LATE QUATERNARY EVOLUTION OF THE NORTHEAST FAN, OFFSHORE NOVA SCOTIA

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Abstract

Northeast Fan is a submarine fan developed seaward of Northeast Channel, located on the southwestern part of the Scotian Margin. Northeast Channel has been recognized as a major ice-stream outlet during the last glacial maximum (18 ka). Seaward of Laurentian Channel, the other major ice stream outlet off Nova Scotia, is the well known Laurentian Fan. The scope of this study is to explore the late Quaternary architecture of Northeast Fan with the use of six strike seismic lines and four piston cores, to test the hypothesis that Northeast Fan resembles a smaller version of Laurentian Fan.

Creation of a detailed contour map of bathymetry for the Northeast Fan showed that the axes of three main channels could be traced, called Western, Central and Eastern channel. The interpretation of acoustic facies within the upper 50 m through the use of the high-resolution reflection seismic profiles (Huntec sparker) provided an acoustic facies distribution map. This map showed that the southwestern and upper slope portion of Northeast Fan is composed mainly of dissected reflectors or stratified and dissected reflectors, while the southeast and northeast portions of the Northeast Fan predominantly comprise of mass-transport deposits (MTDs) and highly stratified and stratified reflectors. Six reflection markers in the Huntec seismic profiles were correlated across most of the Fan, thus creating a stratigraphic framework. Cores showed the existence of one or two distinct units of brick red muds ('b' and 'd') and some contained a small tan mud layer identified as Heinrich layer H1. Turbidite sands found in cores were high above channel floors and some were deposited within the time interval of 18 ka to 14 ka.

On the continental slope northeast of the Northeast Fan, three distinct high amplitude reflectors were observed in a Huntec profile, which show similar features to an area off the St. Pierre slope. They were interpreted to represent ice-proximal deposition at glacial maximums and correlated to Marine Isotope Stage (MIS) 4 and MIS 6. The MIS 6 reflector corresponds to the Pink marker of this study, which allowed the dating of two major MTDs in Northeast Fan. Although Northeast Fan does share some features with Laurentian Fan such as the development of channels across the slope and rise, major differences exist. The upper portion of Northeast Fan rather resembles The Gully or Banquereau canyons with the presence of shelf-breaching canyons.

Key Words: submarine fan, seismic stratigraphy, turbidite, mass-transport deposits, core, chronology, channel, Scotian Slope

Table of Contents

List of Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

List of Abbreviations

DTS………..Deep Tow System

LGM……….last glacial maximum

Mbsl………..metres below sea level

MIS………...marine isotope stage

MTD……….mass-transport deposit

TWTT………two-way travel time

WD…………water depth

AGC………..Atlantic Geoscience Centre

GSC………...Geological Survey of Canada

MST………...Multi-sensor Core Logger

H1…………..Henirich event 1

IRD…………ice rafted debris

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The support I received for this study from various people was greatly appreciated. Dr. David Piper's support through the year in particular was outstanding as his enthusiasm and knowledge towards marine geology truly made it an honour to be his student. The Geological Survey through the Bedford Institute of Oceanography must also be recognized for they allowed the use of their various laboratory facilities, which made this study possible. The support of C. Campbell of BIO with regards to dealing with GIS data must be acknowledged, as figures developed through GIS in this study could not have been completed without his expertise. Additionally, I would like to thank T. Hundert as his initial work conducted on the Northeast Fan helped paved the way for this study. The Department of Earth Sciences of Dalhousie University is also thanked with in particular thanks to Dr. P. Ryall for organizing and conducting the Honours class.

Lastly I would like to thank my family and friends who have been behind me my whole life, supporting me through the good times and the tougher times. Thank you

CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

Parts of the deep-water continental margin offshore Nova Scotia remain very poorly understood, despite studies that span the last few decades. Technologies such as seismic surveys, drill cores, and side-scan bathymetry, to name a few, have played an integral role in developing our current understanding of the margin and will continue to play a role in the future.

Two reasons can be specified for the study of Quaternary sediments on the margin. The practical reason is to make sure we understand slope stability and other geohazards. With the discovery of hydrocarbon deposits along the Scotian margin it is becoming increasingly important to have assessments made about the possibility of geological hazards. Mass flows and sediment failures, for example, have been known to occur, which can, and have in the past, created problems with ocean floor structures such as telecommunication cables or offshore wells. Of course there is scientific reason as well, and this is simply that the relationship of mass flows and turbidity currents to the sedimentary architecture of submarine fans is not well understood. Furthermore, deep-water sediment records provide information about past environmental conditions, including the history of glaciation on the continental shelf.

1.1 OBJECTIVES

The objective of this study is to gain an understanding of the sedimentary architecture in the Late Quaternary (past 150 ka) of the Northeast Fan. This will be established in the following ways;

- With the use of six strike seismic profiles across the Northeast Fan, an along track interpretation of seismic profiles collected with the Huntec deep tow system can be made. Deposits of mass flows or turbidity currents are recognizable and their location entered into an ArcGIS database. The product will be a map in ArcGIS showing facies distributions within the upper 50 m of sedimentation on Northeast Fan, from which the flow paths of turbidity currents can be inferred.

- Hundert (2003) established an age model for the late Quaternary stratigraphic column for the western Scotian Slope, which includes the Northeast Fan area. Two cores within the area have been dated using the AMS (accelerator mass spectrometer) carbon - 14 method, so that using these cores that a chronological history of the turbidity flows can be determined.

- Using newly obtained piston core data combined with the Huntec seismic data, acoustic facies can be interpreted and correlated with sedimentary facies determined in the cores.

- These various data sets will be integrated to provide a better understanding of late Quaternary sedimentation on Northeast Fan and an interpretation of how changes through time in Northeast Channel may have influenced the architecture of the fan.

1.2 PHYSIOGRAPHY

1.2.1 The Scotian Continental Margin

The Scotian basin lies on a passive continental margin and can be divided into a shelf, slope and rise component. Turbidite fans such as the Northeast Fan are found principally in the rise component of a passive margin.

The shelf component of a passive margin can be defined as sediment accumulations that lie above continental basement rock, which extends from the continental shores to the beginning of the continental slope. On the Scotian Shelf, these usually extend in width to about 200 km and have an average water depth of 125 mbsl on the southwest portion of the Scotian Shelf (Wade and McLean, 1990).

The continental slope is defined as the transition between the gently descending continental shelf and the continental rise. Average gradients of the slope on the Scotian margin are 3 to 4 deg (White, 2005). Little deposition occurs along the slope as it is usually bypassed when sediment travels down various slope canyons.

A continental rise marks the transition from the slope to the abyssal plain. Typically the rise of the Atlantic margin displays gradients much less then the slope, with an average gradient of 1 deg (Kidston et al. 2002). Sediment deposition on the rise usually results from turbidity flows that originate from the shelf edge and travel down the slope through canyons.

1.2.2 Study Area

The study area lies on the southwestern part of the Nova Scotian continental margin (Figure 1.1). The Scotian margin extends from the Northeast Channel to the Laurentian Channel, covering a distance of approximately 1000 km. Mean depth of the Scotian shelf below sea level decreases from the southwest to the northeast, and it is unclear which processes are mainly responsible for this trend (Piper, 2005). The eastern portion of the slope is characterized by numerous channels and canyons while the western portion lacks significant canyon structures.

The study area is situated seaward of the Northeast Channel (Figure 1.1). The width of the Northeast Channel is approximately 30 km and reaches a depth of approximately 300 meters (Hundert 2003). During the last glacial maximum (18 ka), the Northeast Channel was a major ice-stream outlet (Denton and Hughes, 1981). Northeast Fan for this study can be defined as the area adjacent to the Northeast Channel that rests on the continental slope and rise. The Northeast Channel and Fan system appears similar to the Laurentian Channel and Fan system, although on a smaller scale.

Hundert (2003) divided the Northeast Fan into an upper and a lower fan. The upper fan consists of steeply incised canyons trending in a SSE direction across the slope, that vary in size and continue to about the 2000 m bathymetric contour. In the upper fan three main canyons dominate, which Hundert (2003) named ‘Eastern’, ‘Central’, and ‘Western’. Several minor canyons also exist, which with the principal canyons, have acted as a drainage system for turbidity current flows exiting the Northeast Channel. When examining the extent of these canyons, it appears they merge along the mid slope at around 2000 meters, and turn slightly southward. The lower fan shows lower relief, with broad levees between the channels (Hundert, 2003).

The continental rise seaward of Northeast Fan was imaged by long-range sidescan sonar from 2500 to 4500 m water depth (Hughes Clarke et al. 1992). This survey showed that channels originating on Northeast Fan extend across the continental rise.

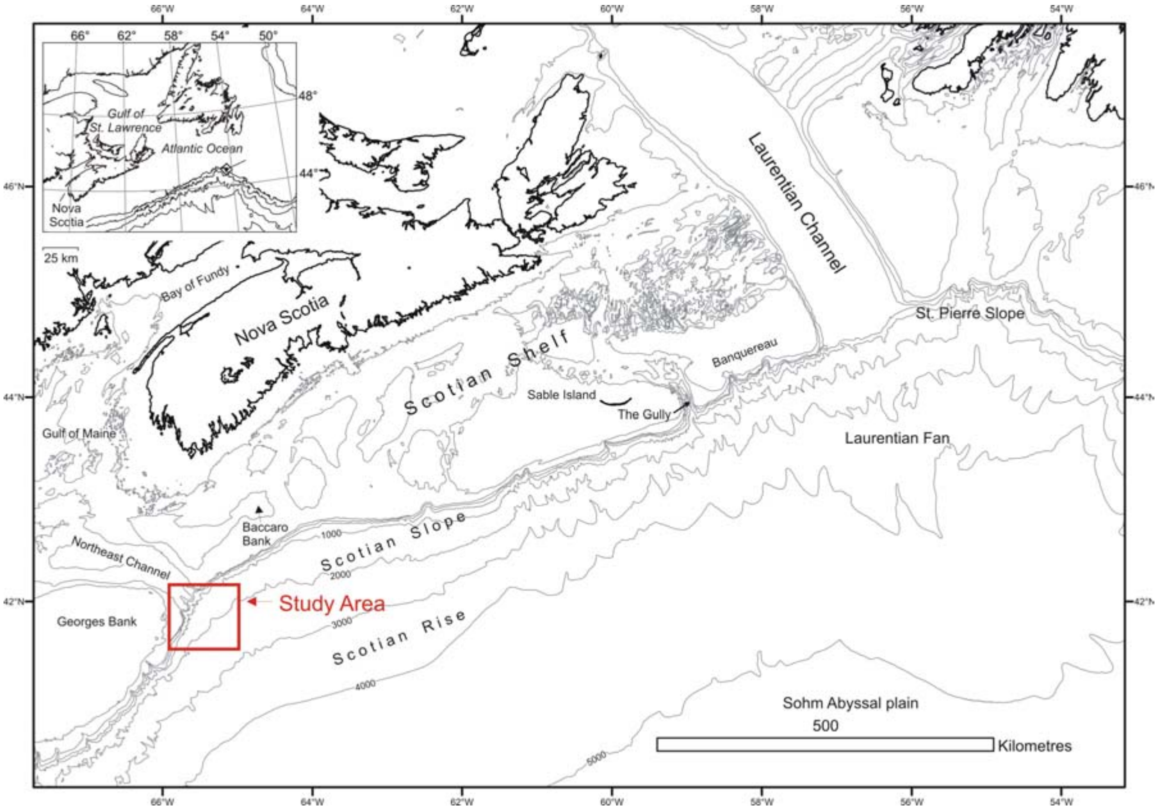


Figure 1.1 Map of Study Area

1.3 REGIONAL GEOLOGICAL BACKGROUND

1.3.1 Scotian Margin Evolution

The Scotian Margin is a passive margin on the North American lithospheric plate. Rifting of this margin initiated in the Mid Triassic to Early Jurassic, which began separating the super continent Pangea and initiated the birth of the Atlantic Ocean (Wade and MacLean, 1990, Kidston et al., 2002).

Deposition of sediments within the Scotian basin first occurred in the Mid-Triassic with red beds (Wade and MacLean 1990). Because Nova Scotia lay near the equator at the time of the early Jurassic, the climate was very hot and dry which resulted in a period of extended evaporation resulting in extensive salt and anhydrite deposits (Argo Formation) (Kidston et al., 2002). Following the evaporite deposits, continental clastics of the Mohican and dolostones of the Iroquois formations were deposited after a period of marine transgression. During the Late Jurassic, clastic and carbonate deposits such as the Mohawk, MicMac, Baccaro, Misaine Shale and Verrill Canyon formations were deposited. Deepwater turbidite deposits are also found throughout the Verrill Canyon marine shale. These deepwater turbidite fan deposits would have formed in a lowstand environment (periods of low relative sea level). The Early Cretaceous again saw more clastic deposition but in the form of fluvial-deltaic deposits, with the Mississauga and Logan Canyon formations being deposited (Wade and MacLean, 1990). The Late Cretaceous Dawson Canyon and Wyandot formations consist of limestones, marine shales, as well as chalk deposits (Kidston, 2002). Overlying all of the mentioned formations is the Banquereau Formation, which consists of marine shelf mudstones, shelf sands, and conglomerates. During this time period in the Tertiary, several major unconformities due to sea level drops occurred, causing progradation and retrogradation of the Banquereau Formation (Wade and MacLean, 1990). In the past 2 Ma (Quaternary Period) several hundred meters of glacial and marine strata were deposited on the outer shelf and upper slope of the Scotian margin (Kidston et al., 2002). A stratigraphic summary of the Mesozoic and Cenozoic geology is illustrated in Figure 1.2 (Kidston et al. 2002)

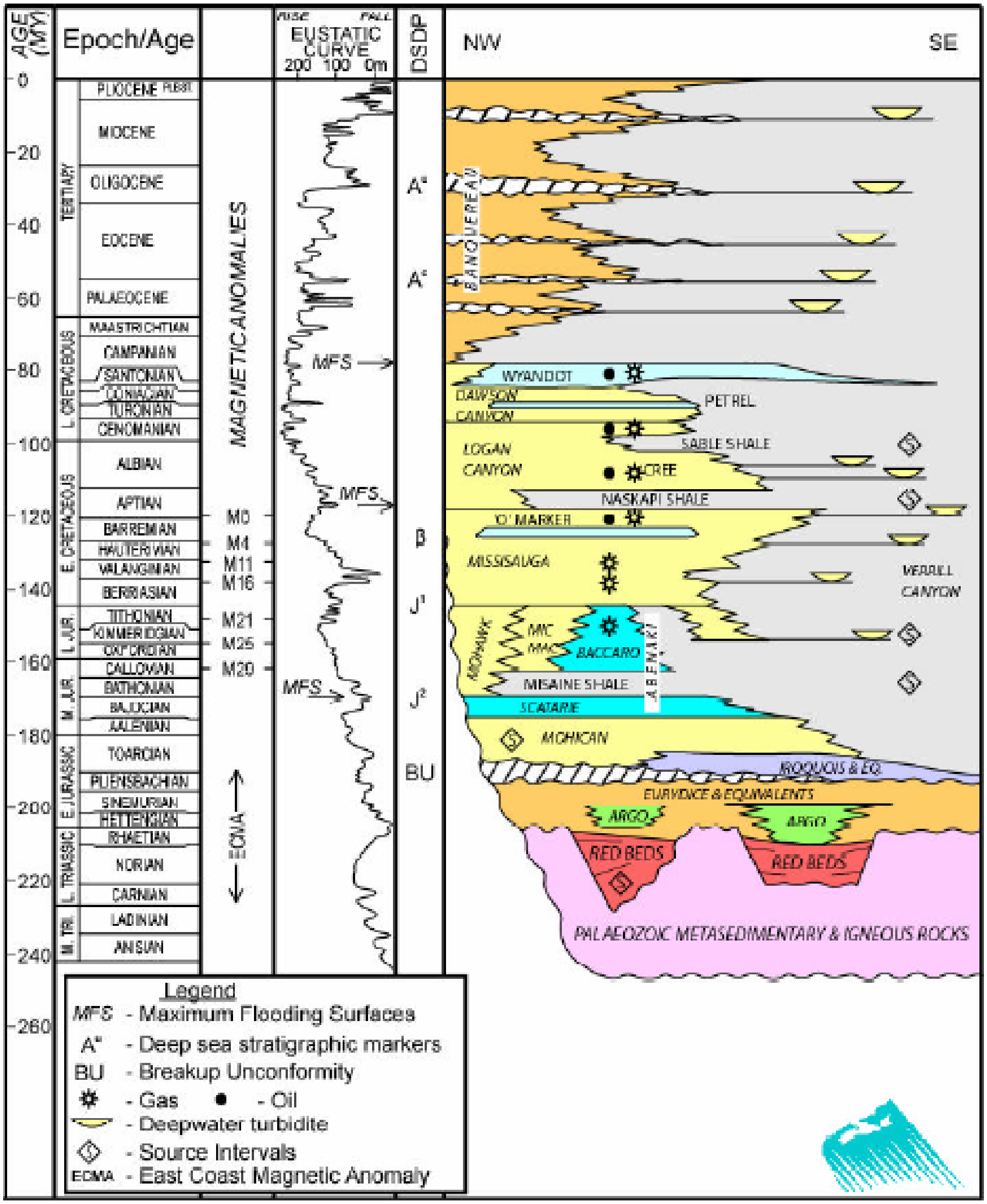


Figure 1.2 Stratigraphic chart of the Scotian Margin (From Kidston et al, 2002)

1.3.2 Atlantic Canada Glacial History

In Atlantic Canada, the most extensive glaciations advanced as far as the edge of the Scotian Shelf during the Quaternary (Stea et al, 1998). Sediments deposited during the Quaternary on the Scotian Slope are typical of glacial margins, such as massive silty clay diamictons, muddy plume fall-out deposits, and mass-wasting and turbidity deposits (Hundert, 2003). During glacial advances and retreat periods, sedimentation rates were higher and as a result caused shelf and slope progradation (Piper et al. 1990). These points are necessary for the background understanding of mass-flow deposition periods on the Scotian Shelf during the Quaternary.

The first glacial crossing of the Scotian Shelf probably occurred during Marine Isotope Stage (MIS) 12 at 450 ka (Piper et al, 1994). This initial crossing was not the only time glaciations crossed the shelf. Stea et al. (1998) examined glacial retreats and advances during the Wisconsinan, and noted that there were five glacier advance events (Figure 1.3). Since this study is dealing with the understanding of Late Quaternary mass transport deposits, these five glacial advances of the Wisconsinan are of most relevance.

The first glacial advance occurred during the early to middle Wisconsinan time and is known as the Caledonia phase (Stea et al. 1998). This phase extended to the continental shelf edge where a calving margin was established. This phase however retreated back to the inner shelf during the middle Wisconsinan time. Between 22-19 ka the second glacial advance occurred, named the Escuminac phase, but retreated again at 18 ka (Stea et al. 1998). The third glaciation advance, called the Scotian phase, advanced over Nova Scotia and the southern shelf off Cape Breton. The Scotian phase however retreated between 15 and 13 ka and during this time the ice margin settled closer to present day coastlines (Stea et al. 1998). In between 13 and 12.5 ka, ice cover (Chignecto phase) was found locally in northern Nova Scotia but once again retreated around 11.7 ka (Stea et al, 1998). The last glacial period (Collins Pond phase) was due to a reactivation of the Chignecto phase glaciers as a result of cooler temperatures during the Younger Dryas phase (Stea et al, 1998). This however was short lived and was the last of the glacial advances to date in Atlantic Canada.

The history of the Northeast Channel glaciations in particular is not well known as little work has been done on the area. Work was however done by King (1996) who dated sediment overlying the Fundian moraine in the Gulf of Maine. This moraine was dated as older than 15.5 ka, which suggests that at that point in time glacial ice had retreated from the shelf edge near the Northeast Channel well into the Gulf of Maine. King (1996) stated that by 20-23 ka ice had began to retreat in the Northeast Channel. This is misleading, as it is not a date but rather an estimate, which he based off the 15.5 ka date and an assumed rate of sedimentation.

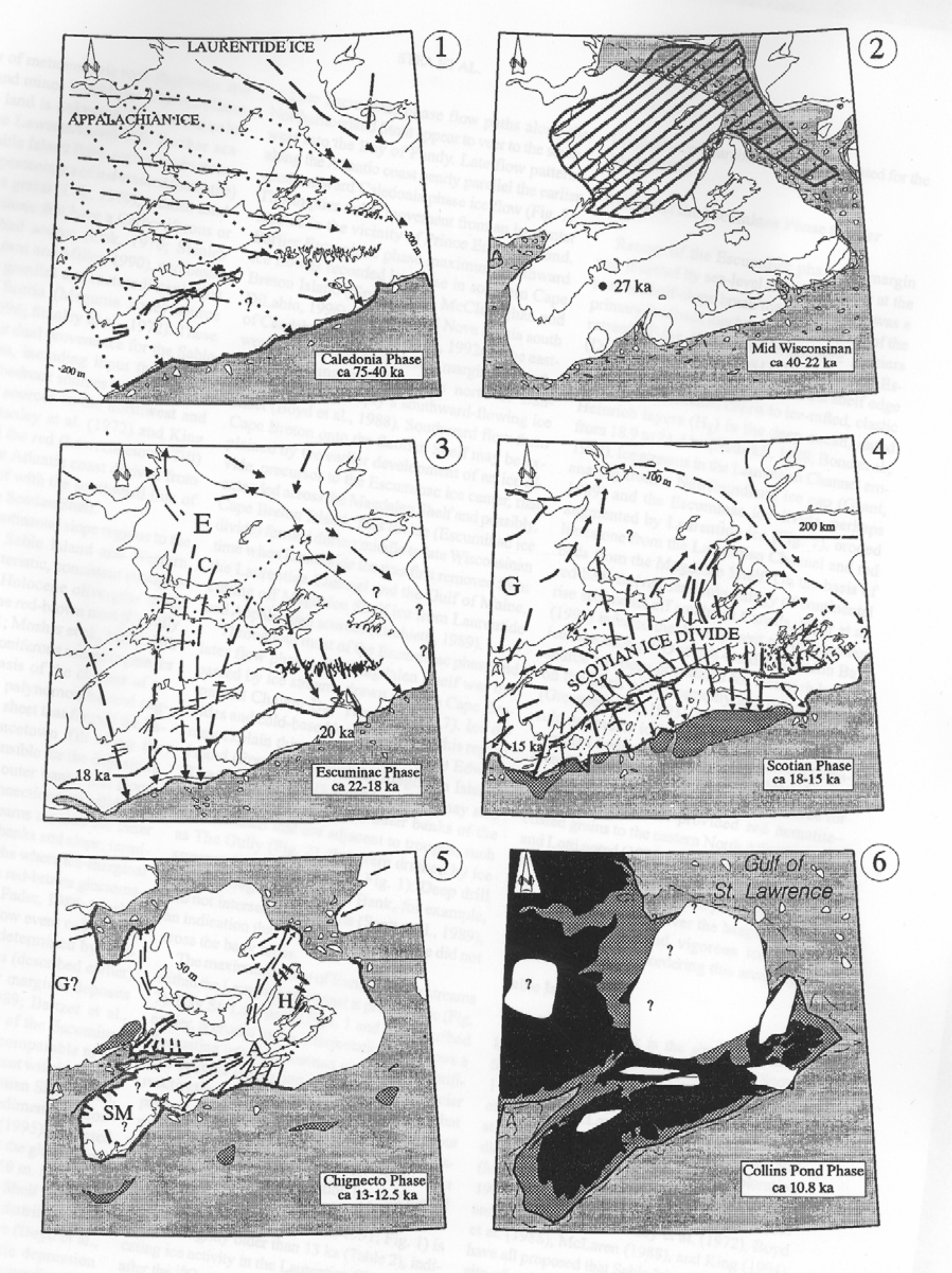


Figure 1.3 Glacial History of the Maritimes in the past 75 ka (From Stea et al. 1998)

1.4 TUBIDITE FANS AND TURBIDITY CURRENTS

Turbidite fans are deposits from turbidity currents that have flowed down the continental slope along canyons and have dispersed in a fan like structure along the continental rise. These turbidity currents generally occupy channels and will spill out onto levees. Normark and Piper (1991) analyzed how there is not one type of turbidity current and that different turbidity currents behave in different ways and display their own types of deposits.

The definition of turbidity currents can be stated as “density currents that move downslope on the ocean floor, driven by gravity that acts on the density difference between the current and the surrounding seawater” (Walker et al 1992). The excess density of a turbidity current is due to the suspended sediments. In 1962 a model was devised for these turbidite deposits called the Bouma sequence (Figure 1.4) (Bouma 1962). This model had been developed after thousands of individual beds had been examined and showed general homogeny with each other. The Bouma sequence consists of “five divisions called A, B, C, D, E(t), and E(h) with each division being distinctive”(Walker et al. 1992). Division A marks the beginning of a turbidite flow and consists of coarse sediment that is structureless. Division B was deposited from the later less energetic part of the flow allowing parallel – laminated sand to develop. As the flow continually loses energy, the layers become finer in grain size and with Division C finer sand is common with rippled and convoluted structures. Division D can be difficult to see in weathered surfaces or outcrops that have experienced deformation. However, when observable, this division contains parallel laminated silt and mud deposits. The last division of the Bouma sequence E contains the finest grained components. It however includes both material of turbidite origin E(t) and partly of hemipelagic E(h) origin (Walker et al. 1992). The Bouma sequence is therefore, a fining upward sequence, which results from deposition from a waning current.

The definition of a turbidite fan was described by Mutti and Normark (1991). They defined it as “a body of genetically related mass-flow and turbidity-current facies and facies associations that were deposited in virtual stratigraphic continuity”. Multiple turbidite fans, when stacked upon each other, are also known as a turbidite fan complex (Bouma 2000). Turbidite fans can be classified into two main groups, which are: coarse-grained, sand-rich submarine fans and fine-grained, mud-rich submarine fans (Figure 1.5). Coarse-grained, sand-rich turbidite systems are generally found in small basins, with canyon sources, have short steep rivers, and have narrower shelves (Bouma 2000). Fine-grained, mud-rich fans on the other hand are typically found in large passive margin basins, have a broad shelf, have long rivers and have sufficient basin transport characteristics that allow much of the sand to bypass the upper fan and onto the lower portion of the fan (Bouma 2000).

When trying to understand the turbidite fan structure of the Northeast Fan it is of interest to explore fans that could be similar in architecture. Hundert (2003) did suggest that the Northeast Fan was a smaller version of the Laurentian Fan, so it would be useful to point out the key architectural components for a comparison later on in this thesis.

The Laurentian Fan comprises of up to 2 km of Quaternary sediment, which extends from the mouth of the Laurentian Channel to the Sohm Abyssal Plain (Piper et al. 1985). The components of the Laurentian fan can be divided into a slope-valley transition, channel-levee complex, valley termination zone, sandy depositional lobe and a silty mud zone (Figure 1.6) (Piper et al. 1985 and Piper et al. 2005). During glaciations the Laurentian Channel was the major outlet ice stream of Atlantic Canada, so glacial melt provided large amounts of sand and gravel to the channel. The transport of this sediment into deep water was by two canyons on the slope. Sediment built up along the shelf edge would eventually cause slumping, which produced turbidity flows down the channels and onto the rise and the Sohm Abyssal Plain. These sediment flows could also be initiated by seismic activity such as the "Grand Banks earthquake" of 1929 (Piper et al. 1985). Distribution of sediment has been determined, with silts and muds occurring on levees and interchannel areas on the fan as well on the distal abyssal plain (Piper et al. 1985). Sands and gravels are found in the fan valleys and sand is dominant on the upper portion of the sediment lobe (Piper et al. 1985).

