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A GEO-ACOUSTIC AND OCEANOGRAPHIC DESCRIPTION OF SEVERAL SHALLOW WATER EXPERIMENTAL SITES ON THE SCOTIAN SHELF

John C. Osler

**Defence
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Director / Sonar Division

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Abstract

This technical memorandum provides a general description of the geo-acoustics and oceanography of the Scotian Shelf. Detailed descriptions are provided for three sites on the Scotian Shelf where the environment can be characterized on the basis of existing geophysical and oceanographic data.These sites will serve as archetypes for much broader regions of the Scotian Shelf with similar geo-acoustic settings.

Résumé

Le présent document technique décrit de façon générale les caractéristiques géo-acoustiques et océanographiques du plateau Scotian. Des descriptions détaillées sont fournies pour trois emplacements du plateau, là où le milieu peut être caractérisé à partir des données géophysiques et océanographiques existantes. Ces emplacements serviront de modèles pour de beaucoup plus vastes régions du plateau présentant des similitudes géo-acoustiques.

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1. Introduction

The Defence Research Establishment Atlantic (DREA) is currently involved in seismo-acoustic research at very low frequencies (below 100 Hz) in shallow water areas. At these frequencies, the rock and sediment layers underlying the shelf waters are an integral part of the acoustic medium. In addition to water borne acoustic paths from source to receiver, energy may propagate through the seafloor in the form of compressional, shear, or interface waves. For ambient noise and controlled sources, it is the physical properties and thicknesses of the rock and/or sediment layers in a given region which dictate: 1) velocity of propagation in a given geological layer, 2) the percentages of reflected and transmitted energy at each geological boundary and 3) the interfaces where conversion of compressional waves to different wave types is most likely. It is therefore beneficial, if not essential, that the physical properties of the sub-seafloor layers at experimental sites be appropriately characterized.

The physical oceanography on the Scotian Shelf is also reviewed in this document. It is relevant to research at DREA for two reasons. The first is a concern that tidal, wind, or density generated currents will influence research gear which is deployed in moored or free floating configurations (*e.g.* the interaction of currents with moored gear can create pressure signals from Von Karman vortex shedding). Secondly, the distribution of water masses and oceanographic fronts on the Scotian Shelf will dictate the speed of sound and propagation paths as these are functions of water temperature and salinity.

This technical memorandum provides a geo-acoustic and oceanographic description of three sites on the Scotian Shelf in areas where future experiments are planned (Figure 1). The site descriptions are based on a review of published and unpublished research material prepared by researchers with diverse interests including: hydrocarbon exploration, marine engineering, national defence, hydrography, and academic pursuits. The site specific details are prefaced by an introduction to the marine geology, geophysics, and oceanography of the Scotian Shelf.

2. Pre-Quaternary Geology

The pre-Quaternary history spans the time interval from the formation of the Scotian Shelf until its more recent history in the Quaternary (approximately the last 1 Ma)[1]. It is within this time interval that the igneous, metamorphic and sedimentary rocks which underlie the unconsolidated Quaternary surficial sediments where formed.

2.1 Passive Margin Evolution

The Scotian Shelf is a passive continental margin which formed as the African and North American continents separated and drifted apart as seafloor spreading formed the central North Atlantic Ocean. In the first stage of the breakup of the super continent Pangaea, rifting between Nova Scotia and Africa caused faulting and volcanism in the Bay of Fundy in the Late Triassic (220 Ma) to Early Jurassic (200 Ma)[2]. Seafloor spreading was established by the mid-Jurassic (175 Ma) based on the identification of the East Coast Magnetic Anomaly [Klitgord and Schouten, 1986]. This is a large positive anomaly which lies at the foot of the

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[1] Mega annum, millions of years before present

[2] These age estimates are from the stratigraphic position of dinosaur and reptile remains above basalt flows and K-Ar dating of the basalt flows

continental slope along the east coast of North America and probably marks the transition from continental crust (granitic) to oceanic crust (basaltic).

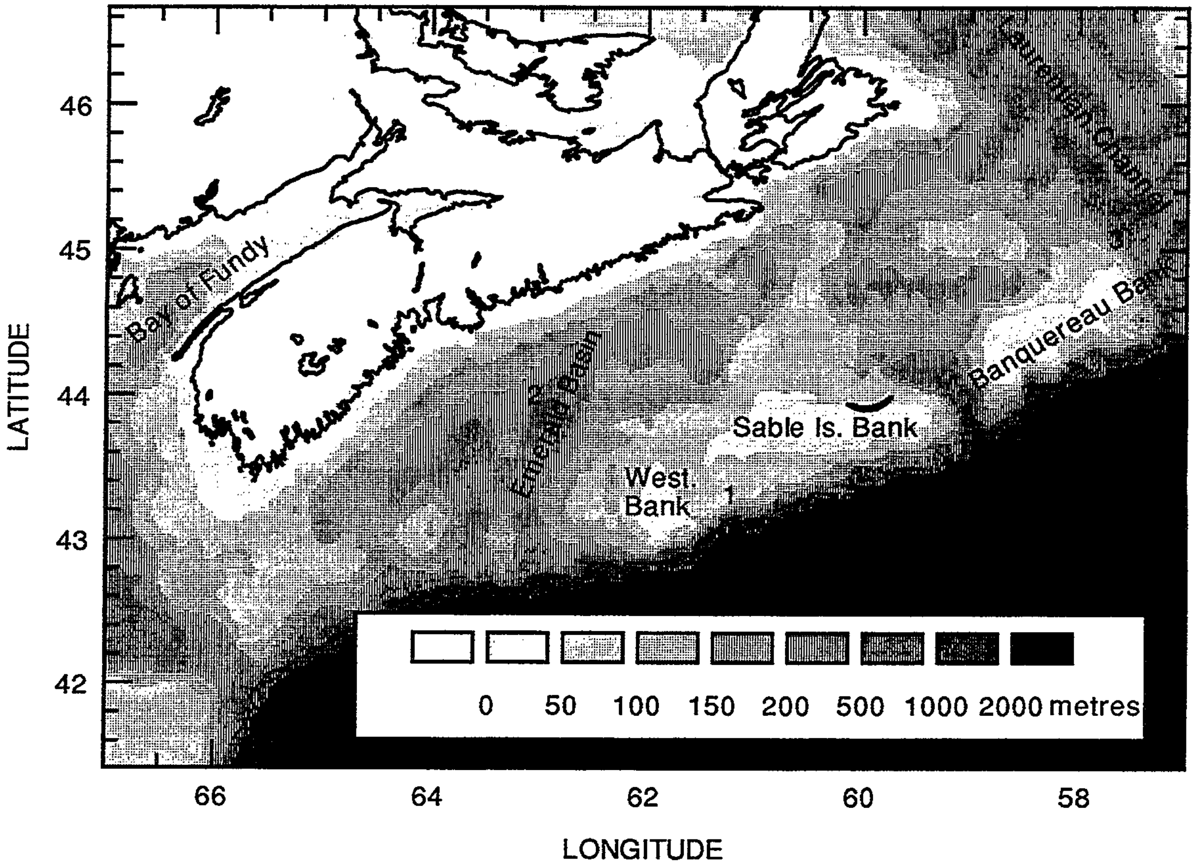

Figure 1: Bathymetric map of the Scotian shelf and DREA experimental locations.

2.2 Crustal Structure

The crustal structure of the Scotian margin has been determined by seismic refraction and seismic reflection transects across the margin [*e.g.* Barrett et al., 1964; Dainty et al., 1966; Keen and Cordsen, 1981]. A typical transect is shown in Figure 2. Three kinds of crust are shown: continental crust underlying the Nova Scotia landmass and inner shelf, transitional crust underlying the outer shelf and slope, and then oceanic crust further seaward. The continental crust is nominally 30 km thick. It is stretched by a factor of 2 under the shelf to form the transitional crust which is also intruded by volcanic material and its upper surface broken into a complex of fault bounded horsts and grabens[3]. The oceanic crust has a nominal thickness of 6 km.

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[3] Terms which describe large blocks of rock, length scales of hundreds to thousands of metres, which are shifted relative to adjacent blocks along steeply dipping faults which bound the blocks. Blocks uplifted are 'horsts' and blocks dropped to form valleys are 'grabens'.

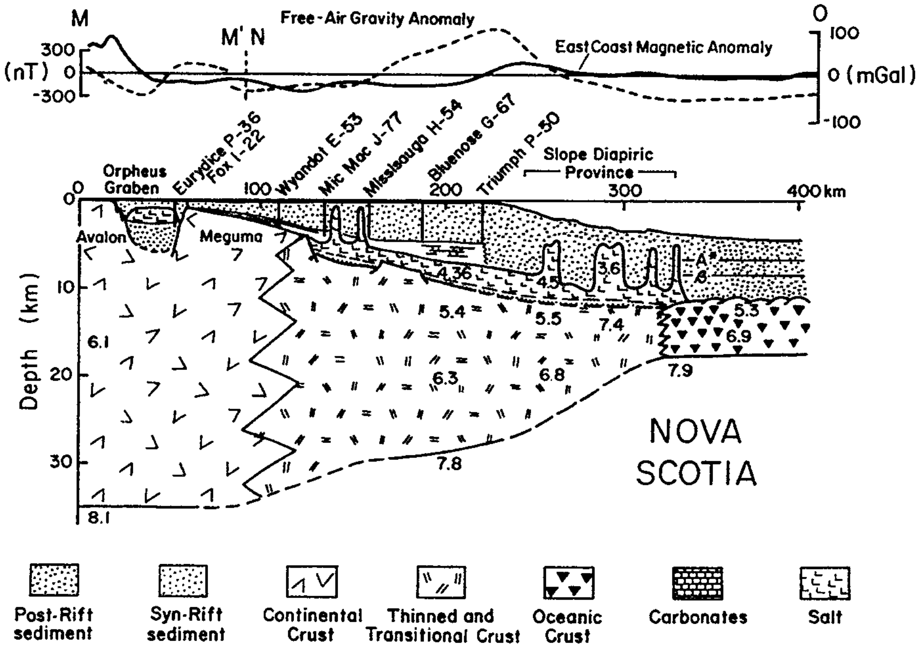

Figure 2: Transect of the crustal structure of the Nova Scotia continental margin with corresponding gravity and magnetic anomalies. Numbers on transects are seismic velocities in km/s. Deep wells near the transects have been projected onto the transect and are indicated by vertical black lines with well names above [Fig. 9.5 in Keen and Beaumont, 1990].

2.3 Sedimentary Basins

Sedimentary rock formations up to 18 km thick overly the crustal rocks on the Scotian Shelf (Figure 3). The Triassic rifting was accompanied by the deposition of non-marine clastic sediments with the rift basin. Following the rifting phase, salt accumulated in the Early Jurassic when sedimentary deposition was in a semi-restricted, shallow, quiet water environment. At sufficient confining pressure the salt behaves as a viscous fluid and can rise because of its low relative density. Accordingly, this salt now forms the diapirs which are prevalent under the Scotian Slope and rise. The deposition of carbonates followed in Middle and Late Jurassic time when the basin became less restricted allowing normal marine productivity. The Early Cretaceous was characterized by thick, regressive (relative sea level lowering), fluvial-deltaic formations of shale and sandstones. Sediments were deposited in a broad alluvial plain and deltas formed as a major river system drained much of the northeastern part of the Canadian Shield. The Late Cretaceous was marked by a global transgression (relative sea level rise) and the deepest waters encountered in the depositional history of the Scotian Shelf. The sediments deposited in this period are dominated by shale, mudstone, chalk and coarser clastics ranging from siltstones to conglomerates. In the Tertiary, mudstones, sandstones and conglomerates were deposited. The thickness of the sediments in this formation varies from zero along part of the middle shelf to more than 1500 m in some of wells in the Sable Subbasin near Sable Island.

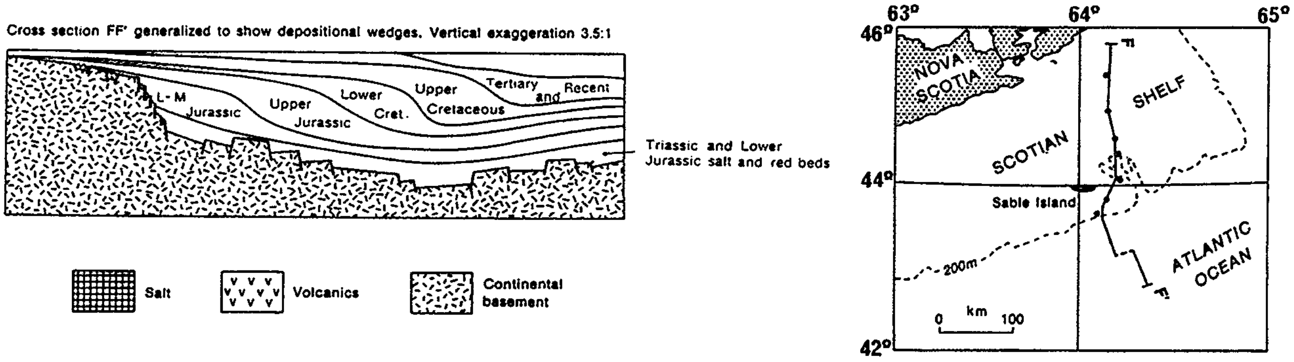

Figure 3: Generalized regional geological cross-section F-F' across the Scotian Shelf and slope [Fig. 5.19 in Wade and MacLean. 1990].

2.4 Hydrocarbon Reserves and Exploration

Hydrocarbon exploration activity has been ongoing for 34 years since initial geophysical surveys by Mobil Oil Canada in 1959. 300 000 line kilometres of seismic data have been acquired on the Scotian margin and 125 wells drilled on the Scotian Shelf and Slope up to July 1987. There have been 21 significant discoveries; 17 pools of gas and condensate, two oil and gas pools, and two oil pools. The most important hydrocarbon reservoirs are the sandstones of the Upper Jurassic and Early Cretaceous in the immediate vicinity of Sable Island. The shales deposited in the Middle Jurassic to Early Cretaceous are the most likely source rocks[4].

2.5 Bedrock Succession

The bedrock succession is the pre-Quaternary sequence of rocks which lie immediately beneath the unconsolidated surficial sediments (section 3). The aerial distribution of bedrock types and their respective physical properties merit discussion as they form the first rock layer which acoustic energy penetrating the surficial sediments will encounter. Following King and MacLean [1976], the offshore of Nova Scotia is divided into four bedrock regions. Two of these predominate on the Scotian Shelf and will be discussed in greater detail.

The first division consists of Cambro-Ordivician aged metamorphosed sedimentary rocks (metasediments) which continue offshore from mainland Nova Scotia. These rocks underlie the Gulf of Maine and the Inner Scotian Shelf (see physiographic definition in section 3). The surface of the bedrock has been modified by glacial erosion and its shape controls much of the bathymetry of the inner shelf. Within this division, there are also some areas of Devonian aged granites, such as the area south of Chebucto Head (Figure 1). The second division is a thick prism of Mesozoic-Cenozoic aged sedimentary rocks that underlie the outer areas of the Gulf of Maine, the Middle and outer Scotian Shelf, and the outer

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[4] Petrographic studies of organic residues showed the rocks to contain abundant herbaceous, woody and coaly material which upon maturation would generate largely gas and condensate.

