SEDIMENTARY ENVIRONMENTS AND DEPOSITIONAL HISTORY OF A PARAGLACIAL, ESTUARINE EMBAYMENT AND ADJACENT INNER CONTINENTAL SHELF: PORTSMOUTH HARBOR, NEW HAMPSHIRE, USA

BY

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THESIS

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DEDICATION

This work is dedicated to my family, friends, co-workers, and teachers who have helped me through this process. You all made this possible by encouraging me and keeping me sane. This is especially true of my husband, Jason Nifong, who followed me here to let me chase my dreams. This is also dedicated to my father, Steven Gregorcyk, who was so very proud of me for this accomplishment.

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TABLE OF CONTENTS

DEDICATION iii

ACKNOWLEDGEMENTS iv

LIST OF TABLES viii

LIST OF FIGURES ix

ABSTRACT xv

Chapter 1 1

INTRODUCTION 1

Chapter 2 5

REGIONAL SETTING, PREVIOUS WORK, AND STUDY AREA 5

Glacial and Sea-Level History 5

Glacial History and Associated Sediments 5

Sea-Level History and Associated Sediments 6

Relevant Regional Studies 10

Study Area 14

Chapter 3 16

METHODS 16

Surficial Geology 16

Bathymetry and Hillshade. 16

Side Scan Sonar Backscatter Survey. 17

Bottom Sediment Sampling and Grain Size Analysis. 19
Backscatter Map..... 21
Development of Surficial Geology Map. 22
Subbottom Seismics..... 23
Chapter 4 25
RESULTS..... 25
Seafloor Characterization..... 25
Inner Harbor..... 27
Backscatter and Bottom Sediment Classification...... 29
Surficial Geology. 33
Seismic Stratigraphy. 34
Harbor Mouth 40
Backscatter and Bottom Sediment Classification...... 42
Surficial Geology. 44
Seismic Stratigraphy. 46
Inner Shelf..... 49
Backscatter and Bottom Sediment Classification...... 50
Seafloor Geology. 55
Seismic Stratigraphy. 56
Chapter 5 60

DISCUSSION 60
Surficial Geology Map 60
Seismic Stratigraphy.. 61
Paleochannel and Channel Fill Sequence.. 61
Moraine Fields. 65
Sand Mound. 68
Further Considerations 70
Chapter 6 73
CONCLUSION 73
REFERENCES 75
APPENDIX I 79
APPENDIX II 105
APPENDIX III 153

LIST OF TABLES

Table 4-1: Sediment grain size statistics for the Inner Harbor (sample locations shown in Figure 4-3). 32

Table 4-2: Sediment grain size statistics for the Harbor Mouth (sample locations shown in Figure 4-10). 44

Table 4-3: Sediment grain size statistics for the Inner Shelf (sample locations shown in Figure 4-16). 54

LIST OF FIGURES

Figure 1-1: Gulf of Maine showing Georges Bank, with Portsmouth Harbor (the mouth of the Piscataqua River), New Hampshire, shown by red square. 2

Figure 1-2: Overview of Portsmouth Harbor and adjacent ahelf with seismic survey area (black) and area of data collected for this study (blue). Bathymetry, gridded at 4 m with vertical exaggeration of 6x, is from the Western Gulf of Maine Bathymetry and Backscatter Synthesis (http://ccom.unh.edu/project/wgom-bathbackscatter). 4

Figure 2-1: Sea-level curve for Maine (from Kelley et al. 2010). 8

Figure 2-2: (Top) Depiction of sea-level highstand of +50 m, showing New Hampshire seacoast and adjacent continental shelf. (Bottom) Depiction of sea-level lowstand of -55 m, showing New Hampshire seacoast and adjacent continental shelf.. 9

Figure 2-3: Location map showing the Great Bay Estuary, Piscataqua River, Portsmouth, and Portsmouth Harbor (red)... 14

Figure 3-1: Bathymetry for Portsmouth Harbor and adjacent inner continental shelf, gridded at 4 m, with vertical exaggeration of 10x. Bathymetry is from the Western Gulf of Maine Bathymetry and Backscatter Synthesis (http://ccom.unh.edu/project/wgom-bathbackscatter)...................... 17

Figure 3-2: Side scan sonar backscatter from EdgeTech 4600 survey conducted in 2015. Bottom video and sediment sampling stations, shown in blue. Bathymetry is from the Western Gulf of Maine Bathymetry and Backscatter Synthesis (http://ccom.unh.edu/project/wgom-bathbackscatter). 19

Figure 3-3: Sampling station locations. Bottom video was collected at all sites and sediment samples large enough to be processed were collected from all sites except 13, 18, and 24. 21

Figure 3-4: 2007 IKB seismic survey (48 lines) shown in black. Birch seismic survey (12 lines) shown in blue. Bathymetry is from the Western Gulf of Maine Bathymetry and Backscatter Synthesis (http://ccom.unh.edu/project/wgom-bathbackscatter), with vertical exageration of 6x. 24

Figure 4-1: Location map showing the divisions of the study area used to describe the results of this study. The Inner Harbor, Harbor Mouth, and Inner Shelf area outlined in black. The major morphologic features Bottom sampling stations shown by black points. Channel thalweg is represent by -18 m bathymetry contour. 27

Figure 4-2: Bathymetry map of the Inner Harbor with vertical exageration of 10x (location shown in Figure 4-1). Channel thalweg is represented by the -18 m bathymetry contour. 28

Figure 4-3: Backscatter map of the Inner Harbor (location shown in Figure 4-1). Sand wave fields are outline by black hash and the channel thalweg is represented by the -18 m bathymetry contour. Morphologic features (bedrock) are shown in red. Station 24 is marked by green square. Sediment samples are shown colored by mean phi size. 31

Figure 4-4: Station 24 (location shown in Figure 4-2) bottom video image. Note the pebbles and cobbles in an apparent sandy matrix. 32

Figure 4-5: Surficial geology map of Inner Harbor (location shown in Figure 4-1). Sediment sample locations shown by colored points. Channel Thalweg is represented by the -18 m bathymetry. Morphologic features (bedrock and sand wave fields) are shown in red and hash marks. 34

Figure 4-6: Seismic lines within the Inner Harbor (location on Figure 4-1) over bathymetry (x10 vertical exaggeration) with morphologic features identified (sand wave fields, bedrock outcrops, and channel thalweg). Channel Thalweg represented by the -18 m bathymetry contour. Seismic profile XC010 shown in red (A-A`), UNH013 in pink (B-B`) and XC021 (C-C`) shown in purple.35

Figure 4-7: Seismic Profile XC010. View is upriver with New Hampshire bank on left (A) and Maine bank on right (A`). The vertical exaggeration is 10x. The sand wave field (Swf) and Holocene sediment (Hc) reflectors are shown in yellow, and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red. 37

Figure 4-8: Seismic Profile UNH013. View is upriver with New Hampshire on left (B) and Maine on right (B`). The vertical exaggeration is 10x. Holocene sediment (Hc) reflectors and estuarine Point Bar Deposit are shown in yellow, and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red. . 38

Figure 4-9: Seismic profile XC021. View is upriver with New Hampshire bank on left (C) and Maine bank on right (C`). The vertical exaggeration is 10x. The sand wave field (Swf) and Holocene sediment (Hc) reflectors are shown in yellow, and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red. 40

Figure 4-10: Bathymetry map of the Harbor Mouth with vertical exageration of 10x (location shown in Figure 4-1). Channel thalweg is represented by the -18 m bathymetry contour. 41

Figure 4-11: Backscatter map of the Harbor Mouth (location shown in Figure 4-1). Sand wave fields are outline by black hash and the channel thalweg is represented by the -18 m bathymetry contour. Morphologic features (bedrock) are shown in red and the De Geer moraines are shown in green. Sediment samples are shown colored by mean phi size.. 43

Figure 4-12: Surficial geology map of Harbor Mouth (location shown in Figure 4-1). Sediment sample locations shown by colored points. Channel Thalweg is represented by the -18 m bathymetry. Morphologic features (bedrock and sand wave fields) are shown in red and hash marks. De Geer moraines are shown by green with lines. 45

Figure 4-13: Seismic lines within the Harbor Mouth (location on Figure 4-1) over bathymetry (x10 vertical exaggeration) with morphologic features identified (sand wave fields, bedrock outcrops, moraines, and channel thalweg). Channel Thalweg represented by the -18 m bathymetry contour. Seismic profile XC028 shown in blue (D-D`) and XC032 (E-E`) shown in teal. 46

Figure 4-14: Seismic Profile XC028. View is upriver with New Hampshire bank on left (D) and Maine bank on right (D`). The vertical exaggeration is 10x. Holocene sediment (Hc) reflectors are shown in yellow and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red. 47

Figure 4-15: Seismic Profile XC032. View is upriver with New Hampshire bank on left (E) and Maine bank on right (E`). The vertical exaggeration is 10x. The Sand Mound and Holocene sediment (Hc) reflectors are shown in yellow. Bedrock (Br) is traced in red. Moraine and Sand Mound features are shown with arrows.. 48

Figure 4-16: Bathymetry map of the Inner Shelf with vertical exageration of 10x (location shown in Figure 4-1). Showing locations of the regions of bedrock outcrops referred to as the northern, southern, and offshore bedrock outcrops for this study. 50

Figure 4-17: Backscatter map of the Inner Shelf over bathymetry with a vertical exageration of 10x (location shown in Figure 4-1). Sand wave fields are outline by black hash. Morphologic features (bedrock) are shown in red and the De Geer moraines are shown in green. Sediment samples are shown colored by mean phi size. 53

Figure 4-18: Surficial geology map of Inner Shelf (location shown in Figure 4-1). Sediment sample locations shown by colored points. Morphologic features (bedrock and sand wave fields) are shown in red and hash marks. De Geer moraines are shown by green with lines. 56

Figure 4-19: Seismic lines within the Inner Shelf (location on Figure 4-1) over bathymetry (x10 vertical exaggeration) with morphologic features identified (sand wave fields, bedrock outcrops, and moraines). IKB Seistec seismic profiles shown in black and Birch seismic profiles shown in grey. Seismic profile NS002 shown in blue (F-F`) and 19july1982_741-759 (G-G`) shown in green. 57

Figure 4-20: Seismic profile NS002. View is landward with New Hampshire on left (F) and Maine on right (F`). The vertical exaggeration is 10x. The Sand Mound and Holocene sediment (Hc) reflectors are shown in yellow and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red. Sand Mound feature shown with arrow. 58

Figure 4-21: Seismic profile 19july1982_741-759. View is landward with New Hampshire on left (G) and Maine on right (G`). The vertical exaggeration is 10x. The Sand Mound and Holocene sediment (Hc) reflectors are shown in yellow and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red. Sand Mound feature shown with arrow. 59

Figure 5-1: Surficial geology map of Portsmouth Harbor and the adjacent inner shelf showing morphologic features and sediment type. 61

Figure 5-2: Depth to bedrock surface based on all of the seismic data analyzed for this study. Bedrock paleochannel location outlined in dark blue. 63

Figure 5-3: View of paleochannel fill sequence on the Inner Shelf (left box) from seismic profile NS002 and in the Inner Harbor (right box) from seismic profile XC010. Holocence sediments (Hc), which include the Sand Mound and Sand Wave Field (Swf), shown in yellow. Unconformity (Un) highlighted by black. Glaciomarine sediments (Gm) in blue and bedrock (Br) highlighted in red. 64

Figure 5-4: Seismic Profile UNH013 (left), location shown in Figure 4-6. View is upriver with New Hampshire on left (B) and Maine on right (B`). The vertical exaggeration is 10x. Holocene sediment (Hc) reflectors and estuarine Point Bar Deposit are shown in yellow, and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red. Maine Quaternary Relative Sea Level curve (right) (from Kelley et al., 2010) with the following depths highligted: 25 m below psl (purple dashed line) and 23 to 16 m below psl (yellow). Note the relationship between the depth of the unconformity (Un) (25 m bsl) and the depth of the point bar deposit (~24 to 17 m bsl) to the relative sea-level curve. 65

Figure 5-5: Location map of glacial moraines within Portsmouth Harbor and on the adjacent inner continental shelf. Moraines are highligted by green........ 67

Figure 5-6: Seismic profile 16july1985_816-915, crossing over Inner Shelf De Geer moraine field. General spacing between moraines is between ~50 to 100 m and generaly height is ~1-2 m tall. 68

Figure 5-7: Location of the bedrock paleochannel (red), the present channel thalweg (black), the Sand Apron (yellow dashes), and the Sand Mound seismic unit (orange). Vertical exageration of 10x (hillshade)........ 69

Figure 5-8: Backscatter map of Inner Harbor (location in Figure 4-1) with channel thalweg shown in blue and sediment samples showen by mean phi size. Station 24 shown by green square with bottom video image. 71

ABSTRACT

SEDIMENTARTY ENVIRONMENTS AND DEPOSITIONAL HISTORY OF A PARAGLACIAL, ESTUARINE EMBAYMENT AND ADJACENT INNER CONTINENTAL SHELF: PORTSMOUTH HARBOR, NEW HAMPSHIRE, USA

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Portsmouth Harbor, Hew Hampshire and the adjacent inner continental shelf are typical of paraglacial, bedrock-influenced embayments that characterize large areas of the Western Gulf of Maine. This thesis describes the surficial geology and seismic stratigraphy of Portsmouth Harbor and the adjacent shelf using high-resolution multibeam echosounder (MBES) bathymetry and backscatter, side scan sonar (SSS) backscatter, subbottom seismics, and ground truth data to develop high-resolution seafloor maps and better understand the influence of Quaternary glaciations, sea-level fluctuations, and marine processes on the sedimentary environments. The results of this study better define the seafloor characteristics and provides an aid for defining habitats, as well as identifying a possible mineral resource (sand and gravel).

The majority of the seafloor within the inner harbor and harbor mouth is a mixture of sand and gravel. Two sand bodies characterized by large-scale bedforms (sand waves), composed of medium to coarse sand, are located north and south of a channel bend within the inner harbor.

An apron of fine sand that begins in the harbor mouth expands onto the inner shelf and connects to another region of fine sand at the southwestern corner of the study area. This apron of fine sand corresponds to a mounded seismic unit that may represent a sand resource for future beach nourishment. The inner shelf seafloor is highly variable with the apron of fine sand, sand and gravel mixture dominating the seaward extent, large areas of bedrock outcrops, and a large moraine field (containing ~30 moraines). Another moraine field is located within the harbor mouth (containing 3-5 moraines).Both of the moraine fields are hypothesized to be De Geer Moraines, which are recognized as features of ice front retreat.

The major stratigraphic features characterizing Portsmouth Harbor and the inner shelf include an early Pleistocene paleochannel, a possible estuarine point bar deposit, and an erosional unconformity at an average depth of ~25 m below present sea level. The channel fill sequence for the entire study area can be generalized as glaciomarine sediments separated from overlying Holocene sediments by an erosional unconformity. The glaciomarine sediments are likely Pleistocene age muds and sands that make up the Presumpscot Formation (Bloom, 1963) and were deposited during the first marine transgression and the sea-level highstand that occurred 15,000 – 12,500 yr B.P. The erosional unconformity, including a ~3 m v-shaped incision that occurs offshore, is the result of the marine regression, sea-level lowstand, and initial phase of the second marine transgression between 12,500 – 11,500 yr B.P. The overlying Holocene sediments, which at the surface are sands and sandy gravels, were deposited during the second (presently ongoing) marine transgression. The possible estuarine point bar deposit is hypothesized to have been deposited during a period of slower sea-level rise, known as the slowstand, between 11,500 – 8,000 yr B.P.

