A SEISMOSTRATIGRAPHIC ANALYSIS
OF HIGH RESOLUTION SEISMIC REFLECTION DATA
FROM THE WESTERN GRAND BANKS OF NEWFOUNDLAND

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ABSTRACT

A seismostratigrapic analysis of data from the western Grand Banks of Newfoundland has enabled the definition of seven acoustic units. Units were defined on the basis of high resolution, seismic reflection profiles, airgun reflection seismics, sidescan sonar, echograms, and bathymetric data. A sparse collection of piston cores, drill cores, vibrocores, and grab samples permitted limited lithologic correlation of these units. Unit 1 is acoustic basement of Hadrynian age and consists of pink and white quartzites, tillites, and granodiorite. Unit 2 is characterized by high intensity, continuous, coherent reflectors averaging 5 m penetration and consists of siltstones and sandstones of Cambrian to Devonian(?) age. Unit 3 is characterized by incoherent reflections with occasional coherent reflections dipping seawards at approximately 2-3°. Penetration averages 20 m and the unit consists of siltstones, mudstones, and sandstones of Cretaceous to Tertiary age. Units 1-3 represent the pre-Quaternary bedrock. Unit 4 has incoherent reflections and is interpreted as glacial till based on correlation with well-sampled areas from the Scotian Shelf. Unit 5 is defined by continuous, coherent reflections and is a rythmically to wispily banded muddy sand to sandy mud dated at 22.015 (+1.35, -1.15) x 1000 y.B.P. Unit 6 is a zone of weak, discontinuous to continuous reflections generally forming veneer deposits of sand and gravel above depths of 110 m (60 fathoms). Unit 7 is characterized by weak to moderate intensity, continuous to discontinuous reflections with no banding and is interpreted as a clayey silty sediment.

TABLE OF CONTENTS

PAGE

TABLE OF CONTENTS (CONTINUED)

PAGE

LIST OF FIGURES AND TABLES

1. INTRODUCTION

Seismostratigraphic analysis of a variety of seismic reflection profiles of varying frequencies has enabled the definition of seven acoustic units from the Downing Basin area on the western Grand Banks of Newfoundland. This study was completed through the analysis of Huntec deep tow, high resolution seismics (DTS) (Hutchins et al., 1976), airgun seismics, sidescan sonar, echograms, and bathymetric data. The areal distribution of these units is mapped at a scale of 1:350,000 using Canadian Hydrographic Charts 8011 (Grand Bank, Northern portion) and 8014 (Grand Bank, Northeast portion) as bathymetric base maps. Mapping is based on data collected on five cruises conducted by the Atlantic Geoscience Centre at the Bedford Institute of Oceanography. Figure 1 is an index map of the Grand Banks showing the study area and the regional distribution of Huntec DTS lines. Piston cores, drill cores, vibrocores, and grab samples have been collected from the study area and permit limited lithologic interpretation of the acoustic units. Interpretations as to the history of the glacial and glaciomarine deposition in the area were then carried out. This paper represents the first detailed seismostratigraphic study of its sort from the western Grand Banks of Newfoundland and it is hoped that the results obtained will provide the basis for an understanding of the glacial and glaciomarine depositional history on the Grand Banks.

2. PREVIOUS STUDIES

Two opposing schools of thought have developed concerning the extent of Wisconsinan ice in Newfoundland and surrounding areas. Coleman (1921), proposed that the coastal mountains of northern Labrador had never been over-ridden by the North American continental ice sheet. His references to "Labradorean" ice when referring to the continental ice sheet later became known more appropriately as the Laurentide ice sheet (Flint, 1943). Coleman (1922), further contended that on the basis of geological evidence the Shickshock Mountains of the Gaspé Peninsula were never glaciated but that the "Labradorean" ice sheet passed through the Gaspé, in an area southwest of the Shickshocks. Coleman's fieldwork in Labrador, Newfoundland, Gaspé and other areas around the Gulf of St. Lawrence led him to propose a limited extent of Wisconsinan glaciation in eastern Canada. He and other workers argued that

FIGURE 1. Index map showing study area and regional distribution of Huntec DTS control lines (after King and Fader, in press).

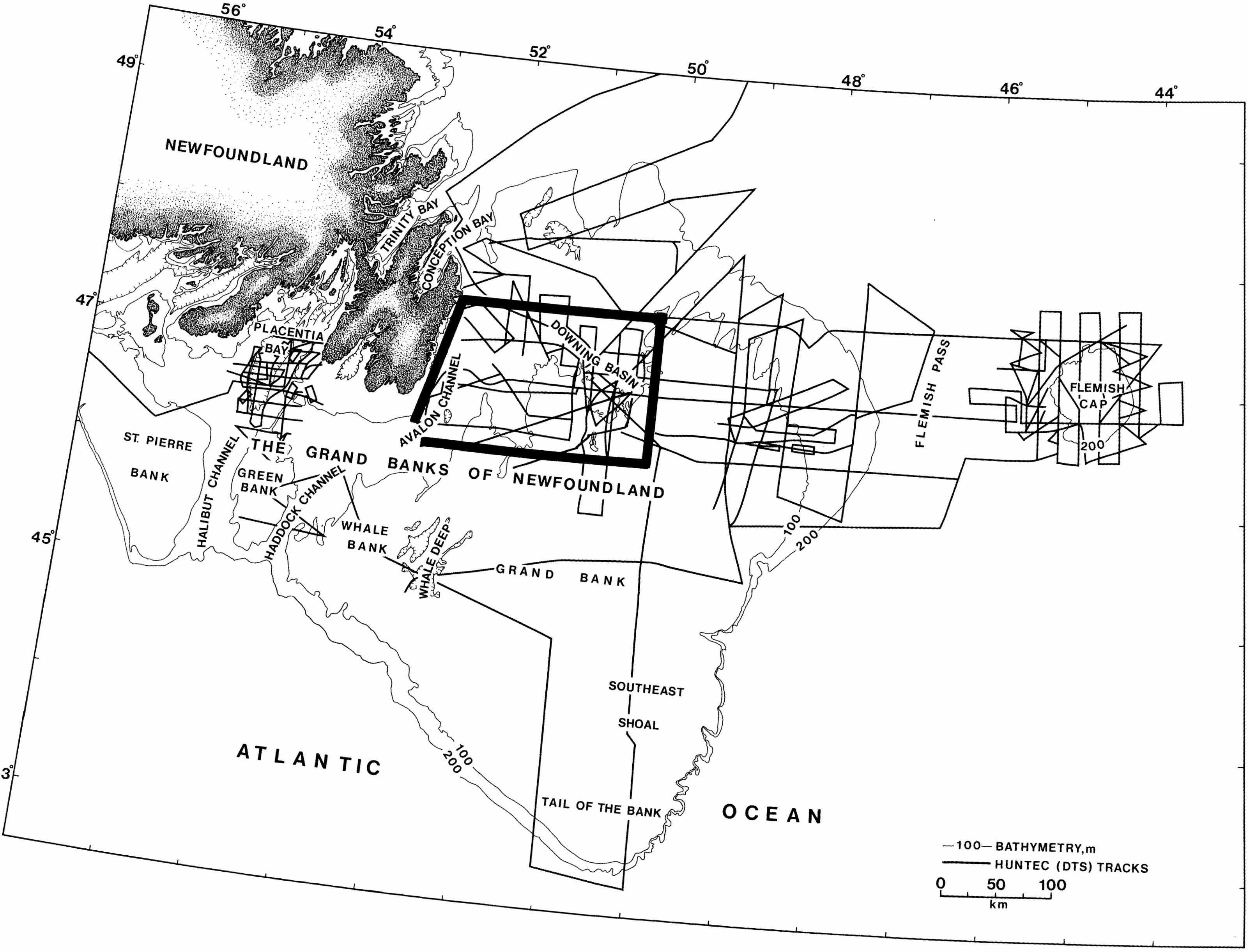
56°
54°
52°
50°
48°
46°
44°
49°
47°
45°
43°
NEWFOUNDLAND
TRINITY BAY
CONCEPTION BAY
PLACENTIA BAY
DOWNING BASIN
AVALON CHANNEL
FLEMISH PASS
FLEMISH CAP
200
ST. PIERRE BANK
HALIBUT CHANNEL
THE GRAND BANKS OF NEWFOUNDLAND
GREEN BANK
HADDOCK CHANNEL
WHALE BANK
WHALE DEEP
GRAND BANK
100
200
SOUTHEAST SHOAL
TAIL OF THE BANK
ATLANTIC OCEAN
100
200
—100— BATHYMETRY,m
HUNTEC (DTS) TRACKS
0 50 100
km

FIG 1

several locations of high mountain ranges, such as the Torngat of northern Labrador, the Long Range of Newfoundland, the Shickshock Mountains of Gaspé, and other highland areas in eastern Canada either remained free of ice as nunataks or were affected primarily by local ice caps[1]. The concept that Wisconsinan glaciation involved only limited extent of the Laurentide ice sheet in eastern Canada, where ice did not reach the edge of the continental shelf, became known as the "minimum Wisconsinan viewpoint" (Ives, 1978) and was popular until the 1940's.

The 1940's and 1950's marked the decline of the "minimum Wisconsinan viewpoint". Flint and co-workers (1942) published a paper based on fieldwork in the Shickshock Mountains formerly studied by Coleman. These findings disputed Coleman's earlier work and there appeared to be no evidence which would confirm that the area had not been glaciated. Flint (1943) claimed that the Laurentide ice sheet was extensive throughout eastern Canada during its maximum advance extending all the way to the continental shelf off Nova Scotia and Newfoundland. Flint's views led to the development of the "maximum Wisconsinan viewpoint" whose proponents advocate an ice sheet extending to terminal position on the continental shelf as emphasized by Denton and Hughes (1981).

