out of Bedford Bay and into Bedford Basin where it is preferentially deposited on the northwest flank.

The anchor-marked surfaces also indicate that since their formation, the amount of material deposited over most areas has not been sufficient to bury and obliterate them, thereby providing a crude record of sedimentation rate. Based on this assumption, the amount of sediment deposited throughout much of the harbour has been less than 2 m since the founding of Halifax over 250 years ago. This has been exceeded in several areas of the harbour, particularly near sewage outfalls, and indicates that some of the material emanating from these discharges is deposited adjacent to the outfall. The distribution of sewage banks, as they are called, can be easily determined using seismic-reflection and sidescan-sonar mapping in areas where they overlie anchor-scoured areas.

The presence of the dense and complex distribution of anchor marks attests to a strong influence by shipping-related activities on disturbance and resuspension of the sediments of the harbour. Of particular concern to the environmental health of the harbour is the frequent remobilization of sediments and their associated contaminants by anchoring.

Borrow pits

Borrow pits are circular to linear seabed depressions formed by the removal of aggregate through dredging techniques (Fig. 75). The largest zone of borrow pits in the harbour occurs in a dense cluster directly north of McNabs Island and east of Ives Knoll (Fig. 13). The pits average 15 m in diameter and range up to 3 m in depth. The material removed was likely sand and gravel of the Sable Island Sand and Gravel. On sidescan sonograms borrow pits can resemble dredge spoils dumped on Holocene mud, as the dredge spoils often consist of coarse debris, and displace mud at the seabed creating a similar-shaped depression. Other circular borrow pits occur adjacent to Dartmouth Cove, north of the Angus L. Macdonald Bridge and off Seaview Park in Bedford Basin (Fig. 13, 18).

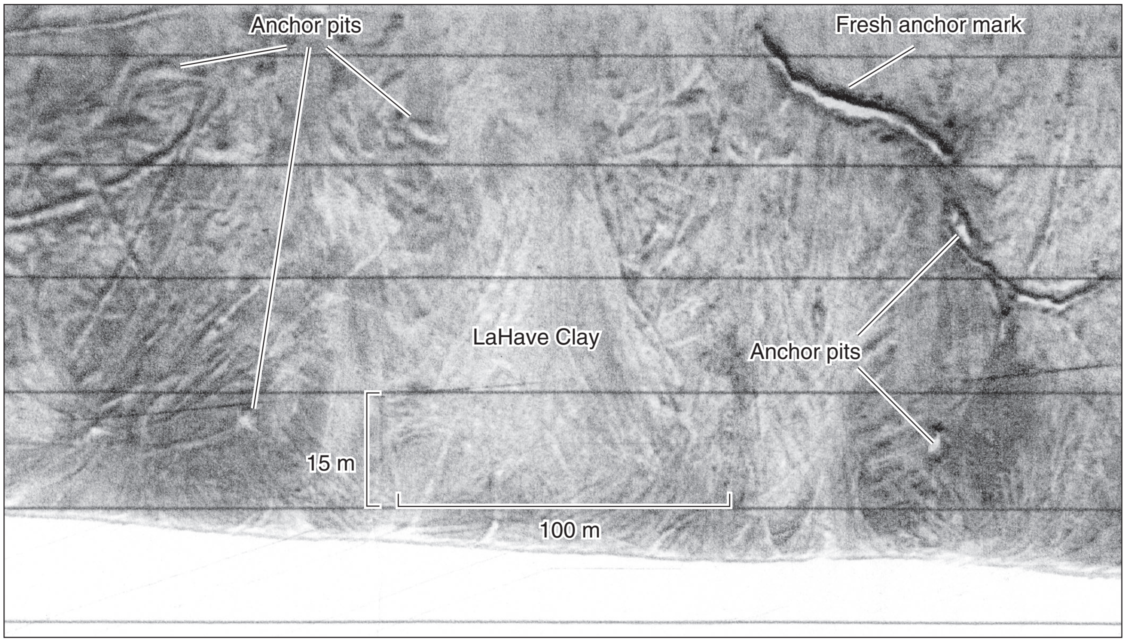


Figure 115. Sidescan sonogram from the central, deep-water area of Bedford Basin showing many generations, sizes, and types of anchor marks at the seabed in LaHave Clay. Some appear fresher and younger as evidenced by well defined berms, sharp edges, and greater relief. An older generation appears less well defined, with smooth and subdued features and less relief. Anchor pits and a fresh anchor mark are illustrated.

A series of large, linear, and oblong pits occurs in the nearshore off eastern McNabs Island (Fig. 13, 75). They are up to 300 m long, 50 m wide, and 5 m deep. Large quantities of material were removed during the 1950s and 1960s from these pits to supply aggregate for construction. They do not appear to be infilled with fine-grained sediment, attesting to low sedimentation rates on the flanks of McNabs Island in Eastern Passage since their formation.

Dredge spoils

Dredge spoils are circular deposits of material discharged to the seabed by barges (Fig. 13, 18, 103). They consist of a wide variety of materials such as dredged sediments, contaminated sediments, construction debris, docking materials, gravel, boulders, garbage, and unidentified debris. Samples collected from one dredge spoil in the deepest water of Bedford Basin consisted of manganese-coated, angular, cobble-sized fragments of Goldenville Formation quartzite, likely gravel dredge spoil. The dredge spoils range up to 40 m in diameter and can occur both as positive features several metres in height above the surrounding seabed, or as coarse debris in slight depressions. Multibeam bathymetry from deep water in Bedford Basin indicates that the dredge spoils are not positive features, but broad depressions at the seabed formed by compression of LaHave Clay. Dredge spoils at the entrance to Northwest Arm have also been dumped on LaHave Clay (Fig. 103), compressing and displacing the mud into depressions that resemble pockmarks. In some areas these dredge spoils have resulted in the venting of the gas-charged sediments in a zone directly beneath the spoils as evidenced by the absence of gas-charged reflections on the seismic-reflection data (Fig. 95).

Dredge spoils are characterized on sidescan sonograms by their circular shape and acoustically rough, high-backscatter surfaces (Fig. 116). They are often clustered together. An unusual type of dredge spoil, characterized by curvilinear areas of high acoustic backscatter, connecting larger circular features of the same acoustic signature, is interpreted to represent sporadic discharge of spoil from a barge while underway (Fig. 117). These features appear concentrated near the naval dockyard in Halifax. The presence of dredge spoils on the harbour bottom masks the naturally occurring sediments.

The largest occurrence of dredge spoils is in Bedford Basin where approximately 200 have been identified, covering approximately 5% of the deep basin floor (Fader et al., 1994). They also occur as positive features at several locations in The Narrows and are scattered about the seabed of other areas of the inner harbour (Fig. 13). Very few were found in the outer harbour. The practice of dumping dredge spoils in the harbour has been largely discontinued.

The process of dredge-spoil dumping has both buried and mixed the sediments on the seabed and disrupted the stratigraphy. In some areas, contaminated sediments have been redistributed to other settings. Cores must be collected away from dredge-spoil areas if the natural stratigraphy is to be determined.

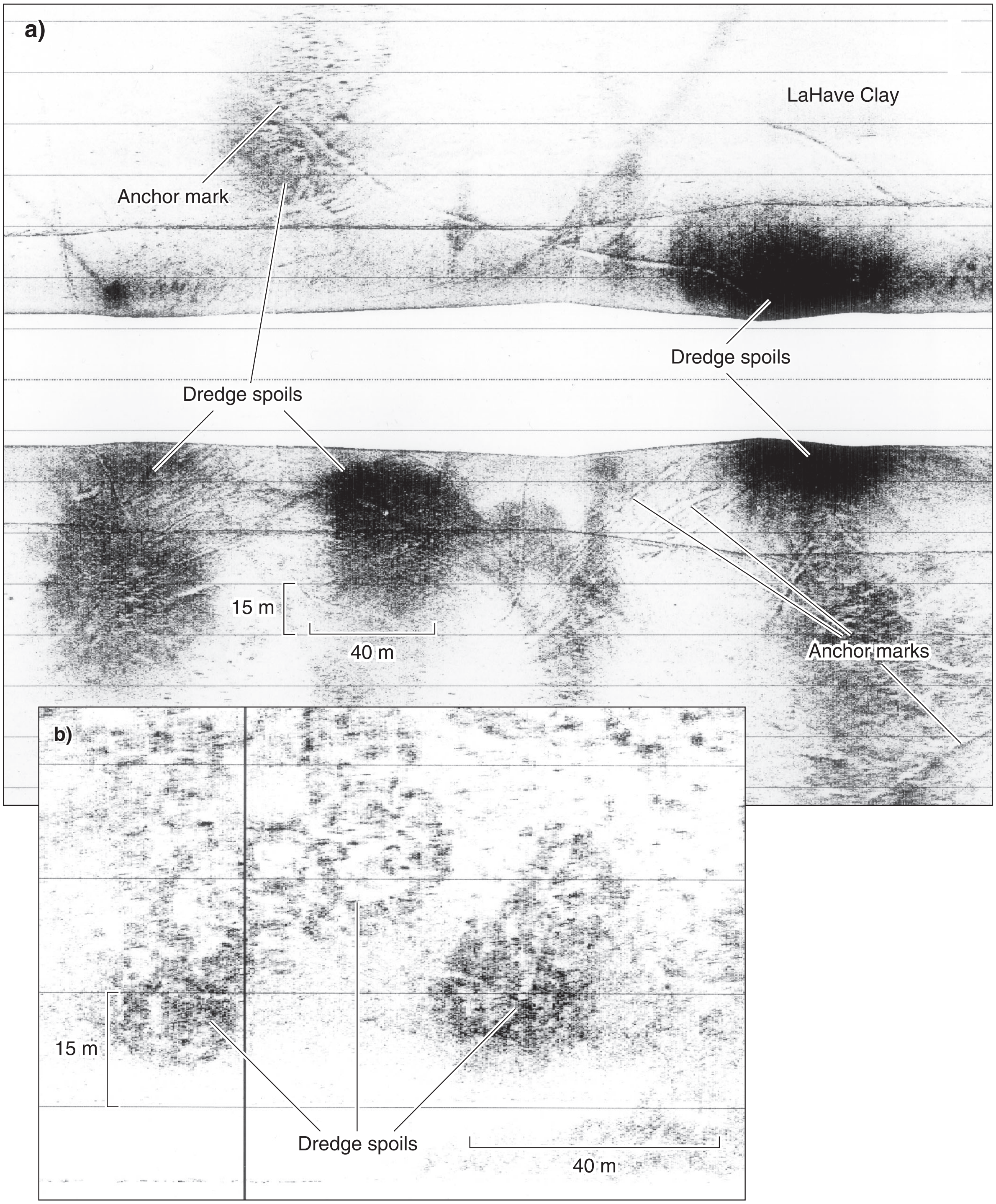


Figure 116. Sidescan sonograms of dredge spoils in **a)** Bedford Basin and **b)** The Narrows. They generally appear as circular, rough, high-backscatter, elevated features. They are common across the seabed of Bedford Basin and the greatest density occurs at the southeast area of the basin where it joins The Narrows. Those in The Narrows (Fig. 116b) appear as circular-rimmed, overlapping features.

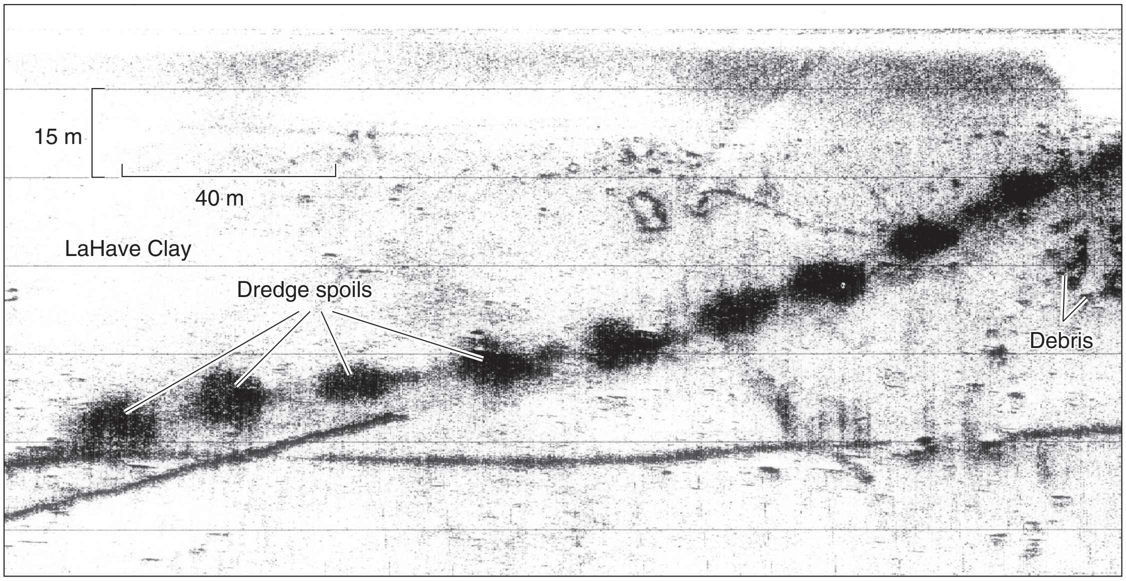


Figure 117. A sidescan sonogram of linear dredge spoils from the inner harbour adjacent to the Halifax shoreline formed by the continuous discharge of spoil while underway. These features are more common in the inner harbour and display linear, high-backscatter characteristics with circular patches along the length of the deposit, giving the features a beaded appearance. A few faint anchor marks and debris occur across the image.

Shipwrecks

Shipwrecks exhibit unique acoustic characteristics on sidescan sonograms, primarily resulting from: the hardness of the material of which they are composed, the presence of large expanses of flat metal or wooden surfaces, high and unusual angles between structural elements, and the presence of features with distinctive shapes such as railings, masts, smokestacks, funnels, bows, anchors, chains, hatches, and openings in the superstructure (Fig. 111). Even when ships are badly broken and sections separated, large fragments can be identified by the presence of their unique sonar characteristics that are much different from natural geological signatures of sediments, boulders, and bedrock. Shipwrecks are characterized on multibeam bathymetry by tight groupings of shallow depths, steep slopes, and scoured depressions. Diagnostic characteristics are better portrayed on higher resolution sidescan sonograms.

Approximately 45 shipwrecks or large sections of shipwrecks have been located on the seabed of Halifax Harbour (Fig. 13, 18, 103). Most were unknown before this study of Halifax Harbour. Some are known wrecks such as the ferry *Governor Cornwallis* that sank on the southeast flank of Georges Island as a result of an onboard fire, whereas others remain unknown and require further investigation for identification. Collectively they represent many marine tragedies that occurred in the harbour. It is important to map their location, the height of their protrusion above the seabed, and to determine their identity as they can represent hazards to navigation if their upper structures rise a considerable distance from the seabed. Some also contain unexploded ordnance or other dangerous cargoes and some represent both military and civilian grave sites.

According to historical documents, a large number of vessels grounded and sank over the past 200 years in the outer harbour extending from Herring Cove to Chebucto Head. Many of these vessels foundered in bad weather or ran aground in fog on the steep granite cliffs of the western harbour flank. One would expect to find the remains of many of these vessels on sidescan sonograms collected close to the shoreline; however, very little evidence was found for shipwrecks along this entire stretch of coastline. Several large, isolated acoustic targets were identified, but large granitic boulders of similar size are also common. The authors interpret the lack of shipwreck debris to result from high-energy storm conditions, which frequently occur along this coastal segment of the outer harbour. These storms have broken, flattened, and redistributed the remains of vessels to the north, for example the *Humbolt* (T. Kenchington, pers. comm., 1996). A modern shipwreck, the *Costa Rican Trader*, is an example of degradation over the past 40 years during which the steel cargo vessel, grounded near Bear Cove, went from an intact condition above water to being completely submerged and flattened.

The identity of many of the shipwrecks is difficult to determine and is usually confirmed by visual observations. For example, a schooner was discovered during the surveys on the seabed in an area adjacent to Pleasant Shoal, in 30 m of water at the entrance of the inner harbour (Fig. 13). It was originally interpreted to be the *Alexander R.* based on historical archival records (Fader et al., 1991). Evidence from divers together with research assistance from the Maritime Museum of the Atlantic now indicates that the vessel is the *Havana*, a ship that sank in 1906 while attempting to salvage the *Alexander R*. The *Havana* was owned by a famous eastern

Canadian sea captain, Captain J.A. Farquar, and at the time of the sinking contained a valuable sextant that had been presented to him by the British Admiralty.

To the south of the *Havana*, off the South End Container Terminal Pier C, lies another schooner, which has been determined to be the *Gertrude de Costa*. It was involved in a collision with an oil tanker in the harbour in 1950, and was never located. Seven seamen went down with the vessel. Unexploded ordnance lies on the deck of the *Gertrude de Costa*. The origin of the ordnance is not known, but in any case it represents a hazard. This illustrates the importance of identification of shipwrecks to assess their hazard potential as well as their historical value.

Several shipwrecks occur in Bedford Basin. These include a barge near the naval magazine dock on which a fire started that resulted in the 1945 explosion of the magazine facility. This explosion scattered unexploded ordnance that still litters the western side of Bedford Basin. A former dockyard tug, the *Erg,* which sank due to a collision that resulted in the loss of 19 lives, was discovered during this survey and has recently been positively identified by divers near Roach Cove in Bedford Basin (Fig. 18). In deep water near the centre of the basin, a large wooden barge and a ship identified as the *Acorn* were found. The *Acorn* was investigated with an ROV and was revealed to be a steel-hulled ship. The main deck and a few side plates were missing and steel ribs could be seen in places along the side of the vessel. The bridge of the ship was also missing and evidence of cutting was observed along the side of the vessel. Scattered pipes and fittings lay across intact parts of the deck. Large biogenic growths were attached to some areas of the ship. The overall assessment of the vessel was hampered by particulate material in the water column disturbed from the adjacent seabed by the ROV. Historical records indicate that the *Acorn* was purposely scuttled in Bedford Basin in the 1950s.

The oldest shipwreck identified to date could be one of the remains of the Duc d'Anville fleet, part of a French military fleet, that was blockaded in the harbour by the English in 1746. The ships were burned and later sank. The wreck consists of a series of ribs radiating from a central keel in 22 m of water in the southwest area of the basin (Fig. 18). Recent archaeological investigations under the direction of the Maritime Museum of the Atlantic suggest that the wreck may not be part of Duc d'Anville's fleet. Other unidentified shipwrecks occur in Birch Cove and in the deep water of the central part of the basin.

Only a few shipwrecks have been located in the inner harbour between The Narrows and McNabs Island. The most well known shipping-related disaster in the harbour was the explosion of the *Mont-Blanc* in 1917, following collision with the *Imo*, that devastated much of the north end of Halifax and resulted in over 2000 deaths. The exact location of this, the world's largest explosion prior to nuclear testing, has been identified near the Halifax shoreline of The Narrows but no debris of the *Mont-Blanc* or proposed crater from the explosion was found (Fader, 1994, 1995). This may have resulted from postexplosion dredging activities to remove seabed obstructions combined with the hardness of the seabed of The Narrows that deflected the blast upward. Recent sidescan-sonar and video surveys by the Department of National Defence in The Narrows located the remains of a copper-clad wooden schooner to the east of the large floating Nova Dock (S. Mudie, pers. comm., 2003). It is not known if this vessel sank as a result of the Halifax Explosion and further investigation continues. It is suspected to be a schooner, the *Lolla R*., lost during the Halifax Explosion (J. Simpson and J. Camano, pers. comm., 2003).

A small boat used as a recreational craft of the Nova Scotia Hospital lies offshore Dartmouth. A large rectangular barge, which sank while transporting sand and gravel in the harbour, lies north of McNabs Island. The *Good Hope*, a fishing trawler occurs near Middle Ground. Its upper structures were later blasted down to remove hazards to navigation. Two small shipwrecks occur in Fergusons Cove and many others occur in Northwest Arm (Fig. 103). These vessels are likely the remains of small fishing boats or pleasure craft. The multibeam EM3000 imagery from Northwest Arm also shows a cluster of shipwreck debris on the east side of the arm opposite the Royal Nova Scotia Yacht Squadron. This debris field is the remains of Brister's Ship Yard, that operated in the arm until the 1920s and includes marine slips and the partial remains of several steel-hulled ships.

One of the most difficult to interpret features on the seabed of Halifax Harbour is a feature the authors term the 'Trongate depression' (Fader et al., 1991). It is a linear depression 125 m in length, deeper at one end, with flanking, asymmetrical berms of mud (Fig. 118, 119). The largest berm extends 2 m above the surrounding seabed. The feature was formed by the sinking of the Norwegian vessel, the *S.S. Trongate*, a 7000 t merchant ship that was purposely sunk in 1942 because of an onboard fire and an explosive cargo. It was later salvaged, but the impression of the hull remains in the mud at anchorage number 4, north of Georges Island. Remotely operated vehicle observations show the presence of rolls of newsprint, wooden planks, boots, and much debris at the location. In 1993 a large cache of unexploded ordnance, which included primed 4-inch shells, cases of .303 rifle ammunition, and scattered cordite (Fig. 118), was found at the 'Trongate depression' and is interpreted as unsalvaged ordnance. Because of the presence of this pile of unexploded ordnance, anchoring is no longer permitted at this designated location.