Laurentian Channel. It is comprised of semi-compacted sandstones, limestones, and shales. The sedimentary beds dip gently seaward and its upper surface is identified by the marked erosional unconformity with the surficial succession. Exposed and buried channels cut into the bedrock are a common feature, particularly north of Sable Island and on Banquereau Bank. The contact between the two divisions occurs approximately 50 km south of Nova Scotia.

Typical physical properties of the rock types in the bedrock succession are as follows (see also tables 8.1 to 8.4 in King et al. [1983a]):

Division 1: Devonian Granite

V_p =	5.860 - 6.570 km/s	Sheridan and Drake [1968]
	4.800 - 5.500 km/s	Beebe and McDaniel [1980][5]
V_s =	3.300 km/s	Beebe and McDaniel [1980]
k =	0.1 dB/m -kHz	Beebe and McDaniel [1980]
ρ =	2.6 g/cm^3	Beebe and McDaniel [1980]

Division 1: Cambro-Ordivician-Silurian Shales

V_p =	3.500 - 3.560 km/s	Sheridan and Drake [1968]

Division 2: Cretaceous Sandstones

V_p =	2.720 - 2.730 km/s	Sheridan and Drake [1968]
	2.300 km/s	Beebe and McDaniel [1980]
V_s =	1.200 km/s	Beebe and McDaniel [1980]
k =	0.009 dB/m -kHz	Beebe and McDaniel [1980]
ρ =	2.3 g/cm^3	Beebe and McDaniel [1980]

Division 2: Tertiary

V_p =	1.935- 2.011 km/s	Hunter et al. [1982]
	2.000 km/s	Beebe and McDaniel [1980]
V_s =	0.900 km/s	Beebe and McDaniel [1980]
	0.520 km/s	Brocher [1983]
k =	0.05 dB/m -kHz	Beebe and McDaniel [1980]
ρ =	2.2 g/cm^3	Beebe and McDaniel [1980]

3. Quaternary Geology

The unconsolidated surficial sediments on the Scotian Shelf were deposited during the Quaternary period, notably the latest part of the Quaternary (<25 ka). Surficial sediment type and distribution is linked to two related events. These are the Wisconsinan Glaciation, the most recent episode of glaciation on the Scotian Shelf, and the relative sea level changes. During the Wisconsinan Glaciation, most of the Scotian Shelf was ice covered. Upon retreat of the glaciers, sediment entrained in the ice was deposited, thus all of the surficial sediment types have this provenance. Maximum ice coverage is estimated to have occurred at 25 ka and

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[5] All of the Beebe and McDaniel [1980] physical properties values are from a handbook, not observed. They were used in some geo-acoustic modelling on the Scotian Shelf.

maximum sea-level change at 18 ka (115 m lower than present) [see review by Piper, 1991]. Large portions of the outer banks remained exposed at 9 ka (40 m lower than present).

Following King and MacLean [1976], the Scotian Shelf has three physiographic divisions: the inner, middle, and outer shelf (Figure 1). The geology of the inner shelf, adjacent to the Nova Scotia coast, is dominated by the continuation of geological units observed on land. The seafloor has a gentle slope seaward and the surficial sediment cover is thin. The bedrock is comprised of resistant strata with limited and localized glacial erosion forming the over deepened basins and valleys. On the middle shelf, deep basins (*e.g.* Emerald and LaHave Basins) are incised into the softer Mesozoic-Cenozoic aged strata [Piper et al., 1990]. As the basins lie in the path of former major ice streams, their formation is ascribed to glacial erosion[6] [King et al., 1974]. On the outer shelf, broad depositional wedges of Quaternary sediment form the shallow banks (*e.g.* Western, Sable Island and Banquereau Banks). These sediments lie on a south dipping Tertiary aged bedrock which is over 200 m below sea level on Sable Island and Banquereau Banks. The bedrock is incised by deep channels (up to 550 m) that resemble tunnel valleys cut by subglacial melt water [Piper et al., 1990].

3.1 Surficial Sediment Types, Distribution, and Physical Properties

The Quaternary lithostratigraphy for the Scotian Shelf was initially defined by King [1970] on the basis of bathymetry echograms, airgun reflection profiles and more than 6000 grab samples. On average the Quaternary succession is 50 m thick and comprised of five formations: Scotian Shelf Drift, Emerald Silt, Sambro Sand, Sable Island Sand and Gravel, and LaHave Clay. The lithology, typical thicknesses, acoustic character, and origin of the formations is summarized in Table I and discussed below following King and Fader [1986] and King et al [1983]. The distribution of these lithostratigraphic units across the shelf [King, 1970] is shown in Figure 4 and an archetypal cross section [King and Fader, 1986; King et al., 1983] is shown in Figure 5. Fader [1991a] prepared an updated interpretation of the surficial geology of the Scotian Shelf which includes information from newer mapping techniques, including sidescan sonar, high resolution seismics and swath bathymetry. A further resource is the large collection of seabed photographs of the surficial geological formations in Lawrence et al. [1985].

3.1.1 Scotian Shelf Drift

The Scotian Shelf Drift is a glacial till (diamicton) deposited from grounded ice. It is a cohesive poorly sorted sediment generally containing angular fragments in the pebble / cobble / boulder range. It is dominantly sandy but contains abundant silt and clay. With the exception of the inner shelf, this formation overlies much of the bedrock on the Scotian Shelf in the sub-surface as a continuous blanket of relatively uniform thickness (10-15 m) in water depths > 120 m. Thick deposits, greater than 100 m, occur in moraines on the flanks of the basins and in a belt of low ridges parallel to the present coast, 30 to 40 km offshore.

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[6] Deep basins of this nature are not found on shelf areas of the southeastern United States which lie outside of the Quaternary ice limit.

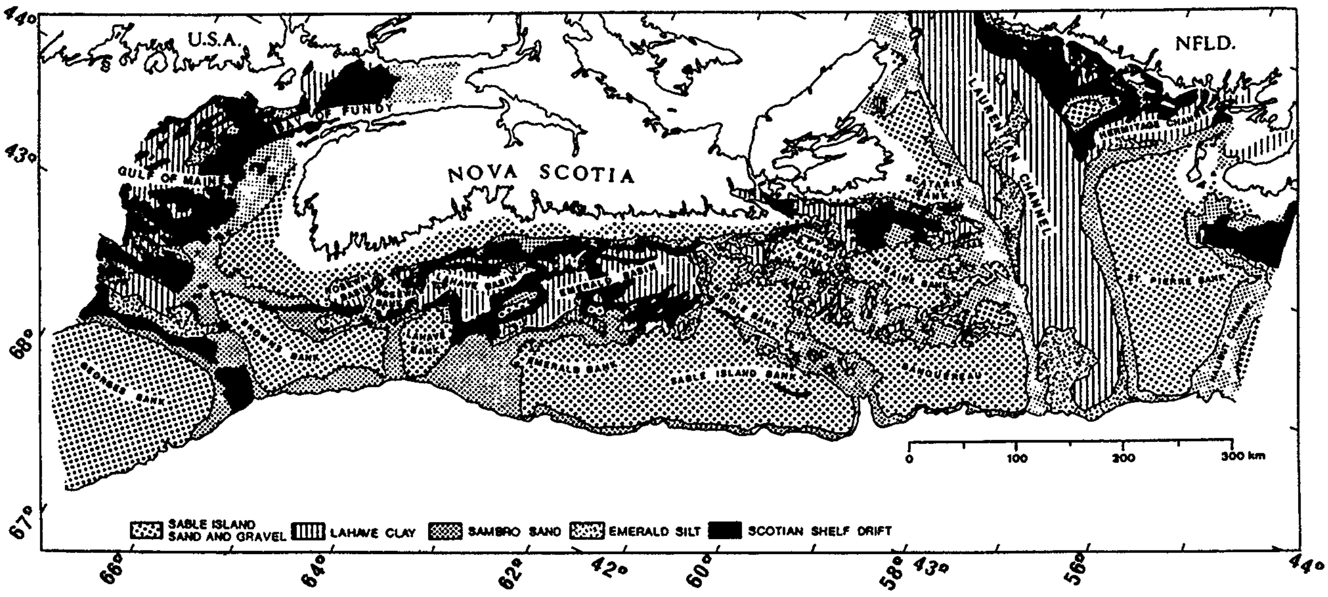

Figure 4: Surficial Geology of the Scotian Shelf [Fig 6.2 in King et al., 1983]

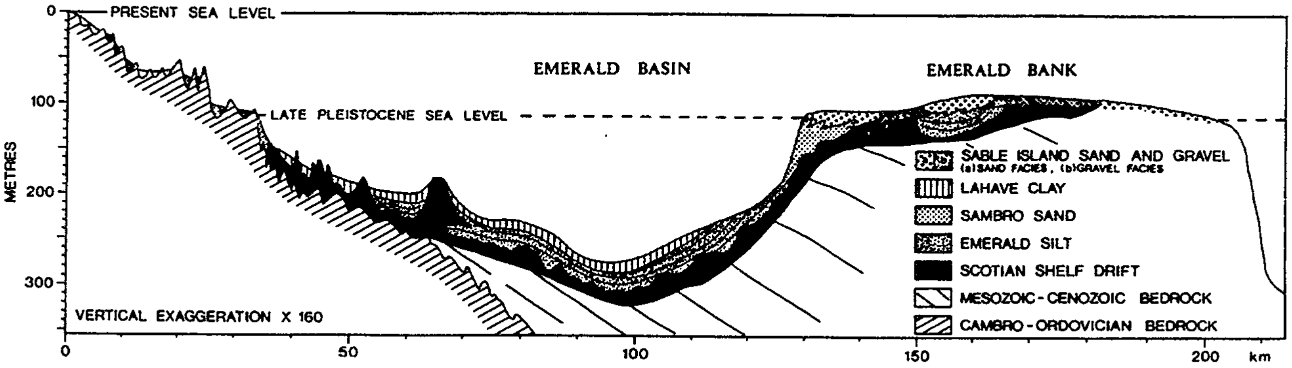

Figure 5: Schematic northwest-southeast cross-section of the surficial succession across Emerald Basin and Emerald Bank [Fig. 6.1 in King et al., 1983].

Formation	Lithology and distribution	Thickness	Acoustic character	Origin
LaHave Clay	Greyish brown, soft, silty clay grading to clayey silt, confined mainly to basins and depressions of shelf.	0-70 m	Generally transparent without reflections. Some weak continuous coherent reflections in base of section becoming stronger in nearshore sandy facies.	Derived by winnowing of glacial sediments on banks and transported to basins. Time equivalent of Sable Island Sand and Gravel and Sambro Sand on banks.
Sable Island Sand and Gravel	Fine to coarse, well-sorted sand grading to sub-rounded to rounded gravels. Unconformably overlies Emerald Silt and Scotian Shelf Drift in water depths less than 120 m.	0-50 m, generally a veneer	Highly reflective seabed. Generally closely spaced, continuous, coherent reflections if deposit is of sufficient thickness to resolve.	Derived from Emerald Silt and Scotian Shelf Drift through reworking during Holocene transgression. Time equivalent of LaHave Clay in basins.
Sambro Sand	Silty sand grading locally to gravelly sand and well-sorted sand	0-20 m, generally a veneer	Similar to Sable Island Sand and Gravel.	Deposited sublitorally with respect to the Late Wisconsin low sea level of 100-120 m. Time equivalent to basal LaHave Clay and upper Emerald Silt facies B.
Emerald Silt facies C	Not well sampled.	0-100 m	Discontinuous coherent reflections; transitional between Emerald Silt facies A and glacial till.	Deposition at grounding line.
Emerald Silt facies B	Dark greyish brown, poorly sorted clayey and sandy silt with some gravel. Poorly developed rhythmic banding.	0-40 m	Medium to low amplitude, continuous, coherent reflections, and to some degree a ponded sedimentational style.	Proglacial deposition.
Emerald Silt facies A	Dark greyish brown, poorly sorted clayey and sandy silt, some gravel. Well developed rhythmic banding.	0-100 m	High amplitude continuous coherent reflections, highly conformable to substrate irregularities.	Deposition from beneath ice shelf. Time equivalent to parts of Scotian Shelf Drift.
Scotian Shelf Drift	Very dark greyish brown, cohesive glacial till comprised of poorly sorted sandy clay and silt with variable gravel.	0-100 m	Incoherent reflections, sometimes with scattered point-source reflections.	Deposition from grounded ice sheet.

Table 1: Quaternary lithostratigraphy of the Scotian Shelf [after King and Fader, 1986].

Acoustically, Scotian Shelf Drift appears on high resolution seismic profiles as a uniform dense pattern of incoherent reflections, including dispersed point source reflections. Typical physical properties are (see also table 8.6 in King et al. [1983a]):

$V_p =$ 1.745 - 1.92 km/s   Hunter et al. [1982]
1.500 - 1.600 km/s   Dodds [1990][7]
$k =$ 0.0065 dB/m -kHz   Beebe and McDaniel [1980]
$\rho =$ 2.1 g/cm^3 Beebe and McDaniel [1980]

3.1.2 Emerald Silt

The Emerald Silt overlies and interfingers with the Scotian Shelf Drift. It is a poorly sorted silt that is acoustically well stratified. It is sub-divided into three facies (types) based on the nature of the high resolution seismic reflection returns: A- high amplitude continuous

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[7] The till in this analysis was deposited when the ice sheet was being lifted off the seabed by its own bouyancy. The relatively low velocities arise from the minimal pressure exerted by the overlying ice and resulting lack of compaction of the till.

coherent reflections; B- medium to low amplitude continuous coherent reflections and C- discontinuous coherent reflections. Reflections from layers in facies A and B show a rhythmic banding of smooth, parallel and closed spaced reflections. Facies A occurs mainly at the base of the Emerald Silt formation and is interbedded with the Scotian Shelf Drift. The reflectors tend to parallel the surface morphology of the underlying till or bedrock. The rhythmic bands arise from alternating bands of silt and clay, both of which vary from 1 to 3 cm in thickness. The average grain size distribution is 3% gravel, 10% sand, 40% silt, and 47% clay. It is formed from subglacial meltout debris from a stable but floating ice shelf. Rhythmic bands developed by the differential sorting of material settling through a water column whose thickness was variable.

Facies B overlies facies A in the basins and depressions on the Scotian Shelf and reaches a maximum thickness of 40 m on the western Scotian Shelf. The rhythmic banding is much weaker than facies A, though the thickness of bands and distribution of gravel is similar. The average grain size distribution is 3% gravel, 13% sand, 47% silt, and 37% clay. Point-source hyperbolic reflections (probably due to boulders) occur in both facies A and B, but appear more common in facies B. Facies B is thought to be deposited from ice which is drifting, that is, more open water conditions than facies A. Facies C is a transitional facies with properties which grade between Emerald Silt facies A and B and the Scotian Shelf Drift. It is most prevalent in the southern Gulf of Maine where it can attain a thickness of 20 m. The strong contrast in the acoustic character of the Scotian Shelf Drift and Emerald Silt result from differing styles of deposition of the material rather than significant textural differences between the two units.

Typical physical properties are (see also table 8.7 in King et al. [1983a]):

$V_p =$	1.480 - 1.590 km/s	Hunter et al. [1982]
	1.550 - 1.600 km/s	Beebe and McDaniel [1980]
	1.470 - 1.530 km/s	Dodds [1990]
	1.430 - 1.520 km/s	Dodds [1990][8]
$k =$	0.056 dB/m -kHz	Beebe and McDaniel [1980]
	0.022 dB/m -kHz	Dodds [1980]
$\rho =$	1.56 g/cm^3	Beebe and McDaniel [1980]

3.1.3 Sambro Sand

Deposits of the Sambro Sand Formation form a thin veneer, thickness less than 0.3 m, which overlies the Emerald Silt and Scotian Shelf Drift Formations. It is restricted to areas of the seabed which are below the level of the lowest sea level stand in the Late Pleistocene (depths > 115 m). It formed as a sublittoral deposit with respect to the paleo-shoreline through the erosion and reworking of the underlying Emerald Silt and Scotian Shelf Drift.

