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BY
GORDON B. J. FADER
ATLANTIC GEOSCIENCE CENTRE
GEOLOGICAL SURVEY OF CANADA
BEDFORD INSTITUTE OF OCEANOGRAPHY
DARTMOUTH , N. S.,
B2Y 4A2

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ABSTRACT

The 1917 explosion occurred on the Halifax side of The Narrows in Halifax Harbour, Nova Scotia, at the northern end of the present Novadock, when, after a collision with the ship *Imo*, the cargo aboard the ammunition ship *Mont Blanc* erupted into one of the world's largest non-natural explosions prior to the detonation of atomic bombs. Several of the historical accounts of the event allude to the formation of a large crater in the seafloor of Halifax Harbour, and to the ejection of sediment and boulders from the seabed to the surrounding land.

Marine geological and geophysical surveys conducted by the Atlantic Geoscience Centre, Geological Survey of Canada, indicate that the seafloor of The Narrows is unlike most other areas of the inner Harbour. It consists of cobble and boulder-sized gravel with outcropping bedrock. The currents are strong enough to prevent significant deposition of fine-grained sediments common to other areas of the inner Harbour. Beneath the gravel, the material consists of overconsolidated till deposited by glaciers, which likely occupied the Harbour many times during the Quaternary. An interpretation of seismic reflection profiles and sidescan sonograms indicate that there is no crater formed by the explosion. Additionally, the seafloor is generally devoid of large pieces of anthropogenic debris that would be expected to remain from the destruction of a large vessel. It is postulated that post-explosion clearance programs in this part of the Harbour may have removed most of the blast debris. Many small sidescan sonar acoustic targets occur on the seabed of The Narrows and some may represent debris from the explosion of 1917, but they require visual identification.

The energy generated by the blast from the explosion on the *Mont Blanc* was directed outward and upward because of the hardness of the

seabed. The large number of marine encrusted boulders found strewn on the decks of vessels docked in the Harbour after the explosion were likely derived from the preblast shoreline or nearshore shallow waters where boulders were abundant.

The minimal impact to the seabed at the site of the explosion in Halifax Harbour is in contrast to the impact of thermonuclear test explosions at Enewetak Atoll, Marshall Islands, which formed craters up to 60 m deep and 1200 m in diameter.

INTRODUCTION

In his 1941 book "Barometer Rising", concerning the 1917 explosion in Halifax Harbour, author Hugh MacLennan wrote: "Underneath the keel of the *Mont Blanc* the water opened and the Harbour bottom was deepened twenty feet along the channel of The Narrows; the rigid ironstone and granite base of Halifax peninsula rocked and reverberated, pavements split and houses swayed as the earth trembled". The explosion was also considered responsible for the ejection of large boulders from the seabed of The Narrows, with one weighing more than a ton and rounded in shape landing on the *Picton*, a ship moored at the Brookfield Sugar Refinery, 250 m south of the epicentre. Additionally, people, houses and the general landscape were showered with black muddy water, presumably containing some sediment from the Harbour bottom. The *Mont Blanc* was considered smashed to atoms by the blast, and fragments were said to have been embedded into the Harbour floor. On the adjacent land, the drumlins of Halifax City (glacial streamline deposits), Fort Needham and Citadel Hill, played a role in deflecting the blast upwards and concentrating the destruction on their northeast, Harbour-facing slopes, but sparing those on the lee side. The original sources for many of these observations are difficult to identify, but such ideas, especially that a large crater formed on the bottom of the Harbour, have become formally entrenched into the history of the explosion in writings both fictional and factual.

From these observations and interpretations of the effects of the explosion of 1917, it is clear that earth materials (geology) played a rather significant role in the event. The purpose of this paper is to assess the geological setting of the explosion of 1917 and to examine the seabed both regionally and at the interpreted location of ground zero (GZ). I will address the assumptions that the explosion developed a large crater on the floor of Halifax Harbour, and that sediments and boulders from the seabed were hurled throughout Halifax, Dartmouth, and the surrounding communities. I will also discuss the nature of the seabed in the vicinity of the explosion and assess it for artifacts, including possible remains of the *Mont Blanc*.

The purpose of the marine geological study of Halifax Harbour was threefold: 1) to study the distribution and characteristics of surficial sediments together with their late-glacial and post-glacial history as part of a regional, eastern Canadian, nearshore marine geological mapping program; 2) to evaluate the mineral and aggregate potential of the nearshore as part of a Canada-Nova Scotia Cooperation Agreement on Mineral Development; and 3) to provide an understanding of the geological environment of Halifax Harbour, as it applies to the discharge of raw sewage and the selection and design of a wastewater management system for the Halifax-Dartmouth area, a project which began in 1990 and which is commonly referred to as the "Halifax Harbour Cleanup" (Fournier, 1990). In this regard, the study was conducted concurrently with geochemical, biological and oceanographic studies by a number of other government and industry groups. This framework can also be extended to an event such as the explosion of 1917, for an understanding of the geological environment and the earth materials present within the system, and how they affected and were affected by such an event. This need particularly arises from a sedimentation and sediment transport perspective, as it is important to understand the present distribution of sediments and their transport pathways in order to assess the infill and burial potential for features formed by the explosion.

GENERAL METHODOLOGY

Two techniques are normally employed to understand the distribution of sediments at and below the seabed and both of these were used in Halifax Harbour. Firstly, remote sensing studies are conducted by towing various acoustic sensors behind a vessel in a grid pattern, (FIGURE 1). These sensors are seismic reflection profilers and sidescan sonars.

HIGH RESOLUTION SEISMIC REFLECTION SYSTEMS

Seismic reflection systems use sound energy to penetrate sediments and resolve layering or internal structure. The data produced present a cross-section (FIGURE 2) of the seabed and subsurface, and exhibit differing character for each of the layers. This provides data for the construction of maps of sediment thickness, boundary relationships and internal structure.

The selection criteria for choice of seismic reflection system pivots on the penetration/resolution tradeoff, whereby low frequency systems provide increased penetration at the expense of resolution. Typically, for example, small sparker seismic reflection systems provide penetration of over 50 m through hard soils such as tills and unconsolidated bedrock, but display vertical resolutions of

approximately 5-10 m. In contrast, high frequency echosounders provide limited penetration but with resolution of often better than 1 m. The choice for the mapping program in Halifax Harbour was a variety of seismic systems covering a range of resolutions and penetrations. Various systems were tested in each new area before final survey configuration. The systems used for the study were:
1) a 280 joule, 20 tipped, surface-towed sparker found to offer resolution of 5-10 m and penetration of 50 m through till,
2) A Datasonics Bubble Pulser system which consisted of a 20 joule vertically mounted surfboard-towed boomer with a resolution of less than 10 m,
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 tills,
4) A ship mounted Elac echosounder, with no penetration of hard soils but some penetration of muds,
5) A Huntec, Seistec boomer, line-in-cone array system, with a resolution of less than 1 m and penetration through 30 m of muds and tills.

SIDESCAN SONAR

Sidescan sonars use a fan-shaped, high frequency sound source that does not penetrate the sediments, but sweeps across the seabed presenting a plan-view image that resembles an aerial photograph on land (FIGURE 3). From this image information can be interpreted on sediment texture and distribution, as well as seabed morphology. These images also reveal anthropogenic features of the seabed such as the presence of shipwrecks, anchor marks, cables and debris. The character of the seabed, as portrayed on the sidescan data, results from an integration of all of the processes that have affected it. For example, the sidescan sonar data can help discriminate whether the seabed is the result of natural sedimentation or whether it is material which may have been taken from another area of the Harbour in a dock maintenance program and dumped by a dredge, forming a dredge spoil.

The system used in the mapping program of Halifax Harbour was a Klein 100 and 500 KHz towfish with a K-wing depressor to stabilize the fish and keep it depressed to desired towing depths. The reader is referred to a publication entitled "Sidescan Sonar: A Practical Guide" (Flemming, 1976) for basic operational principles and applications. The data can be degraded by water property characteristics such as thermoclines, rip currents, discharge outfalls, and ships wakes, most of which occurred in Halifax Harbour and can limit the range of the system or obscure seabed reflections. Images can be obtained in water as shallow as a few metres, but a towfish distance of between 10-20 m

above the seabed offers an optimum height for sonar ranges of 100-150 m.

SEABED SAMPLING

Samples of the seabed and subsurface are collected to "ground truth" the images obtained with the remote sensing equipment (FIGURE 4). In this way, a correlation between sediment type and acoustic signature is developed and the acoustic data can be used to map or trace geographically the three dimensional distribution of sediments. Grab sampling devices are used to obtain seabed materials. To collect samples from beneath the seabed, a variety of coring devices are employed. These are long tubes which when dropped normal to the seafloor, penetrate the sediments and retrieve intact subsurface samples in an internal plastic liner. Simple gravity and piston corers can obtain samples up to 10 m beneath the seabed. They work well in muddy sediments but when hard materials such as bedrock, till or gravel are encountered, drilling must be used to obtain samples. Seismic reflection profiles provide the preliminary data necessary to determine which of the sampling devices to use and where to locate cores for maximum information.

The data included in this report were mainly collected on cruises of the *C.S.S. Navicula* in 1988, 1989, and 1990, and consists of a regional grid of echosounder data, sidescan sonograms, mid- to high-resolution seismic reflection profiles, gravity cores, grab samples, epibenthic dredge hauls, bottom photographs and remotely operated vehicle (ROV) video information. Cruises of the *C.S.S. Hudson* and *C.S.S. Dawson* collected long piston cores and vibrocores of sediment for subsurface stratigraphic information and geochemistry. Cruises by the *C.S.S. Frederick G. Creed* collected additional sidescan data in the nearshore and site-specific samples to ground-truth the acoustic interpretations. Prouse and Hargrave (1987) previously collected 102 samples and the OceanChem Group collected an additional 135 samples in 1988. These earlier samples were generally collected in a grid pattern without the aid of geophysical data to assist in the selection of sample sites, while the most recent samples were targeted to define the characteristics of the sediments previously identified and categorized on the basis of acoustic survey data. These samples provided a comprehensive sample data base and were analysed for organic carbon, nitrogen, redox potential and oxygen uptake.

Information on the characteristics and distribution of subsurface sediments comes from a study of high resolution seismic reflection profiles and cores. Five types of coring systems were used during these surveys: vibro, piston, gravity, Eckman corers and boreholes. Boreholes

collected by the Halifax Harbour Cleanup Corporation for their study of the Harbour sediments were kindly provided. These penetrated not only the soft Holocene muds of the Harbour, but the entire surficial section and bedrock. Sixteen Eckman-style and twelve Leheigh cores were collected from the *C.S.S. Navicula* and *C.S.S Frederick G. Creed* in the inner Harbour.

METHODS/DATA ANALYSES

The previously collected sample data was reviewed before any of the geological/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 seismic reflection profile data. Vessel tracks were spaced for 20 % overlap on sidescan imagery, and in The Narrows approximately 20 passes were made, providing for 100 % overlap on adjacent tracks.

It was necessary to survey small portions of the inner and outer Harbour at a time because of the limitations of the short base line navigation systems. Long regional lines could not be properly navigated. Difficulties were encountered working under high traffic densities and some areas were missed during the first field season surveys. These problems were further enhanced because of the presence of anchored ships, the presence of speed boat wakes, high volumes of pleasure craft, and dredging operations. Limitations were also imposed by the 3 m draft of the survey vessel which restricted operations to depths no shallower than 5 m.

On-line preliminary interpretations of the surficial geology were made during the surveys to locate suitable sampling sites. These were carefully chosen to ground truth all of the seismic and sidescan sonar seabed signatures and to avoid, as well as to purposely sample, features such as dredge spoils, sewage banks, bedforms, etc. Core sites were chosen to sample the stratigraphic units interpreted on the seismic reflection data and to collect valid cores in areas away from dredge spoils, anchor marks and other seabed hazards and anthropogenic features. After interpretation of the first field season data, additional cruises were planned and undertaken to infill missed areas, to collect data on tie lines normal to the previous tracks, to fill in nearshore shallow shoreline areas in as safe a manner as possible, and to collect additional cores and samples necessary for determining the lithologic characteristics of the acoustic facies. During the final part of the survey, ROV's were used to investigate individual targets or seabed features which were difficult to interpret from the acoustic data alone.

The final maps of sediment distribution (FIGURE 5) are based on all of the available sample data. Isopach maps of the Holocene sediment

are derived from the interpretation of the seismic reflection data as well as echograms (Fader et al., 1991). The sidescan sonar data provided backscatter information for the interpretation of sediment distributions as well as seabed features. When shipwrecks and other anthropogenic debris were found, the Nova Scotia Archives, Museum of the Atlantic, the Nova Scotia Museum, and local diver associations provided valuable information on identification.

BATHYMETRY AND GEOMORPHOLOGY OF THE NARROWS

Canadian Hydrographic Service Chart # 4201 (FIGURE 6) is the current published marine bathymetric chart for the area of The Narrows in Halifax Harbour. Some controversy exists concerning the definition of The Narrows: some consider it only to encompass the area of the Harbour where it joins Bedford Basin, in its area of narrowest constriction. Early maps of the Harbour considered The Narrows to include the area between the two Harbour spanning bridges, and the formal definition used by Halifax Traffic, follows that definition. A special series of operating procedures are used in The Narrows for all vessels larger than 150 m in length. These have specifically been developed as a result of the explosion of 1917 in Halifax Harbour, and the vulnerability of the bridges whose footings also occur in The Narrows.

The bathymetric chart #4201 (FIGURE 6) portrays The Narrows as having a sinuous central deep channel reminiscent of a fluvial system. The water depths in the centrally defined channel range between 20 m and 27. 4 m, a depth which occurs east of the Novadock (floating dry-dock). To the north of Pier 9, two small isolated topographic highs occur within the central channel with minimum depths of 17.7 and 19.7 m. The narrowest and shallowest area of The Narrows occurs along the alignment of the old original bridges which spanned the Harbour between Pier 9C and Norris Cove, (Miller et al.,1990). The choice for the location of these first bridges was an excellent one, as it was the shortest and shallowest route for construction of the two bridges in 1884 and 1892.

The central channel narrows adjacent to Pier 9, in an area where bedrock outcrops at the seabed. The Novadock protrudes a considerable distance into The Narrows from the Halifax shoreline. It and the southern end of Pier 9, enclose an unnamed indentation along this section of The Narrows. The area encompasses the former position of old Piers 6, 7 and 8, (FIGURE 7), which are no longer present. The name "Richmond Cove" is herein proposed for this body of water to assist in geographic discussions and to commemorate the location of the

explosion of 1917 which devastated the adjacent onshore region of Halifax, known as Richmond.

SWATH BATHYMETRIC IMAGES

During the summer of 1992, The *C.S.S. F. G. C. Smith*, a Canadian Hydrographic Service vessel, conducted a comprehensive bathymetric survey of Halifax Harbour, extending from McNabs Island in the south to the entrance to Bedford Basin in the north. It used a series of 32 boom-mounted transducers to determine the bathymetry in a single swath over an area approximately 30 m wide, with100% seabed coverage. The digital data collected during this survey was provided by the Canadian Hydrographic Service and processed by Dr. R. Courtney of the Atlantic Geoscience Centre and has been kindly provided for this presentation (FIGURE 8). Unlike the previous bathymetry, which has been contoured at 5 m intervals, the new imagery has a resolution of approximately 0.1 m. This results in a remarkable high-quality bathymetric presentation of the shape of the Harbour floor. In addition, the data has been manipulated to present a shaded-relief map, termed a shadowgram, on which the seabed has been illuminated with an artificial light source from the north (left side of the image).

In contrast to the Harbour floor to the south, which is generally flat, the swath bathymetric image from The Narrows, shows a series of ridges running east-west, particularly near the Dartmouth shore of the northern area of The Narrows. These indicate that the overlying sediments are generally thin and mimic the morphology of the underlying bedrock surface through to the seabed. Smaller curvilinear features in deeper water of the central channel are interpreted to represent former beach ridges, formed as the sea flooded up the Harbour in early Holocene time.

The remains of the first two Harbour spanning bridges, built in 1884 and 1892, can clearly be seen crossing the bottom of the Harbour at the north end of Pier 9. A major ridge cuts across the Harbour from the southern end of Pier 9. Part of this ridge was blasted in 1990, in a Harbour maintenance program to remove a shallow shoal near the Pier 9 side of The Narrows.

Directly south of the ridge, the bottom is smoother in a large isolated muddy depression. The area close to the shore on the Halifax side, south of Pier 9, where old docks 6, 7 and 8 were located, is rough on a small scale, with small isolated objects on the seabed. One larger linear object near the interpreted location of ground zero, may represent the remains of old Pier 6. Adjacent to the Richmond Cove area, toward the central part of The Narrows, the seabed shows the

presence of mounded morphology and other isolated features interpreted as dredge spoils.

The sinuous channel of the Ancestral Sackville River can clearly be seen adjacent to the Novadock in the central area of The Narrows. This area has not been infilled with thick mud and the ancient course of the river is visible, winding southward.

OCEANOGRAPHY

SEDIMENT TRANSPORT UNDER WAVES AND CURRENTS

A discussion on the physical oceanography of Halifax Harbour and The Narrows in particular, is extracted from Fader and Petrie, 1990, and The Final Report of the Halifax Harbour Task Force, (Fournier,1990). Water circulation can lead to sediment transport and its subsequent deposition in regions of very weak flow. High energy currents from tides, storms or waves can scour some areas of fine-grained sediments leaving behind lag deposits of gravel and bedrock. Sedimentary deposits, which reflect water movement over long periods of time, can indicate whether short duration current meter records are representative of long term conditions.

AVERAGE CIRCULATION OF WATER IN THE HARBOUR

Halifax Harbour is an estuary, i.e., a semi-enclosed body of water whose properties are influenced by freshwater runoff from the adjacent land. The near surface water tends to flow towards the ocean, becoming saltier as it moves down the Harbour. The salt is supplied through mixing with waters from the adjacent Scotian Shelf which move into the Harbour from below the outgoing near-surface flow to the seabed. These shelf waters become less salty as they move into the Harbour because of mixing with the shallower, fresher waters from sewage outfalls and the Sackville River.

Salinity measurements in the Harbour confirm this idealized picture of the average circulation and can be used with a model to derive horizontal current strengths and vertical mixing rates. In the surface layer, the weakest outflow, 0.2 cm s^{-1}, occurs in Bedford Basin, and moves a parcel of water approximately 200 m in 1 day. The long term mean or average currents have their highest values of about 5 cm s^{-1} in The Narrows, slow to about 2 cm s^{-1} as the Harbour widens adjacent to the the downtown areas of Halifax and Dartmouth, increase slightly off Sandwich Point, and finally slow to about 1 cm s^{-1} before flowing out onto the Scotian Shelf. The pattern is much the same in the lower layer, except in the opposite direction, i.e., inflow, instead of outflow.

The current-meter data generally support this salinity-derived picture of the circulation in the Harbour. In The Narrows, the instruments recorded the strongest inflows near the bottom of the eastern (Dartmouth) side of the Harbour.

This circulation suggests that there should be a general tendency for the finer sedimentary particles on the bottom to move towards the head of the Harbour. Moreover, sewage particles, which enter the Harbour waters in the surface layer, would be initially carried towards the shelf. However, as they sink, they would be incorporated in the deeper inflow and move back up the Harbour.

VARIABLE CURRENTS IN THE HARBOUR

In the Harbour, currents can change rapidly, with perhaps the most familiar variation being the tidal flows. Wind also can bring dramatic changes to the circulation by causing water borne material to cross the Harbour in perhaps an hour or by stirring up the bottom sediments through wave action.

Variable currents are weakest in Bedford Basin with an amplitude of about 3.5 cm s^{-1}. Sediment deposition should occur in this low energy area. The highest values, ranging from 15-35 cm s^{-1}, are found in The Narrows and are largely due to the tides. If there is one area in the inner Harbour that should be scoured of fine sediments it is The Narrows. From Sandwich Point to Chebucto Head at the Harbour mouth, the time-varying flows have velocities equivalent to 5-15 cm s^{-1}, with the lowest values occurring off Herring Cove. These areas, though having lower current variability than The Narrows, are more exposed to ocean waves which can significantly affect sediment transport because their oscillatory motions suspend bottom sediments. No data is available for the Northwest Arm or Eastern Passage, but it is anticipated that these areas would have varying currents more like those in Bedford Basin than in The Narrows.

GEOLOGY

BEDROCK

The first published map of the bedrock of the surrounding landmass of Halifax Harbour was published by Faribault (1908). It indicated that the Harbour was surrounded by Lower Cambrian metasediments of the Meguma Group with intrusive granite along its western side. The major structural elements (faults and folds) of the area were also mapped (FIGURE 9). The slates and quartzites are folded into a series of southwest-northeast trending anticlines and synclines that were projected to continue beneath the Harbour. The northern part

of The Narrows is underlain by Goldenville Quartzite, as is all of Bedford Basin. The contact between the quartzite and the Halifax Formation occurs in The Narrows, as a southwest-northeast trending contact extending from Pier 9 on the Halifax side to the Dartmouth shore south of Tufts Cove. The remainder of The Narrows and all of central and southern peninsular Halifax City is underlain by the Halifax Formation, a resistant unit of thinly bedded slate. Near the location of old Pier 6, the location of the explosion of 1917, the beds of this formation dip to the southeast at a steep angle of approximately 60 degrees.