A series of smaller, but similar-shaped features to the 'Trongate depression' occurs at the southwestern area of Eastern Passage (Fig. 13, 120). Here, groupings of small parallel ridges occur in the muddy sediments. They were formed by the Canadian Navy in an exercise using a tugboat that was purposely and repeatedly sunk to the seabed and refloated (A. Ruffman, pers. comm., 1997).

In the outer harbour there are fewer shipwrecks largely because those that ran aground near the western shoreline have been broken up over the years and little remains. Other large objects along this coast have not been verified by visual

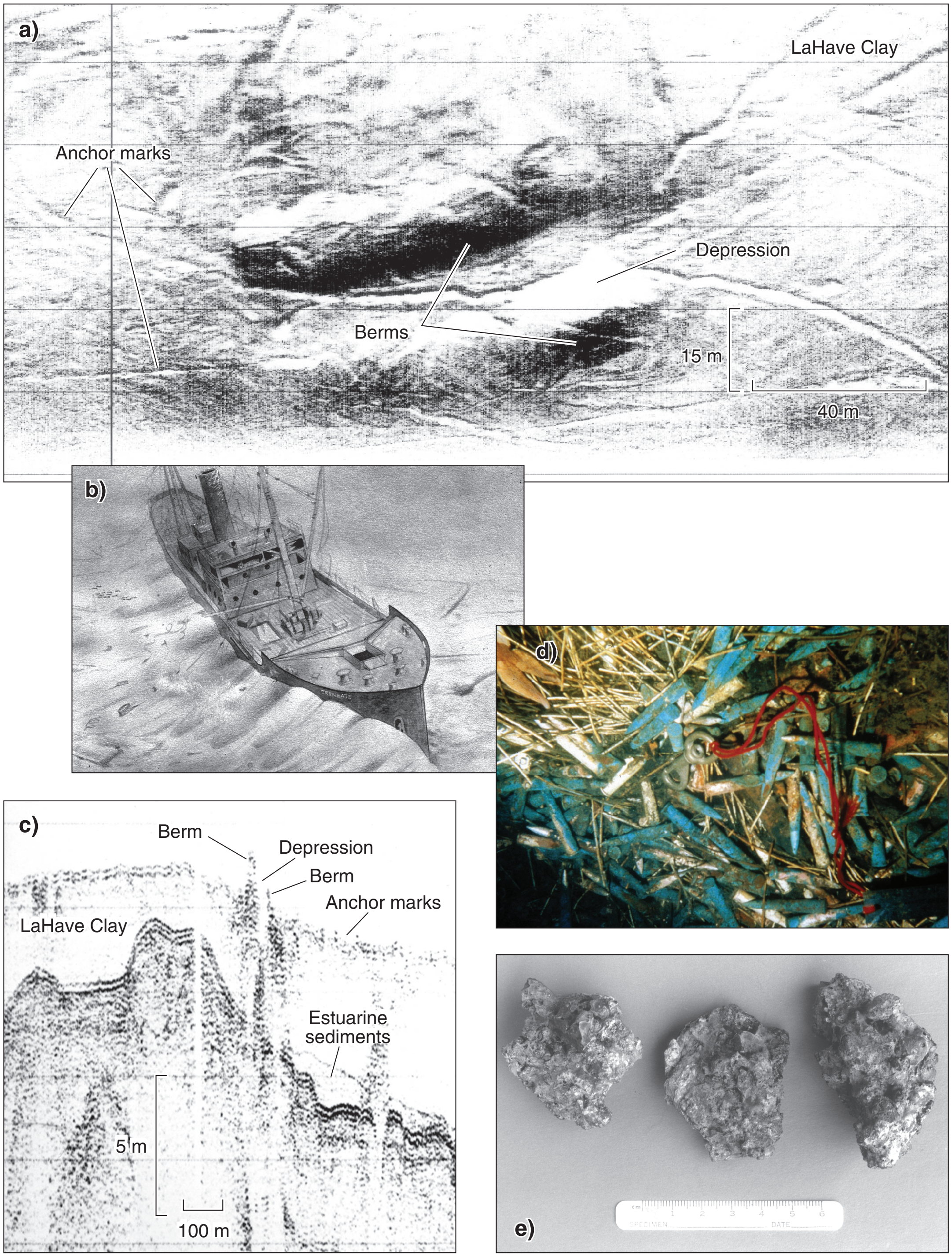


Figure 118. a) A sidescan sonogram, **b)** artists reconstruction, **c)** seismic-reflection profile, **d)** bottom photograph (Photograph by G.B.J. Fader. GSC 2006-211), and **e)** photograph of clinkers of the 'Trongate depression' inner Halifax Harbour (Fig. 11). Photograph courtesy of K. Bentham, BIO Photo Laboratory. The sinking of the vessel *Trongate* in 1944 formed the feature. The vessel was laden with explosives and ordnance and developed an out-of-control fire. The Canadian Navy scuttled it in an attempt to put out the fire and prevent an explosion. Later salvaged, the imprint of the hull in the mud remains as two asymmetric mud berms. Unexploded ordnance consisting of 4-inch shells, some with primers inserted, spilled cordite and .303 rounds (approximately 10 cm long) also remain at the seabed (Fig. 118d). Clinkers (Fig. 118e) are also common at the site as well as in many other areas of LaHave Clay. The 'Trongate depression' is one of the largest anthropogenic features on the seabed of the harbour. Despite the vessel having been salvaged in 1956, and the location of active anchoring at this designated anchorage number 4, the two mud berms and the deeper central depression remain on the seabed, attesting to the strength of the mud, the low rate of sedimentation, and the large initial size of the feature. Anchoring is no longer permitted at this location.

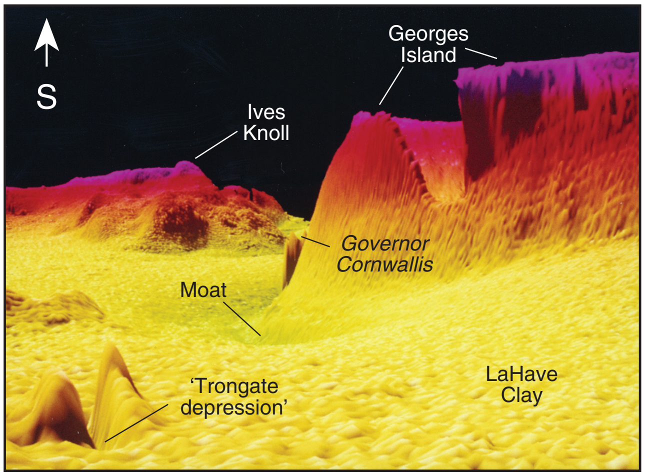


Figure 119. A 3-D multibeam-bathymetric perspective image looking across the seabed of the harbour to the south from a position northeast of Georges Island. The 'Trongate depression' clearly shows as two linear unequal mounds of LaHave Clay. The shipwreck *Governor Cornwallis* lies on the eastern flank of Georges Island. The 'Trongate depression' in the foreground is approximately 40 m wide.

means. Only one shipwreck has been located in the deeper water of the outer harbour to the east of The Gulch and its identity is unknown.

A series of clustered objects overlying linear bedrock ridges (Fig. 121) may represent cannon jettisoned from the H.M.S. *Tribune* in 1797 after it ran aground on Thrumcap Shoal south of McNabs Island. The ship freed itself from the shoal by the discharge of the cannon, but later drifted across the harbour and sank at Tribune Head with a loss of 238 lives. Sonograms show no ship remains on the seabed. This would be expected as the Tribune Head area is periodically subjected to large, storm-generated waves that impact the seabed in water depths as deep as 30 m. The *Deliverance* lies off the entrance to Herring Cove near bell buoy HM-1. It was a steam-engined diving tender that sank after a collision with the steamer *Regin* in 1917. It lies in 30 m of water and is a popular recreational dive location. Scouring of the seabed can be seen around the hull of the *Deliverance* in the sand. Recent infill of the seabed in the scour is attributed to sediment transport during Hurricane Juan in 2004.

Several large shipwrecks occur off the mouth of Halifax Harbour and were found during seabed mapping for this study. Those that have been identified include the *British Freedom*, *Kaaparen*, *Clayoquot, Athelviking*, and *Halma*. The *British Freedom* and the *Athelviking*, both tankers, were torpedoed by a German U-boat on the same day in 1944. The *Clayoquot*, a Bangor Class minesweeper, was torpedoed on Christmas Eve, 1944, with loss of life. The *Kaaparen*, a Swedish cargo vessel loaded with military materials and metal ingots, sank after a collision. Magnetic data collected during the multibeam mapping off Halifax Harbour indicates that as many as 52 shipwrecks may occur in the approaches to Halifax Harbour and other than those that have been identified above, they remain unidentified.

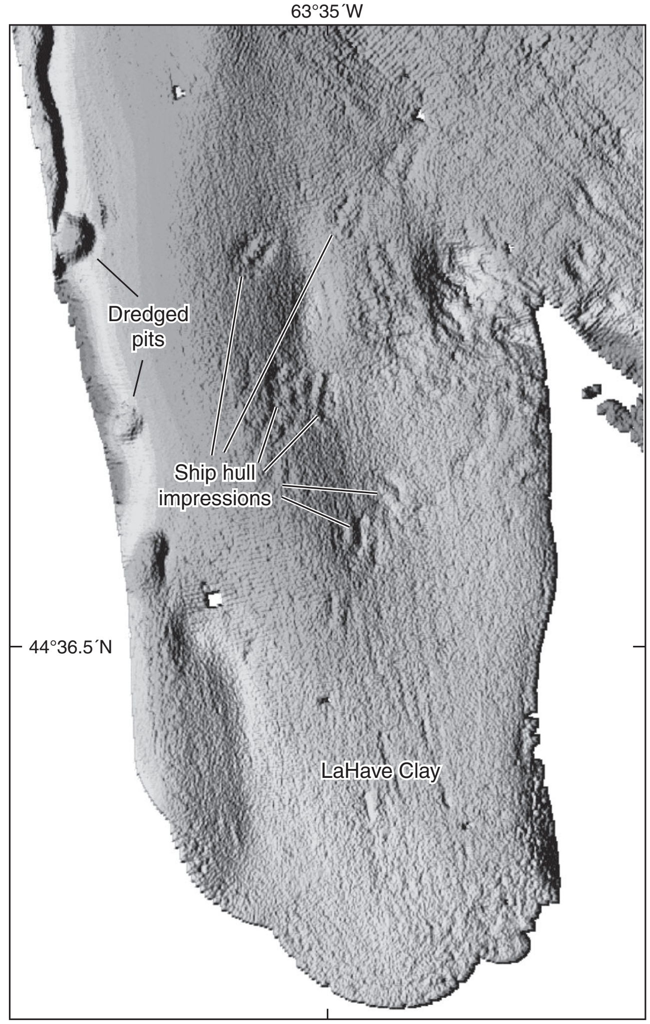


Figure 120. A multibeam-bathymetric image from an area northeast of Lawlor Island, Eastern Passage showing small, parallel sets of mud berms similar in shape to the 'Trongate depression'. These pairs of mud berms formed as a result of Canadian naval diving exercises whereby a small vessel was repeatedly sunk and refloated, thus creating the many hull impressions with mud berms on the seabed.

Ship-related seabed impressions

Spud-can pits

Large circular-bermed pits, interpreted to represent jack-up oil-rig spud-can depressions, occur in the Holocene mud of the eastern inner harbour adjacent to several of the Dartmouth docks (Fig. 13, 122)). These features are up to 3 m in depth and 15 m in diameter. In several of the depressions there appear to be small, internal craters that may have resulted from the release of methane gas as the load was removed from the seabed.

Oil-rig pontoon marks

North of McNabs Island are a pair of two linear parallel impressions in an area where oil rigs commonly anchor that the authors interpret as pontoon marks of a semisubmersible

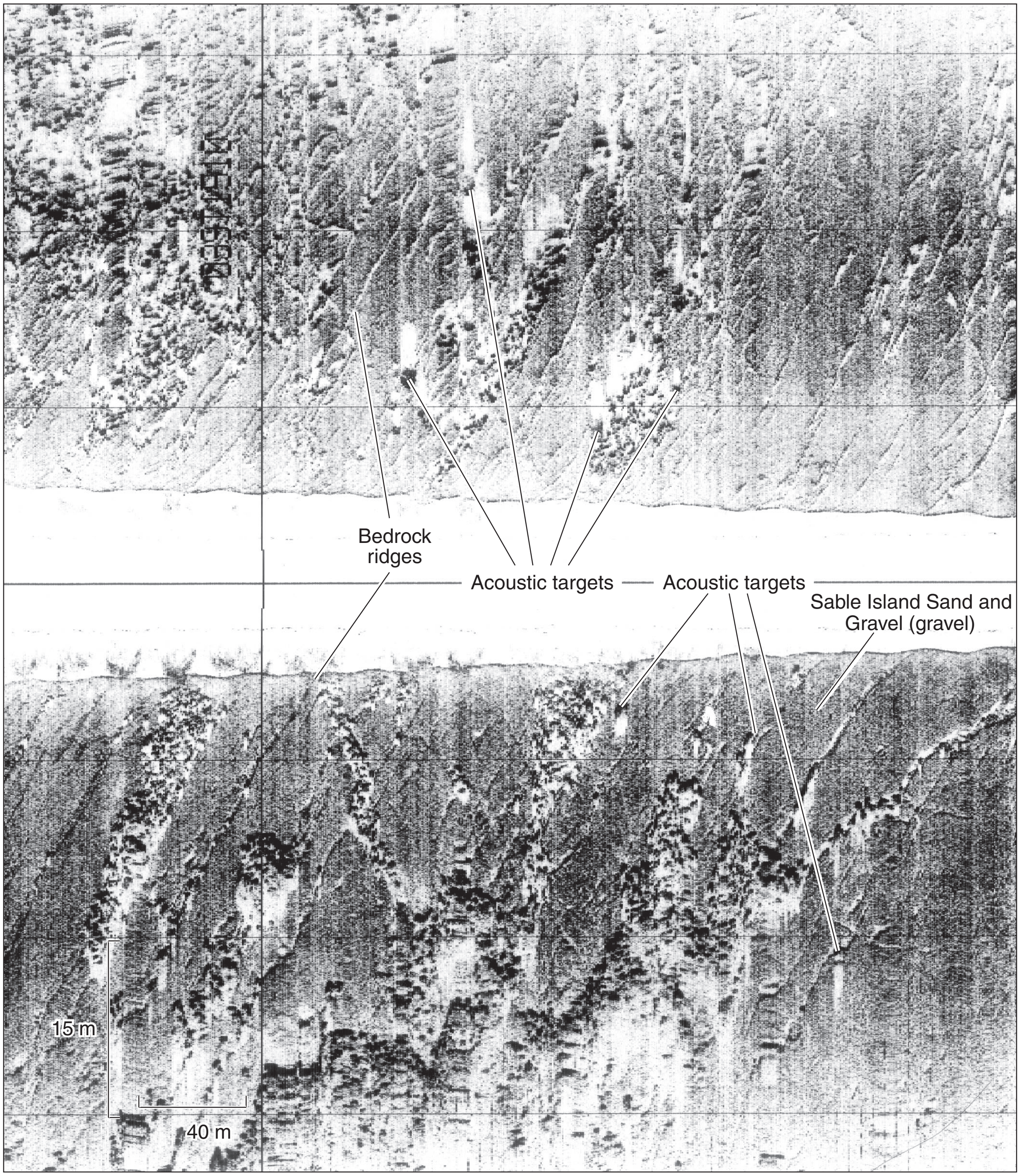


Figure 121. A sidescan sonogram of southern Thrumcap Shoal showing a series of isolated acoustic targets on bedrock and gravel at the location of the grounding of the vessel H.M.S. *Tribune* in 1769. The bedrock is interpreted as Halifax Formation slate with parallel, low-relief ridges. The individual targets are interpreted to represent cannon jettisoned from the *Tribune* to allow the vessel to free the shoal. The *Tribune* lifted off the shoal through the discharge of cannon, but suffered major damage to the rudder. This resulted in the subsequent sinking of the vessel at Tribune Head, across the harbour to the west, south of the entrance to Herring Cove. This loss of the vessel and 238 lives was the second largest marine disaster in Halifax Harbour, next to the Halifax Explosion of 1917. Location information courtesy of Trevor Kenchington (1990).

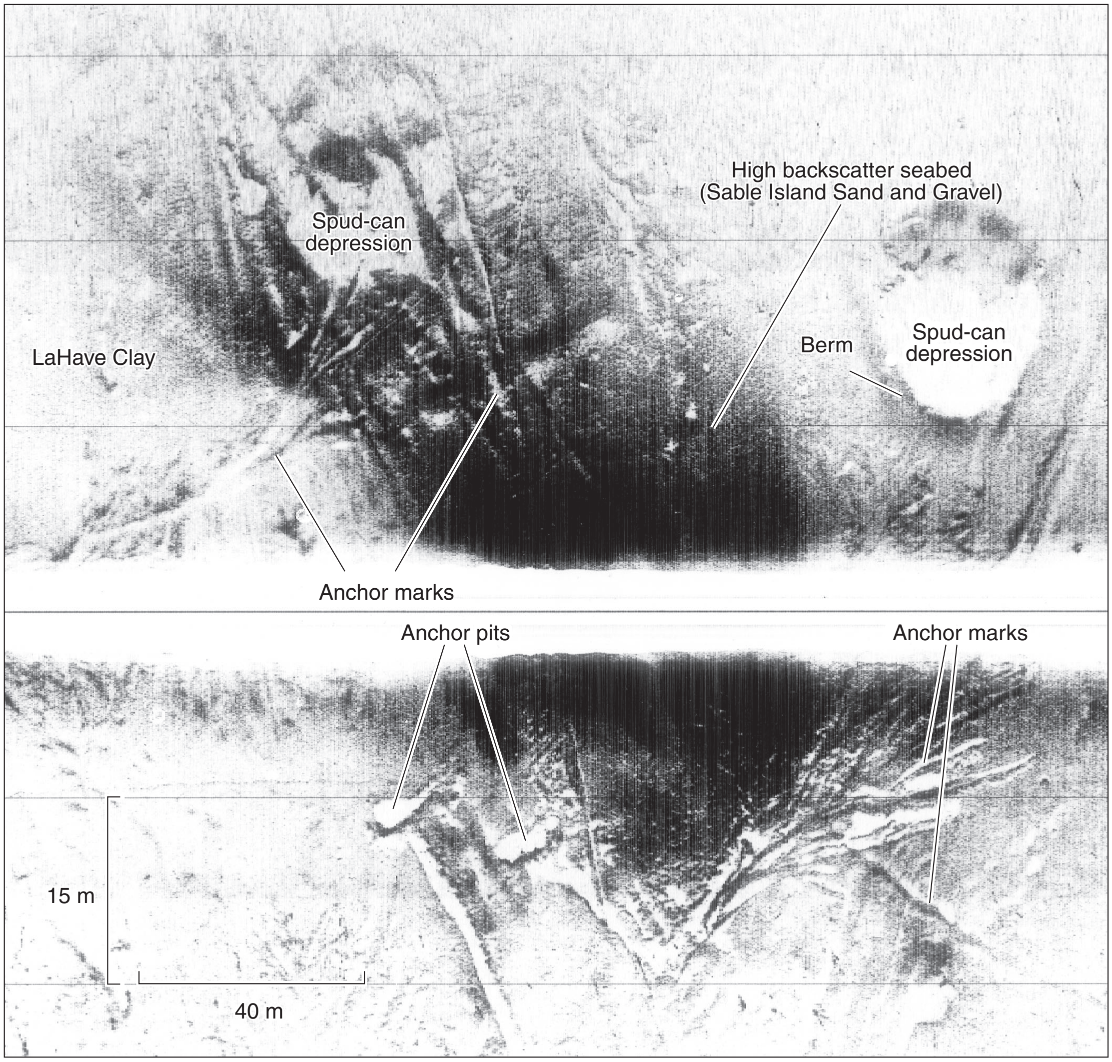


Figure 122. A 330 kHz sidescan sonogram of jack-up oil-rig spud-can marks on the seabed of Halifax Harbour. They are circular, rimmed depressions in LaHave Clay that formed during testing of an oil rig. The mud was displaced and squeezed to form circular berms. These circular, rimmed pits can also be clearly imaged on multibeam-bathymetric data (Fig. 6, 11). Subsequent anchor marks cut across the spud-can marks. *See* Figure 3 for location.