Acoustically, when it is thick enough to be observed on high resolution seismic records, it is characterized by weak fairly continuous coherent reflections. Typical physical properties are (see also table 8.8 in King et al. [1983a]):

$V_p =$	1.590 - 1.640 km/s	Dodds [1990]
	1.650 km/s	Beebe and McDaniel [1980]

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[8] In areas where gas is present, velocities are lower and demonstrate a greater variability in calculated value.

$k =$	0.163 dB/m-kHz	Dodds [1980]
	0.037 dB/m -kHz	Beebe and McDaniel [1980]
$\rho =$	1.96 g/cm^3	Beebe and McDaniel [1980]

3.1.4 Sable Island Sand and Gravel

The Sable Island Sand and Gravel Formation is comprised of well-sorted and well rounded particles of sand and gravel. It is mainly derived from the erosion of former glacial deposits on the shallow banks. These sediments, above the lowest sea level stand (depths < 115 m), were reworked in the high energy environment present when relative sea-level was rising. It is similar to Sambro Sand in terms of its thickness, bedforms and broad aerial distribution. The thickest deposits occur in sand wave fields, relict sand bars, and isolated depressions on the inner shelf.

Acoustically, its reflectors are closely spaced, continuous, coherent, and of medium intensity. Bedding planes which indicate direction of bedform growth are often evident. Typical physical properties are (see also tables 8.9 and 8.10 in King et al. [1983a]):

Sand		
$V_p =$	1.550 - 1.640 km/s	Dodds [1990]
	1.572 - 1.661 km/s	McKay and McKay [1982]
	1.595 - 1.775 km/s	Hunter et al. [1982]
$V_s =$	0.260 km/s	Brocher [1983]
$k =$	0.037 dB/m -kHz	Beebe and McDaniel [1980]
	0.22 dB/m -kHz	Dodds [1980]
$\rho =$	1.96 g/cm^3	Beebe and McDaniel [1980]
	1.7 g/cm^3	Brocher [1983]

Gravel		
$V_p =$	1.850 - 1.900 km/s	Beebe and McDaniel [1980]
	1.670 - 1.780 km/s	Dodds [1990]
$k =$	0.009 dB/m -kHz	Beebe and McDaniel [1980]
$\rho =$	2.06 g/cm^3	Beebe and McDaniel [1980]

3.1.5 LaHave Clay

LaHave Clay is a postglacial loosely compacted silty clay (greater than 50% clay) to clayey silt (greater than 50% silt size). It was deposited at the same time as the Sable Island Sand and Gravel and its distribution is mainly confined to the basins and depressions of the shelf where it is ponded over underlying sediments. It is derived by a winnowing of the fine material from the sediments on the banks during relative sea level rise and from adjacent land areas.

Acoustically, it is generally a transparent layer and can be penetrated using 12 kHz echo sounders. Typical physical properties are (see also table 8.11 in King et al. [1983a]):

$V_p =$	1.460 - 1.490 km/s	Dodds [1990]

	1.261 - 1.420 km/s	McKay and McKay [1982][9]
	1.480 - 1.490 km/s	Beebe and McDaniel [1980]
k =	0.056 dB/m -kHz	Beebe and McDaniel [1980]
	0.023 /m -kHz	Dodds [1980]
ρ =	1.50 - 1.54 g/cm^3	Beebe and McDaniel [1980]

3.2 Maps of Quaternary Sediment Thickness

To complement the maps of surficial sediment distribution prepared by King [1970], DREA contractors prepared maps of the thickness of the Quaternary sediments (isopach maps). Two DREA contractors [King et al., 1985; MacKay, 1990] examined some 25,000 line km of high resolution seismic data (section 4.1) on the Scotian Shelf and Grand Banks and prepared 1:300 000 scale maps. King et al. [1985] mapped isopachs of the Quaternary succession for areas of the Scotian Shelf where there was reflection data, either obtained for DREA [King et al., 1983] or for other public agencies (see compilation in King et al. [1985])

The maps prepared by MacKay [1990] measure the thickness of the Quaternary succession excluding the till[10] and are limited geographically to areas where coverage in the King et al. [1985] study was sparse (*e.g.* Western Bank, Sable Island Bank, and the Gully). Amos and Knoll [1987] have prepared an isopach map for Holocene (most recent part of the Quaternary) sediments on part of Banquereau Bank, though it is some distance from the location of DREA experimental site 3 (section 6.3). Excerpts from MacKay [1990] and King et al. [1985] maps are presented for DREA experimental sites 1 and 2 (sections 6.1 and 6.2) respectively.

3.3 Surficial Bathymetric Features

Several seabed features have been identified from sidescan sonar and high resolution seismic data supplemented with bottom photographs and submersible observations. These are bedrock outcrops, iceberg furrows, pockmarks, sand ridges, and shell beds. Each of these features will be discussed, following Fader [1991b].

(a) Bedrock outcrops are most common on the Inner Shelf. Factors which contribute to their presence are the resistant nature of the metasedimentary and granitic rocks in this area, minimal deposition of glacial sediments and significant erosion of whatever material was deposited.

(b) Iceberg furrows are present on large areas of the Inner and Middle Shelf attesting to the presence of icebergs in late glacial times. They cut into the seabed to a maximum depth of 8 m and are > 100 m in width.

(c) Pockmarks are cone-shaped gas escape craters where deeply generated hydrocarbon gases escape to the seabed [Fader, 1991c]. They are most common in the basins (site 2) and channels on the Scotian Shelf. They range from a few metres to >300 m in diameter and from <1 m to 30 m in depth. They can attract dense communities of bivalves, shell debris and other benthic animals because of the chemosynthetic bacteria which gather at these locations.

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[9] These velocities were calculated by a wide angle reflection technique and appear to be anomalously low.

[10] The sparker source does not penetrate the surficial succession as deeply as in the Huntec DTS or airgun reflection profiles.

Lastly, there may be an association between trawling during fishing operations and pockmarks which appear to be preferentially aligned along the length of trawls. Disturbance of the sediments allows for the preferential venting of gas and suggests that some pockmarks are recent.

(d) Sand ridges are typically found on the bank areas of the Outer Shelf (site 1). They can reach a height of 30 m, length of 60 km and width of 8 km and can migrate slowly. Some are formed by tidal currents and others are associated with storm waves and associated currents.

(e) Shell beds are dense communities of benthic organisms, living or dead. They appear as circular-lenticular patches of high acoustic back scatter on sidescan sonar images. They are widespread on outer Sable Island Bank [Amos and Nadeau, 1988] and Green Bank. They may also be present at other locations on the Scotian Shelf where there is little or no sidescan coverage.

4. Geo-Acoustic Related Databases

4.1 High Resolution Seismic Reflection Data

High resolution seismic data is used in the identification of surficial sediment type and thickness. A map of high resolution reflection track lines on the Scotian Shelf is in the compilation control data prepared by the Atlantic Geoscience Centre [1991]. Systems which have been used to collect high resolution seismic reflection data include the Huntec Deep Tow Seismic (DTS), Nova Scotia Research Foundation (NSRF) surface and deep tow sparker, and airguns. The data principally reside with three agencies: the Atlantic Geoscience Centre (AGC), NSRF, and the Canada-Nova Scotia Offshore Petroleum Board (CNSOPB). King et al. [1985] provide track charts and a tabular summary of AGC seismic data. MacKay [1988] provide track charts and a tabular summary of the NSRF seismic data. The seabed seismic surveys at wellsites are held by CNSOPB who have compiled a list of all the geophysical data at each wellsite [Bigelow, 1993, Personal Communication]. The use of the reflection data in the preparation of maps of Quaternary sediment thickness is discussed in section 3.2.

4.2 Cores, Boreholes, and Wellsites

Cores and boreholes are used to sample the Quaternary sediments on the Scotian Shelf. A map of core locations on the Scotian Shelf is in the compilation of control data prepared by the Atlantic Geoscience Centre [1991]. Typically the cores are used for textural and petrological studies, but some cores also have direct laboratory measurements of surficial sediment physical properties such as V_p, V_s, k, and ρ. Conventional piston cores can penetrate up to 12 m in areas where there is a muddy seabed, and 2 to 8 m in alternating sands and muds. Consequently, most piston cores are limited to the basin areas on the Shelf. On sand bottoms such as the banks on the Outer Shelf, other techniques must be used as core penetration is minimal and sample recovery is even worse. Geotechnical boreholes have been used in these areas, particularly near Sable Island, to determine the shear strength of the seabed for engineering purposes [Jacques, Whitford and Associates, 1985]. Physical properties can also be measured *in situ* at exploratory wellsites, however, there are no measurements in the surficial sediment succession. This portion of the drill hole is cased to provide for stability of the drill stem.

4.3 Swath Bathymetry and Sidescan Sonar

Sidescan sonar has been used principally to map the distribution of surface features (section 3.3) on the Scotian Shelf [e.g. Amos and Nadeau, 1988] and as a qualitative tool to map surficial sediment type. Silt and clay have a low back scatter intensity, while sand and bedrock outcrops have a high back scatter intensity. The distribution of all sidescan sonar tracks on the Scotian Shelf is shown in the map prepared by the Atlantic Geoscience Centre [1991]. Swath bathymetry data are limited; the most extensive survey on the Scotian Shelf is an area south of Chebucto Head [Courtney and Costello, 1993]. In this area, it has revealed a seafloor morphology which is far more complex than revealed by the relatively sparse sampling which typical seismic reflection and 12 kHz bathymetry provide. As with sidescan sonar systems, the potential to remotely classify surficial sediments based on back scatter intensity is being pursued [Hughes Clarke, 1993].

5. Physical Oceanography of the Scotian Shelf

An appreciation of the physical oceanography of the Scotian Shelf is necessary to (a) understand the forces which are currently shaping the seabed, (b) to predict its influence on instruments which are deployed and design experiments accordingly, and (c) to model acoustic propagation when major oceanographic features are present. This discussion is divided into two components which reflect different time scales of ocean water circulation. These are the low frequency mean and seasonal circulation and the higher frequency variability due to tidal and wind forcing.

5.1 Mean Circulation and Vertical Structure

Following a review by Smith and Schwing [1991], there are two main sources of water on the Scotian Shelf: slope water and outflow from the Gulf of St. Lawrence. The waters join to form the Nova Scotian Current flowing southwest, parallel to the coastline, confined to within 80 km of the coast on the inner shelf (Figure 6). As it moves down the coast, it is modified by exchanges with offshore waters which tend to flow in a northeast direction parallel to the coastline and inshore of the Gulf Stream. The rugged topography of the Scotian Shelf strongly influences the path of the current and its exchange with offshore waters. Maximum mean surface velocities of inshore currents on the Scotian Shelf lie between 0.1 and 0.3 m/s. In Figures 7,8, and 9, vector mean currents for all months of a historical current meter data collection[11] are presented for surface (<30 m), mid (30 - 80 m) and deep water (>80 m) on the Scotian Shelf. [Gregory and Smith, 1988] also provide monthly summaries of vector mean currents, low-frequency variability, and mid-frequency (tidal) variability in tabular form as a function of geographical location and in graphical form.

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[11] 672 moorings on the Scotian Shelf with over two thousand months of observations, Gregory and Smith [1988]

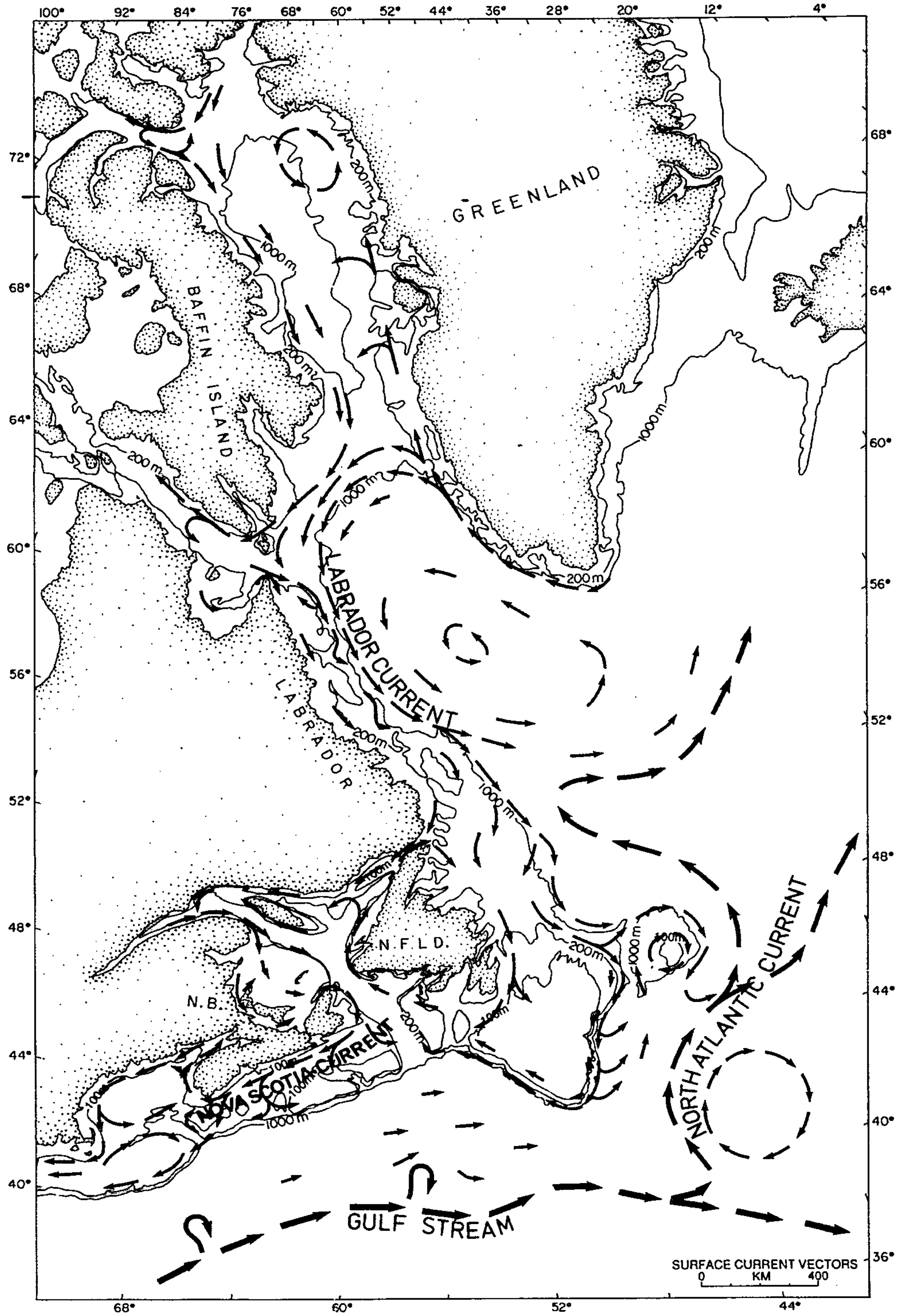

Figure 6: Qualitative estimation of the surface circulation off eastern Canada [Fig. 1b in Smith and Schwing, 1991].