The maximum Wisconsinan viewpoint quickly grew in acceptance, becoming fundamental to the North American concept of the Last Glaciation and has remained essentially unchallenged for the last 40 years with doubt only recently being cast upon its validity. Prest and Grant (1969) challenged popular views of glaciation and deglaciation in the Maritimes by suggesting that the Laurentide ice sheet had not been as active in Atlantic Canada as it had south and southwest toward the continental interior, but rather the

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[1] Nunatak is an Eskimo term referring to a rock mass which projects through an ice sheet.

Atlantic region experienced much influence from local Appalachian ice complexes. Jenness (1960) concluded that Late Pleistocene ice flowed across all of eastern Newfoundland but stopped before reaching the Avalon Penninsula, an area where instead local ice masses collected.

Ives (1978) summarized the two opposing schools of thought concerning the extent of Wisconsinan ice in eastern Canada and proposed a delimitation of the eastern perimeter of the Laurentide ice sheet similar to that proposed by Coleman 50 years ago. Ives conclusions, however, were based on far greater a body of field evidence than was available to earlier workers. Grant (1977) cited evidence casting further doubt on the maximum Wisconsinan viewpoint and advocated restricted late Wisconsinan ice extent in the Laurentian Channel. Much of the debate revolves around the Magdalen Islands strategically located in the Gulf of St. Lawrence. Adherents to the maximum Wisconsinann viewpoint would look for evidence of complete over-riding by the Laurentide ice sheet, whereas a minimum viewpoint would suggest no ice overtopped the islands. Unfortunately, the data appears inconclusive and no concrete evidence has been collected to permit unequivocal conclusions (Denton and Hughes, 1981).

King (1969) identified and dated as Wisconsinan in age, a submarine end-moraine complex 30-40 km offshore Nova Scotia by radiocarbon dating of amorphous carbon from glaciomarine sediments intercalated with the till; and seismic and lithologic studies. He concluded that the moraine complex represented either: 1) a pause or readvance during a major recession of Wisconsinan ice from the shelf; or 2) the maximum southerly limit of the last major advance in eastern Canada. Recent considerations of the regional geology, however, have led him to favour the latter possibility. Thus

glacial till south of the moraine complex may represent a much earlier and more extensive advance (King, 1980). In offshore areas King and co-workers (King, 1970; MacLean and King, 1971; Drapeau and King, 1972; MacLean, Fader, and King, 1977; Fader, 1984; Fader, King, and Josenhans, 1982; King and Fader, in press) mapped the lithostratigraphy of the Scotian Shelf, eastern Gulf of Maine, Bay of Fundy, and southwestern Grand Banks. They used acoustical parameters of the surficial material to delineate boundaries of the formations and then "ground truthed" the formations on the basis of extensive grab sampling. Alam and Piper (1977) cited evidence for the earliest ice advances in the Atlantic region. Cores from the tops of seamounts close to the continental shelf east of the Grand Banks possessing sequences of alternating clays and foramnanno ooze represented glacial and interglacial events back to the Pliocene. They suggested that Wisconsinan glacial stages were minor and that Wisconsinan glaciers, therefore, could not have extended all the way to the shelf edge. They speculated that a major influx of red sediment in late Illinoian time represented substantial erosion of the Gulf of St. Lawrence and Laurentian Channel, and therefore Illinoian glaciation was the most intense experienced on the Grand Banks.

King and Fader (in press) cited a general lack of knowledge of the nature, age, and extent of glacial deposits on the continental shelf as central to the lack of consensus among workers on the extent of Wisconsinan ice in Atlantic Canada. They postulated a Scotian Shelf-Grand Banks advance of ice of Early to Middle Wisconsinan age as being extensive throughout the Atlantic region. In addition, they recognized a resurgence of ice during a long general recession of the Scotian Shelf-Grand Banks advance in Late Wisconsinan time. Distributions of till and reworked lag deposits signified that at least one ice sheet or ice shelf covered the greater part of the Scotian Shelf. Results were based largely upon data from a Huntec deep tow high resolution seismic system (DTS) (Hutchins et al., 1976) correlated with piston cores over critical areas.

Others have also attempted lithostratigraphic mapping on the basis of acoustic information. Dale and Haworth (1979) completed a surficial seismic facies analysis of the northeast Newfoundland shelf and mapped the areal distribution of five acoustic units. They used continuous seismic reflection profiles from both Huntec DTS and airgun systems. Barrie and Piper (1982) identified three major surficial units using 3.5 kHz acoustic analogue data on the coast of central Labrador. These units were defined acoustically and were correlated with short cores and grab samples.

3. DATA AND DISCUSSIONS SECTION

3.1 METHODS

This discussion reviews the evolution of methods used for lithostratigraphic mapping on the eastern continental shelf which is summarized by King (1980). King (1970) surveyed the surficial geology of the Scotian Shelf using a conventional ship's echosounder (Kelvin-Hughs MS 26B). From a study of echograms King noted that the length of the return echo varied with sediment type (signal pulse stretching). Very little pulse stretching occurred over acoustically transparent clay bottoms. Further stratigraphic information could be derived from the echogram since the signal pulse penetrated to lower sub-bottom reflectors. Over areas of sea bottom with harder sediment type, the degree of the pulse stretching increased. Slightly coarser muds retained their acoustic transparency, but showed a grey sub-bottom on the record, the result of internal backscatter caused by fine bedding or other reflectors. Acoustically hard areas of sand and gravel caused an increase in the degree of pulse stretching and penetration was greatly reduced. King was able to undertake a 3-dimensional correlation of the acoustic stratigraphy over the Scotian Shelf by examining a systematic pattern of many echograms, the majority of which were run in parallel tracks spaced 1 to 3 km apart. This close control of echogram data lent a high degree of coherence between the acoustical characters observed, most of the echograms having been collected earlier by the Canadian Hydrographic Service for bathymetric purposes. Echograms were supplemented with airgun profiles for use in areas with acoustically hard bottoms where penetration of the echosounder signal was prevented. Radiocarbon dates were taken at different horizons in cores collected at key sites.

A major problem with this mapping technique was the lack of penetration achieved over areas of acoustically hard bottom. Whereas airgun seismics gave good penetration the large bubble pulse meant poor resolution and much of the detail of the Pleistocene-Holocene section was lost. This problem was largely overcome with the advent of the Huntec deep tow high resolution seismic system (DTS) which permitted penetration of up to 200 m of surficial material (Hutchins et al., 1976). DTS profiles did not have the bubble pulse common to airgun profiles and spatial resolution of seismic events of approximately 0.3 m was achieved. In addition to providing precise data for stratigraphic interpretation, the DTS data was processed to give a quantified measure of seabed reflectivity values enabling direct lithologic interpretation. This was similar to the way direct information of lithology was obtained from the degree of pulse stretching with echogram data. These quantified reflectivity values were expressed in terms of reflectivites r_1 and r_2. The r_1 reflectivity is a measure of the amount of reflected coherent energy at the seabed expressed as a percentage. The r_2 value is the scattered energy at the seabed and within the top metre of sediment, also expressed as a percentage. In addition, reflectivity is measured by the peak amplitude profile which appears immediately above the seabed on DTS records. It determines the peak amplitude of the return signal where a darker, wider line indicates a stronger return echo. More recently, sidescan sonar has been employed as a further aid in mapping the surficial geology of the eastern continental shelf (Fader et al., 1982).

3.2 SCOTIAN SHELF BEDROCK GEOLOGY

The bedrock geology of the Scotian Shelf is reviewed and provides a useful backdrop for later discussion on bedrock occurrences in the study area. King and MacLean (1976) mapped the bedrock geology of the Scotian Shelf using seismic data, acoustic reflectivity, adjacent shore geology, data from ten exploratory wells, dredge samples, and gravity, magnetic and seismic refraction data. These results are summarized below.

3.2.1 Acoustic Basement - The occurrence of rocks pre-Pennsylvanian in age was defined and mapped on the basis of acoustic impenetrability - seismic energy origin is reflected from the surface of these rocks and sub-surface reflections do not occur on seismic profiles. These rocks are called "acoustic basement", and consist of Precambrian volcanic, sedimentary, and plutonic rocks and a suite of Cambrian-Devonian high grade metamorphic and granitic rocks of the Meguma Group which dominate Nova Scotian onshore geology south of the Glooscap fault system. The Meguma rocks out crop at the bedrock surface nearly 50 km offshore and are overlain by a thin veneer of Cretaceous-Tertiary rocks which thicken seaward.

3.2.2 Pennsylvanian - The area between Cape Breton Island and the southwest coast of Newfoundland is known as the Sydney Basin, an area underlain by sediments of Pennsylvanian age. These rocks form the offshore extension of coal-bearing strata on Cape Breton Island and are comprised of conglomerate, sandstone, shale, coal, and minor amounts of limestone.

3.2.3 Mesozoic-Cenozoic - Jurassic, Cretaceous, and Tertiary strata comprise the rocks of Mesozoic-Cenozoic age on the Scotian Shelf. These rocks are a continuation of the sediments underlying the entire eastern North American continental shelf bordering the mainland from the Gulf of Maine to New England. The contact between these sedimentary rocks (referred to as east coast sediments) and the basement Meguma platform occurs about 50 km offshore and parallels the coastline. Similar structurally, these east coast sediments have gentle regional dips of 0.5 to 1° to the south, although some strata just southwest of Cape Breton are gently folded and evidence some faulting.

Jurassic strata occurring at the bedrock surface are confined to the Georges Basin area. Rocks designated Pennsylvanian-Jurassic in age, however also occur in the approach to Chedabucto Bay. Jurassic strata outcropping in Georges Basin are comprised of salt, poorly sorted redbeds at basin flanks, anhydritic domolite, and interbedded red and green sandstone, shales and grey limestones, and marine limestones and clastics. On the central Scotian Shelf Jurassic rocks occur only in cross-section and are not exposed at the bedrock surface.

Cretaceous strata outcropping at the seabed along much of the Scotian Shelf form a discontinuous pattern overlain by a thin veneer of Tertiary strata. These Cretaceous strata overstep the zero isopach of Jurassic sediments and so in some localities rest directly on the eroded quartzites and slates of the Meguma Group. A thick deltaic sequence of massive terrigeneous sandstone describes much of this section.