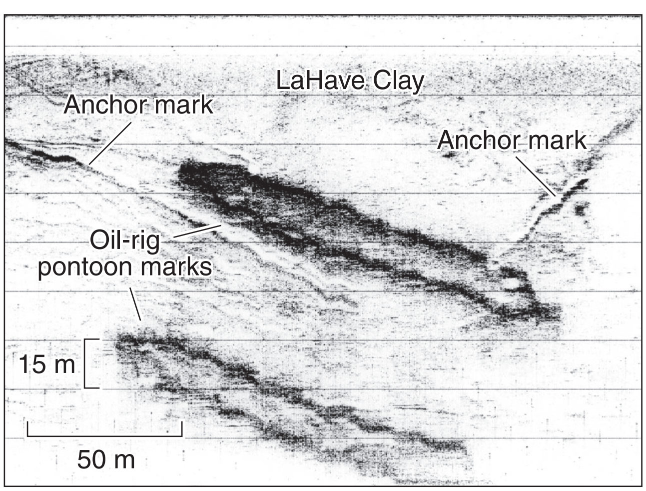


Figure 123. A 120 kHz sidescan sonogram of semisubmersible, oil-drilling-rig pontoon marks on the seabed of Halifax Harbour north of McNabs Island. These are slight depressions in the LaHave Clay of the inner harbour formed by the accidental grounding of an oil rig. *See* Figure 3 for location.

oil-drilling rig (Fig. 123). It appears that an oil rig touched down upon the seabed and formed the depressions. This grounding of the rig was an unscheduled event associated with a ballasting problem that resulted in damage to the pontoons.

Ship-hull grounding marks

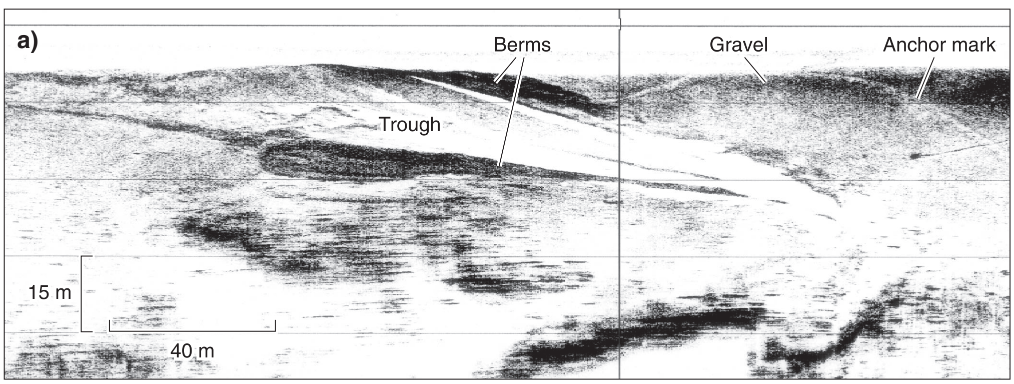
A large depression on the seabed of Halifax Harbour was formed by the grounding of the container ship *Concert Express* in June 1991. It grounded while travelling at a high rate of speed in dense fog on the Dartmouth side of the harbour south of the Irving Oil Ltd. dock in 5 m water depth. The seabed consists of transgressive sand and gravel overlying till. The grounding produced a large triangular gash on the seabed cutting several metres through the gravel lag and into the till (Fig. 124). Small bouldery berms were formed by the grounding on either side of the hull. The feature will likely remain for a long period of time because wave energy is low in this part of the inner harbour and the sediments are coarse grained.

Propeller scour marks

The seabed has been eroded to a maximum depth of 2 m directly adjacent to many of the docks along the harbour waterfront (Fig. 18, 103). The eroded areas appear on the sonograms as a series of scallop-shaped depressions in LaHave Clay (Fig. 125). This morphology is interpreted to result from propeller wash associated with large ships. In some areas this scour of the seabed has resulted in an undermining of the dock face, necessitating costly repairs and the application of scour-protection mattresses.

Dredged and blasted areas

Many areas of the harbour bottom have been dredged to provide deeper water for the passage of large vessels. Some of these appear to be long, linear, bucket-dragged zones whereas others appear to have been deepened by clam-shell dredging (Fig. 6, 18, 103). A drumlin adjacent to the naval dockyard in Halifax has been dredged with a clam-shell



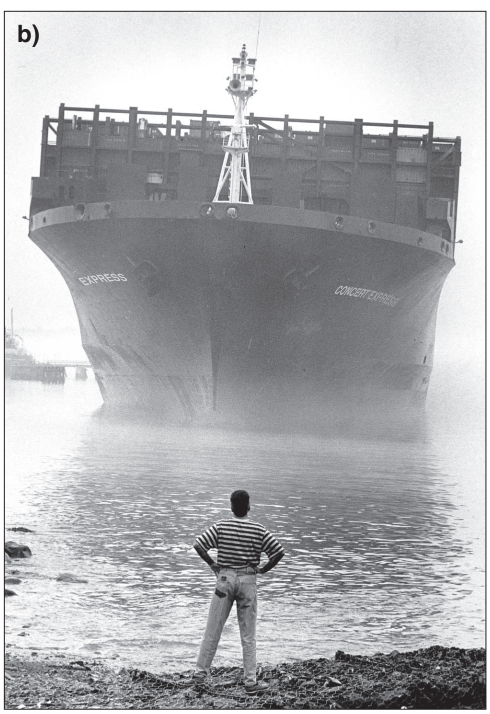


Figure 124. a) A 330 kHz sidescan sonogram of the seabed and **b)** photograph of the grounded container ship *Concert Express* in 1992 along the Dartmouth shoreline of the inner harbour. The grounding mark in Figure 124a is a linear, triangular depression in thin, sandy gravel overlying till, with berms along its flanks. It is over 100 m long. Its formation in gravel and a lack of strong currents and large waves will result in persistence of the mark for a long time. Photograph republished with permission from the Halifax Herald Ltd.

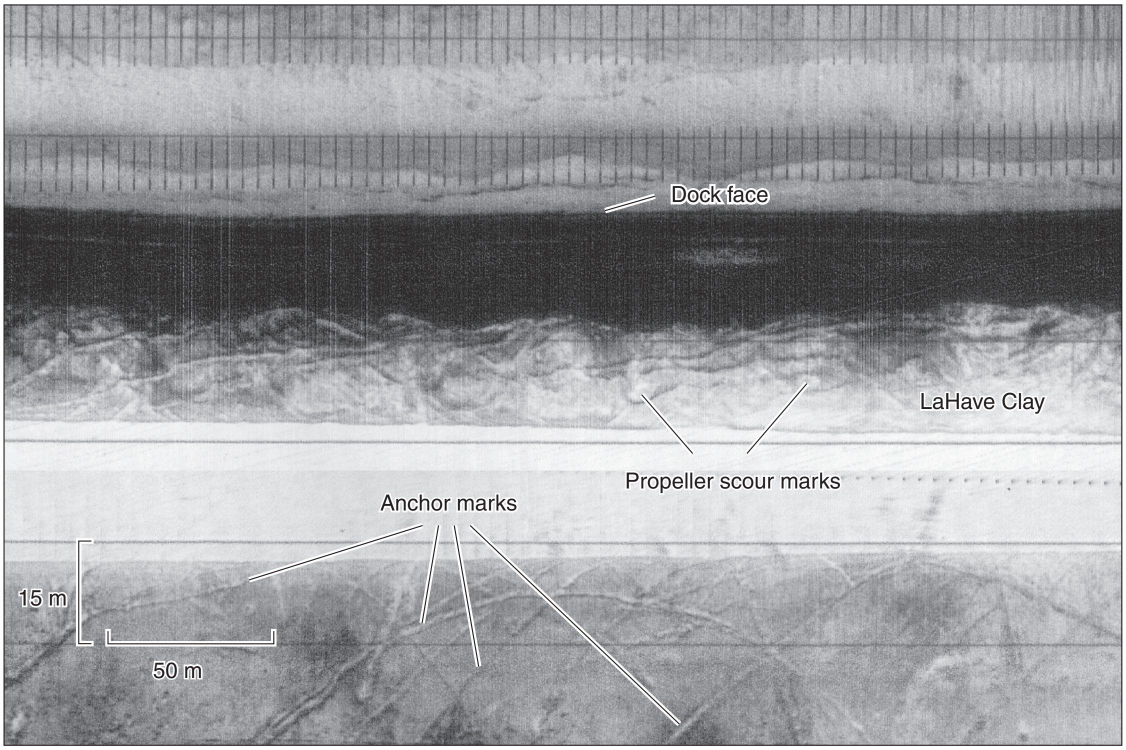


Figure 125. A 120 kHz sidescan sonogram of propeller scours on the seabed of Halifax Harbour adjacent to the container terminal in Fairview Cove, Bedford Basin. The features are scalloped-shaped depressions in mud. They are common characteristics of many of the docks along the Halifax waterfront where LaHave Clay occurs. Propeller scour can cause a maintenance problem along many of the docks, often requiring dock repairs or the laying of scour-protection mattresses adjacent to the dock to prevent undermining processes.

bucket. Remotely operated vehicle observations, sidescan sonograms, and multibeam bathymetry show a very hummocky relief of 2 m on till with a mixture of gravel, sand, silt, and clay (Fig. 126). Boulders are prevalent and organic growth and benthic organisms are absent on this truncated drumlin, 'Little Georges Bank' (Fig. 13).

Other areas of shallow seabed have been dredged in Fairview Cove. An area of the harbour seabed west of McNabs Island has been dredged for the positioning of a naval magnetic and acoustic range. Dredging for fill has taken place in Bedford Bay near the mouth of the Sackville River. This material was pumped through pipelines in a water-sediment slurry to a large land reclamation area in western Bedford Bay. Dredging has been extensive adjacent to the former Texaco Canada refinery dock in Eastern Passage.

An area of seabed adjacent to Pier 9 in The Narrows has been blasted (Fig. 127) to increase depth. Here the sidescan sonograms and seismic-reflection data indicate that the shallow area is outcropping Halifax Formation slate bedrock.

A linear pattern of isolated depressions occurs in the central and northwest area of Roach Cove, Bedford Basin (Fig. 6, 18). A further grouping of overlapping depressions occurs in the eastern area of Roach Cove. These features are formed in LaHave Clay and are interpreted as blast pits formed by the military-controlled detonation of ordnance.

The Narrows is the shallowest area of hard seabed in the harbour and may require future dredging to accommodate the passage of the next generation (post-Panamex) of large container ships in order to use the docking facilities in Bedford Basin. There are many large boulders on the seabed and the cribwork remains of the first bridges crossing The Narrows may require removal for safe deep-draught vessel passage. Dredging is commonplace in large harbours undergoing maintenance and expansion and this activity will likely continue in Halifax Harbour.

The Narrows' bridges

The remains of the first two bridges that spanned the harbour connecting Halifax and Dartmouth were found during this study and lie in The Narrows, approximately 500 m to the south of the A. Murray MacKay Bridge (Miller et al., 1990; Fader et al., 1991). They were constructed in 1886 and 1892. The first bridge was constructed using many individual 20 t cribwork foundations at the seabed and was a railway bridge.

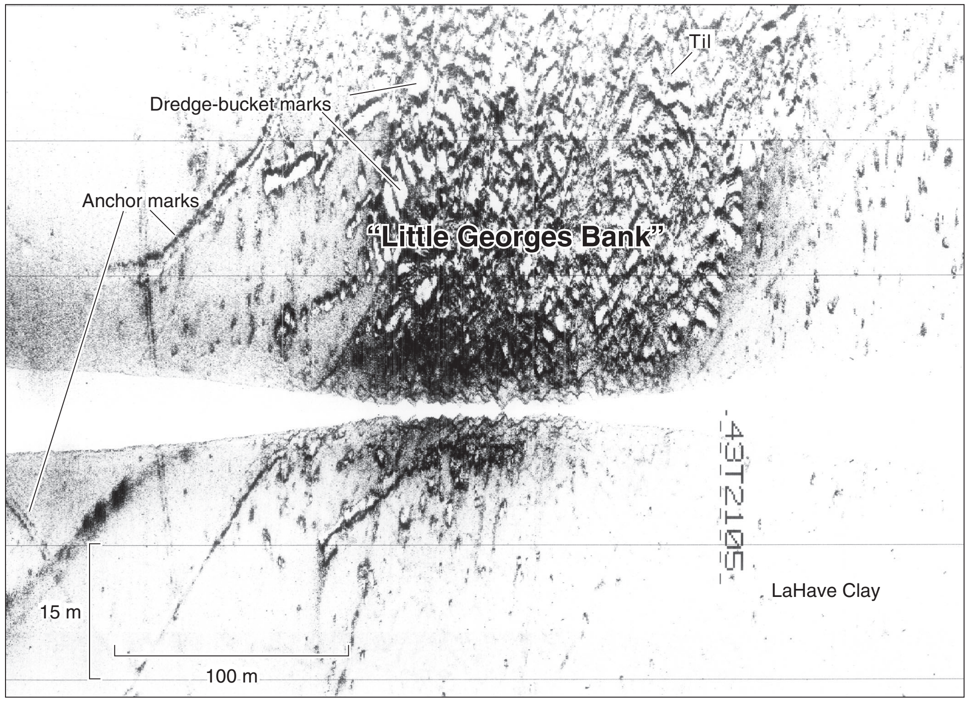


Figure 126. A 330 kHz sidescan sonogram of a dredged drum-lin ('Little Georges Bank') in inner Halifax Harbour, north of Georges Island. The image shows individual dredge-bucket grab marks on the seabed. Remotely operated vehicle observations show a hummocky surface of muddy, sandy gravel devoid of benthic organisms.

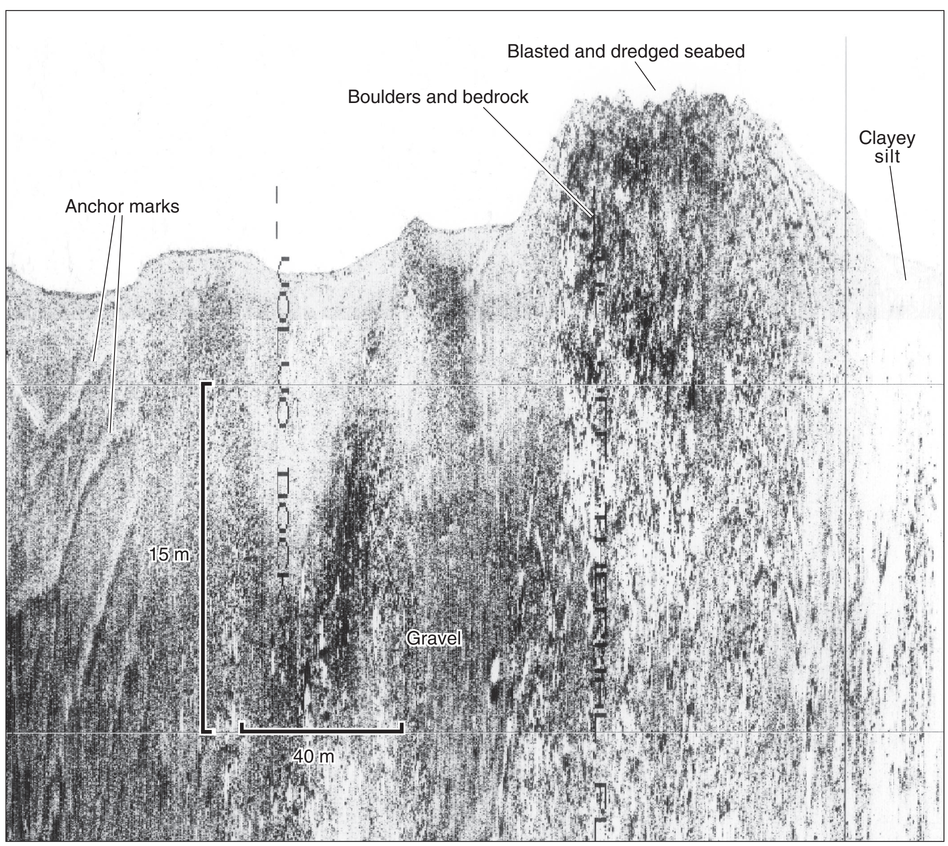


Figure 127. A 330 kHz sidescan sonogram of a blasted and dredged, shallow bedrock area in The Narrows near the western shore adjacent to Pier 9. This shoal was a hazard to navigation. The multi-beam imagery indicates that the shoal is part of a large ridge that extends across The Narrows and is breached in the centre of The Narrows by a former fluvial channel of the 'ancient Sackville River'.

It could accommodate pedestrian traffic on the side. It collapsed in a violent hurricane on September 7, 1891, an event that also destroyed many of the docks along the waterfront.

A new bridge was quickly rebuilt at the same location using piles driven into the seabed for the foundation. This new bridge was observed to be unstable and chains were attached to granite blocks positioned on the seabed for increased stability. This second bridge fell on a quiet summer's night, July 23, 1892. The cause of the failure remained a mystery. The geophysical data collected from the area indicates that outcropping bedrock and gravel-covered till covers most of the seabed throughout The Narrows. This hardness may have prevented sufficient penetration of the wooden piles into the seabed of the second bridge. Sidescan sonograms and ROV observations indicate that the seabed in the area of the bridges is covered with much of the remains. Cribwork, steel rail, and large timbers are widespread (Fig. 128). Large, rectangular granite blocks that were used to stabilize the second bridge also remain at the seabed. An area of water-saturated logs likely used in the construction of the two original bridges (Fig. 129) lies to the south of the bridge remains. An analysis of the morphology of the seabed and width of The Narrows indicates that the 1886 location for the bridge represents the shallowest and narrowest passage across the harbour.

Unidentified debris

Many sidescan-sonar high-intensity backscatter targets occur on the seabed of the harbour (Fader et al., 1991). Some of the largest objects are mapped (Fig. 13, 18, 103). They represent unidentified debris. The targets are greater than 1 m in diameter and cannot be identified from their sonar signature alone. Where clusters of boulder-sized objects occur it is difficult to determine if the objects are all boulders. Where they occur over fine-grained sediments, such as LaHave Clay and sand of the Sable Island Sand and Gravel, they likely represent discarded or lost anthropogenic objects.

Mottled seabed

A peculiar grouping of high-intensity backscatter features on sidescan-sonar imagery occurs on the north slope of Bedford Basin (Fig. 130). The features are circular and approximately 10 m in diameter and display no topographic relief, only a change to higher acoustic reflectivity. They occur at the edge of the subsurface gas-charged sediments and it is possible that they formed as a result of venting gas or may represent a dense benthic community associated with the gas venting. Other possible explanations are old and degraded dredge spoils, but the regularity of their distribution and consistent size and shape suggests otherwise.

Ship moorings

Seabed moorings for ships and boats are common in the harbour. A series of large moorings for military vessels occurs in northern Bedford Basin, in an area south of the Angus L. Macdonald Bridge, and off McNabs Cove (Fig. 6, 18). These consist of large anchors placed on the seabed attached to surface-floating buoys. Most are periodically removed and repositioned for maintenance. This process disturbs the seabed sediments, compressing and penetrating the softer LaHave Clay up to 1 m.