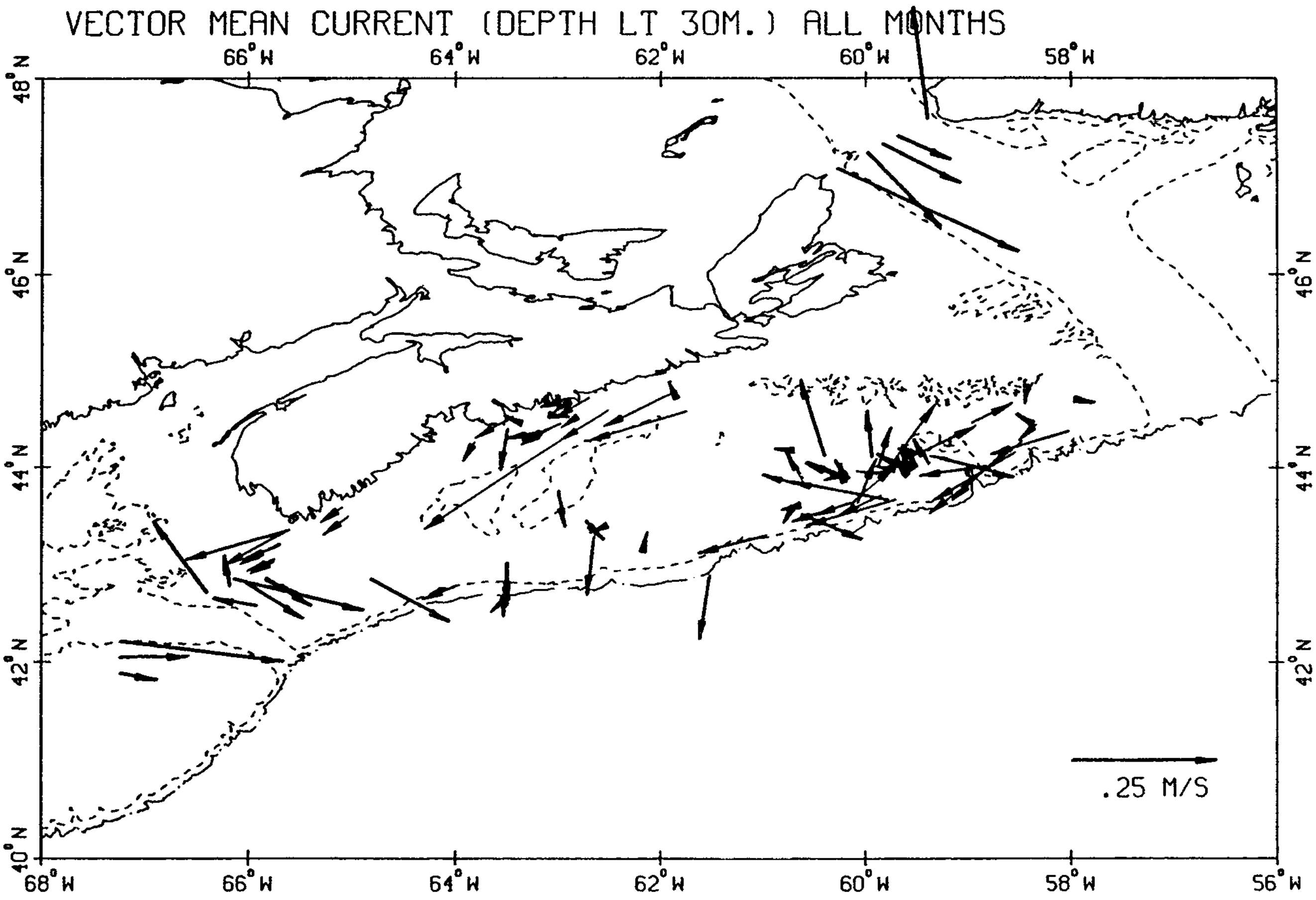

Figure 7: Vector mean currents for all months on the Scotian Shelf at depths < 30 m [Gregory and Smith, 1988].

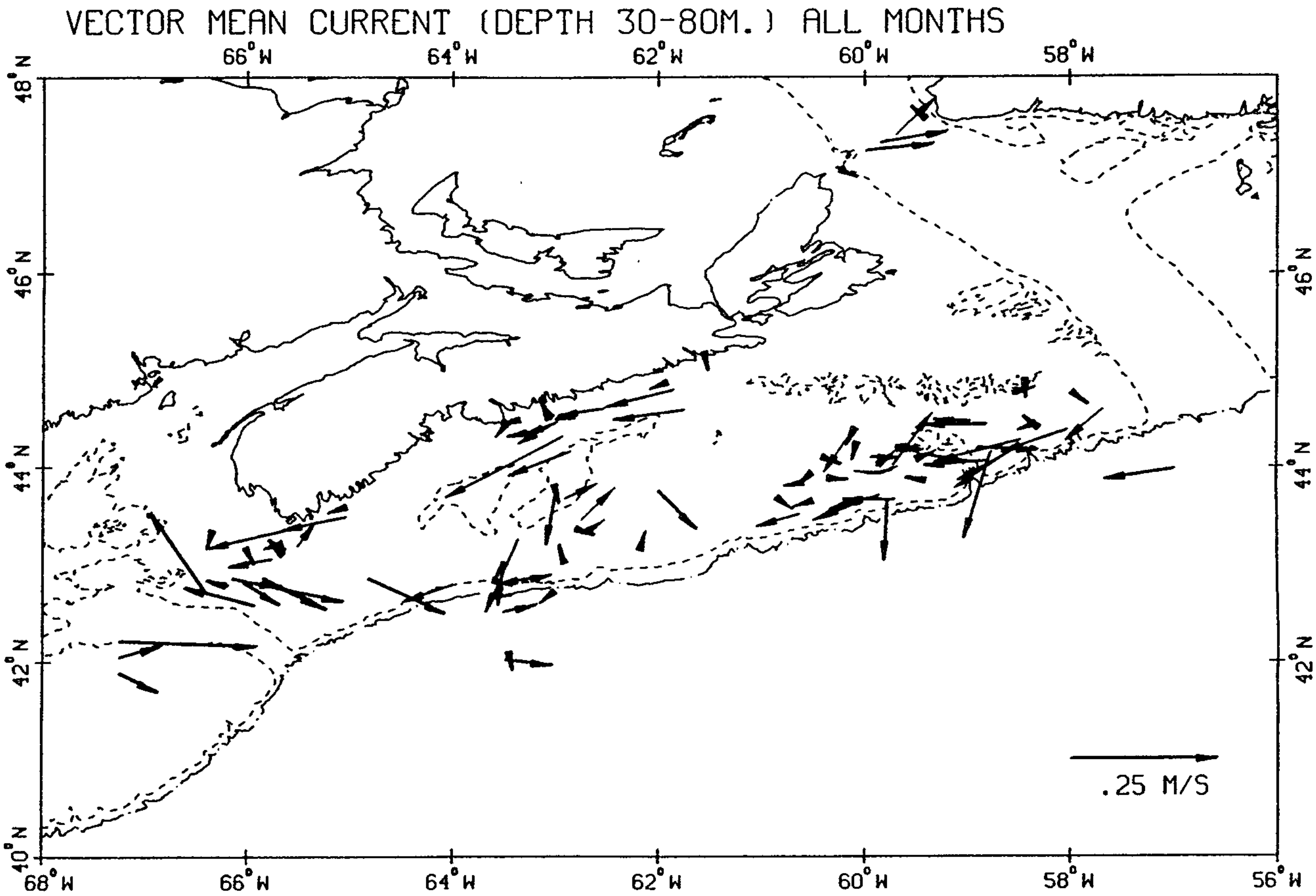

Figure 8: Vector mean currents for all months on the Scotian Shelf, depths from 30 - 80 m [Gregory and Smith, 1988].

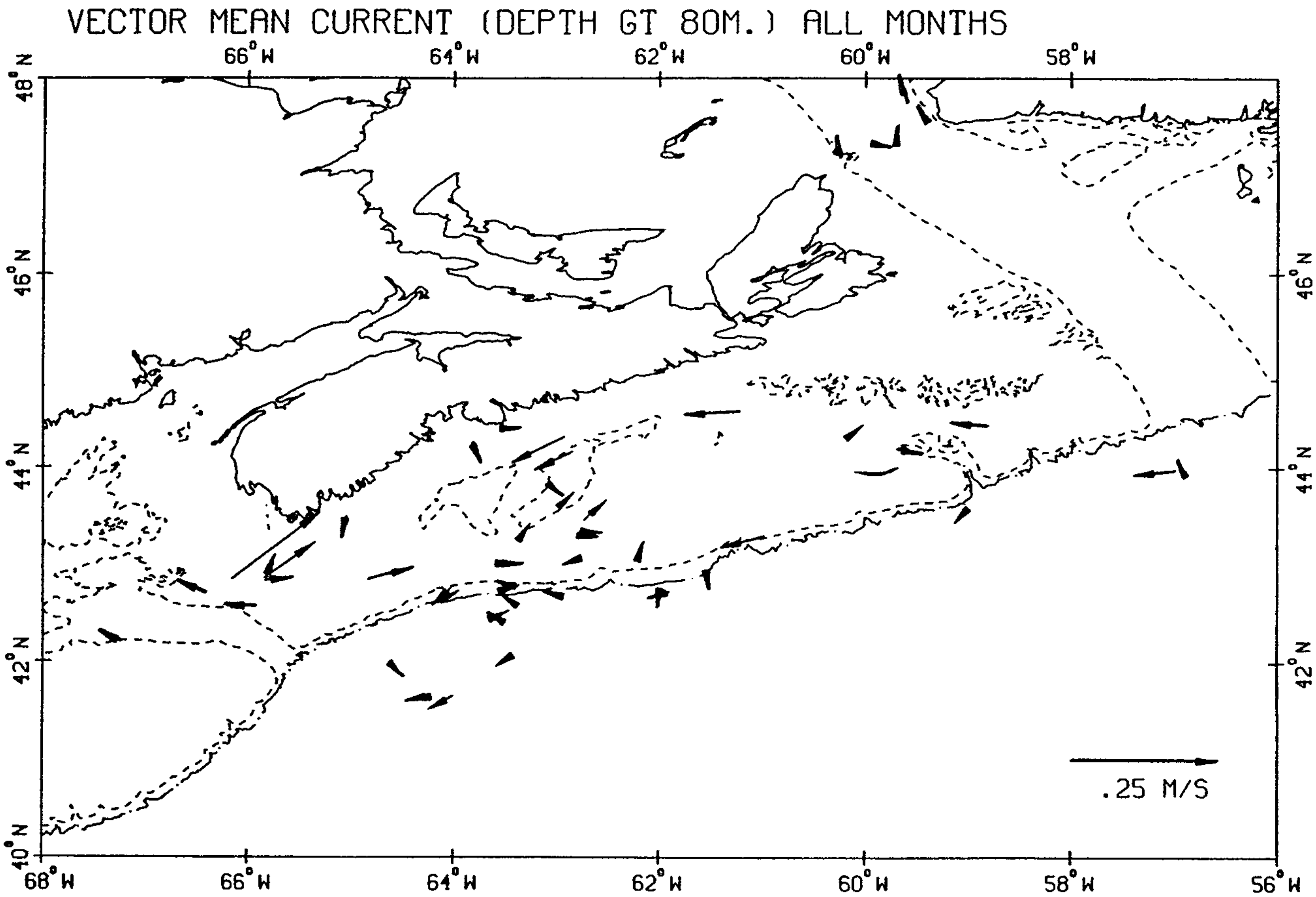

Figure 9: Vector mean currents for all months on the Scotian Shelf, depths > 80 m [Gregory and Smith, 1988].

Within the slope water, two water masses can be distinguished. The surface layer is warm saline water, a mixture of Gulf Stream and coastal waters. Below 200 m is the Labrador Slope water, a mixture of Labrador Current and North Atlantic water. The warm slope water has an eastward component of flow while the Labrador water has a westward component of flow giving rise to a sharp front region at their boundary. The slope water is an area of considerable variability. In particular, the Gulf Stream sheds large scale volumes of water in the form of rings and meanders [Smith, 1978], which move off to the north into the slope water. They carry warm and saline subsurface oceanic water to the edge of the shelf. An example of an eddy shed from the Gulf Stream abutting the edge of the Scotian Shelf is shown in Figure 10, a satellite image of sea surface temperature from the AVHRR (Advanced Very High Resolution Radiometer) on NOAA polar orbiting satellites [Smith et al., 1993]. The fronts between coastal, slope, and Gulf Stream waters are associated with regions of high biological productivity.

The vertical structure of the water column on the shelf has three layers. The surface layer has a low salinity as a result of runoff and a temperature which varies seasonally. The intermediate layer is cold with a higher salinity. The bottom layer, is warmer $T > 5^\circ$ C and saline $> 33.5^\circ$ C. In the summer, light southwesterly winds prevail and the water column is highly stratified. The persistent summer winds produce a band of cold upwelled water near the coast. In the winter, vertical mixing of the water columns increases in shallow water (<100 m) because strong currents are developed, especially near the bottom. However, the water column over the shallowest banks may be well mixed throughout the year. The vertical temperature and salinity structure of the water column dictate its sound speed profile. From bathythermagraph measurements on the Scotian Shelf, Banks [1960] present typical sound speed profiles through all seasons.

5.2 Tidal Variability

Gregory [1988] presents a statistical summary of tidal current variability on the Scotian Shelf based on moored current meter data and also provides a map of simulated data for the entire Scotian Shelf generated by a barotropic tidal circulation model. The observational data (Figure 11), are concentrated in specific areas, such as Sable Island, with very little coverage elsewhere. To avoid clutter, all observations within 0.05 degrees in latitude or longitude were combined. The greatest tidal current variability is found at the entrance to the Bay of Fundy whose geometry produces a near resonant response to the semidiurnal tidal forcing. Gregory [1988] also provide a tabular summary of tidal current variability as a function of geographical location.

In Figures 12,13, and 14, tidal ellipses[12] from the numerical model simulating tidal circulation [Gregory, 1988] are presented for the M2, K1, and O1 tides. These tides are the principal lunar semidiurnal (M2), lunisolar diurnal (K1) and principal lunar diurnal (O1) and have periods of 12.421, 23.935, and 25.819 hours respectively [Apel, 1987]. They are considered to be the most important as they can account for 94% of the observed tidal current variance on the Scotian Shelf. To reduce clutter, every second tidal ellipse is plotted giving a grid resolution of 0.2 by 0.2 degrees. The numerical results also demonstrate that the largest

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[12] When predictions of the speed and direction of the current at a station are plotted as vectors, the end-points of the vectors will trace out an ellipse in the course of a tidal period. The form of the ellipse may be distorted if flood and ebb flows are unsymmetrical or a mean flow is superimposed on the tidal current. Methods for presenting tidal current observations are reviewed in section 2.8.1 of Bowden [1983].

tidal currents are found on the shallow portions of the banks on the outer shelf (K1 and O1 tides) and at the entrance to the Bay of Fundy (M2 tides).