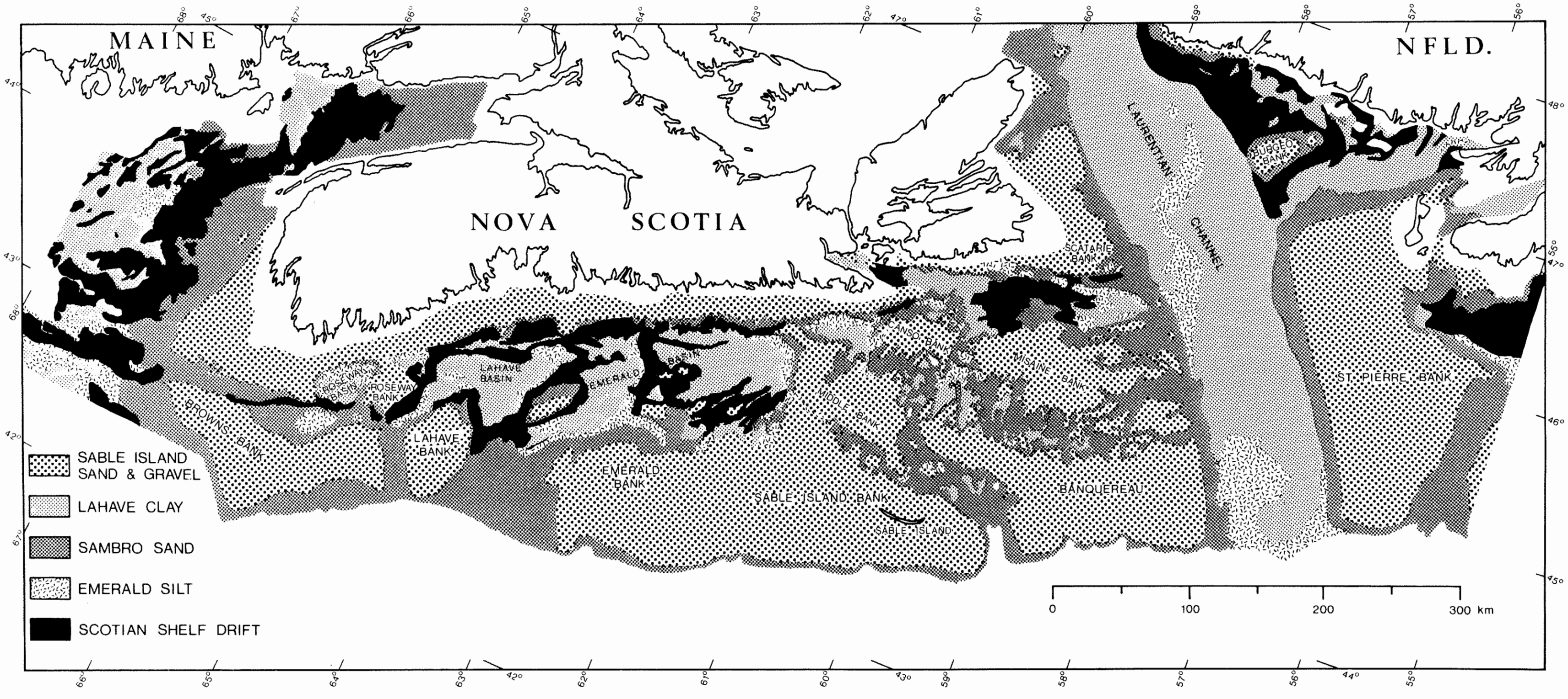
In areas along the inner and central Scotian Shelf Tertiary sediments are developed as a thin veneer or as erosional outliers overlying strata of Cretaceous age. In some localities Tertiary rocks entirely overstep underlying Cretaceous rocks to form the zero edge of the east coast sediments on the basement rocks of the Meguma Group. These Tertiary sediments thicken to about 2 km in some areas along the shelf edge as determined by well data and seismic interpretation (King and MacLean, 1976). Lithologies reflect deepwater sedimentation becoming progressively shallower in time. The lowermost section consists of calcareous muds grading upwards to noncalcareous silts and sands. These sands are generally argillaceous and glauconitic and at the top of the section are medium-grained, well sorted, and clean.

3.3 SCOTIAN SHELF SURFICIAL GEOLOGY

The Scotian Shelf surficial succession was discussed in earlier papers by King, 1980; Fader *et al*., 1982; and King and Fader, in press., and is summarized here to provide background for later discussion on the lithologic interpretation of the acoustic units identified over the study area. The Scotian Shelf surficial succession occurs as a thin blanket of approximately 50 m thickness. It is comprised of five surficial formations: Scotian Shelf Drift, Emerald Silt, Sambro Sand, LaHave Clay, and Sable Island Sand and Gravel. The areal distribution of these formations on the Scotian Shelf and adjacent areas is shown in Figure 2.

3.3.1 Scotian Shelf Drift - This lowermost unit of the surficial succession is composed of very dark greyish-brown, cohesive, poorly sorted sandy clay to silt, with angular gravel sometimes in the boulder size range. This unit seldom outcrops in depths less than 120 m (65 fa.) and thickness varies from 0-150 m. Piston core data reveals it to be glacial till. Scotian Shelf Drift is generally overlain by Emerald Silt although lateral

FIGURE 2. Map showing the areal distribution of surficial formations on the Scotian Shelf (after King and Fader, in press).



SURFICIAL GEOLOGY OF SCOTIAN SHELF AND ADJACENT AREAS

FIG 2

gradational boundaries between the two formations are found. In deeper basinal areas the surface of the Scotian Shelf Drift may display a unique hummocky morphology. These hummocks are generally buried beneath thick sequences of Emerald Silt which possess a markedly different internal structure. This difference between Scotian Shelf Drift and Emerald Silt allows easy discrimination on DTS profiles. These ridges are termed "lift-off moraines" and will be discussed in greater detail later.

3.3.2 Emerald Silt - This formation is a dark greyish-brown, fine grained, finely bedded muddy sediment which may vary at spots from silt to sand. It is texturally heterogenous and may contain some angular gravel. Thickness varies from a few metres to 240 metres. Seismic reflection profiles show individual beds to be continuous over large distances, often truncating and outcropping on the edge of basins. On DTS records it appears as medium to high intensity, continuous coherent reflections generally with a high degree of conformability to substrate irregularities.

3.3.3 Sambro Sand - This formation is characterized by dark greyish-brown medium- to fine-grained and moderate to well sorted sand. Some locations may, however, contain 10% silt and 5% clay, with local occurrences of gravel. Sambro Sand occurs peripherally around the shelf banks. It is a time equivalent of LaHave Clay and varies in thickness from a thin veneer to 100 m. Acoustically, Sambro Sand resembles Sable Island Sand and Gravel.

3.3.4 Sable Island Sand and Gravel - This formation is comprised of clean, buff- to greyish-brown, medium- to coarse-grained very well sorted sand grading laterally into lag gravels. Well rounded boulders may occur. The formation unconformably overlies Emerald Silt and Scotian Shelf Drift and is restricted to depths less than 120 m (65 fa.). Thickness varies between a few metres to 10-15 metres. Its dominant acoustic character shows a highly reflective seabed, and generally closely spaced continuous coherent reflections if the deposit is thick enough to resolve. Sable Island Sand and Gravel is the time equivalent of LaHave Clay.

3.3.5 LaHave Clay - LaHave Clay is restricted to depths less than 120 metres or 65 fa. (the depth of the submarine terrace). Lithologically the formation is comprised of dark greyish-brown loosely compacted silty clay to clayey silt. Thicknesses vary from 0-70 metres. Generally it reveals a ponded style of deposition and is confined to basins and depressions on the shelf. LaHave Clay is the time equivalent of Sable Island Sand and Gravel and Sambro Sand. On DTS profiles, its acoustic character is defined by general transparency without internal reflections with uncommon weak continuous coherent reflections at the base of the section.

3.4 SEISMOSTRATIGRAPHIC ANALYSIS

Examination of Huntec DTS and airgun seismics, sidescan sonograms, echograms, and bathymetric data across the study area has enabled the identification and discrimination of acoustic units. These units were identified and described solely on the basis of their acoustic reflection characteristics and in this sense, represents a "pure" seismostratigraphic analysis. The reflection characteristics used as parameters in defining units included the presence or absence of coherent internal reflections, their continuity, amplitude, spacing, relief, structural form, reflection termination patterns and boundary relationships. In all, seven acoustic units have been identified and type sections are represented in Figures 3 to 9. Table I shows the relationships between seismostratigraphy from DTS profiles, lithostratigraphy, and thickness of each of the units together with a brief description.

3.4.1 UNIT 1 - Figure 3 is the type section for Unit 1 which out crops in the Virgin Rocks-Eastern Shoals area. It is defined on the basis of its acoustic impenetrability as seismic energy from the DTS and airgun systems is reflected from its surface. No sub-surface reflections occur. Reflectivities r_1 and r_2 show large and moderate values respectively. This unit is interpreted as Hadrynian bedrock.

3.4.2 UNIT 2 - The typical acoustic character of Unit 2 is high intensity, continuous coherent reflections, averaging 5 metres penetration with the Huntec DTS system with reflections dipping up to 12°. Reflections are closely spaced and are displaced by local faulting. Unit 2 outcrops on the inner half of the study area and its relationship with Unit 1 is not clearly demonstrated on the seismic profiles. However, it probably overlies this acoustically inpenetrable unit. Figure 4 shows the type section of Unit 2 and in the diagram is overlain by a thin layer of Unit 4. Note the unconformity at the surface of Unit 2 which is widespread over the study area. This unit is interpreted as Cambro-Devonian bedrock.