Chapter 1

INTRODUCTION

The western Gulf of Maine (WGOM) represents a typical mid-latitude (40-45˚ N) paraglacial environment, i.e., an area that is recovering from the effects of the late Pleistocene glaciation and sea-level changes (Hein et al., 2012). The Laurentide Ice Sheet advanced over the continental shelf into the Gulf of Maine to Georges Banks (Figure 1-1), shaping and eroding the bedrock, stripping and/or modifying the sediment cover, and forming glacial features and deposits (Pratt and Schlee, 1969; Ives, 1978; Barnhardt et al., 1997; Schnitker et al., 2001). The corresponding sea-level fluctuations and isostatic adjustments of the crust, due to the weight and subsequent removal of the ice sheet, resulted in a relative sea-level curve that greatly differs from the eustatic sea-level curve for the last 20,000 years before present (B.P.) (Oldale, 1986; Belknap et al., 1987; Fletcher III, 1988; Oldale et al., 1993, Kelley et al., 2010).

The major controls on the surficial geology and shallow stratigraphy of the WGOM coastline, embayments, estuaries and continental shelf include: the last glaciation, resulting sea-level changes, and related marine and fluvial processes (Birch, 1984; Knebel and Scanlon, 1985; Kelley et al., 1989; Kelley and Belknap, 1991; Shipp et al., 1991; Kelley et al., 1995; Barnhardt et al., 1997; Belknap et al., 2002). The sedimentary deposits within the WGOM carry information about how the major forcings of the Late Quaternary shaped the morphology, sedimentology, and depositional environments. Increased knowledge of the surficial geology and depositional history of these systems thus presents an opportunity to further our understanding of the influence of the glaciation, the complex Late Quaternary sea-level changes, and the associated marine and fluvial processes on the sedimentary environments, as well as provide insight into the locations and origins (e.g. relic or actively forming) of possible marine mineral resources (e.g. sand and gravel).

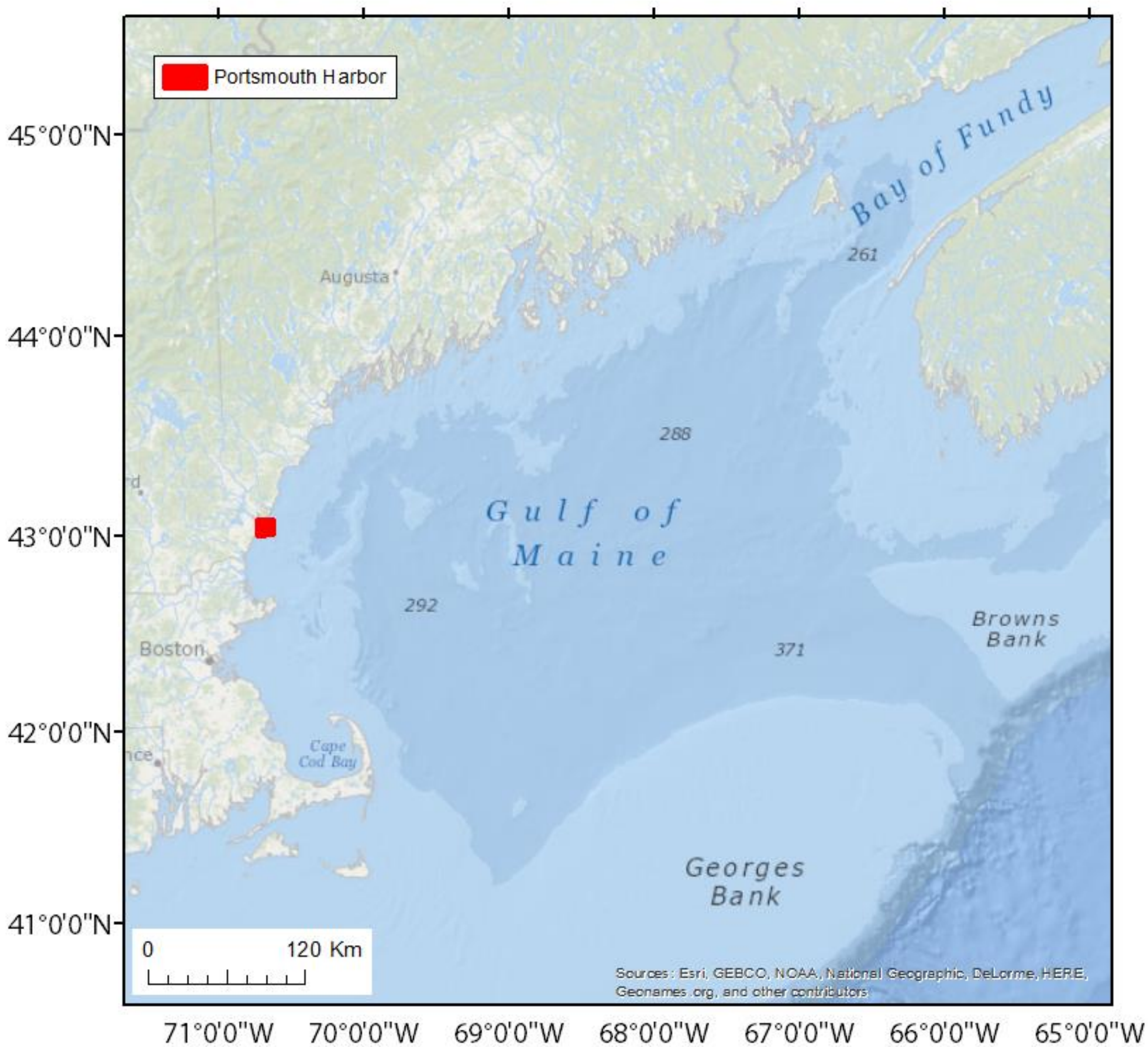

Figure 1-1: Gulf of Maine showing Georges Bank, with Portsmouth Harbor (the mouth of the Piscataqua River), New Hampshire, shown by red square.

Portsmouth Harbor, New Hampshire and the adjacent inner continental shelf (Figure 1-2) is typical of many of the bedrock-dominated estuaries and rocky shelves found in the WGOM, and provides an ideal environment to study the development of sedimentary environments and major morphologic features. Thus, the goals of this study were to describe the major morphologic features, the surficial sedimentary environments, and the subsurface characteristics of Portsmouth Harbor and the adjacent inner continental shelf. This information was used to develop a high-resolution seafloor geology map and description of the shallow subsurface stratigraphy. The surficial geology and shallow seismic stratigraphy were determined using high-resolution multibeam (MBES) bathymetry and backscatter, high-resolution side scan sonar (SSS), the collection and analysis of bottom sediment, archived subbottom seismic surveys, and comparisons to previous work (Birch, 1984; Birch, 1990; Cutter, 2003; Ward 1995; Weber and Ward, 2015).

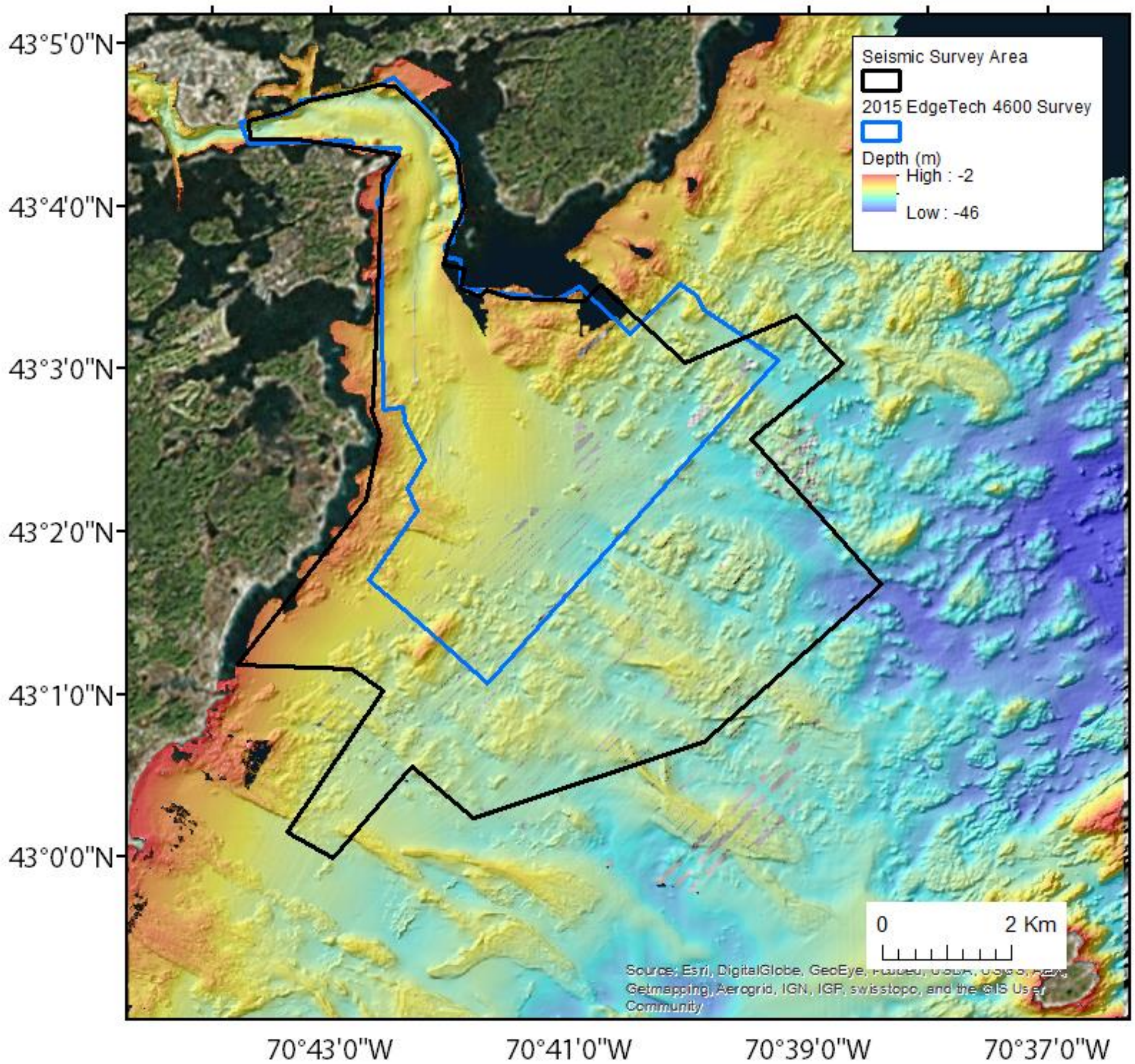

Figure 1-2: Overview of Portsmouth Harbor and adjacent shelf with seismic survey area (black) and area of data collection for this study (blue). Bathymetry, gridded at 4 m with vertical exaggeration of 6x, is from the Western Gulf of Maine Bathymetry and Backscatter Synthesis (http://ccom.unh.edu/project/wgom-bathbackscatter).

Chapter 2

REGIONAL SETTING, PREVIOUS WORK, AND STUDY AREA

Glacial and Sea-Level History

The last glaciation and resulting sea-level fluctuations encompass the major influences on the bedrock and sedimentary environments of the WGOM, and must be considered when investigating the depositional history and regional stratigraphy of the region.

Glacial History and Associated Sediments

During the late Pleistocene, the Laurentide Ice Sheet covered New England and the WGOM, extending south to Long Island Sound, New York, and east into the Gulf of Maine to Georges Bank (Pratt and Schlee, 1969). The ice sheet altered the underlying landscape and continental shelf by carving bedrock, eroding away previously deposited materials, and depositing glacial features such as moraines, eskers, and outwash fans (Smith and Hunter, 1989). The weight of the ice sheet isostatically depressed the crust in the region (Oldale, 1985).

Deglaciation in Georges Basin began around 22,000 yr B.P. (Schnitker et al., 2001), with the retreating ice front passing over the present New Hampshire coastline and reaching the interior of New Hampshire between 15,100 and 14,500 yr B.P. (Balco et al., 2009), once again depositing glacial features. During the subsequent sea-level highstand, while the ocean remained in contact with the retreating ice sheet, a thick blanket of glaciomarine sediments (fine sands and muds) was deposited across the region, filling in bedrock depressions and covering some of the glacial deposits (stratified drifts and moraines) (Oldale, 1985; Shipp et al., 1991; Smith and Hunter, 1989). Bloom (1963) named the thick deposit of glaciomarine sediments the Presumpscot

Formation. Davis and Jacobson Jr. (1985) predicted most of New Hampshire was ice free by 13,000 yr B.P., which agrees with Ridge (2003).

Sea-Level History and Associated Sediments

Relative sea level in the WGOM, which was largely influenced by the Laurentide Ice Sheet, has undergone two transgressions separated by a regression since the last glaciation (Figure 2-1). The isostatic depression of the crust allowed the ocean, which was in contact with the ice front, to follow the retreating ice landward resulting in the first marine transgression (Thompson et al., 1989). The relative sea level during the highstand (Figure 2-2) reached a maximum of 30-33 m above present sea level in Massachusetts (Oldale et al., 1993), 50 m in New Hampshire (Oldale, 1986; Birch, 1989), and 70-130 m in Maine (Belknap et al., 1987; Kelley et al., 1989; Thompson et al., 1989; Belknap et al., 2002) between 15,000 - 12,500 yr B.P. (Kelley et al., 2010).

As the crust began to isostatically rebound, relative sea level rapidly fell to a lowstand between 12,500 – 12,000 yr B.P. (Figure 2-1) in Maine (Kelley et al., 2010). The depth and timing of the sea-level lowstand varies throughout the WGOM due to differences in timing and magnitude of the isostatic rebound across the region (Oldale, 1986; Barnhardt et al., 1995). The estimated depth of the sea-level lowstand is to 43-47 m below present sea level for Massachusetts (Oldale et al., 1983; Oldale et al., 1993), 30-35 m in New Hampshire (Birch, 1984), and 55-65 m in Maine (Belknap et al., 1987; Kelley et al., 1989; Shipp et al., 1991; Barnhardt et al., 1995; Belknap et al., 2002). The estimated depth of 30-35 m for New Hampshire (Birch, 1984) was based on truncated foreset beds on the Merrimack River paleodelta, however, Birch also mentions possible lowstand features at 55-60 m depth. Since the lowstand depth has not been further resolved in New Hampshire, the well-constrained Maine relative sea-level curve was used for this study.

The regression and sea-level lowstand exposed the previously deposited sediments (Presumpscot Formation and glacial features) to erosion (marine, fluvial, and aerial) and downcutting by rivers following the retreating coastline (Knebel and Scanlon, 1985; Oldale, 1985). Portsmouth Harbor and the adjacent continental shelf (out to the Isles of Shoals) were aerially exposed and the Piscataqua River is assumed to have extended to the lowstand shoreline (Figure 2-2), though there is no documented evidence of a paleochannel or paleodelta. Elsewhere in the WGOM, rivers with high sediment output, such as the Merrimack (Oldale et al., 1983; Birch, 1984), Penobscot, and Kennebec Rivers (Belknap et al., 2002; Kelley et al., 2003) built paleodeltas on the inner shelf.

Around 12,000 yr B.P. eustatic sea-level rise overtook the isostatic rebound of the crust starting the current transgression. This resulted in an initial rapid relative sea-level rise (Kelley et al., 2010; Kelley et al., 2013) that slowed to a slowstand between 11,500 - 8,000 yr B.P., which allowed some systems, like the Kennebec River, to build a second paleodelta (Barnhardt et al., 1997). As eustatic and relative sea level continued to rise, the paleodeltas and lowstand deposits were drowned and reworked by wave action, fine-grained sediments were winnowed, lag deposits were developed, and sediments moved landward across the inner shelf (Oldale, 1985).

Sea level reached the present coastline around 4,500-3,000 yr B.P. and has been undergoing a very slow rise since (Belknap et al., 1997; Hein et al., 2012).