Glacial meltwater plumes at three intervals between 16.5 and 14.2 ka (radiocarbon years) and two scales of meltwater discharges are recognized (Piper et al. in press). At 16.5 +/- 0.15 ka the first event occurred in the form of a hyperpycnal flow. This age is well constrained by a dated erosive surface on the upper slope. This hyperpycnal flow resulted in large amounts of gravel being deposited (up to 3 meters) in Laurentian Fan valleys as well as depositing thick sands on the Sohm Abyssal Plain (Piper et al. in press). Two younger discharge events occurred resulting in mud deposits from surface melt water plumes. These three events all discharged approximately the same volume of water (Piper et al. in press), implying that not all large water discharge events from shelf-crossing ice streams result in large scale hyperpycnal flow such as the

16.5 ka event. It would be expected that similar conditions would prevail on other turbidite fans seaward of major ice streams.

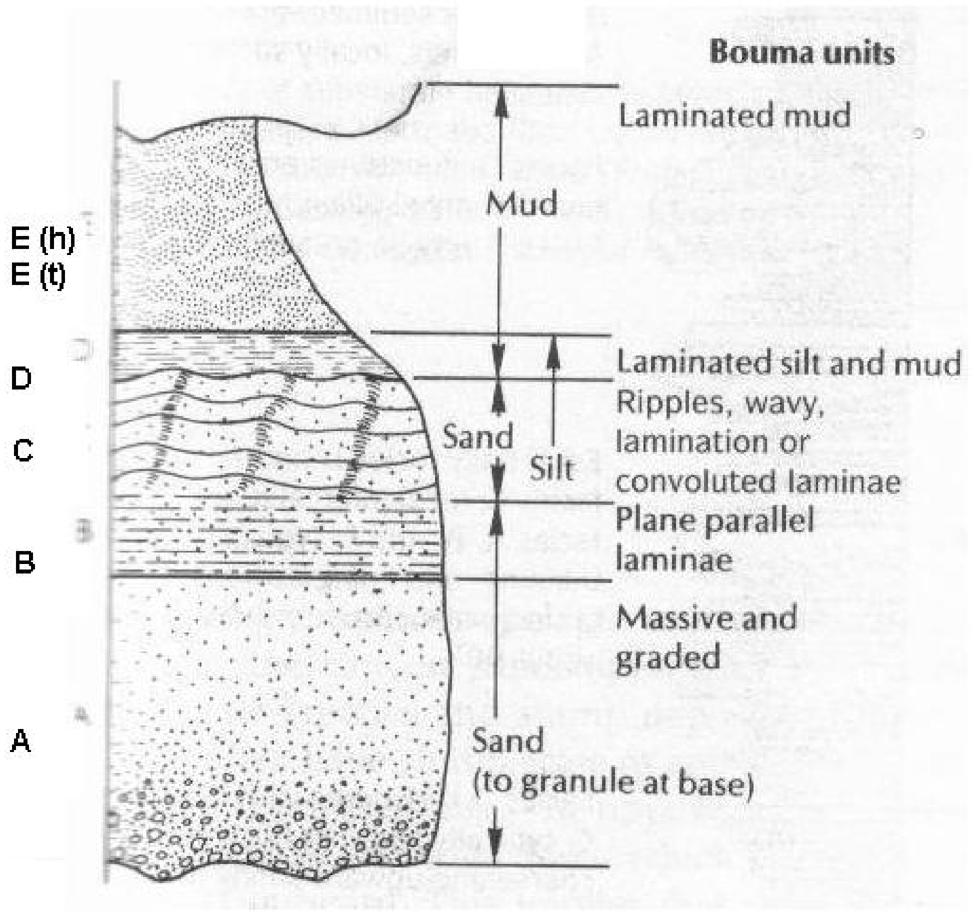


Figure 1.4 Ideal Turbidite deposit known as the Bouma Sequence (From Prothero and Schwab, 1999)

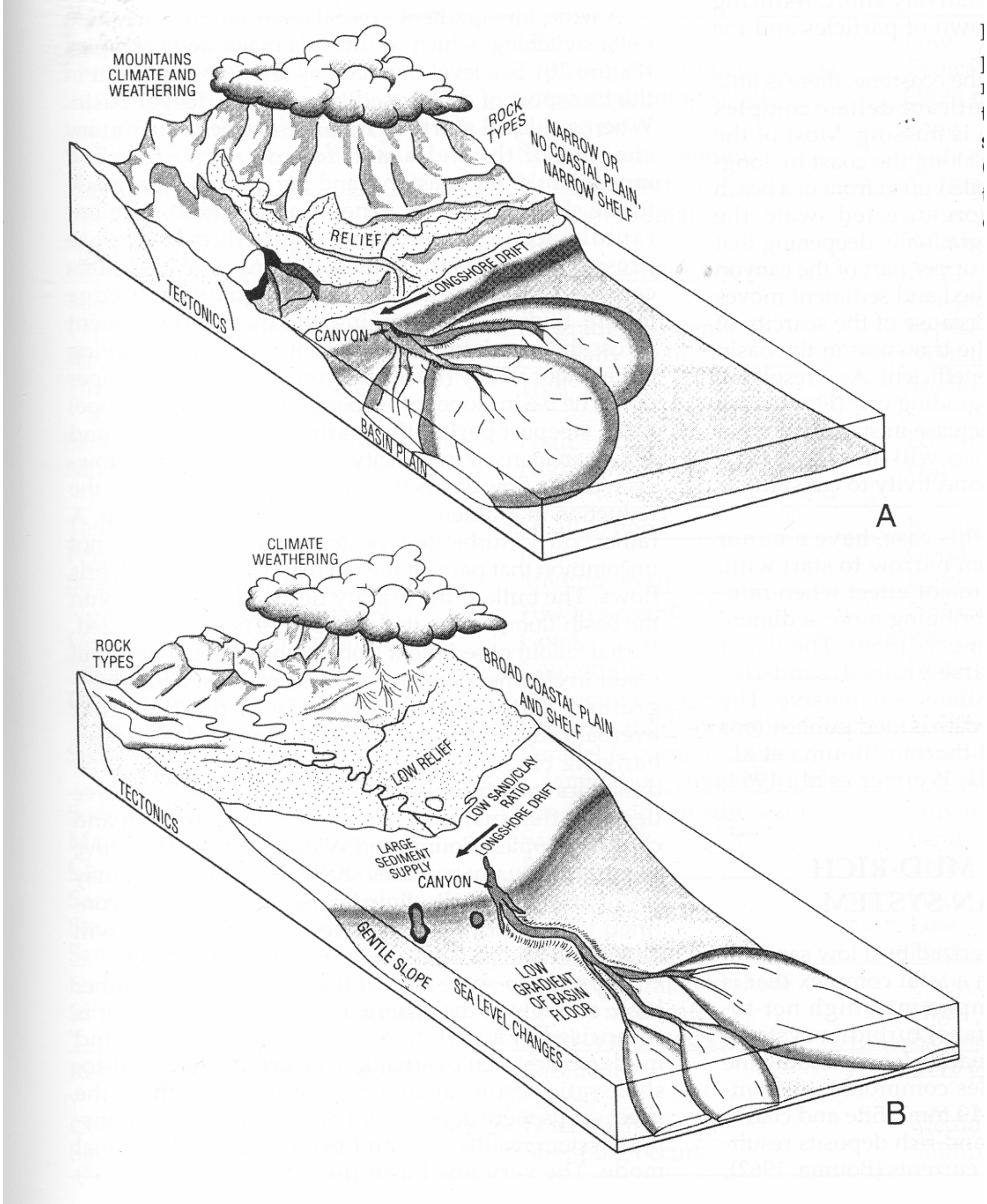


Figure 1.5 (A) Represents typical architecture and setting of a coarse-grained, sand-rich turbidite fan system. (B) Typical architecture and setting of a fine-grained, mud-rich turbidite fan system (From Bouma A.H., 2000)

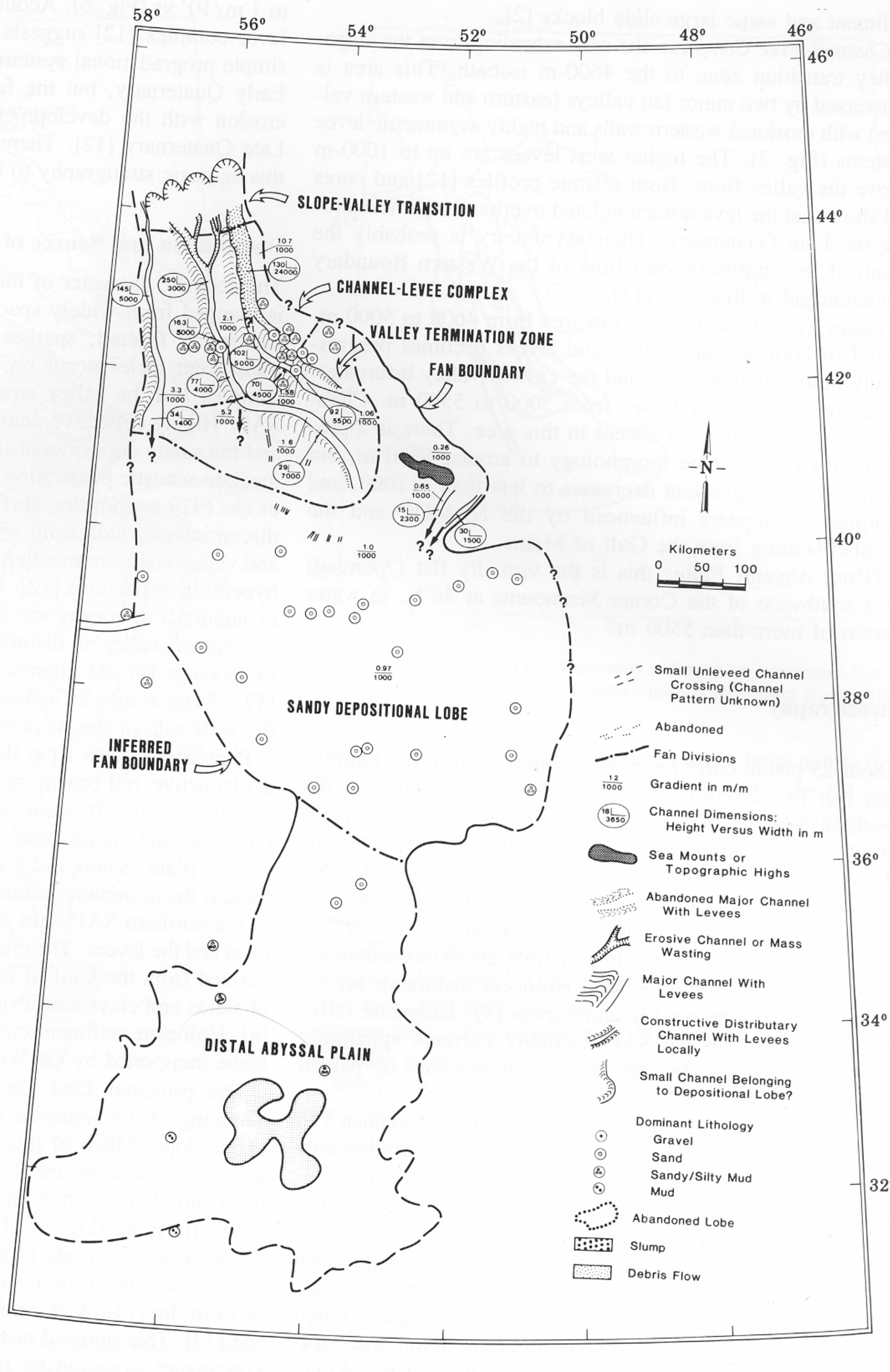


Figure 1.6 Architecture of Laurentian Fan (From Piper et al 1985)

CHAPTER 2

METHODS

The study of marine geology begins with obtaining raw data aboard research vessels. This can be through a number of methods involving various tools that are operated onboard. The data for this study have come from the Bedford Institute of Oceanography, and were collected from two research cruises in 2002 and 2005 aboard the CCGS *Hudson*. High-resolution shallow penetration Huntec Deep Tow System (DTS), lower resolution deeper penetration airgun, and 3.5 kHz and 12 kHz seismic profiles were obtained from sea level. Sediment sampling was conducted using a piston corer. Other methods such as GIS software tools were also used in this study.

2.1 SEISMIC DATA

Within the past 20 to 30 years, high-resolution marine seismic reflection techniques have been used for Quaternary mapping and seafloor investigations (Mosher and Simpkin, 1999). Seismic profiling of marine Quaternary sediments begins when a seismic source such as an airgun, sparker or boomer emits a sound wave into the water column. This sound wave will travel until it meets a reflective medium with an acoustic impedance contrast (for example, at the ocean floor) and then travels back to a receiver. This time is recorded and called the ‘Two-way Travel Time’ (Lillie, 1999). Not all of the seismic energy is reflected at the first medium, as some will penetrate deeper and with each new reflective surface encountered more reflection of this sound will travel back to the receiver. The receiver is comprised of numerous hydrophones (spaced evenly within a streamer) that are pressure-sensitive piezo-electric crystals (Mosher and Simpkin, 1999). The measurements of these various two-way travel times related to acoustic impendence results in our seismic section.

What makes seismic profiling for Quaternary mapping different is that the seismic sources have been set so that the frequency is much higher then in conventional configurations used by petroleum industries. Using a higher frequency allows more resolution but less penetration depth, while the petroleum industry uses lower frequencies with the objective of gaining deeper penetrating depth (Mosher and Simpkin, 1999).

2.1.1 Huntec Deep Tow System (DTS)

The Huntec DTS is a high-resolution, sub-bottom profiler with acoustic source, energy supply, motion sensor, and two receiving hydrophones housed in an underwater tow fish (Figure 2.1). Two types of acoustic signals can be produced with the Huntec DTS, with one being through a boomer and the other a sparker. The boomer generates sound by sending an electrical charge through a flat coil, which forces a coil and a piston apart creating a seismic pressure wave (Hundert, 2003). Using the boomer for a source is reserved for shallow-water surveying typical of the continental shelf. The sparker method generates sound through emitting a pulse of electricity from an electrode mounted on the Huntec fish. This jolt of electricity produces a steam bubble, which is the primary source for the seismic. However there is a problem, with a secondary source being created when the bubble bursts (Mosher and Simpkin, 1999).

The *Hudson* cruises 2002046 and 2005023 used the sparker as the acoustic source. The sparker was a 540 Joule, 20 tip system that was towed from the stern of the ship (King, 2005). The tow depths typically ranged from 60 to 100 mbsl and sparker shot intervals were between 750 and 1250 ms (King, 2005). Huntec penetration typically reaches 100 meters below the sea floor. Signal to noise ratios played a role with the quality of the Huntec data. Water depth, slope angle, and ship or ocean noise can affect the quality, with the Huntec obtaining poorer imaging along steep slopes and deep waters (Piper, 2002).

Interpretation of the Huntec seismic data was done through analyzing paper records with areas of importance being photo copied, scanned and displayed throughout this report.

2.1.2 Sleeve Gun Seismics (Airgun)

Airgun seismics provide deeper penetration then the Huntec DTS, but do not allow such high resolution (Figure 2.1). The acoustic source is produced from an explosive release of high-pressure air through a gun. This release of high-pressured air creates an air bubble, which is the primary source for the seismics (Hundert, 2003). However when this bubble collapses on itself, a secondary source (bubble pulse) is created and this can cause unwanted noise in the survey.

Seismic reflection data was acquired with a 2 x 40 in^3 sleeve gun array (Texas Instruments) and with two hydrophones (Piper, 2002). The guns are spaced apart at 0.75 m, and are located 0.75 to 1 m below sea level at a towing speed of 8 km/hr (Piper, 2002). The air supply was provided by a Price Gunmaster model w2 compressor (Piper, 2002). Air pressure was on average maintained in between 1800 and 1850 psi (King, 2005). Shot point intervals were set between 3 and 6 seconds, which was dependant of water depth (Piper, 2002). Two types of receivers were used to record seismic reflection signals: the Teledyne model 178 streamer and the GSC-A Benthos array. The Teledyne streamer used 50 T-1 acceleration-canceling hydrophones that were spaced apart at 0.5 m totaling 25 meters (Piper, 2002). The Benthos array comprises of two sections of non-canceling hydrophones with a rear section containing 40 hydrophones at 0.6 m spacing (Piper, 2002). The front section contains 13 hydrophones (same spacing as rear) and is separated by a 25-meter dead zone from the front (Piper, 2002).

2.1.3 Raytheon 12 kHz Echo Sounder and ORE 3.5 kHz Profiler

The CCGS *Hudson* is equipped with a ram-mounted 12 kHz transducer which was used throughout the cruises 2002046 and 2005023 (Figure 2.1). This system measures and records water depth through echo sounding. The 12 kHz can be useful for determining topographic lows and relating this to the Huntec and Airgun seismics.

The *Hudson* is also fitted with a hull-mounted ORE 3.5 kHz sonar system. This was recorded at a 250 ms sweep rate on an EPC9800 chart recorder (Piper, 2002). With deeper waters, a sweep spread of 500 ms was used. Like the 12 kHz sounder, the 3.5 kHz profiler is useful for determining water depth as it is running during the whole cruise. It also shows some sub-bottom penetration, which can be useful at a core site when the Huntec is not in the water.

2.2 SEDIMENT SAMPLING

Sediment sampling was possible through obtaining piston cores. On the *Hudson* cruise 2005023 a number of piston cores were obtained using the AGC long corer (14 m long, 10 cm diameter). The selection of locations for these cores was based upon data from the Huntec DTS profiles. The cores were stored at the Core Facility at the Bedford Institute of Oceanography (BIO). The cores were split and logged between September 19th and 21st by Kathleen Graham, a 3rd year Co-op Student from Dalhousie University. These logged cores were later re-examined by myself.

2.2.1 Piston Coring

The AGC long piston corer comprises a number of parts that all work together to provide a core sample. A weight of ~1500kg is added to the top of the piston core so that added penetration into the sediment can be made. A piston is added into the barrel for the purpose of reducing resistance during penetration by adding suction, which holds the sediment in place and therefore reducing compaction (Hundert, 2003). The triggering of the piston core is done by a trigger weight, which upon contact with the ocean floor releases a length of wire from the trip arm. This allows the piston core to free-fall and with the impact of the piston core, the piston slides back and allows limited coring deformation and deeper penetration (Figure 2.2) (Hundert, 2003). Ideally, the maximum amount of core recovered is wanted, but a number of things can hinder this and is usually a result of equipment failure. It is known, however, that over-consolidated material or thick sands cause problems and damage to the piston core when trying to sample (Hundert, 2003). When selecting coring targets these types of deposits are often avoided. There is also a problem with piston coring in respect to disturbance in the uppermost sediment. Impact can cause suction and distortion to the core thus leaving a false impression. The use of the trigger weight core provides a more accurate representation of uppermost sediment.

2.2.2 Standard Lab Procedures

The processing of the piston cores was done at the Core Laboratory at BIO. These cores were analyzed through the GeoTek Mutli-sensor Logger which is also known as the Multi-sensor Track (MST). The MST device measures the following properties; magnetic susceptibility, P-wave velocity, and bulk density. Once this has been done the core is split, and then logged. The logging process involves marking various changes in lithology, sedimentary structures, as well making sedimentological descriptions and indicating if any fossils are present. Photos are also taken of the cores and kept on record. Reflectance spectrometry was also used to measure sediment colour, with a held-hand Minolta C-2002 spectrophotometer. This gives sediment colour in the form of three numerical values; a*, b*, and L* (a* measures the colours green (-a) to red (+a), b* blue (-b) to yellow (+b), and L* measures black to white) (Hundert, 2003).

Each physical property measured within a core has its own usefulness. Magnetic susceptibility measures the sediment response when inducing a magnetic field into the sample. This can be useful for lithological classification and correlation and can also indicate sediments of different sources (Chubbs, 2003). P-wave velocity is important because this again can be useful for correlation purposes. However problems do occur with the P-wave measurement because it is affected by the plastic liner of the core (un-split) (Hundert, 2003). Bulk density is another important measurement, which is also helpful for correlative purposes. To see examples of core plots used in this study refer to the appendix.

2.3 GEOGRAPHIC INFORMATION SYSTEM (GIS) METHODS

ArcGIS and ArcView 3.3 was a very powerful tool for this study, which contributed to this study in three ways. First, it allowed the spatial organization of data sets which could be manipulated to provide detailed maps. This meant data obtained in this study could be placed into detailed maps which could also be compared to already existing data sets. Second, the GIS software enabled the creation of a detailed contour map of depth for the Northeast Fan, which did not previously exist. This was done by using all known 12 kHz sounding conducted by the GSC in the area, as well using updated readings from the 2005023 cruise. These digital points were extrapolated through the Triangulation method in ArcView, creating a layer with assigned depth values to each triangle. This layer was then contoured in ArcView into intervals of 100 meters, which then was ‘cleaned’ to reduce anomalies. Using this detailed contour map of depth, the traces of major channel axes could be made. Lastly, ArcView and ArcGIS were used to display along track (Huntec) facies interpretations. The interpretation focused on assigning acoustic facies to various features on the seismic. The times of these features were recorded making sure one minute was subtracted to allow for layback of the Huntec tow fish. Indicating these times with a feature number, the data was all entered into a database in ArcView. Assignment of these feature numbers to specific colours revealed specific trends once a map was constructed.

Figure 2.3 a product of ArcView, displays the location of seismic lines and cores used in this study.

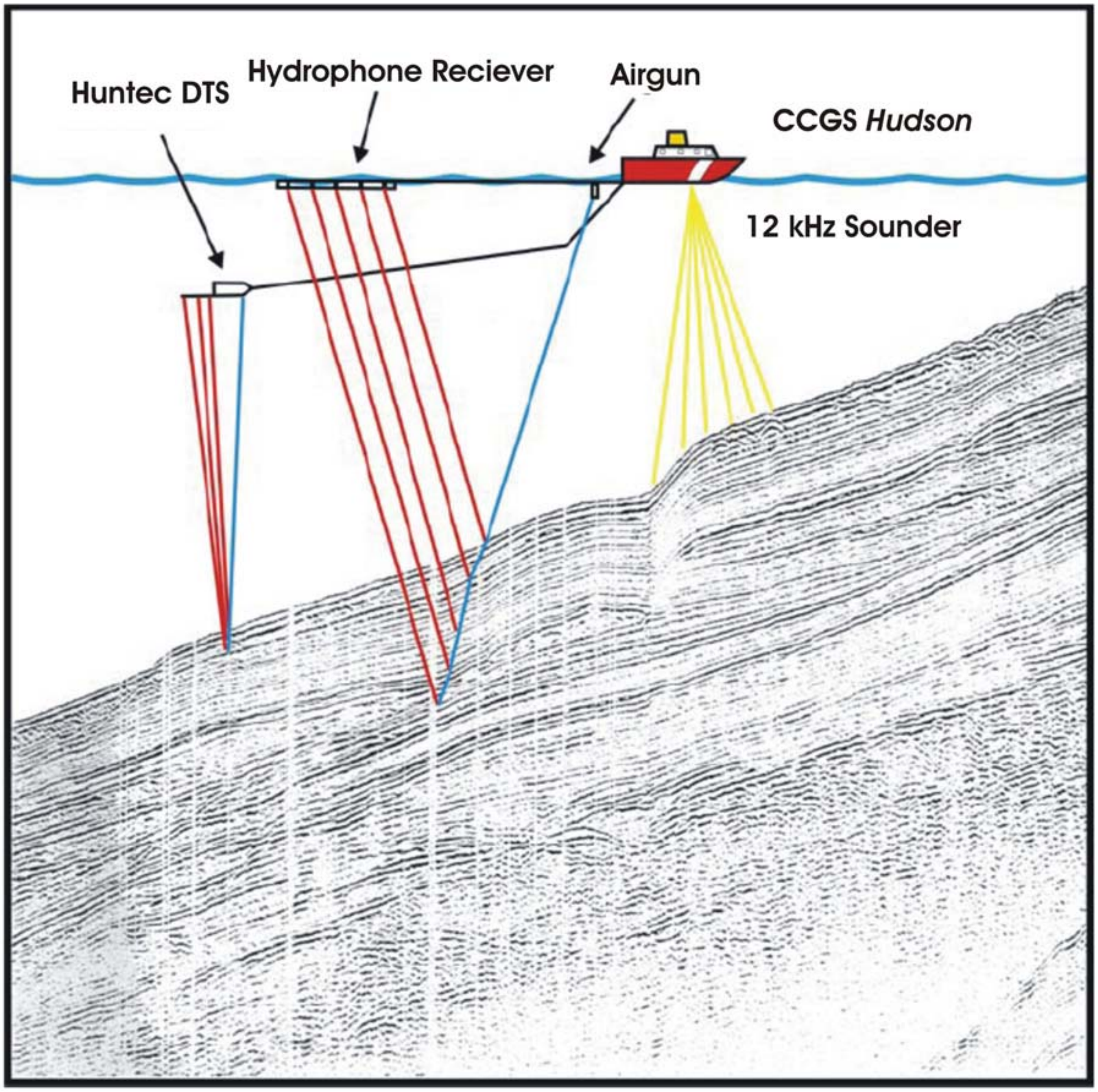


Figure 2.1 Schematic of seismic survey (Modified from Hundert, 2003)

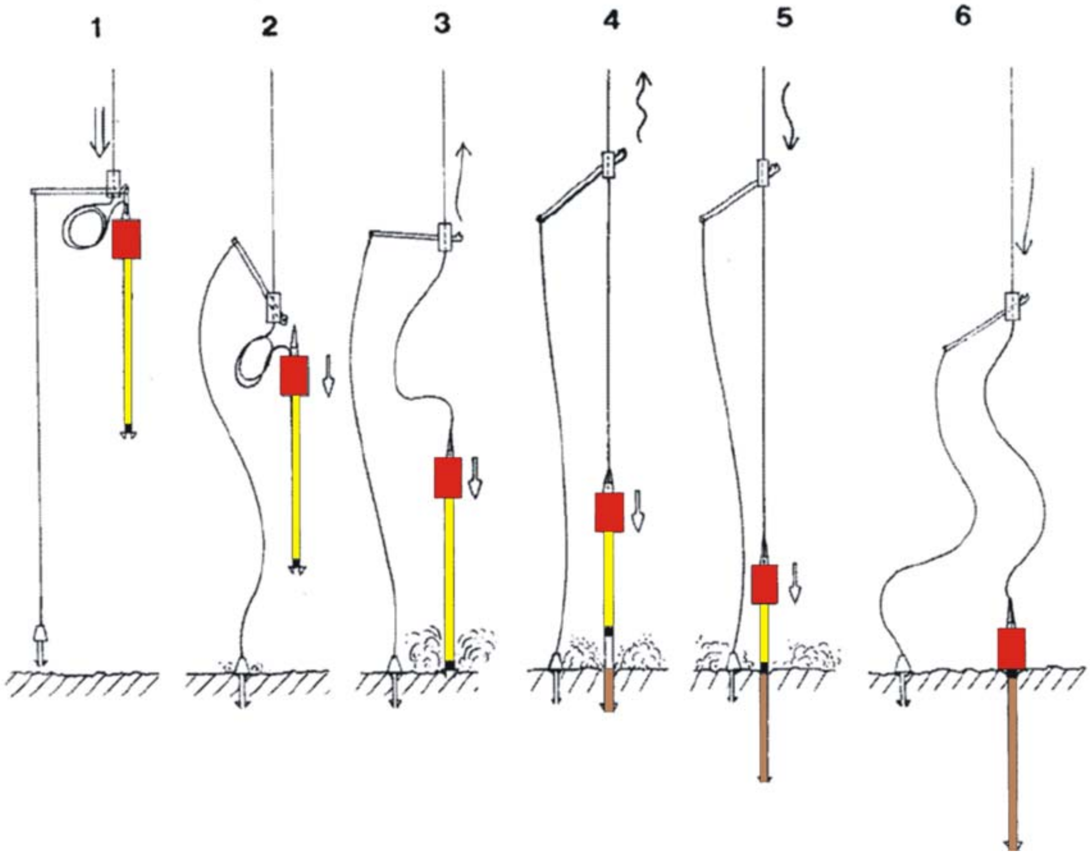


Figure 2.2 Deployment of piston corer (Modified from Hundert, 2003)