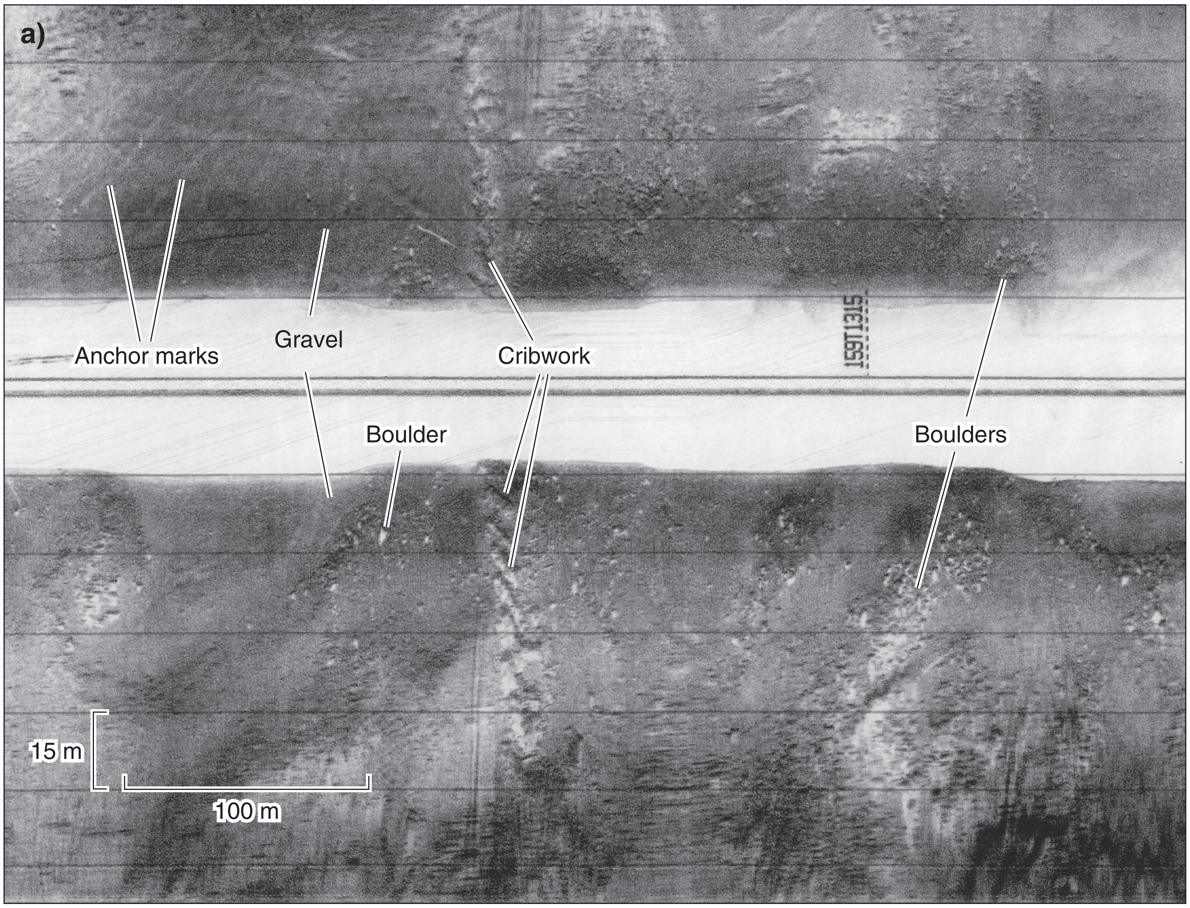
Many other navigational buoys and markers are moored to the seabed throughout the harbour. Most of these are positioned on harder seabeds of gravel and bedrock. Sidescan sonograms show drag marks in the areas where moorings are located, suggesting periodic dragging. Small seabed moorings associated with yacht clubs and private boat owners occur in Wrights Cove adjacent to the Dartmouth Yacht Club, in Bedford Bay adjacent to the Bedford Yacht Club, in Northwest Arm adjacent to the Royal Nova Scotia Yacht Squadron (Fig. 131), the Armdale Yacht Club, and the Waegwoltic Club, and in other near-shore, shallow areas (Fig. 13, 18, 103). In Bedford Bay and Northwest Arm near the yacht clubs the seabed moorings appear on the high-resolution multibeam imagery as a group of regularly spaced, circular depressions often with a central high representing a mooring clump or anchor. The circular depressions are interpreted to have formed through erosion of the LaHave Clay by the circular weather-vaning of chains and mooring lines around the seabed anchors. Similar features occur in Wrights Cove.

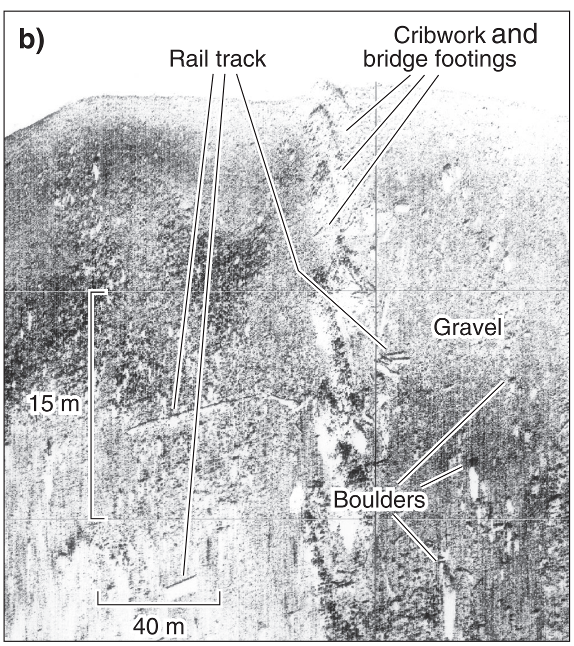
Trawl marks

Trawl marks are linear to curvilinear features on the seabed formed by the dragging of bottom-fishing gear. Where they form in gravel or till, they can remain for a long time. Those that occur in sand that is mobile in storms are quickly obliterated. Browsing organisms also can degrade trawl marks. All of the trawl marks identified during this study occur in the outer harbour and attest to bottom-fishing activities. The process of bottom trawling disturbs the seabed sediments and creates a set of parallel trawl-door marks up to 20 cm deep and hundreds of metres long.

Cables

Cables are common on the seabed of Halifax Harbour. They show up well on sidescan-sonar imagery as continuous to discontinuous, linear, narrow, high-backscatter anomalies (Fig. 132). In the early days of undersea telecommunications, many cables emanated from Halifax Harbour to points in Europe. Early charts of the harbour indicate up to 30 cables on the bottom. Today most of these cables have been abandoned. Another set of seabed cables was used by the military. During the wars, coils of wire were used for magnetic detection of enemy vessels and submarines, and explosive devices were





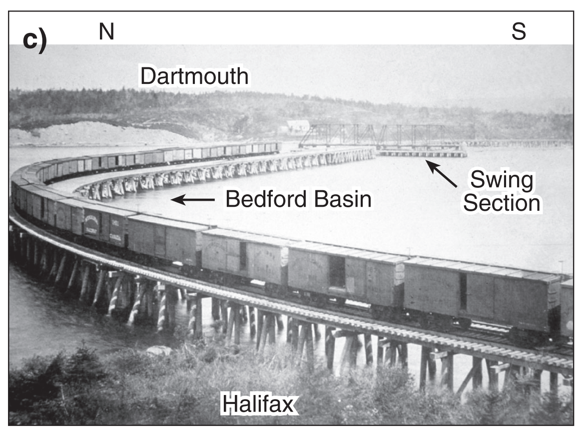


Figure 128. a) A 120 kHz and **b)** a 330 kHz sidescan sonogram of the seabed of The Narrows showing the hardness of the bottom, anchor marks, isolated boulders, as well as the remains of two bridges at the same location constructed in **c)** 1886 and 1891 which crossed the harbour. The bridge remains consist of rail track, cribwork filled with boulder ballast, large timbers, and anchor blocks of cut granite. Strong currents in The Narrows prevent the deposition of silt and clay. The old bridge remains are heavily encrusted with sea anemones. Photograph courtesy of Nova Scotia Archives and Records Management.

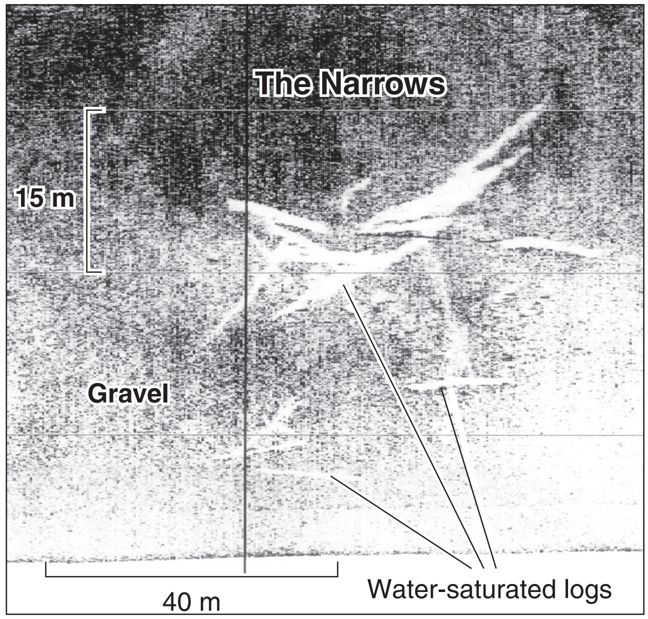


Figure 129. A 330 kHz sidescan sonogram from The Narrows south of the remains of the original bridges, showing large logs lying on the seabed that were part of the original trestle bridge structure. The seabed in this area is gravel.

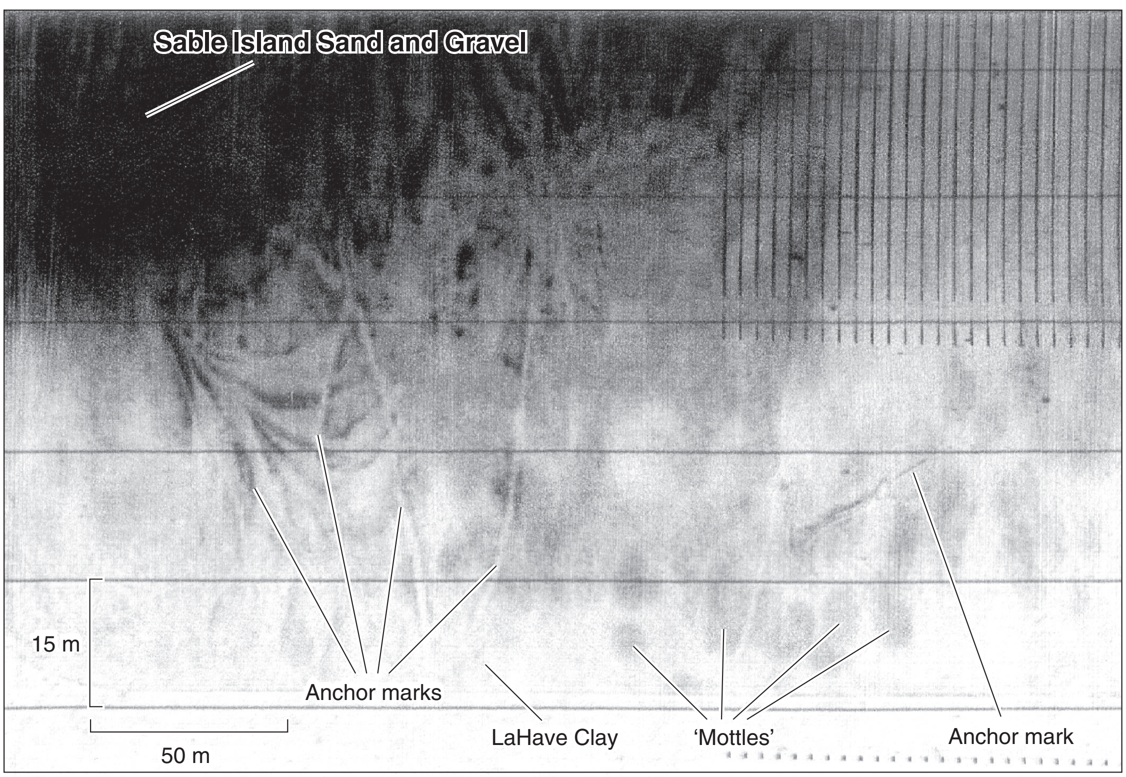
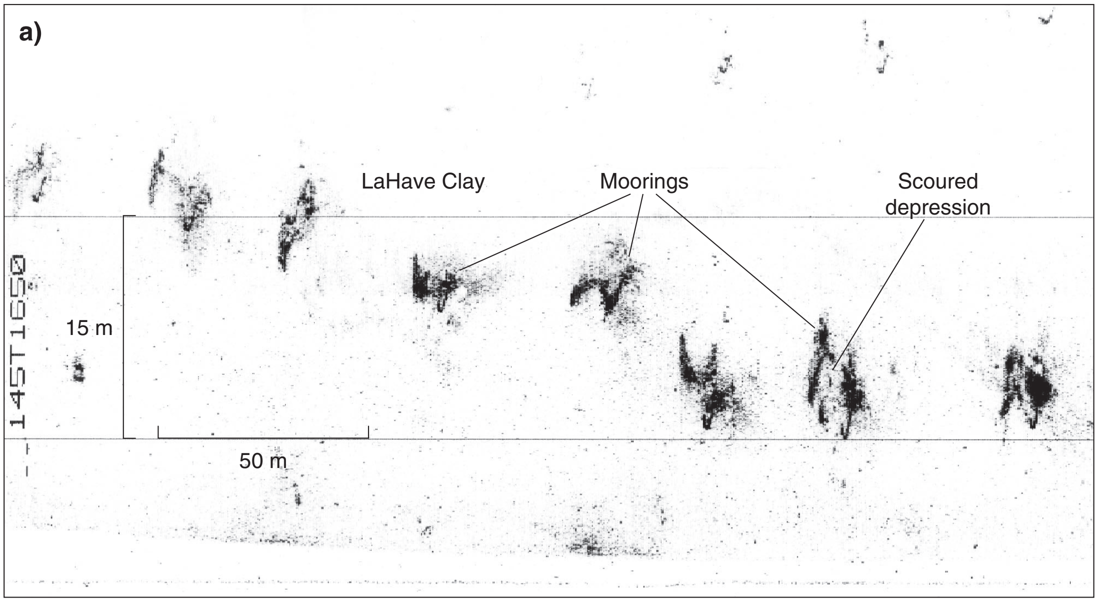


Figure 130. A 120 kHz sidescan sonogram showing a cluster of circular, medium-intensity backscatter features referred to as 'mottles' on the LaHave Clay bottom of northwestern Bedford Basin. They may represent features formed by the release of biogenic gas, benthic biological communities, or dumped debris. Similar features termed 'shell beds' are common on the continental shelf off Eastern Canada (Fader, 1991).



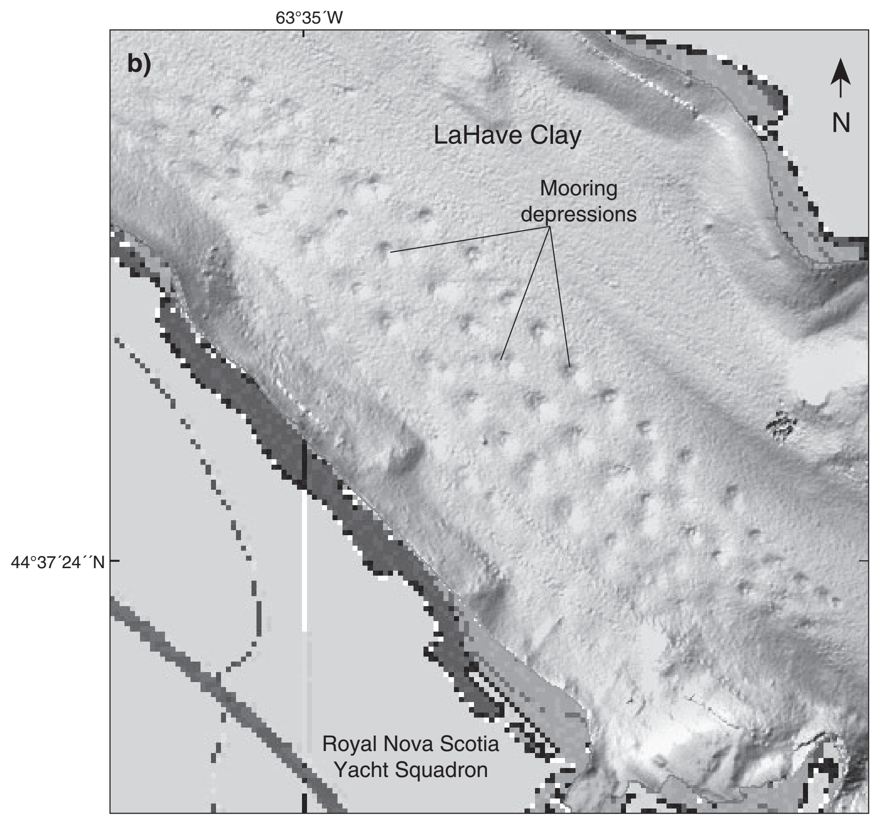


Figure 131. a) A sidescan sonogram and **b)** a Simrad EM3000 multibeam-bathymetric image of seabed moorings from Northwest Arm adjacent to the Royal Nova Scotia Yacht Squadron (Fig. 104). On sonograms they appear as depressions with central high-intensity backscatter reflections. Most occur on muddy bottoms as these areas are the deeper zones of the harbour preferable for ship and boat mooring. The multibeam bathymetry shows an equally spaced distribution of moorings across the seabed. They appear as circular depressions containing individual moorings (anchors). The seabed surrounding the moorings is eroded into circular depressions by chains and mooring lines as they weather-vane in a circular motion from winds and currents. Similar seabed mooring features occur adjacent to all of the yacht clubs in the harbour. In other areas the moorings tend to overlap, resulting from mooring repositioning.

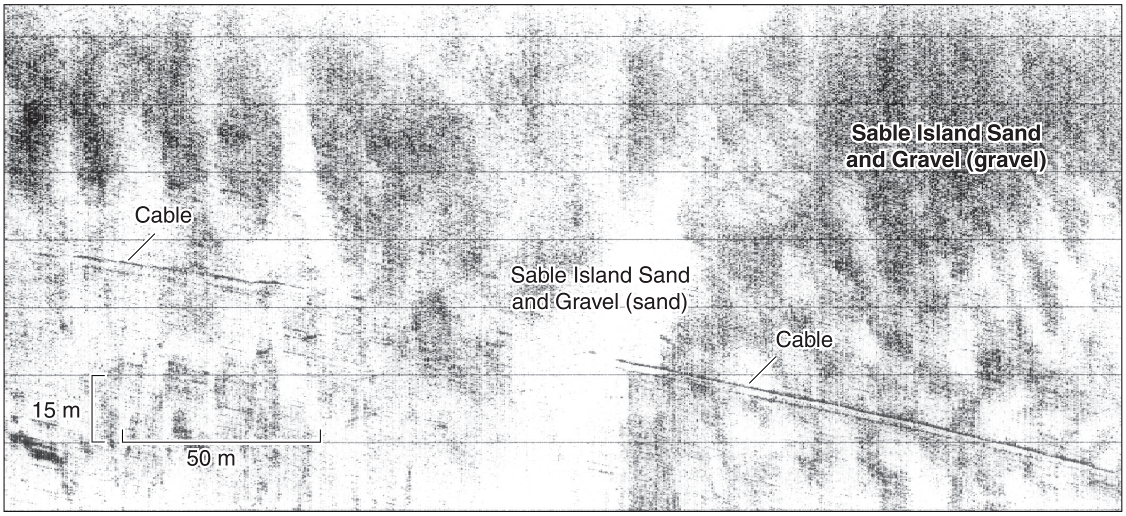


Figure 132. A 330 kHz sidescan sonogram illustrating a cable on the Sable Island Sand and Gravel seabed of the outer harbour. Cables appear as continuous to discontinuous, narrow, linear high-backscatter features. In areas of active bed forms, they can be partially buried by migrating sand as is the case on this sonogram. Many military and communication cables occur in the outer harbour, most of which are abandoned and partially buried.

positioned on the seabed and connected with additional cables for detonation. Some of these also remain on the outer harbour seabed. Cables in the outer harbour can also provide a benchmark for understanding sediment transport. Sonograms show cables buried in places beneath sand megaripple fields, indicating sediment mobility.

Modern telecommunication and electrical transmission cables cross the harbour connecting Georges, Devils, and McNabs islands with the mainland. Other cables on the seabed of the harbour are used in military applications for acoustic, magnetic, and degaussing ranges.

Water intakes and discharges

Salt water from the harbour is used to provide water for the cooling of buildings, industrial processes, scientific research, and lobster holding tanks. Water used for these purposes is from intakes often positioned at a distance from shore to ensure better water quality and more consistent temperature. Purdy's Wharf intakes show clearly on sonograms and multibeam bathymetry as linear features (pipes) ballasted with clump weights (Fig. 133).

At present (2006) most sewage discharge systems empty near the shoreline at or near the sea surface (Fig. 86). Several consolidated outfalls have been placed farther offshore to achieve greater dilution and to attempt to prevent freshwater sewage plumes from reaching the surface. These outfalls consist of pipe held to the seabed with weights. The pipe is often further covered with crushed gravel for protection as is the outfall off Privateers Wharf along the Halifax shoreline. With the final design of a consolidated waste-water treatment system for Halifax Harbour, large outfalls (diffusers) and combined storm overflows will likely be positioned on deeper areas of the floor of the harbour, generally away from adjacent shorelines. The discharge of particulates from these outfalls, in areas different from present, could result in changes to the LaHave Clay depositional system within the inner harbour.

Sewage banks

Despite the approximately 50 large raw-sewage outfalls that have entered Halifax Harbour for many years, only a few clearly display topographic accumulations of material near the outfall. These features are termed sewage banks. A major outfall at the entrance to Northwest Arm is characterized on the sidescan imagery by a small zone of acoustically absorbing, nonreflective seabed (Fig. 86). Immediately seaward of the outfall, the reflectance of the seabed is uniform and higher, and the presence of sewage-derived material cannot be differentiated from the adjacent LaHave Clay. Adjacent to the outfalls from the Eastern Passage and Mill Cove waste-water treatment facilities the sidescan sonograms show no anomalous sediment distributions or textural changes. The major raw sewage outfall in Watleys Cove in the outer harbour also does not display any local accumulation of material at the seabed. In Eastern Passage and Bedford Bay particle removal from the waste stream is largely responsible for nondetectable near-field deposition, whereas in the outer harbour, strong currents and high wave energy prevent local deposition from raw-sewage outfalls.