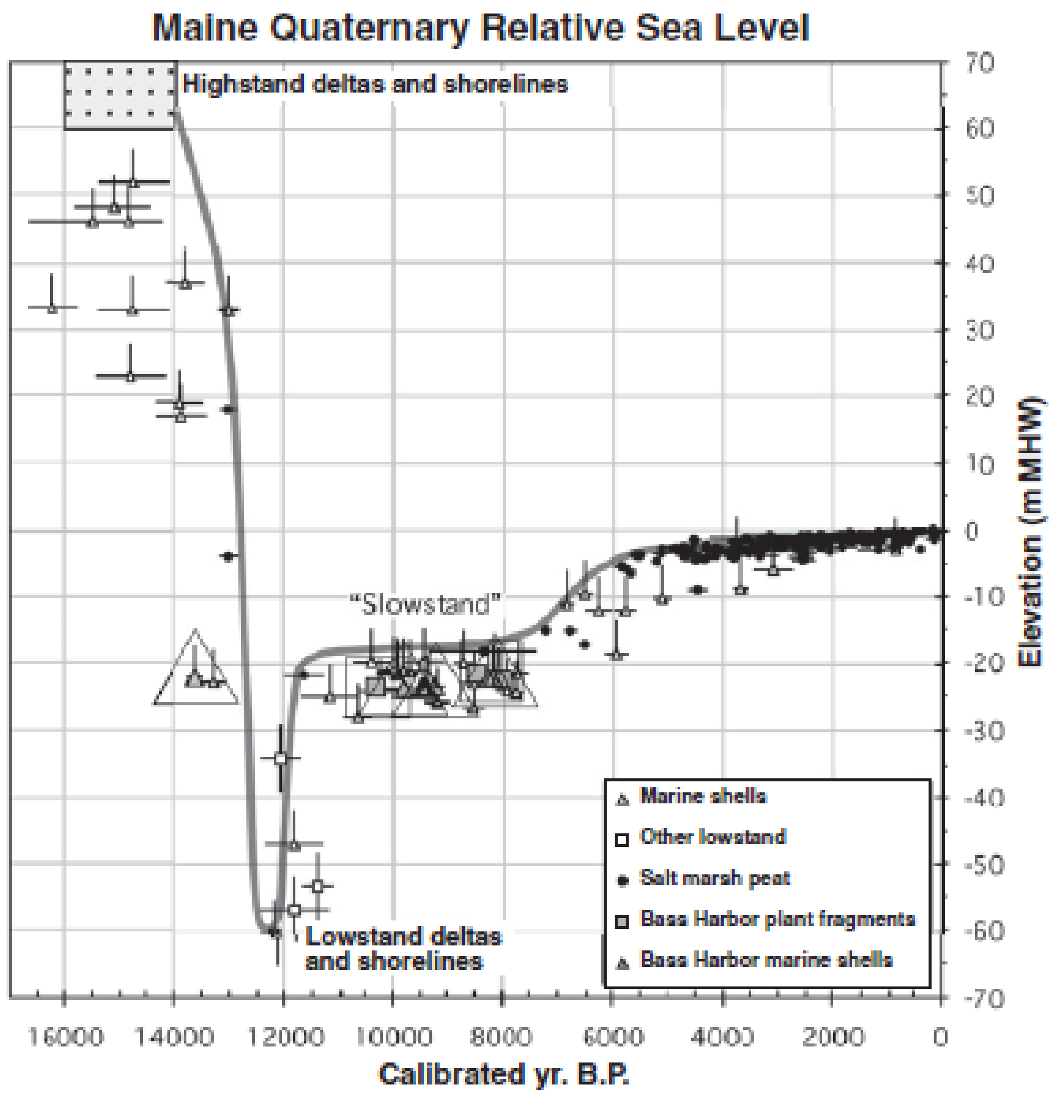

Figure 2-1: Sea-level curve for Maine (from Kelley et al. 2010).

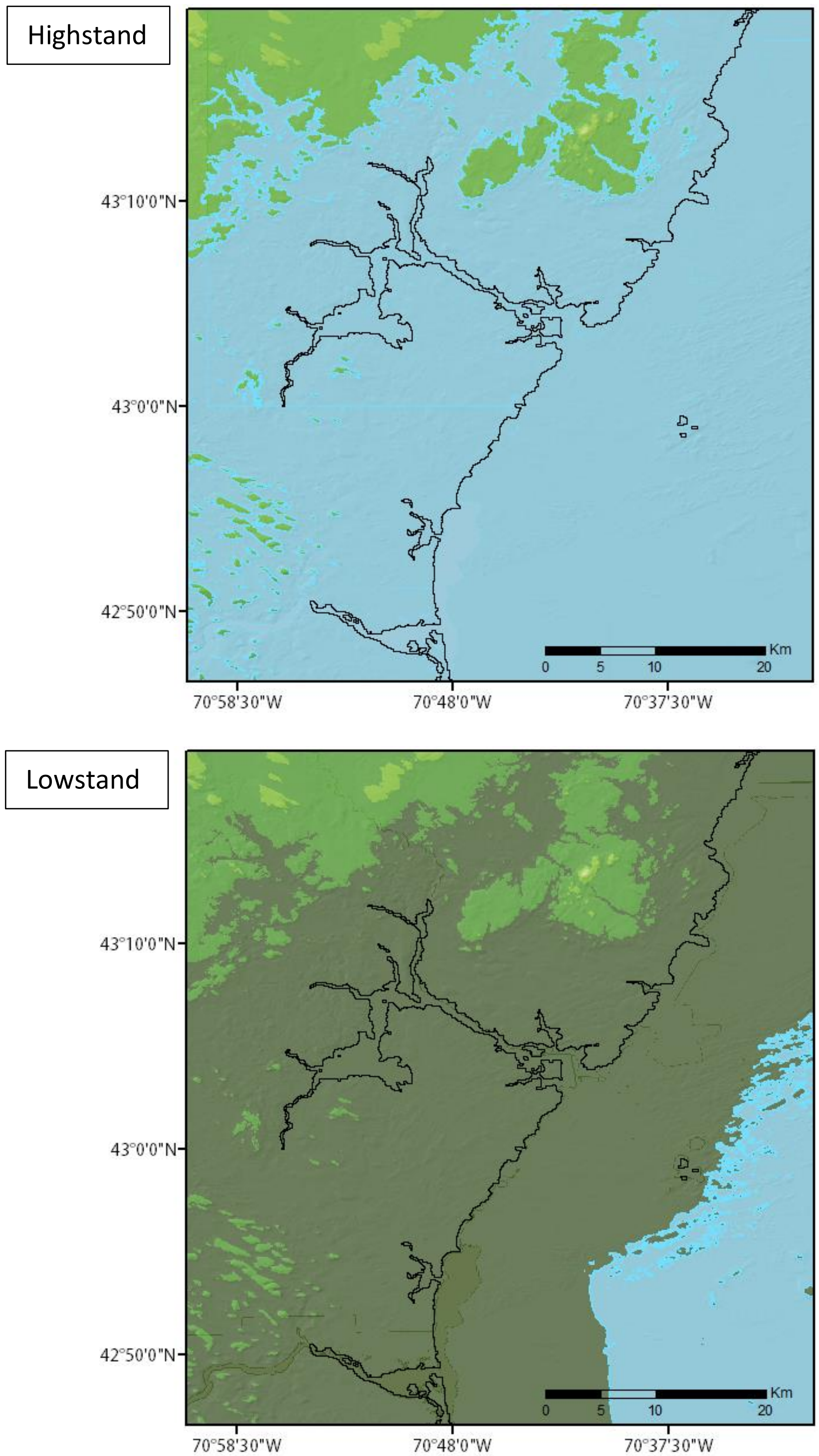

Figure 2-2: (Top) Depiction of sea-level highstand of +50 m, showing New Hampshire seacoast and adjacent continental shelf. (Bottom) Depiction of sea-level lowstand of -55 m, showing New Hampshire seacoast and adjacent continental shelf.

Relevant Regional Studies

Kelley et al. (1989) and Barnhardt et al. (2005) described the complicated surficial and corresponding subbottom environments of the coastal zone and inner continental shelf of Maine and Massachusetts (respectively) by separating the seafloor into distinct physiographic zones: nearshore ramps, nearshore basins, rocky zones, shelf valleys, bay-mouth shoals, and outer basins. The classification of physiographic zones allows mappers to fully classify the highly heterogeneous seafloor with reasonable amounts of data. Barnhardt et al. (2005) comments that "an extraordinarily large number" of sediment samples would be required for a complete and detailed mapping of the sediment characteristics of the shelf. The rocky zone, a dominant zone found by both Kelley et al. (1989) and Barnhardt et al. (2005), is described as areas of bedrock and gravel outcrops mixed with sediment pools and is also seen in this study (see RESULTS).

Coastal Maine's general inland stratigraphy was described by Smith and Hunter (1989) as bedrock overlain by till, ice-contact stratified drift, subaqueous outwash, glaciomarine sediments (Presumpscot Formation), and subaerial outwash (delta). Several studies on the inner continental shelf of Maine (Shipp et al., 1991; Barnhardt et al., 1997) and Massachusetts (Knebel, 1993; Oldale et al., 1993) found the general stratigraphy similar to onshore. The typical offshore stratigraphy was described as follows: irregular bedrock overlain occasionally by till and stratified drift; bedrock and till covered by glaciomarine sediments (stratified sands and muds of the Presumpscot Formation); and erosional unconformities separating Holocene sediments from the underlying Pleistocene sediments. Some of the Holocene deposits have been hypothesized to include eroded sediments from older deposits (Birch, 1984; Oldale et al., 1993; Kelley et al., 2010). In addition, several lowstand paleodeltas have been identified in the region (Oldale et al., 1983; Birch, 1984; Shipp et al., 1991, Barnhardt et al., 1997) and have been used to determine the relative depths of the last sea-level lowstand.

Birch (1984, 1989, 1990) did an extensive study of the New Hampshire inner continental shelf that included over 1300 km of seismics, SSS backscatter, vibracores and gravity cores, and radiocarbon dating. Birch identified 5 major units based on acoustic transparency, internal reflections, and external morphology (Birch, 1984). Unit 0 was suggested to be Oligocene coastal plain sedimentary rock and found only in one location. Unit 1 was identified as lodgement till and presumed to be deposited prior to 14,000 yr B.P. Unit 2 was cored extensively and identified as glaciomarine deposits, also identified as the Presumpscot Formation (Bloom, 1963). Unit 3, which was found primarily in the southern portion of the New Hampshire inner continental shelf, was part fine-grained sediments winnowed from units 1 and 2, and part deltaic sediments from the Merrimack River deposited during the sea-level lowstand. Truncated topset beds on the Merrimack paleodelta were assumed to have been eroded during the lowstand and were used to place the water depth at ~ 30 to 35 m below present sea level between 12,080 and 10,820 yr B.P. (Birch, 1990). Unit 4 was identified by Birch (1984) as Holocene sands that occurs in mounds along the shelf. Birch interpreted this unit as landward migrated sediment deposited during the present transgression. Birch also identified an unconformity separating Unit 2 from Unit 3 and 4 and noted the lack of erosional channels, drowned shoreline features, faults, end moraines, and ice-contact deltas (which were identified in other parts of the WGOM).

The distribution of sand and gravel resources on the inner continental shelf has been a topic of interest throughout the WGOM (Knebel, 1993; Barnhardt et al., 1998; Kelley et al., 2003), despite the acknowledged difficulty in classifying the inner continental shelf and coastal zones due to the highly heterogeneous nature of the area as a result of the glaciations and associated sea-level changes. Knebel (1993) determined areas of erosion, deposition, and sediment reworking in Cape

Cod Bay and related those environments to the controlling processes on their distribution. Kelley et al (2003) focused on determining sand resource sites and the relationship of those sources to the glacial and sea level history, while Barnhardt et al. (1998) determined a way to fully characterize the expansive Maine seafloor. Barnhardt et al.'s (1998) method of characterizing the seafloor determines bottom type as a basic unit of bedrock, gravel, sand, mud, and twelve combination units (i.e. sandy gravel) based on available side scan sonar, seismic profiles, and sediment samples and cores.

Ongoing research on the New Hampshire continental shelf to determine areas of potential sand and gravel resources uses a combination of methods that includes high-resolution MBES bathymetry and hillshade, MBES backscatter, grain size analyses, and ~1280 km of seismic data (Ward et al., 2016). Ward et al. (2016) identified several sites of potential sand and gravel resources by first relating the seafloor features to the sea-level and glacial history of the shelf, and then using available data to classify the features. They also classified a majority of the New Hampshire inner continental shelf by defining major geoforms (distinct morphologic features) and bottom sediment types using the Coastal and Estuarine Ecological Classification Standards (CMECS) (Ward et al., 2016). The CMECS approach for the substrate included identifying areas of bedrock, coarse unconsolidated, fine/coarse unconsolidated, and fine unconsolidated sediments, which were then broken into classifications of gravel, sand, mud, and combinations of the three (i.e. muddy sand). Ward et al.'s (2016) work is a continuation of an ongoing effort to map the New Hampshire continental shelf for the Bureau of Ocean and Energy Management (previously the Mineral Management Services) which began with Birch's work (1984, 1989, 1990).

Several studies have been conducted within Portsmouth Harbor with a focus on the seafloor characteristics. Bilgili et al. (1996, 2003) modelled the tidal currents and sediment transport within the lower Piscataqua River channel (Figure 2-3) over a frequently dredged shoal with large bedforms, noting strong tidal currents that created strong upriver sediment transport, which moved the dredged sediments back upriver to their original location. Another area of large bedforms within Portsmouth Harbor was studied by Cutter et al. (2003) and Felzenberg (2009) who tried an automated classification and studied bedform migrations (respectively), both with MBES data. This same area of bedforms was included in another more recent study of lower Portsmouth Harbor and approach which examined the difference in MBES backscatter intensities at differing frequencies and bottom types (Bajor, 2015; Weber and Ward, 2015). The study area included several types of seafloor within the limited space of Portsmouth Harbor and approach, highlighting the highly heterogeneous nature of the WGOM seafloor.

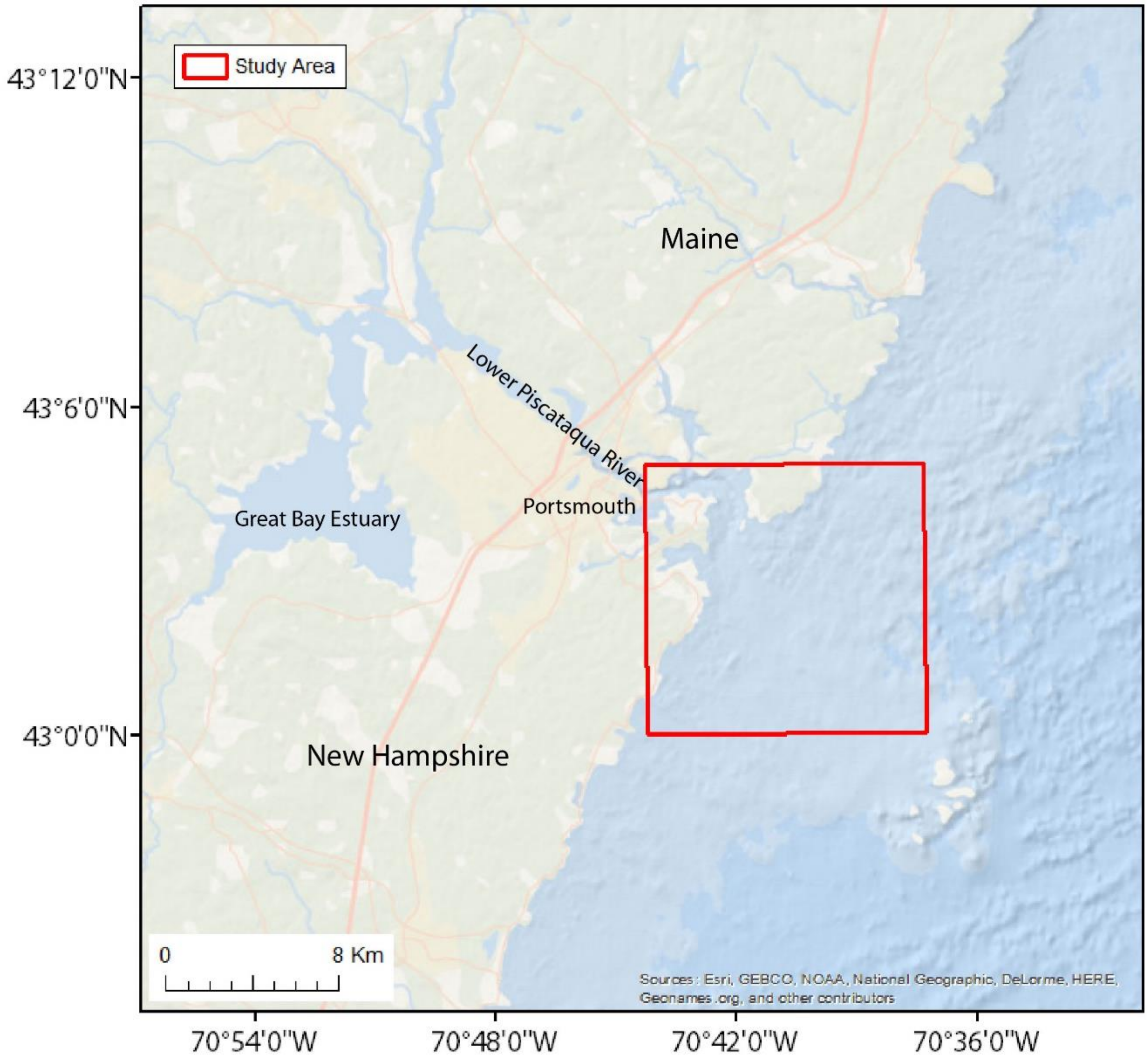

Figure 2-3: Location map showing the Great Bay Estuary, Piscataqua River, Portsmouth, and Portsmouth Harbor (red).