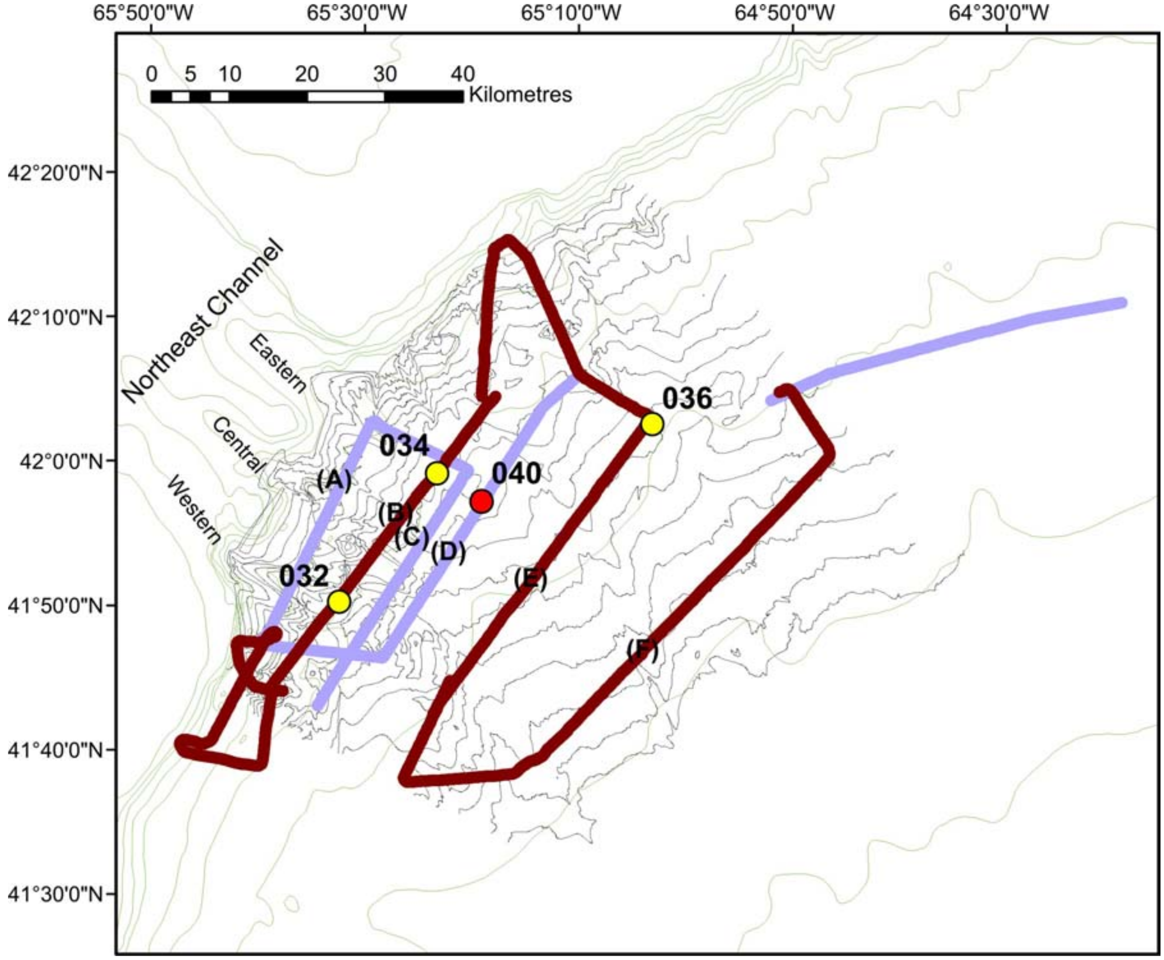


Figure 2.3 Seismic lines and Core Locations

Core stations depicted in yellow are new cores obtained from the 2005023 cruise while the core station in red is from Hundert's (2003) study (cruise 2002046). Maroon line indicates seismic lines taken in 2005 while blue lines were collected in 2002. In total six seismic strike lines exist which for the purpose of this study are named (A), (B), (C), (D), (E), and (F).

CHAPTER THREE

SEISMIC INTERPRETATION

With seismic interpretation of the Huntec DTS tracks, a number of observations can be made to better help the understanding of the architectural components and dynamics of the Northeast Fan. From the Huntec seismic reflection profiles, six seafloor seismic facies have been defined. The mapped distribution of these seafloor facies revealed some interesting trends. With a closer examination of the reflection profiles of the Huntec lines, a number of correlative reflectors can be established throughout the Northeast Fan, which will establish a relative chronology throughout the study area. This is to be discussed in Chapter 4

3.1 AIRGUN DATA : AN OVERVIEW OF NORTHEAST FAN

To gain a general understanding of the Northeast Fan, Airgun seismics can provide a good overview. Airgun seismics provide a deeper but lower resolution look into the subsurface. If we examine the two most basinward lines of airgun lines (E) and (F), we can see an overview of where main channels and mass-transport deposits exist (Figure 3.1). Mass-transport deposits, which could not be seen in the shallower penetration Huntec lines, are visible and are fairly large. Some of these mass-transport deposits measure a width of around 7.5 km, and reach about 100 meters in thickness. The location of major channels can be seen and through correlations, the Western channel and Eastern channel of the Northeast Fan are depicted. The main axis of Central channel is lost by the time it reaches lines (E) and (F) but can be seen in the airgun lines from Hundert's (2003) study (Figure 3.2). The appearance of a levee on the SW portion of line (F) diverts Western channel to the SW.

Hundert (2003) showed a figure of airgun lines (A), (C), and (D) that explained that as we moved down slope, canyons and channels become less defined and seem to merge (Figure 3.2).

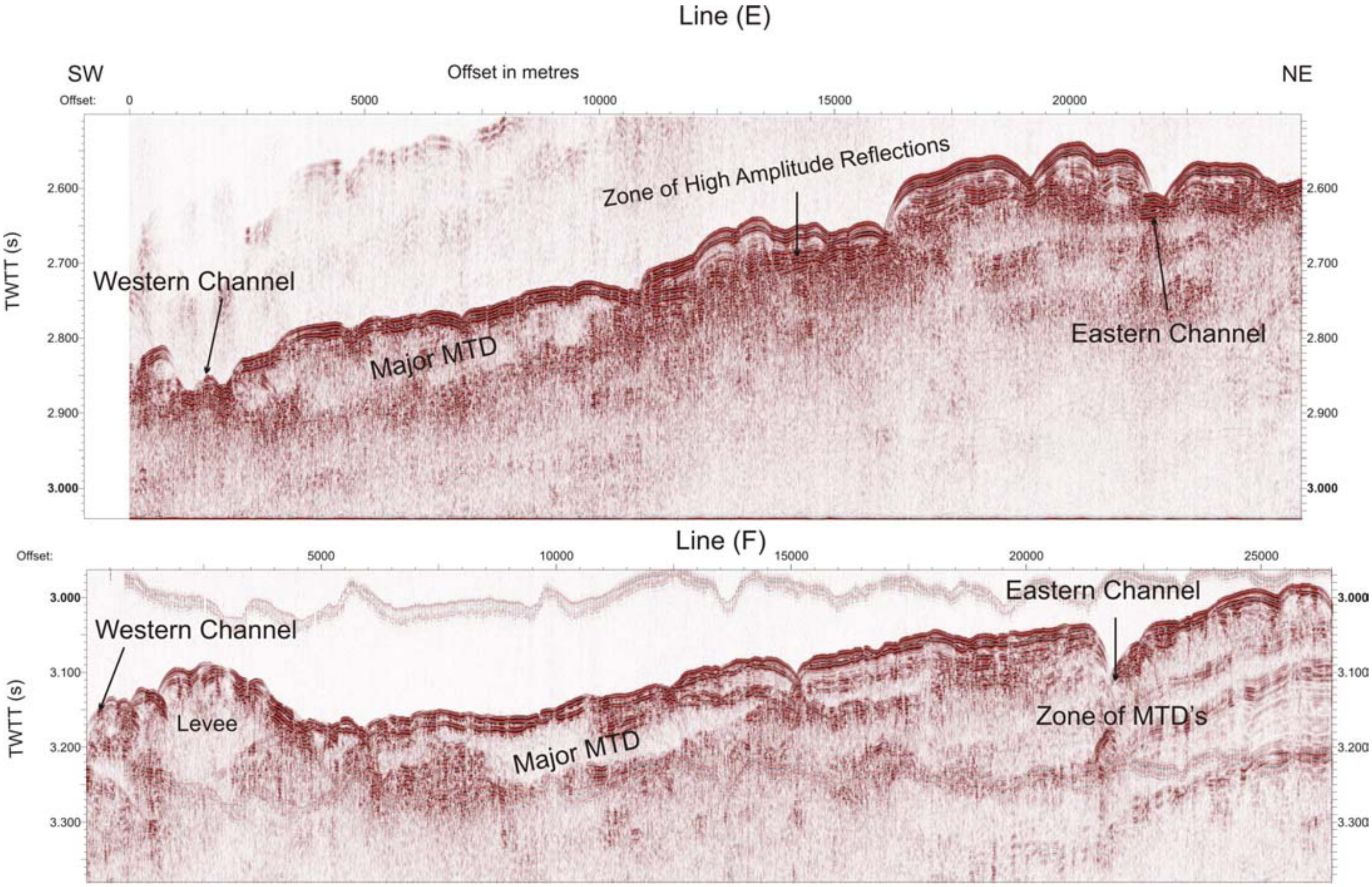


Figure 3.1 Presentation of Airgun lines (E) and (F)

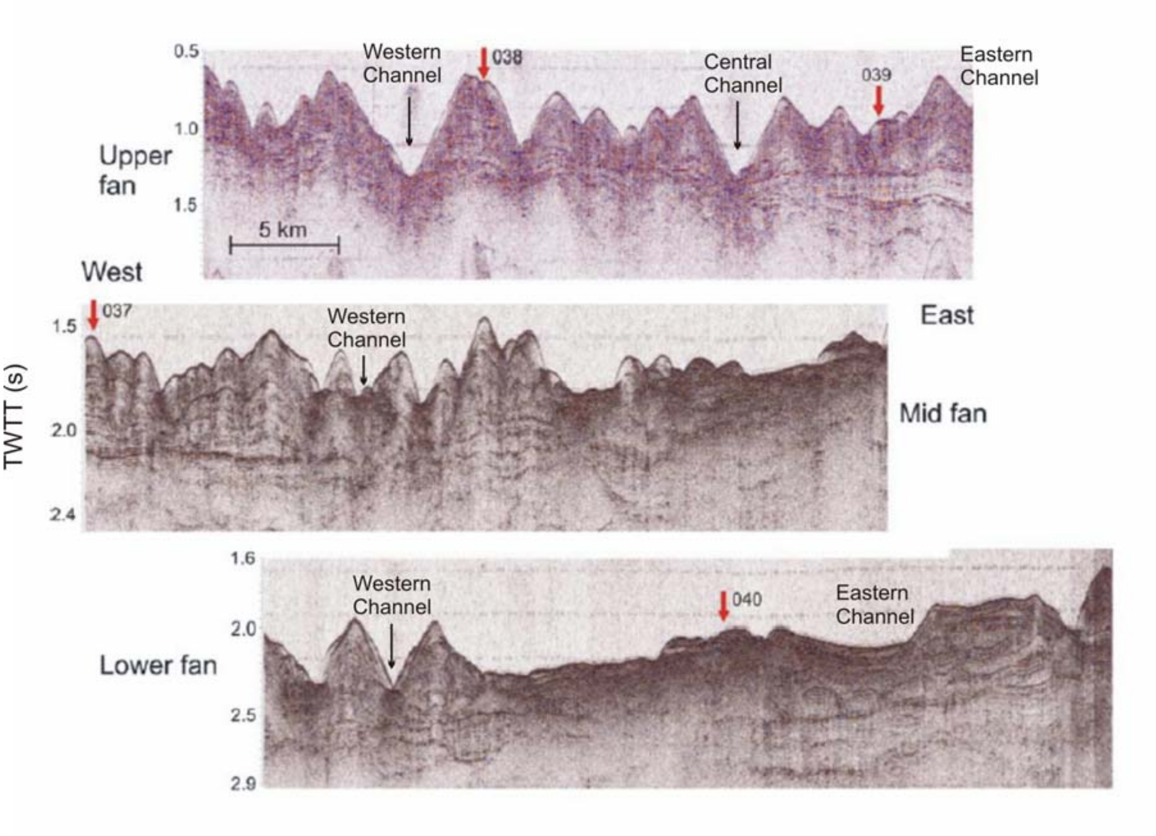


Figure 3.2 Hundert's (2003) airgun lines (A), (C), and (D) (From Hundert, 2003).

Figure shows how channels become broader down slope and merge into larger more focused channels. Red arrows point to core locations in Hundert's (2003) study. Notice core 040 on lower line

3.2 DEFINITION OF SEAFLOOR SEISMIC FACIES

The interpretation and definition of acoustic facies follows previous work of Huntec seismics conducted on other submarine fans. Although the acoustic facies in this study are not grouped the same as others, they are however, similar. All acoustic facies in this study have been tested and shown that they refer to specific lithologies through other studies (Piper et al. 1999 and Mosher et al. 2004).

Six types of seafloor reflection profiles were observed throughout the study area. These facies have been named as Highly Dissected Reflectors, Stratified Reflectors (Sub-parallel), Stratified and Dissected Reflectors, Channel Floor High Amplitude Reflections, Highly Stratified Reflectors, and Mass-Transport deposits. Type sections displaying these acoustic facies in the Huntec can be located on Figure 3.3.

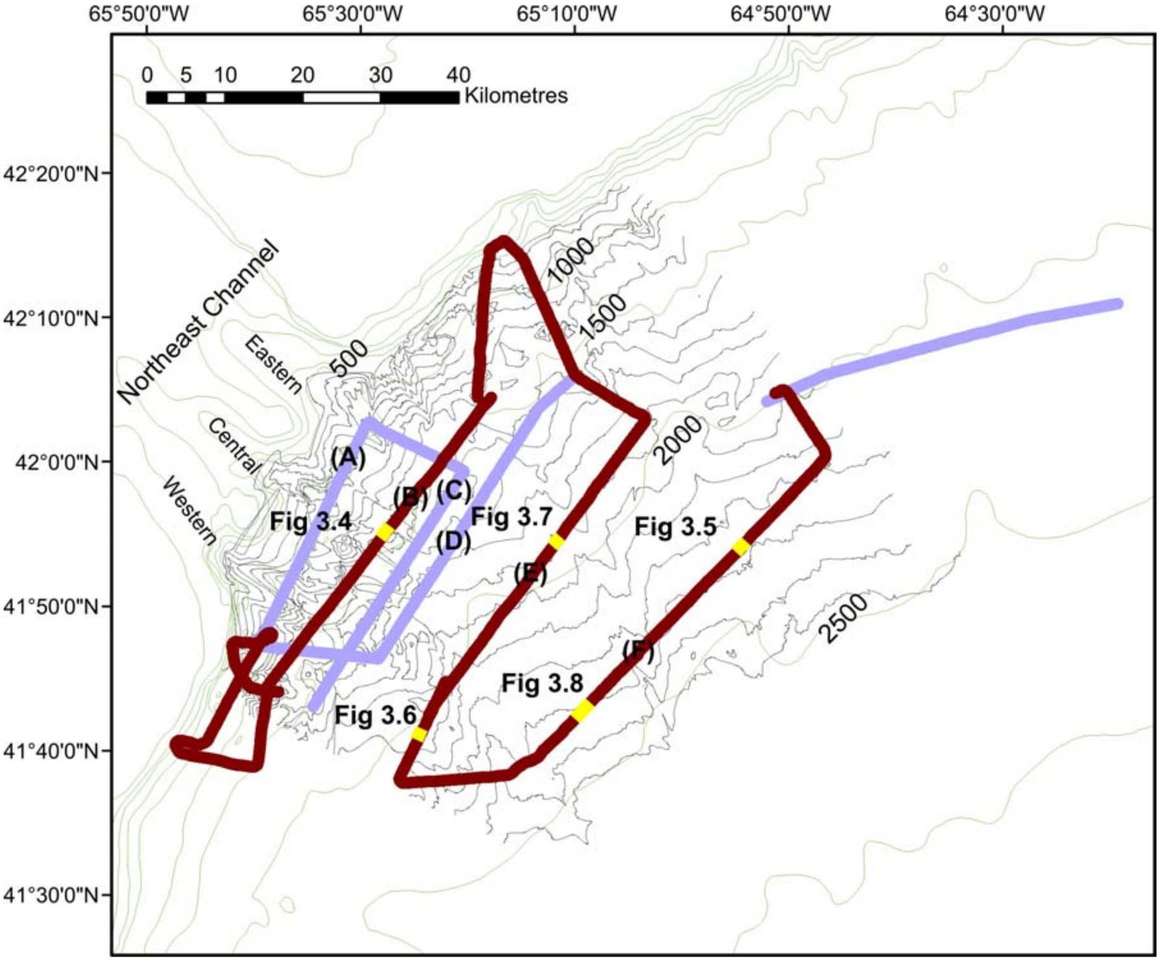


Figure 3.3 Location of Huntec figures showing type acoustic facies (shown in yellow)

Highly Dissected Reflectors

This acoustic facies is generally developed along steeply inclined slopes, with numerous hyperbolic diffractions (Figure 3.4). It consists of discontinuous and irregular reflections with low amplitudes. Acoustic penetration below these reflections is minimal.

Stratified Reflectors (Sub-parallel)

Stratified reflector facies is defined by strong laterally-continuous reflections with minor discontinuous reflections (Figure 3.5). Reflections may also be sub-parallel or appear as wavy. This type of acoustic facies is probably created by sediments which are not very well stratified.

Stratified and Dissected Reflectors

This acoustic facies is intermediate between the Stratified and Dissected facies (Figure 3.6). The typical acoustic signature would display thin fairly stratified reflectors underlain by dissected reflections.

Channel Floor High Amplitude Reflectors

Channel floor reflectors are high in amplitude and are typically found in bathymetric valleys or on the flanks of levees (Figure 3.7). Their particularly high amplitude and the presence of hyperbolic diffractions makes them easy to distinguish from other acoustic facies. There are some instances, however, where smaller channels displayed lower amplitude reflections.

Highly Stratified Reflectors (parallel)

Highly stratified reflectors extend and correlate extremely well laterally. The reflections are generally parallel and may extend for thicknesses of many tens of milliseconds (Figure 3.7). This type of acoustic facies is ideal for “picking” reflections as they are easily visible and can be traced laterally without onlap or discontinuity. The nature of this acoustic facies must indicate that the corresponding sediment, must be well stratified.

Mass-Transport Deposits

These deposits appear as acoustically incoherent material and their characteristics have been summarized by previous studies (Piper et al. 1999; Mosher et al. 2004) and are fairly easy to observe in section. They tend to show positive relief and can exhibit a hummocky top in contact with overlaying sediment. Mass-transport deposits tend to be overlain by stratified sediment with varying thicknesses (Figure 3.7 and 3.8). The bases of these deposits are erosive.

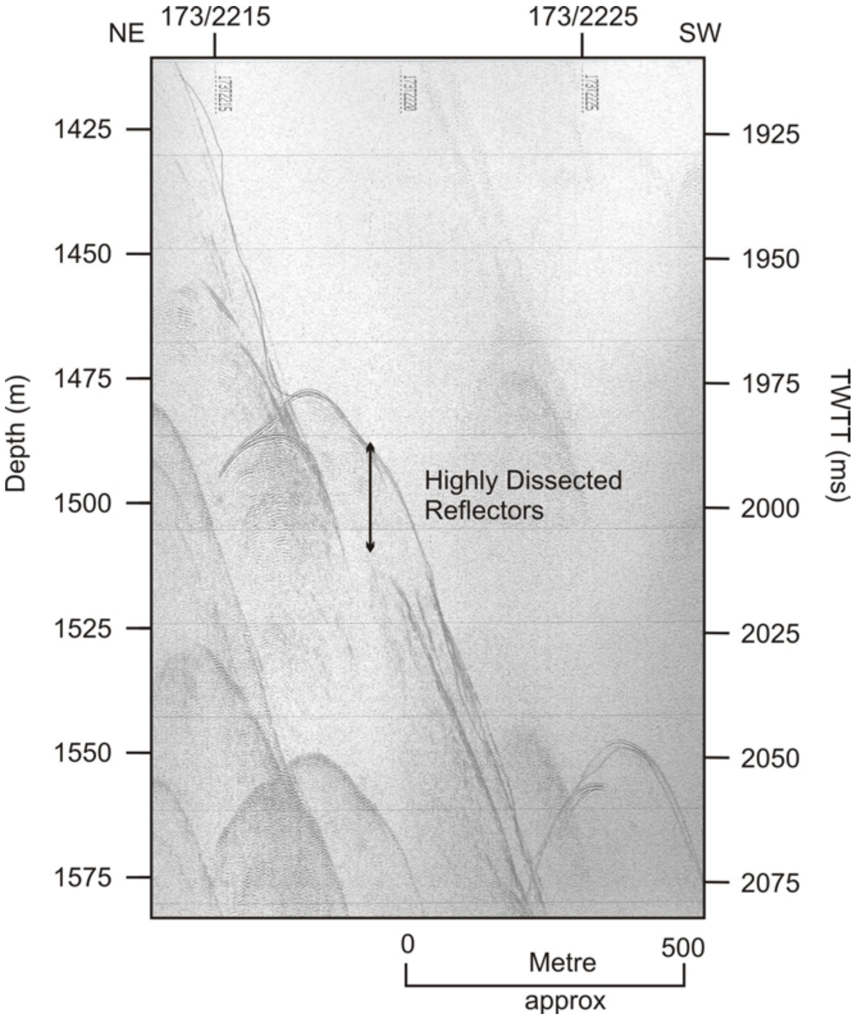


Figure 3.4 Huntec showing Highly Dissected Reflectors facies

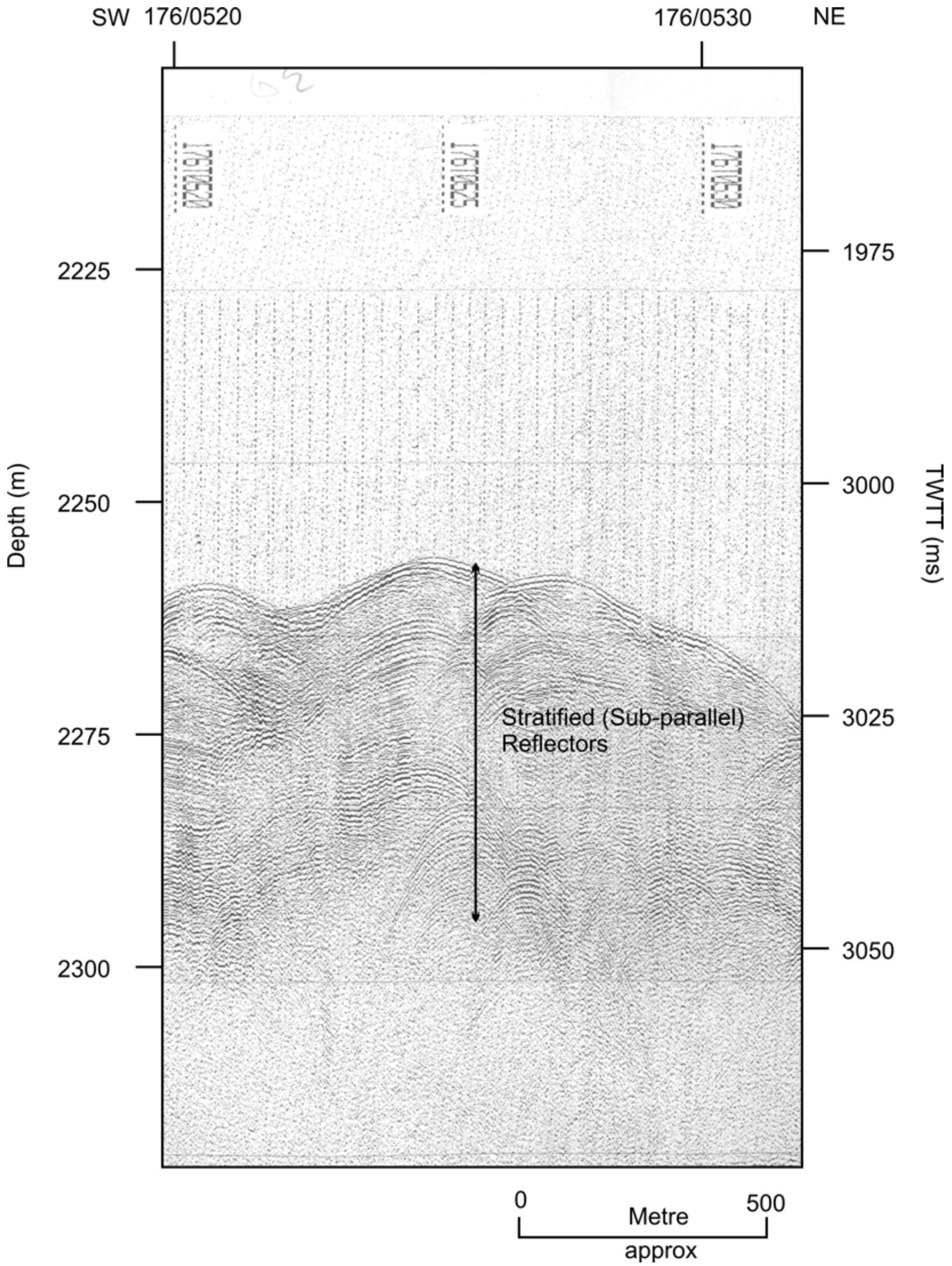


Figure 3.5 Huntec showing Stratified (Sub-parallel) Reflectors facies. (Note: Possibly overlying a Mass-transport deposit)