Continuing on the early work of Faribault, Cameron, 1949, attempted an assessment of faulting in the vicinity of Halifax, largely based on an interpretation of aerial photography. He identified a series of lineaments interpreted as faults both in the granite and the Meguma Group. Many of these faults were projected beneath the Harbour (FIGURE 10) and this has influenced others to consider a structural control for the location, shape, and orientation of Halifax Harbour.

The major fault interpreted to occur beneath the Harbour begins as the Mill Cove Fault in Bedford Bay and extends beneath Bedford Basin, The Narrows and the Harbour bottom through Eastern Passage to Devils Island at the mouth of the Harbour. This fault is further interpreted to connect with the Kearney Lake Fault which extends beneath Halifax City and joins with the Mill Cove Fault in the vicinity of Georges Island. A fault, termed the Arm Fault, is interpreted to follow the axis of the Northwest Arm.

The most recent bedrock geology assessment of the 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 which occur along the western margins of the study area. Based on studies by Schenk, (1982), the country rocks of the Meguma Group are described as metagreywackes of the Goldenville Formation and metapelites of the overlying Halifax Formation. The Meguma Group rocks contain a thermal metamorphic aureole adjacent to the contact with the granite. The granitic rocks are part of the South Mountain Batholith. The contacts with the Meguma Group are sharp and discordant and the regional structural trends in the Meguma Group are abruptly truncated.

In all of the bedrock structural assessments from both sides of the Harbour (FIGURE 9) (Keppie, 1982) the major anticlinal and synclinal features are clearly identified and often extrapolated beneath the Harbour. Faribault, (1908) identified six structural elements extending from Bedford Bay to Sandwich Point. In all cases faults are not interpreted to occur beneath the Harbour and offset on any of the structures, from one side of the Harbour to the next, does not appear to

occur. This is in sharp contrast to the interpretation of Cameron, who suggested the presence of major faults beneath the Harbour. These would be expected to result in structural offset as is the case along many of the faults further to the east, 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, show a series of anomalies associated with the Halifax Slate Formation trending southwest to northeast across the Harbour. None of the anomalies appears to be broken by northwest trending lineaments that could be interpreted as faults.

To the high-resolution seismic reflection systems used in the study, the bedrock of the Harbour is acoustic basement. The metamorphic grade of the sediments is high enough so that the acoustic energy of the seismic systems does not penetrate the bedrock and resolve internal structure. These systems are therefore of little use in defining bedrock type. Information on characteristics of the bedrock surface, however, is provided, and this can sometimes be used as a discriminating criteria. Varying lithologies have responded in different ways to erosional processes.

The most important information on bedrock type is provided by sidescan sonar data, in areas where the bedrock is exposed at the seabed. These areas are the sill between Bedford Bay and Bedford Basin, The Narrows, shoal areas in the Inner Harbour, and large areas of the Outer Harbour. Details of structure including faults, joints and other lineaments can clearly be observed and measured. These data do not show the presence of offsets which could be interpreted as faults. In addition, the new swath bathymetric images of the Harbour (FIGURE 8), particularly from The Narrows, show a strong influence on the morphology, by bedrock ridges, either exposed or buried. They appear to be broken only by glacially overdeepened depressions and a meandering stream, the Ancient Sackville River (King, 1970).

SURFICIAL GEOLOGY

REGIONAL LAND SETTING

The regional surficial geology of the area adjacent to Halifax Harbour has been mapped and described by Stea et al., (1992) and Finck et al. (1992) (FIGURE 11). The dominant unit occurring around the northeast and western area of Bedford Basin and extending along the western side of the Northwest Arm to Chebucto Head is largely a bedrock zone with isolated basins and knobs shaped by glacial erosion and overlain by thin discontinuous till. Throughout this area bedrock structure and large scale glacial features can easily be seen on aerial photographs. The topography of the terrane consists of flat to highly

rolling surfaces with frequent exposed ridges of bedrock with stoss and lee-form roche moutonnee. The till ranges in thickness to 4 m. This area is generally underlain by Devonian Granites and Goldenville Quartzite.

The dominant unit in the area occupied by peninsular Halifax City and extending to the northeast across the Harbour in Dartmouth, including the southeastern side of Bedford Basin and MaNabs Island, is a Wisconsinan stony till plain with drumlins (FIGURES 11 and 12). The till is very stony with a sandy matrix, with lithologies derived from local bedrock sources: that is, Halifax Slate beneath Halifax City and Goldenville Quartzite beneath the Dartmouth area adjacent to The Narrows and the southeastern side of Bedford Basin. The drumlins are generally siltier as a result of incorporation of older till units by the Wisconsinan glaciers. The terrane of such deposits is generally flat to rolling with many exposed surface boulders. The drumlins are elongate oval-shaped hills veneered with stony till with underlying multiple till layers (FIGURE 11). The thickness of the till plain ranges to 20 m with the drumlins reaching thicknesses of 30 m. These tills are generally thought to have been deposited from ice centered over Nova Scotia.

The unit underlying the eastern area of the Harbour, extending from Dartmouth Cove to Hartlen Point, is a silty till plain with drumlins. The till is compact with material derived from both local and distant sources. The drumlin facies is siltier still, with a high percentage of distant source material including red clay. The terrane is flat to rolling and the till is generally thick enough to mask undulations on the bedrock surface. The drumlins consist of multiple stacked units. Both the till plain and the drumlins range to 30 m in thickness. These tills are generally thought to have been deposited by ice sheets centered outside Nova Scotia.

Drumlins are common to the north throughout the Sackville River Valley but their greatest concentration surrounding Halifax Harbour is on the Dartmouth side of the Harbour extending from Bedford Basin to Eastern Passage (Figure 12). McNabs and Lawlor Islands are primarily a series of overlapping drumlins and Georges Island in the inner Harbour consists of one isolated drumlin. Peninsular Halifax City has three large drumlins along its north and eastern flank: Strawberry Hill, Fort Needham and Citadel Hill. These drumlins played a major role in deflecting the blast of the explosion of 1917 by concentrating the effects on their northeastern slopes and sheltering those on the lee sides.

Ice flow directions interpreted from the orientation of drumlins, and large and small glacial striae on bedrock, generally indicate a northwest to southeast direction throughout the Harbour. An older set

of striae prevalent in the area north of Bedford Basin, indicates a more north to south ice flow direction.

Stea et al. (1992) interpreted the glacial history of Nova Scotia based on the distribution and characteristics of Quaternary glacial and other surficial deposits. The timing of the formation of the first glaciers during the Wisconsinan, the last glacial period, is not clearly understood but a continuous ice cover of mainland Nova Scotia is suspected. This was punctuated by short intervals of ice retreat. The earliest ice flows were eastward then southeastward.

In the area around Halifax Harbour, the Hartlen Till was deposited by these flows. It generally forms the cores of drumlins. The second ice flow was south and southwestward from a center located near Prince Edward Island and referred to as the Escuminac Ice Center. The Lawerencetown Till was deposited by this ice with its characteristic red color and muddy to sandy texture derived from a source to the north. The next flow direction was from an ice divide over southern Nova Scotia which resulted in material transport to both the north and south. This ice extended across the inner Scotian Shelf to at least the Scotian Shelf moraine complex (King, 1970). The final phase of ice flow was from a series of remnant ice caps along the Scotian Ice Divide which cut across the trend of features previously formed and was largely restricted to low-lying areas.

A final late local ice advance, largely confined to eastern Nova Scotia, occurred at approximately between 11 and 10 ka (Younger Dryas Oscillation) and resulted in the nucleation and advance of ice over organic deposits (Stea and Mott, 1989).

SEDIMENT DISTRIBUTION

THE NARROWS

The distribution of sediments at the seabed (FIGURE 5) is derived from analyses of seabed samples, sidescan sonar imagery, seismic reflection profiles, echograms, bottom photographs, seabed video and bathymetry. In this discussion we are concerned with the distribution of sediments at the immediate seafloor and not in the subsurface. The classification of sediment texture is based on the Wentworth Scale, and the sediments are classified as gravel, sand, silt and clay. The fine-grained sediments of silt and clay also contain minor trace elements and more organic matter than coarser sand and gravel.

Between the A. Murray MacKay Bridge and Halifax-Dartmouth Industries Novadock, for a distance of approximately 1 km, the seabed sediments are generally coarse and consist mostly of gravel with broken and whole shells. Boulders are common and bedrock crops out. Some of the boulders are very large, up to 3 m in diameter. Curvilinear

ridges of boulders likely represent old gravel beach ridges formed as the sea transgressed The Narrows before flooding into Bedford Basin (FIGURE 8). This unit is termed the transgressive sand and gravel unit (Fader et al., 1990) and is an equivalent of the Sable Island Sand and Gravel Formation of King (1970) and King and Fader (1986). Several circular mounds of gravel covered till may represent small drumlins on the floor of The Narrows. It is probable that not all of the isolated objects on the seabed are boulders, despite the fact that they occur within large groups. Some of these targets identified on sidescan sonar could represent anthropogenic debris including small fragments of the *Mont Blanc*. All ships moving into Bedford Basin must pass through The Narrows, and as a result of the hard bottom and lack of accumulation of fine-grained sediments, all discarded material remains on the seabed and is not buried. An area of the seabed near the southeastern corner of Pier 9 was recently blasted and dredged to remove a shallow hazard to navigation which consisted of outcropping bedrock. Pebbles and cobbles are subrounded and form the dominant grain-size of the floor of The Narrows. Samples also contained fragments of broken glass and wood.

The footings of the first two bridges constructed in 1884 and 1892 remain on the Harbour floor, approximately 500 m south of the A. M. MacKay Bridge (FIGURE 13) Miller et al., (1990) and Fader et al. (1991). They clearly show as a linear segment on the swath bathymetric image of The Narrows (FIGURE 8). The footings consist of wooden cribwork filled with boulders. Approximately 19 of the bridge footings span The Narrows. Corroded and twisted rail track is scattered across the seabed, as are large granite blocks which were used as anchors to stabilize the second of the old Harbour-crossing bridges.

At the south end of Pier 9, off the Duffus St. sewage outfall, a zone of fine-grained sediment up to 0.5 m in thickness partially covers the gravelly seabed in a depression extending to the east across the Harbour. This unit is the Holocene mud of Fader et al. (1991) and is a stratigraphic equivalent of the LaHave Clay of King (1970) and King and Fader (1986) found on the adjacent Scotian Shelf. Some of this sediment may originate from discharge of the nearby Duffus St. sewage outfall which drains a large area of the western side of Bedford Basin. Similarly, Tufts Cove is floored by soft, fine-grained sediment which continues out into the main channel of The Narrows where it terminates.

The main body of Holocene mud in Halifax Harbour begins adjacent to the Halifax Dartmouth Industries Drydock (Novadock) and continues to the south throughout the inner Harbour to the Maugher Beach area on McNabs Island. From the Novadock to the Macdonald Bridge, the mud is patchy and thin in the southern part of The Narrows

and appears on the sonograms as infilling on a rough and irregular till surface which protrudes in many areas. Anchor marks are widespread and the sidescan imagery indicates that they cut through the thin mud to the underlying gravel and sand (FIGURE 14). Dredge spoils which are circular mounds of dumped debris, occur in a few areas of The Narrows.

SUBSURFACE GEOLOGY

The stratigraphy of The Narrows is simple, however, the interpretation of the seismic reflection data is difficult. As a result of the hardness of the seabed in The Narrows which consists of gravel with boulders, bouldery ridges and bedrock outcrop, (FIGURE 15) the high-resolution boomer seismic data could not resolve subsurface events or define the bedrock surface. The Datasonics Bubble Pulser was however, able to penetrate to the bedrock surface in most localities. It depicts till overlying a rough and undulating bedrock surface and extending up to 16 m in thickness. Thicknesses of till are confirmed by boreholes drilled for the footings of the A. Murray Mackay Bridge. Acoustically the till in The Narrows appears overconsolidated as the higher frequency seismic reflection systems were unable to penetrate it.

The subsurface relief on the bedrock surface averages 10 m and likely formed as a result of both fluvial and glacial erosion. The swath bathymetric image (FIGURE 8) demonstrates clearly the relationship between the buried bedrock surface and seabed morphology. Despite being buried by up to 16 m of till and gravel, the prominent ridges of the bedrock surface remain expressed at the seabed throughout much of The Narrows.

GEOLOGICAL HISTORY

ORIGIN OF HALIFAX HARBOUR

Most published accounts of the formation of Halifax Harbour attribute its origin to the presence of interpreted northwest-southeast bedrock structural lineaments beneath the Harbour that may have been zones of weakness for preferential erosion by rivers and glaciers. As discussed earlier, there is very little evidence for the presence of faults beneath the Harbour. All of the major synclines and anticlines on either side line up without displacement, and this evidence is supported by the aeromagnetic data which indicates structural continuity from east to west beneath the Harbour.

Halifax Harbour most likely owes its origin not to structural control within the bedrock, but to the distribution of bedrock type, namely, the dominant presence of the eastern flank of the South

Mountain Batholith along the western zone of the map area (FIGURE 9). This large, resistant granitic intrusion, influenced fluvial drainage systems in preglacial time, confining their location to areas to the east of the batholith. The batholith extends for over 30 km offshore and may have acted as a major divisional boundary for drainage systems and glacial ice that flowed across the adjacent Scotian Shelf.

Before glaciation, Bedford Basin did not exist as a large isolated depression. The present Sackville River continued on its course across a gently dipping Cretaceous peneplain through the present area of the Basin and out the Harbour (FIGURE 12). With the onset of glaciation, radical changes occurred in the system. Largely following the course of an early fluvial drainage system, glaciers eroded and overdeepened the area of Bedford Basin, excavating the present deep depression. It is not known which of the major glaciations created the extensive overdeepening of the Basin. Coincident with the deepest area of Bedford Basin is the position of the Birch Cove Anticline (FIGURE 9). Because of massive beds present in the Goldenville Quartzite, and the fractured nature of the rocks in the anticline, the ice and associated subglacial meltwater were able to effectively erode the anticline and produce 50 m of overdeepening in the Basin. Surrounding the Dartmouth shoreline of Bedford Basin are many very large quartzite blocks in the till which may have been quarried from the Bedford Basin area by ice.

Between successive glaciations Bedford Basin would have ceased to exist as a river channel for the ancient Sackville River. It would have been interrupted along its course with a lake, whose sill would have been controlled by the 20 m depth of The Narrows. It is at The Narrows where a new outlet would form for drainage from the ancient lake. As the glacial ice moved through the Harbour, the varying rock types controlled the amount of erosion and the eventual shape of the present Harbour. As the ice moved across the Halifax Slate Formation it was no longer able to remove large blocks of material as it could over the Goldenville Quartzite beneath the Basin. It therefore eroded much less, resulting in the topographic high of Halifax City. The channel which is now The Narrows, remained restricted and narrow. North of Georges Island, the Goldenville quartzite on the Dartmouth side of the Harbour provided for greater erosion, effectively producing the widening of the Harbour north of Georges Island, south of The Narrows. The channel again narrowed to the west of McNabs Island as Halifax Slate became the dominant bedrock between Halifax City and McNabs Island.

In the Outer Harbour the granite batholith on the western side, continued to control the direction of the ice as it flowed across the inner continental shelf. These granite cliffs of resistant lithology remain as

high ground along the western side of the Harbour from Herring Cove to Chebucto Head.

Following glaciation, the sea level is interpreted to have stood at a present depth of 70 m water depth on the inner Scotian Shelf off Halifax (Stea et al.,1992). Halifax Harbour existed as a series of lakes connected by rivers which drained the ancient Sackville River. The marine transgression of the Harbour began at approximately 11,000 ka as sea level began to return to its former interglacial position. The lakes were transgressed and the surfaces of both tills and fine-grained sediments were eroded in some cases, and armored in others. A layer of sand and gravel (Sable Island Sand and Gravel Formation) (King, 1970 and Fader et al., 1991) was formed over the Harbour bottom and is still exposed at the seabed in The Narrows.

Bedford Basin is interpreted to have changed to a marine embayment at 5800 ka as the sealevel finally breached the sill in the present Narrows (Miller et al.,1982). As sea level rose further, Holocene muds began to accumulate over the transgressed surface in the Harbour. This process still continues. The mud attains a thickness of over12 m north of Georges and McNabs Islands.

Today the seafloor of the Harbour still reflects a large part of this ancient history, as the sediments formed by these early processes remain either buried beneath younger sediments, or lie presently exposed at the seabed. Some sediments have experienced little modification since they were deposited. With the founding of Halifax in 1749, major changes took place on the surrounding land and shoreline areas which 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 discharge of waste water and the channeling of runoff into the Inlet. As the urbanization of the surrounding area of the Harbour continued at a rapid pace, so did the deposition of sediments into the Harbour. In addition to the natural glacial soils and bedrock that were eroded from the adjacent land, 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, because of increased industrial and military development, the sediments on the Harbour floor were further modified by direct disturbance. Dredges scoured and deepened many areas, docking facilities were built, sand and gravel was mined, dredge spoils were dumped, ships' anchors were dragged, old ships and debris were scuttled, bridge footings were constructed, and the explosion of 1917 occured. All of these types of activities have influenced the seabed and sediments in different ways.

SEDIMENT TRANSPORT

No direct measurement of sediment transport in Halifax Harbour has been undertaken. Such studies require the use of tracers together with subsequent monitoring programs and in the Nova Scotia region have only been conducted on Sable Island Bank on the Scotian Shelf (Amos and Nadeau, 1988). However, many other characteristics of seabed sediments can be used as qualitative indicators in an interpretation of the orientation of features with respect to the responsible currents. These include distribution patterns of gravel, sand, silt and clay; bedforms in sand and fine-grained gravel; scour features around seabed obstructions; the distribution of sewage banks; the distribution of geochemical anomalies relative to injection points; and the distribution of exposed bedrock.

The most easily identified sediment transport indicators are the bedforms in the outer Harbour. Unfortunately there are no bedforms at the seabed of The Narrows which can be used to understand the direction and magnitude of sediment transport. The seabed in The Narrows consists of coarse gravel and bedrock while silt and clay-sized sediment is absent. Conditions of flow are, however, high enough to prevent deposition of fine-grained sediments, indicating a bed shear stress of greater that 1 n. per m squared. Currents of this strength have been observed in fact, to 90 cm per sec in The Narrows.

The distribution of geochemical anomalies in Harbour sediments provides another indicator of sediment transport (Buckley and Hargrave, 1989). Many of these distributions suggest dispersion and settlement of material from the sewage discharge locations along the shores of the Harbour in a northerly direction, in agreement with mean flow. Anomalies of mercury suggest that material discharged from the Duffus St. and Tufts Cove area are transported through The Narrows and deposited on the southeast side of Bedford Basin. In a similar fashion, material emanating from the South End Halifax sewage outfalls can be traced up the Harbour to an area north of Georges Island. A large moat occurs around the south side of Georges Island while on the northern side is a thick deposit of Holocene mud. These sediment distribution characteristics support the south to north transport pathways indicated by the geochemical anomalies.

SEABED FEATURES OF THE NARROWS-NATURAL AND ANTHROPOGENIC

Sidescan sonograms (Miller and Fader, 1989) and (Miller et al., 1990) present a set of images which can be interpreted for an understanding of the natural and anthropogenic processes that have

affected the seabed of the Harbour. In addition to differentiating sediment type (soft muddy seabeds from hard coarse-grained materials), the sidescan data have identified a large variety of other features such as, dredge spoils, dredge marks, borrow pits, pockmarks, wrecks, cables, sewage and cooling water intakes and plumes, anchor drag and pit marks, propeller wash scours, bedforms, and unidentified objects. These features indicate a dominant anthropogenic influence on the seabed of the Harbour since the founding of Halifax, in contrast to the adjacent inner continental shelf where the dominant processes are natural. The following is a description of the anthropogenic features from The Narrows.

ANCHOR PIT AND DRAG MARKS

The presence of anchor pit and drag marks are a dominant characteristic of the seabed over broad areas of the Harbour. In areas of anchor drag marks, the seabed has criss-crossing, linear-curvilinear trenches, up to 3 m in depth and 5 m in width, with adjacent flanking berms (FIGURE 14). Anchor pit marks are circular depressions formed where anchors have impacted the seabed during deployment or retrieval. The anchor mark pattern dominates the floor of Bedford Basin and the seabed north of McNabs Island.

They are significant for two reasons. Firstly, from a sampling and coring perspective, it is important to know the relationship between the anchor marks and the collected samples. The sediments have been highly disturbed in the anchor marks and do not necessarily represent natural depositional relationships. The base of the anchor marks may expose sediments several thousand years old. If the history of the most recent past is desired, then cores must be collected in non-anchored areas. In addition, because the anchor marks are depressions, they may preferentially trap sediments and present an exaggerated sedimentation rate or contaminant concentration.