3.4.3 UNIT 3 - This unit is characterized by an undulating, ill-defined surface averaging 5 metres in relief with internal incoherent reflections. Occasional continuous coherent reflections are found, as shown in Figure 5. These reflections have a gentle dip seawards of about 2-3°. A well developed system of subaerial channels often occurs throughout this succession. In the Downing Basin area the unit occurs as a thin veneer which thickens seaward to at least 2 km at the shelf edge (King and Fader, in press), and in fact the contact between Unit 3 and the underlying Unit 2 approximately parallels the northwest-southeast elongation of Downing Basin. Unit 3 is typically unconformably overlain by a veneer of Unit 6. Unit 3 is interpreted as Cretaceous-Tertiary bedrock.

3.4.4 UNIT 4 - Acoustically, Unit 4 is characterized on Huntec DTS profiles by a uniform dense grey pattern of incoherent reflections (see Figure 6) often occurring as a continuous blanket of relatively uniform thickness (3-15 m). Generally, it unconformably overlies Unit 2 (Cambro-Devonian bedrock) and sidescan sonograms reveal extensive furrowing by icebergs on its surface. These furrows have average depths of 2-3 metres and can extend to over 200 m in width. The occurrence of Unit 4 is generally restricted to depths greater than 110-130 m (60-70 fa.). "Lift-off moraines" are particularly common in the deeper portions of Downing Basin. This unit is interpreted as glacial till (King and Fader, in press).

TABLE I - TABLE OF UNITS

AGE	UNIT	SEISMOSTRATIGRAPHY FROM HUNTEC DTS PROFILES	THICKNESS	LITHOSTRATIGRAPHY
15,000 y.B.P. to present	7	Continuous to discontinuous medium intensity reflections. No banding. Forms a smooth blanket deposit with a ponded structural style. Unconformably overlies Unit 5. Found in basinal areas of the shelf.	1-10 m	Clayey silt. May be locally sandy.
15,000 y.B.P. to present	6	A zone of low to medium intensity, weak discontinuous to continuous reflections. Bedforms found on its surface. Occurs above 110-130 m (60-70 fa.).	1-5 m generally veneer	Well sorted sand and gravel.
Late Wisconsinan 22.015 (+ 1.35, -1.15) x 1000 y.B.P.	5	Continuous to discontinuous parallel coherent reflections of medium to high amplitude (banded). Reflections spaced 0.3 m apart. Highly conformable to substrate irregularities (generally). Found below the 110-130 m (60-70 fa.) contour and occurs as channel above 120 m (65 fa.).	1-60 m	Rythmically to wispily banded muddy sand to sandy mud. Very little gravel. Subglacial to proglacial.
Interpreted as Early-Mid-Wisconsinan	4	Uniform dense grey patterns of incoherent reflections occurring as a continuous blanket of uniform thickness. Often extensively iceberg furrowed. Restricted to depths greater than 110-130 m (60-70 fa.).	10-15 m	High gravel content. Interpreted to be glacial till (King and Fader, in press)
Cretaceous to Tertiary	3	An undulating ill defined surface averaging 5 m in relief with incoherent reflections. Occasional coherent reflections dip seawards gently (2-3°). Extensive channeling.	Penetration of up to 20 m.	Grey siltstone, mudstone, and thin glauconitic sandstone (bedrock).
Cambrian to ? Devonian	2	High intensity continuous coherent reflections averaging 5 m penetration. Reflections are closely spaced and dip up to 12°. Some local faulting evident.	Penetration averages 5 m.	Bedrock. Siltstones medium grey and red in colour. Grey and red sandstones.

TABLE I - TABLE OF UNITS - CONTINUED

AGE	UNIT	SEISMOSTRATIGRAPHY FROM HUNTEC DTS PROFILES	THICKNESS	LITHOSTRATIGRAPHY
Hadrynian	1	Seismic energy is entirely reflected at its surface. No subsurface reflections occur. R_1 and R_2 show large and moderate values respectively. Termed "acoustic basement".	No penetration.	Pink and white quartzites, tillites and granidiorite.

3.4.5 UNIT 5 - Unit 5 is defined acoustically by continuous to discontinuous parallel coherent reflections of medium to high amplitude (banded). Reflections are closely spaced at an average distance of 0.3 m (see Figure 7). Throughout the vertical section these reflections may vary from strong to weak in intensity. Over large horizontal distances, however, reflections maintain their intensity despite variations in depth of occurrence. Unit 5 ranges in thickness from a few metres to over 60 metres in the deeper parts of the study area. In the lower part of the section this unit displays a high degree of conformability as it mimics the underlying Unit 4 (glacial till). In contrast the upper section has a more ponded style with associated reflection onlap on basin flanks. Unit 5 appears restricted to depths greater than 120 m (65 fa.). The thicker occurrences found within Downing Basin are generally overlain by continuous deposits of Unit 7. On shallower areas above 110-130 m, the unit occurs in isolated depressions overlain by a thin veneer of Unit 6. This unit is interpreted as a subglacial to proglacial silt.

3.4.6 UNIT 6 - The acoustic character of this unit may be defined as a zone of low to medium intensity, weak discontinuous to continuous reflections. This zone commonly occurs as a thin veneer deposit 1-5 m in thickness and may be difficult to resolve on DTS profiles (see Figure 8) in some areas. Unit 6 is found above 110-130 m (60-70 fa.) where it is usually underlain by Units 2 or 3. Sidescan sonograms are particularly useful in determining the acoustical nature of this unit. Depth limitations of the sidescan system rendered it incapable of obtaining data from the units which occur in deeper water (Fader _et al._, 1982). Over the shallow bank areas, however, sidescan sonar data reveals uniformly dense dark patches contrasting intermittently with much lighter toned areas. Sampling procedures have revealed this pattern to represent gravel and sand respectively. Lithologic interpretations will be discussed in more detail later. Sonograms also highlite a variety of bedforms on Unit 4 such as mega-ripple fields,

FIGURE 3. A Huntec DTS profile over the Virgin Rocks - Eastern Shoals area illustrating the type section of Unit 1. A. Peak amplitude profile. B. Seabed C. May be Unit 6. D. Unit 1, forming acoustic basement of Hadrynian age. Unit 1 does not permit penetration by the Huntec DTS signals. The very weak subsurface reflections are the product of acoustic ringing within the Huntec system.

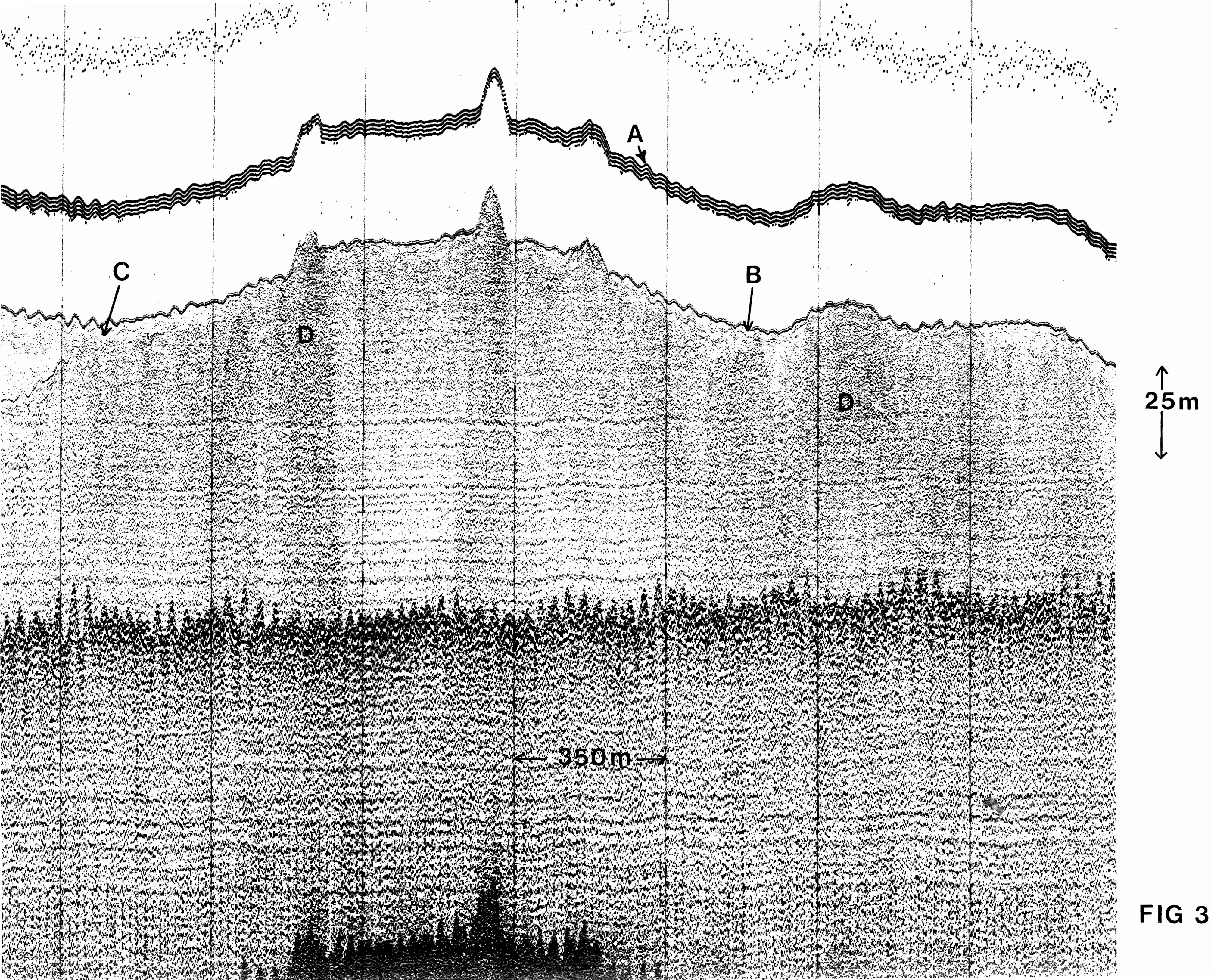


FIG 3

FIGURE 4. A Huntec DTS profile across Avalon Channel. A. Seabed. B. Unit 4. C. Unit 2. Unit 2 is characterized by high intensity continuous coherent reflections averaging 5 m penetration and represents Cambro-?Devonian bedrock.