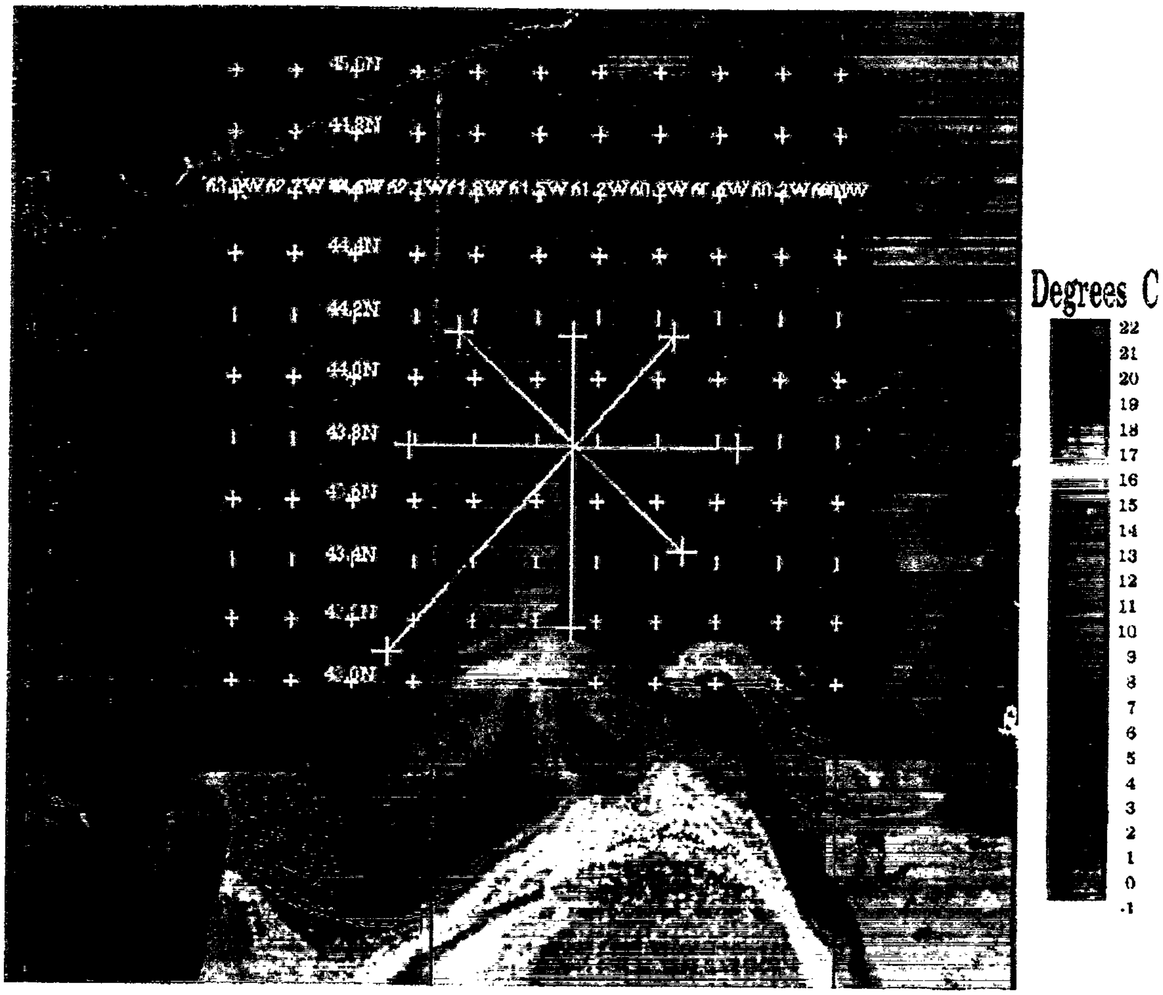

Figure 10: Advanced Very High Resolution Radiometer satellite image (AVHRR) of sea surface temperature on the Scotian Shelf and Slope on 8 May 1993 [Smith et al., 1983].

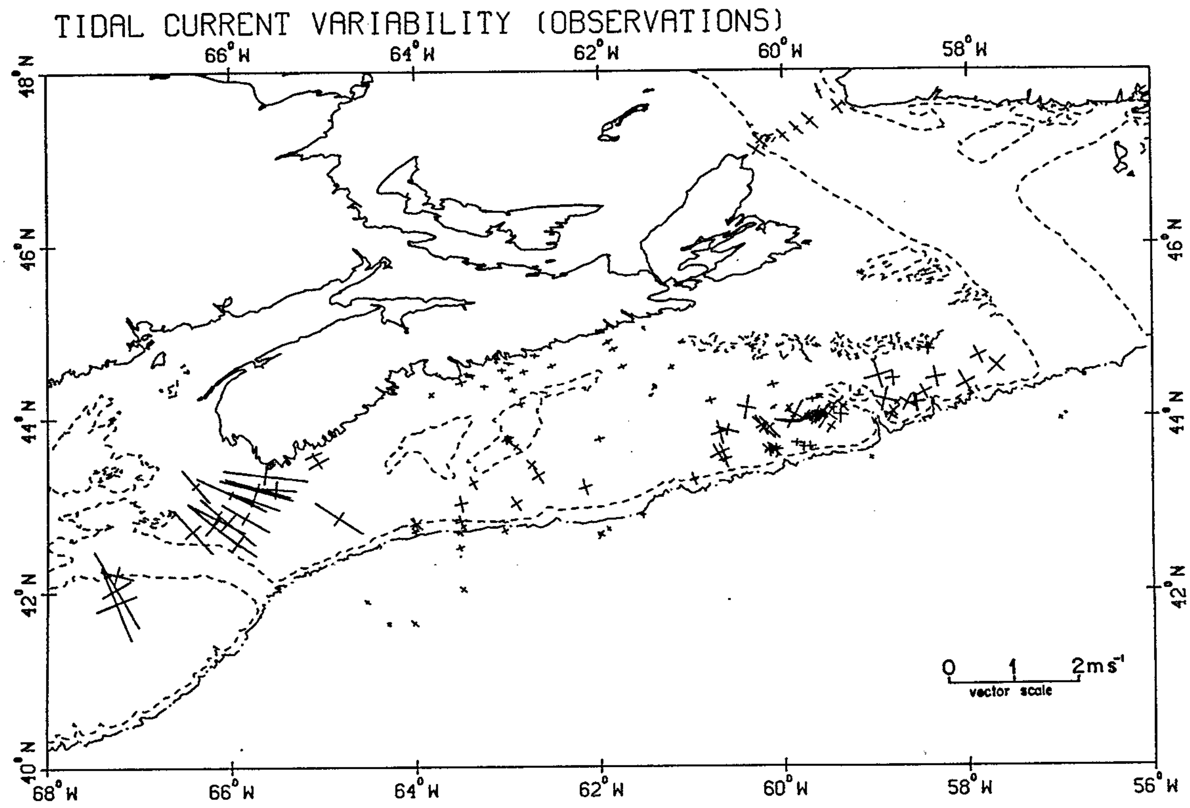

Figure 11: Observations of tidal current variability on the Scotian Shelf [Gregory, 1988].

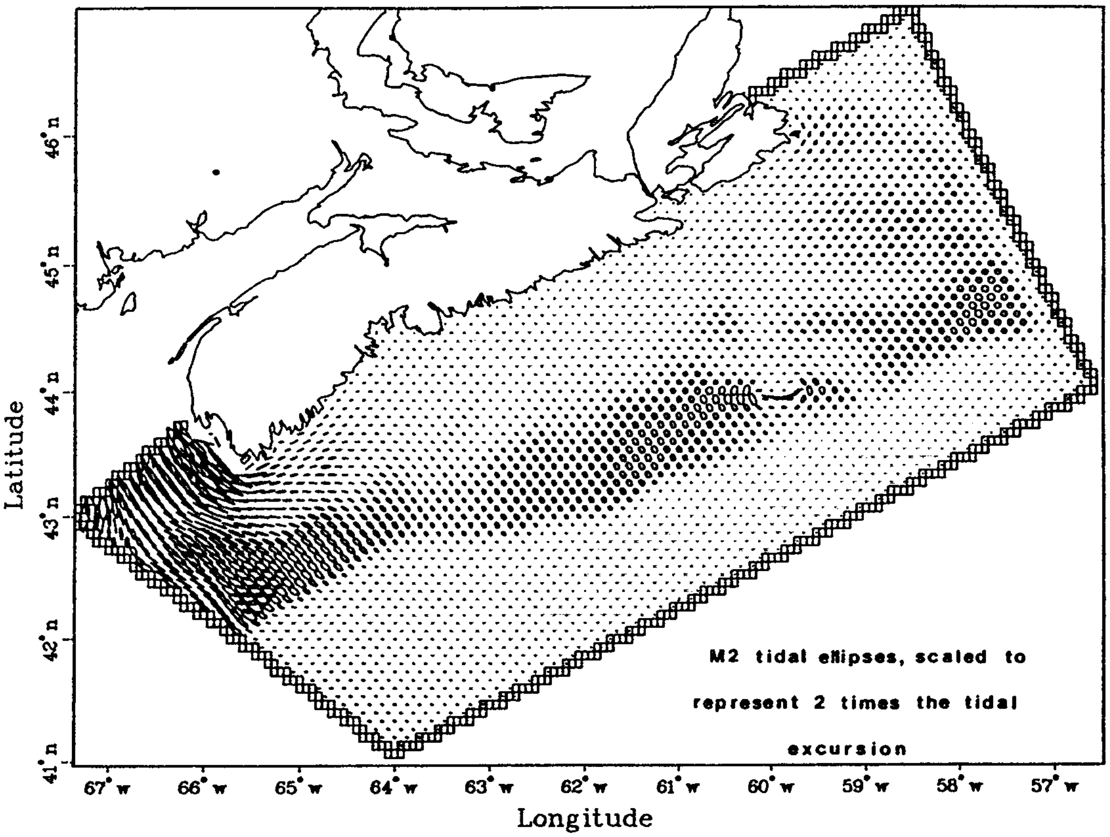

Figure 12: Tidal ellipses from a numerical model simulating tidal circulation for the principal lunar semidiurnal (M2) tide [Gregory, 1988].

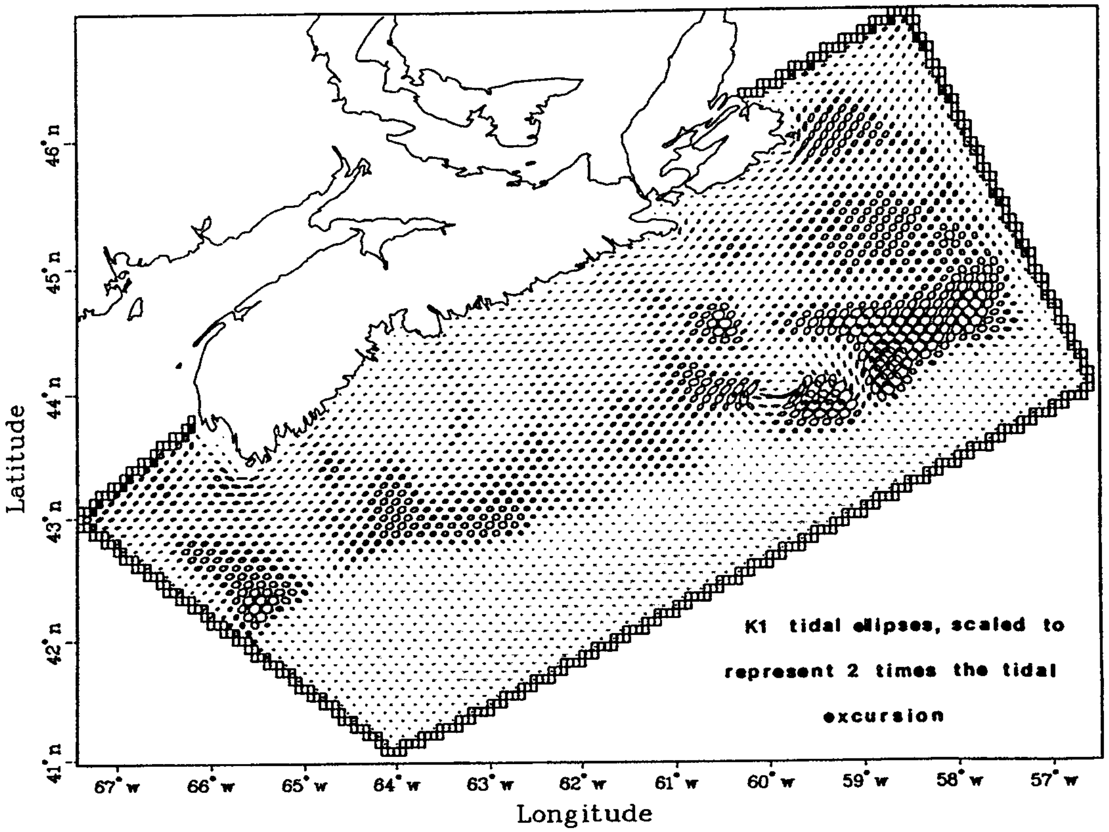

Figure 13: Tidal ellipses from a numerical model simulating tidal circulation for the principal lunisolar diurnal (K1) tide [Gregory, 1988].

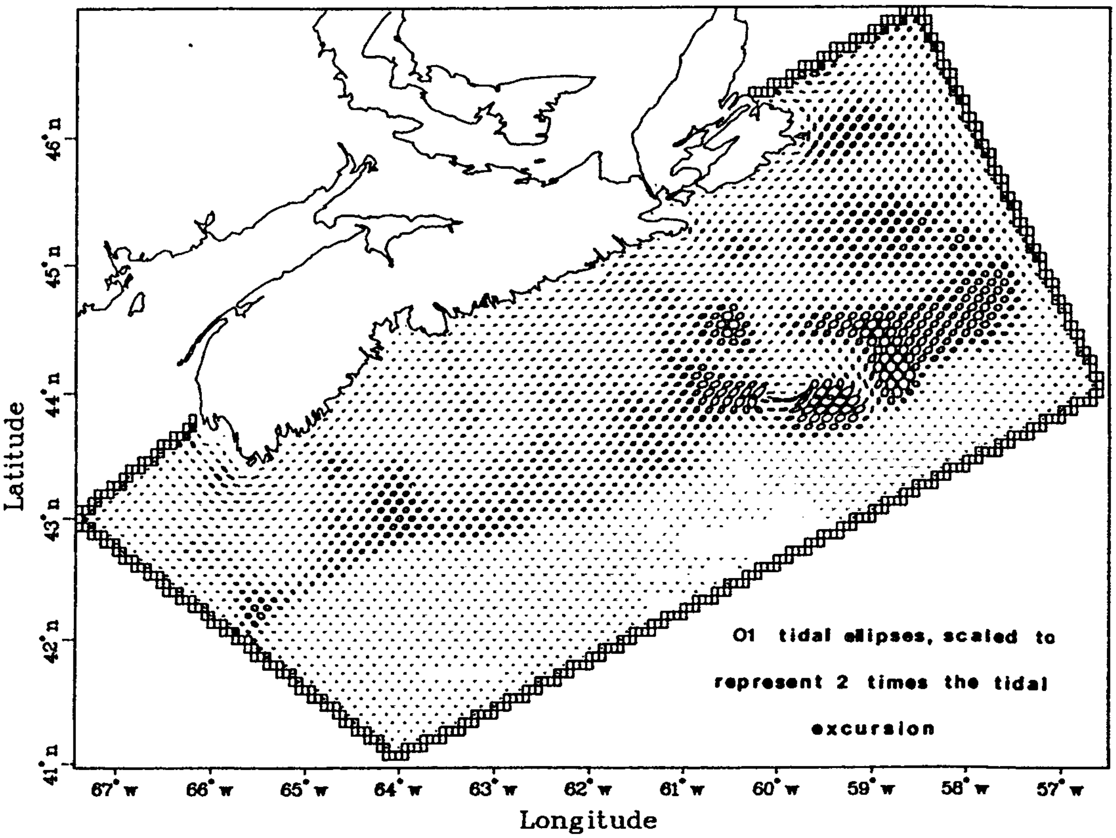

Figure 14: Tidal ellipses from a numerical model simulating tidal circulation for the principal lunar diurnal (O1) tide [Gregory, 1988].