The anchor marked areas of seabed can also be used to define the distribution of modern sediments and sewage banks, and assist in understanding sediment transport. The sidescan data indicate that many of the anchor marked areas are likely relict. Those in Bedford Basin are interpreted to have developed during the second world war when large convoys of ships assembled and anchored over broad areas of the Basin, prior to sailing across the north Atlantic to Europe. Those in Halifax Harbour, particularly in the present main navigational channel, are probably much older, and in some areas may represent the total population of anchor marks formed since the founding of Halifax. In places, this surface is covered with modern sediment and the old anchor marks can be seen dipping beneath them. The anchor marked

surface also indicates that since its formation, the amount of material deposited has not been enough to completely bury them. Thus, the sedimentation rate throughout much of the Harbour has been less than 2 m since the founding of Halifax.

Anchor marks are widespread in The Narrows, with the greatest concentration near the dock areas (FIGURE 16). This suggests that anchors are used during docking and when leaving berth, perhaps as a speed and directional control measure. Anchor marks in the central deeper water of The Narrows are either an old population formed when anchoring was permitted in The Narrows, or may have resulted from emergency measures undertaken by vessels under threat of a possible collision.

The many linear drag marks near old Pier 6 may have resulted from dredging operations undertaken after the explosion of 1917. The series of hydrographic charts from the post explosion period, indicate that the remains of Piers 6 and 8 were removed from the seabed. The hard character of the seabed in this area would likely preserve any marks formed by such a dredging operation.

PROPELLER-WASH SCOURS

A large number of scours occur on the seabed close to the docks and wharfs along the waterfront. These erosional features appear to be formed by propeller-wash scouring processes. Adjacent to the container pier in Bedford Basin and the seawall in Southend Halifax, the scours have a scalloped appearance, suggesting that the energy from large ship propellers is impinging on the seabed and causing considerable erosion. Many of the outer ends of the docks along the Halifax Harbour water front experience undermining, whereby gravel-sized sediment is eroded by propeller-wash. Adjacent to Pier 9 is a scour depression that formed after the1989 surveys and was identified on the1990 data. The rate and amount of material eroded by this process is not known.

BEDROCK OUTCROP

Adjacent to the Pier 9 dock in The Narrows, an area of seabed, 50 m offshore, has been blasted and dredged to deepen an underwater shoal. The sidescan sonar and seismic reflection data indicate that the shallow area is outcropping bedrock. The swath bathymetric images (FIGURE 8) also show the domination of the topography of The Narrows by ridges on the bedrock surface. Despite burial of up to16 m by overconsolidated till, the relief on the bedrock ridges is mimicked through to the seabed.

REMAINS OF FIRST NARROWS BRIDGES

In The Narrows, approximately 500 m to the south of the A. Murray MacKay Bridge, lie the remains of the first two bridges that spanned the Harbour connecting Halifax and Dartmouth (FIGURE 13). They were constructed in 1884 and 1892. The first bridge was constructed using a foundation of individual, 20 ton cribworks, placed on the seabed. It was used as a railway bridge, but could also accommodate pedestrian traffic on the side. On Sept. 7, 1890, it collapsed in a violent hurricane, which also destroyed many of the docks along the waterfront. It was quickly rebuilt using a different construction technique with piles driven into the seabed. Upon completion, this new bridge was unstable, and chains, connected to large granite blocks placed on the seabed, were attached for increased stability. Unfortunately, the second bridge fell on a quiet summer's night, July 23, 1892. The cause of the failure remained a mystery.

The hardness of the seabed, consisting of exposed bedrock, overconsolidated till, and gravel with boulders, may have prevented the proper penetration of the piles of the second bridge into the seabed and contributed to its premature failure. Sidescan sonar data and ROV observations indicate that the seabed in the area of the bridges is littered with much of the remains (FIGURE 8). Cribwork, twisted and straight sections of steel rail, and timbers are widespread. Large carved rectangular granite blocks that may have been used to stabilize the second bridge also remain at the seabed.

DREDGE SPOILS

Dredge spoils are circular-shaped features, consisting of deposits of material discharged to the seabed by barges. They range in diameter up to 40 m and may exhibit positive relief of several metres above the surrounding seabed, or occur as coarse debris in depressions several metres in depth. Dredge spoils are recognized on sidescan sonar imagery by their acoustically rough scattering surface and blocky texture. Their signature on sidescan imagery is highly variable. They are often clustered together (FIGURE 8). An unusual type of dredge spoil, which is characterized by linear, high-intensity acoustic backscatter features, connecting much larger circular features of the same acoustic signature, is interpreted to represent sporadic barge discharge of spoil while the vessel is moving. These features appear in The Narrows near the Naval Dockyard of Halifax and are widespread in other areas of the inner Harbour.

The dredge spoils consist of a wide variety of materials such as construction debris, old wooden discarded docks, gravel, boulders, muddy sediments, garbage and unidentified debris. Samples collected from one dredge spoil in the deepest water of Bedford Basin consisted

of manganese-encrusted, angular, cobble-sized fragments of Goldenville Quartzite, likely a gravel dredge spoil. Their presence on the Harbour bottom often makes it difficult to sample the naturally occurring sediments, as they mask the underlying substrate in areas where their density is high. Sidescan sonar data is essential for their recognition and control regarding sampling.

In The Narrows, dredge spoils occur adjacent to the Novadock and off Pier 9 (FIGURE 8) but the largest number are found north of the A. Murray Mackay Bridge at the entrance to Bedford Basin. This area is likely an old dumping ground for dredge spoils, as ships and barges appear to have discharged their cargo immediately upon entering Bedford Basin. Some of the dumps at the entrance to Bedford Basin may contain material discarded from the cleanup and rebuilding of Halifax and Dartmouth after the explosion of 1917.

BOULDERS AND UNIDENTIFIED DEBRIS

There are many sidescan sonar, high intensity backscatter targets on the seabed of the Harbour, particularly in The Narrows, which are classified as unidentified objects (FIGURE13). Boulder berms are common and likely represent old shoreline features formed during the marine transgression of The Narrows. They are similar to the boulder berms found at a depth of 23 m fringing Bedford Basin (Fader et al., 1991). Many of the boulders are larger than 1 m in diameter but cannot be identified from their sonar signature alone. Where clusters of boulders occur, especially over gravelly seabeds, it is assumed that the targets are indeed boulders. Where they occur over fine-grained sediments, they likely represent discarded anthropogenic debris. Several objects in the northern area of The Narrows are 2-3 m in diameter and cast long sonar shadows on the sidescan imagery. They may represent artifacts from the explosion of 1917, such as pieces of the *Mont Blanc*, but this requires visual confirmation. Some objects are linear features up to 5 m long and could represent remains of railtrack or wooden trusses from the original bridges.

LOCATION OF GROUND ZERO

In order to assess the effects on the seabed of the explosion of 1917, and to search for possible remains of the *Mont Blanc*, it is important to determine the exact location of the ship at the time of detonation, referred to as ground zero or "GZ". The many references to the 1917 explosion in Halifax Harbour often contain maps showing the interpreted location of the *Mont Blanc* at the time of the explosion.

These positions vary widely, from the center of The Narrows adjacent to the southern end of Pier 9, to an area south of the old finger Pier 6, very near the present shoreline. In discussions with survivors of the disaster and those who have researched the literature on the event, it is clear that much confusion exists.

In order to assess shoreline changes and alterations in the location of construction and docking facilities in The Narrows, before and after the explosion of 1917, a series of Canadian Hydrographic Service Charts, on file with the Nova Scotia Archives, were compared. These date from 1889, 1916, 1917, 1918, 1920 1953, 1962 (FIGURES 17 and 18) and 1992, the present modern chart (FIGURE 6). The four earliest charts are presented at a scale of 1:10,560 whereas the 1920 chart is 1:12,170, the 1953 is 1:12,176, the 1962 is 1:12,100 and the most recent one is 1:10,000. In addition to the changes in scale, geodetic datum has varied throughout the series by several hundred metres, preventing alignment and comparison based on latitude and longitude alone. For this study the charts were photographically adjusted to a common scale (1:10,000) on transparencies and overlain for comparison. The following is a brief description of the changing character of the area of The Narrows (Richmond Cove), covering the time period from 1889 to the present.

The chart of 1889 clearly shows the location of Piers 6, 7, 8 and 9 (FIGURE 17). At this time, Pier 7 was a functioning pier on both east and west sides. It was later filled in on its western flank. Water depths surrounding Pier 6, near the interpreted site of the explosion of 1917, are registered as 30 ft. on both sides of its central area, and 38 ft. at its seaward end. Pier 6 extended approximately 350 ft. out into The Narrows at this time from its westerly shore connection.

The 1916 chart shows identical offshore bathymetry but considerable change to the shoreline and docks. The area between Pier 7 and the western shoreline was completely infilled, altering the use of Pier 7 as a finger pier. In addition, the south side of Pier 6 near the shoreline was partially filled in, modifications were made to Piers 8 and 9, and the area to the south of Pier 6 near the sugar refinery saw the construction of several new small finger piers for a sailing club.

The 1917 chart shows continued infill of the shoreline seaward, both north and south of Pier 6, but the most dramatic change is evidenced by alterations in the offshore contours, including the placement of spot depths on the chart. This indicates a resurvey of the bathymetry, perhaps in response to a dredging program north of Pier 6 which deepened the seabed from 12 to 25 ft. South of Pier 6, the 20 ft. contour was pushed considerably seaward and the chart now indicated new depths of 18 and 10 feet, which were greater than 20 feet in the

previous surveying. This was the existing chart at the time of the explosion of 1917.

From the next Chart in the series, 1918, it appears that the bathymetry is the same as that portrayed on the 1917 Chart and the only changes reflect the destruction of the seaward two thirds of Pier 6, the complete destruction of Pier 8, and the demise of small finger piers to the south of Pier 6 north of the sugar refinery. The outline of the former positions of Pier 6 and 8 are both indicated on the 1918 chart and have the words "sunken piles" superimposed, indicating that remains of these wharfs lie on the seabed as a hazard to navigation.

The 1920 chart (FIGURE 18) is similar in bathymetry and shoreline configuration to the 1918 chart, but has an additional dashed line extending parallel to, and south from the eastern edge of Pier 7, across the centre of Pier 6, to the sugar refinery lands in the south, with the annotation "proposed improvements" on the line. This suggests that the area encompassed by the line to the west, was under study for possible infill.

The 1953 chart shows considerable change to the shoreline, docking facilities and bathymetry, although the offshore bathymetry in the adjacent deeper areas of The Narrows was not changed. The proposed infill of 1920 appears to have been undertaken with the construction of large pilings along the dock at the site of Pier 7 and the construction of cribwork docking facilities where Pier 6 once stood. However, the comparison clearly indicates that the area once encompassed by Pier 6, projects seaward beyond the new shoreline approximately one third of the original length of Pier 6, that is, 125 ft. The bathymetric survey of the Pier 6 area shows depths of 30, 36 and 49 feet where Pier 6 once stood. The 1962 Chart indicates a further southward elongation of the Pier 6 dock area with only minor encroachment seaward.

The present Chart for the area (1992) shows a similar shoreline to the 1962 Chart but with the addition of the large floating dock (Novadock) and its smaller counterpart now oriented parallel to the axis of The Narrows. The seaward end of old Pier 6 occurs at the location of an 8.5 m depth posting and an R symbol, indicating a rocky hard seabed. Three additional R symbols occur to the north and south of the area indicating a continuation of the hard seabed.

THE COLLISION AND EXPLOSION LOCATION

A description of the position of the *IMO* and the *Mont Blanc* at the time of collision and their subsequent movements up to and including the time of explosion suggests that the *Mont Blanc* drifted to the south side of Pier 6 (MacLennan, 1941). Fire from the *Mont Blanc* spread to

Pier 6, and it was approximately 20 minutes after the encounter with Pier 6 that the explosion occurred. During this time interval the Mont Blanc drifted further to the south a short distance enough to allow a small rescue vessel to pass between the *Mont Blanc* and the southern side of Pier 6. This indicates that the *Mont Blanc* was located with its bow adjacent to the southern outer edge of Pier 6 and its stern positioned further seaward toward the deeper water of The Narrows (FIGURE 6). The length of the *Mont Blanc* was 330 ft., indicating that it likely protruded at least 200 feet out into The Narrows beyond the seaward end of Pier 6.

The sidescan sonograms are particularly helpful in locating the former position of Pier 6. They show the a series of 10 nearshore submerged pilings, adjacent to the fourth large piling south of the southern edge of Pier 9, that are interpreted to represent the former location of Pier 6 (FIGURE 19). Seaward of the pilings, the sonar data indicates a large amount of debris on a hard seabed, with short linear objects which likely represent broken timbers that formed the original Pier 6.

Based on these features and the analysis of the earlier hydrographic charts above, the location of the *Mont Blanc* at the time of explosion can be narrowed to an area southwest of the northern end of the Novadock. Its bow was in a position represented on the modern Chart, by an 8.5 m spot sounding accompanied by an R (rock) symbol modifier. This position is interpreted to represent the location of the bow of the *Mont Blanc*.

The orientation of the *Mont Blanc* before the explosion is not known, hence it is difficult to determine exactly where the stern would have been located. As the tide at the time of the explosion was on the rise, the stern may have been deflected to the north. Extending seaward in an easterly direction, this orientation would place the stern beneath the northern end of the Novadock or slightly to the north of it (FIGURE 6 and 20). The *Mont Blanc* could not have been located much further to the west along the south side of Pier 6, because of the shallowness of the water at low tide, and the 6 m draft of the *Mont Blanc*.

DETAILED SEABED CHARACTER OF EXPLOSION LOCATION

The following is a detailed discussion of the sediments and features in the area of the explosion of 1917 defined as the zone confined by a line extending from the northeastern end of the Novadock to the southeastern corner of Pier 9, the proposed Richmond Cove. The sidescan sonogram shown on FIGURE 19 covers an area of the seabed

extending from the southeastern corner of Pier 9, to beneath the northern part of the Novadock, and extends westerly to the present shoreline. The most conspicuous features in the western part of Richmond Cove are the shoreline pilings which project into the Harbour. The northerly pair in the group are mapped on the present Chart of the area (FIGURE 6), while the southerly 5, are covered with a surface dock and can only be seen when looking shoreward/westerly from the Harbour.

The seabed around the pilings is very hard as evidenced by the dark tone on the sonograms. Adjacent to the first two northern pilings, the seabed consists of fine-grained muddy sediments, most likely derived from the Duffus Street sewage outfall which dumps into the Harbour at the juncture between the southern edge of Pier 9 and the shoreline. These muds continue further out into The Narrows and tend to be deposited into local depressions on the seabed. At the former location of Pier 8, which extended to the south from the southeast corner of Pier 9, are a series of shallow depressions with small berms on either side. The linear arrangement of the slight depressions likely defines the previous location of Pier 8. Their formation is attributed to dredging operations to remove the submerged piles and other debris from Pier 8 which was largely destroyed in the explosion.

At the fourth piling, from north to south along the shoreline, is the location of 10 piles at the seaward extent of the large piling. Seaward of this piling is a hard seabed with a gentle rise and many point source reflectors and short linear segments. These characteristics suggest that this was the location of the original finger Pier 6, and that the debris is the remains of the Pier. The location of Pier 6 on a topographic high is characteristic of the setting of most of the old piers along the shoreline of Halifax Harbour. They tended to be built where local shallow ground previously existed and this appears to be the case with finger Pier 6.

Near the southern area of Richmond Cove, the sediments are fine-grained muds and these continue from the shoreline to beneath the northern area of the Novadock. However, the seabed is crisscrossed with many generations of drag marks which penetrate through the mud indicating that it is thin, less than 1 m in thickness. Subsurface harder materials are exposed in the form of berms or ridges on the flanks of the linear drag marks. The sidescan sonar systems were able to look beneath the floating Novadock and indicate that the seabed is also mud but with fewer drag marks. Most of the linear drag marks are concentrated around the perimeter of the Novadock. In addition, the sidescan sonogram shows details of the structural steel on the bottom of the Novadock.

REMAINS OF THE MONT BLANC

Shipwrecks normally exhibit unique characteristics on sidescan sonar data, primarily resulting from the hard nature of the material, the presence of large expanses of flat metal or wooden surfaces, high and unusual angles between structural elements and the presence of diagnostic-shaped features such as railings, smokestacks, funnels, bows, hatches and openings in the superstructure (FIGURE 3). Even when ships are badly broken, large fragments can be identified by the presence of unusual sonar characteristics, much different from natural geological signatures of sediments and bedrock.

There are very few unnatural objects on the sidescan imagery near the location of ground zero of the *Mont Blanc*. The targets that do occur are small boulder sized and short linear objects that would require visual observation for identification. The large number of boulders on the seabed of The Narrows, as observed from ROV dives (Fader and Miller, 1992), suggests that most of the targets are likely boulders. Further north in The Narrows, however, are a large number of targets, some of which are 3 m in diameter and cast long acoustic shadows on the sonar imagery. Some of these targets could indeed represent pieces of the *Mont Blanc*.

At the interpreted location of the former Pier 6 is a large amount of debris consisting of short, 2-4 m linear objects. These are interpreted to represent some of the remains of Pier 6, such as pilings and broken wharf wooden fragments.

The lack of large fragments in the general area suggests that clearance dredging operations were conducted by the adjacent shipyard. Immediately following the explosion of 1917, the remains of Piers 6 and 8 were removed, as indicated on the chart of 1920. It is possible that these clearance programs covered a larger area and removed remains of the *Mont Blanc*. It is likely that such dredging operations were undertaken because of the intense shipbuilding and repair activity planned for the area and the possibility of submerged obstructions. The large number of linear drag marks on the seabed could have been formed by such a clearance operation. Records of such a clearance program of the seabed adjacent to Halifax Industries were not kept, but senior dockyard personnel agree that such a program would likely have taken place.

THE ORIGIN OF EXPLOSION BOULDERS

The description of a large number of boulders from the seabed of The Narrows scattered across Halifax by the Explosion is likely accurate, but they did not necessarily have to come from the deepest water areas

of the central Narrows. Early pictures of the preblast shoreline show a large number of scattered boulders at the waters edge, and the sidescan sonar imagery indicates many boulders on the seabed of The Narrows. Those that were scattered by the explosion could easily have come from the shallow water areas around Pier 6, 7 and 8 where the seabed remains composed of coarse gravel with boulders.

SEDIMENTATION RATE AND BURIAL IN THE NARROWS

An understanding of the sedimentation rate in The Narrows is very important in assessing whether seafloor features formed by the 1917 explosion, or indeed remains of the *Mont Blanc*, could be buried and therefore, difficult to identify. From a study of cores collected in the Harbour, Buckley and Winters, (1992) and Miller et al., (1990), determined that the amount of sedimentation since the founding of Halifax has not exceeded 43 cm. Exceptions occur in areas adjacent to sewage outfalls where thick sewage banks can be deposited.

In the areas adjacent to the downtown of Halifax older anchor marked surfaces appear to be infilled, suggesting a sedimentation rate of greater than 2 m since the founding of Halifax. Fader et al., (1991) presented an isopach map of the Holocene mud in the central area of the Harbour which clearly showed isolated depositional zones to the north of Georges and McNabs Islands. Based on sea level curves for the area, determined from cores collected in Bedford Basin and beyond the mouth of the Harbour, most of the Holocene mud appears to have been deposited after 6000 ka (Miller et al.,1979; Stea et al.,1991) The thickest Holocene mud sections occur north of McNabs and Georges Islands (Fader et al., 1991) where they are up to 12 m in thickness (the presence of methane gas makes their maximum thickness difficult to determine). Such zones indicate a maximum rate of deposition of 1.6 m per thousand years. In comparison with the modern measured rate for the inner Harbour, which is an average of 1.7 m per thousand years, the input from storm drains and domestic and industrial sewage has not considerably increased the sedimentation rate.

In The Narrows, the sedimentation rate is much less. In the northern area, extending from the Novadock to the entrance with Bedford Basin, fine-grained muds are virtually absent, with the exception of a few isolated depressions near the Novadock. Where they do occur, the mud is thin (FIGURE 21). This surface is dominantly gravel with boulders overlying overconsolidated till and bedrock. It was essentially formed by the marine transgression of The Narrows at approximately 6000 ka, and little has happened since, with the exception of anchoring, dredge disposal, bridge construction and the dumping of debris. The muds are likely associated with material

emanating from both the sewage outfalls at the foot of Duffus St. and from Tufts Cove, where fine-grained material moves out into the main channel of The Narrows, toward Bedford Basin. The seismic data indicates that the mud is less than 1 m in thickness.

The sidescan imagery also shows that the mud is very thin, as evidenced by many crisscrossing anchor drag marks which cut through the mud to the underlying gravel and produce linear ridges which protrude through the mud. (FIGURE14). The thin mud continues to the south in The Narrows toward the Angus L. Macdonald Bridge, interrupted by ridges of gravel. Only a few small patches of mud appear continuous.

If a crater had been formed by the explosion of 1917, and later infilled with fine-grained sediments, such an acoustically transparent sediment would have been easily penetrated and resolved by the various seismic reflection systems used during the surveys (FIGURE 21). However, no such fine-grained sediments were found. To the south of the Angus L. Macdonald Bridge, where the Holocene muds thicken, the seismic systems (including echosounders), easily penetrate the soft sediments and resolve subsurface features and bedrock (Figure 2).