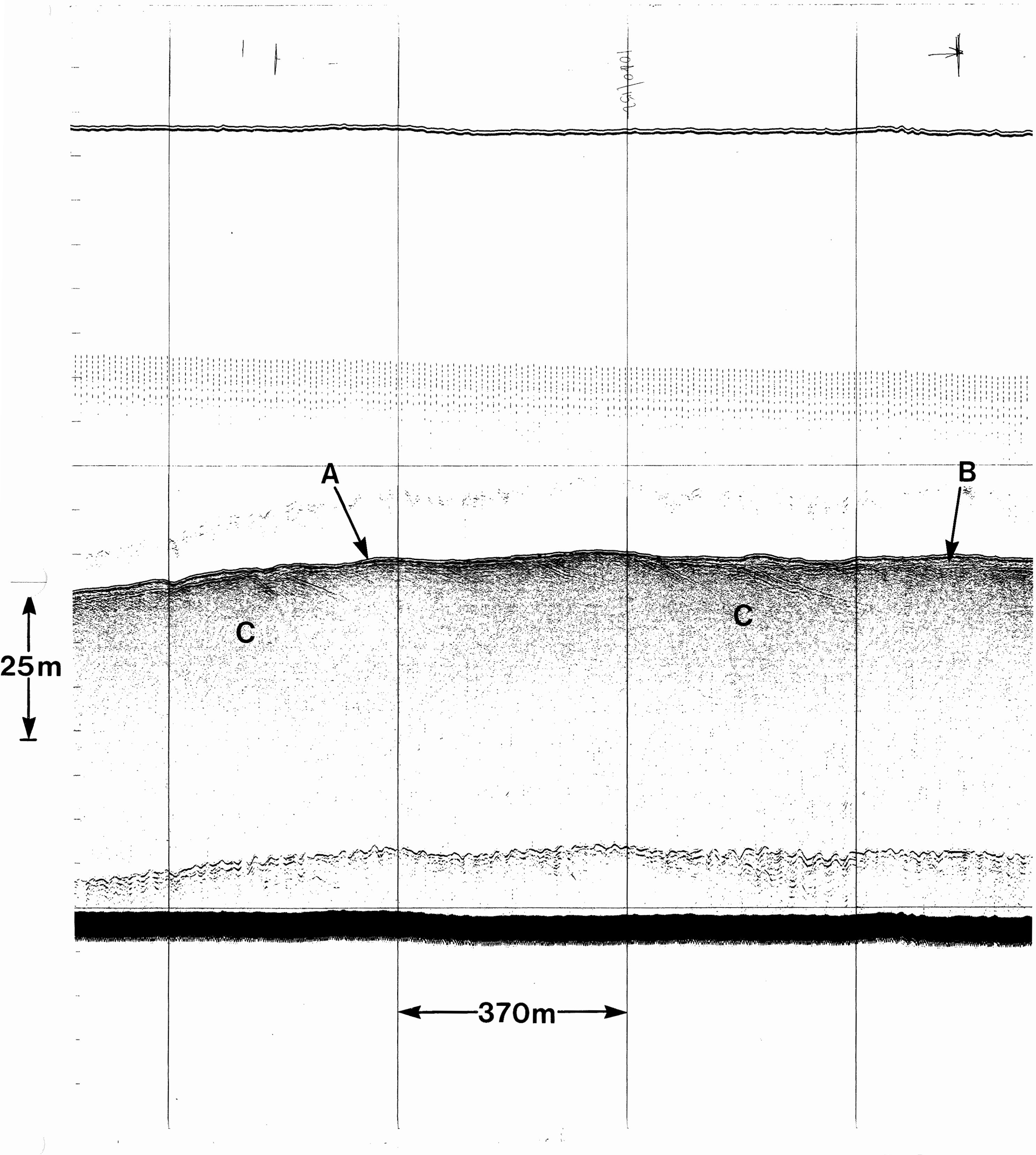


FIG 4

FIGURE 5. A Huntec DTS profile north of Downing Basin. A. Acoustic reflectivity r_1. B. Acoustic reflectivity r_2. C. Peak amplitude profile. D. Seabed. E. A thin veneer of Unit 6 (difficult to resolve in some cases). F. Unit 3, characterized by an undulating ill-defined surface with up to 20 m penetration. A coherent reflection is shown dipping gently seaward.

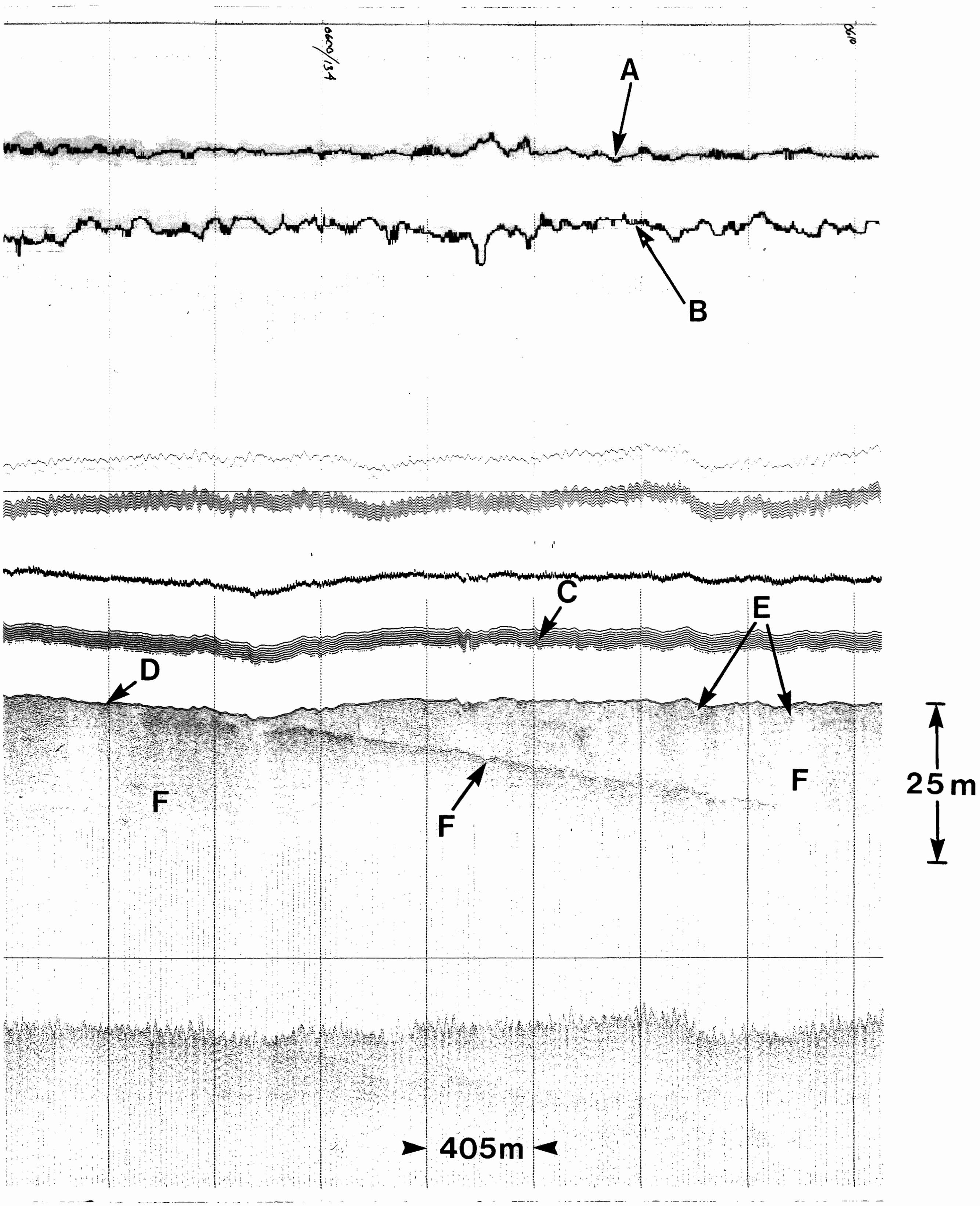


FIG 5

FIGURE 6. A Huntec DTS profile across Avalon Channel. A. Seabed. B. Unit 4. C. Unit 2. Unit 4 is characterized by uniform dense grey patterns of incoherent reflections occurring as a continuous blanket of uniform thickness. It is interpreted as glacial till of Early to Middle Wisconsinan age.