Study Area

Portsmouth Harbor, New Hampshire is located at the mouth of the Piscataqua River, which connects the Great Bay Estuary (GBE) to the Atlantic Ocean and is located on the boundary between New Hampshire and Maine (Figure 2-3). The climate is temperate with four distinct seasons. The Lower Piscataqua River is characterized by deep, narrow channels, strong tidal currents ranging from 0.5 to 2.0 m/s, and a mean tidal range of 2.6 m with a spring tide mean of 3.0 m (NOAA Tides and Currents: https://tidesandcurrents.noaa.gov/).

Typically, the freshwater discharge is extremely low, between 1-2% of the tidal prism (Short, 1992), however, significant freshwater discharge occurs during spring freshets or floods (Ward and Bub, 2005). The system is a well-mixed estuary (Ertürck et al., 2002).

The GBE and Piscataqua River channel are dominated by Cambrian-Silurian crystalline bedrock (Lyons et al., 1997). Ward and Birch (1999) described the nearshore environment of the New Hampshire coast ~15 km south of Portsmouth Harbor as extensive bedrock outcrops, boulder fields, sands, and muds. Ward et al. (2016) mapped the shelf adjacent to Portsmouth Harbor as an area of bedrock outcrops, gravels, and sand. This agrees with Knebel (1993) and Barnhardt et al. (1998) who describe the Massachusetts and Maine nearshore environments as highly variable surficial materials with complicated bathymetry.

Chapter 3

METHODS

Surficial Geology

Bathymetry and Hillshade. Bathymetry for this study was obtained from the Western Gulf of Maine Bathymetry and Backscatter Synthesis (http://ccom.unh.edu/gis/scenes/wgom/) at 4 m resolution (Figure 3-1). The synthesis was developed by the University of New Hampshire Center of Coastal and Ocean Mapping/Joint Hydrographic Center (CCOM/JHC) using data from NOAA NOS Hydrographic surveys including H10763, H10771, H11014, H11296, W00178, W00244, W00277, W00277, as well as in-house archives. Hillshade, a shaded relief surface from a raster with a default infinite illumination source and azimuth of 315 degrees, was created from the high-resolution bathymetry within ArcGIS (v10.3.1) using the Image Analysis window processing function "Hillshade". A vertical exaggeration of 10x was used to help identify morphologic features in the study area.

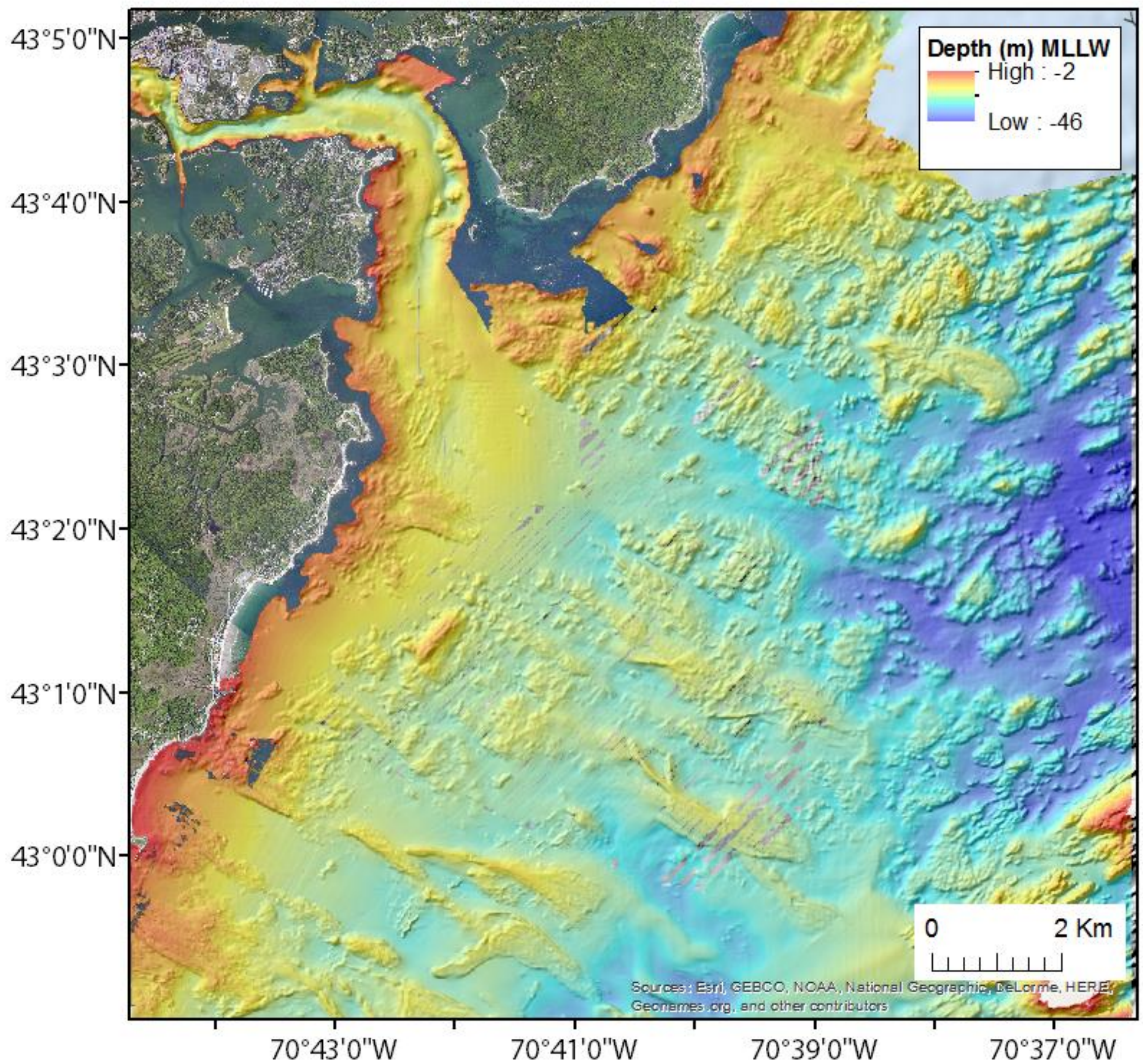

Figure 3-1: Bathymetry for Portsmouth Harbor and adjacent inner continental shelf, gridded at 4 m, with vertical exaggeration of 10x. Bathymetry is from the Western Gulf of Maine Bathymetry and Backscatter Synthesis (http://ccom.unh.edu/project/wgom-bathbackscatter).

Side Scan Sonar Backscatter Survey. Approximately 260 km (168 lines with 50-150 m spacing) of SSS backscatter (Figure 3-2) and swath bathymetry were collected on the University of New Hampshire CCOM/JHC Research Vessel *Coastal Surveyor* from May 13-22, 2015, using an EdgeTech 4600 swath bathymetry sonar (frequency range 490-550 kHz). Navigation and positioning collected during the survey were Real-Time Kinematic Global Positioning System (RTK-GPS) using an Applanix POS/MV Inertial Measurement Unit (IMU), a Trimble RTK receiver, and two Trimble Zephyr GNSS antennas. The RTK corrections were broadcast to the R/V *Coastal Surveyor* from a base station located on the roof the Seacoast Science Center at Odiorne State Park, New Hampshire, located at the entrance of Portsmouth Harbor. Swath bathymetry and SSS backscatter were processed in Caris HIPs & Sips (v9). SSS backscatter was additionally processed in Fledermaus FMGT (v7.4.4b) to create a final mosaic gridded at 0.5 m resolution. Some positioning offsets were present in the SSS backscatter mosaic and were resolved by removing the affected data files. The final swath bathymetry surface, created in Caris HIPs and Sips was gridded at 1 m, but was omitted from this study due to unresolvable motion artifacts.

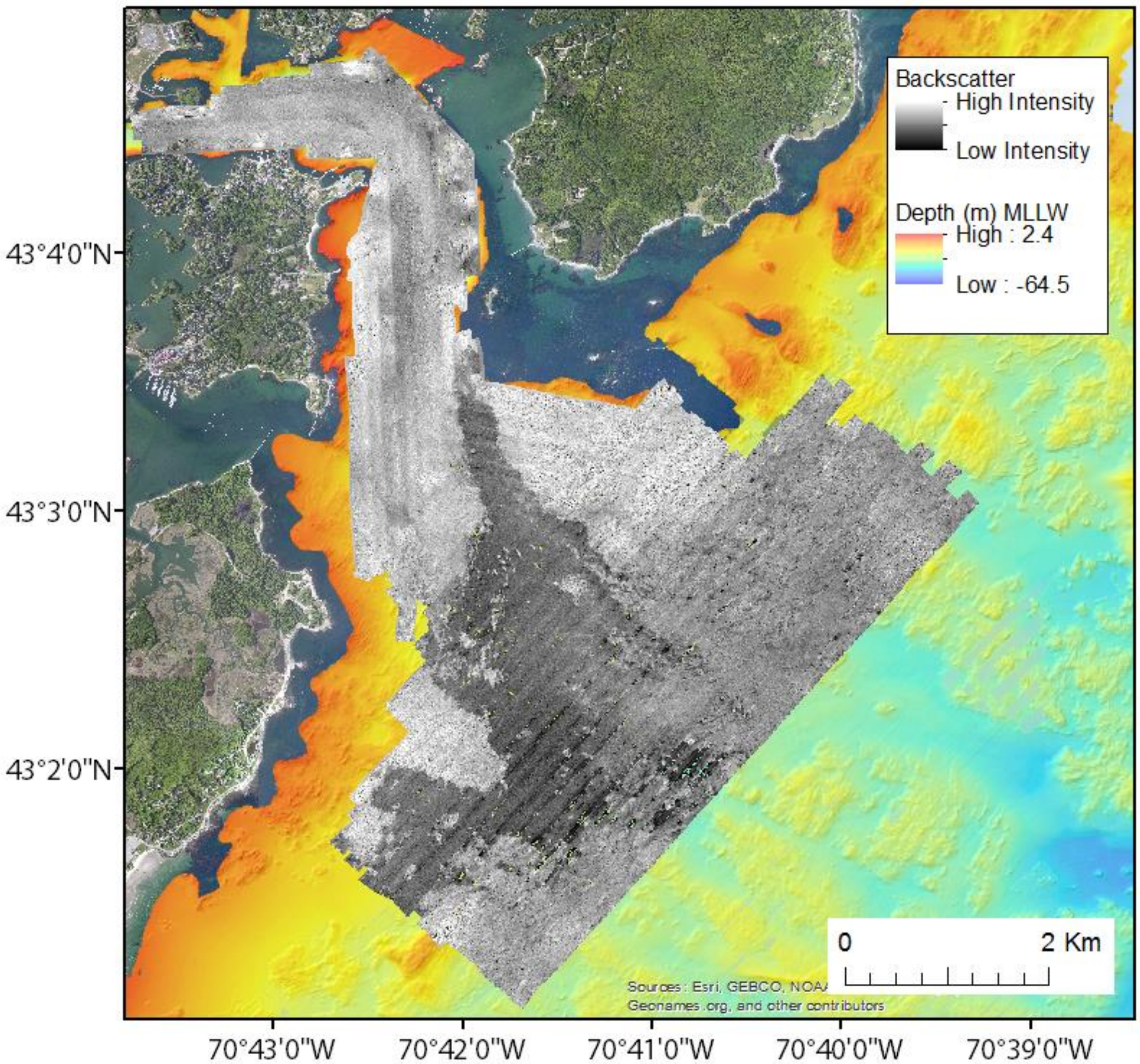

Figure 3-2: Side scan sonar backscatter from EdgeTech 4600 survey conducted in 2015. Bottom video and sediment sampling stations, shown in blue. Bathymetry is from the Western Gulf of Maine Bathymetry and Backscatter Synthesis (http://ccom.unh.edu/project/wgom-bathbackscatter).

Bottom Sediment Sampling and Grain Size Analysis. Sample locations were chosen based on backscatter variability with the goal to sample a wide variety of bottom types and to ground truth the backscatter data (Figure 3-3). Twenty-four locations were sampled using bottom video and a Wilco Grab Sampler from May 27-29, 2015 (Appendix I). Samples were collected on the

University of New Hampshire CCOM/JHC Research Vessel *Cocheco*. Navigation was differential GNSS with a Trimble DSM212h receiver and two Trimble 27207 antennas. Bottom video was collected with a Delta Vision Industrial Underwater video camera mounted on a 0.4 m tall frame with a 0.3 m by 0.3 m base. Bottom videos were primarily used to determine if sediment sampling was possible. Twenty-one stations yielded samples large enough to be analyzed. However, three of the stations were located on, or in proximity to, bedrock outcrops so no sample was attempted, or the samples collected were too small for valid results. Sediment samples were analyzed for grain size and organic content, which was estimated by loss on ignition (LOI). LOI was determined by drying between 10-60 grams (average around 30 grams) of sediment and subsequently combusting the sample at 450˚C for 4 hours. Grain size was determined using sieve and pipette analyses (modified from Folk, 1980). Sediment size statistics were determined using GRADISTAT (v8) from Blott and Pye (2001).