Airplanes

The remains of several airplanes have been located on sidescan sonograms. These lie on the seabed north of Indian Point on McNabs Island and on the eastern side of Bedford Basin near the naval magazine dock. The tail section of an airplane in Bedford Basin is illustrated in Figure 134.

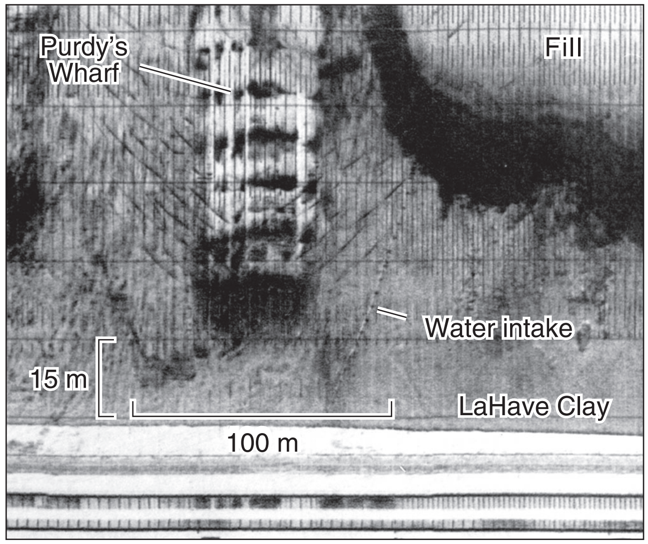
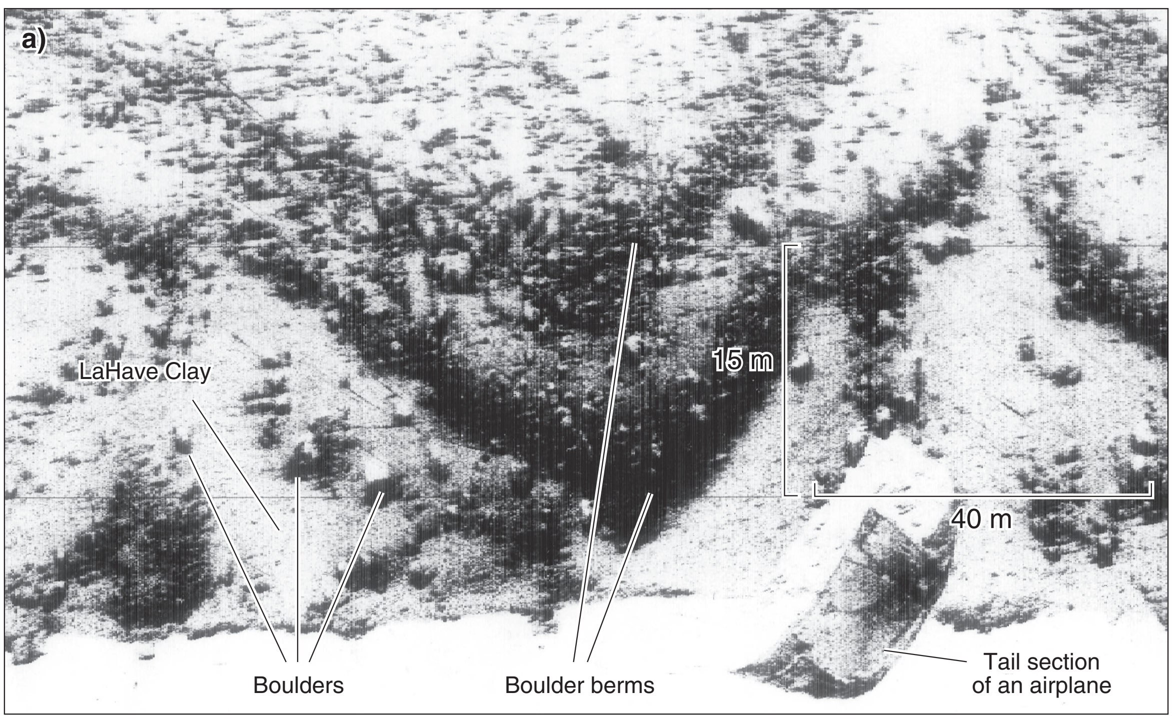


Figure 133. A 120 kHz sidescan sonogram off Purdy's Wharf, inner Halifax Harbour, showing a water intake for building cooling. Intakes and outfalls consist of pipe anchored to the seabed with clump weights spaced at intervals along the pipe.



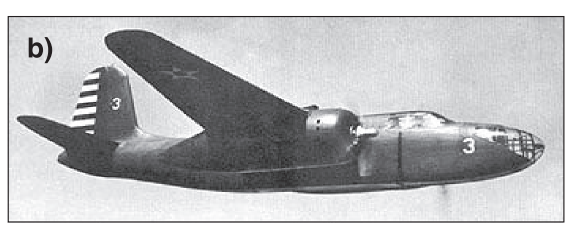


Figure 134. a) A 330 kHz sidescan sonogram showing the terrain of northeast Bedford Basin and a sonar target interpreted as the tail section of **b)** a Havoc airplane adjacent to the Naval magazine dock. Although the sonar image does not resemble an airplane, it was confirmed by R.C.M.P. diver observations in 1990. Two boulder berms and isolated boulders protruding through the LaHave Clay also occur on the image. Some of the boulder-sized, highly reflective objects may represent ordnance on the seabed from the 1945 magazine explosion. Figure 134b courtesy of daveswarbirds.com (accessed 2006-12-01).

Automobiles

A group of approximately twenty-six 1969 Volvo automobiles has been found on the seabed of Bedford Basin in 60 m of water (Fig. 18). They were dumped to the seabed after severe water damage in transit across the Atlantic Ocean on a container ship. They provide excellent calibrated seabed targets for sidescan-sonar and multibeam-bathymetry equipment trials (Fig. 135). Other automobiles have been found on the seabed of the harbour adjacent to the downtown docks.

Cribwork

South of the Point Pleasant Park breakwater is a large cribwork on the seabed (Fig. 136), located during this study. It is believed to have been used by the Royal Nova Scotia Yacht Squadron and scuttled to the seabed during moving of the facility. It is a hazard to navigation and is marked on Canadian Hydrographic Service navigation charts of Halifax Harbour. In addition to the cribwork located at the former Brister's Ship Yard in Northwest Arm (Fig. 103) is a marine slipway adjacent to the former Dartmouth shipyards near Dartmouth Cove (Fig. 13).

GEOCHEMISTRY

Geology and geochemistry

The marine geology of Halifax Harbour presented in this report was well integrated and conducted concurrently with geochemical investigations (Fader and Buckley, 1997). Earlier studies on sediment chemistry (Prouse and Hargrave, 1987) had little or no geological input in the choice of sample locations or knowledge of the varied processes acting on the harbour bottom that could affect results. Sample validity and integrity were compromised in some cases, as materials were collected in areas of intense anthropogenic disturbance that altered sediment texture and overturned the stratigraphy. In order to avoid such problems, and to integrate the geological and geochemical studies, joint surveys were planned and conducted for mutual benefit (Miller et al., 1990; Fader and Buckley, 1997). Geological surveys utilizing seismic-reflection and sidescan-sonar technology were first undertaken and the data interpreted to choose appropriate locations for the collection of valid samples and cores. This avoided areas of anthropogenic disturbance, targeted anomalous features, and investigated other site-specific features developed by known seabed processes.

This section is a brief summary of the geochemistry of the harbour sediments conducted by Dale Buckley and colleagues of GSC (Atlantic). Specific geochemical examples are utilized that apply to understanding aspects of the marine geological setting, sediment transport, and anthropogenic influences. A series of detailed data reports provide information on the geochemistry of Halifax Harbour sediments and pore water from cores that concentrated on the upper 100 cm of section, but also in some cases penetrated to older stratigraphic horizons below the anthropogenic layer (Buckley et al., 1991; LeBlanc et al., 1991; Winters et al., 1991; Fitzgerald et al., 1992). Textural data obtained from these studies have also been incorporated in interpretations of sediment distribution and correlation of the acoustic reflectivity from sidescan sonograms.

Sediment geochemistry

The first regional geochemical studies of the harbour sediments were reported in Prouse and Hargrave (1987) and the OceanChem Group Ltd. (1988). Major and trace elements were assessed as well as total and organic carbon, nitrogen content, redox potential, water content, and sediment texture (Buckley et al., 1989; Buckley and Hargrave, 1989). A variety of contoured maps were prepared showing distribution of geochemical and sedimentological characteristics. These were later revised to include information on sediment distribution interpreted from sidescan sonograms and seismic-reflection profiles and thus have the benefit of acoustic backscatter information for extrapolation between widely spaced sample locations (Winters et al., 1991).

A map of the distribution of clay (Fig. 137) clearly differentiates zones of high clay content within the LaHave Clay in the eastern and central areas of Bedford Basin and the inner harbour north of Georges Island (Fader and Buckley, 1997). A map of organic carbon distribution (Fig. 138) shows high concentrations in Bedford Bay, east Bedford Basin, Northwest Arm, and adjacent to large sewage outfalls in the inner harbour. Beneath a thin layer of brown oxidized sediments, often less than a few millimetres in thickness, the mud of the harbour is grey to black with a hydrogen sulphide smell. A measure of the redox (Eh) potential is used to characterize the presence of oxidizing or reducing environments within the sediments especially near the seabed. The lowest Eh values occur in the inner harbour off the Imperial Oil refinery, in Mill Cove, Wrights Cove, Tufts Cove, off Canadian Forces Base Halifax, along the Halifax waterfront, in Dartmouth Cove, and in Eastern Passage adjacent to the sewage-treatment plant. Values from Bedford Basin and Northwest Arm are higher (Buckley and Hargrave, 1989).

Distributions of contaminant metals such as lead, zinc, lithium, cadmium, and copper relate to sediment transport, depositional processes, dredge disposal, and proximity to sewage outfalls and land-based leached sources. Distributions of copper and zinc show untreated sewage outfalls as major sources. Zinc anomalies adjacent to Seaview Point in Bedford Basin indicate leaching from the former location of the Halifax city dump.

Geochemical synthesis

A factor analysis technique was used by Buckley and Winters (1992) and Winters and Buckley (1992) to interpret the complex distribution of geochemical anomalies relative

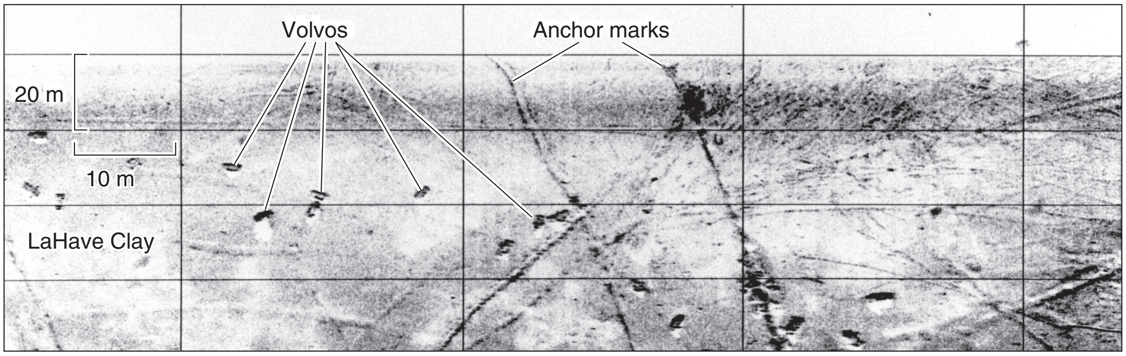


Figure 135. A 330 kHz sidescan sonogram of approximately 26 Volvo automobiles on the bottom of Bedford Basin. They were discarded to the seabed in 1969 after seawater damage during a trans-Atlantic crossing. They serve as calibrated targets for sidescan-sonar trials and tow-fish stability testing. Also shown are anchor-drag and -chain marks. The automobiles also show on the Simrad EM3000 multibeam imagery.

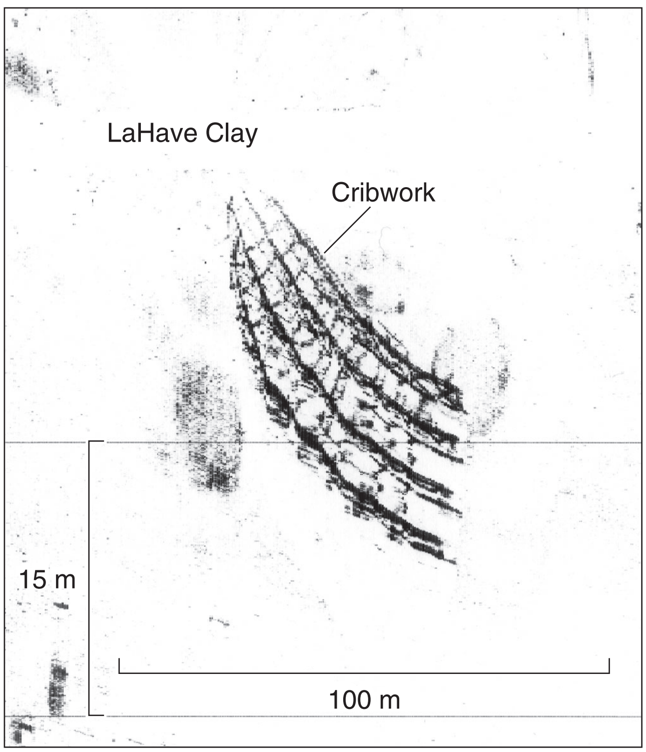


Figure 136. A 330 kHz sidescan sonogram of a large cribwork or marine slip that lies on the seabed south of the breakwater and container pier off Black Rock beach in south Halifax. It represents a hazard to navigation and was found during this study. Its location has been placed on the navigation charts for Halifax Harbour. The Royal Nova Scotia Yacht Squadron used the slip when it was located where the container pier presently is situated. It may have been lost or scuttled to the seabed during relocation of the yacht club.

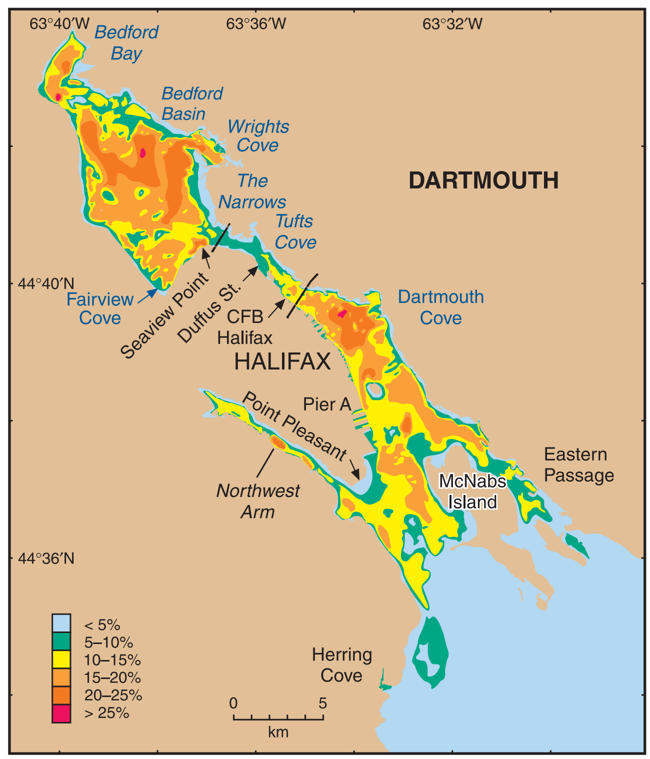


Figure 137. A map showing the distribution of the clay content in sediments of Halifax Harbour (*after* Winters et al., 1991). The highest percentages of clay are found to the north of Georges Island, in a small area north of McNabs Island, and in areas of northeastern Bedford Basin and central Bedford Bay. The map of sediment texture used the backscatter information from sidescan sonograms for additional control.

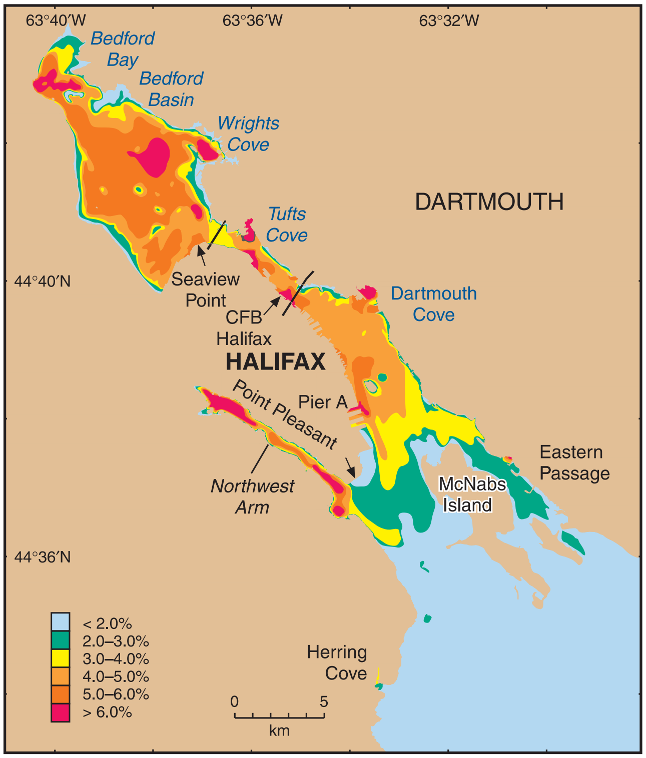


Figure 138. A map showing the distribution of organic carbon in sediments of Halifax Harbour (*after* Winters at al., 1991). Highest values occur near the shoreline adjacent to the major sewage outfalls in the inner harbour, in Bedford Basin, and in Northwest Arm. Note the extension of organic carbon values of 5–6% from the sewage outfalls at Pier A, Halifax, to a depositional area north of Georges Island. This is similar to mercury contaminant pathways from the same outfalls.

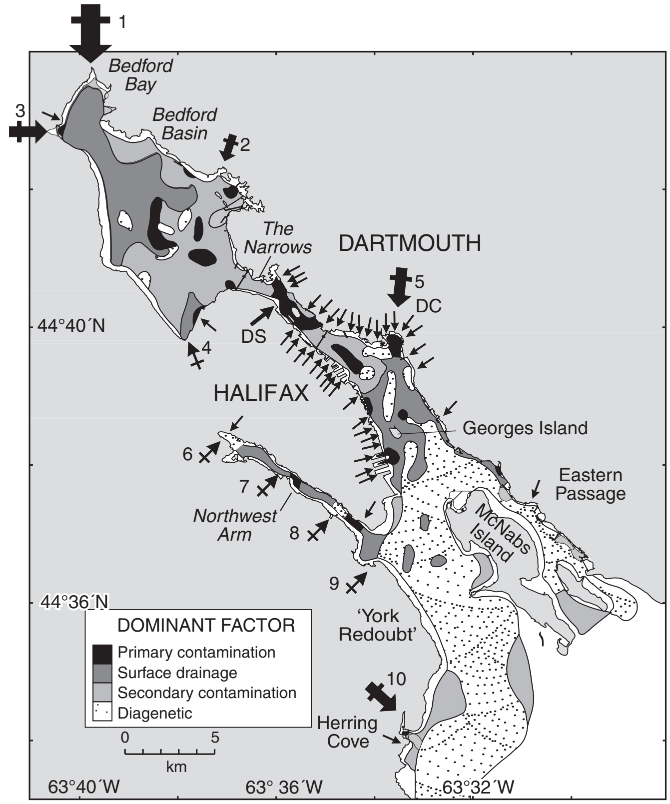


Figure 139. A factor map showing areas dominated by contamination processes and source areas for Halifax Harbour (Buckley and Winters, 1992; Fader and Buckley, 1997). Arrows designate sewage outfalls with major designated outfalls being Duffus Street (DS) and Dartmouth Cove (DC). Fluvial inputs and surface drainage are represented by numbered and scaled 't' vectors: 1 = Sackville River, 2 = Wrights Brook, 3 = Paper Mill Lake, 4 = Fairview Cove, 5 = Lake Banook, 6 = Chocolate Lake, 7 = Frog Lake, 8 = Williams Lake, 9 = brook flowing from Purcells Pond, and 10 = Powers Pond. *See* text for detailed explanation.

to contamination processes. This provided a coherent synthesis mechanism to consolidate a vast amount of analytical information. It allowed four factors to characterize the surficial sediments (Fig. 139). The first factor, accounting for 41% of the variance, is attributed to primary contamination associated with sewage and industrial discharge. Factor 1 areas are located near the many sewer outfalls. The second factor, accounting for 8% of the variance, is associated with surface drainage, and affects the seabed of northern Bedford Basin, the area of the inner harbour around Georges Island, and parts of Northwest Arm. The third factor, accounting for 6% of the variance, is interpreted to result from post-depositional alteration of metals originally associated with sewage and drainage sources. These areas include southern Bedford Basin, the southern part of The Narrows, and a few zones in the outer harbour. The fourth factor, accounting for 5% of the variance, suggests that labile metals are the product of diagenetic remobilization from subsurface layers and may be associated with the presence and passage of methane from subsurface gas-charged sediments. An additional, smaller factor, is associated with calcium and restricted to the outer harbour and the presence of broken and whole shells.