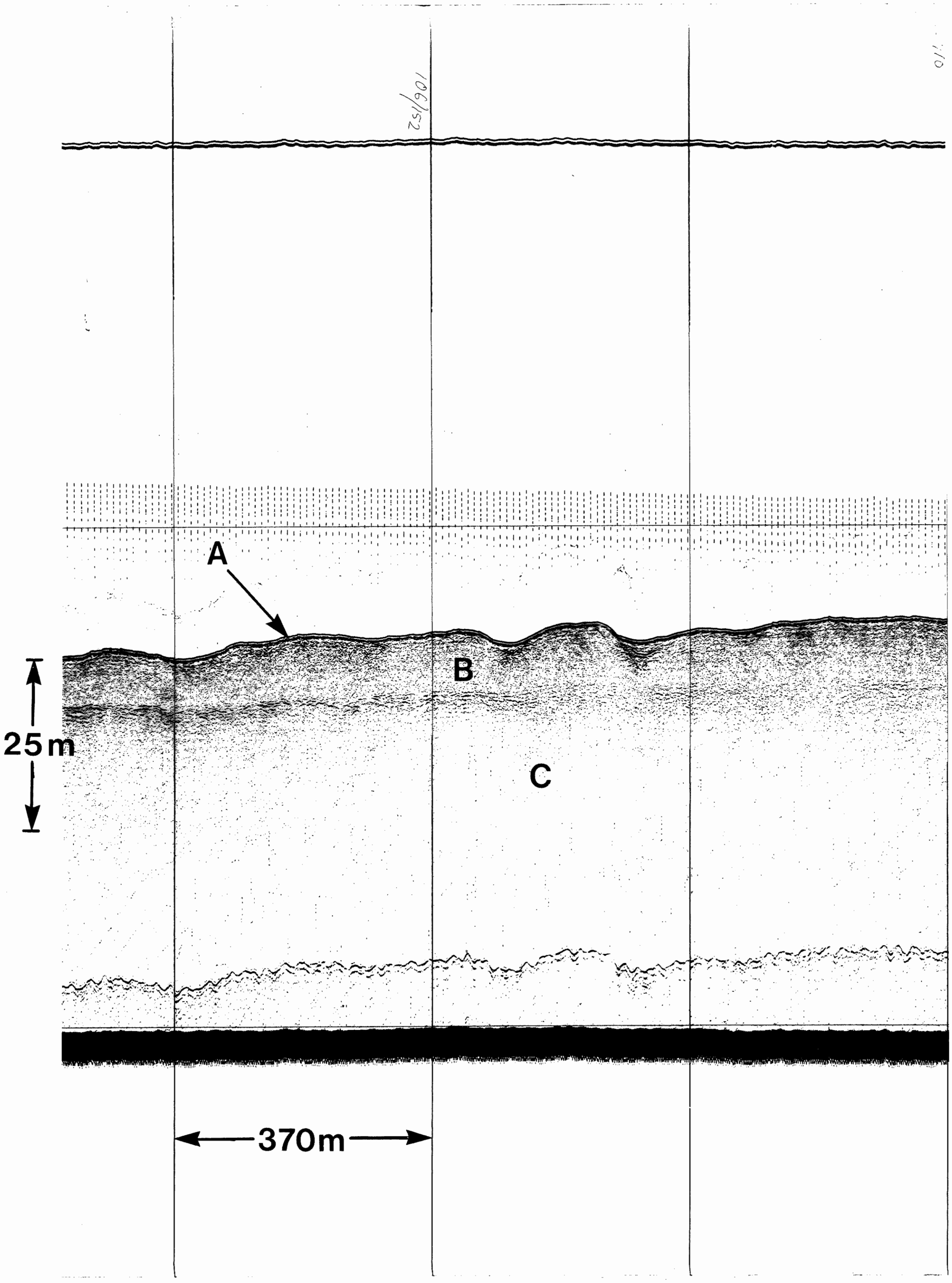


FIG 6

FIGURE 7. A Huntec DTS profile across Downing Basin. A. Acoustic reflectivity r_1. B. Acoustic reflectivity r_2. C. Peak amplitude profile. D. Seabed. E. Unit 7. F. Unit 5. G. Unit 4 showing minor lift-off moraine development. H. Unit 3. Unit 5 is equivalent to Emerald Silt on the Scotian Shelf and is characterized by continuous to discontinuous parallel coherent reflections.

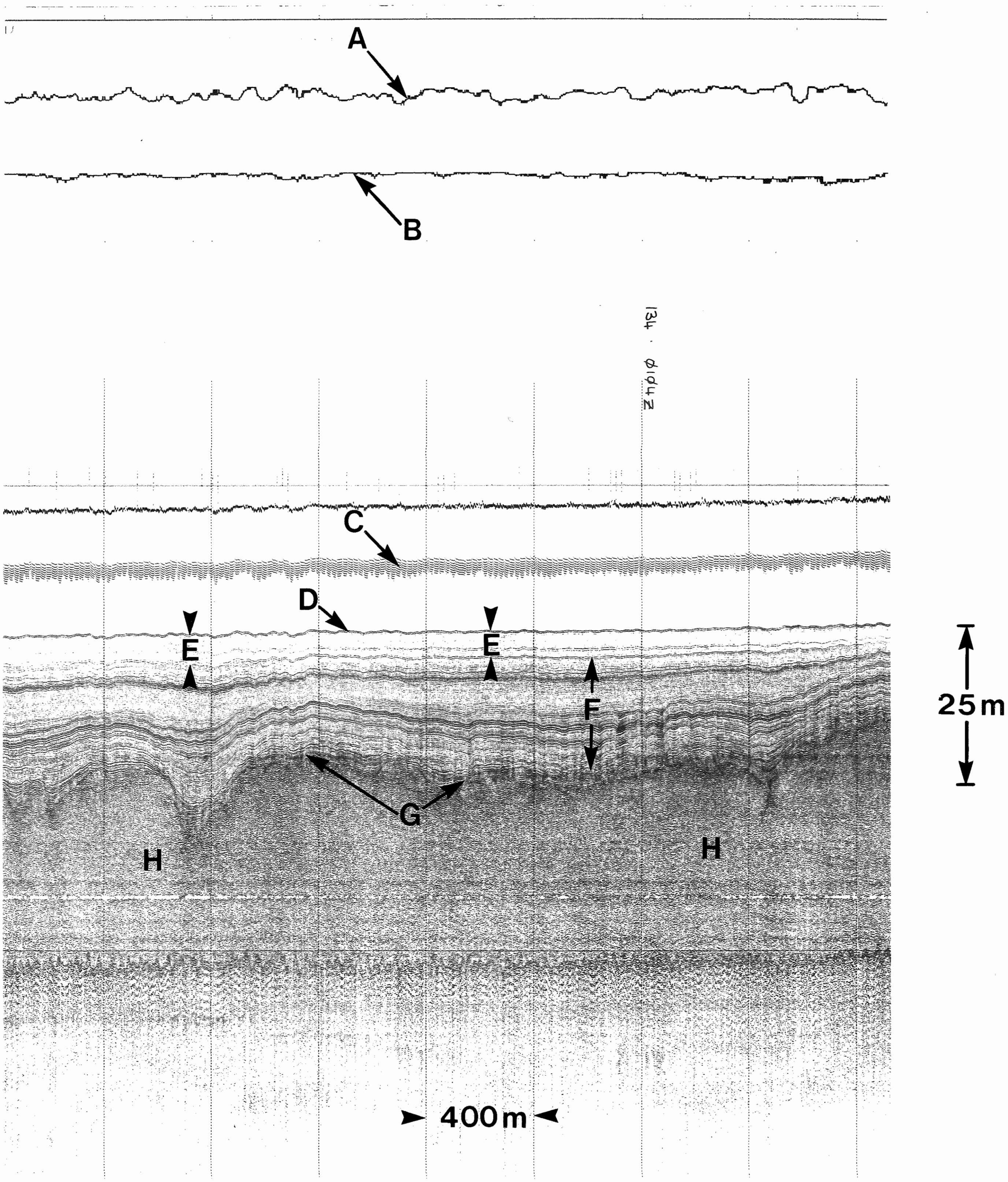


FIG 7

FIGURE 8. A Huntec DTS profile east of Downing Basin. A. Acoustic reflectivity r_1. B. Acoustic reflectivity r_2. C. Peak amplitude profile. D. Seabed. E. Unit 6. F. Unit 3. Unit 6 is a veneer deposit of well sorted sand and gravel and is represented acoustically by a zone of low to medium intensity discontinuous to continuous reflections. This is the dominant seismic character over much of the shallower bank areas of the study area.

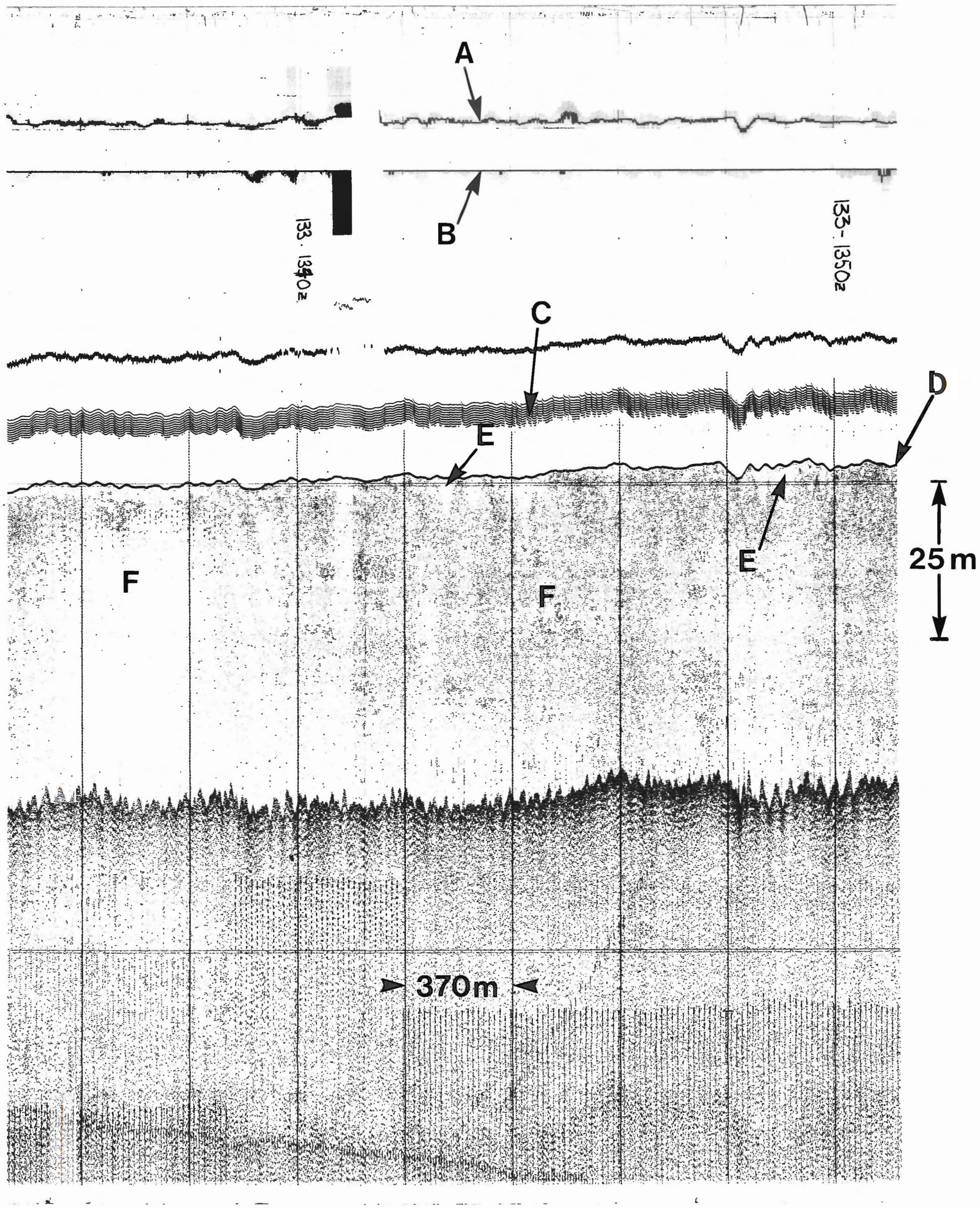


FIG 8

FIGURE 9. A Huntec DTS profile over Downing Basin. A. Seabed. B. Unit 7. C. Unit 5. D. Unit 4 forming lift-off moraines. E. May be Unit 2 or Unit 3. Unit 7 is a clayey silt characterized acoustically by continuous to discontinuous medium intensity reflections. Note the lack of fine banded in Unit 7 as seen in sections of Unit 5.