6. DREA Experimental Locations

6.1 Site 1: Sable Island - Western Bank

Location: 43° 20.15' N, 61 ° 12.75' W
Water depth: 95 m
Quaternary sediment thickness: 37.5 m
Surficial sediment type: Sable Island Sand and Gravel

6.1.1 Features

This site is located at the edge of the continental shelf near the head of Dawson Canyon on high reflectivity surficial sediments. Quaternary sediment thickness, surficial sediment type and water depth are relatively uniform in directions along the shelf edge (section 6.1.2). Landward of the site, Quaternary sediment thickness increases and water depth decreases until the top of sand banks are reached. It is expected that propagation in these directions will be through a reasonably homogeneous medium. The other extreme is encountered in the seaward direction where water depth changes abruptly and there is a rugged downslope bathymetry with scarps up to 80 m in relief. The surficial sediment type varies from Sable Island Sand and Gravel to Sambro Sand to Emerald Silt as depth increases downslope. Sediment thickness is shown to be variable in a detailed study of the adjacent Verrill Canyon area (section 6.1.3) due to mass-wasting processes (slumps, bedding plane failures, etc...). Oceanographically, eddies of warm water which are shed from the gulf stream are frequently juxtaposed against the edge of the continental shelf. Accordingly, water temperature may increase by approximately 10° C in several kilometres as one travels seaward from the site.

6.1.2. Data Available (at site):

a) 12 kHz bathymetry survey of the head of Dawson Canyon (Figure 15)
b) NSRF seismic reflection data, the site is located at the intersection of two reflection lines (see track chart in Figure 16 and reflection profile in Figure 17).
c) Map of Quaternary sediment thickness (Figure 18) by MacKay [1990].
d) DREA propagation loss measurements at very low frequency along the strike of the shelf edge. These were made during *CFAV Quest* cruise Q211 in December 1993 and complement wider bandwidth propagation loss studies on the sand banks landwards of this site (section 6.1.3).

6.1.3 Data Available (nearby):

a) NSRF Deep Tow Sparker seismic reflection data (section 6.1.2)
b) Wellsite seabed surveys of Oneida O-25 (43.25 N, 61.58 W) and Evangeline H-98 (43.29 N, 60.98 W)
c) Detailed study of slope area to east of Verrill Canyon [Mosher et al., 1991]. The study surveys an area 15 km along shelf by 50 km downslope centred near (42.8 N, 61.75 W). It includes sidescan sonar, high resolution seismics, and 4 cores (2 of which have measured physical properties).
d) DREA propagation loss experiments at 43.45 N, 61.3 W

e) The closest historical current meter data [Gregory and Smith, 1988] is a mooring at (43° 17.44' N, 60° 58.82' W). In September 1984, at 20 m depth, mean current speed was 0.084 m/s bearing 257° and at 136 m depth mean current speed was 0.056 m/s bearing 251°. Maximum current speeds for the respective depths were 0.561 and 0.301 m/s. In October, 1984, at 20 m depth, mean current speed was 0.151 m/s bearing 256° and at 136 m depth mean current speed was 0.095 m/s bearing 258°. Maximum current speeds for the respective depths were 0.684 and 0.465 m/s

f) In late April and early May 1993, as part of a project tracking cod larvae, a number of CTD stations, current meters and drifting buoys were deployed in a grid pattern centred on the cap of Western Bank [Smith et al., 1993]. Two of the moorings lie in shallower water to the northeast (no. 1 at 43° 31.00 N, 60° 53.90) and northwest (no. 2 at 43° 27.99 N, 61° 42.24). Currents at 20 m depth reveal a tidal origin with maximum values of approximately ± 0.3 m/s in both northward and eastward components.

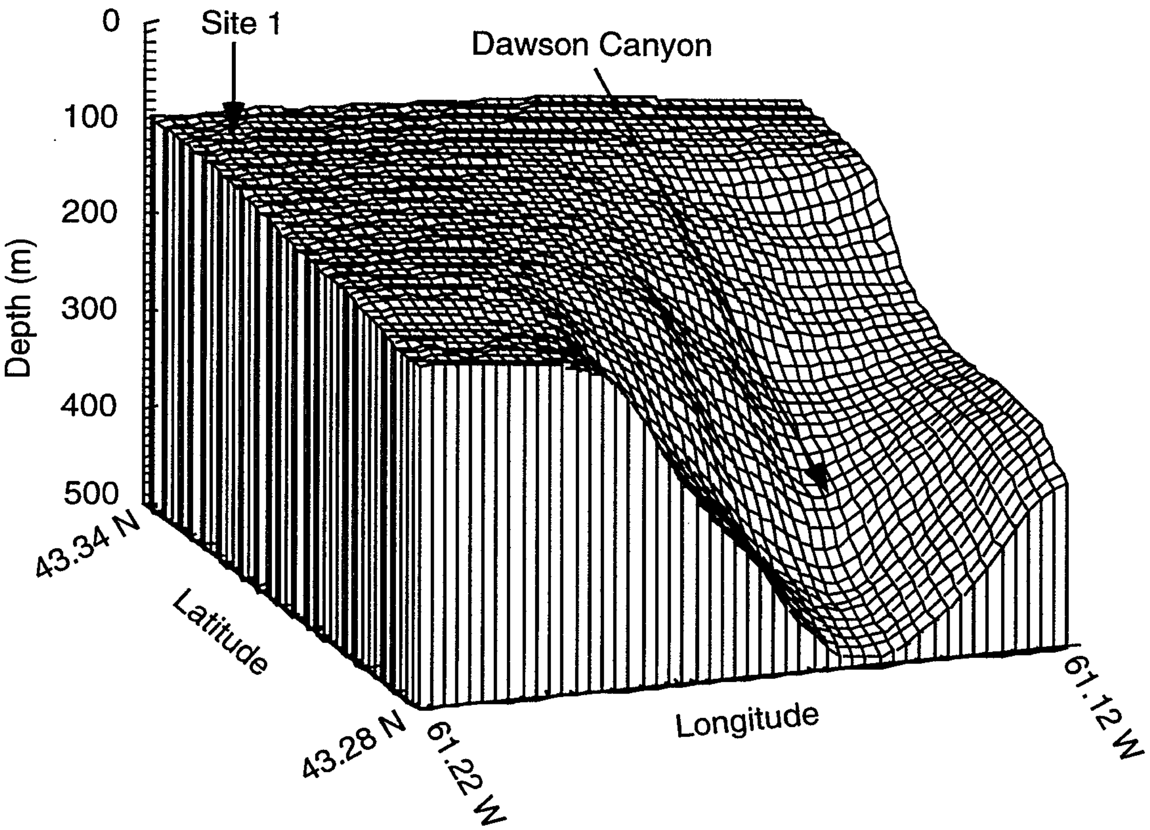

Figure 15: 12 kHz bathymetry survey of the head of Dawson Canyon conducted during CFAV Quest cruise Q211. Dawson Canyon is southeast of DREA experimental site 1.

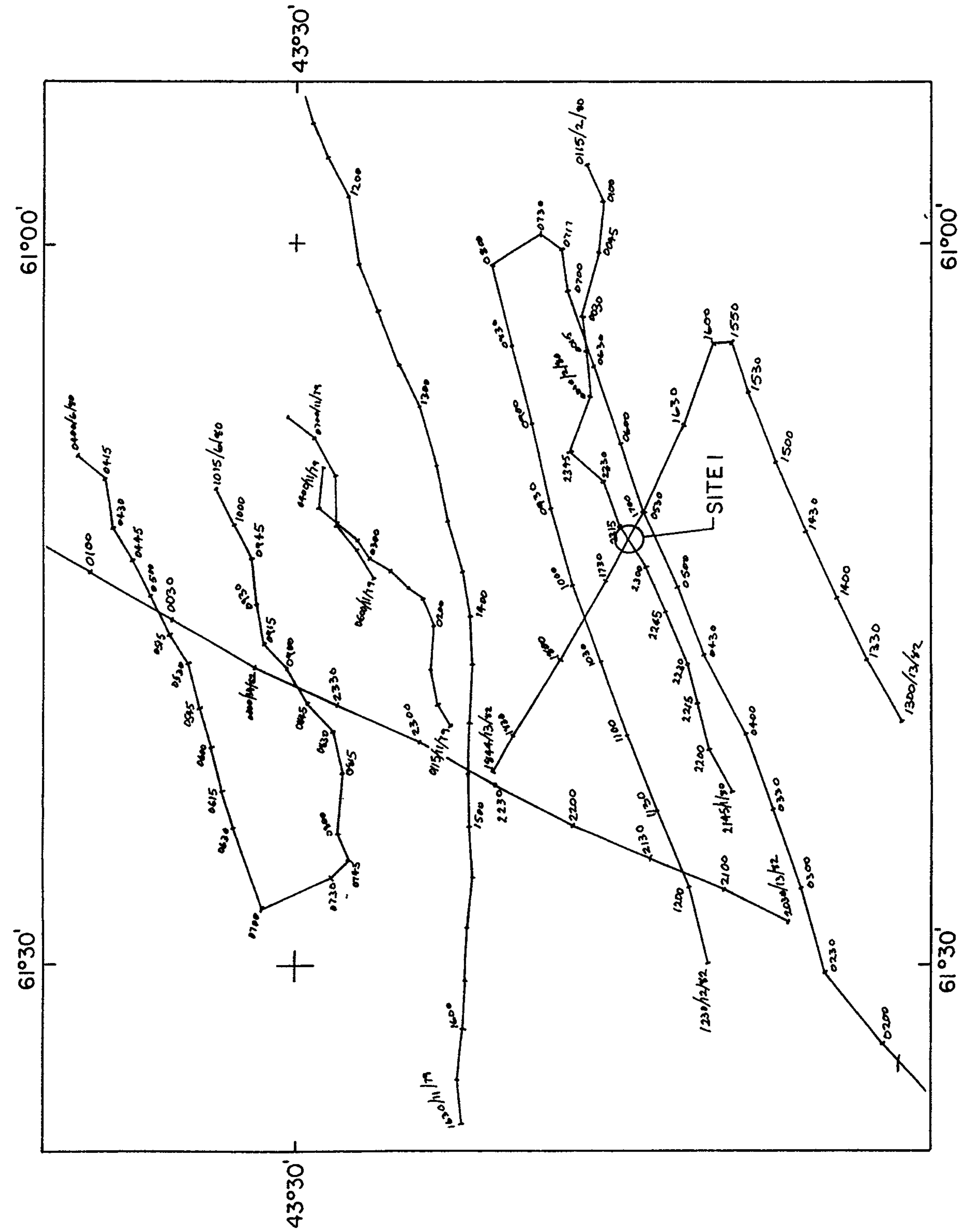

Figure 16: NSRF deep tow sparker seismic reflection track lines surrounding DREA experimental site 1 on Western Bank. Scale is 1:300 000 at 48° latitude mercator

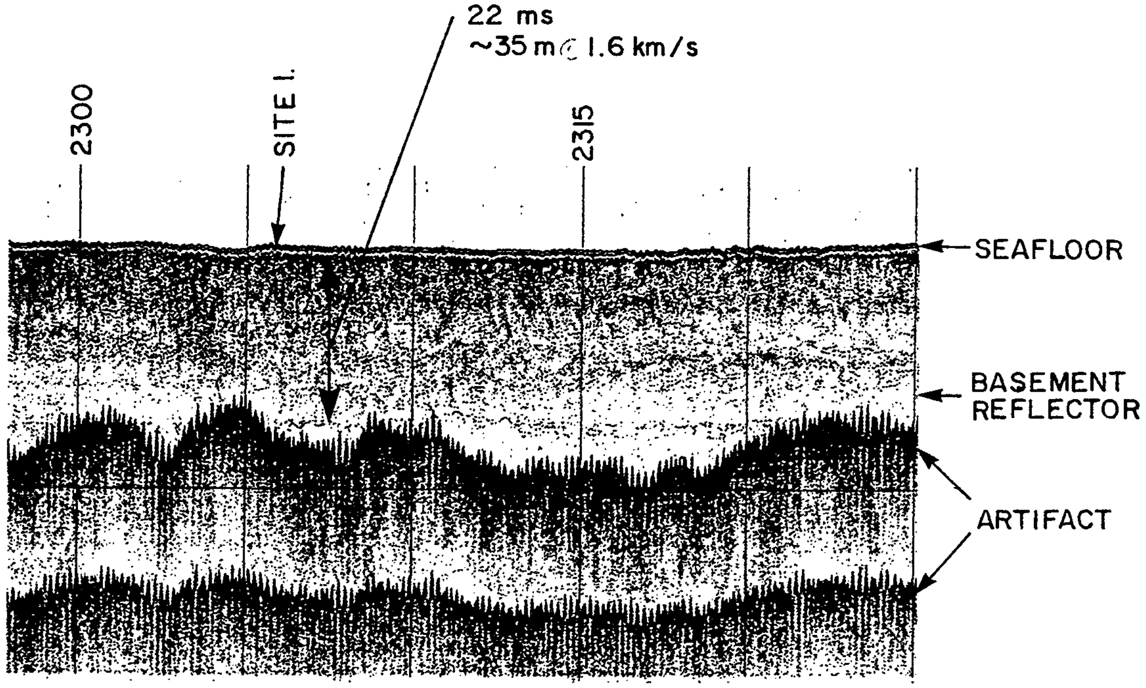

Figure 17: NSRF deep tow sparker seismic reflection profile at DREA experimental site 1 on Western Bank.