Buckley and Winters (1992) also estimated metal budgets within the sediments and attempted to assess the input from drainage and sewage discharge. They concluded that 90% of copper and zinc is contributed from sewage outfalls and that 17% of the dissolved copper and 36% of the zinc is ultimately incorporated in the bottom sediments. In contrast, all of the sewage-derived dissolved lead remains in the sediments. They concluded that the level of contamination of metals in the sediments of Halifax Harbour is among the highest in comparison with similar environments in the world and is directly related to the sediment-trapping properties of the harbour. The sediments hold a large repository of contaminants, but because of anoxic conditions in the immediate subsurface, they are in a chemically reduced state of restricted mobility (Buckley et al., 1995); however, physical disturbance by a variety of anthropogenic activities, particularly ship anchoring and propeller scour, can remobilize the sediments.

Historical contamination record

In addition to studies of the metal contaminants at the seabed of the harbour, it is important to understand the historical contaminant record. Cores were critical to this study and were collected in areas where natural and anthropogenic disturbance was assessed to be minimal, based on the previously collected geophysical data. High-resolution ^{210}Pb and ^{137}Cs dating techniques were applied to provide the temporal framework. These cores revealed that hydrocarbon concentrations increased 100-fold from 1900 to 1990, and mercury, zinc, lead, and copper peaked in the 1970s. Using the factor analyses techniques developed for the surface distribution of contaminants, Buckley and Winters (1992) and Buckley et al. (1995) applied the analysis to the shallow subsurface to characterize the dominant environmental conditions prevailing when the sediment was deposited, or the dominant process for modification after deposition. Historical trends could clearly be detected. For example, sediments in Northwest Arm indicate a change from surface drainage character to one derived from recent sewage discharge. In Bedford Basin, primary contamination has never become a dominant factor. In the inner harbour prior to 1880, diagenetic processes dominated, after which secondary and primary contamination dominated. These changes result from industrial and urban activities that alter the kind, quantity, and location of inputs to the system.

High-resolution dating of the cores provided information on the sedimentation rates of the LaHave Clay in the harbour since approximately 1880. For Bedford Basin, approximately 35 cm of sediment were deposited between 1880 and 1990, whereas the amount in the inner harbour, to the southeast of Georges Island was approximately 90 cm over the same period. Amounts in Northwest Arm are similar or less than those in Bedford Basin. Areas of maximum sedimentation are located adjacent to large sewage outfalls in the inner harbour in features termed sewage banks.

Geochemical evidence for sediment transport

The maps of geochemical anomalies in surface sediments provide an indirect assessment of sediment-transport pathways and depositional zones. In the inner harbour, the distribution of mercury (Fig. 140) sourced from the sewage outfalls of the Pier A area of the south end of Halifax shows a distinct pattern of northward migration west of Georges Island, to a depocentre north of Georges Island. Mercury-contaminated sediment sourced from the large sewage outfall in western Point Pleasant Park at the entrance to Northwest Arm migrates both to the northwest up the arm and southeast toward the outer harbour. A large mercury anomaly in southeastern Bedford Basin is attributed to sourcing from outfalls in The Narrows at the foot of Duffus Street and in Dartmouth Cove, with transport to Bedford Basin and eventual deposition in a reduced current, Coreolis-controlled, flow regime. With few exceptions such as the entrance to Northwest Arm, the patterns of contaminated sediment transport show an overall inward movement to the north. This is supported by many other observations on textural distributions, bed-form symmetry, and erosional and depositional seabed features and is discussed in greater detail under 'Sediment transport'.

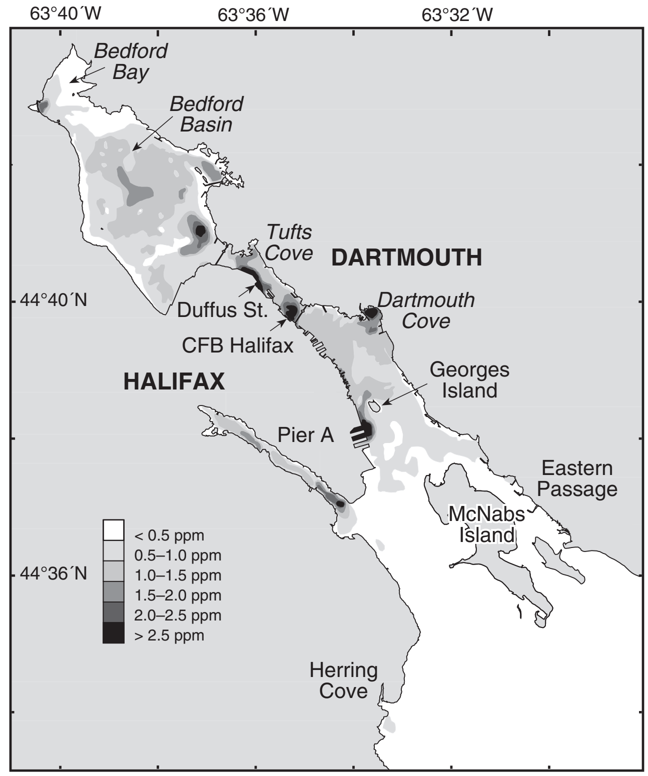


Figure 140. A map of the distribution of mercury anomalies in seabed sediments of Halifax Harbour from 1990. Anomalies greater than 2.5 ppm occur in southeast Bedford Basin, off Duffus Street, and Canadian Forces Base Halifax in The Narrows, in Dartmouth Cove, adjacent to Pier A, and near the large sewage outfall at the entrance to Northwest Arm (*after* Buckley et al., 1995). The mercury anomaly in the southeast area of the basin is interpreted to be sourced from outfalls to the south in The Narrows and other inner harbour areas with transport by currents.

GEOLOGICAL HISTORY

Preglacial bedrock origin of the harbour

The emphasis of this bulletin is the surficial sediments of Halifax Harbour, but the bedrock is important as it influenced the location and shape of the harbour and provides the framework for the deposition of surficial materials. Previous accounts of the formation of Halifax Harbour attribute its origin to the presence of northwest-southeast structural lineaments (faults) (Cameron, 1949) (Fig. 25). It was suggested that the faults may have been zones of weakness for later preferential erosion by preglacial rivers, followed by glacier ice and meltwater. As discussed earlier, there is very little evidence for the presence of large faults beneath the harbour. The major synclines and anticlines on either side of the harbour appear aligned without offset (Fig. 24), and this evidence is supported by aeromagnetic data showing structural continuity of anomalies beneath the harbour (Fig. 26). Sidescan-sonar and multibeam-bathymetric images of bedrock show no recognizable regional faults or offsets within the areas of exposed bedrock on the seabed. In fact, the major fault in the region, where greater erosion would be expected to occur, is the Chain Lakes–Sheehan Cove fault system (Fig. 25), which lies to the west of the harbour. Indeed the channel of the ancient Sackville River follows the location of the Sheehan Cove Fault in an area extending from Herring Cove to Chebucto Head. A large number of linear lakes occur along this fault zone including Long and Governors lakes (Fig. 15), but substantial erosion does not appear to have occurred. This fault continues to the southeast through Sheehan Cove, south of Herring Cove, and coincides with the western margin of the outer harbour continuing to Chebucto Head and beyond. This outer western margin of the harbour is likely the only morphological segment controlled by the presence of faults; however, borehole samples from bedrock in the centre of outer Northwest Arm and several other areas of the harbour indicate that the bedrock can be severely fractured. These structural weaknesses lend some support to ideas concerning the presence of minor faults in the bedrock beneath the harbour.

The authors suggest that the location of Halifax Harbour owes its origin not to faults within the bedrock, but to the distribution of bedrock type, namely, the dominant presence of the eastern flank of the South Mountain Batholith to the west of the harbour. This large, erosion-resistant granitic intrusion confined the location of Meguma Terrane fluvial drainage systems in preglacial time to weaker metasedimentary rocks east of the batholith. The batholith extends for over 30 km offshore (Fig. 27) and may have acted as a major divisional boundary for fluvial drainage systems and glacial ice streams that flowed across Nova Scotia and the adjacent Scotian Shelf. Sambro Bank lies south of the batholith on the inner Scotian Shelf and is a large, shallow Cretaceous bedrock feature with overlying till (Scotian Shelf Drift). Both Sambro Bank and the granite batholith offshore extension effectively separated fluvial and glacial ice drainage into Emerald and LaHave basins (Fig. 141). Sambro Bank may have been protected from erosion by ice as a result of steering of the ice streams to either side by the resistant granite body.

King (1970) mapped the surficial sediments on the inner Scotian Shelf off Halifax and identified a channel to the east of the batholith that connects with Halifax Harbour. He proposed the term 'ancient Sackville River' for this feature. It is clearly evident on the multibeam-bathymetric image off Halifax Harbour (Fig. 9, 22), although its width is considerably less than originally interpreted.

An ancient preglacial Sackville River likely flowed through the area of Bedford Basin and the harbour and across the inner Scotian Shelf, but the presence of a deep inner harbour subsurface basin trending towards Dartmouth Cove,

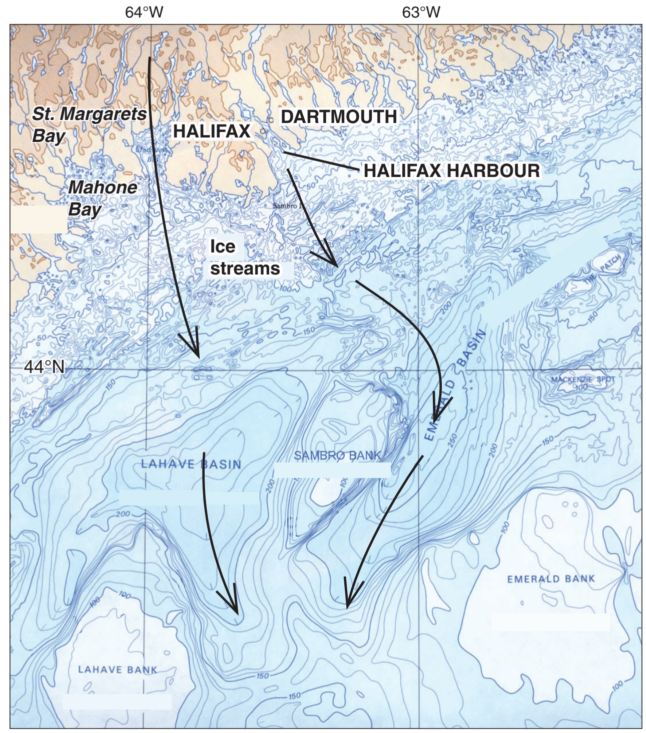


Figure 141. Regional bathymetry of the inner Scotian Shelf off Halifax Harbour showing the major topographic elements that controlled the direction of inferred glacial-ice movement from the land to the offshore. The western outer Halifax Harbour granite batholith offshore extension, together with Sambro Bank, a Cretaceous sedimentary-bedrock shallow bank, channelled ice streams in Halifax Harbour to Emerald Basin and separated it from adjacent ice streams to the west that moved through St. Margarets and Mahone bays and across LaHave Basin (*after* Canadian Hydrographic Service, 1990b).

suggests another drainage system that joined with the Sackville River in the inner harbour to the north of Georges Island. Such a system existed in the present location of a series of lakes in Dartmouth: Banook, Charles, and Micmac, that at present empty into Dartmouth Cove (Fig. 15). This system also was a spillway for later glacial lakes in central Nova Scotia (Stea and Mott, 1989). Therefore, it is likely that two early drainage systems contributed to the preglacial formation of Halifax Harbour. The present authors propose to retain the term 'ancient Sackville River' as defined by King (1970) for the system in the harbour and on the adjacent inner shelf. The exact location of the preglacial drainage system is difficult to accurately define beneath the thick and gas-charged sediments of the inner harbour and overdeepened Bedford Basin, but it was clearly confined to the western part of the outer harbour (Fig. 142, 143, 144).

Glacial history

Before Pleistocene glaciations, which began approximately 2.5 million years ago, Bedford Basin did not exist as a large, isolated circular depression. The 'ancient Sackville River' extended across the gently dipping

Cretaceous peneplain of the Atlantic Uplands physiographic province, through the present area of the basin, and out of the harbour along the outer western flank. With the onset of glaciation, radical changes took place in the drainage system. Glaciers eroded and overdeepened the area of Bedford Basin by more than 50 m, excavating the present deep depression, following the course of the earlier fluvial drainage system. It is not known which of the glaciations created the extensive overdeepening of the basin and perhaps all contributed to some degree in the formation of this bowl-shaped depression. Research on the relative effects of multiple glaciations of Atlantic Canada from the continental margin (Piper and Normark, 1989) suggests that the largest erosional event took place in stage 6, the Illinoian Glaciation, prior to the last glaciation, the Wisconsinan.

The location of the Birch Cove Anticline is coincident with the present deepest central area of Bedford Basin (71 m water depth) (Fig. 24). Because of the thick, massive beds present in the Goldenville Formation (metasandstone), and the fractured nature of the rocks in the anticline, ice and associated subglacial meltwater were able to effectively erode the anticline by processes of hydraulic jacking, freeze and thaw cycles, and abrasion and plucking by glacial ice to produce the overdeepening. Surrounding the southeastern shoreline of Bedford Basin are many large 1 m to 2 m quartzite blocks in the till that have been eroded from Bedford Basin. Similar processes of glacial overdeepening occurred throughout the harbour to alter the previous fluvial drainage system. The most extensive overdeepening occurred in the buried harbour basins where the lacustrine and/or estuarine sediments are located (Fig. 56). Local overdeepening of up to 10 m occurred in the northern part of The Narrows with the formation of small, local depressions that are evident on the multibeam bathymetry (Fig. 6). As a result of the glacial overdeepening of the basin, a continuous river channel for the ancient Sackville River ceased to exist in the area of Bedford Basin subsequently occupied by a lake. The authors propose the term 'Lake Bedford' for this early lake (Fig. 145). At The Narrows, a new outlet formed for drainage from the Sackville River and 'Lake Bedford'.

Glacial control on harbour morphology

As glaciers moved through the harbour, variations in bedrock lithology and structure controlled the amount of erosion as well as the width and morphology of the present harbour. As the ice moved across the Halifax Formation it was not able to remove large blocks of material as readily as it could over the Goldenville Formation quartzite beneath the basin and in other areas of the harbour. The widely spaced fractures and thick beds allowed the Goldenville Formation to be more susceptible to glacial block quarrying, whereas the Halifax Formation with its thinner beds is more closely cleaved providing for limited glacial removal and the generation of smaller fragments. Therefore, glaciers eroded much less over the Halifax Formation. This differential erosion resulted in the topographic high of the peninsular component of Halifax and the narrow channel of the inner harbour which is now The Narrows. Additionally, the till in The Narrows acoustically appears to be more consolidated than in other areas of the harbour. This may also result from confinement of ice flow in The Narrows as a result of bedrock topographic control on local ice dynamics.

North of Georges Island, the Goldenville Formation quartzite continues on the Dartmouth side of the harbour and the bedrock was more easily eroded in this area, producing the present widening of the inner harbour south of The Narrows. The channel narrowed to the west of McNabs Island as Halifax Formation slate forms the bedrock between south Halifax and McNabs Island. In the outer harbour and beyond, the massive granite batholith of the western harbour continued to control the direction of ice as it moved across the

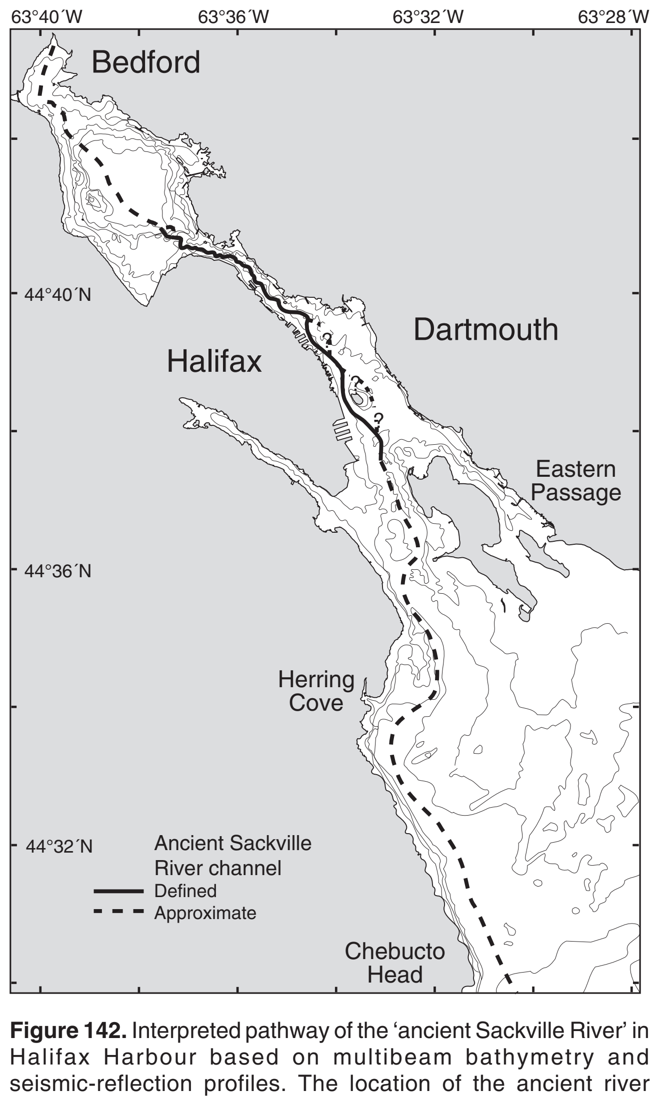


Figure 142. Interpreted pathway of the 'ancient Sackville River' in Halifax Harbour based on multibeam bathymetry and seismic-reflection profiles. The location of the ancient river beneath gas-charged sediment in Bedford Basin and the inner harbour, as well as to the east or west of Georges Island cannot be accurately determined. The ancient river channel maintained a course along the western side of the outer harbour.