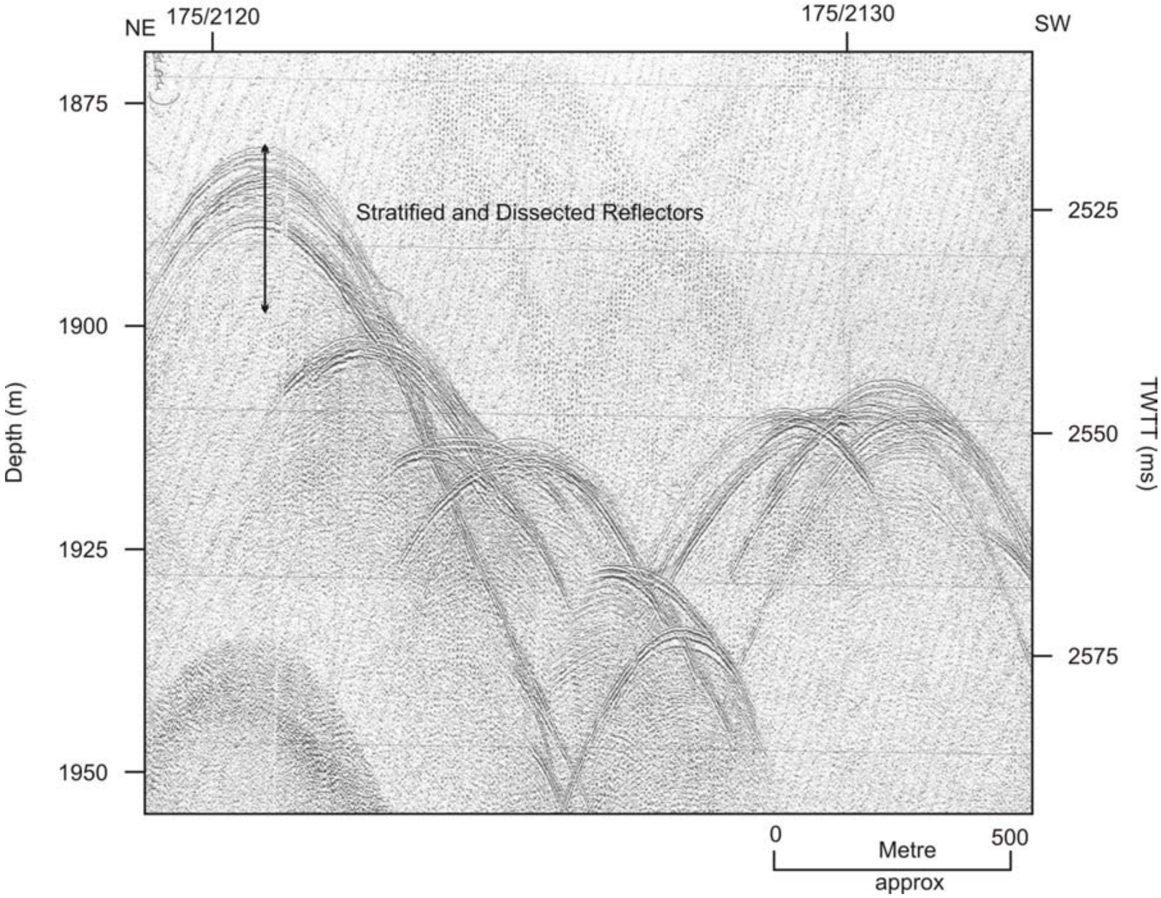


Figure 3.6 Huntec showing Stratified and Dissected Reflectors facies

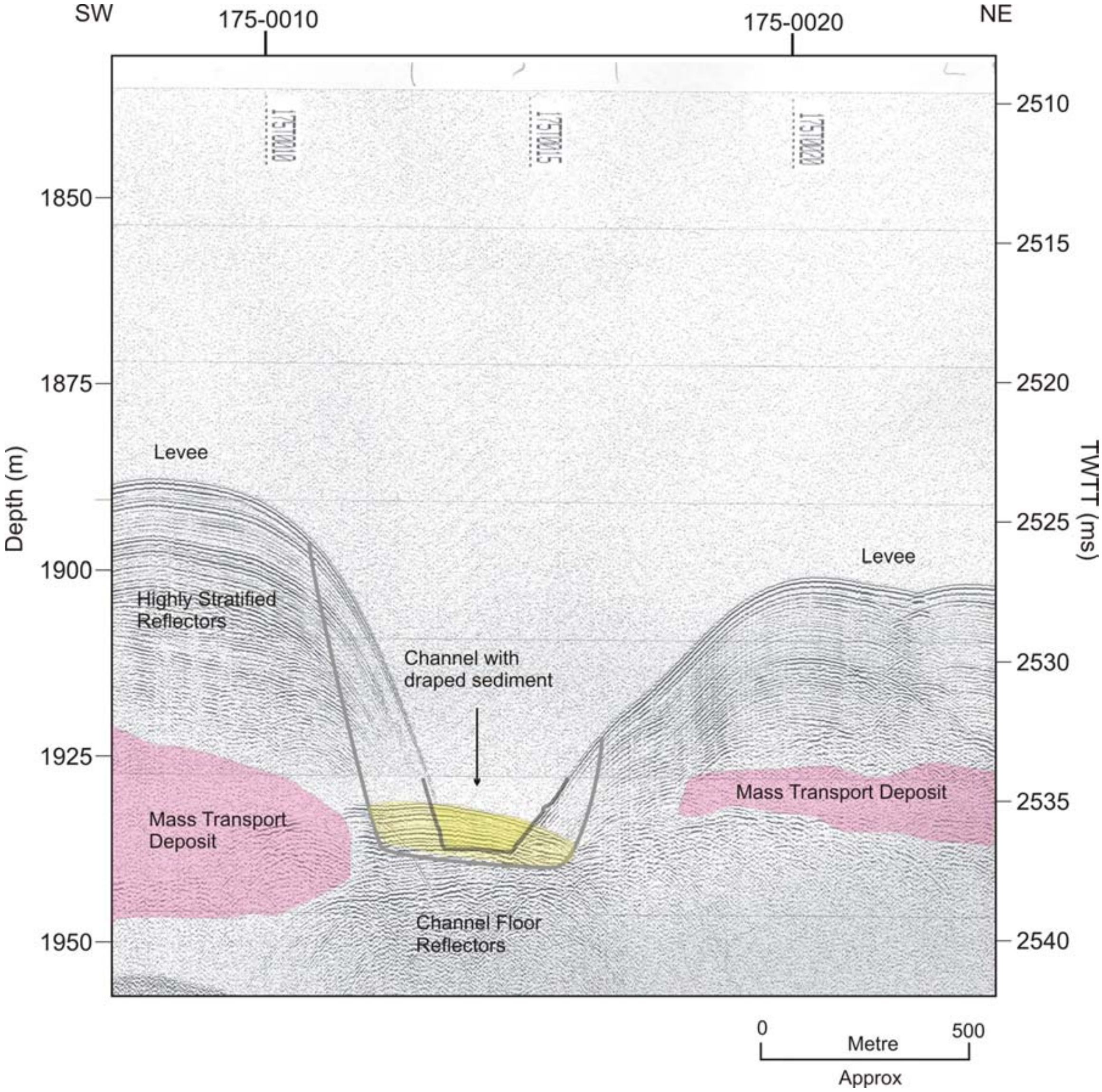


Figure 3.7 Thick Stratifieds overlaying Mass-Transport Deposits

Located on seismic line (E) on the northeast portion. Zone with strata above Mass transport deposit (highlighted pink) recorded as light blue on Figure 3.9. Notice how the channel floor has high amplitude reflections and is overlain by a drape of stratified sediments (Highlighted in yellow). Artifact of channel size exists due to steep channel walls. Probable position of channel walls is outlined in grey.

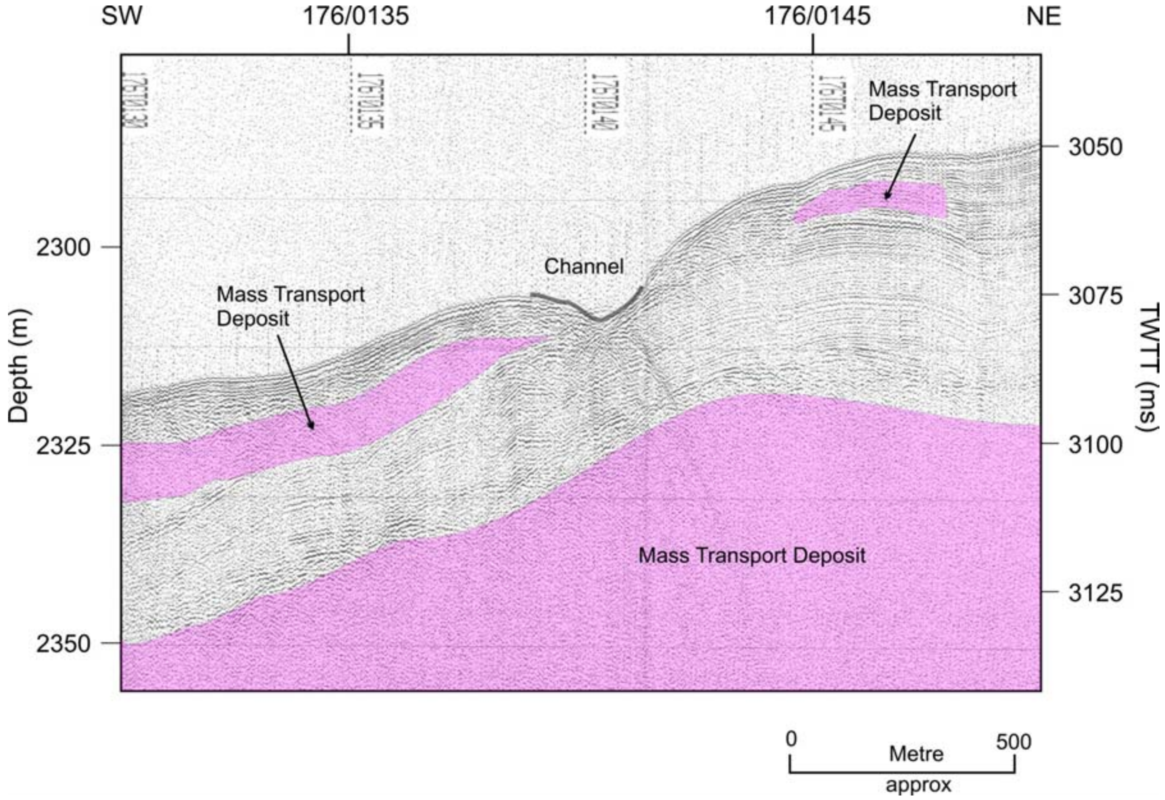


Figure 3.8 Thin stratifieds overlaying Mass Transport Deposits

Located on seismic Line (E). Figure 3.9 depicts this facies assemblage as dark blue in color. Notice how a major MTD is located at greater depth.

3.3 DISTRIBUTION OF SEAFLOOR SEISMIC FACIES

The distribution of the described acoustic facies in section 3.2 can be observed along the Huntec lines in Figure 3.9, which is a product of ArcView GIS software. The distribution of Mass-Transport deposits was further divided into deposits with thin overlying sediment and deposits with thick overlying sediment for the purpose of having a better understanding of the stratigraphic distribution of MTDs throughout the Northeast Fan.

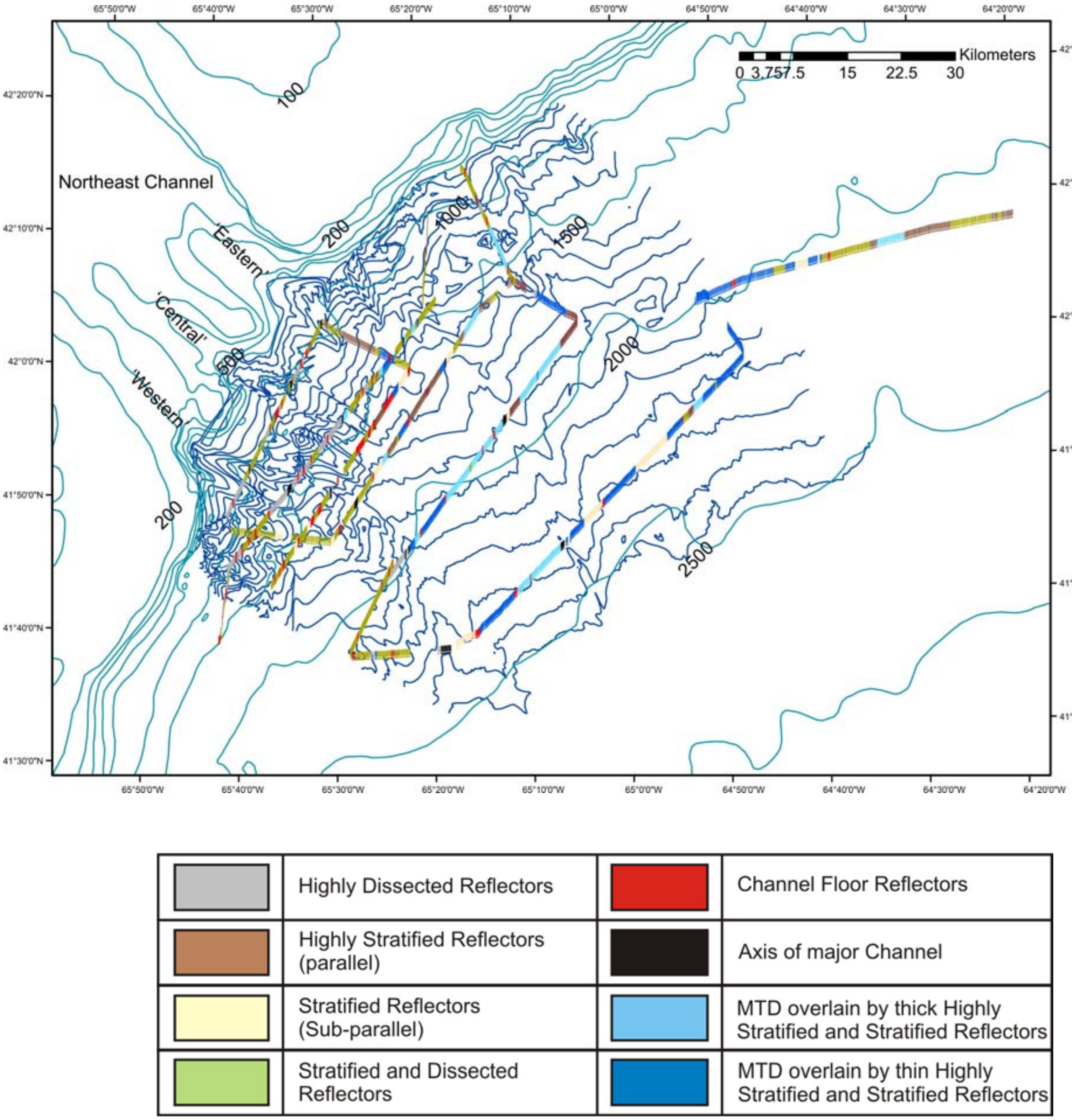


Figure 3.9 Interpretation of Huntec lines

Mass-Transport Deposits (Thin and Thick)

The distribution of Mass-transport deposits is restricted mainly to the lower slope and continental rise portion of the Northeast Fan (Figure 3.9). These MTDs can be traced to a depth around ~2350 mbsl and are first recorded at a depth of around 1500 mbsl. Prominent Mass-transport deposits are restricted to the northeastern portion of the study area. The Western channel appears to lack any significant mass-transport deposits, which suggests it does not direct mass flows as much as the Central and Eastern channel.

Stratified Reflectors (Sub-parallel)

This acoustic facies is rare. Deposits are found around ~2300 mbsl (line (F) and as well at ~1850 mbsl (line (E) and typically are in zones of levee or ridge architecture on the lower slope and upper rise (Figure 3.9).

Highly Dissected Reflectors

This type of acoustic facies can be found throughout the Northeast Fan, almost wherever there is a steep slope. This facies is particularly abundant on the upper and mid slope, where numerous channels can be found (Figure 3.9). Here it is quite common to find channels, which are flanked by sharply inclined slopes thus producing poor reflections, which are highly dissected. In contrast, on the rise portion of the Northeast Fan, few shallow channels exist, which are flanked by levee systems that pass laterally into either Mass-Transport Deposits, Highly Stratified, or Stratified acoustic facies deposits.

Highly Stratified Reflectors (parallel)

The Highly Stratified Reflectors facies is most common on the lower slope and upper rise of the northeastern part of the Northeast Fan, between 1500 to 2500 mbsl (Figure 3.9). Like Mass-Transport deposits, this acoustic facies is rare around the Western channel.

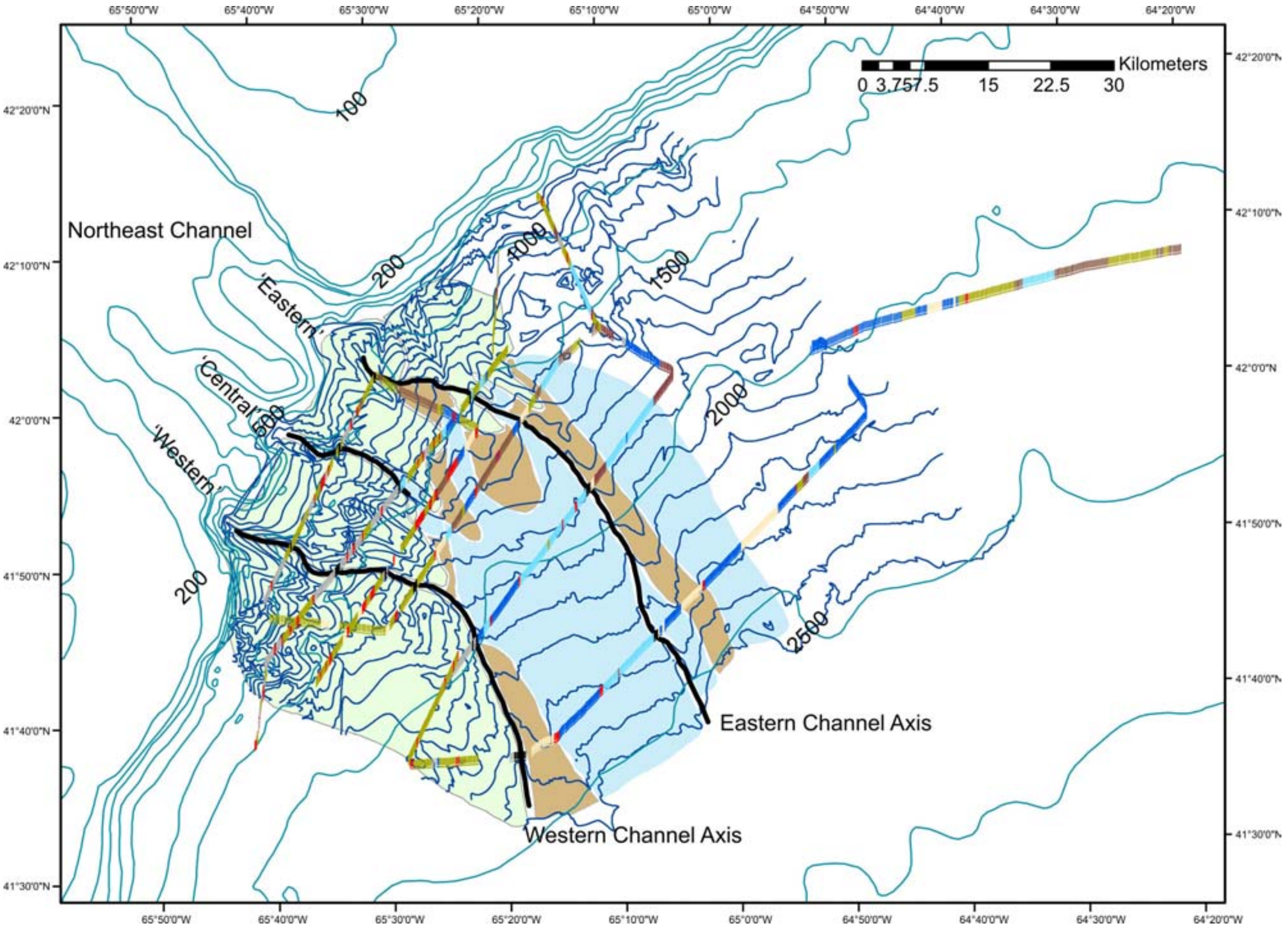
Stratified and Dissected Reflectors

Stratified and Dissected Reflector facies are found throughout the Northeast Fan but are mainly located on the slope and upper continental rise (Figure 3.9). This acoustic facies is associated with sloped terrain but not as steeply inclined as the Highly Dissected Reflectors facies. This acoustic facies is common in the southern area of the Northeast Fan and extends all the way up the Western channel of the Northeast Fan.

Channel Floor High Amplitude Reflectors

The distribution of channel body facies for the most part correlate very well with the seafloor contours of the area. Some minor channels were recognized in the 12 kHz paper record but did not appear in the automatically contoured bathymetry map. Channel floor facies are much more frequent on the upper and mid slope of the Northeast Fan (Figure 3.9). Moving down slope and onto the continental rise, channels become less frequent, suggesting that channels coalesce down slope. Some channels can be traced and correlated with each other, while others proved to be more difficult with the amount of information available. Figure 3.10 shows the traces of the Western, Central and Eastern channels through the Northeast Fan.

To summarize the distribution of seismic facies found throughout the Northeast Channel three major groups can be distinguished. Figure 3.10 depicts these zones, which are highlighted as the ‘Green zone’, Blue zone’, and ‘Brown zone’. The ‘Green zone’ represents predominantly seismic reflections which contain Dissected facies or Stratified and Dissected facies. The ‘Blue zone’ indicates the presence of Mass-Transport Deposits while the ‘Brown zone’ includes zones of Highly Stratified and Stratified reflectors usually in the form of levees.



🟦	Predominantly Mass Transport Deposits
🟫	Predominantly highly stratified and stratified reflectors
🟩	Predominantly dissected reflectors or stratified and dissected reflectors

Figure 3.10 Distributions of Seismic Facies Associations

The black lines indicate the main channel axis of Western, Central, and Eastern channels.

3.4 SEISMO-STRATIGRAPHIC CORRELATION

When examining the Huntec from this study, it can be useful to establish markers that are found throughout the Northeast Fan This is important because it sets a framework which allows correlations to be made throughout the Northeast Fan. Correlation of markers is based on a few assumptions. First, we assume that sedimentation rates are reasonably uniform in areas of well stratified sediment accumulations. Evidence for this is the relative consistency of stratal thickness in Huntec and Airgun strike lines. Second, we assume that sedimentation rate decreases down slope, as shown on dip lines elsewhere on the Scotian margin (Mosher et al. 1989, Mosher et al. 2004). Third, we assume that distinctive patterns of higher and lower amplitude reflections can be correlated over large distances. This has been demonstrated for other parts of the Scotian margin (Piper et al. 2001). Using these assumptions, the six markers for the type section were correlated throughout the Northeast Fan.

A type section of six correlative markers was defined (Figure 3.11), termed brown, red, blue, green, yellow and pink with increasing age. Figure 3.12 shows how these markers can be found throughout the Northeast Fan. The brown marker is a strong, high amplitude reflection and could be found in most profiles. The red marker is also a strong, high amplitude reflection, also used by Hundert (2003). The third marker in succession, blue, could only be recognized on the two basin-ward strike lines (E) and (F). Small scale seismic onlapping suggested that this marker represents a small unconformity or erosive surface. The next marker in succession found throughout the Northeast Fan is the green marker. This marker usually marked the top of a set of lower amplitude reflections. The green marker passes laterally into a MTD at 2002 T233-2318. The next reflection marker yellow, is also a high amplitude reflection. The last correlative marker, pink, represents the top of a mass transport deposit.

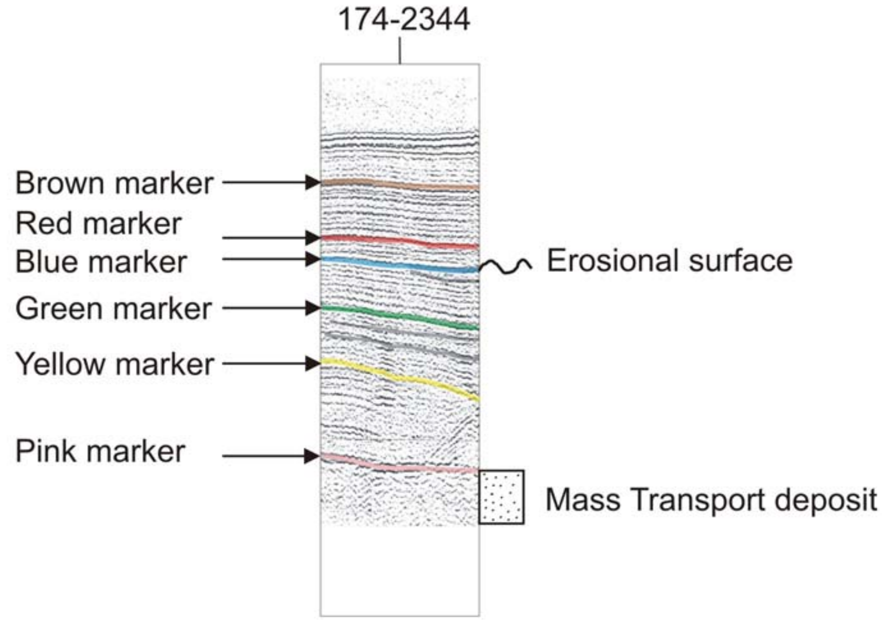
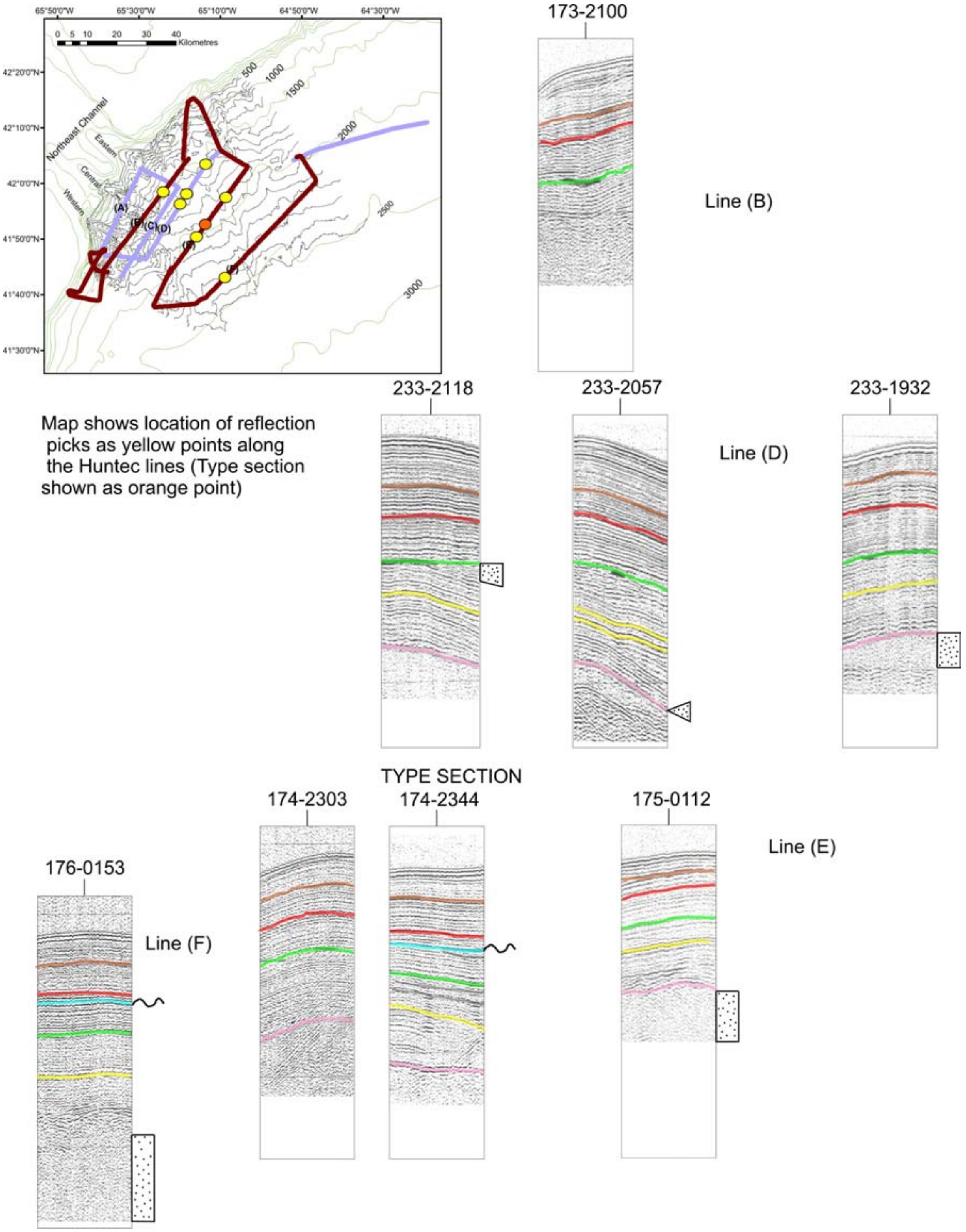


Figure 3.11 Type section for reflection picks in Huntec DTS profiles. Location shown in Figure 3.12



Map shows location of reflection picks as yellow points along the Huntec lines (Type section shown as orange point)

Figure 3.12 Reflection picks across the Northeast Fan (In relative position to each other)

CHAPTER FOUR

CORES AND CHRONOLOGY

A 10 meter long piston core (2002046-040) from the Northeast Fan was described and dated by Hundert (2003). This core is used as a reference section and is correlated to the new cores of the 2005023 cruise in the study area. Correlating the cores across the Northeast Fan, combined with seismic markers which Hundert (2003) described, and the new correlations in this thesis proved to be a key tool for establishing a relative age framework throughout the study area.