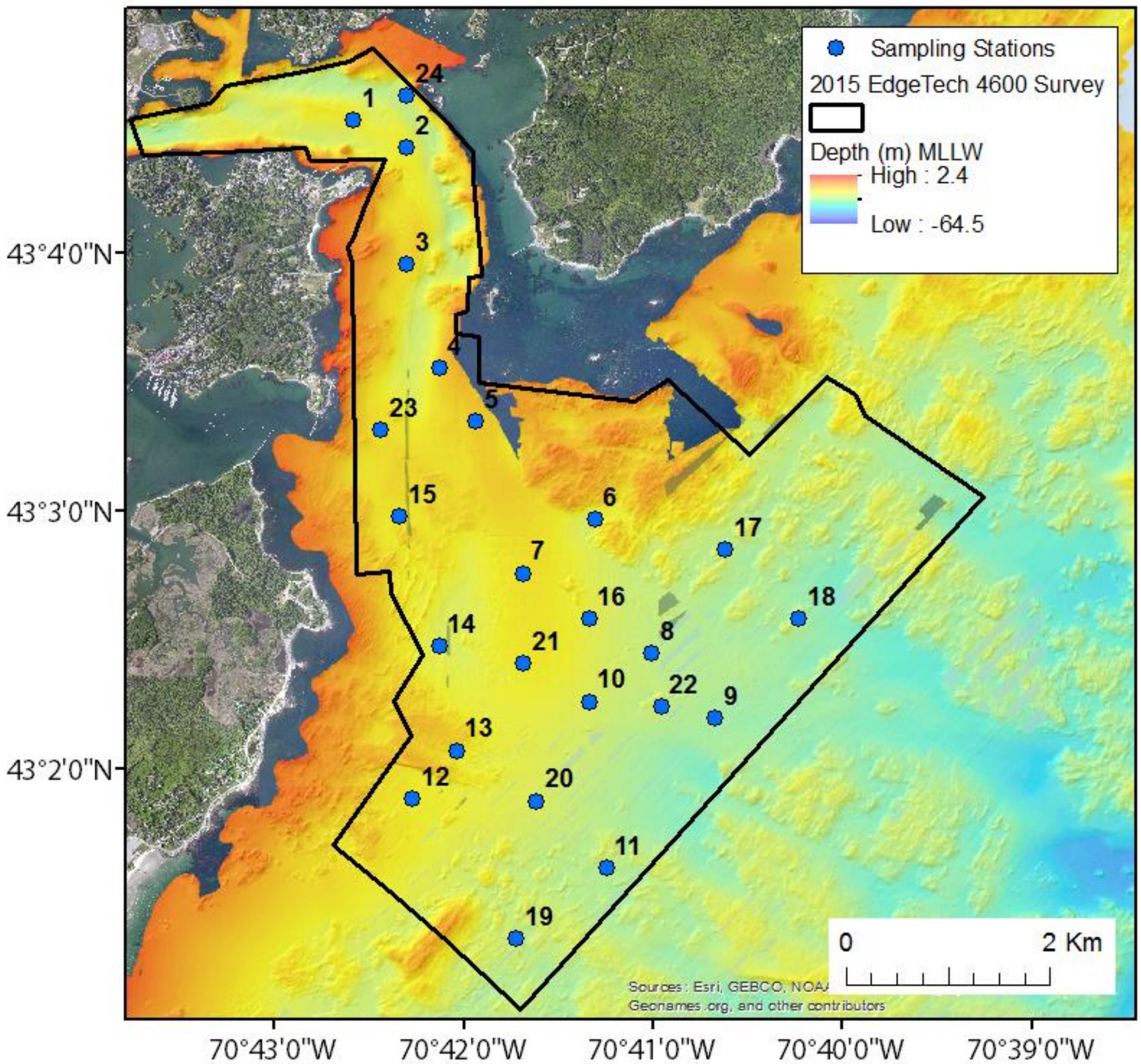

Figure 3-3: Sampling station locations. Bottom video was collected at all sites and sediment samples large enough to be processed were collected from all sites except 13, 18, and 24.

Backscatter Map. The primary backscatter source for this survey was the EdgeTech 4600 survey (described above). Additional backscatter data included to fill gaps was from the NOAA NOS Hydrographic survey W00244 (Kongsberg EM2040; MBES), NOS Hydrographic survey H11014 (Klein 5500 SSS), and archived MBES backscatter from CCOM/JHC Summer Hydrographic Survey Course 2013 – Nearshore Rye (Kongsberg EM2040 MBES). The resolutions of the mosaics were 2 m, 0.5 m, and 0.5 m, respectively. The backscatter maps from each of these surveys were left as individual layers in ArcMap to preserve the data and the separate map resolutions. The primary survey conducted for this study (EdgeTech 4600) served as the topmost layer with the other surveys positioned underneath (in ArcMap). The majority of the area for this study was covered by the EdgeTech 4600 side scan backscatter, with minimal coverage by the additional backscatter data.

Backscatter for all the maps are depicted by relative intensities using a grayscale ranging from very dark (low backscatter intensity) to white (high backscatter intensity). Backscatter, as defined for this study, is the strength of the acoustic return, which is affected by the characteristics of the water column and the seafloor (i.e. sediment size, bottom roughness, and biota). The backscatter maps were used primarily to identify areas of similar backscatter intensities and to create polygons.

Development of Surficial Geology Map. Hand-drawn polygons were developed from the seafloor bathymetry, hilllshade, and backscatter mosaics (based on grey-scale intensity). Subsequently, the polygons were classified as low backscatter intensity, medium backscatter intensity, medium/mixed backscatter intensities, and high backscatter intensity, The polygons were then converted to a sediment classification based on the grain size analysis of the samples within the polygon. Not all polygons contained sediment samples, therefore bottom images or comparison to classified polygons with sediment samples with similar backscatter characteristics were used to complete the map.

Subbottom Seismics

Subbottom seismics analyzed for this study were from two archived seismic surveys (Figure 3-4). The primary survey for this study was conducted by CCOM/JHC in 2007 with ~62.5 km of seismic lines (48 profiles) collected using an ITK Seistec Marine Sediment Profiler (sampling rate of 100 kHz) onboard the Research Vessel *Cocheco* (Appendix II). The boomer transducer and line-in-cone receiver were towed on a 2.5 m long catamaran with an attached GARMIN GPS antenna (Appendix II). The raw seismic data collected was combined with navigation data and converted to digital SEG-Y files.

The IKB survey was supplemented with seismics collected in 1981, 1982, and 1985 by Dr. Francis Birch of the University of New Hampshire, and the United States Geologic Survey (USGS). A total of ~1280 km of 300 joule E.G. & G. Uniboom data (with a 0.5 s repetition rate) was collected as analog data using Loran-C navigation with handwritten fixes at 5 minute intervals (Appendix III). The analog records were scanned to TIFF or JPG images (using WIDEimage software) and then converted to digital SEG-Y files using Chesapeake ImageToSEGY software (see Ward et al., **2016**). Only the sections of the 1980's seismic profiles that intersected the IKB survey (~44.5 km) are used for this study, and are referred to as the Birch survey.

The seismic profiles from both surveys were processed using Chesapeake SonarWiz (v6). Seismic units were identified based on reflector intensity, internal structure, external structure, and surrounding units, based on Shipp (1991).

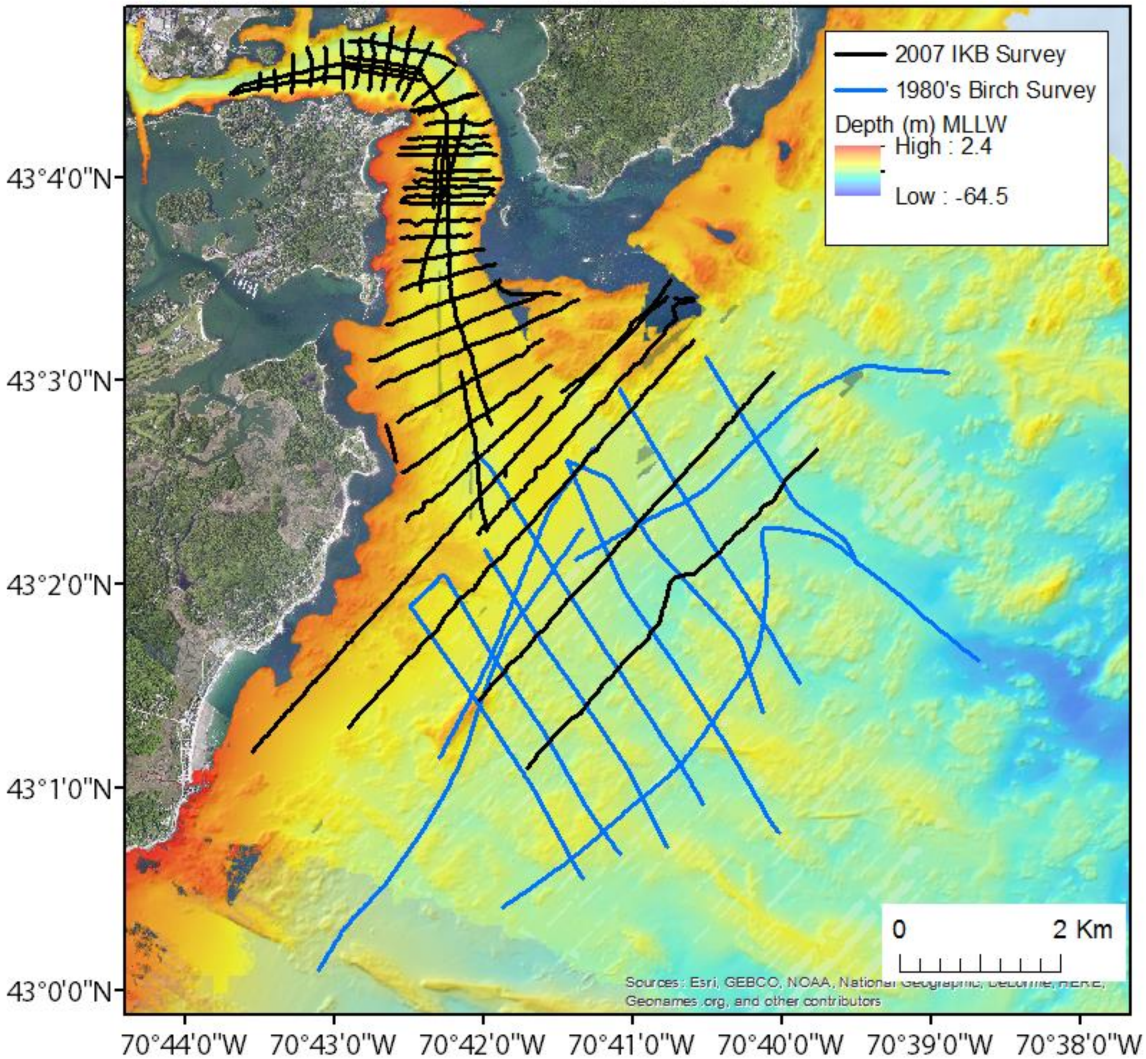

Figure 3-4: 2007 IKB seismic survey (48 lines) shown in black. Birch seismic survey (12 lines) shown in blue. Bathymetry is from the Western Gulf of Maine Bathymetry and Backscatter Synthesis (http://ccom.unh.edu/project/wgom-bathbackscatter), with vertical exageration of 6x.

Chapter 4

RESULTS

Seafloor Characterization

The study area is split into three sections due to the highly diverse morphology and sedimentary environments: Inner Harbor, Harbor Mouth, and Inner Shelf (Figure 4-1). The Inner Harbor is the most landward portion of the survey area and is considered part of the Piscataqua River channel. The Inner Harbor is relatively narrow, confined by bedrock outcrops at the margins and includes a distinct (almost 90 degree) bend in the river channel, which abruptly changes the channel orientation from east-west to north-south. At the Harbor Mouth the river channel widens considerably and a distinct change in morphology and sedimentary environments from the Inner Harbor occurs. The mouth of the Piscataqua River, which includes the Inner Harbor and Harbor Mouth, is an estuarine system that connects the Great Bay Estuary to the Atlantic Ocean. The Inner Shelf area extends from the Harbor Mouth to about 6 km offshore and is a marine system.

Morphologic features, such as bedrock outcrops, glacial moraines, and large-scale bedforms were identified based on high-resolution bathymetry and hillshade (using a vertical exaggeration of 10x). The bedform areas are likely composed of ripples (wavelengths of <60 cm), megaripples (wavelengths of 60 cm to 6 m), and sand waves (wavelengths >6 m). The resolution of the bathymetry was too large (4 m) to identify anything smaller than sand waves, however, the resolution of the backscatter mosaics allowed smaller bedforms, such as megaripples, to be identified. For this study, all identified bedform areas were classified as Sand Wave Fields (SWF) for continuity. The backscatter maps were used primarily to determine morphologic feature boundaries (Figure 4-1) and build the surficial geology map.

The analyzed sediment samples were grouped into four classes based on the mean phi of the samples: Gravel (16 to 2 mm or -4 to -1 phi); Coarse Sand (2 to 0.5 mm or -1 to 1 phi); Medium Sand (0.5 to 0.25 mm or 1 to 2 phi), and Fine Sand (0.25 to 0.0625 mm or 2 to 4 phi). Note that the Fine Sand class includes both fine sand and very fine sand. However, many of the samples were bimodal, showing high percentages of both gravel and sand (see Table I-2 in Appendix I). To account for the bimodality, the surficial sediment classes were defined as Bedrock, Gravel, Sandy Gravel, Medium to Coarse Sand, and Fine Sand.

Shallow subbottom seismics were used to describe the seismic stratigraphy of the overall study area and some of major morphologic features. The extent of the total subbottom data used for this survey extends beyond the boundaries of the surficial geology map.

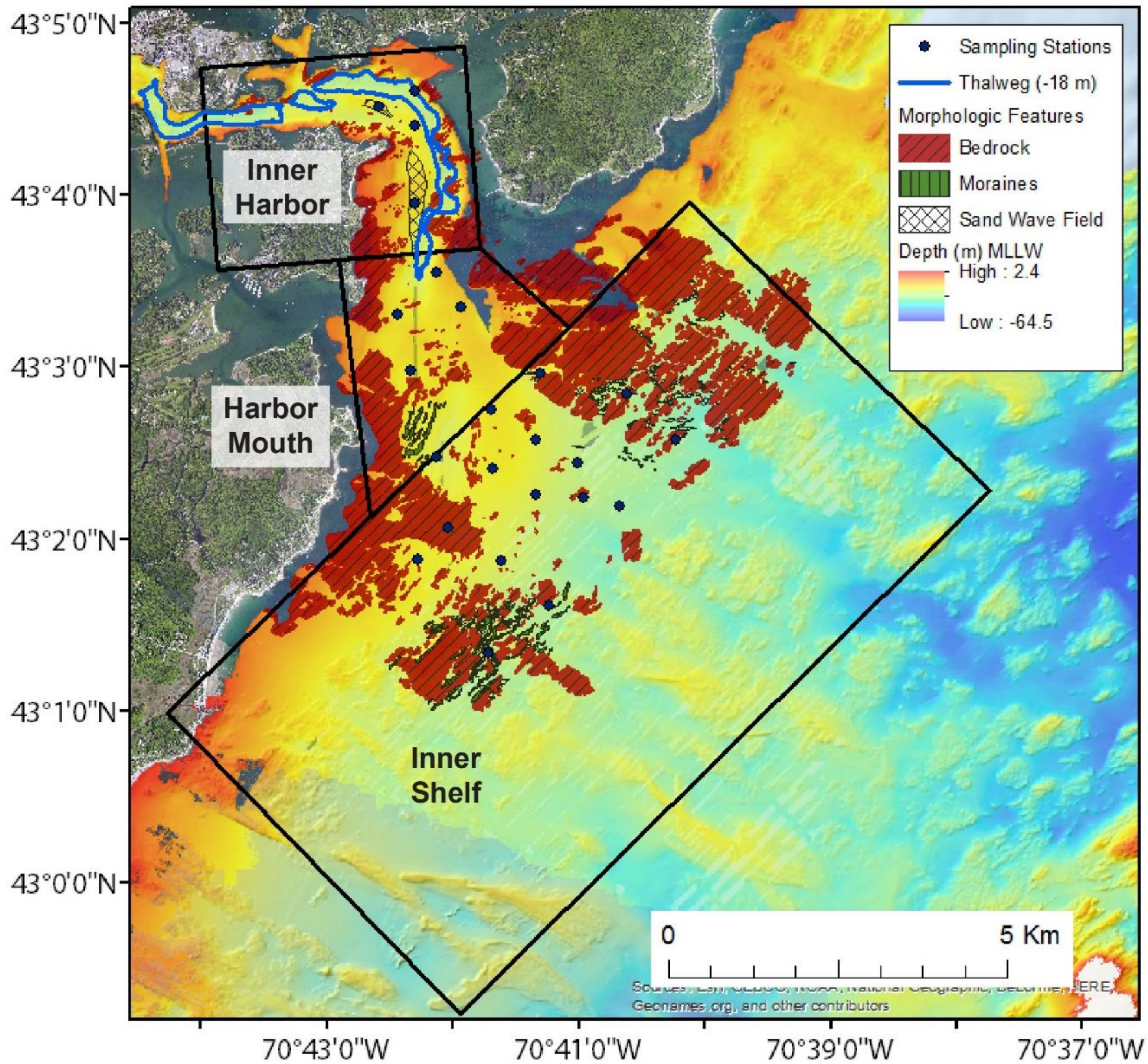

Figure 4-1: Location map showing the divisions of the study area used to describe the results of this study. The Inner Harbor, Harbor Mouth, and Inner Shelf areas are outlined in black. The major morphologic features are shown by colors and patterns. Bottom sampling stations shown by black points. Channel thalweg is represent by -18 m bathymetry contour.