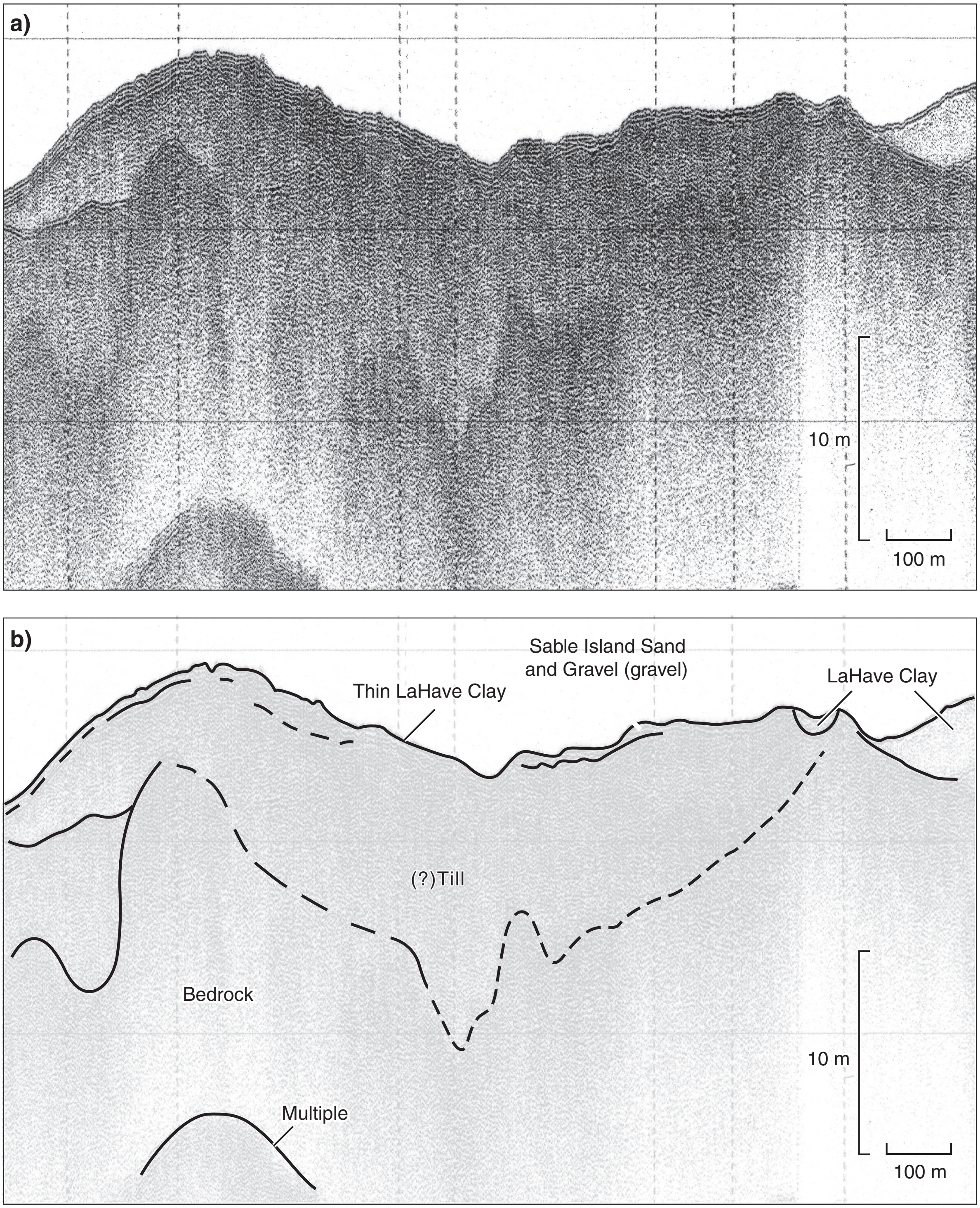
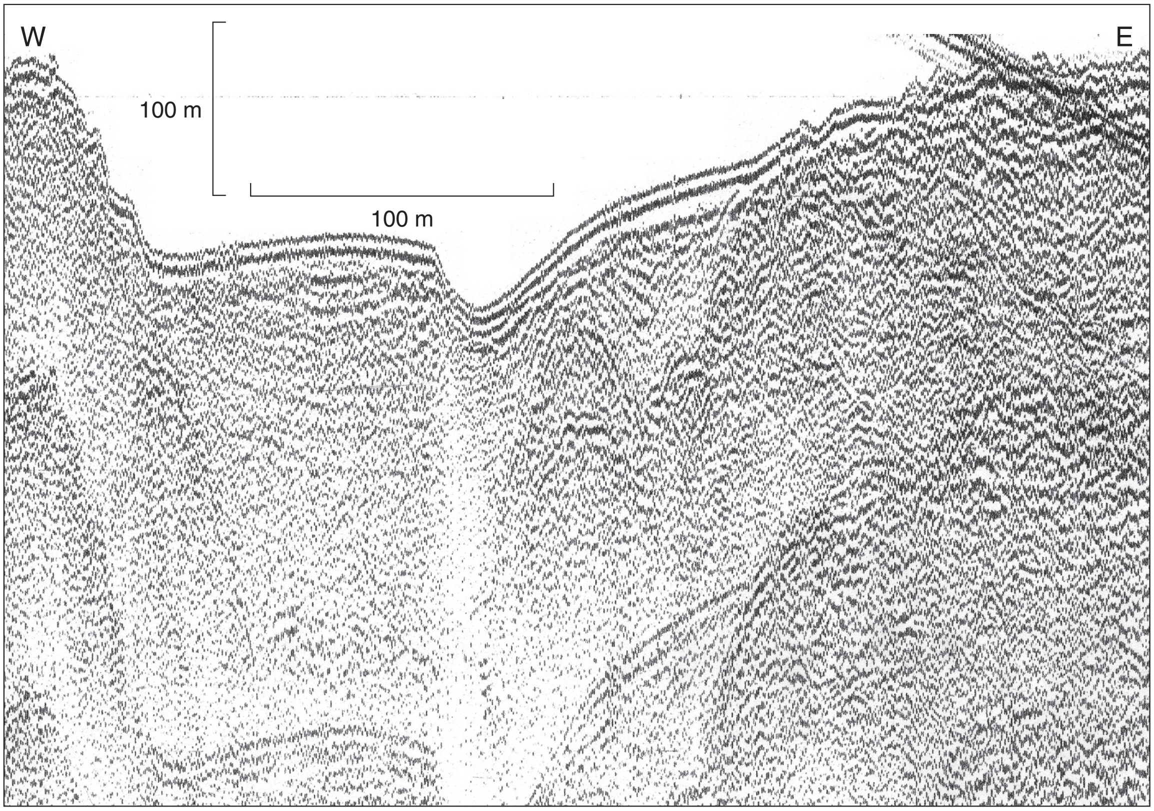


Figure 143. a) A Seistec seismic-reflection profile and **b)** interpretation between Georges Island and the adjacent Halifax shoreline. A deep channel can be seen cut into the bedrock which may represent a channel of the 'ancient Sackville River' passing to the west of Georges Island.

a)



b)

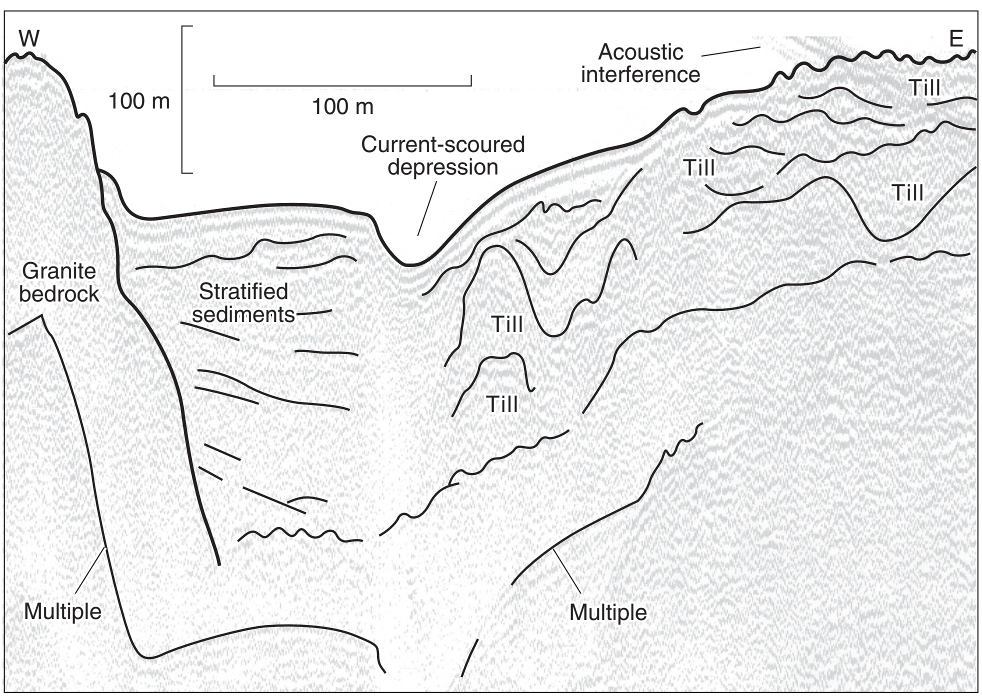


Figure 144. a) A 40 cubic inch air-gun seismic-reflection profile and **b)** interpretation at the mouth of Halifax Harbour south of Chebucto Head crossing the channel of the 'ancient Sackville River' from west to east. This channel is filled with over 200 m of material and the water depth is over 100 m in places. The channel is flanked by Devonian granite in the west. The basal material consists of incoherent reflections suggestive of till, but the upper sections exhibit continuous coherent reflections indicating glaciomarine-lacustrine sediment deposition. Multiple tills occur in the east. Strong currents have produced deep-scoured depressions in the seabed. Submersible observations at the base of the scoured depression at the contact with the steep granite western flank show gravel in the pebble and cobble size range.

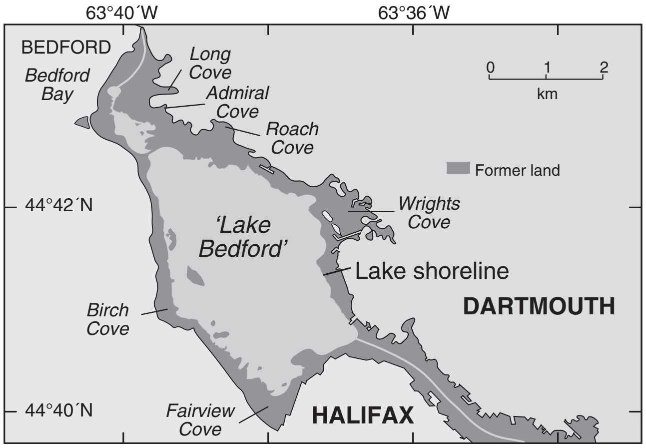


Figure 145. A paleogeographic reconstruction of Bedford Basin at approximately 6000 BP, (radiocarbon years.) The former lake shoreline is defined by the presence of regional boulder berms at 23 m water depth that were formed by repeated seasonal freezing and the development of shoreline ice-push ridges. The subsequent marine transgression of the basin has partially liberated the boulders in the ice-push ridges from a matrix of sand and mud. Numerous islands would have been present on the western side of the lake.

inner shelf. These high, resistant granite cliffs remain along the western side of the harbour from Herring Cove to Chebucto Head.

Ice in the inner harbour area in Dartmouth Cove may have converged with ice following a channel presently occupied by the lakes in the Dartmouth area. Erosion by southward-flowing ice likely overdeepened the bedrock to produce depressions now occupied by lakes Charles, Micmac, and Banook. Other buried and possibly glacially overdeepened depressions occur beneath the harbour to the south and east of Georges Island, in Eastern Passage, in Northwest Arm, between McNabs Island and Pleasant Shoal, off Herring Cove, and adjacent to Portugeuse Cove.

New ideas regarding the role of subglacial meltwater have been proposed to explain glacial landforms such as tunnel valleys, channels, and drumlins (Shaw et al., 1989). On the outer Scotian Shelf, Boyd et al. (1988) attributed multigenerational, buried, deep depressions to subglacial meltwater erosion. Forbes et al. (1991) suggested that a large valley joining the 'ancient Sackville River' off the mouth of Halifax Harbour was formed by subglacial meltwater. Piper et al. (1986) mapped channels called 'Rinnental' in adjacent St. Margarets Bay that were formed by subglacial meltwater processes. In contrast, evidence to support classical glacial ice erosion of Halifax Harbour is the presence of over-deepened basins with rock sills and striated bedrock surfaces adjacent to the harbour. The timing and role of subglacial meltwater in the formation of harbour morphology and buried isolated depressions is not fully understood.

Wisconsinan Glaciation

Glaciers likely occupied the area of Halifax Harbour many times beginning in the middle Pleistocene, but most of the surficial materials overlying bedrock and the glacial landforms are interpreted to relate to the last major episode of glaciation, the Wisconsinan. On the shelf adjacent to the mouth of the harbour are several fields of oriented drumlins, eroded drumlins, linear bedrock scours, till ridges, and moraines that indicate a complex history of ice advance and retreat, erosion, and deposition (Fig. 22). The effects of sea-level variation including lowstands and transgressions are also overprinted on this glacial surface.

The oldest terrestrial Quaternary sediments recognized in Nova Scotia are the Bridgewater Conglomerate and Mabou Conglomerate. They are iron-cemented drift composed of slate and granite clasts that lie below tills and over striated bedrock. Their age and origin is uncertain, and some consider them to be Tertiary to early Pleistocene (Stea, 1978). The Bridgewater Conglomerate occurs in areas around Halifax Harbour particularly in Northwest Arm and likely beneath other areas of the harbour. These materials were not sampled in the marine studies. Overlying the Bridgewater Conglomerate regionally are peat- and wood-bearing organic horizons that have been assigned to the last interglacial, Sangamonian, 75 000–128 000 BP (Fulton, 1984).

The last major period of glaciation began in maritime Canada at about 75 000 BP during the early Wisconsinan. An ice sheet is interpreted to have extended eastward and southeastward to the edge of the Scotian Shelf over 100 km away, where it formed a shelf-edge-calving margin. A tripartite stratigraphy of the tills offshore and onshore reflects changing ice centres in the maritime region during the Wisconsinan, and has been collectively termed the Appalachian ice complex (Stea et al., 1998). Five glacier-flow events have been recognized representing separate phases evolving from shifting ice centres and divides. These appear to have occurred without intervening nonglacial intervals (Stea et al., 1992a, b). The first ice advance is interpreted to have deposited the Hartlen Till, a grey, matrix-rich, and overconsolidated silty till that occurs in and around Halifax Harbour and is commonly found at the base of the surficial succession in drumlins (Stea and Mott, 1989; Stea et al., 1992a, b). It is exposed at the base of cliff sections along the eastern shoreline of the outer harbour to the southeast of Eastern Passage and has been encountered in several of the boreholes in Halifax Harbour at the base of the surficial succession. The large linear scours in the bedrock off Halifax Harbour may have been formed by this ice advance (Fig. 9, 22).

Ice is interpreted to have retreated to the inner Scotian Shelf during the mid-Wisconsinan Phase, 40 000–22 000 BP. During this time the area of Halifax Harbour likely remained under ice cover. This was followed by the Escuminac phase of the Late Wisconsinan, 22 000–18 000 BP, with an advance of ice centred over the Magdalen Shelf in the Gulf of St. Lawrence (Goldthwait, 1924; Shepard, 1930; Prest, 1973;

Rampton et al., 1984). Large, parallel, linear depressions on the granitic South Mountain Batholith west of Halifax Harbour (Fig. 30) that trend north-northeast, are parallel to this ice-flow direction and may have been formed at this time. Drumlins to the west of the granite batholith offshore may also have formed during this advance (Fig. 22). The glacial ice also transported and deposited large quantities of red hematitic till to the shelf edge. This till is termed the Lawrencetown Till, and it is characterized by high percentages of rock types from the Cobequid Highlands located 80 km north of Halifax. It is a silty till with a sharp contact with the underlying grey Hartlen Till that is often defined by boulder-rich horizons. The Lawrencetown Till contains more clay than the underlying Hartlen Till and is less compact. The till is found only in narrow drumlin fields of the eastern shore of Nova Scotia. For areas of the inner shelf, including Halifax Harbour, the ice that formed these drumlins has been interpreted to have been over 1 km thick (Stea, 1995). This ice formed the drumlins of Halifax Harbour: Jonquière Bank, 'Little Georges Bank', and Georges Island, as well as the many drumlins of the surrounding land areas such as 'Citadel Hill', 'Fort Needham Memorial Park', and McNabs and Lawlor islands.

By 18 000 BP, Late Wisconsinan ice began to calve and retreat back across the Scotian Shelf, pinned for times at locations of bedrock highs that controlled the deposition of moraines with floating front till tongues in the basins and on their northern flanks (King and Fader, 1986). The Scotian Phase followed and resulted in a major change in ice-centre locations as a result of ice-stream drawdown into the deep areas surrounding Nova Scotia such as the Bay of Fundy and Laurentian Channel. The Scotian Ice Divide developed over mainland Nova Scotia and the shelf south of Cape Breton Island and terminated on the Scotian Shelf at the Scotian Shelf end-moraine complex. It may have extended across the eastern Scotian Shelf on Canso, Misaine, and Artimon banks. Textural comparisons of terrestrial Beaver River Till and inner Scotian Shelf Drift of the end-moraine complex indicate similarity (Stea et al., 1994). The till of the Halifax Moraine on the inner Scotian Shelf off Halifax Harbour (Fig. 29) and a series of till ridges to the north of this moraine were formed at successively shallower depths as the grounding zone retreated toward the land. Till tongues, which are interbedded Emerald Silt and Scotian Shelf Drift, occur on the seaward side of the moraines.

On land, bedrock striae suggest a southeastward flow in the area of Halifax Harbour. The till deposited during this retreat phase is a stony, sandy till, derived from local bedrock sources with a high percentage of angular boulders. It has been termed the Beaver River Till from a type section in southwest Nova Scotia (Grant, 1980; Finck and Stea, 1995). This till overlies both the Lawrencetown and Hartlen tills in drumlins and forms a bouldery till plain over most areas of the Atlantic coast including the area of Halifax Harbour. The Beaver River Till was formed during 17 000–15 000 BP.

By 13 000 BP the ice margin was situated near the present-day Atlantic coast of Nova Scotia. These glaciers further retreated landward with probable re-entrants up some of the larger embayments. The buried channel-fill sediments in outer Halifax Harbour (Fig. 144) could represent glaciomarine sedimentation, but these deposits have not been sampled because of their depth of burial beneath thick transgressive sand and gravel. As the glacial ice retreated up Halifax Harbour, small linear moraines parallel to the ice front formed on Middle Ground, in the inner harbour northeast of Georges Island, and in Bedford Bay. They represent ice-marginal deposits that formed as ice lifted off the seabed and are similar to large fields of lift-off (King and Fader, 1986) or De Geer moraines that are found west of the entrance to Halifax Harbour (Fader et al. 1997; Fig. 22). A prominent end moraine was formed at the head of Northwest Arm during this time (Fig. 146) by a local readvance of ice. The moraines formed sometime after deposition of the northern Scotian Shelf end moraines dated at 14 000 BP (King, 1996) and before the 11 700 BP age of the low sea-level stand off Halifax. The climate warmed considerably during this period and the glaciers shrank to a series of small terrestrial centres in Nova Scotia, leaving deposits of hummocky ground moraine as they ablated during downwasting (Grant, 1977).

A low sea-level stand has been identified on the inner Scotian Shelf at a depth of between 65 m and 70 m at 11 7 00 BP (Fig. 9, 22, 147) (Stea et al., 1994). This former

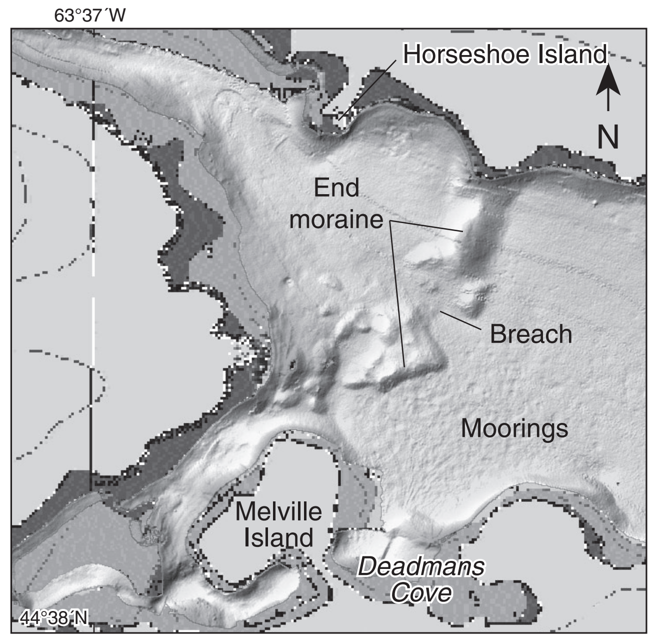


Figure 146. A Simrad EM3000 multibeam-bathymetric image from the inner area of Northwest Arm, Halifax Harbour, northeast of Melville Island. Note a seabed ridge crossing the arm, interpreted as an end moraine deposited by a local ice advance during overall glacial retreat from the region. The age of the moraine is unknown. Early postglacial rivers that flowed down the arm when sea level was lower have breached the central area of the moraine.

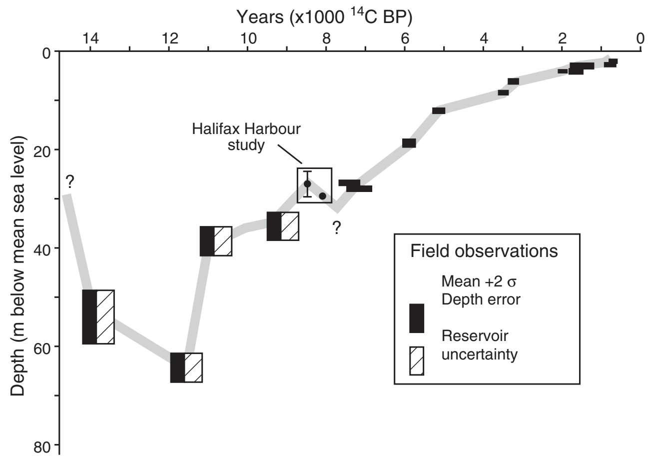


Figure 147. A Holocene relative sea-level curve for Halifax Harbour and the adjacent inner Scotian Shelf based on cores collected at a low sea-level delta off the harbour (Stea et al., 1994) and vibrocores from in the inner harbour near Georges Island (Edgecombe et al., 1999).

shoreline is defined on the basis of major changes and distributions in terrane character, the presence of erosional features, and sediment textures. Relative sea level quickly rose after 11 600 BP, transforming areas above 65 m water depth into a low-relief surface of gravel lag, bedrock outcrop, and small areas of well sorted, coarse sand devoid of silt and clay. A field of drumlins east of Chebucto Head (Fig. 22) was severely eroded and evidence of their previous existence remains only as linear mounds of aligned boulders (Fig. 9, 22). Former gravel beach ridges are rare. Some drumlins remain that were protected from erosion by their location in depressions behind bedrock sills or gravel barriers. In these areas only the tops of the drumlins have been eroded, slightly flattened, and armoured. Fine-grained sediments that formed part of the drumlins and other glacial materials were eroded and transported farther seaward, giving the inner shelf its present coarse-grained and muted morphological character.