4.1 NEW CORES (2005023)

Of the new piston cores taken in the vicinity of Northeast Fan (cruise number 2005023), only three cores proved to be of relevance for this study (Figure 4.1). The location of these cores, determined by lead scientists aboard the CCGS *Hudson,* are shown in Figure 4.2 and have been named 032, 034, and 036. Core 032, which is the most southeastern located core, was targeted to sample a terrace on the flank of the Western channel (Figure 4.3). Core 034 is located on the same seismic line as core 032 but to the northeast. The aim for obtaining this core was to target a terrace/levee on the flank of a channel (Figure 4.4). Core 036 is the most northeastern core used in this study and was targeted for a ridge in order to get a long stratigraphic record (Figure 4.5).

CORE	**032**	**034**	**036**	**040**
Latitude	41.827733 N	41.971325 N	42.017361 N	41.562407 N
Longitude	-65.563902 W	-65.404184 W	-65.068219 W	-65.202327 W
Water Depth (m)	1504	1492	1798	1752
Recovery (cm)	370	729	963	949
Notes	Target is terrace on flank of western valley registered on seismic profile at 173/2332; terrace flank of western valley; recovered grey MUD, over interbedded fine sand and mud; section AB fine sand; BC sand at base, mud at top; CD mud at base, fine sandy mud at top	Target is terrace/levee on flank of channel in a valley identified on profiles at 173/2059; base of core contained a grey SANDY MUD which transitioned to a silty mud nearer the surface; section EF and FG were separated by a 140 cm empty space in the liner; section CD had a crack in the liner near the top (D); section D/E contains sand	Target is ridge based off line 175/0241; no trigger weight core recovered; apparent full penetration of piston core; noted black layering in the constant volume sample of stiff MUD extracted from the base of section A/B, a pebble was extracted from the base of section D/E(~488.5cm); 30cm split in centre of linear section E/F & depression at top (F); section FG linear is depressed, good stratigraphic core	N/a

Figure 4.1 Core Station Summary

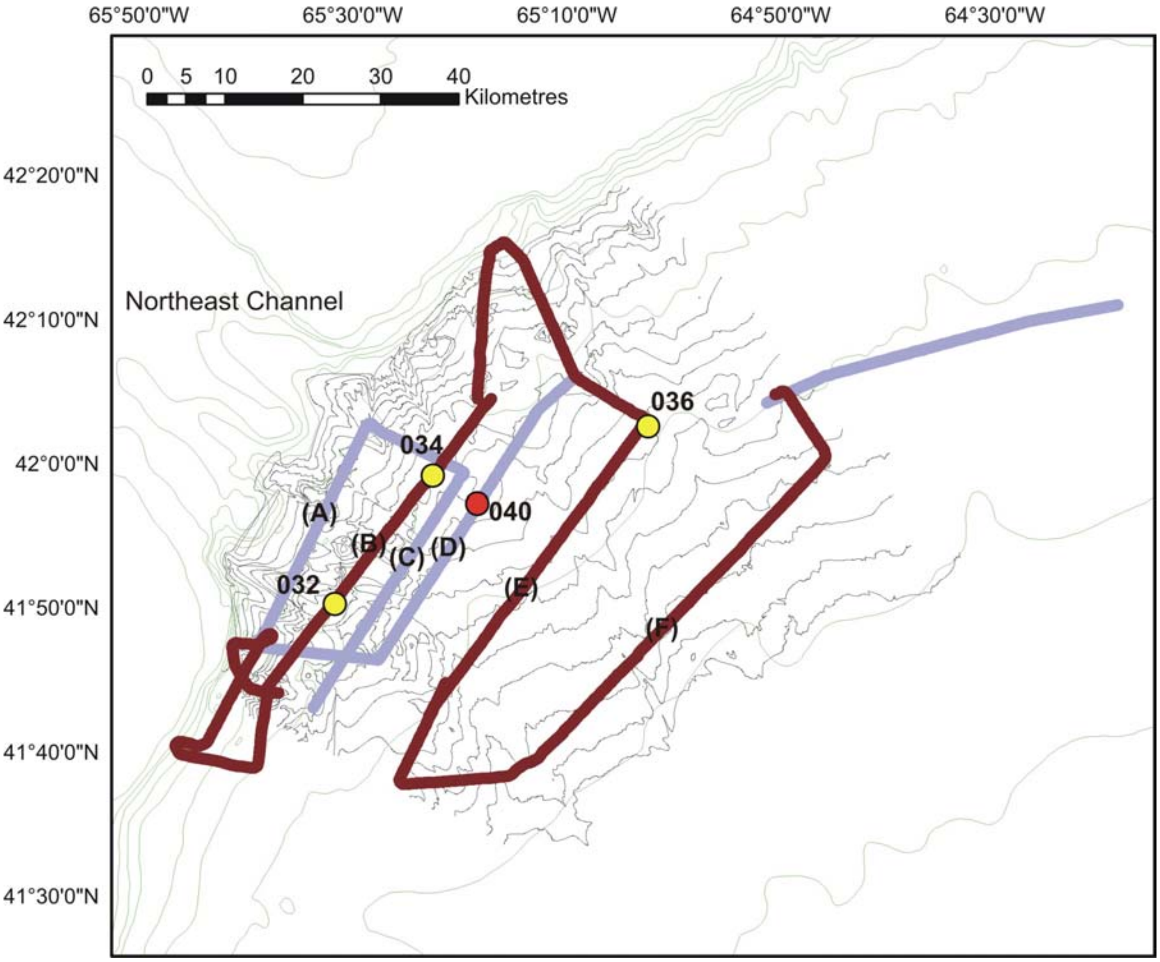


Figure 4.2 Core locations in study area

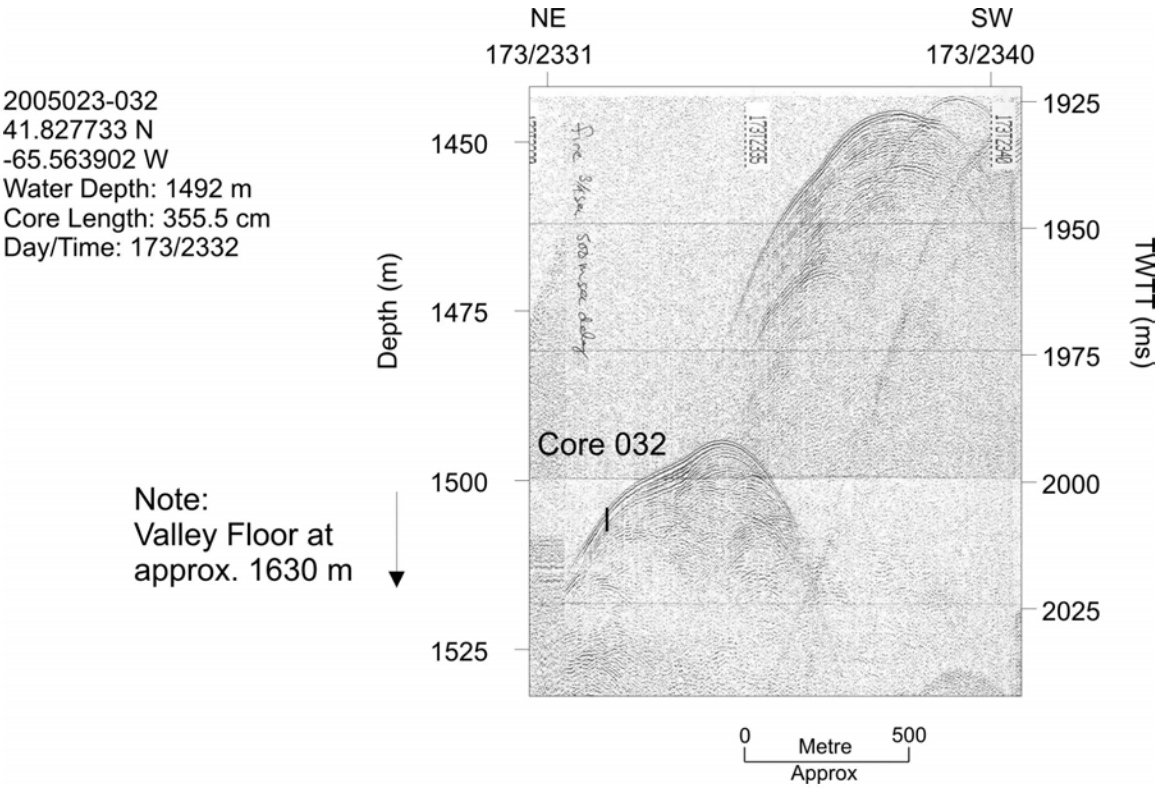


Figure 4.3 Core 032 site location with Huntec Line (B)

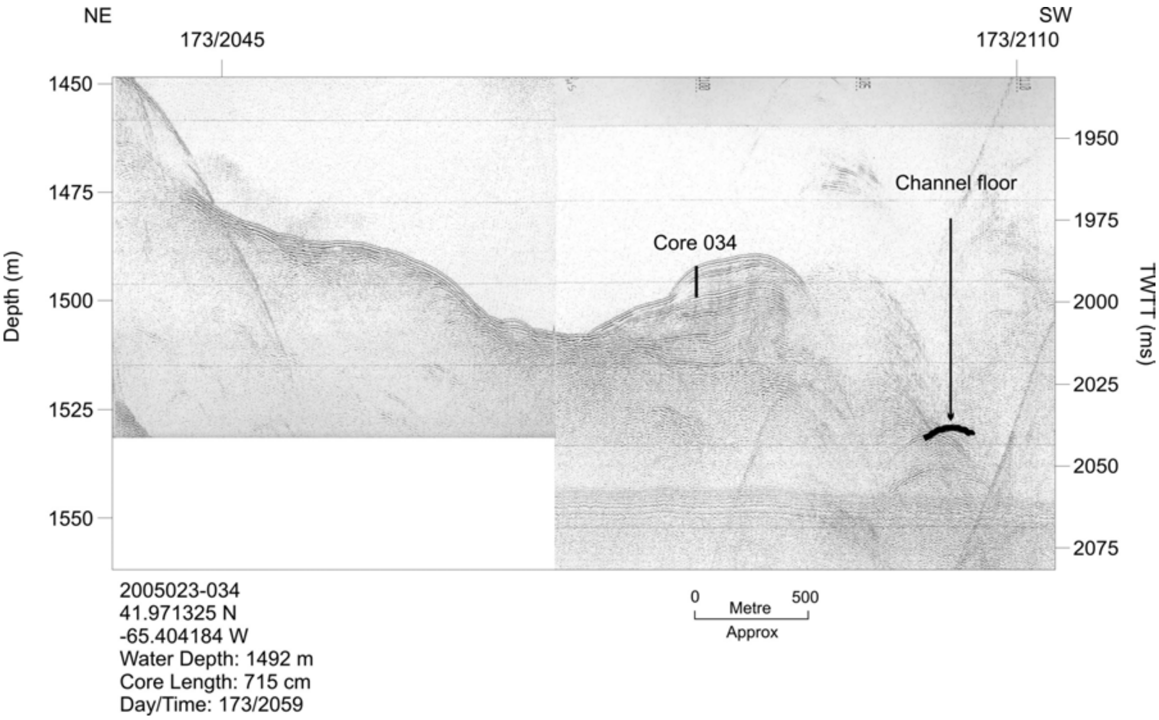


Figure 4.4 Core 034 site location with Huntec Line (B)

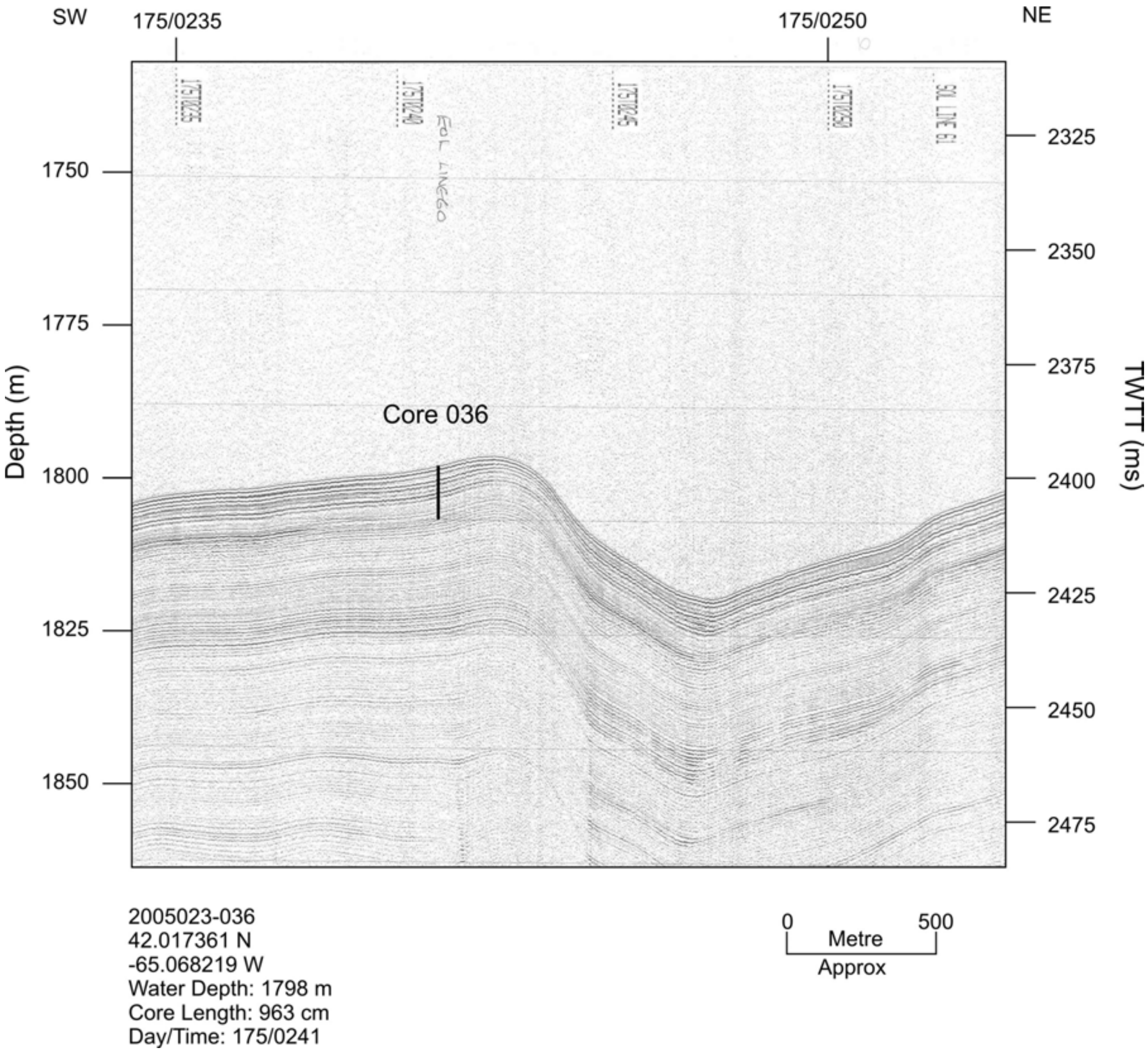


Figure 4.5 Core 036 site location with Huntec Line (E)

4.1.1 Lithofacies

The lithostratigraphic sequence in the cores was divided into four facies. These facies are common throughout the Scotian Margin and have been documented by numerous marine geologists over the past decades. The four facies defined for this study are classified as: Olive grey muds/sandy muds, Turbidite sands and silts, Brown/grey muds with rare ice-rafted debris (IRD), and Brick red muds.

Olive grey muds/ sandy muds:

This facies is dominated by olive-grey muds and is only found in the upper portions of the cores (<3 m sub-bottom). Trace fossils in the form of *Zoophycos* burrows dominate the upper portion of this facies. The presence of these burrows indicates that the sedimentation rate during this time was low (Hill, 1984). This facies has been recognized as sedimentation during the interglacial period of the Holocene (Piper and Skene, 1998; Hill, 1984). Small sandy turbidites are also sometimes found within this facies, such as in core 034.

Brown/grey muds with rare ice-rafted debris (IRD):

The brown/grey mud with IRD facies is found to underlie the olive grey muds. Granules and mud clasts are not uncommon, and the granules have been identified as ice-rafted clasts from Nova Scotia basement rocks, i.e. Meguma Group meta-sediments, and red sandstones of the Carboniferous or Triassic (Hundert 2003, Piper and Skene 1998). The depositional environment has been interpreted as from ice-margin plume fallout, derived from ice that crossed the Scotian Shelf (Piper and Skene 1998, Hill 1984). Turbidite deposits are more common in this facies than in the overlying olive grey muds.

Turbidite sands and silts:

This lithological group includes all sand and silt layers found throughout the cores. These sands are massive and some show a fining upward sequence with a base that is commonly in sharp contact with underlying strata. These types of features are typical of turbidite sands. The appearance of turbidite layers are found to be more frequent in the Brownish-grey muds with IRD facies, however thin beds can be seen in the Olive grey muds of the Holocene (Piper and Skene 1998). Thickness of sands can be only a few centimeters or up to tens of centimeters thick.

Brick red muds:

Cores used in this study showed one or two beds of the Brick red mud facies. Its distinctive color (10YR 4/4 on the Munsel Color Chart) made it very easy to distinguish. This type of facies has been studied and described by Piper and Skene (1998) and has been traced all across the Scotian Margin. They found that up to four discrete beds were present, that they defined as brick red muds ‘a’, ‘b’, ‘c’, and ‘d’ (‘a’ being closer to the surface and ‘d’ deepest). Brick red muds ‘b’ and ‘d’ are identified as the two layers found in this study, with ‘d’ found to be more distinctive and in some cores (034 and 040) overlain by a tan carbonate bed identified by Piper and Skene (1998) as the Heinrich layer H1 derived from the Hudson Strait. Layer ‘d’ also was generally thicker then brick red mud ‘b’. The brick red units could be found in both the olive grey muds and the brownish grey muds and are also thought to have been deposited by meltwater plumes that originated from the Laurentian channel (Hundert 2003, Piper and Skene 1998)

4.1.2 Position of turbidite sands in cores

The stratigraphic position of turbidite sand beds can be observed in Figure 4.6. Bulk density plots and P-wave velocities also show where these beds exist in core simply because of the contrasting densities (To see core plot summaries of all cores refer to appendix A). All but one core recorded deposits of sand. Core 036, which was taken on a small ridge, was the core that lacked these sands. This was probably because of its lack of close proximity to a channel, which would have allowed turbidity currents to spill across the banks of levees, leaving sands in the core record.

Core 032 contained the most significant turbidite sand beds. These beds consist of very fine sands and ranged from about 2 cm to about 15 cm in thickness. The bases of these sands were in sharp contact with the underlying strata, which probably indicates that these are erosive events. The terrace where the core was collected is located approximately 125 meters above the channel floor. This implies that there must have been fairly large turbidity currents traveling through Western channel in order for very fine sands to be deposited on the elevated terrace.

Core 034 contained some minor sands throughout the core (Figure 4.6), with some varying in sediment size. The thickness of these sands ranged from 2 to 6 cm and the contact with the underlying mud sediment is mostly sharp. The channel which is located in a SW direction from the core is probably not a major channel system of the Northeast Fan but rather is more of a distributary channel. The close proximity of the core to the channel and the lack of significant sands suggest that only relatively minor turbidity currents flowed down the channel.

Hundert's (2003) core 040 contained two very fine sand beds. These sands are found towards the base of the core and are approximately 40 and 50 cm in thickness. A minor channel is near core 040 with the core located up on a levee about 35 meters up above the channel floor.

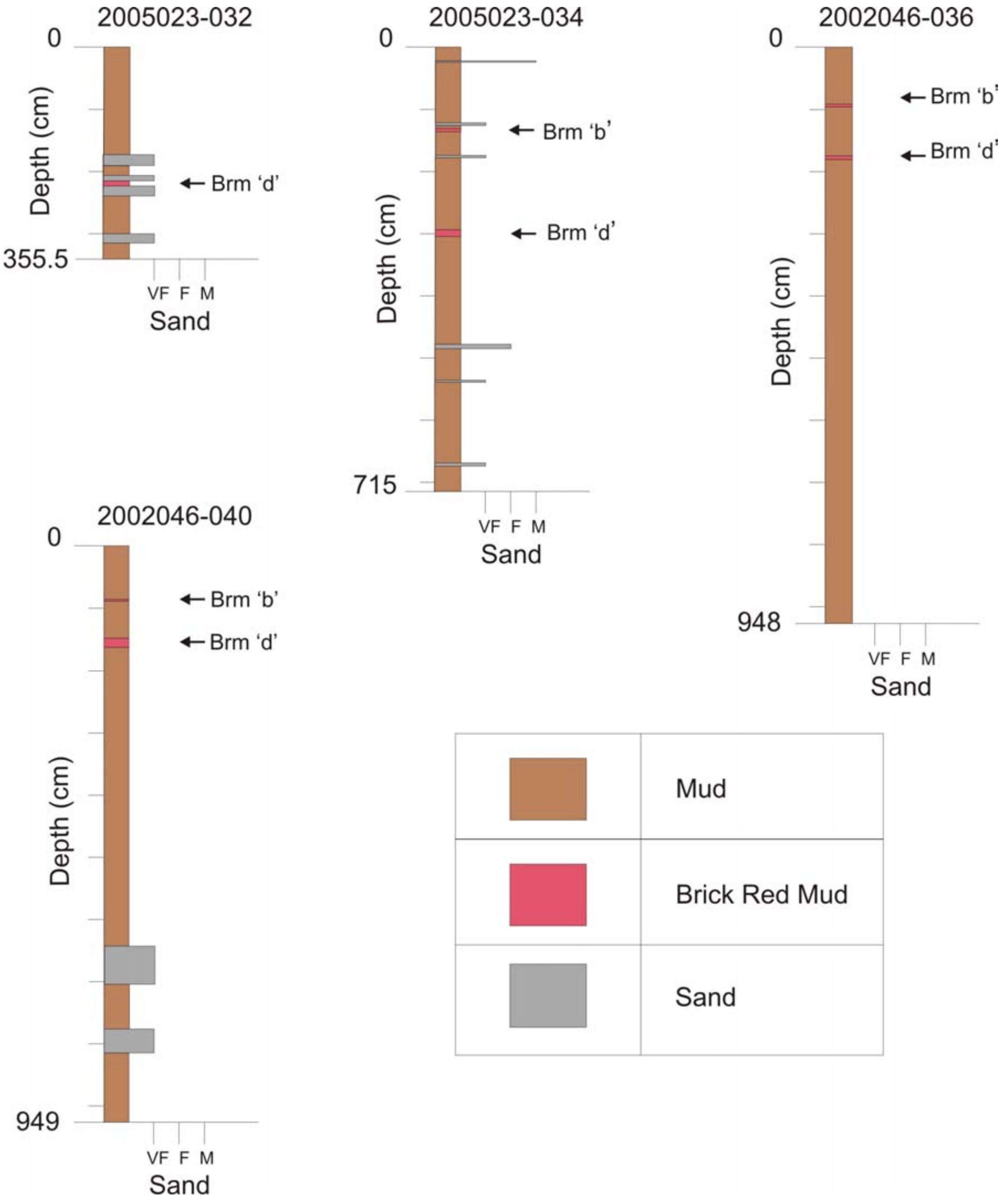


Figure 4.6 Core Summaries showing position of sands

4.1.3 Correlation of Cores

The key to understanding the stratigraphy of cores 032, 034 and 036 was to compare these to Hundert's (2003) core 040, which is located down slope from core 034 (water depths of 1752 m and 1492 m respectively).

Hundert (2003) was first to describe the existence of some distinct markers, which are found to be similar to other stratigraphic markers across the western Scotian Slope. Two markers of 'brick-red' color clay around 10 cm thick contrasted with the normal olive-grey and brownish-grey clay sediment, which is found mostly throughout the core. After obtaining radiocarbon dates, Hundert suggested that these brick red muds were synchronous with the brick red muds 'b' and 'd' of Piper and Skene (1998).