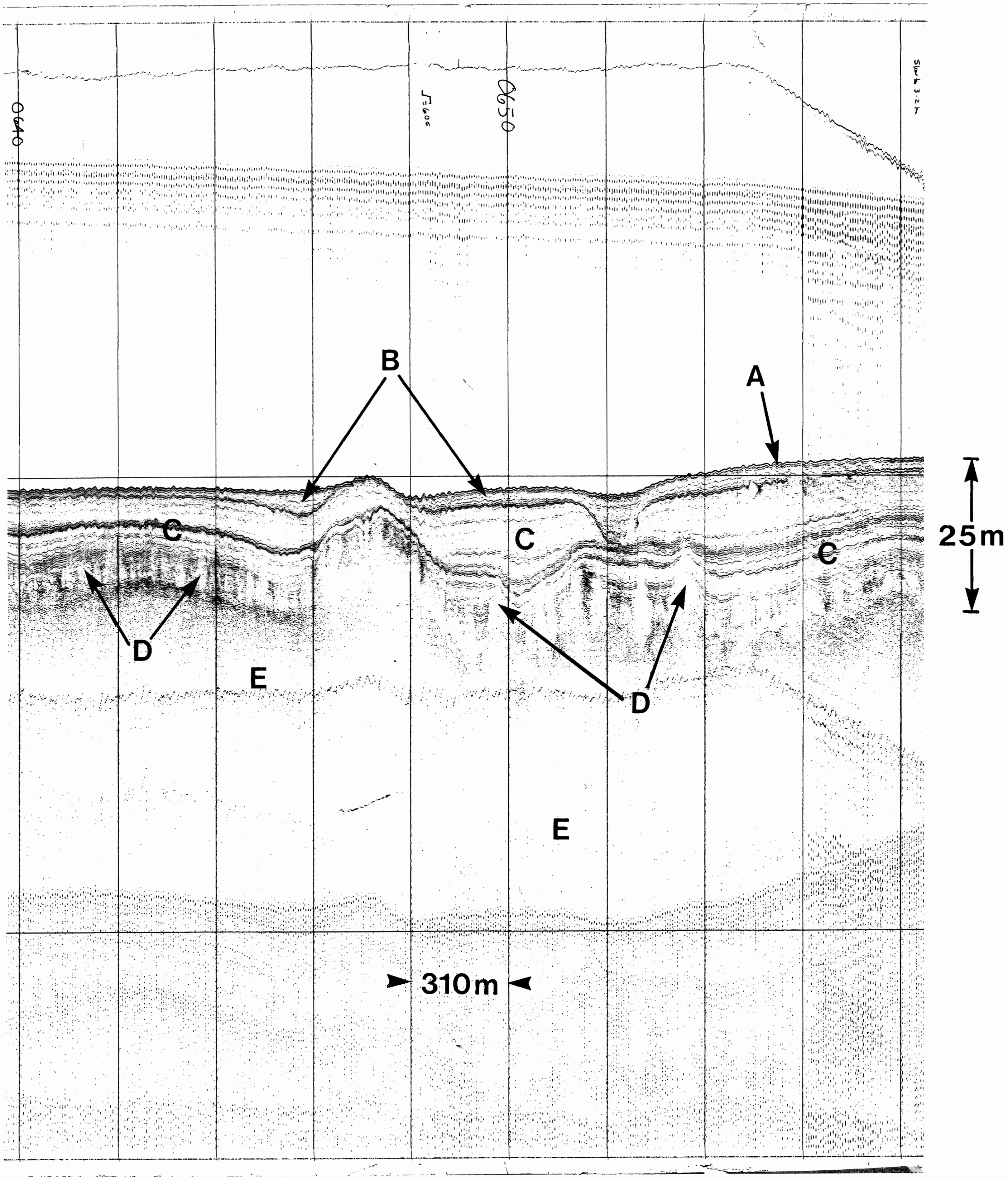


FIG 9

harchan-like sand dunes, iceberg furrows, sand waves, and occasional boulder fields. A more detailed discussion of these features may be found in Fader et al., (1982).

3.4.7 UNIT 7 - This acoustic unit is characterized by continuous to discontinuous medium intensity reflections with no internal banding as in Unit 5. It unconformably overlies Unit 5 and tends to form a smooth blanket deposit of uniform thickness (approximately 5 m) with a ponded structural style. Its acoustic character can be readily confused with that of the upper section of Unit 5 as the acoustic character of both units is similar (see Figure 9).

3.5 SAMPLE DATA BASE

The enclosed map shows the location of all sample stations in the study area relevant to this paper (Fader 1985, Open File 1128). The most obvious feature of the extent of sample control is that it is very limited. The sample stations that exist unfortunately are not located in strategic areas, such as the deep portions of Downing Basin. Thus existing data is only marginally useful for detailed lithogic correlation purposes.

Several drill cores, Van Veen grab samples, and vibrocores were obtained over the study area by Hudson 75-009 Cruise. The two vibrocores are 75-009-28 and 75-009-21 of which the latter yields most data. Vibrocore 75-009-21 is perhaps the only useful core in the entire study area and it lies just outside the deeper portions of Downing Basin. An extensive bedrock coring program yielded data concerning the nature of the bedrock geology (King et al., in press) but is of little value in describing lithologies of the overlying surficial sediments.

Dawson 71-021 Cruise collected 11 grab samples located at the northern end of the study area and none within Downing Basin. Hudson 77-011 Cruise obtained many short cores employing an electric drill. Most of these sampled submarine bedrock outcrops and contained no data on the overlying unconsolidated material. Fourteen grab samples collected by Mobil Oil in 1980 are located within the study area but only one was taken directly within Downing Basin. Two Van Veen grab samples were gathered in Downing Basin by Baffin 81-012 Cruise.

3.6 LITHOLOGIC CORRELATIONS

Despite the obvious shortcomings of the sample data base in the study area some correlation are possible and the results are summarized in Table I.

3.6.1 UNIT 1 - Seismic energy is highly reflected at the surface of this unit and internal penetration does not occur. This unit is therefore termed "acoustic basement" and outcrops in the Virgin Rocks-Eastern Shoals. Several drill cores were obtained in this area as part of a bedrock study over the Grand Banks (King _et_ _al_., in press). These cores are 75-009-22, 77-011-24, 24A, 25, 25A, 26 and 27A. On the basis of drilling results Unit 1 consists of pink and white quartzites, tillites and granidiorite. Radiocarbon dating gives age within Hadrynian time.

3.6.2 UNIT 2 - DTS profiles of Unit 2 reveal several locations of outcrop or near-surface highs within the landward half of the study area. Lithologic and age determinations of cores 75-009-24A, 25, 77-011-2; 2A, 3, 28A, and 30 were completed by King _et_ _al_., (in press) and suggest rocks of low metamorphic grade Cambrian to possibly Devonian age. Core 75-009-24A is comprised of grey sandstone and determined to be Late Ordovician in age. Core 75-009-25 is comprised of medium grey siltstone and is Silurian in age. Core 77-011-2 consists of red sandstone tentatively of Devonian age. Core 77-011-3 is a red siltstone also tentatively of Devonian age. The average of 5 m penetration achieved by the DTS system is in contrast to the near zero penetration achieved over rocks of similar age on the Scotian Shelf, where all rocks pre-Pennsylvanian in age were termed acoustic basement.

3.6.3 UNIT 3 - The contact between Unit 3 and the underlying Unit 2 occurs within the study area. Unit 3 forms a wedge thickening seaward and it generally lies close to the seabed. No drill cores appear to have been taken over this unit but published well records proved it to consist of grey siltstone, mudstone, and thin glauconitic sandstone (Fader _et_ _al_., 1982). These sedimentary rocks were dated at Cretaceous to Tertiary in age.

3.6.4 UNIT 4 - This unit is especially common in the Avalon Channel where numerous grab samples have been taken. These samples indicate high gravel fractions and King and Fader (in press) interpret it to be glacial till of Early to Mid-Wisconsinan age. No vibrocores have been taken of Unit 4.

3.6.5 UNIT 5 - King and Fader (in press) examined core 75-009-21, a 4 m vibrocore of Unit 5. They identified a rythmically to wispily banded sediment ranging in composition from a muddy sand to a sandy mud. Textural composition averaged 50% sand, 35% silt and 15% clay with a virtual absence of gravel. Sand content increased to 70% toward the bottom of the core. A radiocarbon date acquired about halfway down core yielded an age of 22.015 (+1.35, -1.15) x 1000 y.B.P. Vibrocore 75-009-21V permits safe correlation between acoustic Unit 5 and the subglacial to proglacial Emerald Silt Formation found on the Scotian Shelf.

3.6.6 UNIT 6 - Numerous grab samples on the shallower portions of the study area above 110-130 m (60-70 fa.) suggests that sand and gravel dominates Unit 6. Sidescan sonar data over Unit 6 show intermittent unformly dense, dark patches contrasting with more lighter toned patches. It is postulated that gravel being "harder" acoustically causes the darker patches on the sidescan sonogram while sand appears as the lighter toned patches.