Between 11 000 BP and 10 000 BP the climate of Nova Scotia cooled, which greatly affected the land and marine areas. Both lake and offshore sediment cores show a distinct coarsening that marks the Younger Dryas period. Land-based glaciers were reactivated during this time and overrode pre-existing organic materials (Grant, 1989; Stea and Mott, 1989; Mott and Stea, 1994). On the inner shelf off Halifax, a distinctive, coarse sediment horizon and extensive local erosion of glaciomarine Emerald Silt suggest increased storminess, sea ice, and possibly small icebergs (King and Fader, 1988; Piper and Fehr, 1991; Gipp, 1994; Stea et al., 1996). It is not known what effect this cooling event may have had on the sedimentology of Halifax Harbour.

Postglacial history

With final removal of glacial ice, the area of Halifax Harbour existed as a series of lakes in the location of Bedford Bay, Bedford Basin, Fairview Cove, the inner harbour around Georges Island, Northwest Arm, Eastern Passage, an area west of McNabs Island, off Herring Cove, and in an area extending from Portuguese Cove to Chebucto Head (Fig. 56). Other lakes may have existed in the channel of the 'ancient Sackville River' beyond Chebucto Head. The lakes were connected by a series of rivers and streams cutting through bedrock-dominated sills separating the lakes, connecting the 'ancient Sackville River' with the Atlantic Ocean.

Boulder berms formed in ancient shorelines in some of these lakes as the result of seasonal freezing and ice expansion. In some areas they are exposed at the present seabed such as in Bedford Basin (Fig. 72) and in the area between McNabs Island and Pleasant Shoal (Fig. 13, 74). Other boulder berms may be buried beneath younger sediments, but have not been identified.

The sill between Bedford Bay and Bedford Basin, 'Wellesley Ridge', is a series of near-continuous bedrock ridges, suggesting that waterfalls existed along the course of the early rivers (Fig. 18). The Bedford Bay sill at 'Wellesley Ridge' displays a small bedrock notch on multibeam bathymetry that locates an ancient waterfall. Continuous bedrock ridges that cross the harbour in The Narrows also indicate that local waterfalls and isolated small ponds or lakes could have existed there. The roughness of the seabed and bedrock-ridge outcrop pattern of The Narrows suggests that the former fluvial drainage system was complex and irregular. A prominent, partly exposed, section of the former 'ancient Sackville River' occurs in the southern part of The Narrows where it is well defined on the multibeam-bathymetry imagery (Fig. 6, 13, 19). This segment is a sinuous channel formed by both fluvial and glacial processes. Bedrock ridges have been truncated by the erosion (Fig. 13). Little is known about the complete pathway of fluvial systems that continued through the harbour (Fig. 142, 143) as the area of the inner harbour to the south of The Narrows is covered by thick gas-charged sediments and the subsurface cannot be acoustically imaged. Conditions are likely to have resembled areas of The Narrows.

The early marine Halifax Harbour was confined to a narrow channel in the western outer harbour, as the present major shoal areas in the east were emergent until approximately 7000 BP (Fig. 6, 21). As sea level continued to rise, intense erosion occurred in the outer harbour. The present bedrock shoal areas east of the western deep channel, presumed to have originally been covered with till, were subjected to large waves and strong currents at the shoreface. Most of the till was eroded, leaving only scattered boulders on bedrock. Large flute-shaped, linear glacial scours were exhumed during the transgression and can be seen on the multibeam imagery over Bear Cove Shoal (Fig. 6, 12). Similar shoreface erosional processes are presently taking place at the seaward, south side of McNabs Island, with erosion of the drumlins and exposure of the underlying bedrock platform. During the transgression of the outer harbour, sand-sized material was transported and deposited in the deep channel of the western outer harbour where it remains today. Fine-grained mud was transported farther seaward to the northern part of Emerald Basin on the inner shelf. The marine transgression continued to migrate up the harbour with the formation of the Sable Island Sand and Gravel overlying bedrock, till, and lacustrine, and perhaps glaciomarine sediments. Where the transgression breached sills and flooded former lakes, Sable Island Sand and Gravel deposition was thin or absent.

In contrast to the effective erosion by the transgression in the outer harbour, erosion was much less severe in the inner harbour as a result of sheltering by McNabs and Lawlor islands, the narrowing of the entrance of the inner harbour between McNabs Island and Halifax peninsula, and the increasing distance from the open Atlantic Ocean. In many places till units were preserved and only their upper surfaces were modified. Fine-grained sediments were removed and lag surfaces of angular clasts were developed.

From a study of vibrocores in and around Georges Island of the inner harbour, a complex sea-level history has been revealed that indicates that the marine transgression of the harbour was not a simple continuous rise from a lowstand of approximately 65 m (Edgecombe et al., 1999). The recognition of an estuarine sequence overlain by a soil horizon, indicates that sea level was higher and then fell through this level allowing for a short period of subaerial exposure. The occurrence of a transgressive unconformity overlying the estuarine unit indicates that sea level then rose from the lower position. This new sea-level data (Fig. 147) indicates that sea level was higher than -25 m below present before 7000 BP. The presence of a marsh deposit at the same elevation, more than 1000 years younger suggests that sea level fell between 8400 BP and 7000 BP. This sea-level curve corresponds to zone C of zonations observed by Scott et al. (1987) and theoretical zonations of Quinlan and Beaumont (1981). It likely records the migration of a peripheral forebulge, resulting in a period of emergence along the present coastline. After the crest of the forebulge passed, the area was once again submerged with the rising sea passing over the previous, slightly raised marine terrace.

The marine transgression continued up the inner harbour with minor erosional effects, whereas in the outer harbour erosion was extensive. The pre-existing harbour lakes were inundated with marine waters as their sills were successively breached and overstepped. Erosion of the lacustrine sediments took place in some areas with several metres of material removed. In The Narrows, beach processes were more intense, perhaps as a result of the longer fetch up the harbour and funnelling effects of both narrowing and shallowing. Curvilinear boulder berms were formed at successively shallower depths until the sill at the junction with The Narrows was finally breached at 5800 BP. As most of the inner harbour is presently covered by Holocene LaHave Clay, it is not known if depositional features of the Sable Island Sand and Gravel are present in the subsurface, but based on their distribution in the exposed area of The Narrows, similar features are considered to be present.

The earliest deposition of LaHave Clay in the inner harbour occurred at approximately 5500 BP, overlying transgressed surfaces and deposits of Sable Island Sand and Gravel. Much of the deposition of LaHave Clay took place under conditions and in areas similar to the present. Nondepositional moats formed early around Georges Island and in other areas, indicating that oceanographic conditions were similar to those at present. Minor variations in depositional patterns and fining-upward textures suggest higher energy during early stages of LaHave Clay deposition, which is to be expected under shallower water conditions. With the breaching of the sill in The Narrows, marine sedimentation was initiated first in Bedford Basin and later in Bedford Bay as its sill was also breached. The boulder berms that formed at a depth of 23 m in the basin when it was a lake were not, in most areas, buried by subsequent LaHave Clay sedimentation and remain exposed at the seabed today. The boulder berms are partially buried in Birch Cove, off Wrights Cove, Roach Cove, and perhaps in Bedford Bay in areas near the junction with Bedford Basin.

As sea level continued to return to its former preglacial position, the harbour became deeper and fine-grained mud was deposited, overlying more areas of coarse sediment. Some of these mud units are seasonally deposited over coarse gravel as thin coatings and layers and are later eroded and transported during periods of higher energy conditions.

Within the LaHave Clay, degradation of organic material took place, leading to the generation of methane gas and the development of gas-charged zones. These occurrences are extensive over areas of the inner harbour including Bedford Basin, Northwest Arm, and Eastern Passage. Gas began to leak out of the sediments, resulting in the formation of pockmarks in Northwest Arm and large depressions in Bedford Basin. The present venting of methane gas is not well understood.

As the water depths increased in the outer harbour, gravel surfaces became more stable. By approximately 3000 BP, when sea level had returned to within 5 m of its present position, modern conditions had largely developed in the harbour. Estuarine circulation was well established, largely driven by the Sackville River, with the dominant movement of water in on the bottom and out on the top. The seabed sediments of the outer harbour were periodically affected by large storms and waves with the development of sand ribbons, megaripples, ripples in gravel, and gravel circles. Energy conditions interpreted from bed forms in the outer harbour indicate a consistent decrease with distance upharbour from Chebucto Head. Lichfield Shoal acts as a major topographic barrier to bottom currents, thereby sheltering areas to the north.

The area of Sandwich Point is a critical transitional zone for both sediment type and seabed processes. Here the mud of the inner harbour terminates in a complex distribution with the development of sedimentary furrows. These bed forms indicate both periodic deposition of fine-grained materials from the north and intermittent erosion with transport of sand to the north in response to strong currents from the south, likely generated in storms.

Recent changes

With the founding of Halifax in 1749 by the British, the harbour seabed and coastline began a new phase of alteration, largely driven by anthropogenic activities of land clearing, waste disposal, and shipping. These earliest activities were initiated with the anchoring of ships in the harbour that produced distinctive patterns of erosional marks on the seabed and resuspension of sediments. This activity continues today in a more intense way, as much larger anchors and bigger ships are involved. It also includes disturbance and resuspension of sediments by propellers. The early vessels regularly dumped clinkers, unburned coal, and other mixed debris on the seabed and discharged raw sewage. Some of these vessels also sank as a result of storms, collisions, and fire, and over 45 vessels or parts of vessels have been identified on the harbour floor. Other smaller boats may be buried beneath the LaHave Clay.

Early settlers built docking facilities and began the process of infilling areas of the waterfront for a variety of shipping-, construction-, and industry-related activities. This has continued to the present day with the construction of container piers, housing developments, and waterfront commercial and tourism facilities. A major breakwater was constructed shortly after 1913 in south Halifax that constricted the main channel into the inner harbour by one-quarter. It was built on a shallow bedrock ledge previously called 'Reed Rock' and provided a sheltered area for the boat basin of the Royal Nova Scotia Yacht Squadron. The construction of the Halterm South End Container Terminal in the 1970s in the south end of Halifax to the north of the pre-existing breakwater further constricted the flow between McNabs Island and Halifax. Scoured depressions in the LaHave Clay offshore from the breakwater may have formed or been enhanced as a result of this process of harbour narrowing and resultant increased current velocity.

Sewage banks are thick adjacent to raw-sewage outfalls in the inner harbour and occur as testimony to a lack of strong currents for transport as well as a lack of waste-water treatment facilities. Geochemical anomalies of mercury and other metals help define sediment-transport pathways in the inner harbour and indicate net transport of fine-grained sediments to the northwest, upharbour, with deposition in well defined locations north of Georges Island (Fig. 13).

The World Wars I and II and associated military activities have had a dominant influence on the seabed of the harbour. Large convoys of ships assembled in the harbour and Bedford Basin before leaving for Europe. These ships anchored over large areas, eroding and mixing sediments as well as discharging materials to the seabed. Submarine detection and destruction devices were placed in the outer harbour and were connected with electrical transmission cables, some of which remain on the harbour seabed. Antisubmarine nets were strung across areas of the harbour to control the passage of submarines. Remains of these structures are still present on the harbour bottom. As time markers, they assist in understanding subsequent processes of erosion and deposition. Large anchor blocks on the harbour bottom off Sandwich Point have induced local scour with transport of the material to the north. Recent military activities include the emplacement of acoustic and magnetic sensors on the seabed. Dredging and seabed foundation preparations were associated with these activities.

Dredge spoils have been dumped to the seabed, particularly in Bedford Basin. They contain a wide variety of materials ranging from construction debris to dredged sediments from other areas. To enhance the shipping-related activities in the harbour, areas were dredged, docks were constructed, and several shallow areas including drumlins and bedrock outcrop were blasted and dredged for safe vessel transit. Seabed mining for aggregate took place in areas to the north and east McNabs Island, exploiting some of the Sable Island Sand and Gravel deposits in the near shore.

Major recent engineering projects, such as the construction of the two bridges spanning The Narrows, and the container terminals, have infilled large areas of the harbour and changed conditions that effect the present and future deposition of sediments. The Halifax Explosion, the world's largest manmade explosion prior to the atomic bomb, took place in The Narrows. It only altered the seabed in a minor way (Fader, 1994, 1995), however, as the *Mont-Blanc* was grounded at the time of the explosion and the blast was directed upward and outward as a result. The majority of the damage was on land and the seabed was altered more by the postexplosion dredging efforts to remove debris and the remains of Pier 6 and Pier 7 for safe navigation, and construction of future shipbuilding and repair facilities.

In the outer harbour, particularly along the McNabs Island and Lawlor Island seaward coasts, as well as the Dartmouth side of the harbour beyond Eastern Passage, modern processes of rapid coastal erosion continue. Drumlin shorelines are particularly vulnerable as sea level continues to rise at a modern rate of approximately 0.3 m/century. The less exposed and more resistant western bedrock shore of the outer harbour has changed little over the past several hundred years. Storms and hurricanes affect the Nova Scotia coast and send very large waves crashing into this coastal segment. In areas of the outer harbour in depths to 20 m, gravel in the cobble size range is affected by large waves and continues to be redistributed.

Within Bedford Basin, three large depressed areas in the deep-water seabed are interpreted as subsidence features. The freshness of the en échelon edges of the features, despite continued anchoring and sedimentation, supports recent activity. It is not known if they are the result of methane gas venting, dewatering, or differential compaction, but the relationship with subsurface gas-charged zones suggests that gas venting may be the responsible agent. The hazard potential of venting gas has not been assessed.

Anthropogenic activities in the inner harbour are the dominant processes that are presently affecting the distribution of sediments, their characteristics, and seabed processes. This is in sharp contrast to the outer harbour, where highly energetic natural processes dominate along an exposed shallow Atlantic inner shelf.

APPLICATIONS

This bulletin, including its associated enclosures and supporting data can be used for a variety of applications pertaining to Halifax Harbour. It can serve as the basis for additional studies of the benthic communities, oceanography, and geochemistry through the provision of a regional geological framework of materials and processes for the selection of appropriate sampling sites. Engineering activities related to the siting and construction of harbour facilities such as wharfs, cables, and pipelines can draw on the database for site-specific knowledge of materials, conditions, and hazards.

Marine outfalls

An important application is associated with the selection of appropriate marine outfall locations (diffusers and storm overflows) from waste-water treatment facilities planned for the harbour. The Halifax Harbour Task Force recommended a containment philosophy for the discharge of effluent from waste-water treatment facilities and this has been supported by subsequent advisory groups. A containment philosophy led the task force to select inner harbour locations for outfalls that considered seabed foundation conditions, sediment transport, and depositional regimes as selection criteria. In order to determine appropriate inner harbour sites for these outfalls, an understanding of seabed materials and sedimentation and erosional processes is essential. This study provides that understanding. In the outer harbour near Herring Cove, for example, the location of potential marine outfalls would result in greater dilution and dispersion if situated south of Lichfield Shoal rather than to the north.

Waste-water facility operation and monitoring

Knowledge of the depositional characteristics of sediments in the harbour can greatly assist in monitoring waste-water facility performance. Areas of persistent and continuous deposition have been identified to the north and southeast of Georges Island. These areas can be monitored with minimal focused sediment-sampling programs to assess facility performance and compliance, and to determine the effectiveness of source control measures. Areas of recent and intense seabed disturbance, particularly by ship anchoring have been defined in this study. These zones must be avoided in sampling programs if intact and meaningful samples and complete stratigraphies are to be collected.

Cable routing and seabed hazards

Route selection for underwater telecommunication and electrical transmission cables can be facilitated by the geological information. Saltwater intakes for building cooling and lobster holding tanks can be better positioned with knowledge of seabed characteristics. The identification of many shipwrecks and unidentified objects provides an assessment of potential seabed hazards. This information is necessary for future dredging and other engineering activities.

Marine aggregates

Aggregate resources occur largely in the outer harbour, but the inner harbour has a history of aggregate resource extraction around McNabs Island. These sand and gravel deposits of the Sable Island Sand and Gravel are suitable as construction materials for a wide variety of applications (Fader and Miller, 1994). Ripples in gravel, large areas of gravel lag, and isolated sand patches in the outer harbour are potential areas for aggregate sourcing.

Archaeology

The identification of shipwrecks provides opportunities for marine archaeological research. Many of the shipwrecks discovered during these surveys were previously unknown and some remain unidentified. Sea-level information, particularly that provided by the presence of the boulder berms and transgressed surfaces in Bedford Basin, permits paleo-geographic reconstructions of former shorelines with potential opportunities for investigation of early peopling in the Halifax Harbour area. The identification of many former islands along the western shore of Bedford Basin provides unique opportunities in this regard. Morphological data from the multibeam bathymetry provides maps and information for the diving community to explore seabed terrain with a resolution comparable to aerial photographs.

Fishing

Fishing for both finfish and lobsters is an important commercial activity in the harbour. The information on sediment type, morphology, slope, and subtle areas of bottom-current interaction with the seabed can enhance these activities by providing new opportunities. Seabed hazards can also be avoided.

Research

A large marine research community is centred on the harbour and regularly conducts equipment calibration tests and experiments. Knowledge of the seabed presented in this report provides essential information for efficient and economic operations as well as suitable site locations. As the outer harbour offers conditions similar to many environments on the adjacent Scotian Shelf, tests conducted in that area of the harbour, rather than at greater distances offshore, can enhance the efficiency of these activities.

EFFECTS OF HURRICANE JUAN

In the fall of 2003, Hurricane Juan made a direct pass over Halifax Harbour as it crossed Nova Scotia, resulting in a large amount of damage to homes, power lines, and in particular many trees of Halifax and Dartmouth. Winds were reported to reach a maximum of 198 km at Chebucto Head and waves reached 19 m high in the outer harbour. Many boats moored at the various yacht clubs throughout the harbour were dragged and parted from their moorings and were transported to the north up the harbour. Many eventually sank or were deposited above the present shoreline from associated tidal surges. Questions arose as to what changes may have occurred on the bottom of Halifax Harbour from such a violent storm. The simple way to assess the effects of the hurricane was to resurvey the harbour with multibeam bathymetry and undertake a comparison with the earlier imagery. In the summer of 2004 the C.C.G.S. *Frederick G. Creed* conducted a series of small surveys of critical areas of the harbour where change would be expected to occur (E. King, pers. comm., 2004).

Four areas were surveyed: between 'York Redoubt' and McNabs Island, the entrance to Northwest Arm, an area south of Georges Island, and an area north of Georges Island where the outfall from the first sewage treatment plant in Halifax will be positioned. Preliminary analysis of the multibeam bathymetry indicates that changes occurred in the outer harbour off 'York Redoubt', the entrance to Northwest Arm, and south of Georges Island. The area to the north of Georges Island does not appear to have been altered by sediment deposition or erosion and the data sets cover a 12-year period. Both individual and groups of large anchor marks appear in the same locations and with similar characteristics, suggesting little or no change.

For the area south of Georges Island, new marks from anchor dragging and jack-up oil-rig spud-can depressions can be identified. Sediment erosion occurs around the shipwreck *Havana*. Off 'York Redoubt' one of the previously mapped sedimentary furrows now displays a linear zone of small sand megaripples along its eastern flank. This suggests that during Hurricane Juan, sand from the outer harbour was transported to the north. At the entrance to Northwest Arm, a sedimentary furrow now displays five large objects (possibly shipwrecks or exhumed features) that were not on the data collected in 2002. It is not clear from this preliminary analysis if the objects are new shipwrecks sunk to the seabed or if they are other objects emerged from scouring of the sedimentary furrow. An area of seabed slumping also occurs in the outer arm. Sidescan-sonar data collected in October 2004 at the location of the moorings of the Royal Nova Scotia Yacht Squadron in Northwest Arm clearly show an extensive pattern of anchor-drag marks from the effects of Hurricane Juan. The moored vessels dragged their anchors for considerable distance up the arm and many moorings became entangled and later parted.

Overall, the harbour seabed displays many erosional and depositional features that are interpreted to have formed by large storms (strong currents); therefore the fact that Hurricane Juan modified only a few small areas suggests that much larger and more energetic storms have affected Halifax Harbour over the past several thousand years.

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