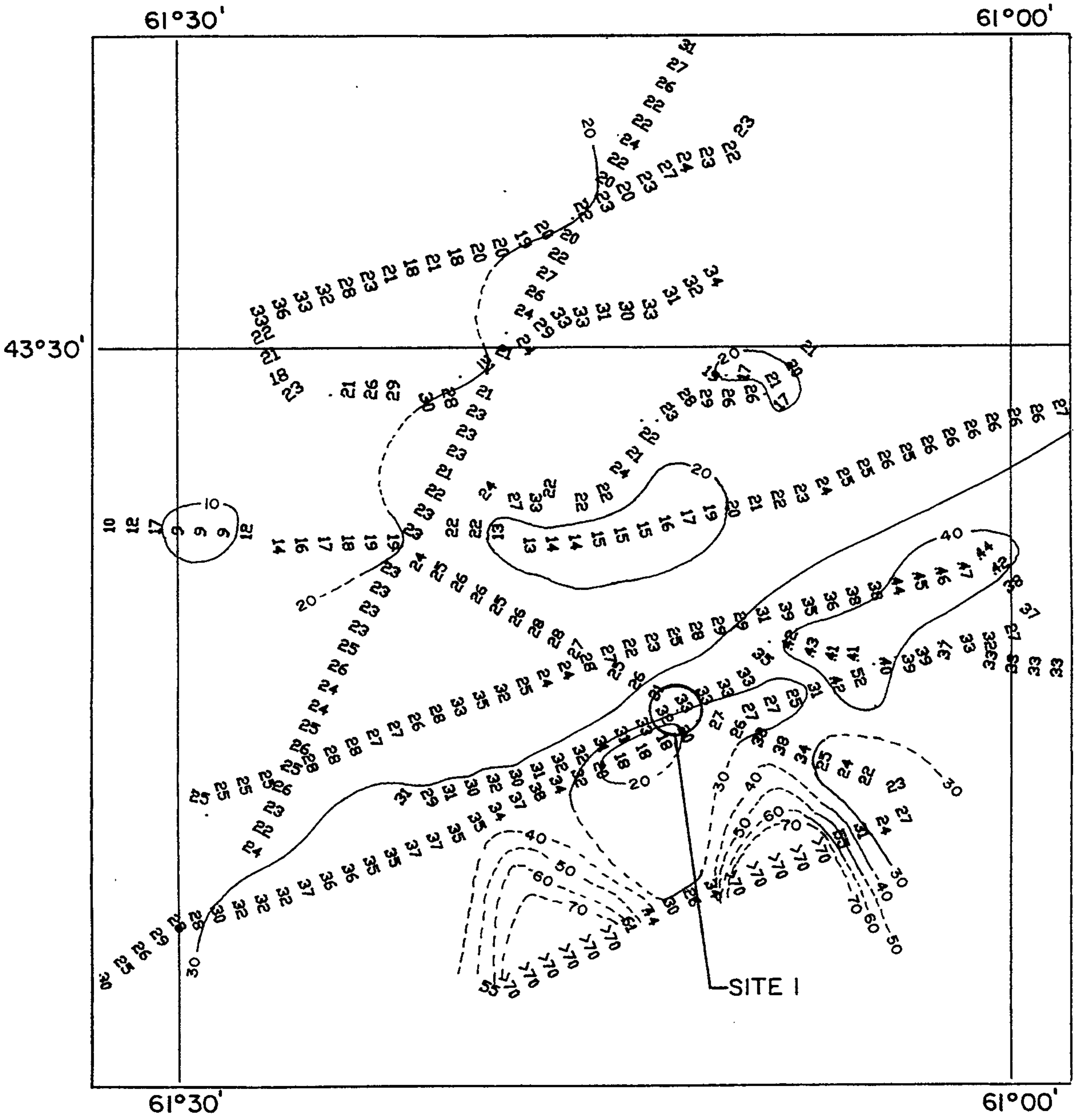

Figure 18: Map of Quaternary sediment thickness at DREA experimental site 1 [MacKay, 1990]. Values of sediment thickness, in metres, are printed along ship tracks and contours are provided where track coverage permits. Scale is 1:300 000 at 48° latitude mercator.

6.2 Site 2: Emerald Basin

Location: 44° 0.96' N, 63 ° 2.04' W
Water depth: 218 m
Quaternary sediment thickness: ~30 m
Surficial sediment type: LaHave Clay (~ 9 m)

6.2.1 Features

This site is located on the northeast flank of Emerald Basin, one of the basinal depressions on the Middle Shelf. Its surficial sediment succession is LaHave Clay overlying a layer of Emerald Silt, providing a seabed with a low reflectivity. The particular site within Emerald Basin was chosen because of the availability of cores with measurements of physical properties and Huntec DTS and airgun seismic reflection data (section 6.2.2). Pockmarks (section 3.3) are abundant in Emerald Basin as shown in sidescan sonar images [Fader, 1991c] and a proprietary swath bathymetry track which passes through the site [Courtney, R.C, 1993, Personal Communication]. There is also the possibility of trapped gas within the surficial sediments at this site [Moran et al., 1991].

6.2.2 Data Available

a) Huntec DTS seismic reflection profile (Figure 19) which crosses the site on a northwest to southwest bearing strike [Moran et al., 1991].
b) Airgun seismic reflection profile (Figure 21) which crosses the site on an east-west bearing track (Figure 20a) [Louden, 1994].
c) Airgun seismic refraction profile (Figure 22) along the track shown in Figure 20b. V_p = 1.9 km/s is measured for the layer of Emerald Silt and Scotian Shelf Drift which overlies the acoustic basement with V_p=5.1 km/s [Louden, 1994]. No velocity could be determined for the surficial layer of LaHave Clay.
d) Map of Quaternary sediment thickness (Figure 23) prepared by King et al. [1985].
e) Atlantic Geoscience Centre geotechnical core 87003-002 (Figure 24). It has a 17 m penetration with measurements of V_p, bulk density, grain size, shear strength, impedance, magnetic susceptibility, attenuation, and water content .
f) Measurements of ambient noise on hydrophone and geophone sensors at very low frequencies made during *CFAV Quest* cruise Q211 in December 1993.
g) The closest historical current meter data [Gregory and Smith, 1988] is a series of moorings during 1967 and 1968 near 43° 45' N, 63° 0' W. In summer months, at 20 m depth, mean current speeds of 0.08 m/s bearing south to east are typical. At 50-100 m depth, mean current speeds of 0.02 m/s also bearing south to east are typical. At 250 m depth, mean currents are very small <0.01 m/s. Maximum current speeds for the respective depths are 0.62, 0.49, and 0.23 m/s.

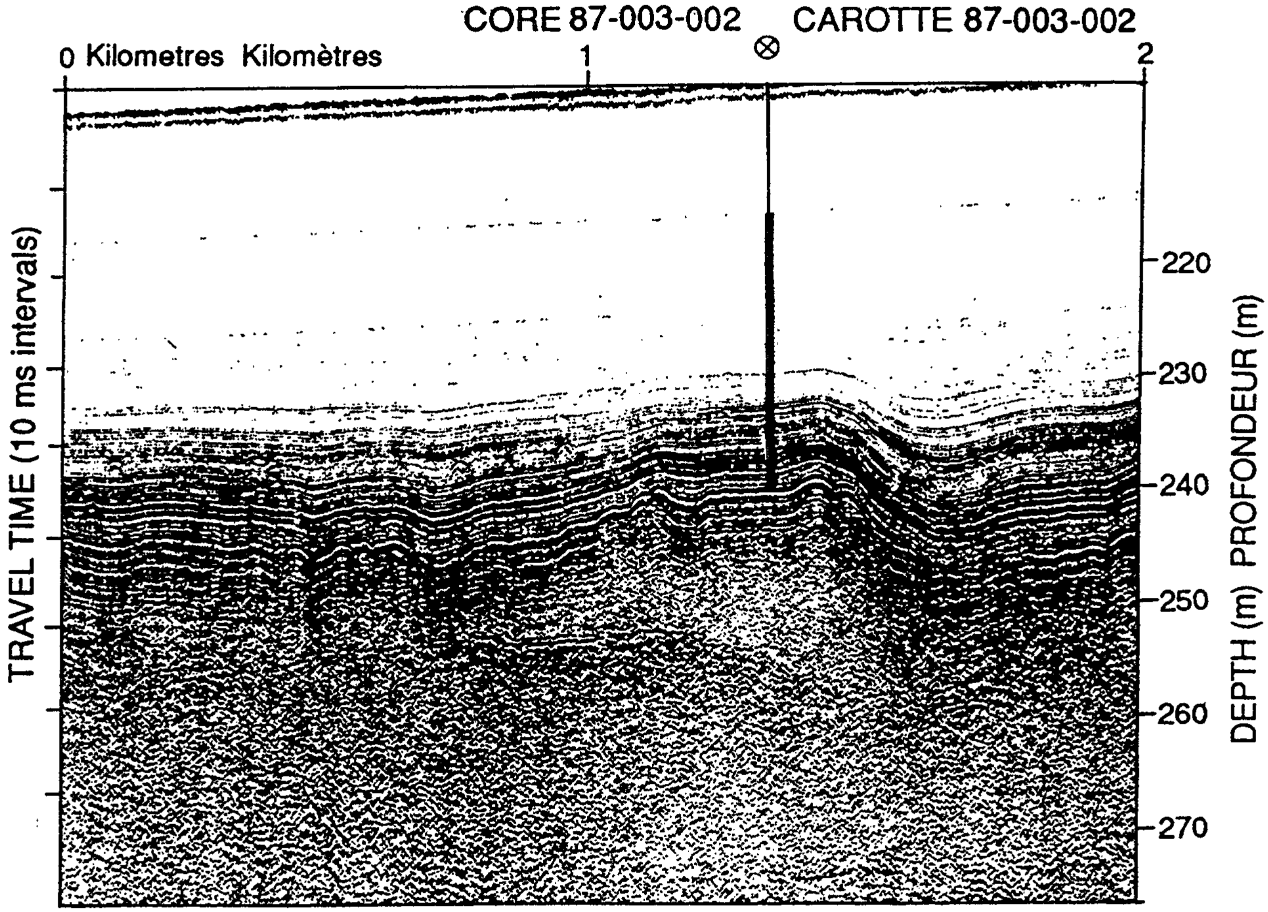

Figure 19: Huntec deep tow seismic reflection profile at DREA experimental site 2 in Emerald Basin [Moran et al., 1991]. Core 87-003-002 location is superimposed (physical properties are in Fig. 24).

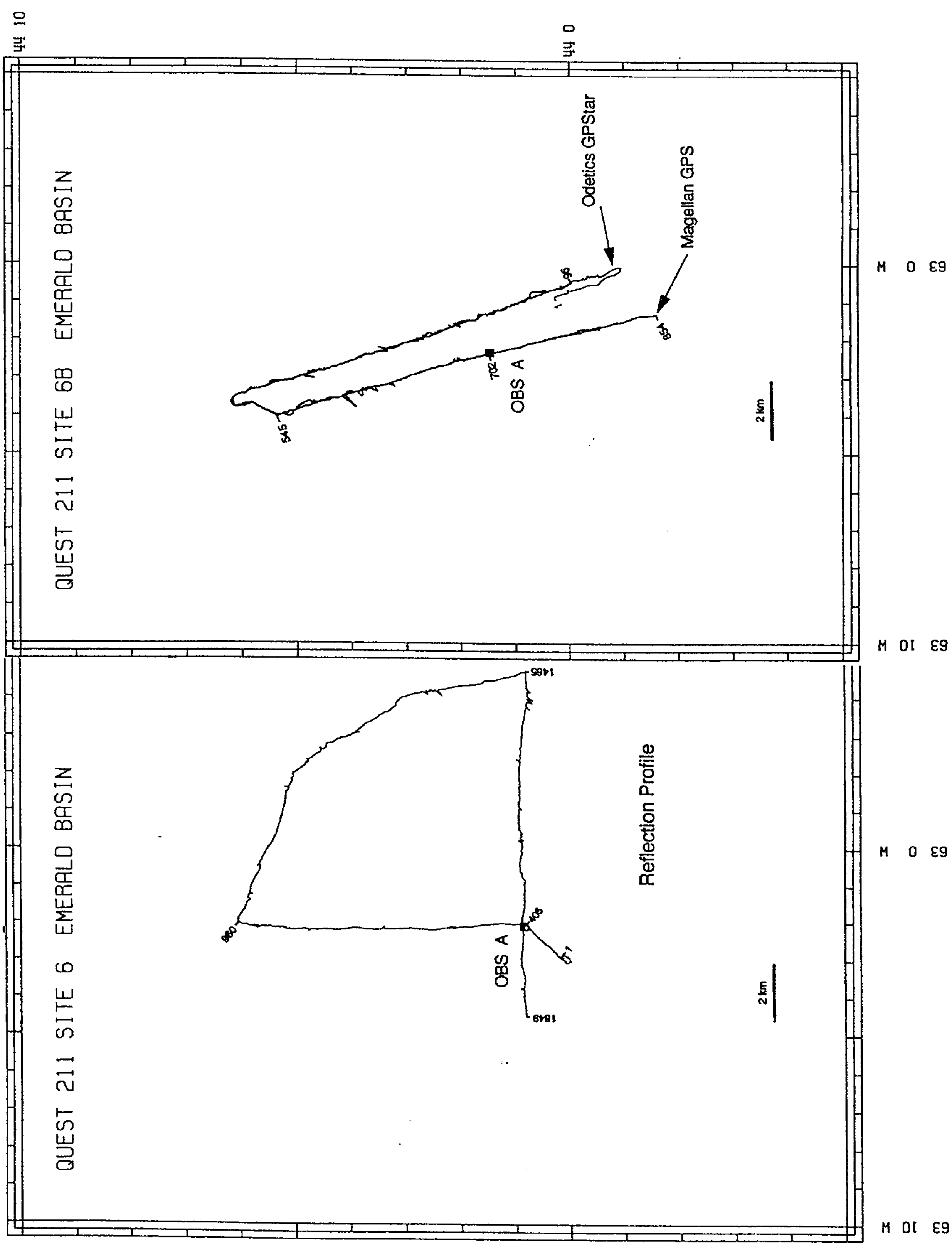

Figure 20: Navigation for (a) airgun seismic reflection profile (Fig. 21) and (b) airgun seismic refraction profile (Fig. 22) at DREA experimental site 2 in Emerald Basin [Louden, 1994].

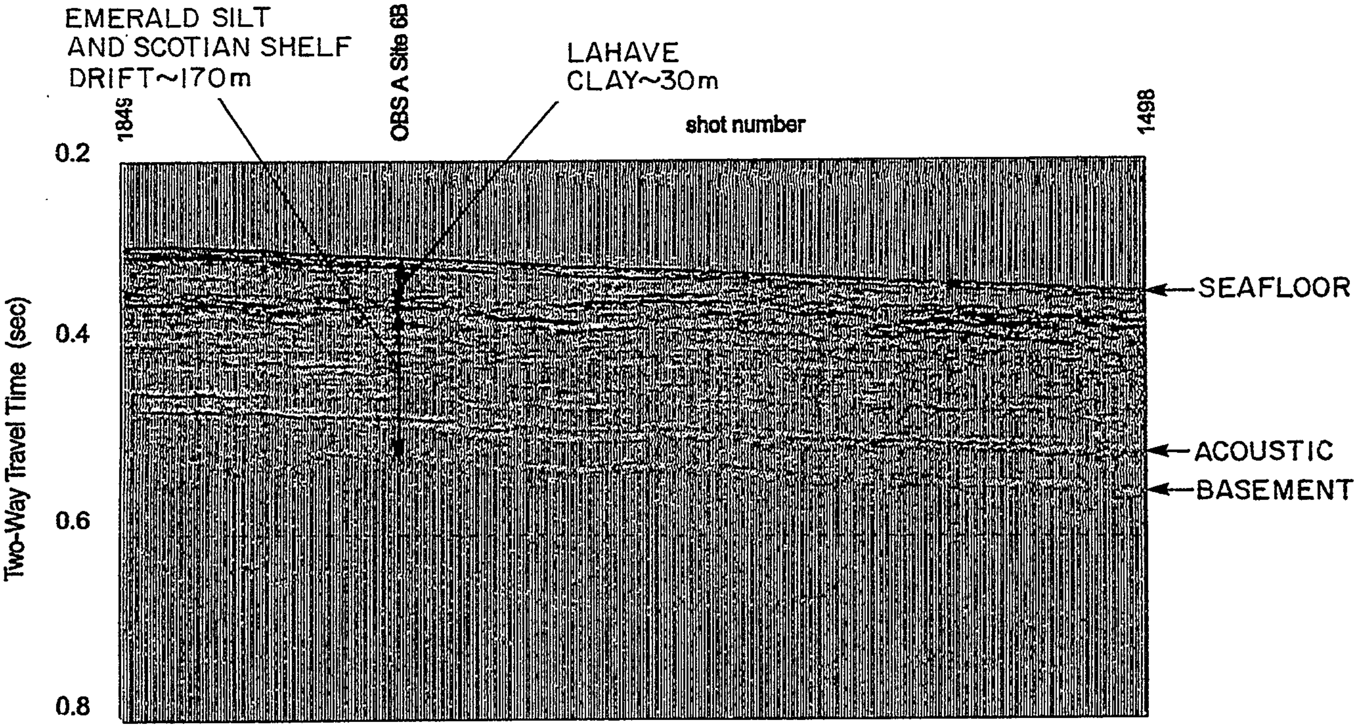

Figure 21: Airgun seismic reflection profile at DREA experimental site 2 in Emerald Basin with penetration through the surficial succession of LaHave Clay, Emerald Silt and Scotian Shelf Drift [Louden, 1994].