Inner Harbor

The Inner Harbor is characterized by a narrow, bedrock-dominated channel with a sharp bend, a prominent channel thalweg, multiple bedrock outcrops, and two sand bodies with prominent bedforms (Figure 4-2). The smaller sand body, located north of the channel bend, and the larger sand body, located south of the channel bend, are both covered with sand waves. These features are referred to here as the Northern SWF and the Southern SWF, respectively (Figure 4-3).

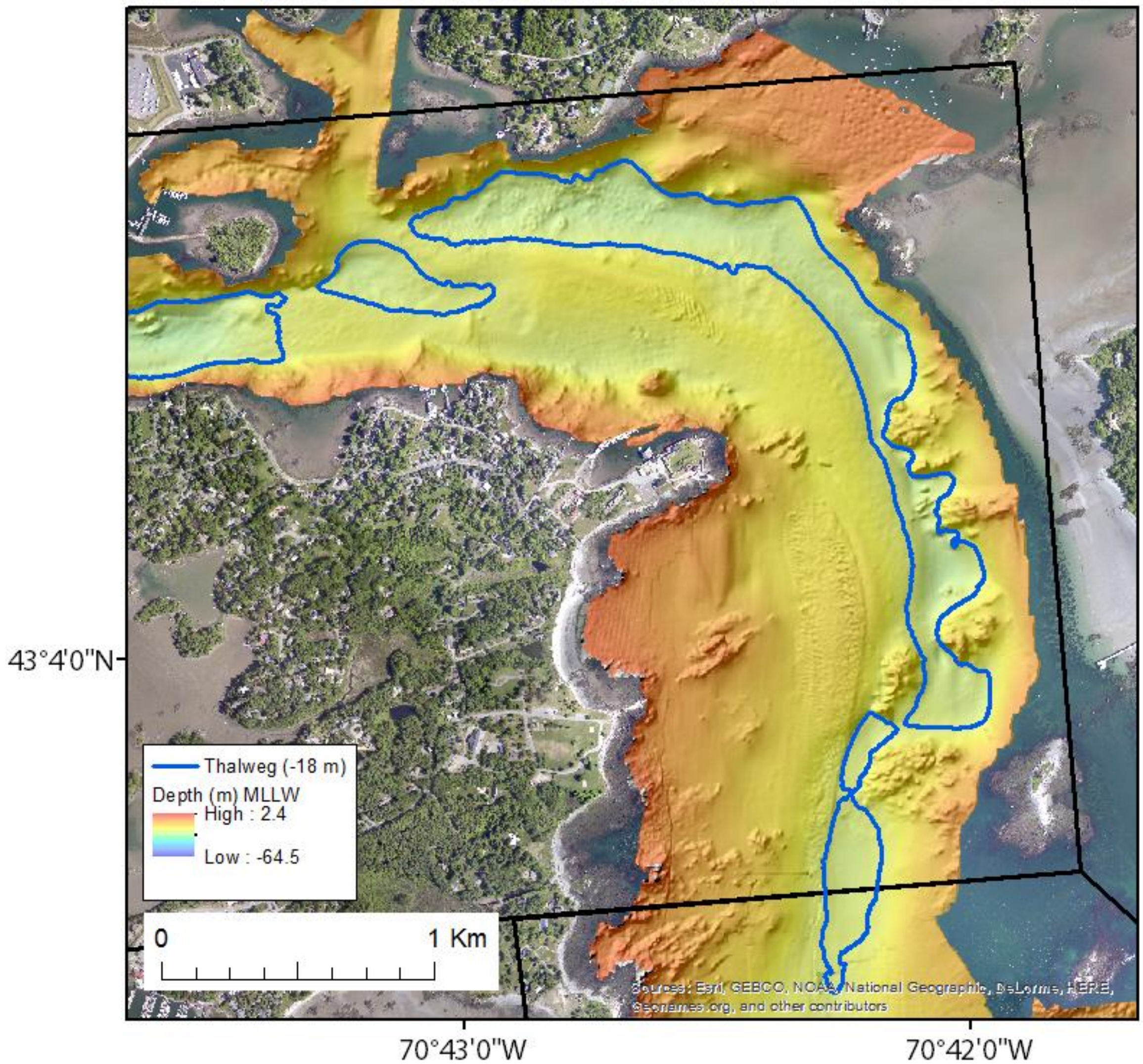

Figure 4-2: Bathymetry map of the Inner Harbor with vertical exageration of 10x (location shown in Figure 4-1). Channel thalweg is represented by the -18 m bathymetry contour.

Backscatter and Bottom Sediment Classification. When considering the backscatter map for the whole study area (Figure 3-2), little to no variation is observed in the Inner Harbor section. However, when the Inner Harbor is viewed with the major morphologic features highlighted (e.g. channel thalweg and sand wave fields), subtle distinction in backscatter intensities from the surrounding seafloor can be observed for the highlighted features (Figure 4-3).

The channel boundaries of the Inner Harbor are dotted with areas of high backscatter intensity, indicating very coarse sediments or hard-bottom (e.g. large gravel or bedrock). This interpretation matches well with the bedrock outcrops identified from the high-resolution bathymetry and hillshade (seen in Figures 4-2 and 4-3). The majority of the river channel seafloor exhibits medium backscatter intensity, likely indicating coarse sediments (e.g. coarse sand to fine gravel). This is confirmed by sediment sample 2A and 2B, which are poorly sorted, bimodal samples with modes of medium sand (2 phi) and pebble gravel (-4 phi) (Table 4-1).

The sand wave fields, which have slightly lower backscatter intensity than the surrounding river channel seafloor (outlined in Figure 4-3), are presumed to be areas of sediments differing from the surrounding seafloor. The slightly lower backscatter may indicate slightly finer grained sediments. This is verified by the sediment samples from station 1 and station 3. Sediment sample 1A appears to have been collected just outside the Northern SWF, and sample 1B collected from within the field. Despite the apparent difference in locations, both samples 1A and 1B are bimodal samples with modes of medium sand (2 phi) and pebble gravel (-4 phi) (Table 4-1 and Appendix I),. The Southern SWF includes sediment samples 3A and 3B, which are both very well sorted, unimodal samples of medium sand (1.1 and 1.6 phi) (Table 4-1). This agrees with previous work done by Ward (**1995**) and Weber and Ward (**2015**) which sampled the Southern SWF and determined the sediment to be medium sand with high shell hash content.

The channel thalweg (shown by the -18 m contour, Figure 4-3) shows a slightly lower backscatter intensity than the majority of the channel seafloor, indicating a slight change to finer grained sediment types. Unfortunately, no samples were recovered from the channel thalweg in this study. However, bottom video was collected at sampling station 24, located on the on the edge of the channel thalweg (location shown by green square, Figure 4-3). The bottom images from station 24 showed a gravelly (pebbles and cobbles) seafloor (Figure 4-4), which does not agree with the assessment of the area from the backscatter intensity. The discrepancy between the backscatter intensity and the gravelly bottom type seen in the bottom image (Figure 4-4) will be addressed in the Discussion.

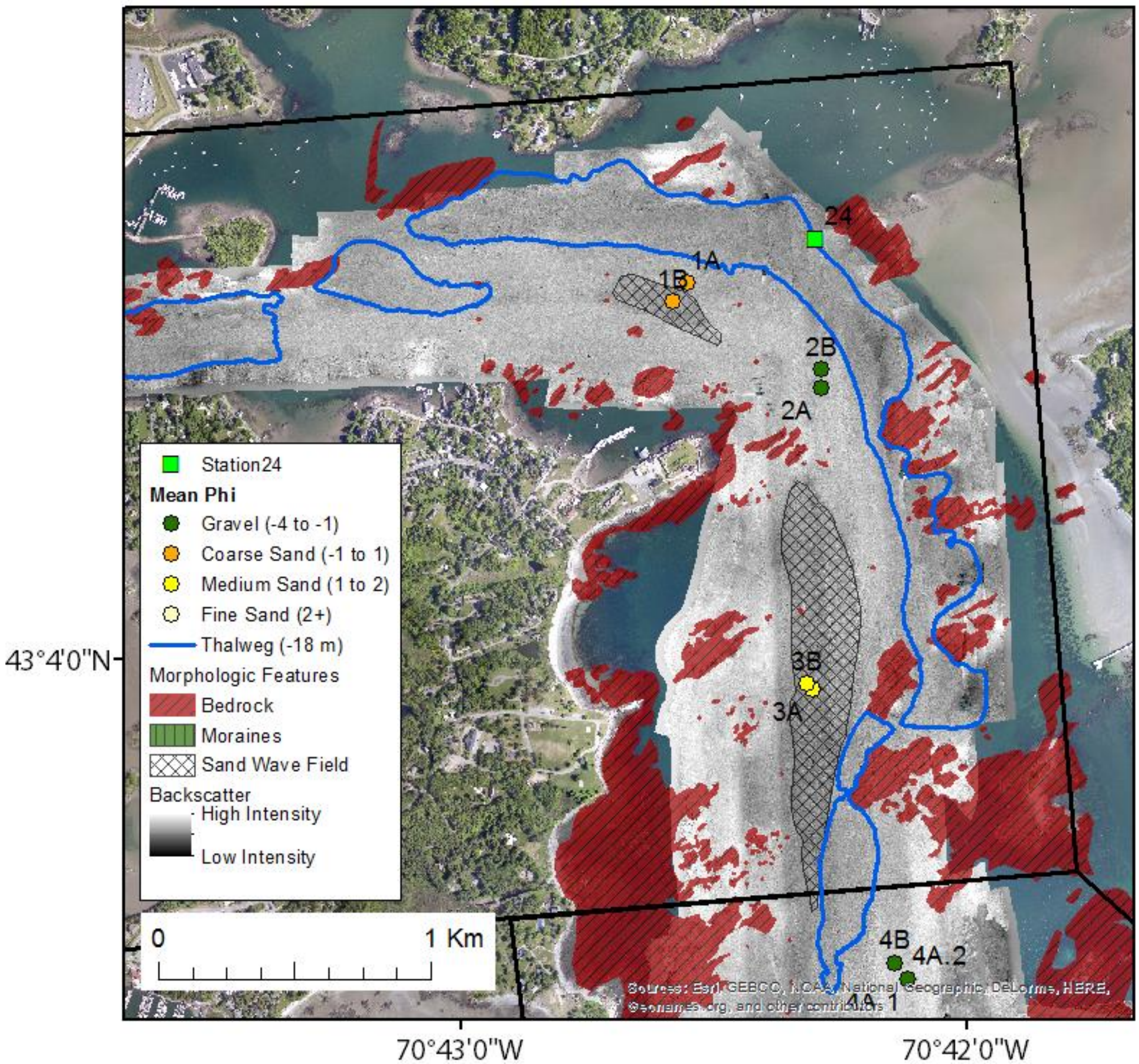

Figure 4-3: Backscatter map of the Inner Harbor (location shown in Figure 4-1). Sand wave fields are outline by black hash and the channel thalweg is represented by the -18 m bathymetry contour. Morphologic features (bedrock) are shown in red. Station 24 is marked by green square. Sediment samples are shown colored by mean phi size.

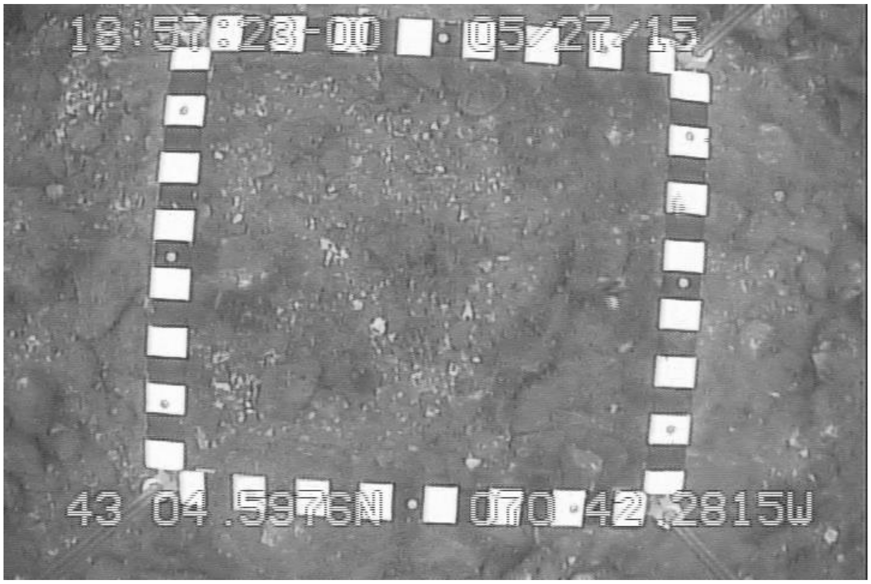

Figure 4-4: Station 24 (location shown in Figure 4-2) bottom video image. Note the pebbles and cobbles in an apparent sandy matrix.

Table 4-1: Sediment grain size statistics for the Inner Harbor (sample locations shown in Figure 4-3).

Sediment Sample	Location (Lat/Long)	Depth (m)	Sediment Name (Wentworth)	Mode (unimodal or bimodal)	% Gravel	% Sand	% Mud	Mean Phi	Mean mm	LOI %	Sample Weight (g)
1A	43 04.5451 N 070 42.5531 W	15.2	Sandy Pebble Gravel	BM	39.5	59.6	0.9	-0.278	1.21	0.89	265.4
1B	43 04.5182 N 070 42.5806 W	15.2	Sandy Pebble Gravel	BM	37.2	62.5	0.3	-0.462	1.38	3.18	259.8
2A	43 04.3922 N 070 42.2874 W	15.2	Sandy Pebble Gravel	BM	77.9	21.6	0.5	-2.696	6.48	N/A	725.9
2B	43 04.4187 N 070 42.2874 W	15.2	Sandy Pebble Gravel	BM	69.6	29.7	0.7	-2.226	4.68	1.89	539.3
3A	43 03.9563 N 070 42.3047 W	12.2	Slightly Granule Gravelly Medium Sand	UM	2.3	96.6	1.1	1.127	0.46	1.46	158.4
3B	43 03.9630 N 070 42.3164 W	12.2	Slightly Granule Gravelly Medium Sand	UM	0.6	98.5	0.9	1.638	0.32	0.92	263.8

Surficial Geology. In general, the bedrock outcrops that occur along the banks of the Inner Harbor are presumed to be surrounded by gravel, based on the high backscatter intensities immediately surrounding the outcrops (Figure 4-3). The majority of the channel seafloor within the Inner Harbor, including the Northern SWF and the channel thalweg, are likely composed of sandy gravel (classification in Figure 4-5). This is based on the medium to high backscatter intensities and the bimodal samples from stations 1 and 2 (Table 4-1). The Southern SWF is a medium to coarse sand, based on station 3, and agrees with previous mapping efforts of the Inner Harbor (Cutter et al., 2003; Ward, 1995; Weber and Ward, 2015).

The overall interpretation of the Inner Harbor seafloor agrees with Cutter et al. (2003) who described the seafloor surrounding the Southern SWF via automated classification and sparse sediment samples. Cutter et al. (2003) described the seafloor as primarily sandy gravel and gravelly sand, and the Southern SWF as sand, based primarily on sediment samples from Ward (1995). These findings also agree with Weber and Ward (2015) who, through multiple mapping and sampling efforts, determined the regions just north and south of the large sand wave field were "Channel Lag Deposits", which they identified as pebbles and cobbles in a sandy matrix. This agrees with the coarse sediments seen at station 24 (Figure 4-4) and the sandy gravel at station 2 (Table 4-1).