Of the new cores, core 036 showed the best correlation of the brick red muds. These brick red muds are fairly easily to correlate with the use of the a* color plot which shows changes in sediment color from green to red (Figure 4.7). Sharp peaks can be seen in the a* plot of core 036, which correlate quite nicely with Hundert's core 040. Core 034, which is found closest to core 040 but upslope, showed only one obvious red brick layer and is thought to represent Piper and Skene's (1998) marker 'd' due to existence of H1 above. The absence of brick red marker 'b' in core 034 is puzzling considering the relative short distance from core 040 where it is present, and it may have been destroyed by bioturbation, leaving only a small spike in the a* plot. The last core in this study (032) was rather different, making correlation difficult. The only significant spike in the a* plot corresponds to a grayish turbidite sand bed. However, a closer examination of this portion of the core revealed that there was some presence of the typical brick red color mud at the very base of the turbidite and a bit at the top. It is unsure if this brick red mud is Piper and Skene's (1998) marker 'b' or 'd'.

Another correlation could be made through out all of the cores in the study. All cores contained within the upper 1.5 m to the surface a zone of trace fossils. The appearance of these *Zoophycos* burrows marked this correlation and could also be observed with the a* plot.

4.2 CHRONOLOGY

4.2.1 Chronology from cores

With the use of Hundert's core 040, a relative chronology can be developed for cores 032, 034 and 036. Through radiocarbon dating he estimated the age of three horizons within core 040. The brick red muds of Piper and Skene (1998) found in the core represented brick red mud 'b' and 'd' respectively were dated by Piper and Skene (1998) at 12.7 ka and 14 ka. Hundert (2003) obtained a radiocarbon age of 18 ka, near the base of the core, which this approximately represents the last glacial maximum (LGM).

To infer ages on the newer cores, correlations must be done. As discussed above, this was done principally using the a* plot. An age framework could then be established (Figure 4.7).

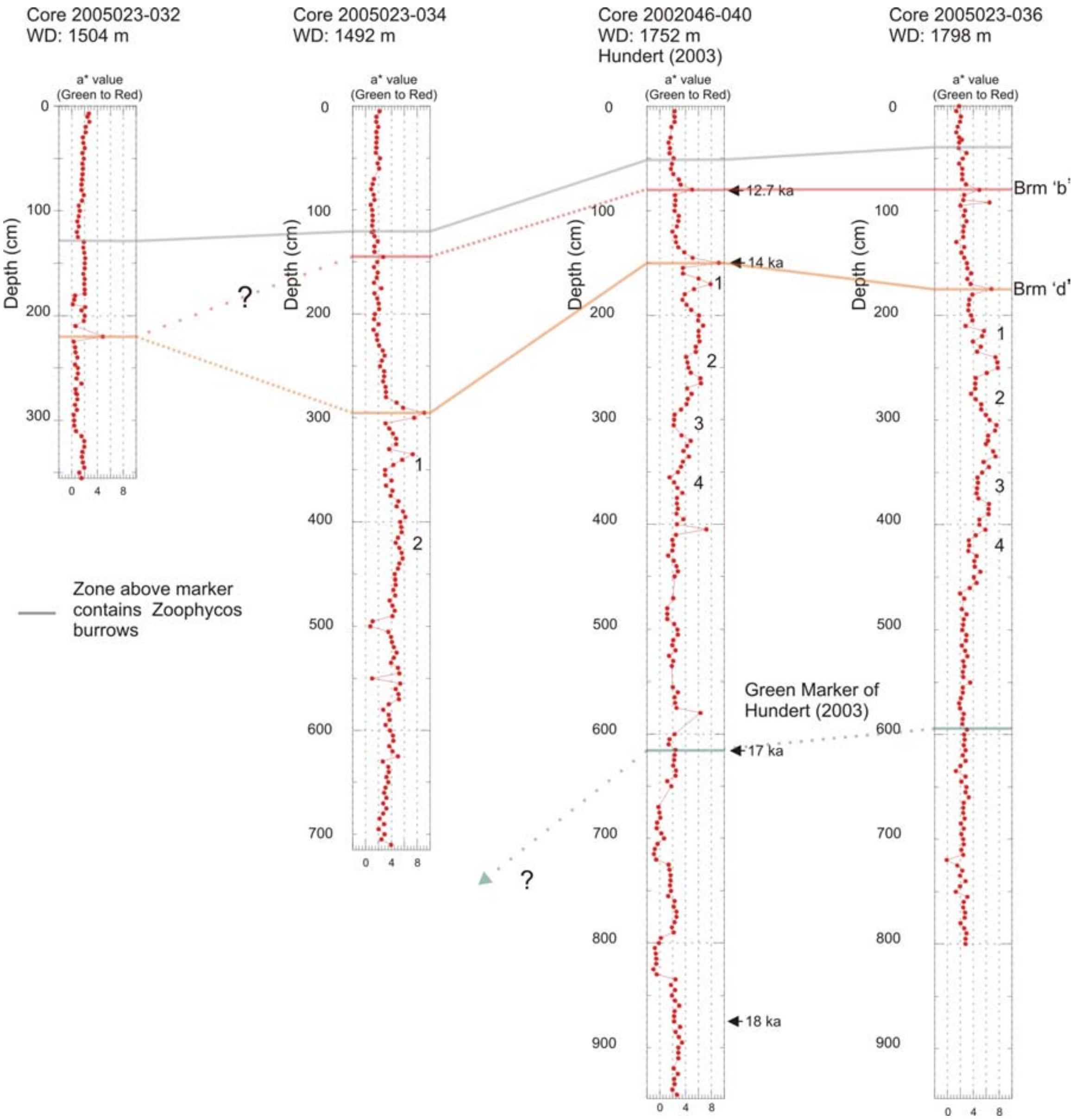


Figure 4.7 Correlation of a* color measurements between cores

Core 040 provides three absolute dates and one relative date with the 17 ka marker. With these dates a relative chronology is established for the cores used in this study. 'Green marker' is from Hundert's (2003) Huntec picks, 'Orange marker' is brick red mud 'd', and 'Red marker' is brick red mud 'b'. The 'Grey marker' marks the zone above Zoophycos burrows occur. Core 032's brick red mud unit is thought to be probably brm 'd' but it could be brm 'b'.

4.2.2 Chronology from Seismic

Hundert (2003) used two key reflections in his seismic analysis that had been dated from intersected cores. He called these the green and purple markers. Both of these markers are traced through the Huntec seismic data on the southwest Scotian Slope and can be seen in the airgun profiles with lower resolution. The green marker was dated by Hundert at 17 ka in radiocarbon years from core 99-036-57. The purple marker used by Hundert was dated at 32 ka (radiocarbon years) and used by both Gauley (2001) and Campbell (2000). Both of these markers can be traced into the tips of upper slope till tongues along Scotian margin (Hundert, 2003).

The green and purple markers were initially established for the western Scotian Slope but Hundert (2003) showed that this correlation could be traced to the Northeast Fan (Figure 4.8). After carefully examining the Huntec profiles of this study, the green and purple marker were identified in areas where thick stratified sediments accumulated. Purple marker of Hundert corresponds to the red marker, which we described in chapter three (Figure 4.9). The green marker of Hundert is located just above the brown marker, which was also mentioned in chapter 3 (figure 4.9).

The intersection of the green marker with core 040 provided an additional time constraint for the use in correlating cores (Figure 4.7). The purple marker of 32 ka provides the oldest direct time constraint for the use of correlation in this study. Any chronology below this marker is speculation.

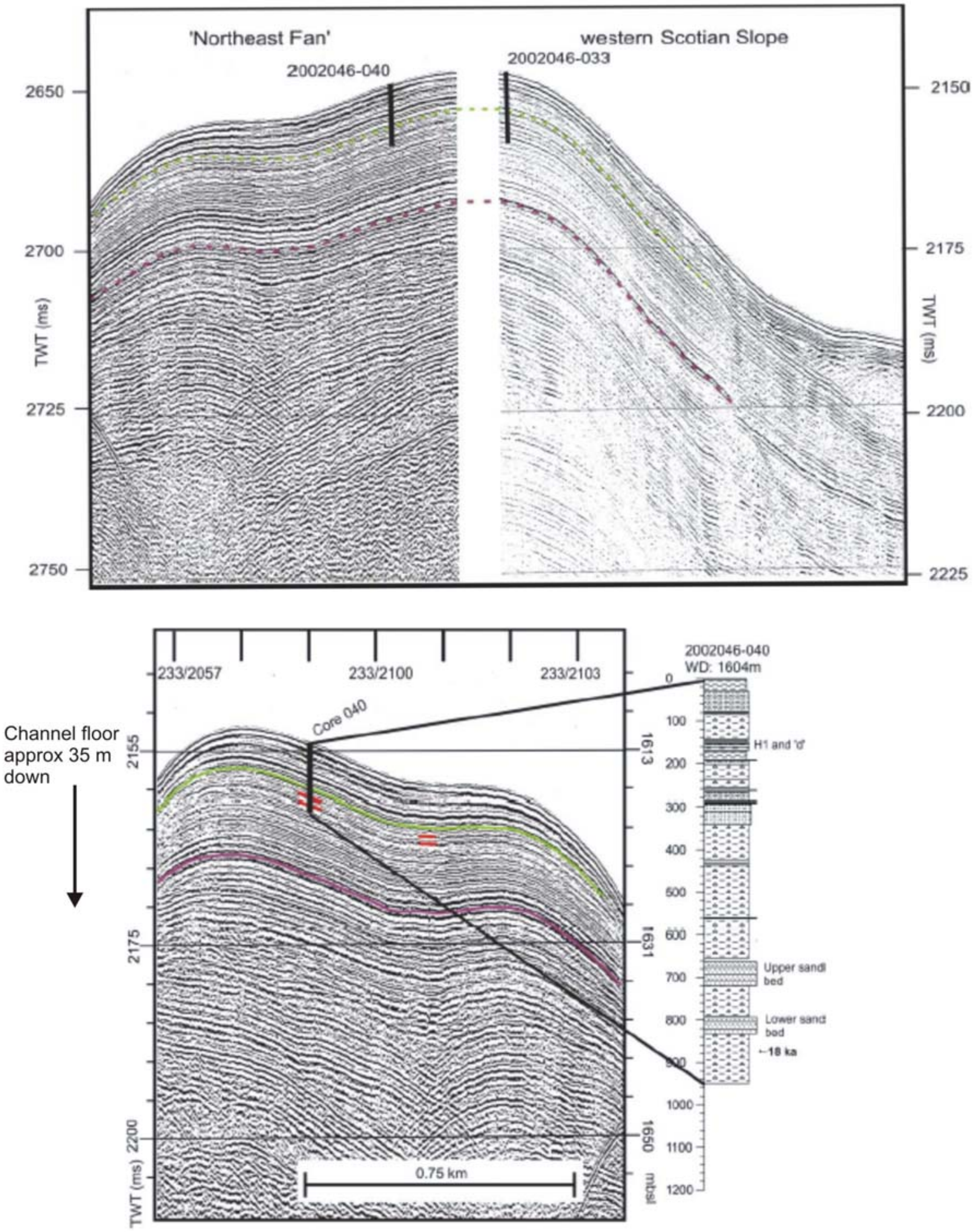


Figure 4.8 Huntec profiles, from Hundert (2003) showing correlation of reflectors between the Western Scotian Slope and the Northeast Fan. Note the relative position of a channel in respect to Core 040 is shown.

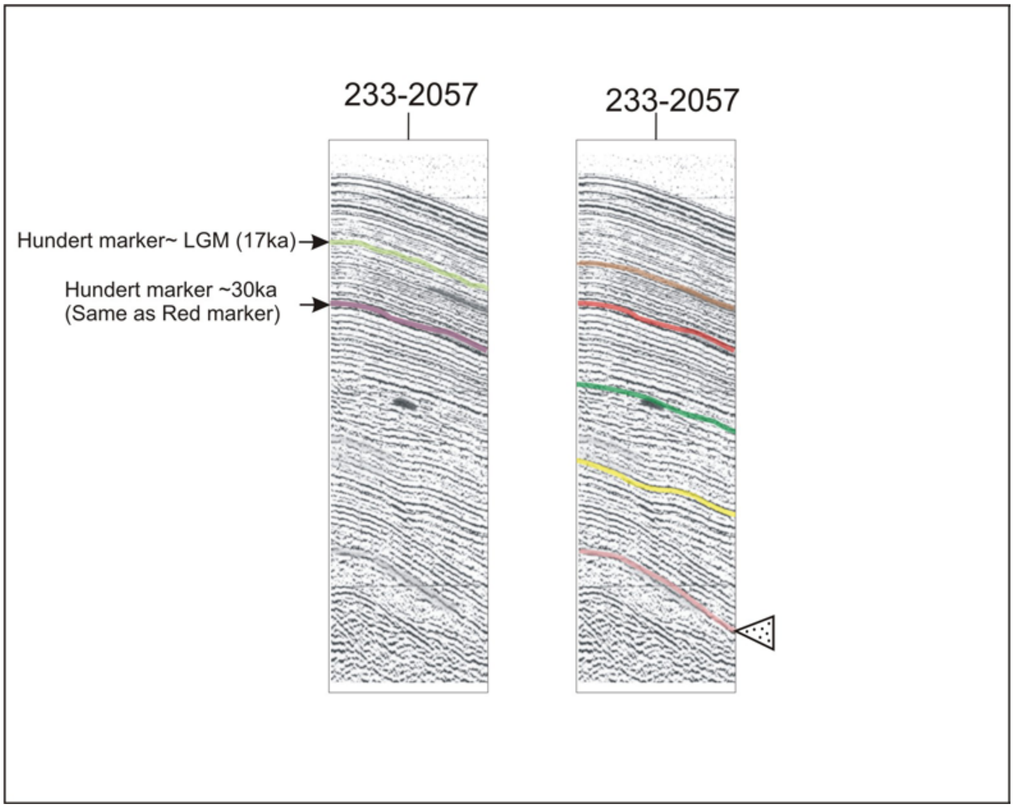


Figure 4.9 Huntec sections showing comparison of markers of Hundert (2003) and markers from this study

CHAPTER FIVE

SYNTHESIS

5.1 THE PLANFORM OF THE NORTHEAST FAN

When trying to understand the planform of the Northeast Fan, a comparison between the facies distribution map of this study to the GLORIA side scan imaging done by Hughes Clarke et al. (1992) provides a good overview of the entire sedimentary system. The GLORIA covers approximately 70,000 km^2 of the Western Scotian Rise, between 2500 and 5000 mbsl contours (Figure 5.1). Figure 3.10 displays the distribution of seafloor acoustic facies of the Northeast Fan from the Northeast Channel termination to about the 2500 mbsl contour. With these two sets of neighbouring data, we can see if there are correlations to be made. As a whole we can then compare the results to typical structures of deep sea turbidite fans to gain a general understanding of the planform of the Northeast Fan.

The GLORIA side scan imaging measures the backscatter of sonar rays which are emitted in a swath array from a tow fish. Penetration is a few meters into the seafloor. In the Holocene, sediment rarely exceeds 1.5 meters (Hughes Clarke et al, 1992), which indicates that the imaging reflected the distribution of Upper Pleistocene sediment. The backscatter of channel floors varies with depth from high backscatter (appears light) at shallow depth to low backscatter (appears dark) at depths greater then 4500 meters (Hughes Clarke et al. 1992).

When comparing the axial traces of the Northeast Fan principal channels to the GLORIA data, it can be seen that there is a match (Figure 5.2). Both the Western and Eastern channel correlate with linear zones of high backscatter, with the Western channel zone much larger. These high backscatter zones, interpreted as channels, do not trace very far into the GLORIA image (to about the 3000 mbsl contour). The GLORIA image shows no major channel system that runs across the rise of the Northeast Fan, but rather is made up of numerous channels that are discontinuous and often merge and bifurcate (Figure 5.3) (Hughes Clarke et al. 1992).

An interesting possible correlation is that there appears to be a dark lobe on the GLORIA image just south of the study area (Figure 5.3). This lobe seems to correlate well with the facies distribution of mass-transport deposits. The only problem with this is that Hughes Clarke et al (1992) point out that debris flows show up as streams of high backscatter (white) imaging. The lobe correlation appears as a low backscatter on the GLORIA image, which could be just indicating that the apparent match is just by coincidence.

Does this planform resemble a typical submarine fan system? Shanmugam and Moiola (1985) suggested that a typical submarine fan should appear as in Figure 5.4. A submarine fan should contain a main channel that originates on the slope and feeds outward onto the rise. These channels act to control turbidity currents, which allows the deposition of turbidite sequences (Shanmugam and Moiola, 1985). As the channels move basinwards, they become less significant and branch off. Comparing this type analogy to the Northeast Fan planform, there appears to be points of difference (Figure 5.4). As mentioned before the channels seen in the GLORIA do not appear to be focused into a main system, but rather is widespread and discontinuous. Also the channels do not seem to differ in size on the upper rise or lower rise. The Northeast Fan in addition lacks a morphological depositional lobe on the sea floor surface, which suggests that it does not follow the shape of a typical modern submarine fan.

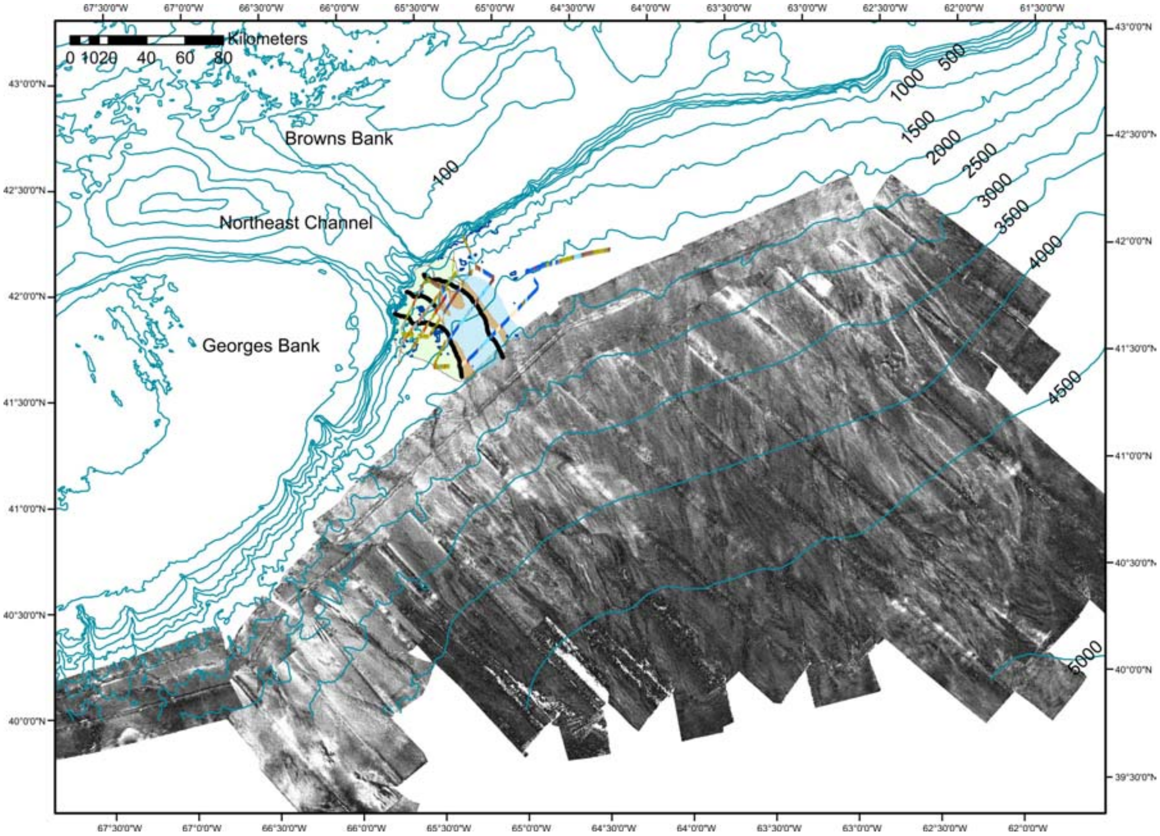


Figure 5.1 Map showing extent of GLORIA side scan survey along the Western Scotian Rise and its relationship to the Northeast Fan study area.

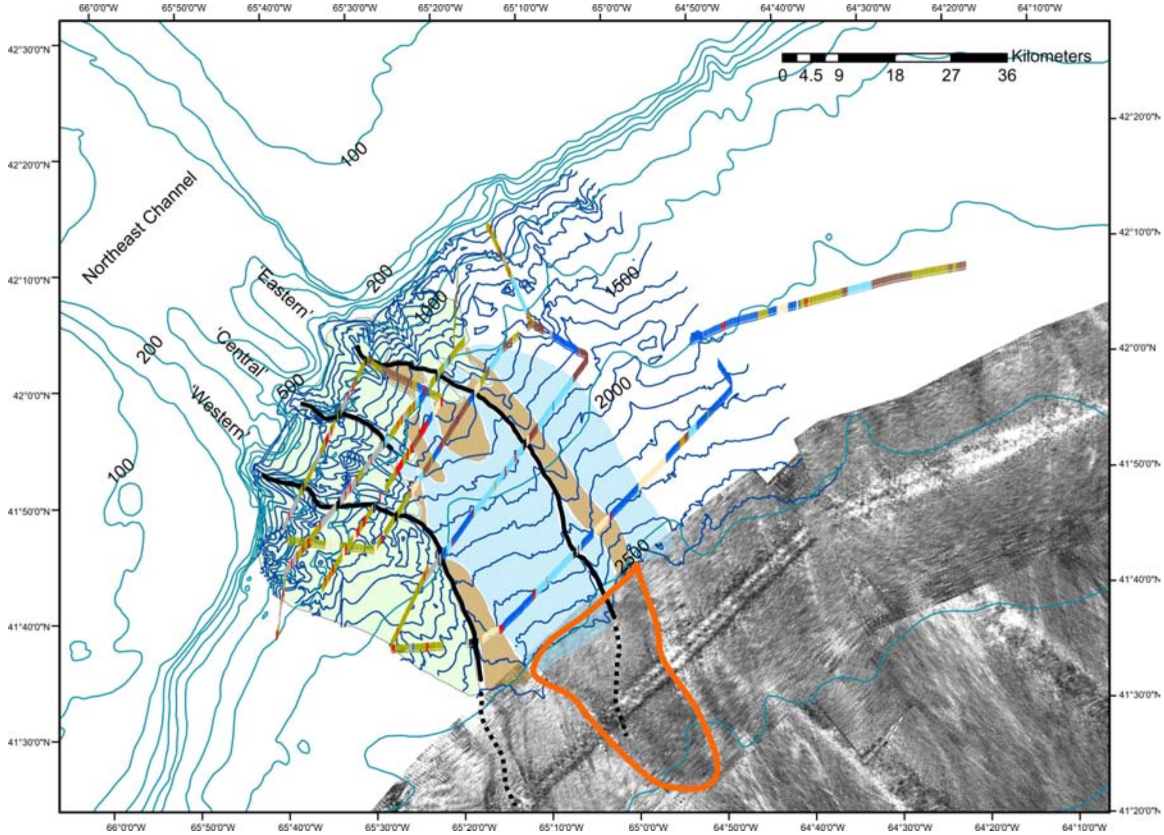


Figure 5.2 Channels axes matches with GLORIA data. Highlighted orange lobe is also shown on GLORIA (low backscatter)

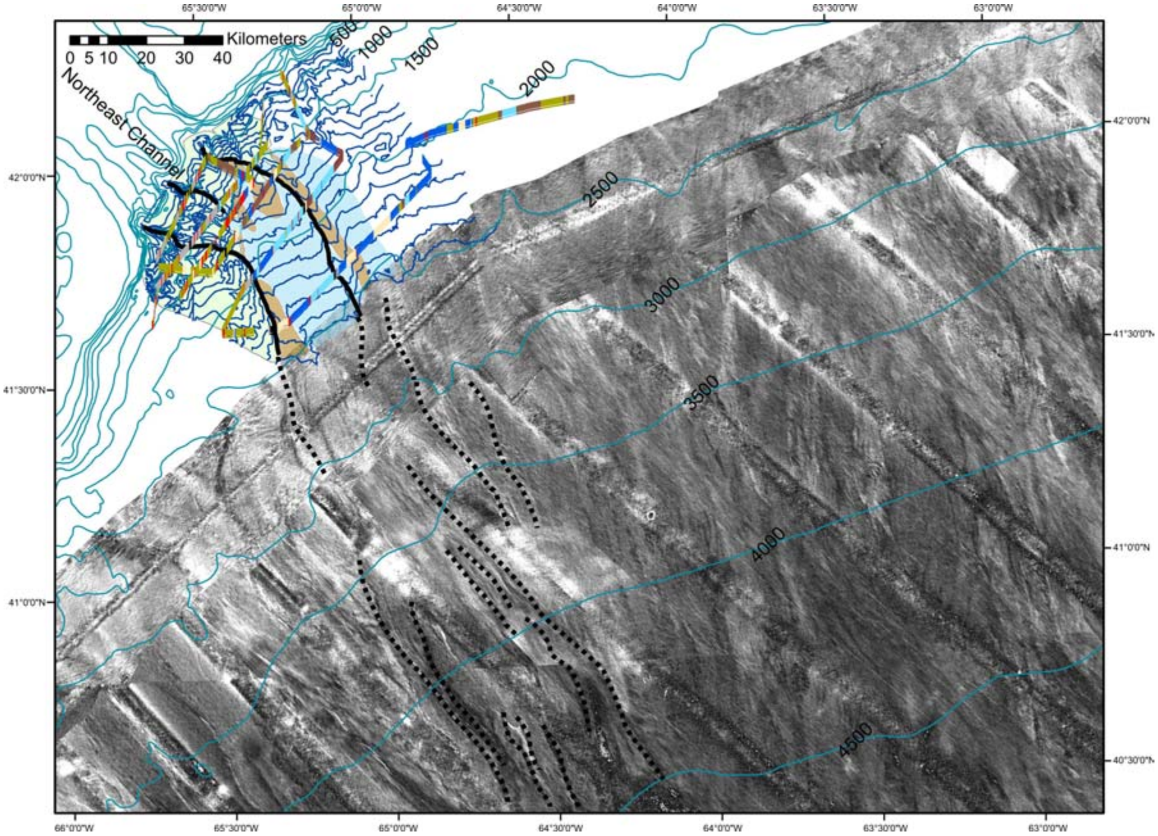


Figure 5.3 Channels across the rise (GLORIA)

Some channel traces downslope from Northeast Fan are shown as dashed lines

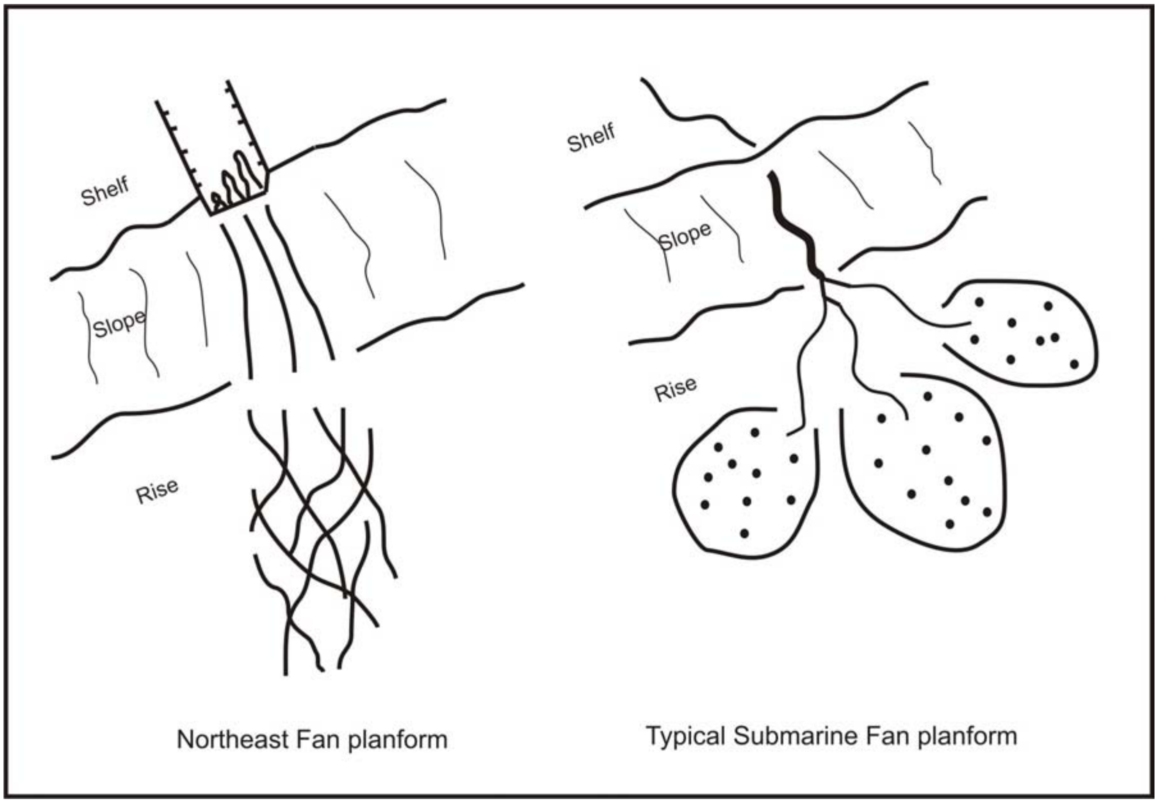


Figure 5.4 Typical Submarine Fan planform (Based from Shanmugam and Moiola, 1985) vs. Northeast Fan planform

5.2 EVOLUTION OF THE CHANNEL SYSTEM THROUGH TIME

The airgun profiles of lines (E) and (F) provide an overview of the stratigraphic distribution of mass transport deposits within the Northeast Fan (Figure 3.1). Line (E) shows a zone with major MTDs from the Western channel till about 10 km to the northeast. Farther northeast, high amplitude reflectors dominate, overlying major MTDs. In Line (F) high amplitude reflections are less well developed on the NE half of the line. The Western channel appears to have been displaced to the southwest with the appearance of a levee, which appears built on an older MTD. This MTD may occupy an older position of the Western channel, and its channel was plugged and diverted by the MTD. Morphologically Line (F) is smoother with fewer mounds, not unexpected with the transition from the slope to the rise.