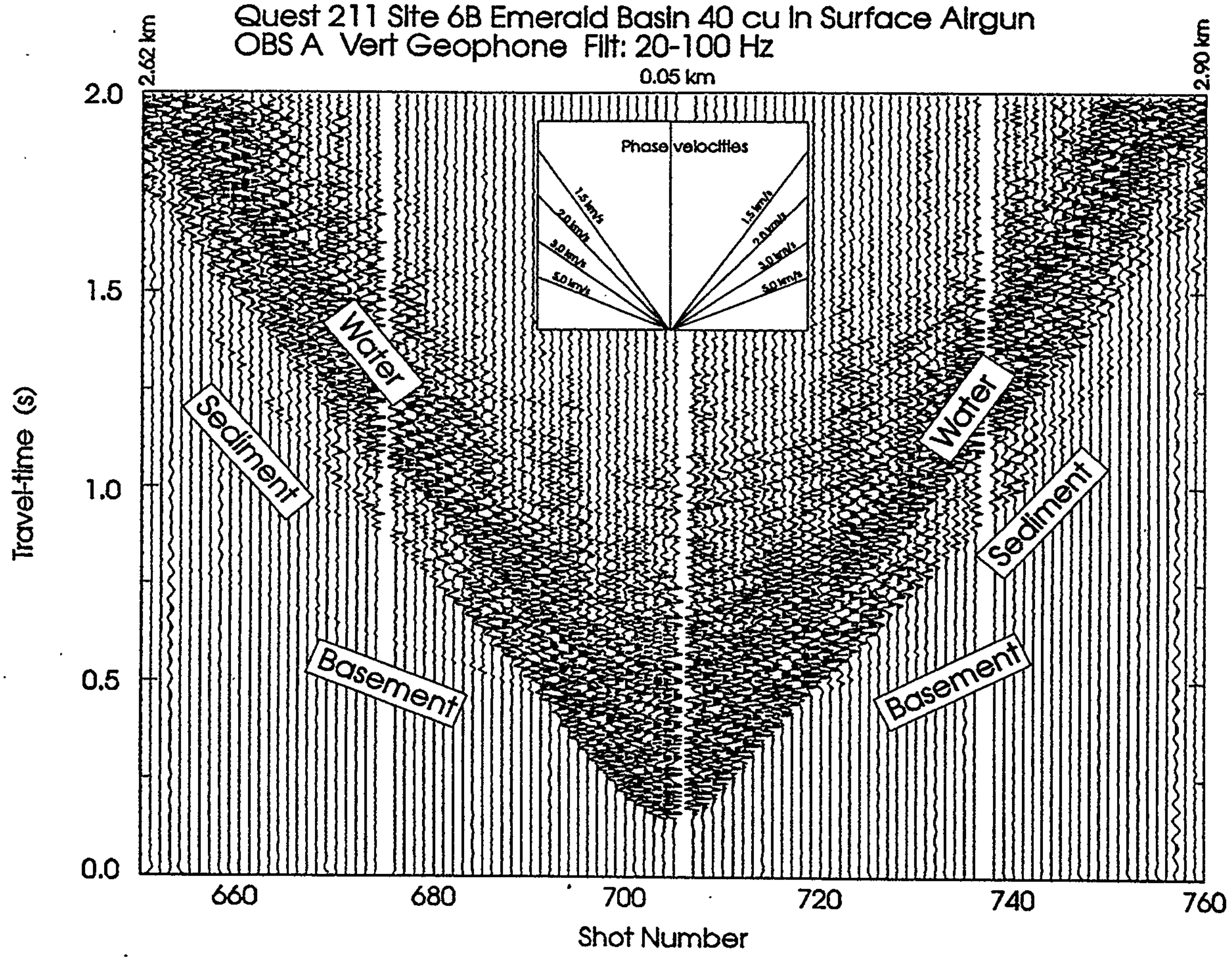

Figure 22: Airgun seismic refraction profile at DREA experimental site 2 in Emerald Basin [Louden, 1994]. The low amplitude refracted arrivals from the acoustic basement beneath the surficial succession have a phase velocity of 5.1 km/s.

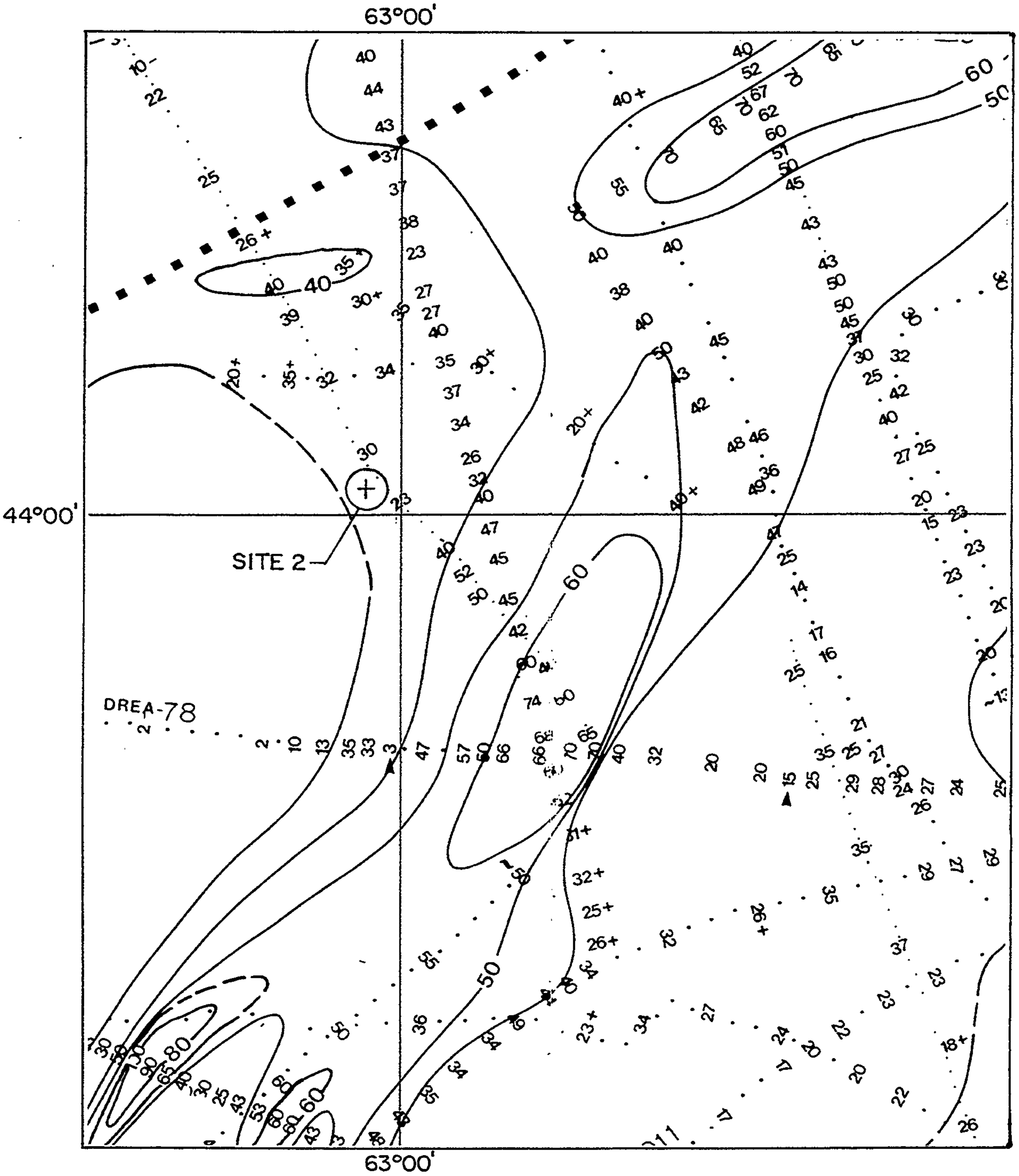

Figure 23: Map of Quaternary sediment thickness at DREA experimental site 2 in Emerald Basin [King et al., 1985]. Values of sediment thickness, in metres, are printed along ship tracks and contours are provided where track coverage permits. Scale is 1:300 000 at 48° latitude, mercator projection.

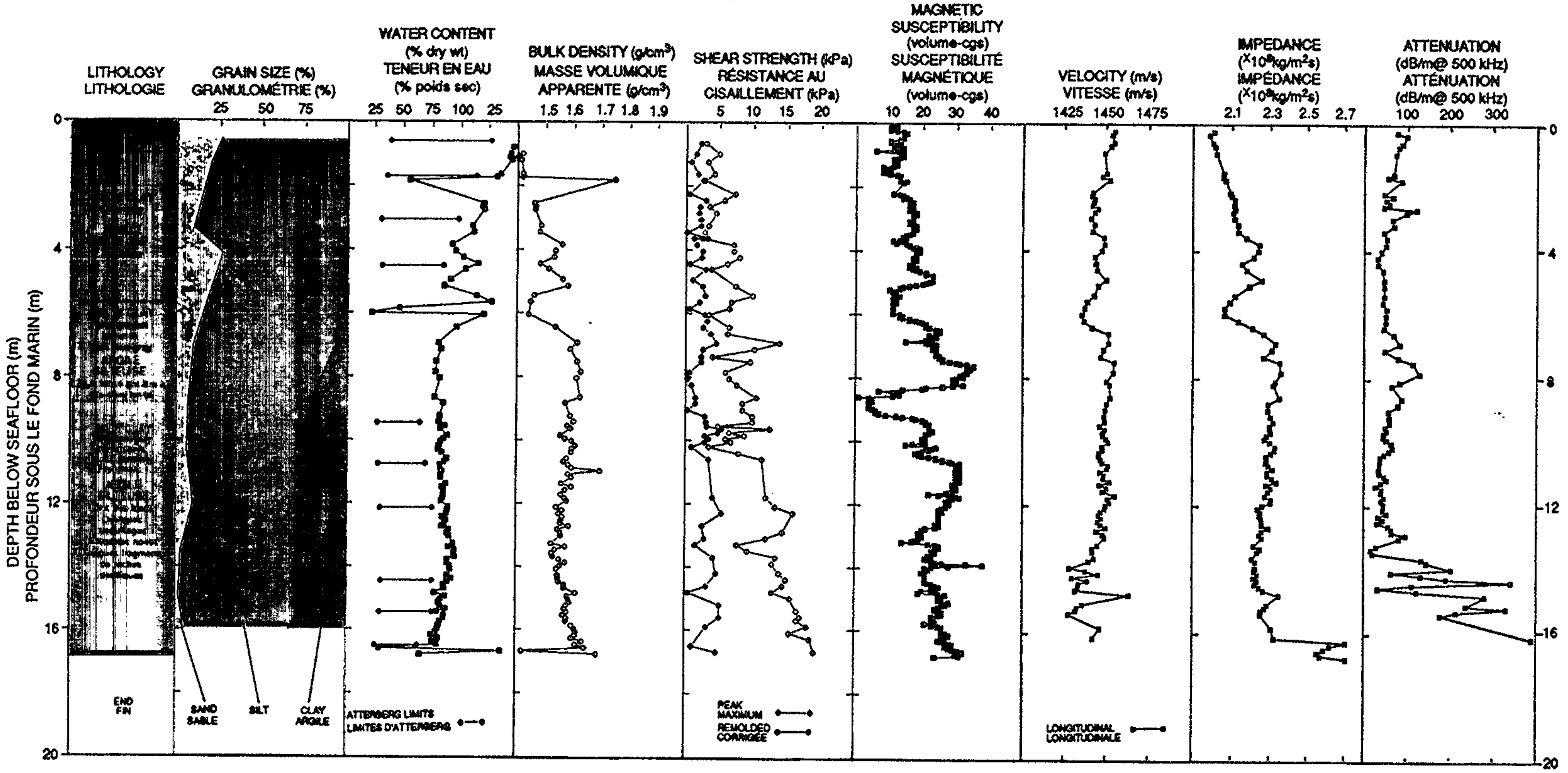

Figure 24: Lithology and physical properties of Atlantic Geoscience Centre core 87-003-002 at DREA experimental site 2 in Emerald Basin [Moran et al., 1991].

6.3 Site 3: Banquereau Bank, adjacent to Laurentian Channel

Location: 45° 6.00' N, 57° 39.00' W
Water depth: 70 m
Quaternary sediment thickness: 60-80 m
Surficial sediment type: Sable Island Sand and Gravel

6.3.1 Features

This site is located at the extreme northeastern tip of Banquereau Bank, adjacent to the Laurentian Channel. The seabed is very rugged and highly reflective. It is dominated by coarse gravel and many large boulders (section 6.3.2). Adjacent to the site, there are three contrasting regions. To the west, a region of complex morphology of sand ridges and basement outcrops interspersed with basins filled with LaHave Clay and Emerald Silt. To the east is the Laurentian channel, a wide trough-like depression, 200 to 500 m deep, with steep parallel walls which formed through glacial erosion. The surficial sediment succession in the Laurentian Channel is a thick layer of LaHave Clay (~20 m) underlain by a thick layer of Emerald Silt and Scotian Drift [King et al., 1983]. To the south is Banquereau Bank where some of the thickest deposits of Quaternary sediment (100-200 m) are found overlying a Tertiary aged bedrock which is incised by deep erosional channels.

6.3.2 Data Available (at site)

a) Video images of the seafloor filmed from the submersible launch of *HMCS Cormorant* in conjunction with *CFAV Quest* cruise 138.

6.3.3 Data Available (nearby)

a) Huntec DTS reflection profile 9D across the Laurentian Channel (beginning at 45.2 N, 57.5 W and bearing NNE), and profiles 10A and 10B which are to the SW on Banquereau Bank [King et al., 1983].
b) DREA has made propagation loss measurements [Staal and Desharnais, 1989].

7. Summary

Following a review of marine geological, marine geophysical and physical oceanographic databases, three sites on the Scotian Shelf have been selected for future experiments and detailed site descriptions are included. Experiments conducted at these sites will have the best geo-acoustic control data currently available. This will facilitate an extrapolation of the results to much broader regions of the Scotian Shelf where similar surficial sediments are found and will provide a basis for detailed acoustic modelling. It is anticipated that additional geo-acoustic information will be forthcoming as DREA is in contact with the Atlantic Geoscience Centre and the Canadian Hydrographic Service and has presented its requirements for detailed sidescan sonar and swath bathymetry surveys at these sites [Dr. D. Prior and Lt. Cdr. J. Bradford, Personal Communication, 1994].

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