3.6.7 UNIT 7 - Acoustic Unit 7 is limited to the deeper portions of Downing Basin, an area having minimal sample coverage. Vibrocore 75-009-28V is 40 cm long and was obtained over Unit 7 but a complete analysis of results could not be found. Grab sample results do prove, however, that Unit 7 is comprised of clayey silt with 60% mud.

3.7 GEOLOGICAL HISTORY OF GLACIAL AND GLACIOMARINE DEPOSITION

In this section the development of the glacial history of the Grand Banks is discussed by examining relationships between the 7 seismostratigraphic units and their lithologic interpretations. This in turn is correlated with the bedrock and surficial geology of the Scotian Shelf, the best studied area of the northeast Canadian continental shelf. Conclusions drawn by previous workers (King and Fader, in press; King and MacLean, 1976; Fader _et_ _al_, 1982; King, 1980) of the sequential development of the glacial history of the Scotian Shelf and the pertinence of these views to the glacial history of the Grand Banks are explored.

3.7.1 Scotian Shelf - According to King (1980) three factors dominate the Late Pleistocene and Holocene geological evolution of the Scotian Shelf: 1) the morphology of the bedrock surface over the shelf; 2) the advance and recession of the Laurentide ice sheet and its terminal relations to the ocean; and 3) a Late Wisconsinan low sea-level stand at about 120 m (65 fa.) and its subsequent transgression.

The morphology of the Scotian Shelf is thought to be controlled largely by the underlying bedrock with landforms typical of a coastal plain environment influenced by subaerial erosion. The Shelf has a rough inner zone reflecting offshore extension of the land area, a middle zone of transverse and longitudinal depressions with adjacent banks, and an outer zone of large, shallow banks with intervening topographic lows. The inner zone consists of rocks of the Meguma Group which outcrop at the seabed to about 50 km offshore where the zero isopach of Mesozoic-Cenozoic strata is located. The longitudinal troughs of the middle zone are formed on this relatively soft strata and parallel the contact with the more resistant rocks of the inner zone (Meguma Group). The troughs commonly coalesce with traverse depressions to form lowlands or basins. These troughs are analogous to the lowlands of the emerged coastal plain south of New Jersey, where rivers flowing seaward off the Piedmont at the fall zone change course and run for some distance subparallel to the inner margin of the coastal plain before crossing to the ocean.

The distribution (see Figure 2) of glacial till (Scotian Shelf Drift) and lag deposits of reworked till implies that at least one continental ice sheet covered the greater part of the Scotian Shelf. The submarine end moraine complex identified by King (1969) lying 30-40 km offshore mainland Nova Scotia indicates the last major ice advance on the Scotian Shelf. King and Fader (in press) suggest that complex is Middle Wisconsinan in age. The advancing ice sheet would have eroded any glacial and glaciomarine deposits formed by earlier glaciations. As the grounded ice sheet advanced, Scotian Shelf Drift was deposited as meltout debris which accreted to the seabed as glacial till. The ice sheet began to float as recession commenced and this meltout debris was dispersed into the water column to form Emerald Silt.

In the deeper portions of the Scotian Shelf discrete hummocks occur as parallel ridges of till on the surface of the basal Scotian Shelf Drift. These ridges range in height from a few to 20 m, in width from 20-150 m, and are spaced about 40 m apart and one also seen over the study area (see Figures 7 and 9). Discrete correlatable bands of Emerald Silt occur between ridges and indicates contemporaneous deposition of Emerald Silt and glacial till ridges. King and Fader (in press) suggest that lift-off moraines are subglacial recessional features formed as the grounded ice sheet becomes buoyant. Each hummock would represent a zone where the ice sheet remained pinned while the adjacent floating sections deposited meltout debris in the water column to form Emerald Silt.

By 15,000 y.B.P. eustatic sea level had reached its minimum still stand at 115-120 m or 63-66 fa. (Fader et al., 1982) where a wave-cut platform was formed. Wisconsinan ice had completely receded from the shelf by this time and the consistent occurrence of the submarine terrace at 115-120 m strongly implies that isostatic rebound was more or less complete. Sambro Sand was formed by reworking of glacial till and Emerald Silt in adjacent basins. Except for the deeper basins, the shelf was exposed to subaerial erosion until Late-Wisconsinan-Holocene time when a marine transgression occurred. All glacial and glaciomarine sediments between the old and present shorelines were modified in response to a high energy beach environment, resulting in lag deposits of well rounded, well sorted sand and gravel (Sable Island Sand and Gravel). The finer sediments were winnowed away and deposited in adjacent basins as LaHave Clay.

3.7.2 Grand Banks - The morphology of the bedrock surface over the western Grand Banks plays an equally important role as for that of the Scotian Shelf. Although the longitudinal troughs and traverse depressions common to the Scotian Shelf are less obvious, the elongation of Downing Basin itself may represent such a feature. Examination of airgun seismic profiles during the course of this study confirms findings of King et al., (in press), who claimed that the contact between Cambro-Devonian bedrock (Unit 2) and Cretaceous-Tertiary bedrock (Unit 3) lies within Downing Basin. The northwest-southeast elongation of Downing Basin should parallel this contact. Channelling in the Cretaceous-Tertiary bedrock surface is extensive (see Figure 8) and points to subaerial drainage patterns. Hadrynian acoustic basement, not found out cropping on the Scotian Shelf, forms the very shallow Virgin Rocks-Eastern Shoals area.

On the Scotian Shelf the widespread occurrence of glacial till and reworked lag deposits of glacial till was cited as evidence confirming the presence of an ice sheet during the Last Glaciation. Such reasoning may be transferred to the study area where similar deposits occur. On the basis of its identical acoustic character and similar occurrence, Unit 4 is defined as a Grand Banks equivalent of the Scotian Shelf Drift and represents what Fader et al., (1982) termed the Newfoundland Shelf Drift. Vibrocore analysis of Core 75-009-2iV revealed Unit 5 to be equivalent to Emerald Silt on the Scotian Shelf, and so represents a subglacial to proglacial deposit formed in brackish to marine conditions under a floating ice sheet. Lift-off moraines on the surface of the Scotian Shelf-Newfoundland Shelf Drift are identified in the deeper parts of Downing Basin (see Figures 7 and 9) and indicate ice recessional movements similar to those found on the Scotian Shelf. The radiometric date of approximately 22,000 y.B.P. for Unit 5 would point to a fully developed continental ice sheet in a stage of recession at this time.

On the Scotian Shelf the submarine terrace at 115-120 m occurred as a wavecut platform during the minimum sea level still stand at 15,000 y.B.P. Distribution of the acoustic units over the study area would suggest a submarine terrace between 110 and 130 m (60 and 70 fa.). Unit 6, comprised of well sorted sand and gravel and limited to depths less than 110-130 m, is equivalent to Sable Island Sand and Gravel, and was derived during the Late Wisconsinan-Holocene transgression by reworking of Unit 4 (glacial till) and Unit 5 (Emerald Silt). Unit 7 represents an equivalent of the LaHave Clay Formation, consisting of the fines winnowed from Units 4 and 5 and sand spillover from the surrounding shallow banks. The Late Wisconsinan-Holocene transgression was a very effective sorting mechanism and all glaciomarine and glacial sediments on the Grand Banks above 110-130 m were almost completely removed. Therefore, it is difficult to ascertain whether or not the Wisconsinan ice sheet advanced beyond Downing Basin to the shelf edge. Given that Wisconsinan ice managed to reach Downing Basin, it would be entirely reasonable to suspect its extension a further 200 km to the shelf edge across a smoothly, flat bedrock (Tertiary) surface.

4. SUMMARY AND RECOMMENDATIONS

This seismostratigraphic study of acoustic reflection characteristics at the seabed on the western Grand Banks has permitted the definition of 7 acoustic units. These units have been mapped at a scale of 1:350,000. A limited sample data base including piston cores, drill cores, vibrocores, and grab samples allows marginal lithologic correlation.

Comparing the seismostratigraphy and lithology of these units with that of the Scotian Shelf bedrock and surficial geology enabled some correlation between the two areas. Unit 1 is acoustic basement. Units 2 and 3 show limited penetration by the Huntec DTS system and represent Cambro-? Devonian and Cretaceous-Tertiary bedrock respectively. These bedrock units strongly control the morphology of the Scotian Shelf and western Grand Banks. Unit 4 consisting of uniform incoherent reflections is equivalent to the Scotian Shelf Drift and was formed as basal meltout debris beneath a grounded ice sheet. Unit 5, possessing continuous coherent reflections and correlated with the Emerald Silt Formation on the Scotian Shelf, is Late Wisconsinan in age and represents a subglacial to proglacial silt deposited from a floating ice sheet. Unit 6 has discontinuous reflections and is equivalent to Sable Island Sand and Gravel. It was formed as a lag deposit by erosion of Units 4 and 5 during the Late Wisconsinan-Holocene transgression. Unit 7 is similar to Unit 5 acoustically, yet lacks banding. It may represent a coarse equivalent of LaHave Clay formed by the deposition of fines winnowed from Units 4 and 5 during the marine transgression.

The acoustic and lithologic similarities between the Scotian Shelf bedrock and surficial formations and the 7 acoustic units defined in this study permit extension of a model for the glacial and glaciomarine history of the Scotian Shelf to that of the western Grand Banks study area. Thus it is seen that the Wisconsinan ice sheet extended onto the Grand Banks at least as far as Downing Basin, and it is not unreasonable to assume its extension all the way to the shelf edge.

It is recommended that a detailed coring and sampling program be initiated over the deeper areas of Downing Basin using former Huntec DTS lines as control. This would lend greater confidence to the definition and areal distribution of the acoustic units identified in this study. This study provided the basis on which such a sample program could be designed.

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MAP OF THE AREAL DISTRIBUTION OF SEISMOSTRATIGRAPHIC UNITS