This paucity of fine-grained sediment in The Narrows, along with low sedimentation rates throughout the Harbour, suggests that the present seabed has characteristics that are similar to those at the time of the explosion. Additionally, features formed by the explosion would not have been buried. A possible exception could be the burial of objects beneath the small sewage bank off the Duffus St. outfall. Furthermore, the consistently hard character of The Narrows (FIGURE 22) has been, and is, conducive by diving or the use of sidescan sonar, to the easy discovery of pieces of the *Mont Blanc* or other explosion artifacts. These objects would not sink into mud and would be exposed on a gravel surface.

THE EFFECTS OF THE EXPLOSION OF 1917 AT GROUND ZERO

Many writers consider the effects on the seabed of the blast at ground zero to have been substantial. The large number of scattered boulders throughout the surrounding communities and the amount of explosive material detonated in the blast, suggests that the seabed could have been severely altered by the event. The fact that a crater has not been located, does not mean that perhaps a small one may have formed.

The removal of Piers 6 and 8, the lack of remains of the *Mont Blanc*, and the large number of drag marks on the seabed, all indicate

that substantial alterations to the bottom have taken place since the explosion. It is possible that a small blast crater could have formed in the thin till overlying bedrock, but would have been smoothed and partially infilled by the dredging operations.

Only the upper part of Pier 6 was destroyed by the explosion and many of the submerged pilings remained on the seabed, as indicated on the post-blast bathymetric Chart. The presence of these pilings supports the idea of a limited effect of the explosion, as the *Mont Blanc* was very close to the outer end of Pier 6 at the time of the explosion.

COMPARISON WITH THE OAK AND KOA CRATERS

In 1958, the Government of the United States conducted test thermonuclear explosions at Enewetak Atoll, Marshall Islands, South Pacific. These were the only events conducted at or near sea level before test-ban treaties required that further tests be conducted beneath ground. In 1984, the effects of these tests were studied using seismic reflection, sidescan sonar, sampling and submersible techniques (Folger, 1988), similar to those employed in the study of Halifax Harbour. The setting of the Enewetak tests, that is, depth of water, placement of the explosive device, hardness of the seabed, are all characteristics of the tests very similar to conditions in Halifax Harbour during the explosion of 1917. This makes the Enewetak tests suitable for comparison, although they were of much greater magnitude. The OAK site used a 8.9 megaton device and the KOA site detonated a smaller 1.4 megaton device.

OAK CRATER

The 8.9-megaton device at the OAK location was detonated from a barge positioned in 4 m of water depth. The power of this device is approximately 3500 times that of the explosion in Halifax Harbour and it formed a very large crater, 1200 m in diameter and 60 m in depth (FIGURE 23). Fracturing may extend as deep as 425 m beneath the floor of the crater. Its geometric centre is offset by 100 m from ground zero. The bottom of the crater is flat and circular in shape and the walls consist of hummocks and terraces formed by slumps and mass movements of material. The seismic reflection profiles indicate that the bottom is underlain by a mixture of chaotic debris and post event deposits suggesting that the base of the crater is actually 110 m below the former seabed.

KOA CRATER

The KOA device was a smaller 1.4 megaton explosion and the crater produced was 1000 m in diameter and 33 m deep. The device was approximately 500 times the size of the explosion in Halifax Harbour. The floor of the crater is elliptical in shape and the bottom is

hummocky with numerous slump masses. Similarly, an acoustically transparent infill occurs in the bottom of the crater extending to a depth of 80 m.

Clearly both of these test explosions are considerably larger than the explosion of 1917 in Halifax Harbour but they can provide a relative comparison of the potential expected effects. If we assume that the conditions of the explosion in Halifax Harbour were similar to those on Enewetak Atoll, i.e. depth of water, hardness of seabed, we can estimate the expected effects to the seabed of Halifax Harbour from the detonation of a 1.6 kiloton device. Assuming a simple arithmetic scaling down factor, such an event would only be expected to produce a crater with a maximum depth of 1 to 3 m. This is consistent with the observations in Halifax Harbour concerning the formation of a small crater and its later demise.

CONCLUSIONS

1) The 1917 explosion in Halifax Harbour does not appear to have formed a crater. There also is no crater buried beneath sediments. This results from the hardness of the seabed of The Narrows which consists of exposed bedrock, overconsolidated till and gravel with boulders. If a crater had formed, it would have been less than 3 m in depth. Dredging activities to remove the post-blast remains of Piers 6 and 8, as well as remains of the *Mont Blanc*, could have contributed to the infilling of such a feature.

2) The exact present location of the original, 1917 position of Pier 6, is the 4 th piling south of Pier 9, and the location of ground zero of the 1917 explosion is approximately southwest of the north end of the Novadock, with the bow of the *Mont Blanc* near an 8.5 m contour on Canadian Hydrographic Chart #4201. The stern of the *Mont Blanc* extended to the east in The Narrows and this area presently lies beneath the northern end of the Novadock.

3) Large fragments of the *Mont Blanc* have not been identified on the seabed. Small fragments 1 to 2 m in size could possibly exist, but would have to be verified by visual observations. This implies that either the entire vessel was destroyed and pieces ejected outward, or salvage clearance operations were later conducted to remove large fragments of dangerous debris from the area for future safe shipbuilding operations.

3) Boulders scattered about the decks of vessels in the Harbour at the time of the explosion likely came from the adjacent shoreline and shallow water areas where they were plentiful in the area surrounding old Pier 6, 7 and 8.

4) Many unidentified objects larger that 1 m in diameter litter the Harbour floor, particularly in The Narrows. The seabed of The Narrows is one of the few locations in the Harbour where all anthropogenic debris is exposed at the seabed and material discharged to this bottom since 6000 ka has accumulated, overlying a gravel substrate. This results from a lack of fine-grained sediment deposition under strong currents. Some of these unidentified objects could represent small pieces of the *Mont Blanc,* but this hypothesis must await visual confirmation.

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I wish to thank the captains and crews of the *C.S.S. Navicula* and the *C.S.S. Frederick G. Creed* for their assistance in the collection of the data. Survey operations in busy harbours, such as Halifax Harbour, are very difficult, and their special efforts to collect the highest quality data are appreciated. The Program Support Subdivision technicians of the Atlantic Geoscience Centre provided excellent support to the field aspects of the study. This often involved non-standard operation of equipment and modifications to many systems for nearshore studies. D. Clattenburg produced timely sediment analyses and D. Beaver carefully provided navigational data for the cruises. I also thank R. Chittleburg for operation of the ROV and excellent piloting of the vehicle. Bottom photographs of the seabed were collected by H. Wiele of the BIO Photo Laboratory. The Canadian Hydrographic Service provided the digital swath bathymetry of the Harbour and I thank M. Lamplugh and the officers and crew of the *C.S.S. F. C. G. Smith* for their support collecting the data during the summer of 1992. I also thank R. Courtney for his expertise in producing the swath image for The Narrows. R. O. Miller is especially thanked for his provision of interpretations of the regional geology of The Narrows, all of the technical support to the project and the design of associated diagrams. S. Pecore produced the digital maps of control and seabed character. B. Petrie and D. Greenberg provided helpful advice on the oceanography of Halifax Harbour. G. Shutlak of the Public Archives of Nova Scotia, provided information on the early charts of Halifax Harbour. P. Klaamas kindly provided the aerial photograph of the Novadock area of The Narrows. I also thank J. Kitz for information on the *Mont Blanc* and A. Ruffman for lively discussions on the effects and location of the explosion. The manuscript was critically reviewed by B. Loncarevic and J. Shaw of the Atlantic Geoscience Centre.

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CAPTIONS

FIGURE1. Seismic reflection, echogram and sidescan sonar tracks from The Narrows, Halifax Harbour, interpreted in this study. Approximately twenty passes were conducted through The Narrows.

FIGURE 2. Typical high-resolution seismic reflection profile from the central area of Halifax Harbour adjacent to Georges Island. Note the thick deposit of acoustically transparent Holocene mud deposited in this area. A depression in bedrock is filled with sediment consisting of a series of parallel continuous reflections. This sequence is interpreted as lake sediments. Similar fine-grained sediments are rare in The Narrows. The rough surface of the mud is caused by anchoring.

FIGURE 3. Sidescan sonogram from an area of the Harbour near Georges Island showing the shipwreck of the *Governor Cornwallis*, resting on a muddy seabed (light tone) adjacent to a gravel bottom overlying till (dark tone). Structural details such as deck openings can clearly be seen on the ship. Large pieces of the *Mont Blanc* would be expected to show similar characteristics as the *Governor Cornwallis*.

FIGURE 4. Location of seabed samples, camera stations and remotely operated vehicle (ROV) video observations from The Narrows.

FIGURE 5. The distribution of surficial sediments in The Narrows. North of the Novadock the seabed mostly consists of gravel with boulders and occasional bedrock outcrop. South of the Novadock the mud is patchy and thin, with numerous anchor marks cutting through the thin mud to subsurface gravel.

FIGURE 6. Portion of Canadian Hydrographic Service Chart 4201 showing the bathymetry of The Narrows. The interpreted position of the Mont Blanc at the time of the explosion is superimposed.

FIGURE 7. Part of the1916 bathymetric map of The Narrows showing the original locations of Piers 6, 7, and 8 and associated water depths. The interpreted location of the Mont Blanc at the time of the explosion is superimposed.

FIGURE 8. A swath bathymetric image of The Narrows produced from digital data collected by the *C.S.S. F. C. G. Smith* ,during the summer of 1992. It is provided courtesy of the Canadian Hydrographic Service. The image is presented as a shadowgram, whereby the bathymetry is illuminated from the north, producing an image similar to an aerial photograph. The image was created from raw, unprocessed data, and is not to be used for navigation.

FIGURE 9. A simplified bedrock map of the Halifax-Dartmouth area showing the location of major structural elements (anticlines and

synclines) from Keppie, (1982). Anticlines are represented by filled slashes and synclines by open slashes. All structural elements are continuous across the Harbour and do not appear to be offset, indicating that faults do not occur beneath the Harbour. ATs is the South Mountain Batholith; CT the Goldenville Formation and Tt the Halifax Formation.

FIGURE 10. Structural map of Cameron (1949), showing the location of interpreted faults in the Halifax-Dartmouth area including those projected beneath Halifax Harbour. Modern seismic reflection and magnetic surveys do not support this interpretation.

FIGURE 11. Block diagram of the surficial geology showing the subsurface interpretation of glacial sediments, including drumlins, around Halifax Harbour, from Stea et al., (1992).

FIGURE 12. Map of the adjacent land area surrounding Halifax Harbour showing the bedrock geology with the location of drumlins (Donahoe and Grantham (1990), Nova Scotia Geological Highway Map). Also shown is an interpreted course of the ancient Sackville River.

FIGURE 13. Sidescan sonogram from The Narrows at the northern end of Pier 9 (upper left corner of image) showing the old bridge footings from the first two bridges that spanned Halifax Harbour. The seabed in this area is very hard, consisting of gravel and bedrock with numerous boulders. Remains of the *Mont Blanc* could lie on this hard seabed but no large pieces were identified.

FIGURE 14. Sidescan sonogram to the south of the Novadock in The Narrows showing the distribution of anchor drag marks at the seabed which cut through the thin Holocene mud to the underlying transgressive sand and gravel overlying till. The dragging of anchors produces this characteristic pattern of sets of linear, coarse parallel ridges.

FIGURE 15. Interpreted crossection from north to south in the centre of The Narrows, showing the morphology of the seabed, the bedrock surface, the thickness of till and a few isolated thin occurrences of Holocene mud. The till in this area of the Harbour is very consolidated and difficult to penetrate with the acoustic energy of the seismic reflection systems.

FIGURE 16. Map of the density and distribution of anchor marks in The Narrows interpreted from sidescan sonograms.

FIGURE 17 and 18. Composite of bathymetric charts from The Narrows for 1889, 1916, 1917, 1918, 1920, 1953, 1963 and 1992. See text for description of changes to the shoreline and bathymetry in The Narrows.

FIGURE 19. Sidescan sonogram covering the seabed of Richmond Cove and the interpreted location of the explosion of1917. Note the location of the 10 small pilings adjacent to the fourth piling (left to right) along the shore south of Pier 9, and the offshore adjacent debris field interpreted as the remains of the old Pier 6.

FIGURE 20. Photograph of the area of GZ for the explosion of 1917. The bow of the *Mont Blanc* is interpreted to have been beneath the mid-section of the freighter tied at Pier 6, and the stern was underneath the northern end of the Novadock, floating dry-dock. North is to the right and the photograph is looking northwest.

FIGURE 21. Seismic reflection profile from Richmond Cove crossing the location of old Pier 6. The lack of penetration on the profile indicates that the seabed is very hard and that no crater, which had been later infilled with fine-grained sediment, exists in this area.

FIGURE 22 . Bottom photograph of the seabed in The Narrows showing a hard gravelly seabed. The gravel is well-rounded consisting of cobbles with boulders, and large, disarticulated mussel shells. Note the fishing rod in the upper photograph and the trip weight/compass of the camera, for scale.

FIGURE 23. An enhanced sidescan sonar mosaic from the OAK crater site on Enewetak Atoll, Marshall Islands, from Folger, (1986). This crater was formed by the detonation of a thermonuclear device in 4 m of water. The crater is 60 m deep and 1200 m in diameter. For a size comparison to Halifax Harbour, it is approximately half the width and of a similar depth as Bedford Basin.

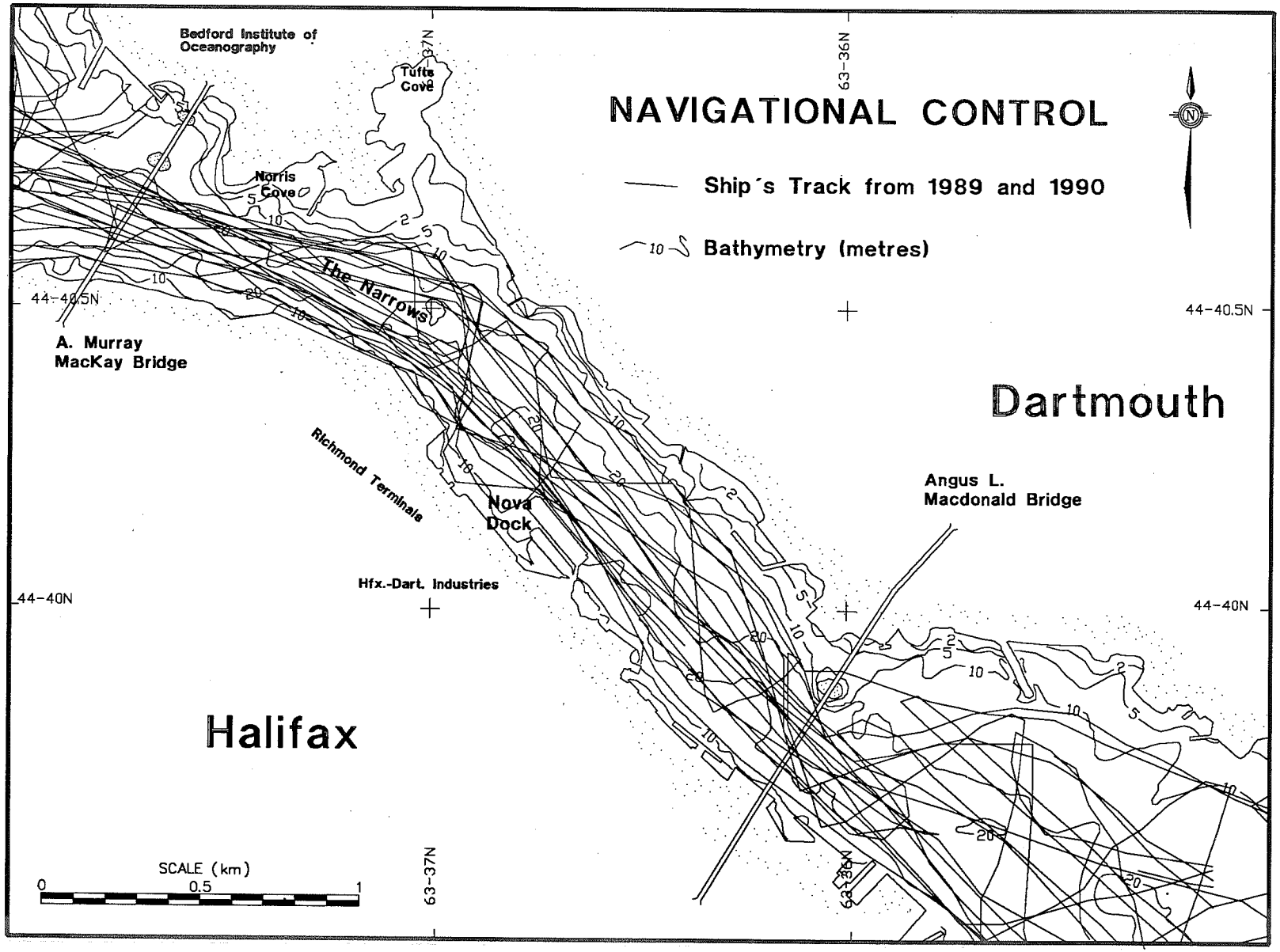

NAVIGATIONAL CONTROL
Ship's Track from 1989 and 1990
Bathymetry (metres)
Bedford Institute of Oceanography
Tufts Cove
Norris Cove
The Narrows
A. Murray MacKay Bridge
Richmond Terminals
Nova Dock
Hfx.-Dart. Industries
Angus L. Macdonald Bridge
Halifax
Dartmouth
44-40.5N
44-40N
63-37N
63-36N
SCALE (km)
0
0.5
1