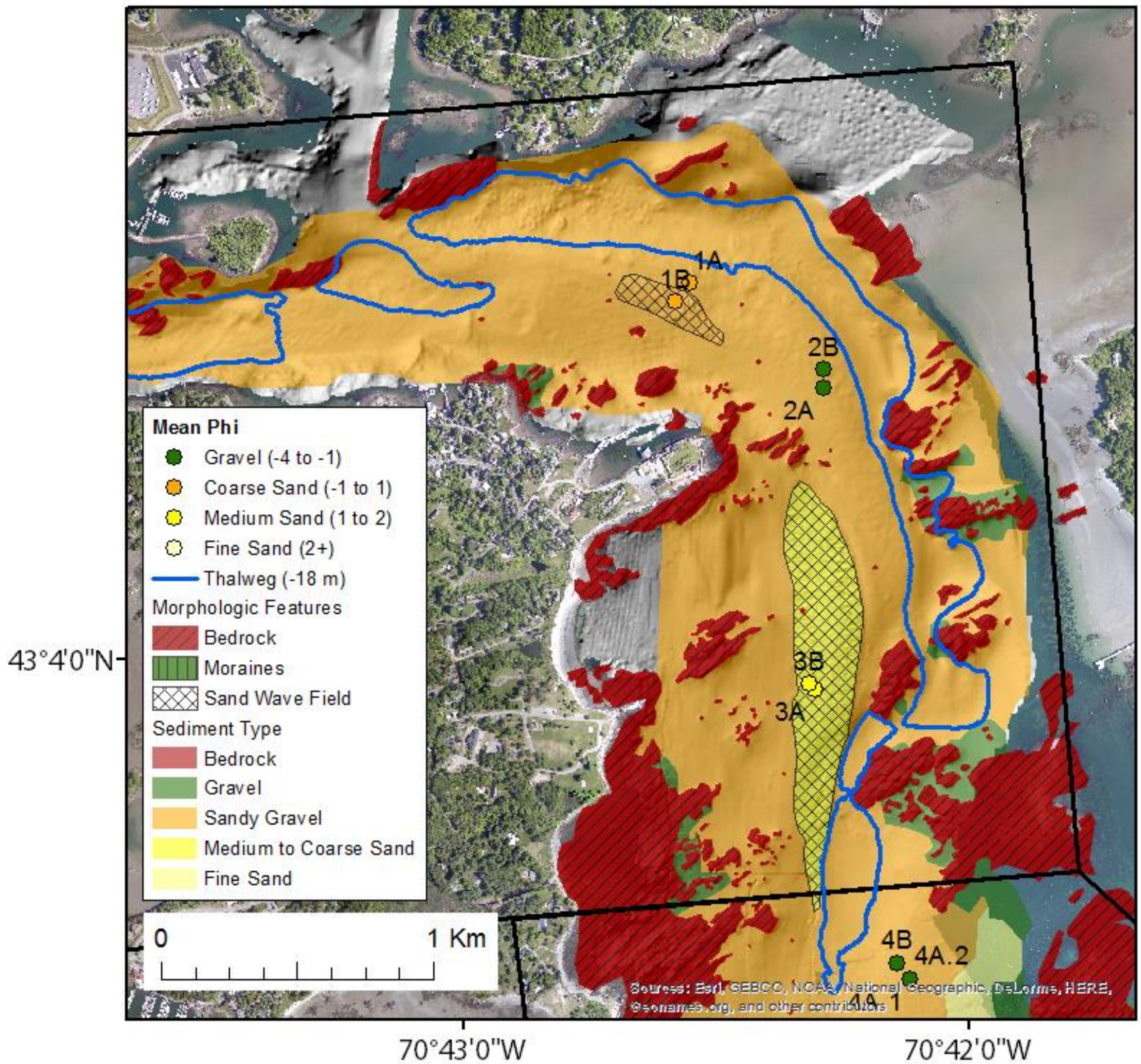

Figure 4-5: Surficial geology map of Inner Harbor (location shown in Figure 4-1). Sediment sample locations shown by colored points. Channel Thalweg is represented by the -18 m bathymetry. Morphologic features (bedrock and sand wave fields) are shown in red and hash marks.

Seismic Stratigraphy. The majority of the IKB seismic profiles (33 of 50) are located in the Inner Harbor, with 25 channel cross-sections and 8 longitudinal profiles (Figure 4-6).

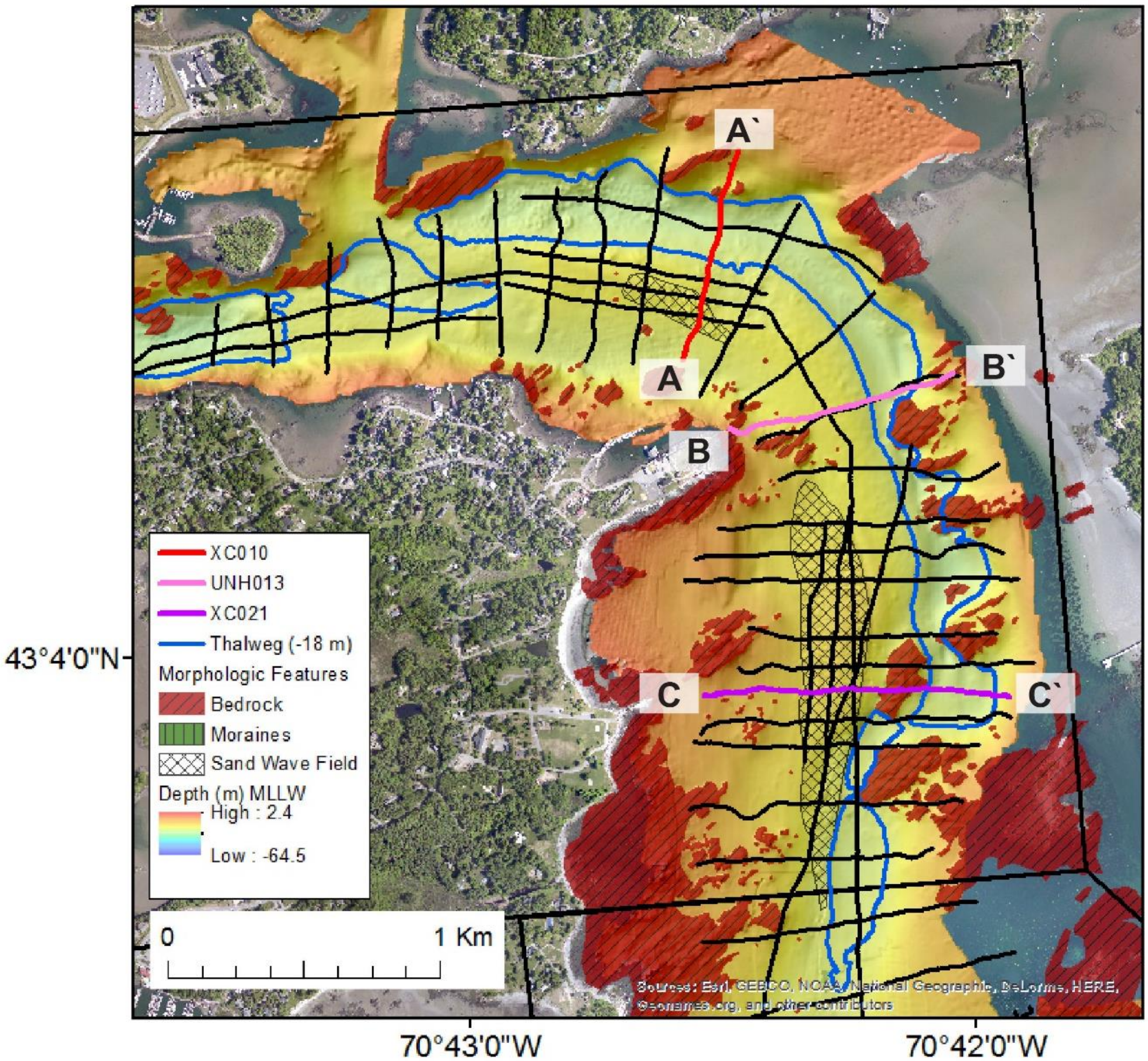

Figure 4-6: Seismic lines within the Inner Harbor (location on Figure 4-1) over bathymetry (x10 vertical exaggeration) with morphologic features identified (sand wave fields, bedrock outcrops, and channel thalweg). Channel Thalweg represented by the -18 m bathymetry contour. Seismic profile XC010 shown in red (A-A`), UNH013 in pink (B-B`) and XC021 (C-C`) shown in purple.

Seismic profile XC010 (Figure 4-7) provides an overview of the paleochannel, the channel fill sequence, and the Northern SWF. The bedrock (Br), which outcrops on the right side of profile (near A`), drops sharply down into the paleochannel to ~40 m below present sea level (psl) directly below the present channel thalweg. A portion of the bedrock that forms the left boundary of the paleocahnnel is visible at ~31-35 m below psl. The channel fill sequence shows a continuous dark reflector across what is visible of the paleochannel at ~25 m below psl. This reflector, which is interpreted as an erosional unconformity (Un), is present in many of the seismic profiles in the study area. The seismic unit below the unconformity, which fills the paleochannel, is interpreted as Pleistocene age glaciomarine sediments (Gm) based on spatial relationships (since little to no internal structure is visible). Glaciomarine sediments from the region are typically stratified and fill or drape bedrock and till. This glaciomarine sediments unit is equivalent to the Presumpscot Formation identified by Bloom (1963). The seismic unit above the unconformity is interpreted as Holocene sediments (Hc). The Holocene sediments contrast the glaciomarine fill and appear darker with more internal reflectors than the underlying glaciomarine sediments in this cross-section of the Inner Harbor. The sand wave field (Swf) is identified as a separate seismic unit that clearly contrasts with the underlying Holocene sediments and appears darker with no internal structure. The lack of internal structures of both the glaciomarine sediments and sand wave field units may be due to the limitations of the IKB Seistec system.

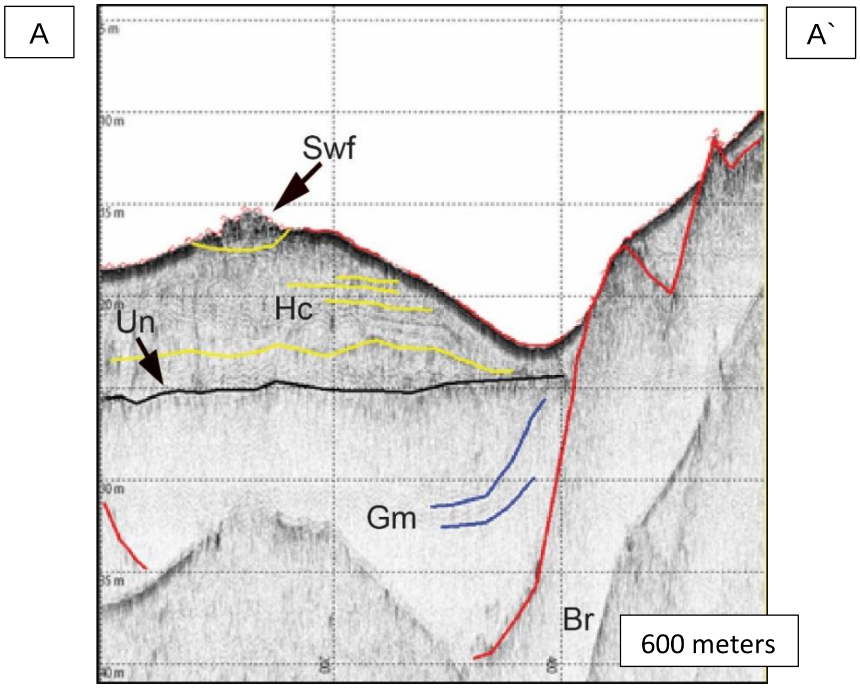

Figure 4-7: Seismic Profile XC010. View is upriver with New Hampshire bank on left (A) and Maine bank on right (A`). The vertical exaggeration is 10x. The sand wave field (Swf) and Holocene sediment (Hc) reflectors are shown in yellow, and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red.

Seismic profile UNH013 (Figure 4-8), located at the bend in the channel, shows the paleochannel, the channel fill sequence, and a possible estuarine point bar deposit. Bedrock (Br) can be seen across most of the profile, with highs on both sides of the profile (on the channel banks), but no outcrops. There is a bedrock high toward the middle of the channel at ~20 m depth that appears to be the right boundary of the paleochannel. The entire paleochannel can be traced and has a low of ~35 m depth on the left (B`) side of the profile. The paleochannel is crossed by a dark reflector ~25-27 m depth that interpreted as an erosional unconformity. Glaciomarine sediments (Gm) can be seen underneath the unconformity within the paleochannel. The bedrock on the right side of the profile is topped by Holocene sediments (Hc), including a set of dipping beds at ~18-

24 m depth on the right on the bedrock high in the middle of the profile. The group of dipping bed is interpreted as an estuarine point bar (see DISCUSSION).

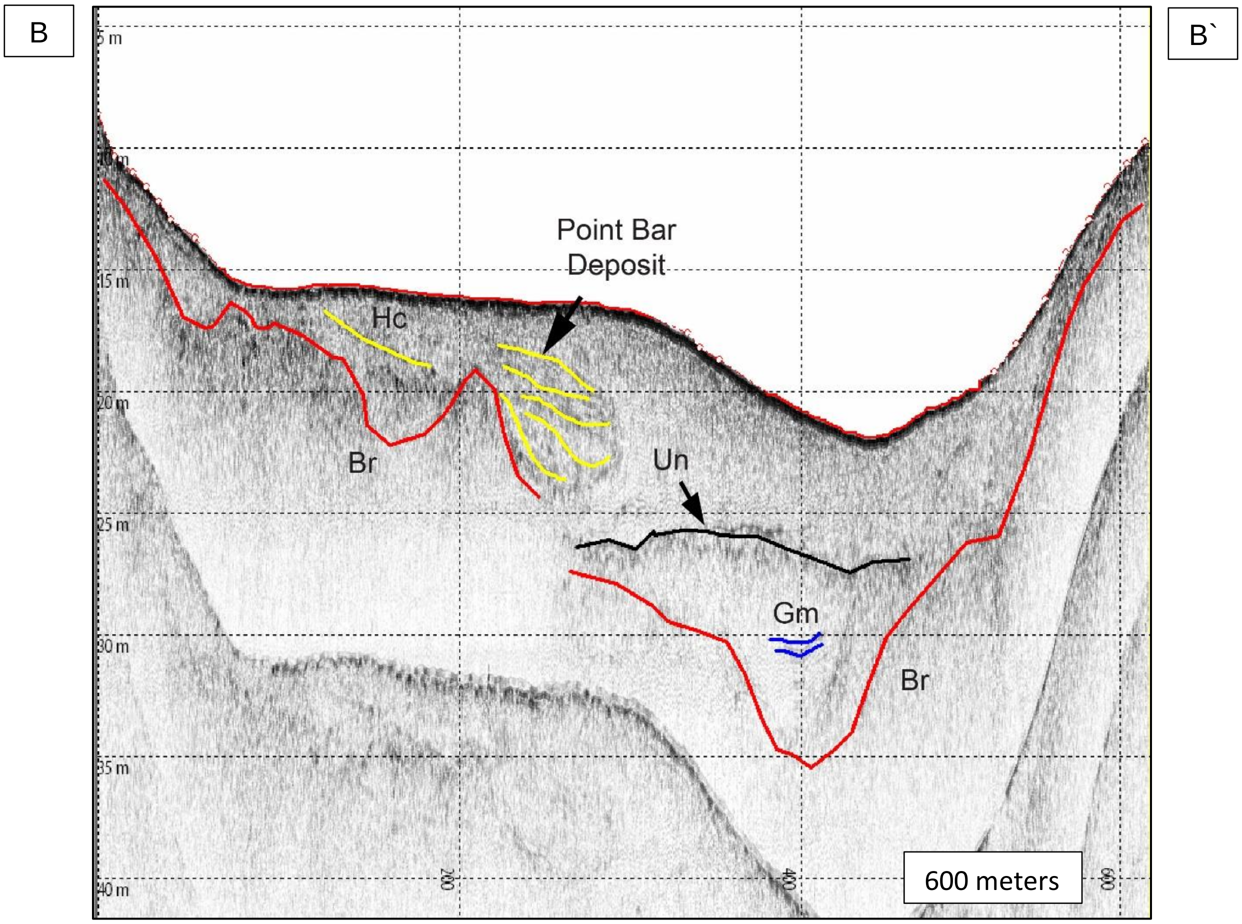

Figure 4-8: Seismic Profile UNH013. View is upriver with New Hampshire on left (B) and Maine on right (B`). The vertical exaggeration is 10x. Holocene sediment (Hc) reflectors and estuarine Point Bar Deposit are shown in yellow, and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red.