To the northeast of line (E) in figure 3.1, thick stratified reflectors overlie thin MTDs, whereas Line (F) has thinner stratified sediments overlying MTDs. This suggests that there is bypassing of mass-transport deposition on the slope (Figure 5.5), with preferential deposition of MTDs on Line (F) compared with (E). This bypassing occurs NE of the Eastern channel, which indicates that those particular MTDs originated as failure on the upper southwest Scotian Slope. Similar bypassing of MTDs most likely also occurs within the Northeast Fan study area as well.

Assigning speculative ages to MTDs of the Northeast Fan proved to be difficult. One approach is to use the Huntec record on the adjacent continental slope in an area with thick accumulations of highly stratified reflectors. In this packet of reflectors, three groups of distinct high amplitude reflections can be observed (Figure 5.6). Piper et al. (2005) showed that on the St. Pierre Slope at a similar water depth to our area a similar set of reflections can be seen (Figure 5.7). These distinct high amplitude reflection packets when traced up slope are found to correlate to the tips of glacial till tongues (Piper et al. 2005). They were inferred to represent strata that contains higher amounts of glacial sediments. This means a higher percentage of silt and the presence of more ice-rafted debris. Till tongues represent the extent of glacial maximums (Mosher et al. 1989; Piper et al. 2005) therefore these reflection packets mark times of glacial maximums. The deepest of the three high amplitude reflections packets correlates with the tip of a major MTD, and correlates with the seismic marker Pink (Figure 5.6). If this correlation is correct, then the Pink marker is MIS 6 in age based on the ages of Piper et al.(2005) and provides an excellent tool for relative dating of MTDs in the Northeast Fan.

The distinct reflectors seen at the St. Pierre Slope is in an area of much higher sedimentation, which is why Figure 5.7 is an airgun profile (deep penetration) compared to Figure 5.6 which is a Huntec profile (shallow penetration). This is reasonable because Gauley B.J (2001) showed that sedimentation rates are much lower on the Western Scotian Slope compared to the St. Pierre slope.

With the assumption that Pink marker represents MIS 6 we can develop a basic age framework for two major MTDs. Figure 5.8 shows a summary of the airgun line (E) highlighting the relative ages of major MTD (A) and (B). Because we know Pink marker represents MIS 6 in relative age we can infer that the MTD (B) (in the northeast portion of the airgun line) is probably MIS 6 in age. This horizon when followed to the southwest dips below at the transition from thick stratified reflectors to a packet of High Amplitude reflectors. The major MTD (A) on the southwest portion of the line contains stratified sediments which are < 5ms thick, well away from Western Channel. Based on the depth to Hundert's green marker and the depth to LGM in core 040, it seems unlikely that the sequence above the MTD can be older then LGM.

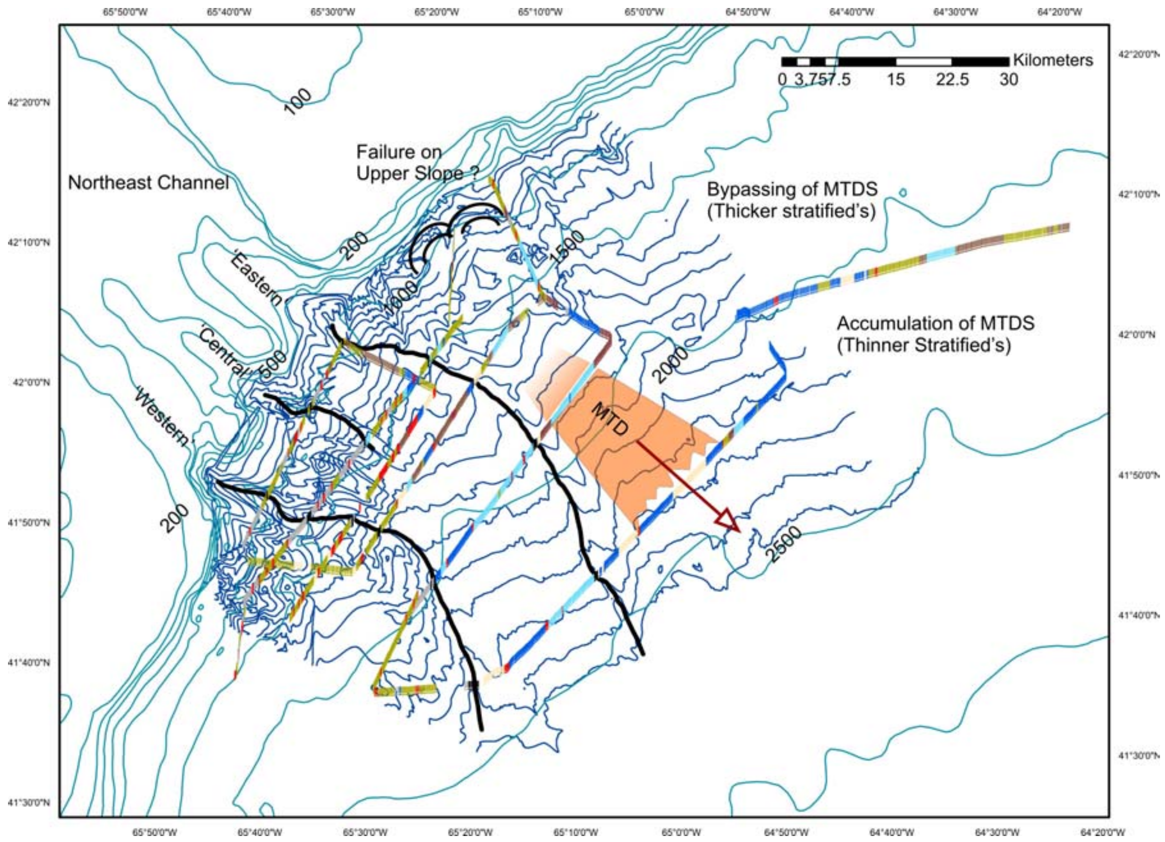
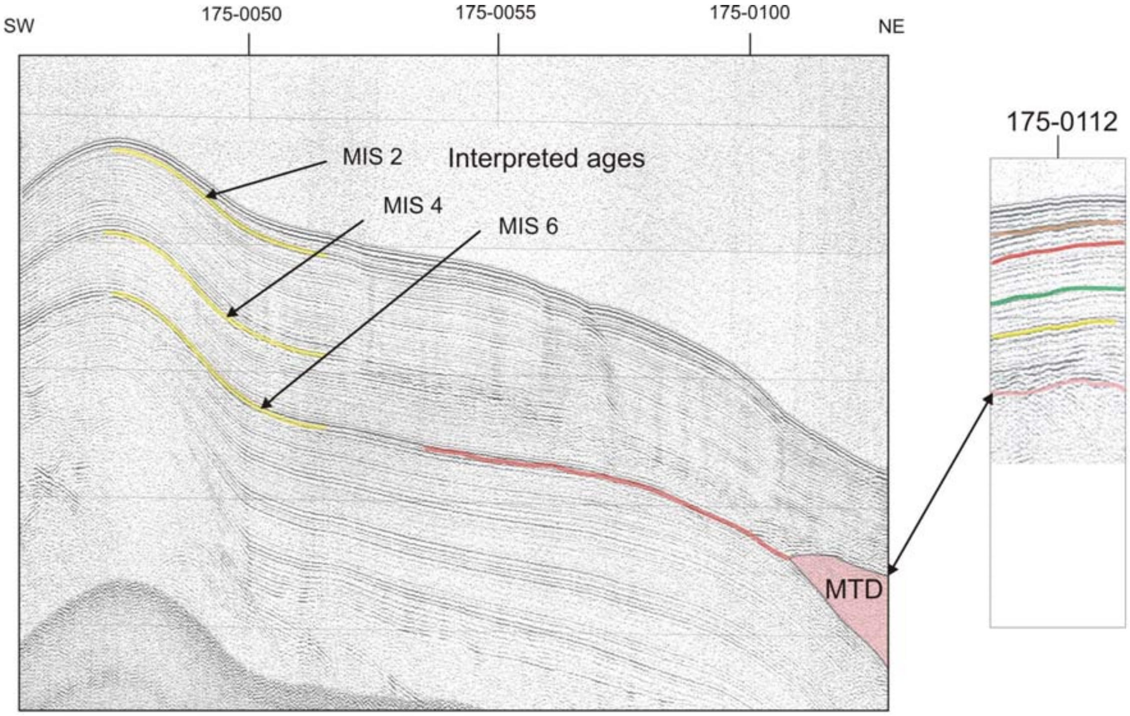


Figure 5.5 Bypass of mass-transport deposit, which potentially could have originated on the upper slope northeast of the Northeast Channel.



MIS 6 correlates to Pink Marker

Figure 5.6 Reflections near Northeast Fan showing three high amplitude reflectors packets

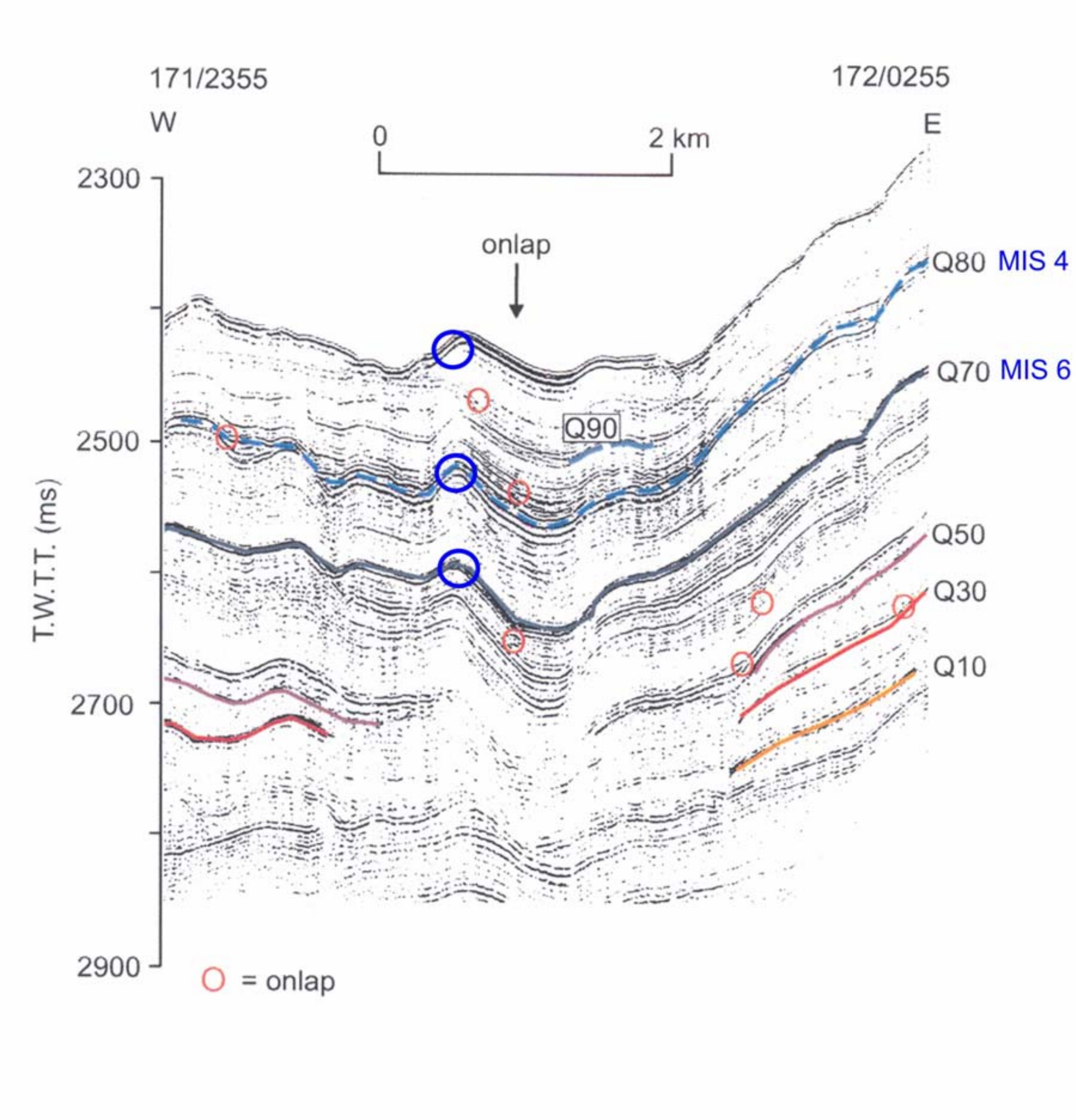


Figure 5.7 MIS reflectors found at St. Pierre slope (From Piper et al. 2005). Blue circles mark three packets of high amplitude reflectors.

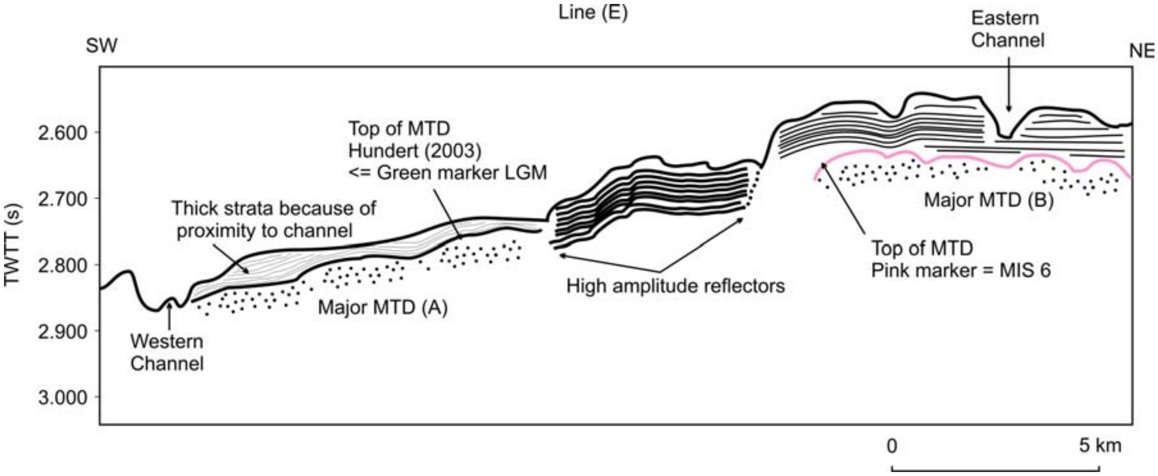


Figure 5.8 Summary of line (E) with relative ages of major MTDs.

5.3 DISCUSSION

5.3.1 Comparison of Northeast Fan with Laurentian Fan

One of the initial goals of this study was to explore the idea of whether or not the Northeast Fan is a smaller version of the Laurentian Fan. At first glance one would say “sure why not? They are both located on the Scotian margin, and they both represent major ice stream outlets for meltwater during glaciations”. One familiar with the Laurentian Fan while reading this study would have noticed some interesting differences between the two systems.

Morphologically the fan architecture of both channels seems to share some features. Both include multiple canyons and channels crossing the slope and delivering sediment to the rise. The Laurentian Fan has the Western and Eastern Valley while in this study it was determined that there was a Western, Central, and Eastern channel for the

Northeast Fan. There is however a major difference in the size of these channels. Laurentian Fan valleys show much wider and broader channel floors than the Northeast Fan and show features that suggest that it is much more erosive (Skene and Piper, 2005) (Figure 5.9). At times in the past, Western channel of the Northeast Fan may have been wider with a ~2.3 km wide highly reflective floor (Figure 5.10). Although larger, this still does not compare in size with the Laurentian Fan channels.

At the termination of the fan valleys on Laurentian Fan, there is a large sandy depositional lobe, recognized by a bulge in bathymetric contours and a hard bottom with 3.5 kHz profiles. There is no similar bathymetric feature at the termination of the Northeast Fan channels, suggesting that they have transported much less sandy sediment than the Laurentian Fan channels.

With the Northeast Fan, the lower slope and upper rise portion seems to be dominated by large mass-transport deposits. The airgun profiles of line (E) and (F) show this feature quite well (Figure 3.1). Laurentian Fan airgun lines such as in Skene and Piper (2005) show mass-transport deposits on levees, which are fairly large but not on the scale as the Northeast Fan. Reflectors of strata as well seem to be much more developed in the Laurentian Fan with the number of debris flows significantly less. Also seismics revealed that mass-transport deposits underlie the channels of the Northeast Fan, while the Laurentian Fan valleys and channel floors lack major MTDs. This lack of major MTDs found in the Laurentian Fan compared to the Northeast Fan could be due to the erosive nature of Laurentians Fans valleys.

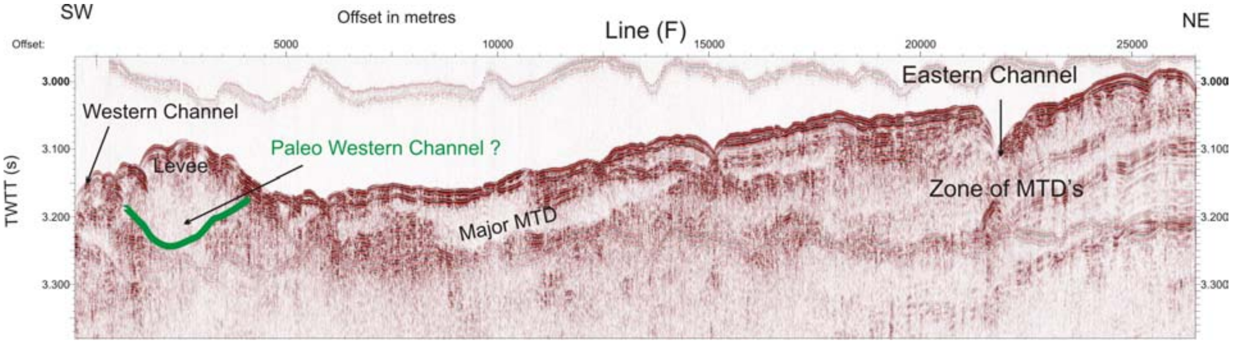
Another interesting feature noticed in the Northeast channel was that deposits from young turbidity currents (<= 14 ka radiocarbon years) were present (Figure 4.6).

Observing Laurentian Fan, young (10-13 ka) turbidites result from flows down the "Grand Banks Valley" (Skene and Piper 2003). At this time on the "Grand Banks Valley" there was late ice at the head of the valley and sea level was lower on a shallow shelf break so it was a dynamic place. On the Northeast Fan there is no evidence of any ice near the shelf edge by 15.5 ka or 16 ka (King, 1996), as well, since the shelf break is deep, lowered sea level had little effect. This being said, there must have been another mechanism to explain sandy turbidites which are as young as ~14 ka on the Northeast Fan. For this study this has been left as an unresolved problem.

When analyzing the Northeast Channel and Laurentian Channel, there also appears to be a major morphological feature difference. The Laurentian Channel meets the edge of the continental shelf with there being a fairly uncut edge, while with the Northeast Channel there are three major cuts into shelf with the channel/slope front. This cutting into the shelf margin at Northeast Channel, which is not seen at Laurentian Channel, is however seen at The Gully as well as in canyon heads on Banquereau (Figure 5.11) (Piper et al. in press). These shelf–breaching canyons are believed to be formed from glacial melt water events, which leaves us with the question "Why are there no shelf-breaching canyons at the head of Laurentian Channel?" Could the carved shelf edge canyons of the Northeast Channel be the reason why the Northeast Fan is constructed of major MTDs? Again these are matters which cannot be solved within the scope of this study.

	Western Channel	**Eastern Channel**	**Central Channel**
Northeast Fan	@ ~2100 mbsl ~1.15 km wide @ ~2400 mbsl ~1.5 km wide	@ ~1900 mbsl ~0.5 km wide @ ~2300 mbsl ~0.25 km wide	@ ~1000 mbsl ~1.15 km wide
Laurentian Fan	@ ~3750 mbsl ~3.0 km wide	@ ~3500 mbsl ~24 km wide @ ~4850 mbsl ~5.5 km wide	N/A

Figure 5.9 Channel widths at Northeast Fan and Laurentian Fan (Piper et al. 1985)



	Current Channel Width	**Paleo Channel Width**
Northeast Fan Western Channel	@ ~2400 mbsl ~1.5 km	@ ~2400 mbsl ~2.3 km

Figure 5.10 Airgun profile (F) showing possible location of paleo Western channel

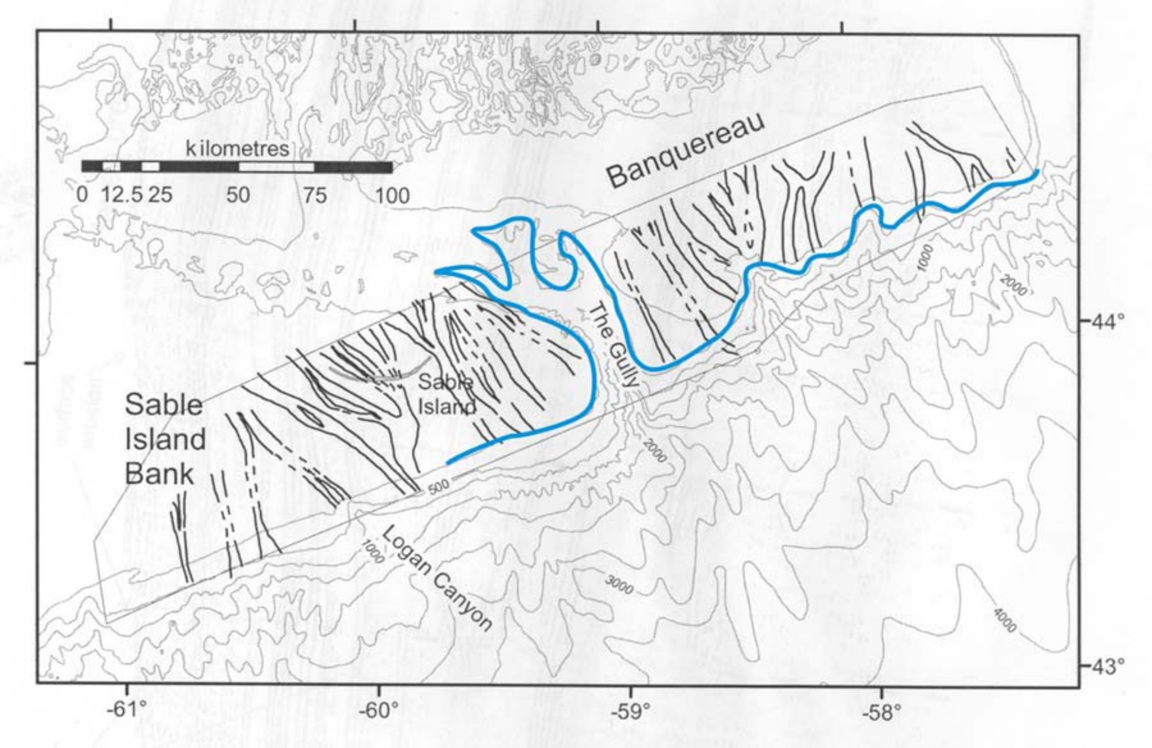


Figure 5.11 Shelf cutback feature of The Gully and Banquereau (In Blue) (Modified from Piper et al. in press). Channels shown in bold are tunnel valleys, which are filled with sediment from the outer bank.

5.3.2 Relationship of the fan to glacial history of Nova Scotia and Scotian Shelf.

With the Northeast Channel being recognized as a major ice stream during the last glacial maximum (Denton and Hughes, 1981), it now becomes important to try and connect the results of this study to glacial models which would act as an explanation for depositional features. King (1996) had showed that the Fundian moraine in the Gulf of Maine had been dated as older than 15.5 ka, which suggests that ice had retreated well into the Gulf of Maine by that time. As for the ice sheet being located at the shelf edge on the Northeast Channel, all we can say is that it is older than 15.5 ka (reasonably at least 16 ka based on extrapolated sedimentation rates). It is likely that as a mid-latitude ice stream, substantial amounts of meltwater discharged through Northeast Channel by analogy with Laurentian Channel (Piper et al. in press)

The cores examined in this study (032, 034. 036, and Hundert's 040) were found to show similar stratigraphy to elsewhere on the Scotian Slope, suggesting that, like the Scotian Slope, they are dominated by the southwest drift of proglacial plumes from the Laurentian Channel. The recognition in cores of brick red muds 'b' and 'd', as well as the presence of Heinrich layer H1 at roughly the same stratigraphic level as on the Scotian Slope, suggests that there is no strong proglacial signature from the Northeast Channel. This is contrary to the view of Hundert (2003) who suggested that the brick red muds found in Northeast Fan were derived from Triassic aged bedrock around the Bay of Fundy, rather then the Permian –Carboniferous strata of the Gulf of St Lawrence.