FIGURE 1

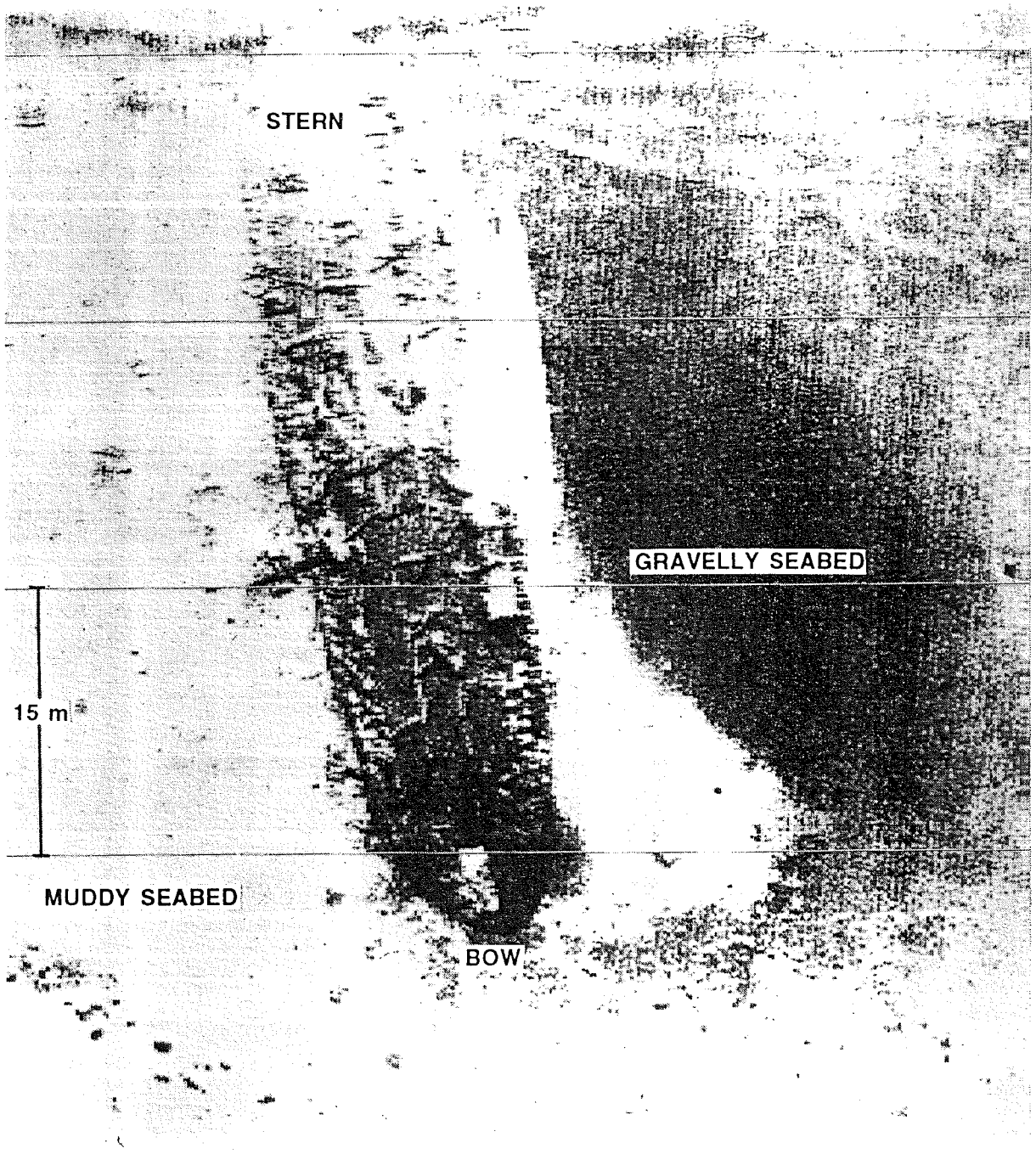


FIGURE 3

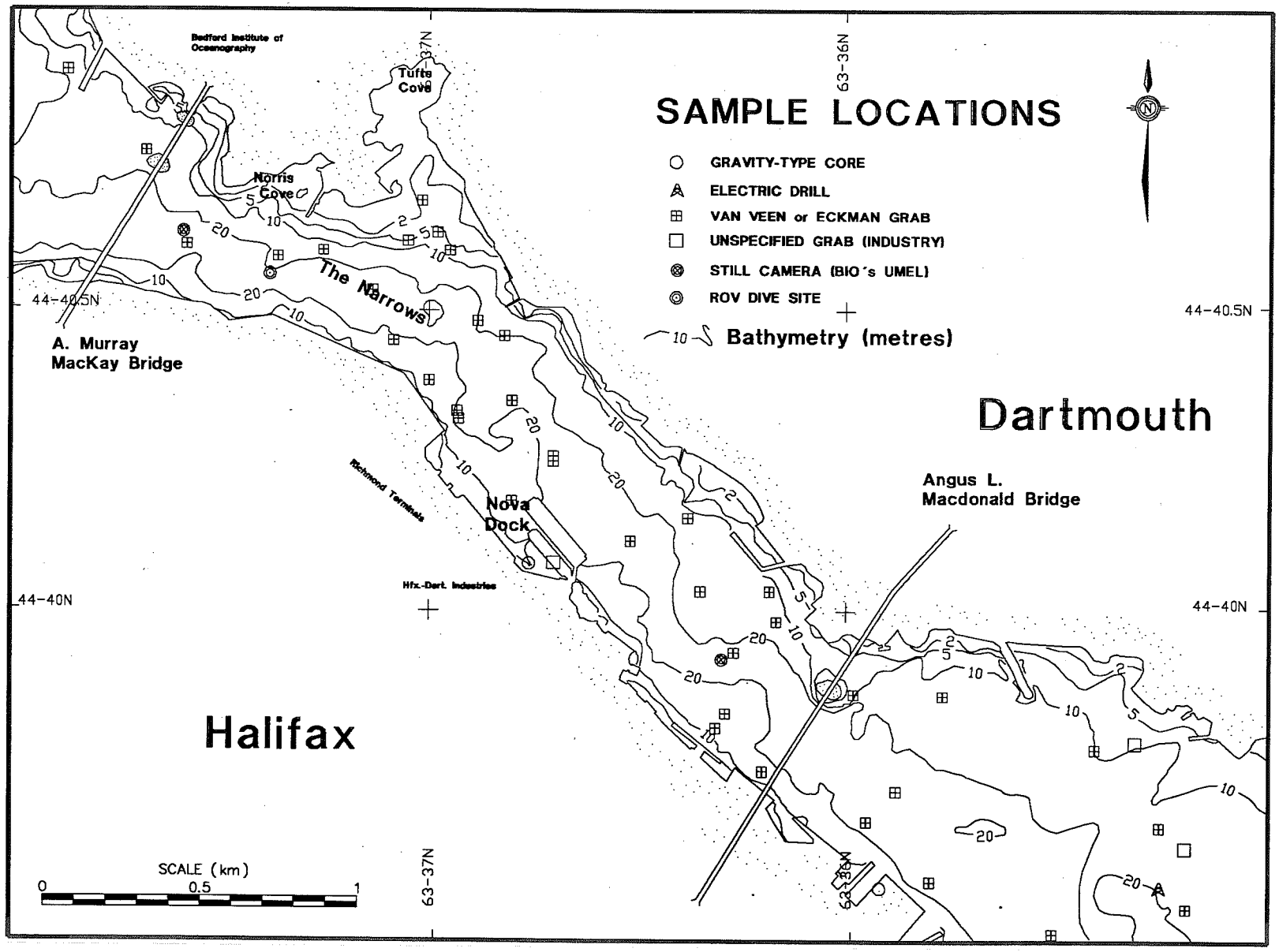

Bedford Institute of Oceanography
Tufts Cove
Norris Cove
The Narrows
A. Murray MacKay Bridge
Richmond Terminals
Nova Dock
Hfx.-Dart. Industries
Angus L. Macdonald Bridge
Halifax
Dartmouth
SAMPLE LOCATIONS
GRAVITY-TYPE CORE
ELECTRIC DRILL
VAN VEEN or ECKMAN GRAB
UNSPECIFIED GRAB (INDUSTRY)
STILL CAMERA (BIO's UMEL)
ROV DIVE SITE
Bathymetry (metres)
SCALE (km)
0
0.5
1
44-40.5N
44-40N
63-37N
63-36N

FIGURE 4

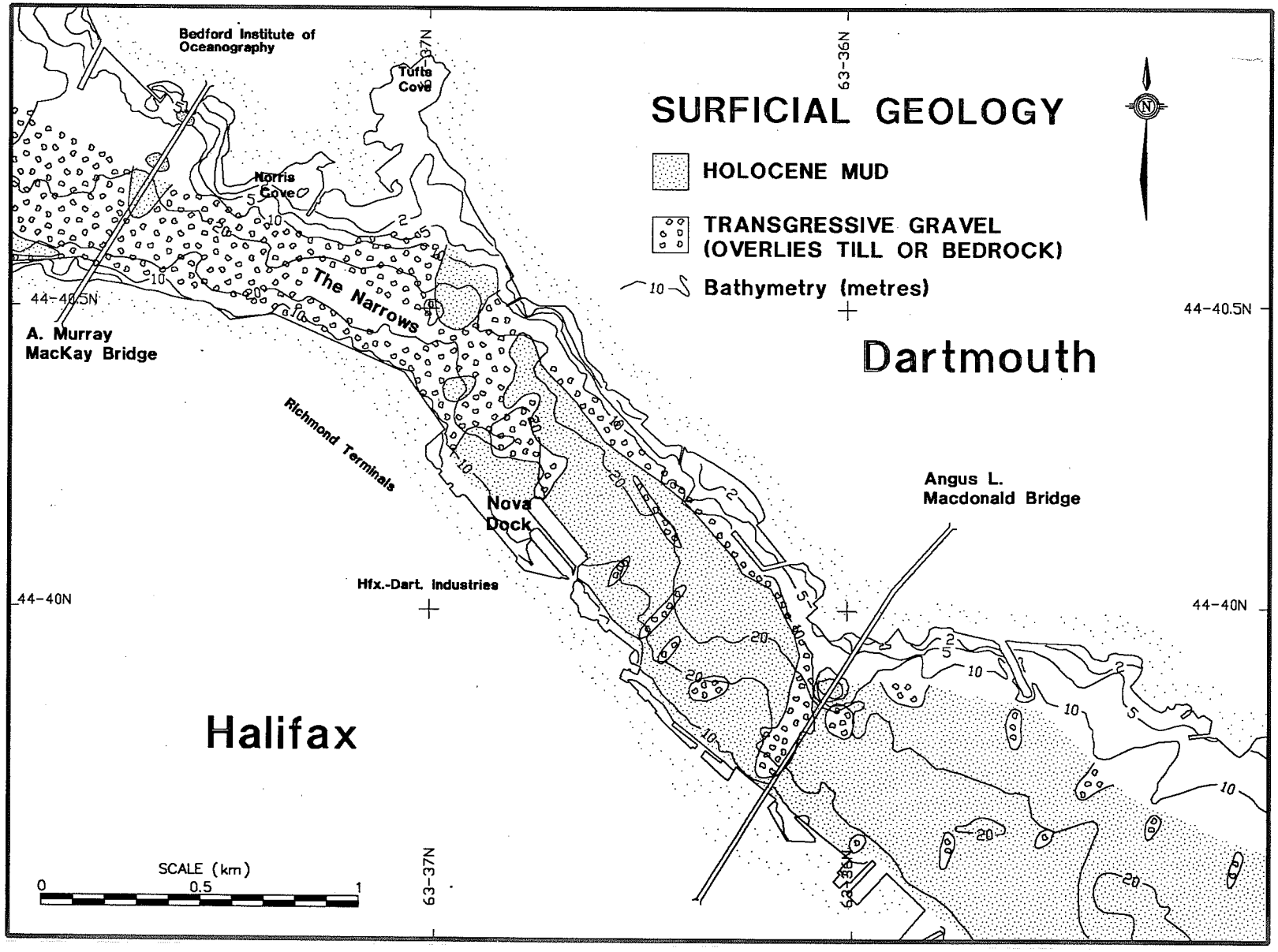

SURFICIAL GEOLOGY
HOLOCENE MUD
TRANSGRESSIVE GRAVEL
(OVERLIES TILL OR BEDROCK)
10 Bathymetry (metres)
Bedford Institute of Oceanography
Tuffs Cove
Norris Cove
The Narrows
A. Murray MacKay Bridge
Richmond Terminals
Nova Dock
Hfx.-Dart. Industries
Angus L. Macdonald Bridge
Dartmouth
Halifax
44-40.5N
44-40N
63-37N
63-36N
SCALE (km)
0
0.5
1

FIGURE 5

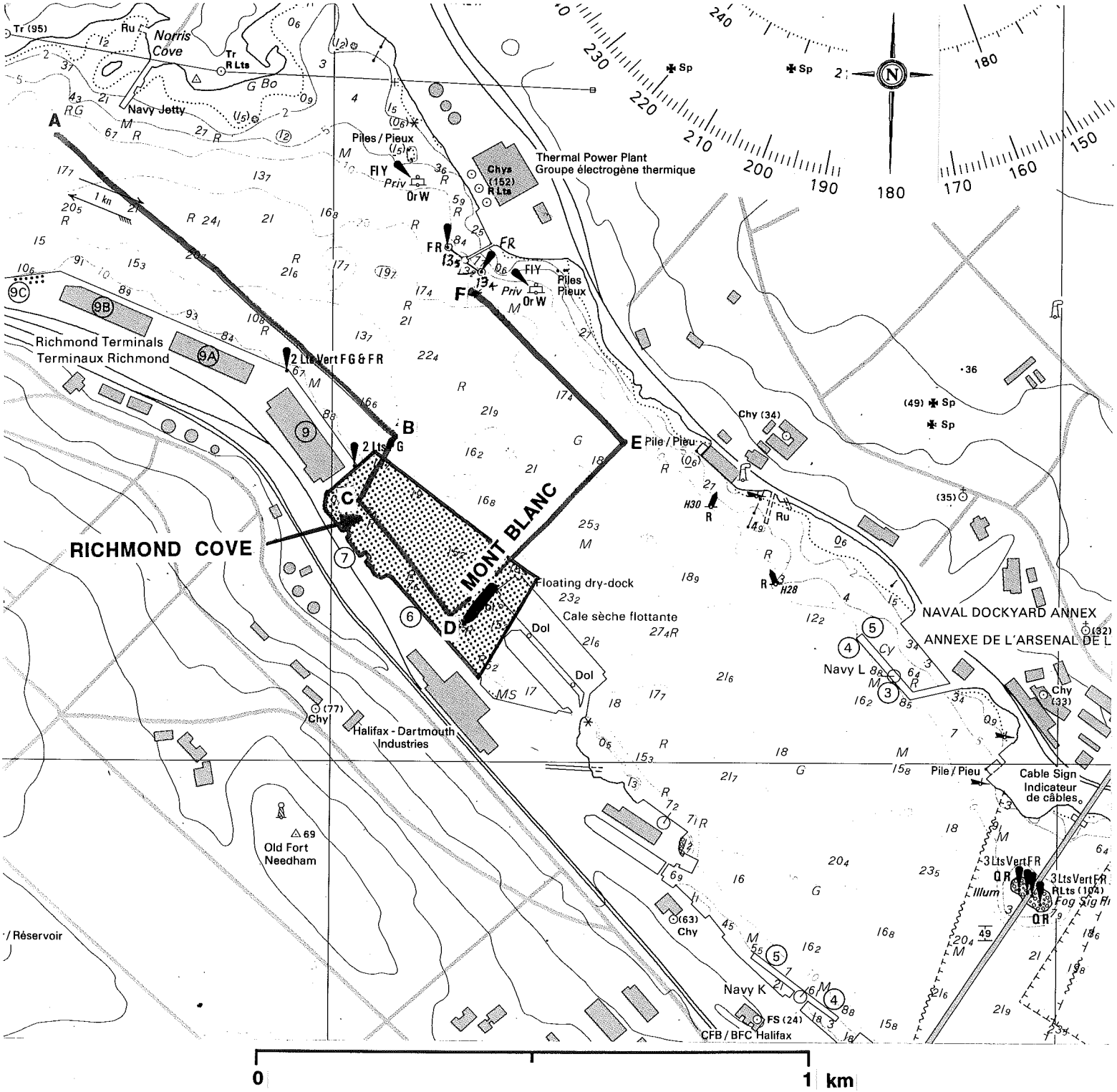

Norris Cove
Navy Jetty
Piles / Pieux
Thermal Power Plant
Groupe électrogène thermique
Richmond Terminals
Terminaux Richmond
2 Lts Vert FG & FR
2 Lts G
RICHMOND COVE
MONT BLANC
Floating dry-dock
Cale sèche flottante
Dol
Halifax - Dartmouth Industries
Old Fort Needham
Pile / Pieu
NAVAL DOCKYARD ANNEX
ANNEXE DE L'ARSENAL DE L
Navy L
Navy K
Cable Sign
Indicateur de câbles
3 Lts Vert FR
RLts (104)
CFB / BFC Halifax
/ Réservoir
0
1 km

FIGURE 6

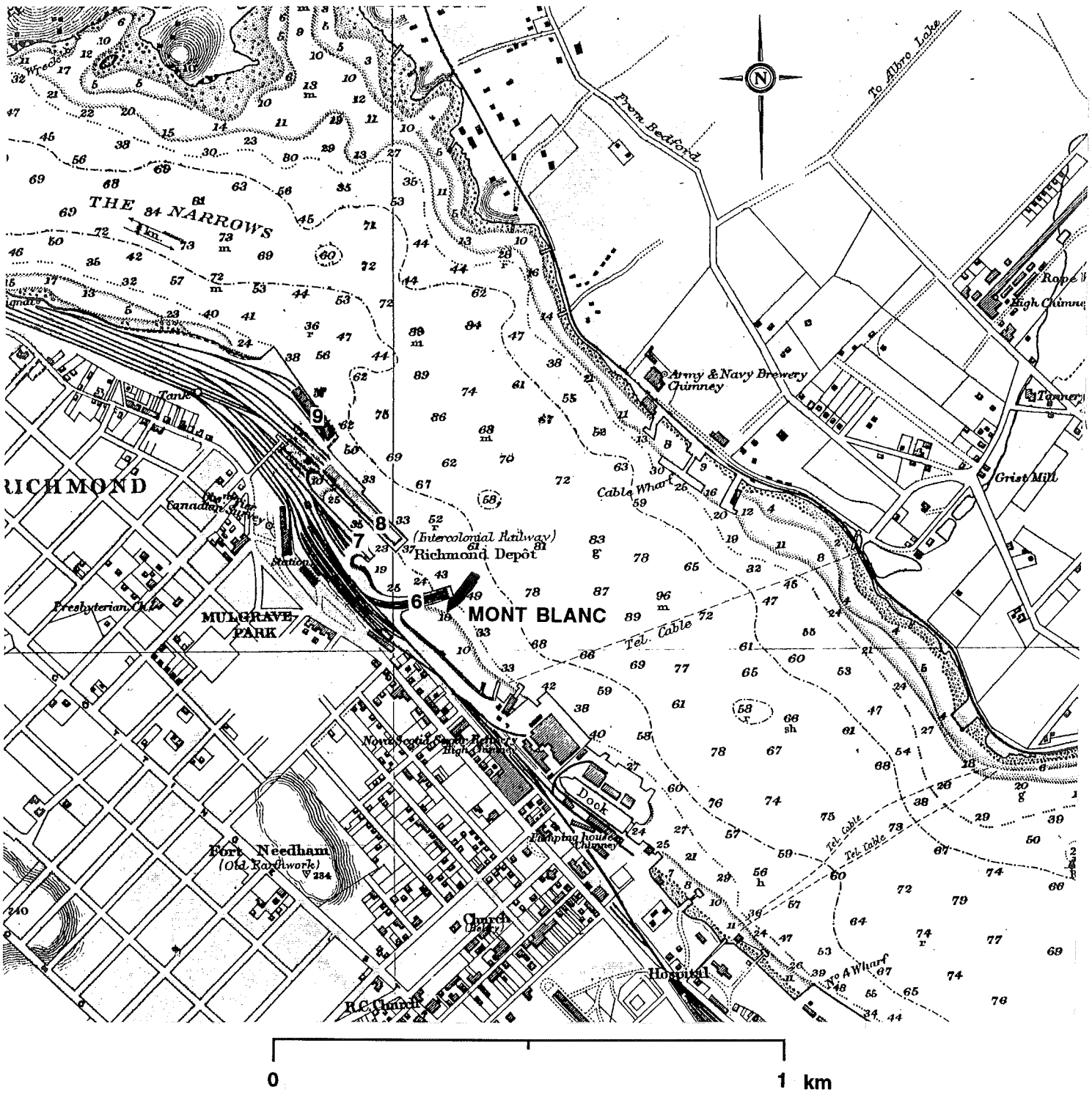

THE NARROWS
RICHMOND
MULGRAVE PARK
MONT BLANC
Richmond Depot
(Intercolonial Railway)
Cable Wharf
Army & Navy Brewery Chimney
Grist Mill
From Bedford
To Albro Lake
Tel. Cable
Dock
Fort Needham
(Old Earthwork)
Hospital
R.C. Church
No 4 Wharf
0
1 km