Glacial influence on the Northeast Channel within the Quaternary is quite evident morphologically. The deeply carved canyons on the outer portion of the Northeast Channel and the Upper slope, which in this study have been referred to as Western, Central, and Eastern channels, are believed to be the product of subglacial meltwater actively eroding the shelf floor. This canyon erosion through subglacial melt water has been evident in other places across the Scotian margin such as The Gully and canyons off Banquereau (Piper et al. in press). Why does the Northeast Channel have three canyons maybe instead of one, two, or four? This is not known at present time, but it can be thought that glacial meltwater in some way is responsible.

The relationship between the timing of mass-transport deposits and glaciations appeared to be strong in the Northeast Fan. Figure 5.8 summarizes speculative ages for two major MTDs on Line (E). Both appear to correspond to times of last glacial maximums with MTD (A) believed to be LGM or younger (Hundert's Green marker). MTD (B), argued on independent grounds, was also found to be a glacial maximum, MIS 6. This was done by recognizing a packet of high amplitude reflectors just east of the Northeast Fan that passed into a mass-transport deposit whose top was marked by the Pink marker. This could mean that other MTDs recognized in the airgun profiles could also represent periods of glacial maximums. A question to consider is "What direct influence did glaciations play on initiating mass-transport deposits?" Is it because an ice stream reached the shelf edge and dumped glacial till that flowed as an MTD, or is it because it discharged subglacial meltwater that flowed hyerpycnally and undercut canyon walls? It is also important to consider that although the two MTDs dated in this study are found to be deposited at roughly glacial maximums, there is still the potential that other MTDs found in the airgun lines could be deposited in times other than glacial maximums thus being triggered by other mechanisms unknown to this study.

CHAPTER SIX

CONCLUSION

This study has provided a number of conclusions, which help define the history of Late Quaternary evolution in the Northeast Fan. These conclusions are stated below.

1. New bathymetric compilations and new seismic reflection profiles show clearly the gross planform of major channels that cross the Northeast Fan which have been named Western, Central, and Eastern Channel. Channels could be correlated onto the GLORIA data from the Scotian Rise.
2. Near surface acoustic facies have been mapped across the Northeast Fan and could be grouped into zones of similar features.
3. A stratigraphic framework was established through the correlation of marker horizons seen in Huntec seismic reflection profiles. Shallow reflectors are correlated to cores, which can be related to LGM.
4. Correlation of Huntec markers showed that some major MTDs in Northeast Fan could be dated approximately to times of glacial maxima. This was done through matching patterns of glacial reflectors from St. Pierre slope to similar reflectors near the Northeast Fan. The Pink marker is thought to be MIS 6 in age.
5. Cores show sands on terraces high above channel floors between the times of the LGM and 14 ka implying thick sandy turbidity currents. For sands as young as 14 ka, some process other than glacial meltwater is needed to initiate the turbidity currents.

6. The upper Northeast Fan resembles The Gully and canyons off Banquereau in having shelf-breaching canyons. Also there are some similarities to Laurentian Fan such as the development of multiple valleys/channels. Still the question remains as to ‘Why there are no shelf-breaching canyons at head of Laurentian Channel?’

REFERENCES

Bouma A.H., [1962], "Sedimentology of some Flysch deposits; a graphic approach to facies interpretation", *Amsterdam, New York, Elsevier Pub. Co.*

Bouma A.H., [2000]. "Fine-grained, Mud-Rich Turbidite Systems: Model and Comparison with Coarse-grained, Sand-Rich Systems" *In: Fine-Grained Turbidite Systems, ed Bouma A.H. and Stone C.G AAPG Memoir 72, SEPM Special Publication No. 68., p 9-19*

Campbell D.C., [2000], "Relationship of sediment properties to failure horizons for a small area of the Scotian Slope", *Geological Survey of Canada Current Research 2000.*

Chubbs J.F., [**2003**]. "Geohazards at the proposed Weymouth wellsite, Central Scotian Slope, offshore eastern Canada", *B.Sc. Honours Thesis, Saint Mary's University, Halifax, Nova Scotia.*

Denton G.H. and Hughes T.J., [1981], "The last great ice sheets", *Toronto, John Wiley & Sons Inc p.284*

Garrison T., [2002], "Oceanography; An Invitation to Marine Science", *4th edition, Orange Coast College, University of Southern California, Thomson Learning, Inc.*

Gauley B.J., [2001], "Lithostratigraphy and sediment failure on the Scotian Slope", *M.Sc. Thesis, Halifax, Nova Scotia, Dalhousie University*

Hill P.R., [1984], "Sedimentary facies of the Nova Scotian upper and middle continental slope, offshore eastern Canada", *Sedimentology Vol. 33, p. 293-309*

Hughes Clarke J.E., O'Leary D.W., and Piper D.J.W. [1992], "Western Nova Scotia Continental Rise: Relative Importance of Mass Wasting and Deep Boundary-Current Activity", *In Poag, C.W., and de Graciansky, P.C.,eds., Geological evolution of the Atlantic continental rise: New York, van Nostrand Reinhold, p. 266-281*

Hundert T., [2003], "Western Scotian Slope stratigraphy: insights into late Quaternary deglaciations of the western Scotian Slope, eastern Canada", *M.Sc. Thesis, Dalhousie University, Halifax, Nova Scotia*

Kidston A.G., Brown D.E., Altheim B., and Smith B.M., [2002], "Hydrocarbon Potential of the Deep-water Scotian Slope", *Canada-Nova Scotia offshore Petroleum Board Publication, October 2002 version 1.0 .*
http://www.cnsopb.ns.ca/resources/pdf/Hydrocarbon_Potential_Scotian_Slope.pdf

King E.L., [2005]. Cruise Report, Hudson 2005-024. Geological Survey of Canada.

King L.H., [1996], “Late Wisconsinan ice retreat from the Scotian Shelf”, *GSA Bulletin; August 1996; Vol. 108, p. 1056-1066*

Lillie R.J., [1999], “Whole earth Geophysics; An Introductory Textbook for Geologists & Geophysicists”, *Prentice Hall, Upper Saddle River, New Jersey 07458*

Mosher D.C., Piper D.J.W., Vilks G., Aksu A.E., and Fader G.B., [1989], “Evidence for Wisconsinan Glaciations in the Verrill canyon Area, Scotian Slope, Canada: *Quaternary research, v. 31, p. 27-40.*

Mosher D.C. and Simpkin P.G., [1999], “Environmental Marine Geoscience 1. Status and Trends of Marine high Resolution Seismic Reflection Profiling: Data Acquisition”, *Geoscience Canada, v.26: p. 174-188*

Mosher D.C., Piper D.J.W., Campbell D.C. and Jenner K.A., [2004], “Near surface geology and sediment-failure geohazards of the central Scotian Slope”, *AAPG Bulletin, Vol. 88, p. 703-723*

Mutti E., and Normark W.R., [1991], “An integrated approach to the study of turbidite systems” *In: Seismic facies and sedimentary processes of submarine fans and turbidite systems, ed P. Weimer, and M.H. Link, New York, Springer-Verlag, p. 75-106.*

Normark W.R., and Piper D.J.W., [1991]. “Initiation Processes And Flow Evolution Of Turbidity Currents: Implications For The Depositional Record”. *Special Publication No. 46, Society for Sedimentary Geology (SEPM) p. 207-230*

Piper D.J.W., Stow D.A.V., and Normark W.R., [1985]. “Laurentian Fan, Atlantic Ocean” In: *Submarine Fans and Related Turbidite Systems, ed Bouma A.H., Normark W.R., and Barnes N.E., p 137-142*

Piper D.J.W., Mudie P.J., Fader G.B.J., Josenhans H.W., MacLean B., and Vilks G., [1990], “Quaternary Geology”, *In: Keen M.J., and Williams G.L., eds, Geology of the continental margin off Canada: Geology of Canada, Geological Survey of Canada, p.475-607 (also Geological Society of America, The Geology of North America, vol. I-1).*

Piper D.J.W., Mudie P.J., Aksu A.E, and Skene K.I., [1994], “A 1 Ma record of Sediment Flux South of the Grand Banks Used to Infer the Development of Glaciation in Southeastern Canada”, *Quaternary Science Reviews, Vol. 13, p. 23-37*

Piper D.J.W. and Skene K.I., [1998], “Latest Pleistocene ice-rafting events on the Scotian Margin (Eastern Canada) and their relationship to Heinrich events”, *Paleoceanography, Vol. 13, p. 205-214*

Piper D.J.W., Hiscott R.N., and Normark W.R., [1999], "Outcrop-scale acoustic facies analysis and latest Quaternary development of Hueneme and Dume Submarine fans*", Offshore California", Sedimentology, Vol. 46, p 47-78*

Piper D.J.W., Mosher D.C., Jenner K.A., Campbell C.D., and Gauley B., [2001], "The Surficial Geology of the Central Scotian Slope", *Unpublished report, Geological Survey of Canada (Atlantic)*

Piper, D.J.W., [2002]. Cruise Report, Hudson 2002-046. Geological Survey of Canada

Piper D.J.W., [2005], "Late Cenozoic evolution of the continental margin of eastern Canada", *Norwegian Journal of Geology, Vol. 85, p 231-244*

Piper D.J.W., Macdonald A.W.A., Ingram S., Williams G.L., and McCall C., [2005], "Late Cenozoic architecture of the St. Pierre Slope", *Canadian Journal of Earth Sciences, Vol, 42 p. 1987-2000*

Piper D.J.W., Shaw J., and Skene K.I., [In Press], "Stratigraphy and Sedimentological evidence for late Wisconsinan subglacial outburst floods to Laurentian Fan", *Palaeogeography, Palaeoclimatology, Palaeoecology*

Prothero D.R. and Schwab F., [1999], “Sedimentary Geology: An introduction to sedimentary rocks and stratigraphy”, *W.H.Freeman and Company, Third Printing*

Shaw J., and Courtney R.C., [2002], “Postglacial coastlines of Atlantic Canada: digital images”, *Geological Survey of Canada Open File 4302, p. 13.*

Shanmugan G. and Moiola R.J., [1985], “Submarine Fan Models: Problems and Solutions” *In: Submarine Fans and Related Turbidite Systems, ed Bouma A.H., Normark W.R., and Barnes N.E., p 29-34*

Skene K.I. and Piper D.J.W., [2003], “Late Quaternary stratigraphy of Laurentian Fan: a record of events off the eastern Canadian continental margin during the last deglacial period”, *Quaternary International, Issue 99-100, p. 135-152*

Skene K.I. and Piper D.J.W., [2005], “Late Cenozoic evolution of Laurentian Fan: Development of a glacially-fed submarine fan”, ***Marine Geology, Vol. 227, p. 67-92***

Stea R.R., Piper D.J.W, Fader G.B.J., and Boyd R., [1998], “Wisconsinan glacial and sea-level history of Maritime Canada and the adjacent continental shelf: A correlation of land and sea events”, *GSA bulletin; July 1998; v. 110; no. 7; p. 821-845; 16 figures; 2 tables*

Wade J.A. and Maclean B.C., [1990], “Chapter 5: The geology of the Southeastern margin of Canada” *In: Continental Margin of eastern Canada, ed Keen M.J. and Williams G.L., Geological Survey of Canada, Geology of Canada, no. 2, p167-238*

Walker R.G., [1992]. “Turbidites and Submarine Fans” *In: Facies Models; Response to Sea Level Change, ed Walker R.G. and James N.P., p 239-263*

White M., [2005]. “Late Cenozoic Seismic Stratigraphy of the Mohican Channel Area, Scotian Slope”. B.Sc. Honours Thesis, Dalhousie University, Halifax, Nova Scotia

Appendix A: Core plot summaries

Core Summary Legend for Core 40 (Hundert 2003)

Symbol Legend

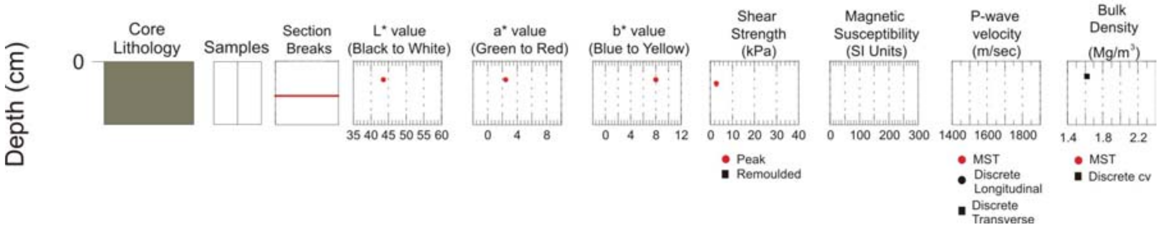
Erosional Contact	∼
Lamination/Thin Beds	≡
Core Disturbance	|
Radiocarbon Date	→
Grain Size Subsample	●
Bulk Density Subsample	▲
Atterberg Limit Subsample	■
Gas Subsample	G
Geomechanical Subsample	M
Shell Hash	⬭

Colour Legend

Foram Ooze	🟨
Olive Grey Mud (Ogm)	🟩
Olive Grey Sandy Mud (Ogm1)	▨
Olive Grey Mud with Ice-Rafted Detritus (Ogm2)	▨
Brick Red Mud (Brm)	🟥
Red Brown Mud (Rbm)	🟫
Red Brown Sandy Mud (Rbm1)	▨
Red Brown Mud with Ice-Rafted Detritus (Rbm2)	▨
Brown Mud (Bm)	🟫
Brown Sandy Mud (Bm1)	▨
Brown Mud with Ice-Rafted Detritus (Bm2)	▨
Grey Mud (Gm)	⬛
Grey Sandy Mud (Gm1)	▨
Grey Mud with Ice-Rafted Detritus (Gm2)	▨
Tan Mud	🟫
Sand or Gravel	▨
Debris Flow	⬛
Mudclast Conglomerate	▨
Diamicton	▨
Folded Mud Block	▨

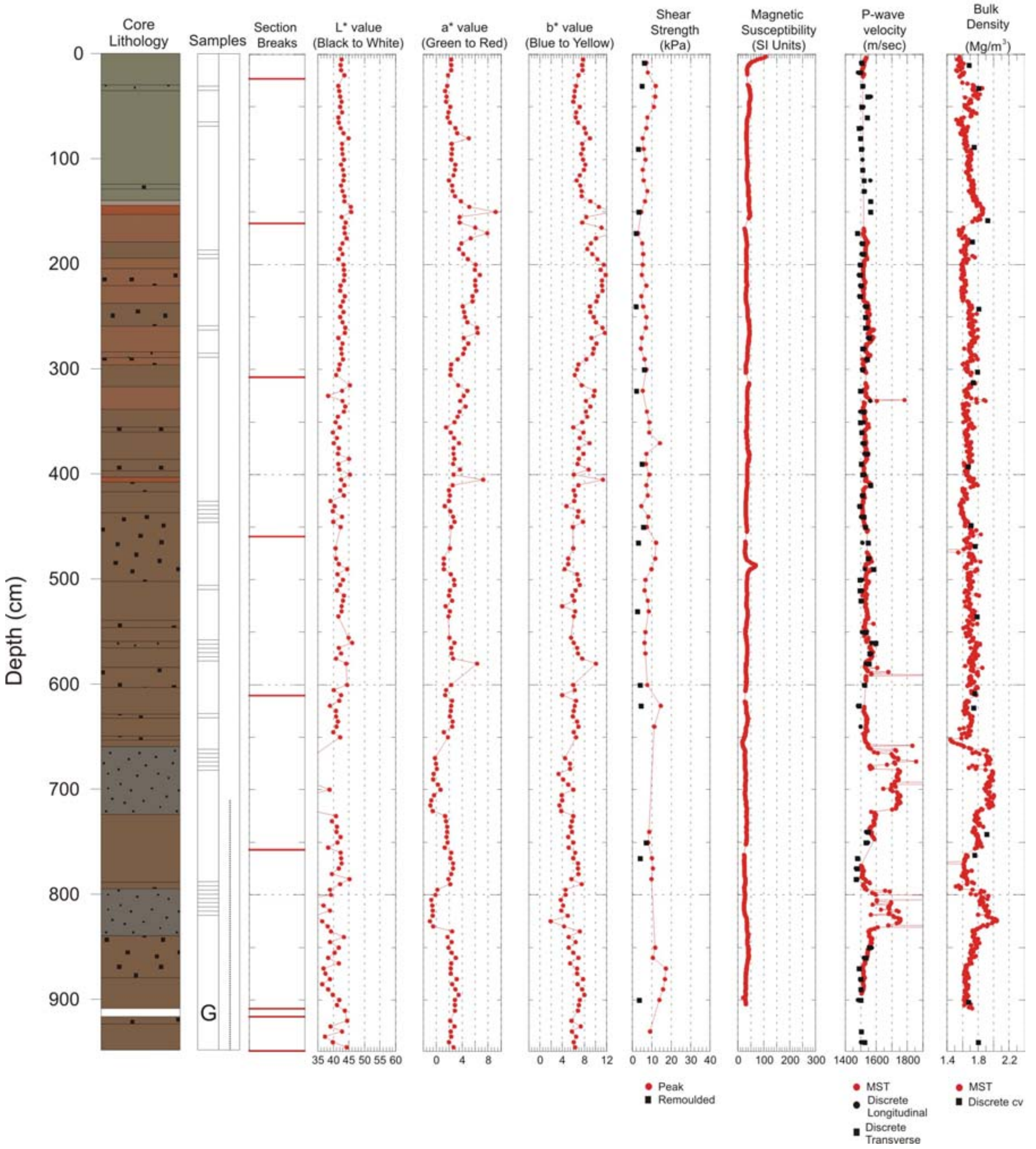
Hudson 2002046 Trigger Weight Core 040

TD 17cm 41°56.2407 N 65°20.2327 W Water depth 1752 m



Hudson 2002046 Piston Core 040

TD 949cm 41°56.2407 N 65°20.2327 W Water depth 1604 m



Core Plot Summary Legend

Cores 032, 034, and 036 2005023

Colour Legend

🟫	Orange brown mud
■	Olive grey mud, massive
▒	Olive grey sandy mud
▪	Olive grey mud with IRD
☰	Red brown mud, stratified
▪	Red brown mud with IRD, mud clasts
■	Pinkish brown mud, mottled
🟫	Brown mud, mottled with mud clasts
▪	Brown mud with IRD
🟪	Purple grey mud
■	Greenish grey mud, massive
☰	Greenish grey mud, stratified
■	Grey mud, massive
▪	Grey mud with IRD
■	Tan Mud
▒	Sand
▪	Gravel
🟥	Brick Red Mud

Symbol Legend

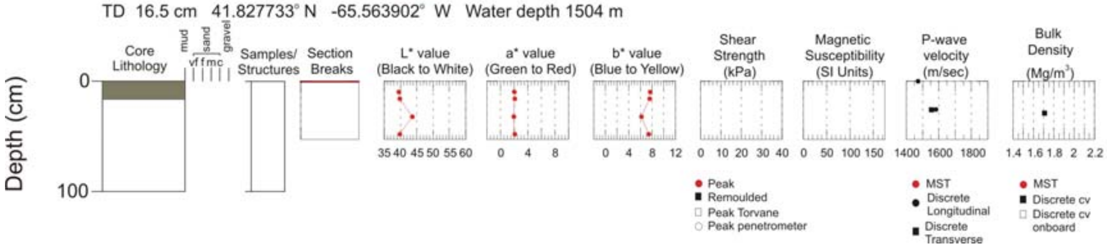
Bioturbated contact	ssssss
Gradational contact	⋯
Distinct contact	- - -
Sharp contact	—
Erosional contact	〜
Lamination/thin beds	☰
Turbidites	☰
Dateable shell	⬭
Bioturbation	ss sss
Worm burrow	▽
Mud clast	⊖
Core disturbance	⋮
Subsampled core	☒

Mass Transport Deposit Lithofacies

▨	Clast-supported mud-cast conglomerate
▨	Matrix-dominated mud-clast conglomerate
▨	Matrix-supported mud-clast conglomerate
▨	Diamicton
▨	Folded mud interval
▨	Allochthonous stratified mud interval

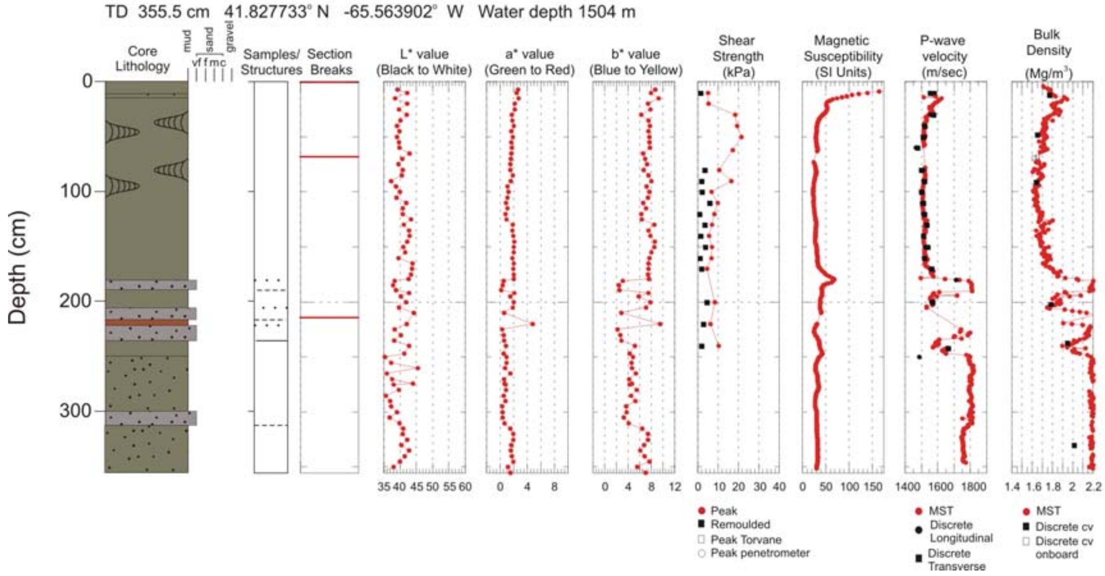
Hudson 2005023 Trigger Weight Core 032

TD 16.5 cm 41.827733° N -65.563902° W Water depth 1504 m



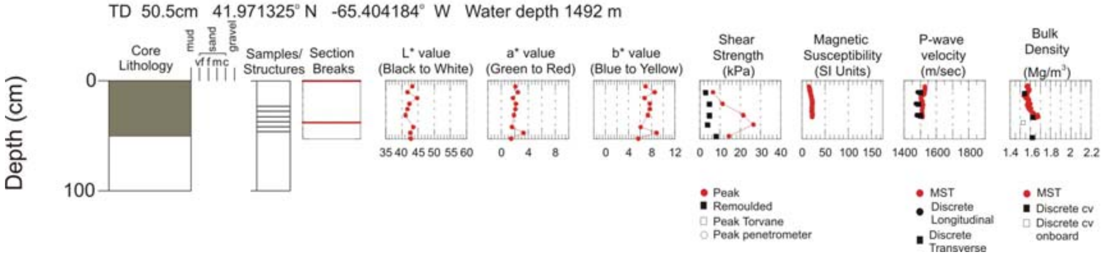
Hudson 2005023 Piston Core 032

TD 355.5 cm 41.827733° N -65.563902° W Water depth 1504 m



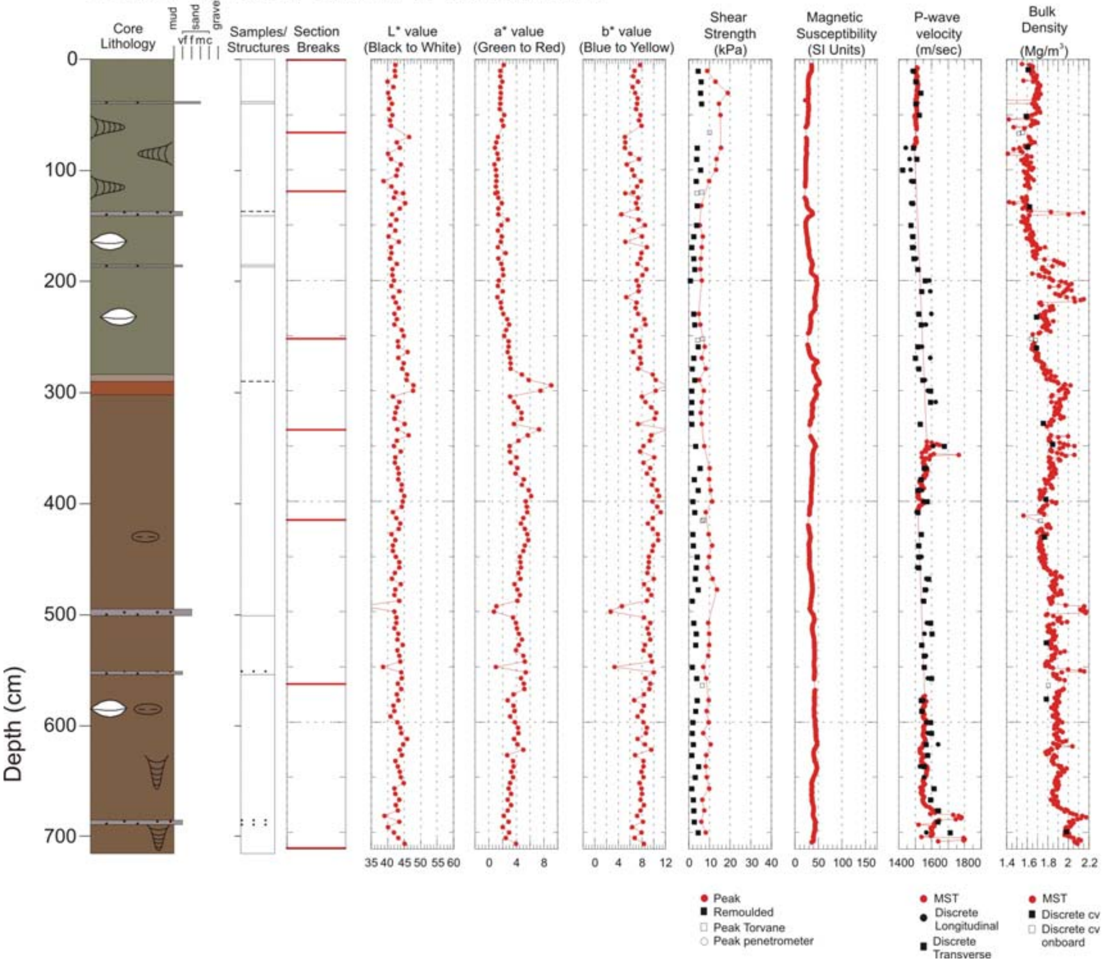
Hudson 2005023 Trigger Weight Core 034

TD 50.5cm 41.971325° N -65.404184° W Water depth 1492 m



Hudson 2005023 Piston Core 034

TD 715cm 41.971325° N -65.404184° W Water depth 1492 m



Hudson 2005023 Piston Core 036

TD 948cm 41.01736° N -65.068219° W Water depth 1798 m