FIGURE 7

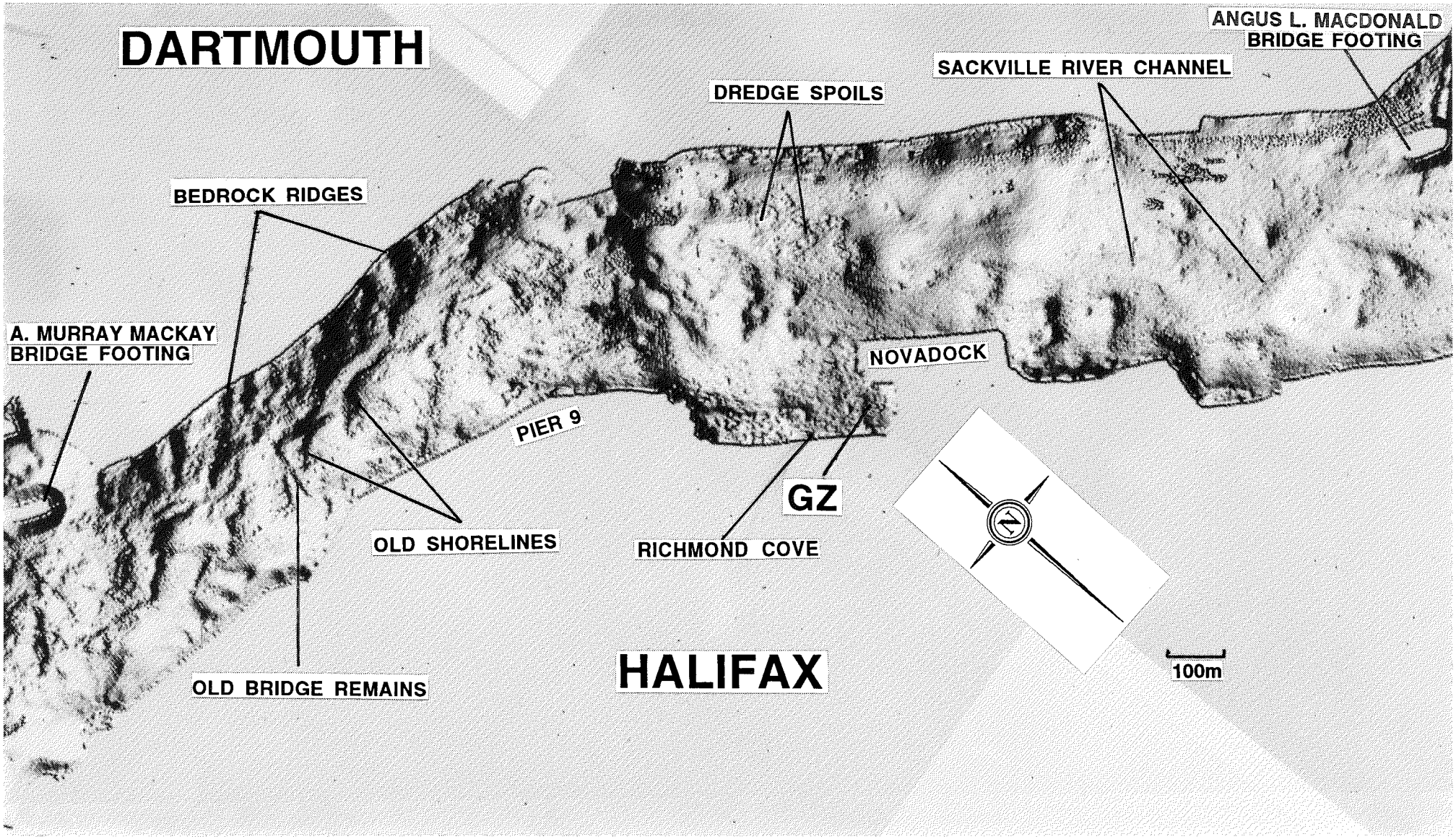
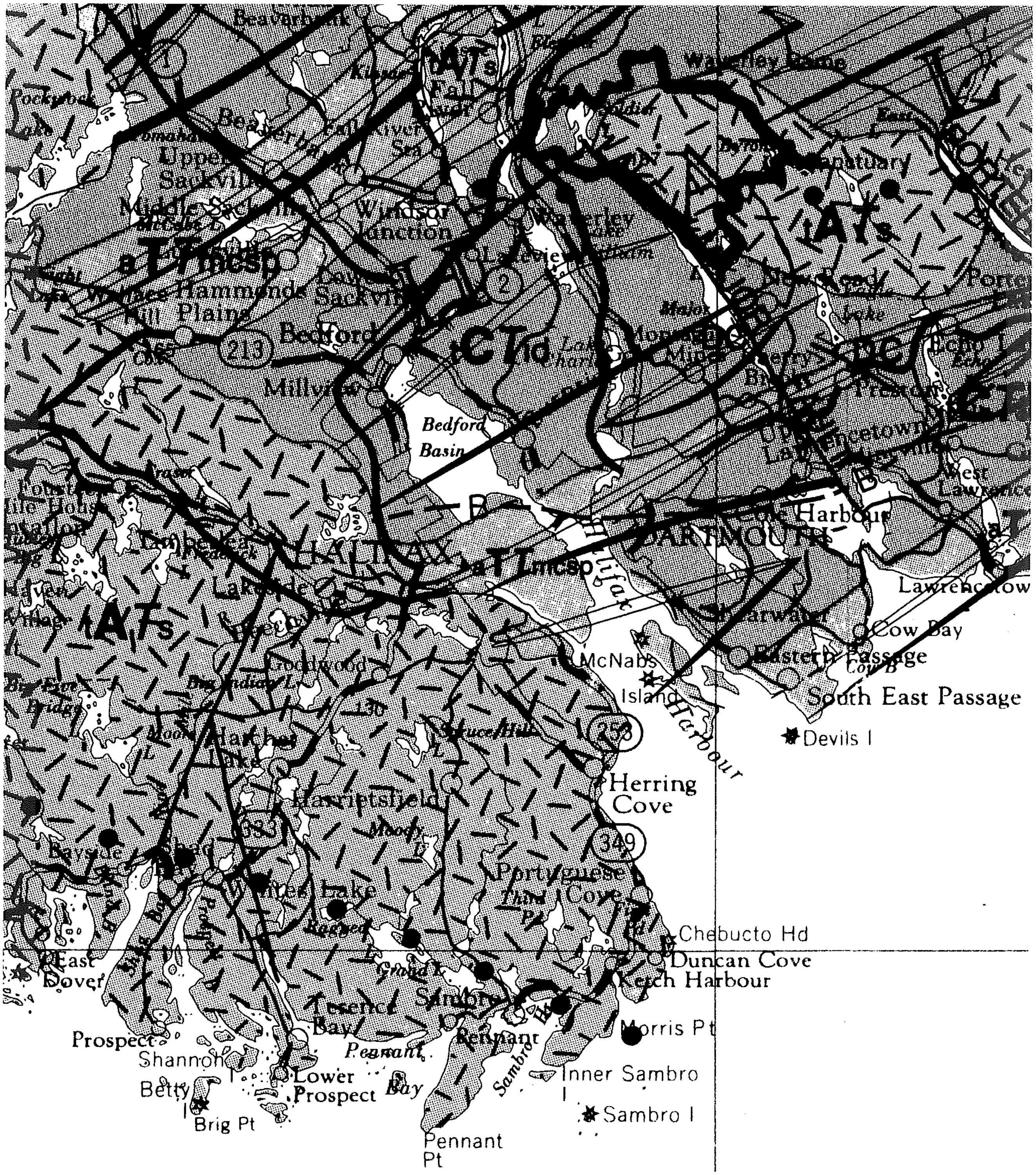

DARTMOUTH
ANGUS L. MACDONALD
BRIDGE FOOTING
SACKVILLE RIVER CHANNEL
DREDGE SPOILS
BEDROCK RIDGES
A. MURRAY MACKAY
BRIDGE FOOTING
NOVADOCK
PIER 9
GZ
OLD SHORELINES
RICHMOND COVE
OLD BRIDGE REMAINS
HALIFAX
100m

FIGURE 8



Bedford Basin
Bedford
213
Millview
Windsor Junction
Harriettsfield
Herring Cove
349
253
McNabs Island
Cow Bay
South East Passage
Devils I
Lawrencetown
Portuguese Cove
Chebucto Hd
Duncan Cove
Ketch Harbour
Morris Pt
Inner Sambro I
Sambro I
Pennant Pt
Pennant Bay
Lower Prospect
Prospect
Shannon I
Betty I
Brig Pt
East Dover

FIGURE 9

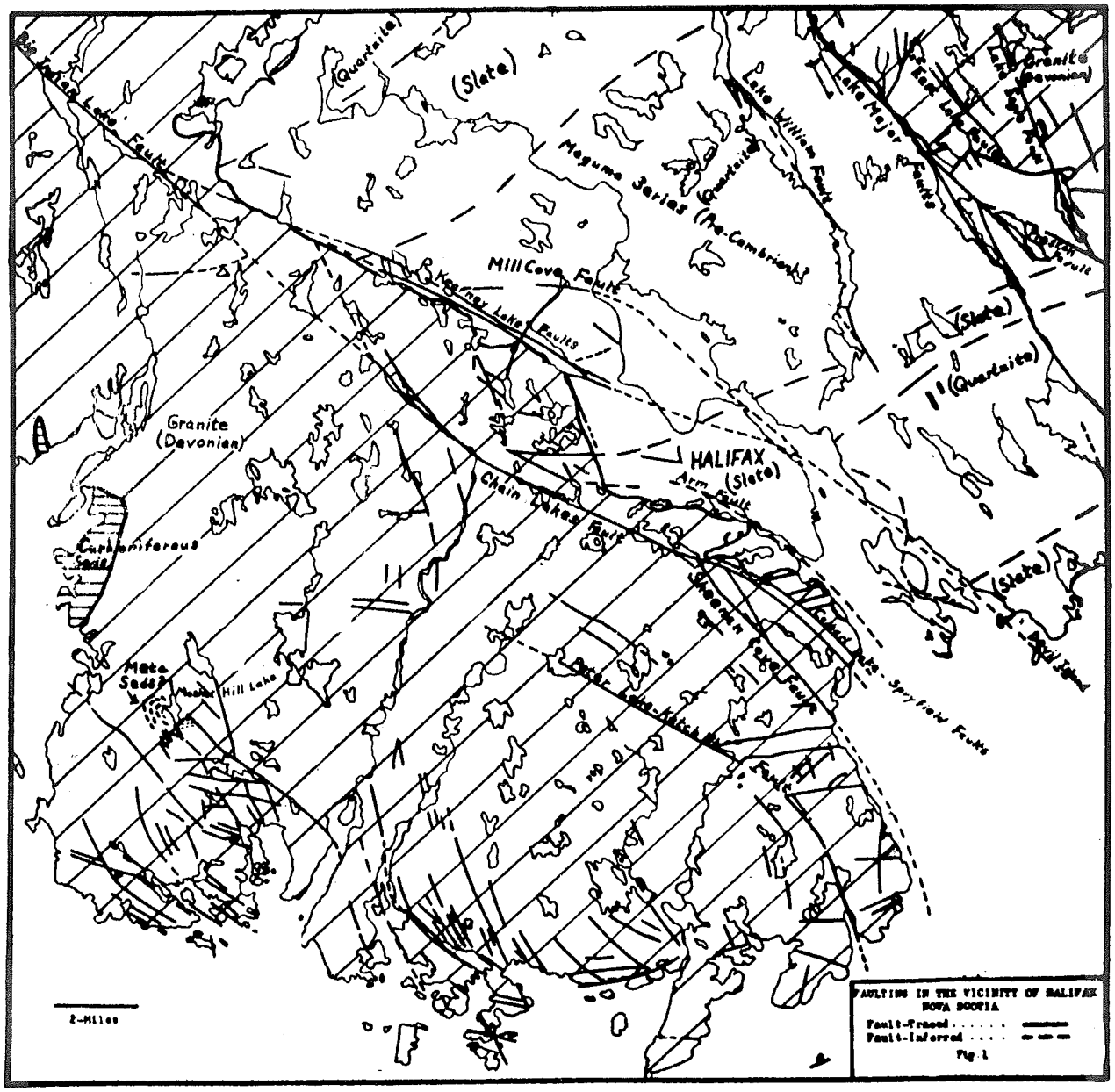

(Quartzite)
(Slate)
Lake William Fault
Lake Major Faults
Granite (Devonian)
Mill Cove Fault
Kearney Lake Faults
(Slate)
(Quartzite)
Granite (Devonian)
HALIFAX
(Slate)
Arm Fault
Chain Lakes Fault
Carboniferous Seds
Meta Seds
Hill Lake
(Slate)
Spryfield Faults
2-Miles
FAULTING IN THE VICINITY OF HALIFAX
NOVA SCOTIA
Fault-Traced
Fault-Inferred
Fig. 1

FIGURE 10

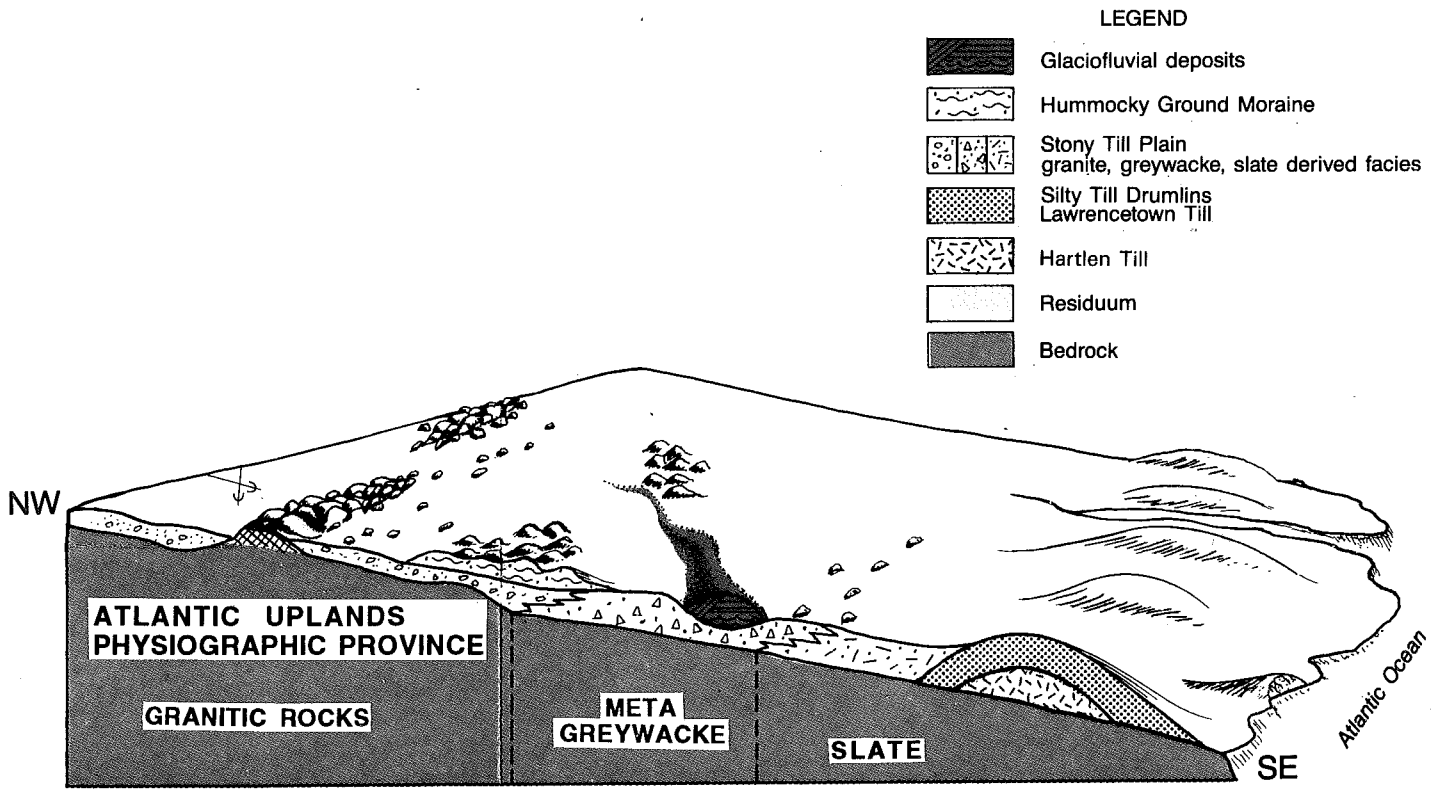

LEGEND
Glaciofluvial deposits
Hummocky Ground Moraine
Stony Till Plain
granite, greywacke, slate derived facies
Silty Till Drumlins
Lawrencetown Till
Hartlen Till
Residuum
Bedrock
NW
ATLANTIC UPLANDS
PHYSIOGRAPHIC PROVINCE
GRANITIC ROCKS
META
GREYWACKE
SLATE
SE
Atlantic Ocean

FIGURE 11

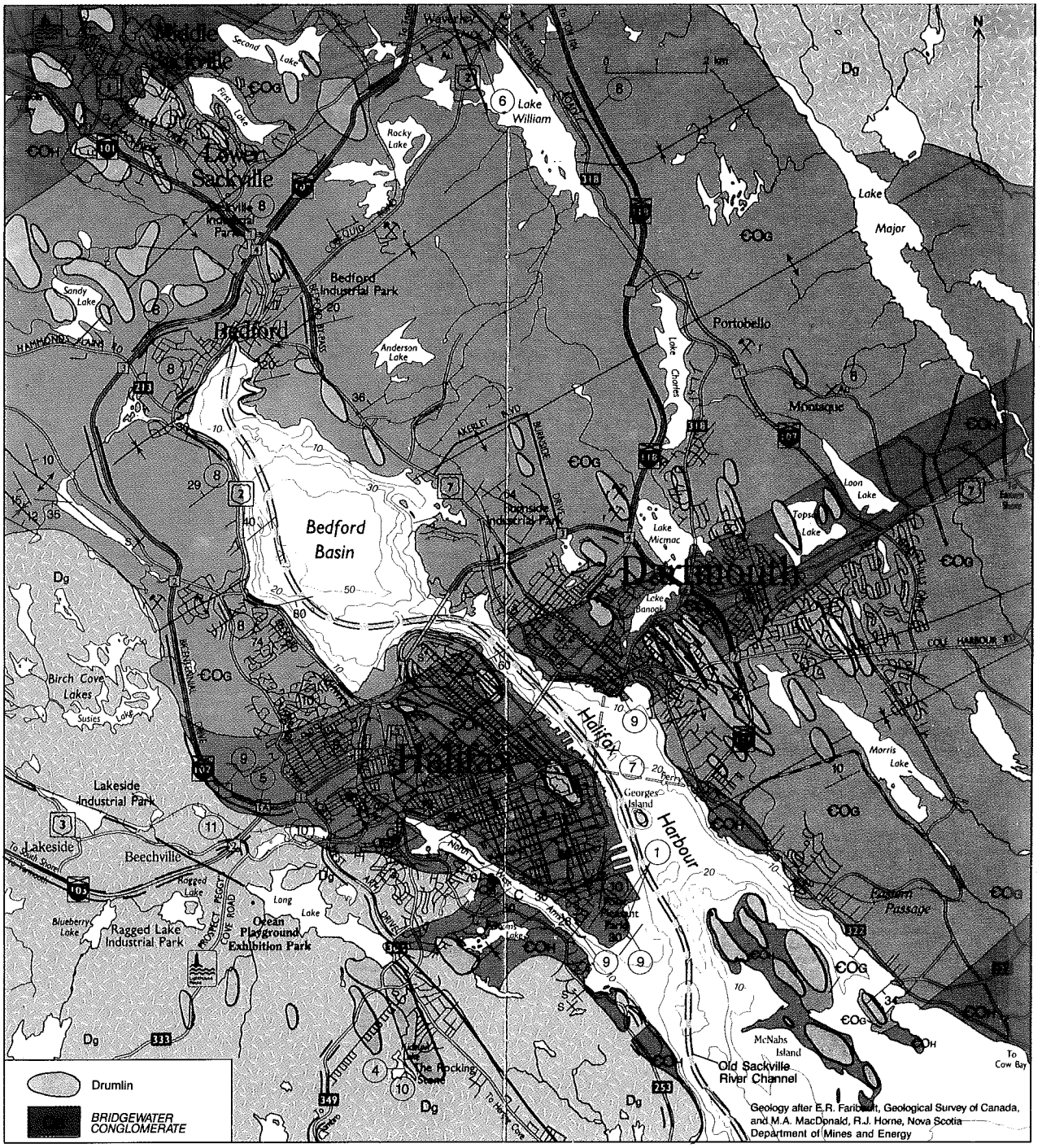

Middle Sackville
Second Lake
First Lake
Lower Sackville
Sackville Industrial Park
Rocky Lake
Lake William
Waverley
Lake Major
Sandy Lake
Bedford
Bedford Industrial Park
Anderson Lake
Portobello
Lake Charles
Montague
Loon Lake
Topsail Lake
Bedford Basin
Burnside Industrial Park
Lake Micmac
Dartmouth
Lake Banook
Birch Cove Lakes
Susies Lake
Halifax
Halifax Harbour
Georges Island
Morris Lake
Lakeside Industrial Park
Lakeside
Beechville
Ragged Lake
Long Lake
Blueberry Lake
Ragged Lake Industrial Park
Ocean Playground Exhibition Park
Eastern Passage
McNabs Island
Old Sackville River Channel
The Rocking Stone
To Cow Bay
Drumlin
BRIDGEWATER CONGLOMERATE
Geology after E.R. Faribault, Geological Survey of Canada, and M.A. MacDonald, R.J. Horne, Nova Scotia Department of Mines and Energy

FIGURE 12

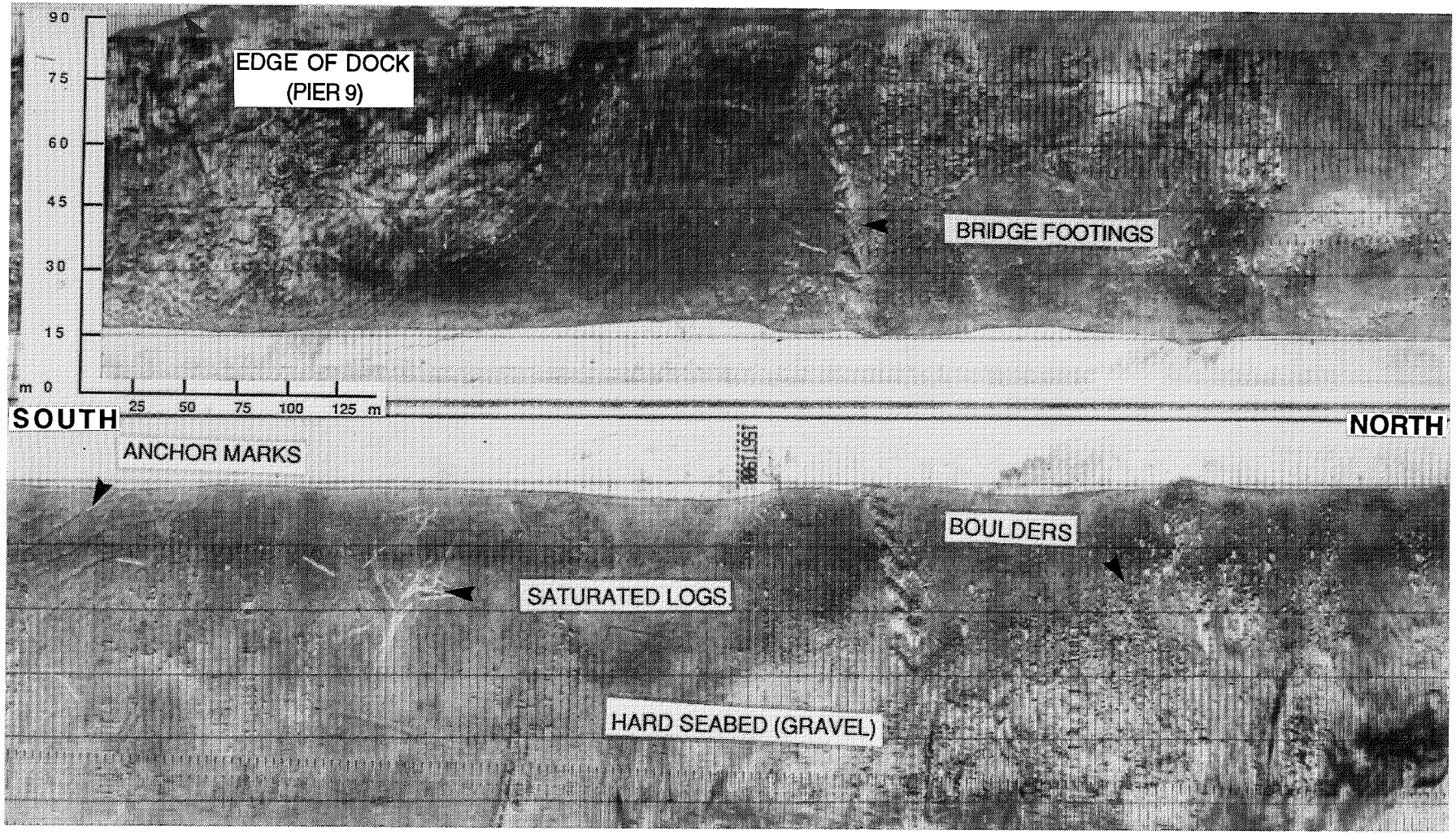

90
75
60
45
30
15
m 0
25
50
75
100
125 m
EDGE OF DOCK
(PIER 9)
BRIDGE FOOTINGS
SOUTH
NORTH
ANCHOR MARKS
1951/1998
BOULDERS
SATURATED LOGS
HARD SEABED (GRAVEL)

FIGURE 13

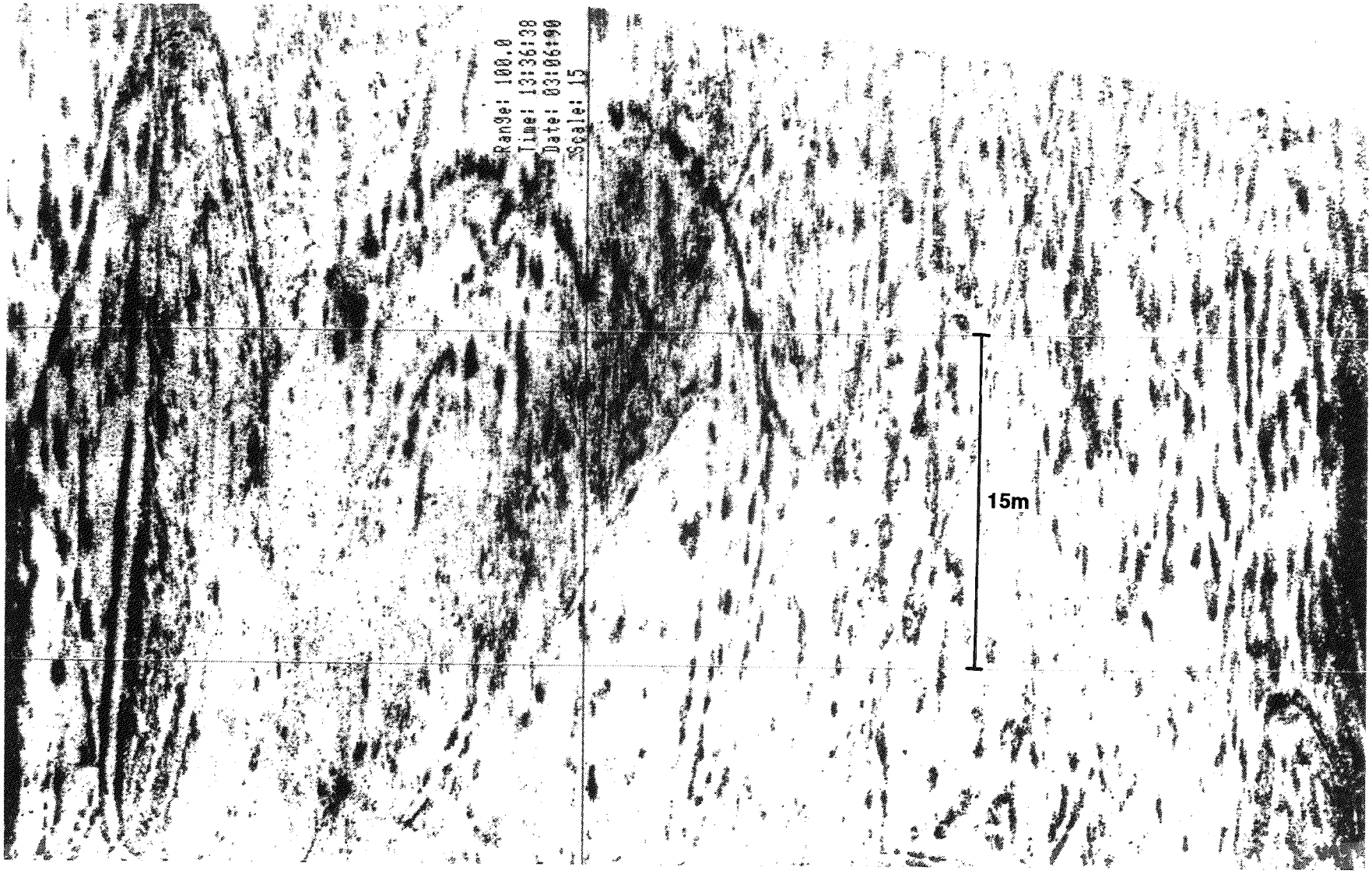


FIGURE 14

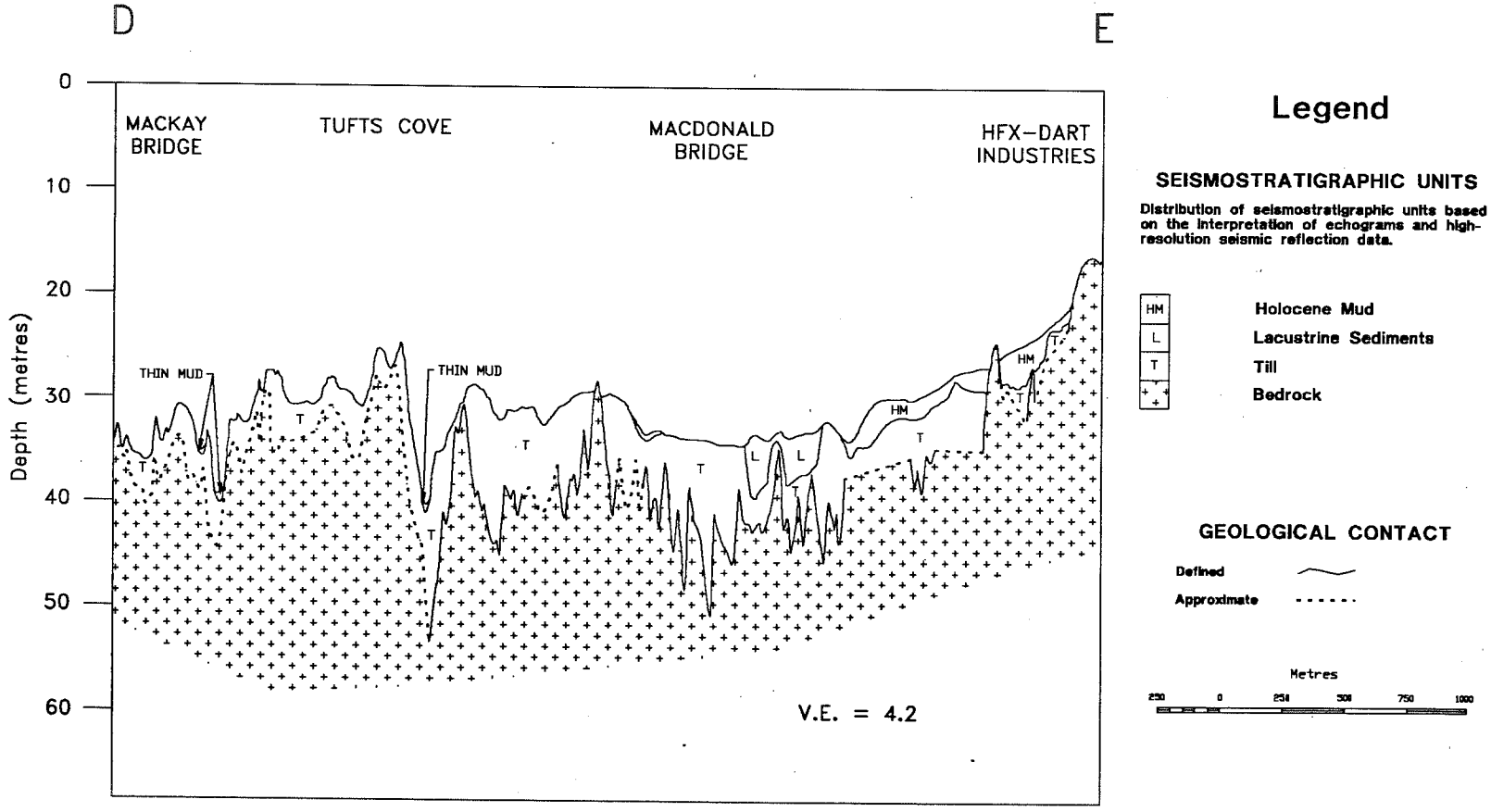

D
E
0
10
20
30
40
50
60
Depth (metres)
MACKAY BRIDGE
TUFTS COVE
MACDONALD BRIDGE
HFX–DART INDUSTRIES
THIN MUD
THIN MUD
HM
HM
T
L
V.E. = 4.2
Legend
SEISMOSTRATIGRAPHIC UNITS
Distribution of seismostratigraphic units based on the interpretation of echograms and high-resolution seismic reflection data.
HM
L
T
Holocene Mud
Lacustrine Sediments
Till
Bedrock
GEOLOGICAL CONTACT
Defined
Approximate
Metres
250
0
250
500
750
1000

FIGURE 15

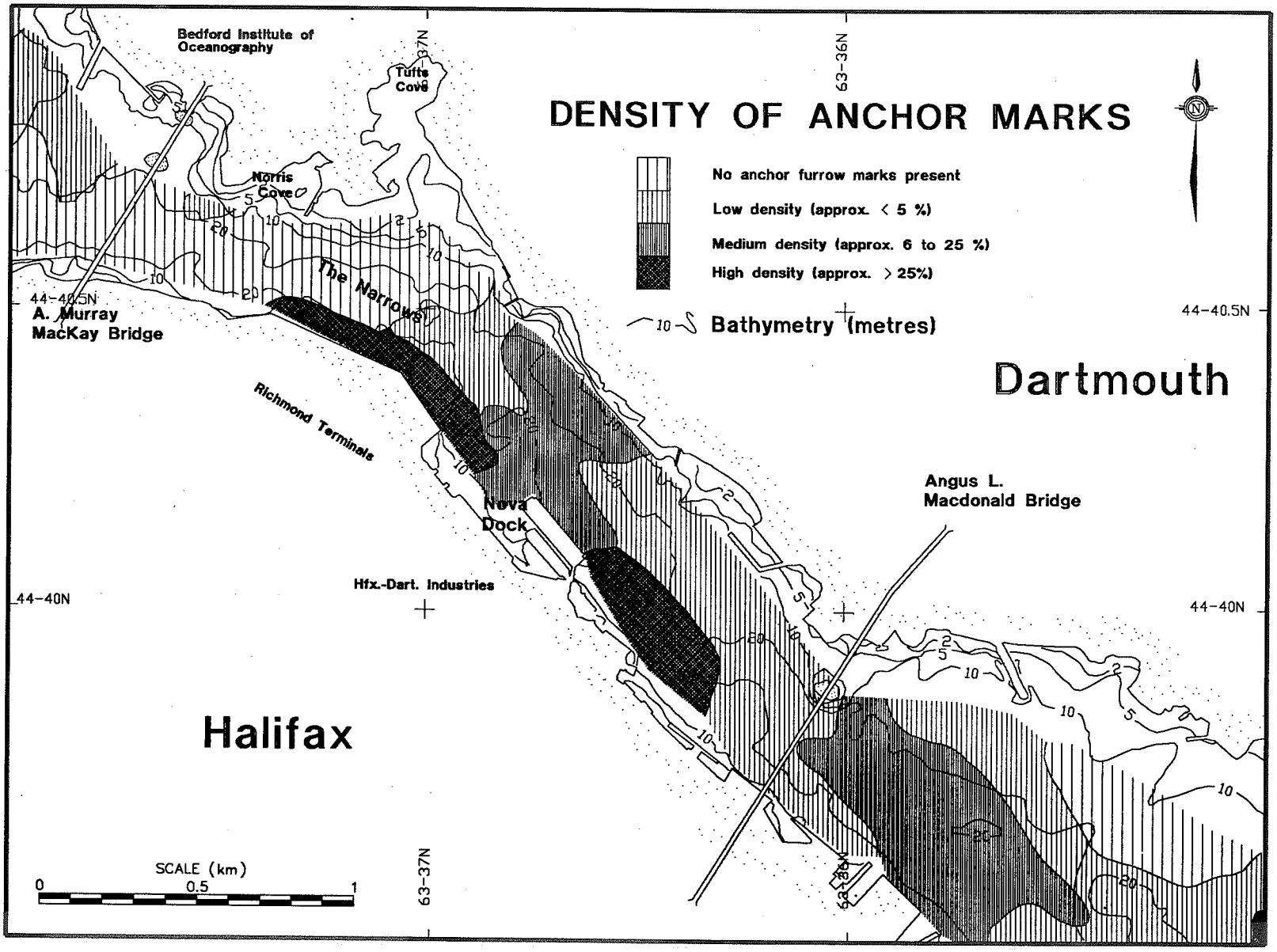

DENSITY OF ANCHOR MARKS
No anchor furrow marks present
Low density (approx. < 5 %)
Medium density (approx. 6 to 25 %)
High density (approx. > 25%)
Bathymetry (metres)
Bedford Institute of Oceanography
Tuffs Cove
Norris Cove
The Narrows
A. Murray MacKay Bridge
Richmond Terminals
Nova Dock
Hfx.-Dart. Industries
Angus L. Macdonald Bridge
Dartmouth
Halifax
44-40.5N
44-40N
63-37N
63-36N
SCALE (km)
0
0.5
1

FIGURE 16

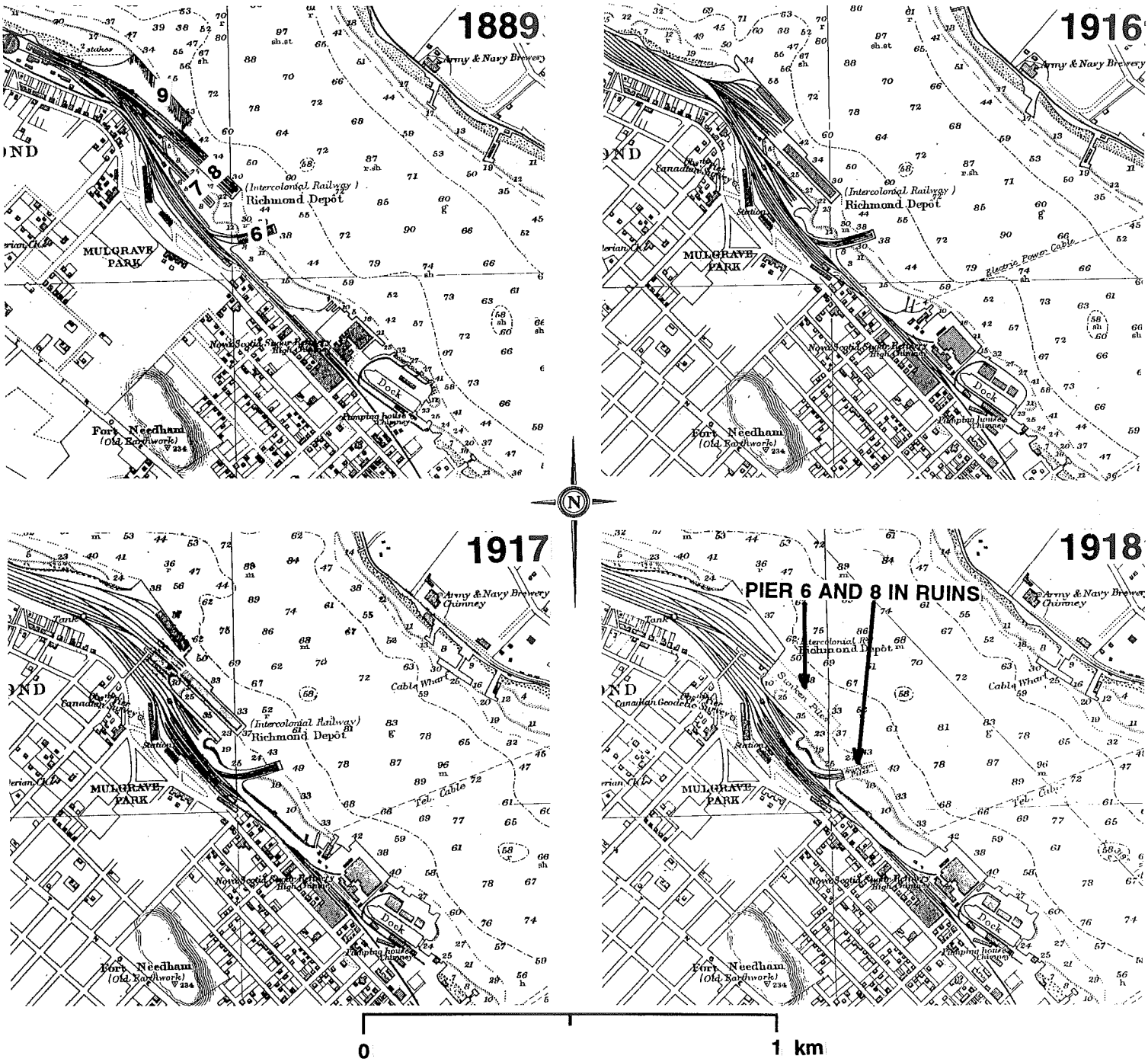

1889
1916
1917
1918
PIER 6 AND 8 IN RUINS
Richmond Depot
(Intercolonial Railway)
MULGRAVE PARK
Fort Needham
(Old Earthwork)
Army & Navy Brewery
Dock
Cable Wharf
Tel. Cable
Electric Power Cable
N
0
1 km

FIGURE 17

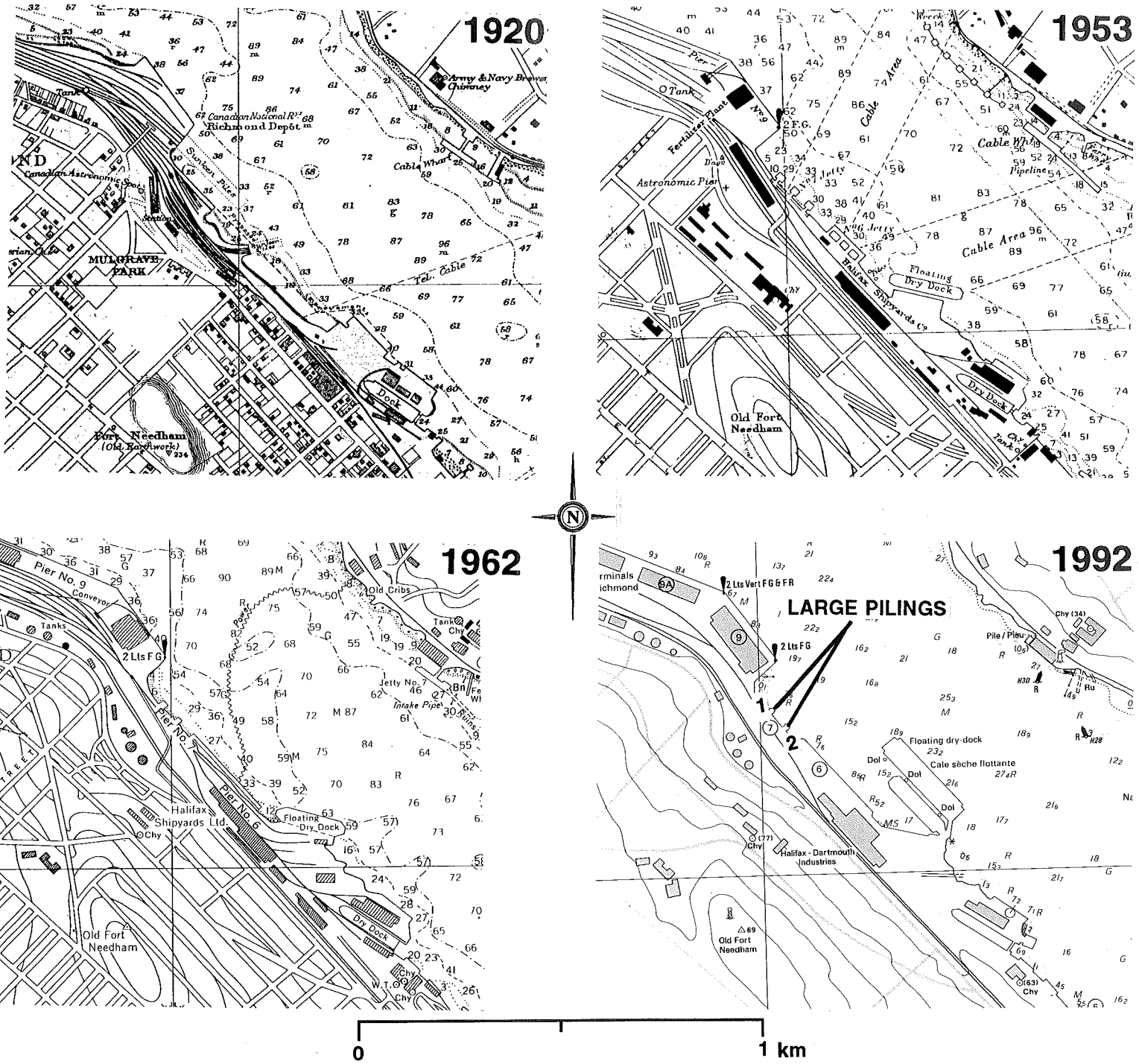

1920
Army & Navy Brewery Chimney
Canadian National Ry
Richmond Depôt
Canadian Astronomic Spot
MULGRAVE PARK
Tel. Cable
Dock
Fort Needham
(Old Earthwork)
1953
Pier
Tank
Fertilizer Plant
Astronomic Pier
Cable Area
Cable Wht
Pipeline
Floating Dry Dock
Halifax Shipyards Co
Dry Dock
Old Fort Needham
1962
Pier No. 9
Conveyor
Tanks
2 Lts F G
Old Cribs
Jetty No. 7
Intake Pipe
Pier No. 7
Pier No. 6
Halifax Shipyards Ltd.
Floating Dry Dock
Dry Dock
Old Fort Needham
1992
LARGE PILINGS
2 Lts Vert F G & F R
2 Lts F G
Floating dry-dock
Cale sèche flottante
Halifax - Dartmouth Industries
Old Fort Needham
0
1 km

FIGURE 18

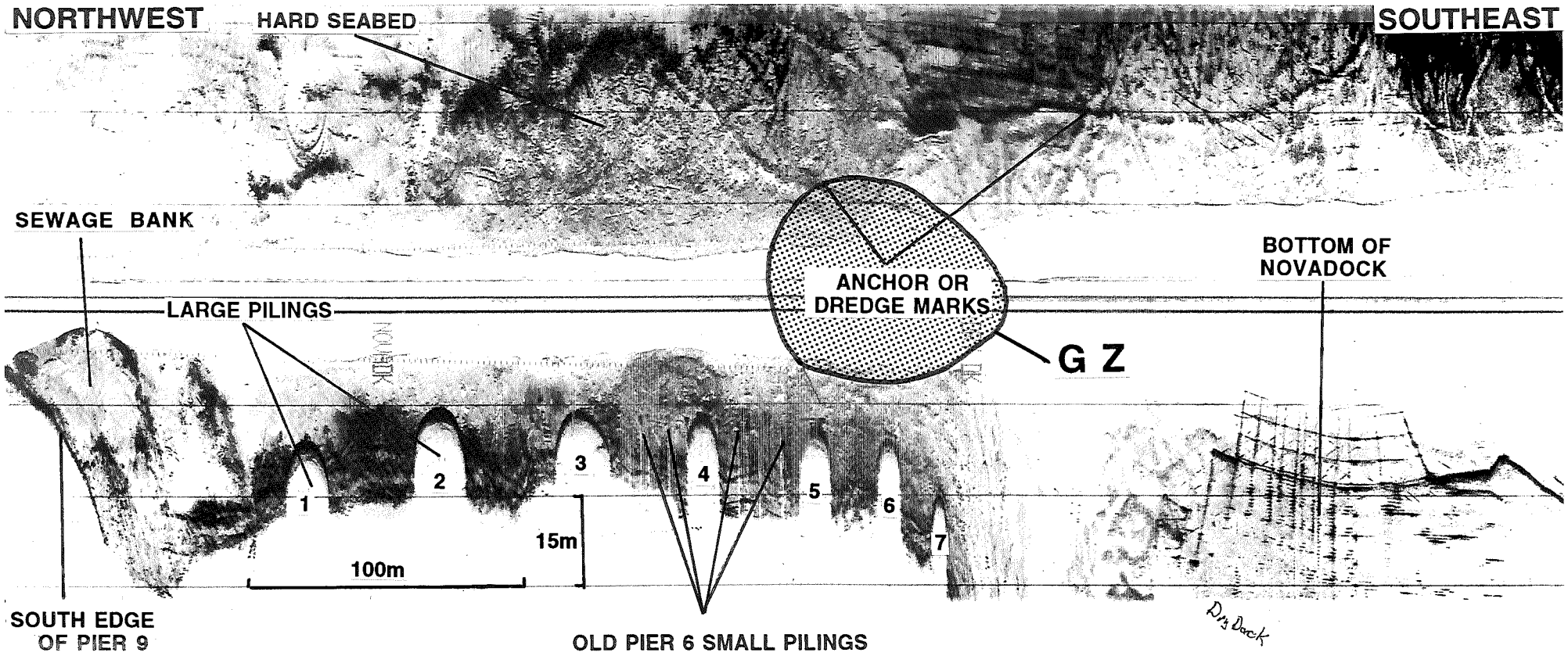

NORTHWEST
HARD SEABED
SOUTHEAST
SEWAGE BANK
BOTTOM OF
NOVADOCK
ANCHOR OR
DREDGE MARKS
LARGE PILINGS
G Z
1
2
3
4
5
6
7
15m
100m
SOUTH EDGE
OF PIER 9
OLD PIER 6 SMALL PILINGS
Dry Dock

FIGURE 19

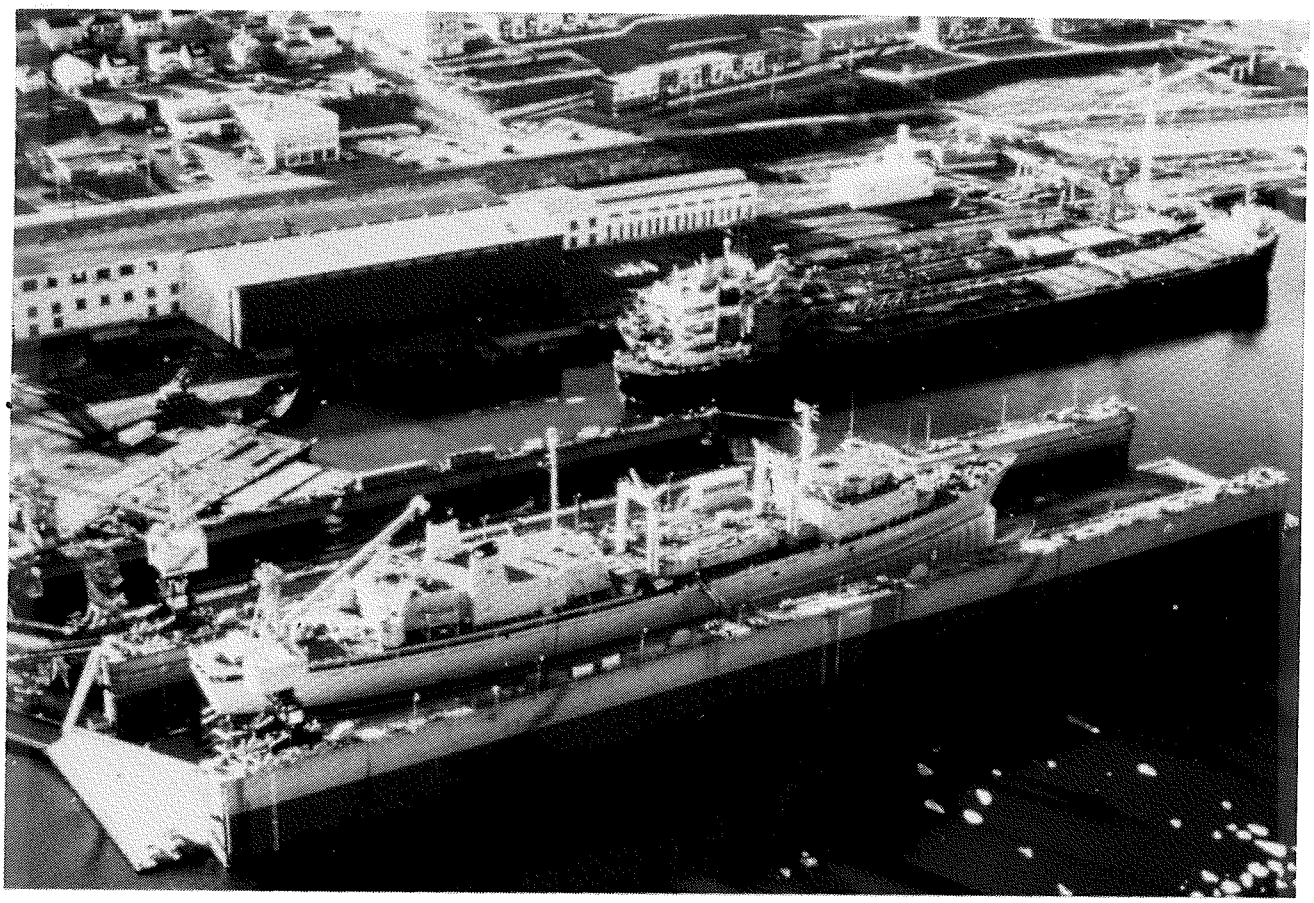


FIGURE 20

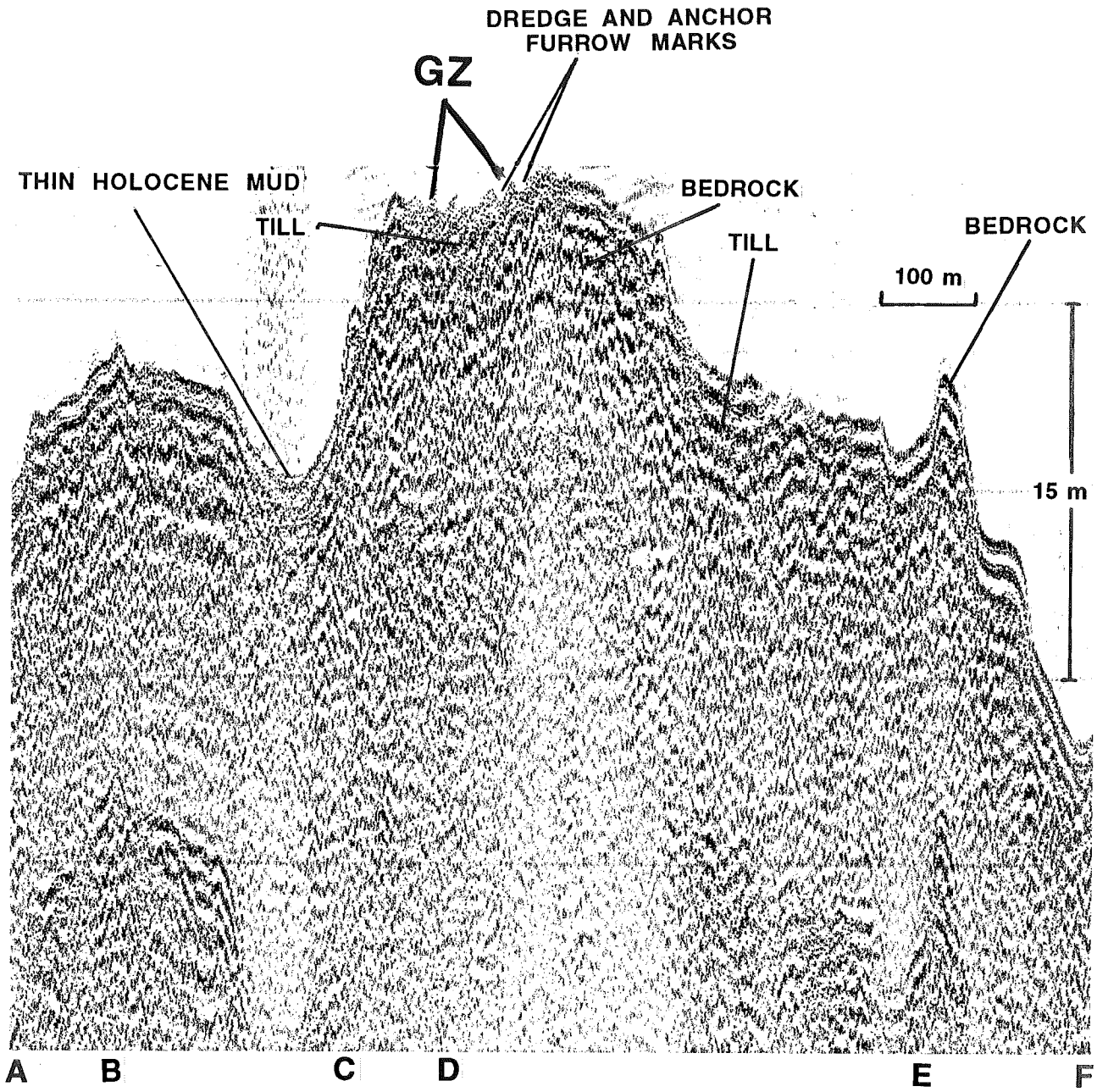

DREDGE AND ANCHOR
FURROW MARKS
GZ
THIN HOLOCENE MUD
TILL
BEDROCK
TILL
BEDROCK
100 m
15 m
A
B
C
D
E
F

FIGURE 21

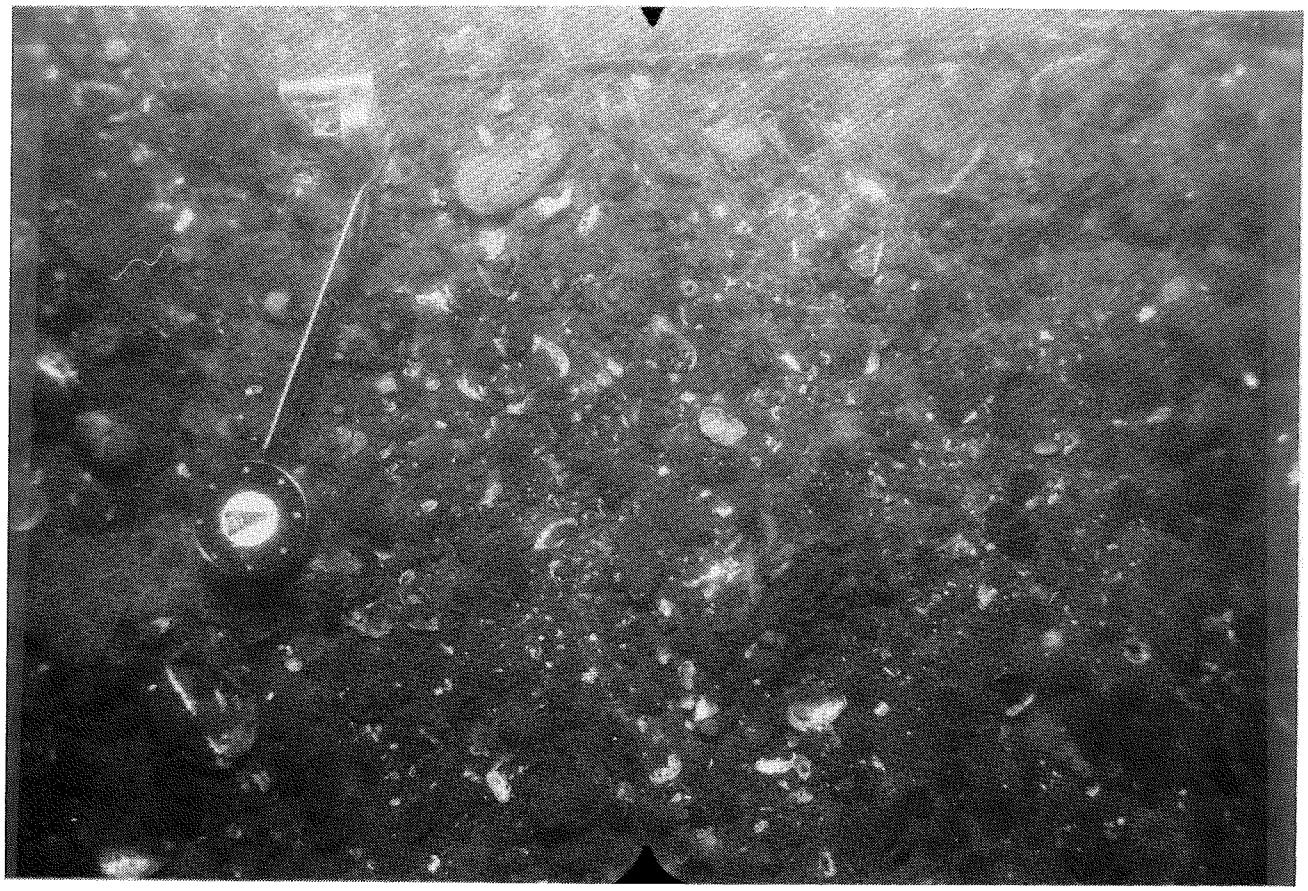


FIGURE 22

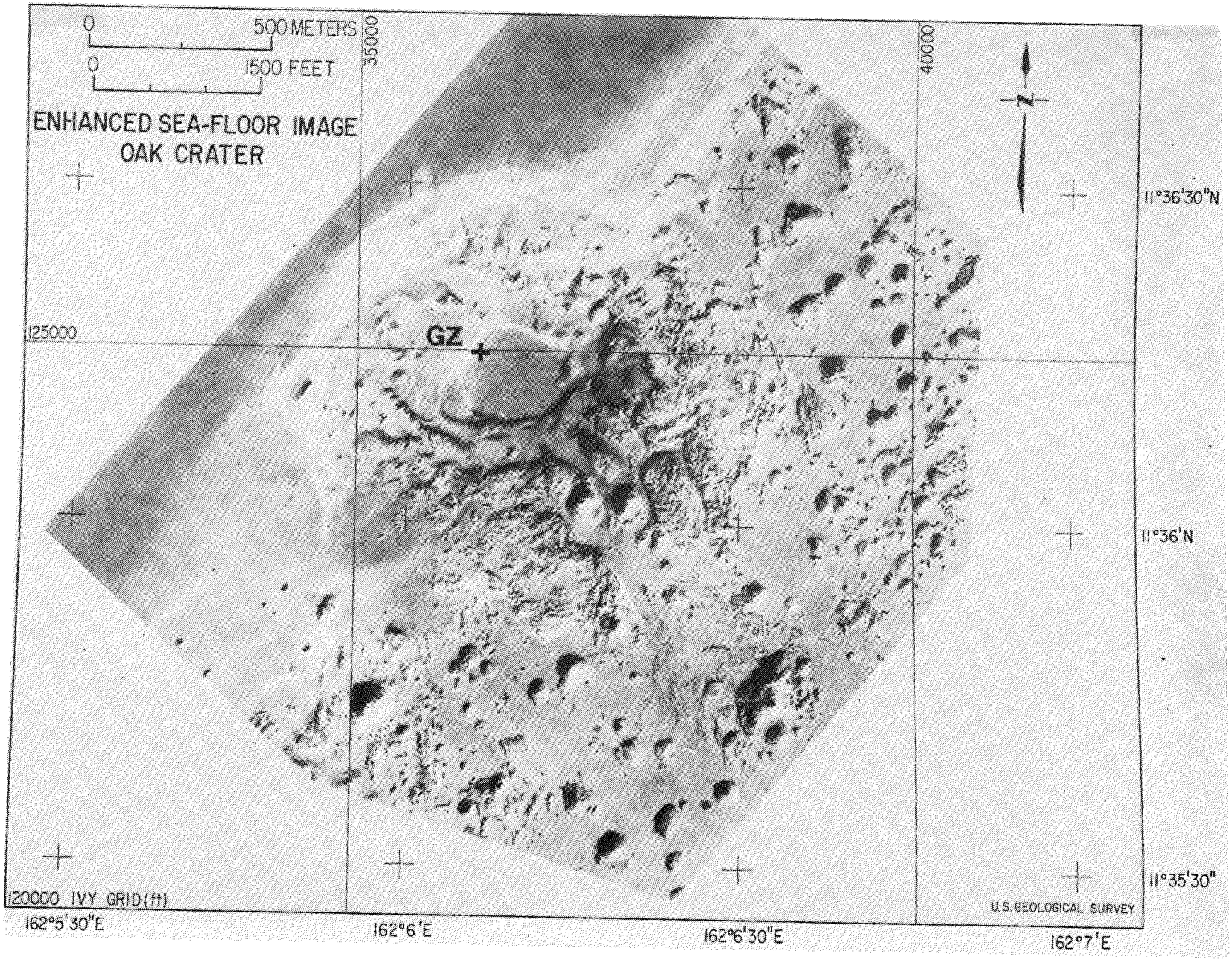

0
500 METERS
0
1500 FEET
ENHANCED SEA-FLOOR IMAGE
OAK CRATER
35000
40000
N
GZ
125000
11°36'30"N
11°36'N
11°35'30"
120000 IVY GRID (ft)
162°5'30"E
162°6'E
162°6'30"E
162°7'E
U.S. GEOLOGICAL SURVEY

FIGURE 23