Seismic profile XC021 (Figure 4-9) provides another view the paleochannel, channel fill sequence, and a view of the Southern SWF. At this cross-section, there are two Bedrock (Br) highs separated by a depression. One bedrock high outcrops in the middle of the river channel, separating the Southern SWF from the channel thalweg on the right side of the profile. The bedrock outcrop drops sharply on the right side to ~40 m below psl beneath the channel thalweg, and represents the western boundary of the paleochannel for this cross-section. The second bedrock high, located on the left side of the profile, is covered by Holocene sediments (Hc). The bedrock (Br) depression between the two bedrock highs reaches at depth of ~27 m below psl beneath the southern SWF. This depression is present through 7 seismic profiles (located up and down river from XC021), but does not continue out of the Inner Harbor into the Harbor Mouth. The depression could be either a basin or another paleochannel, however the presence of the depression only within the Inner Harbor supports the feature being a basin between the bedrock highs. The sand wave field unit (Swf) clearly contrasts the underlying Holocene sediments and is darker with no internal reflectors, similar to the Northern SWF seen in seismic profile XC010 (Figure 4-7). The channel fill sequence in profile XC021 underlying the channel thalweg shows a near continuous dark reflector, interpreted as an erosional unconformity (Un) at ~28 m. A reflector interpreted as an erosional unconformity (Un) is also seen within the bedrock depression at ~23 m below psl. The paleochannel fill below the unconformity is a highly stratified unit identified as glaciomarine sediment (Gm) (as discussed above). The stratified unit above the unconformity within the paleochannel is interpreted as Holocene sediments (Hc). The bedrock depression is also topped with Holocene sediments (Hc), including the Southern SWF.

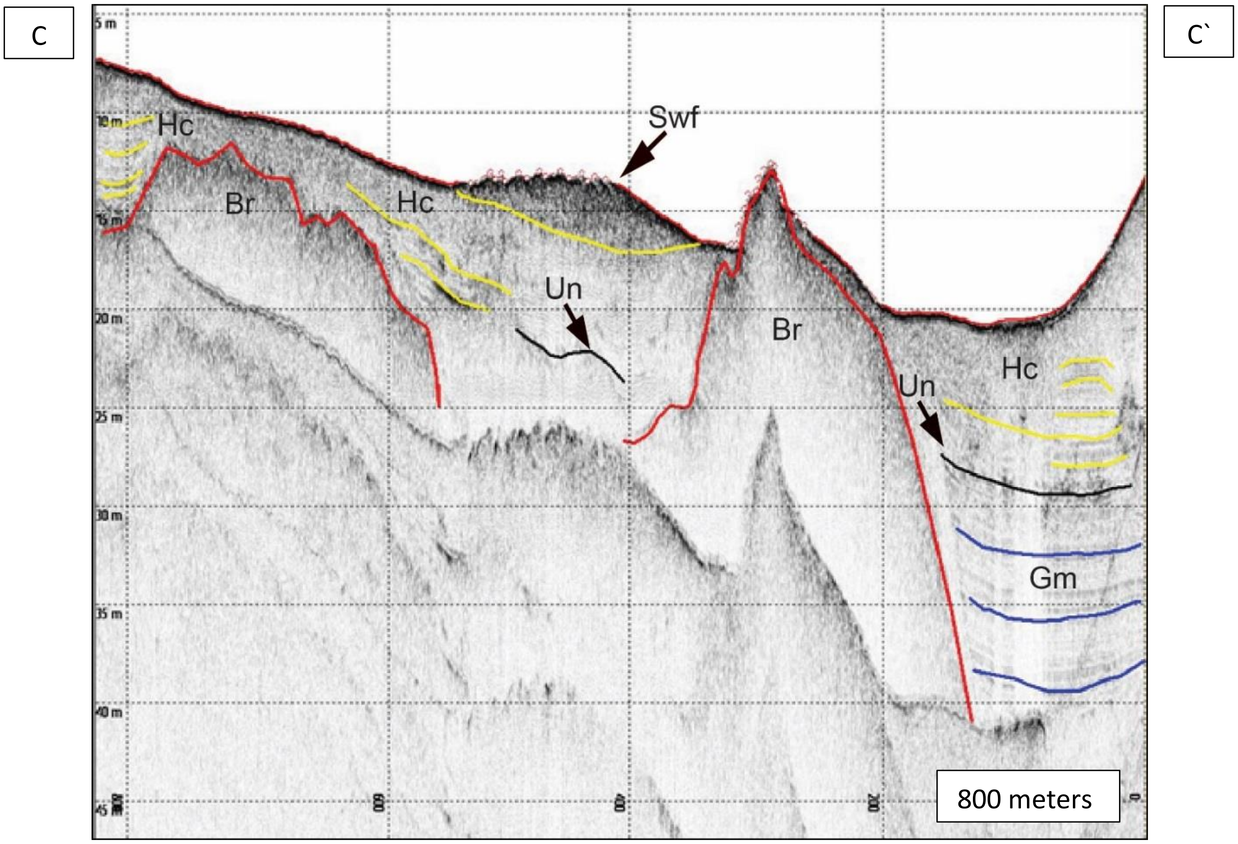

Figure 4-9: Seismic profile XC021. View is upriver with New Hampshire bank on left (C) and Maine bank on right (C`). The vertical exaggeration is 10x. The sand wave field (Swf) and Holocene sediment (Hc) reflectors are shown in yellow, and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red.

Harbor Mouth

The Harbor Mouth, which is dominated by large bedrock outcrops along the channel banks, is where the river channel widens and the channel thalweg becomes indistinct (Figure 4-10). This area includes the entrance to Little Harbor, a small embayment next to New Castle Island, New Hampshire. The entrance to Little Harbor is marked by a break in the bedrock outcrops that define the banks of most of the Harbor Mouth.

One of the more prominent morphologic features at the seaward edge of the Harbor Mouth is a set of glacial moraines, presumed to be De Geer moraines which are recognized as features of ice margin retreat (Sinclair, 2015). The moraine field is small, with only 4-5 large ridges that range in size from 200 to 900 m in length and 15 to 50 m in width (Figure 4-11). The moraines were identified using high-resolution bathymetry, hillshade, and subbottom seismics. No samples were collected within the moraine field.

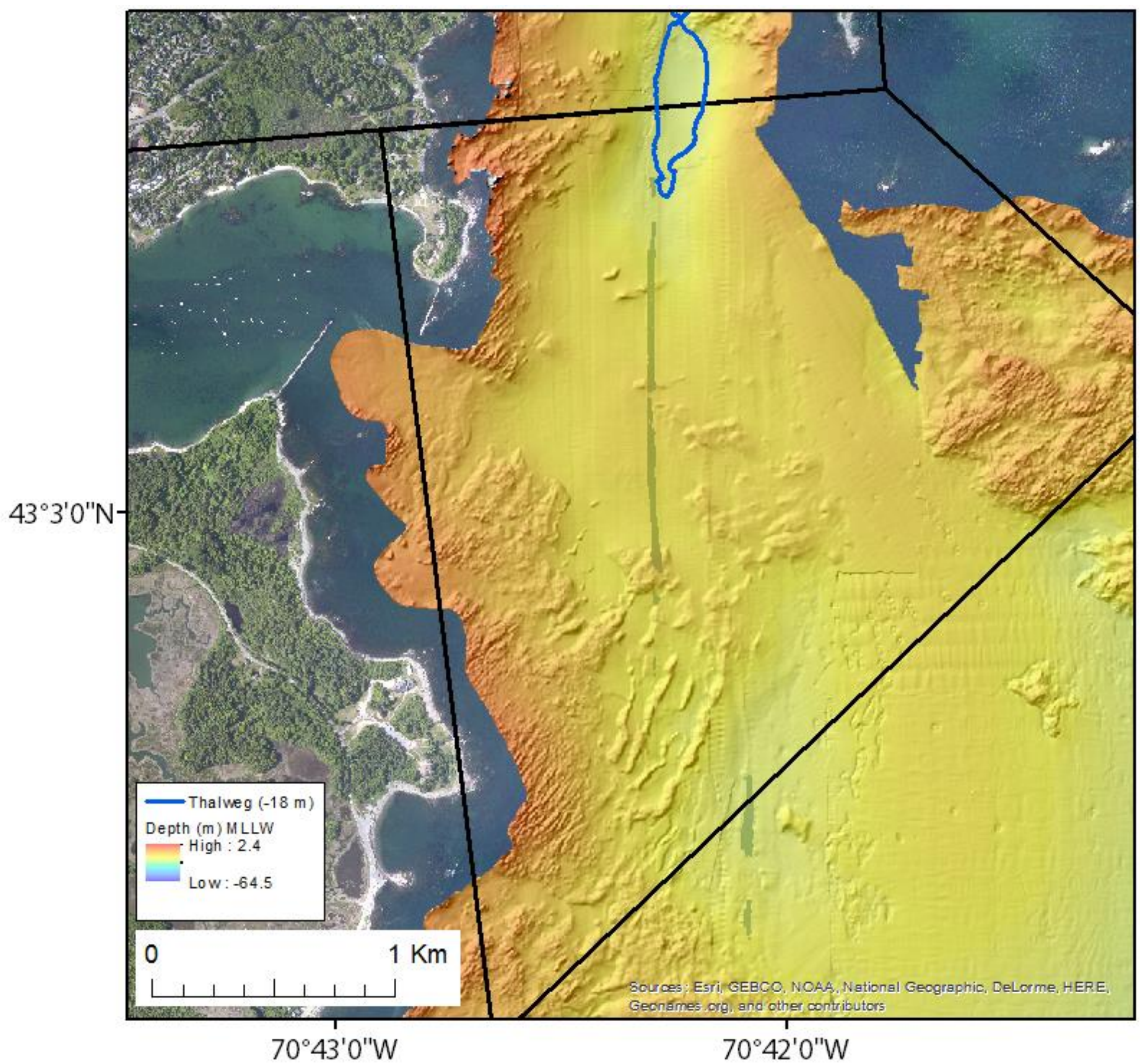

Figure 4-10: Bathymetry map of the Harbor Mouth with vertical exageration of 10x (location shown in Figure 4-1). Channel thalweg is represented by the -18 m bathymetry contour.

Backscatter and Bottom Sediment Classification. The major sedimentological feature of the Harbor Mouth is the beginning of an apron of low backscatter intensity indicating fine grained sediments, which expands in a seaward direction onto the Inner Shelf (Figure 3-1, Figure 4-11). The composition of the apron is confirmed by sediment samples 5A and 5B, both very well sorted, unimodal fine sand (3 phi) (Table 4-2). The majority of the rest of the seafloor within the Harbor Mouth is characterized by medium to high backscatter intensity that is likely coarse sediments or hard bottom. This is confirmed by sediment samples from stations 4 and 23, with all of the samples being poorly sorted bimodal samples with modes at medium to fine sand (2 to 2.5 phi) and pebble gravel (-3 to -5 phi) (see Table 4-2).

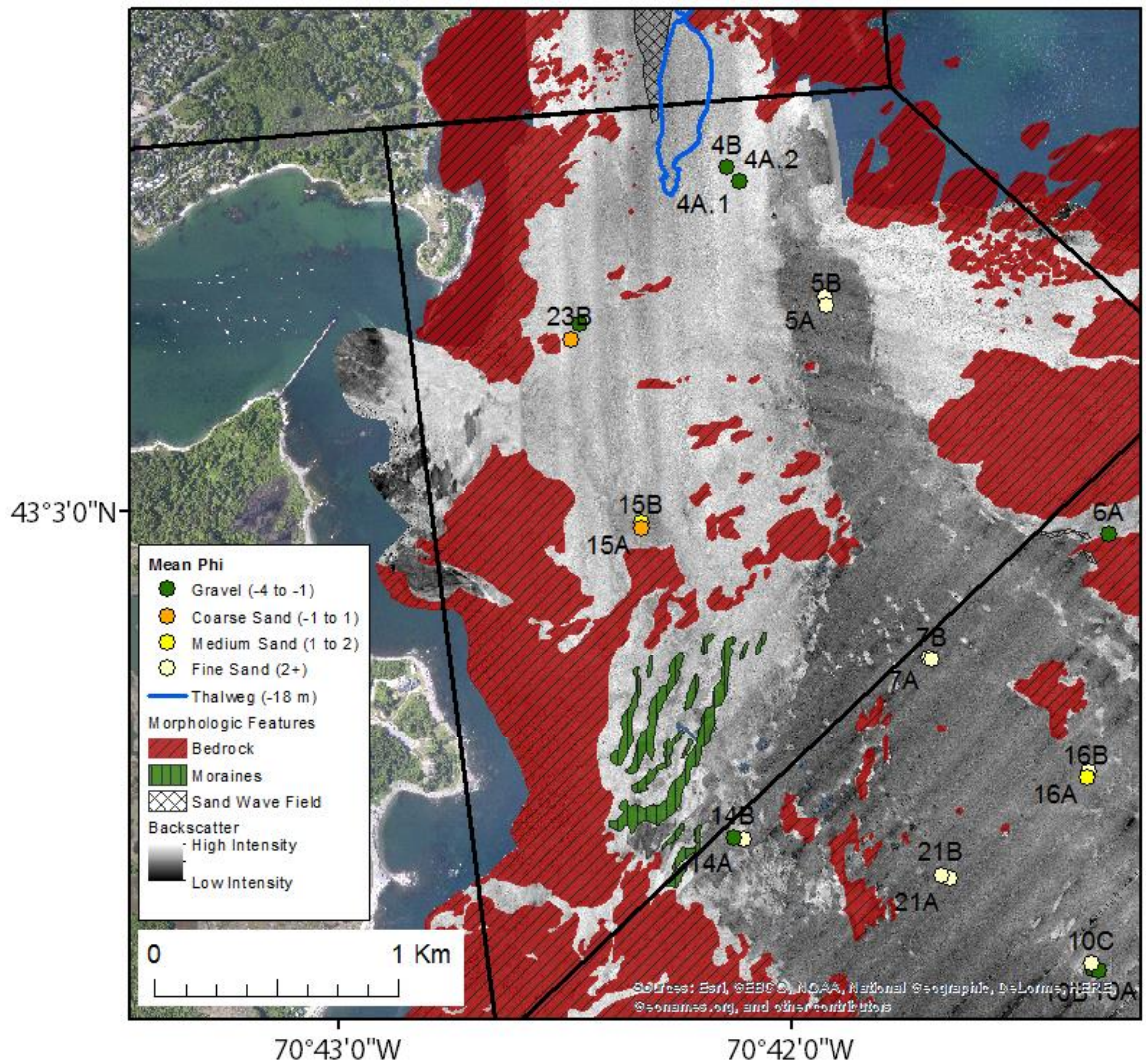

Figure 4-11: Backscatter map of the Harbor Mouth (location shown in Figure 4-1). Sand wave fields are outline by black hash and the channel thalweg is represented by the -18 m bathymetry contour. Morphologic features (bedrock) are shown in red and the De Geer moraines are shown in green. Sediment samples are shown colored by mean phi size.

Table 4-2: Sediment grain size statistics for the Harbor Mouth (sample locations shown in Figure 4-11).

Sediment Sample	Location (Lat/Long)	Depth (m)	Sediment Name (Wentworth)	Mode (unimodal or bimodal)	% Gravel	% Sand	% Mud	Mean Phi	Mean mm	LOI %	Sample Weight (g)
4A-1	43 03.5354 N 070 42.1144 W	10.7	Sandy Pebble Gravel	BM	59.6	39.9	0.5	-1.407	2.65	0.79	279.0
4A-2	43 03.5354 N 070 42.1144 W	10.7	Sandy Pebble Gravel	BM	53.2	46.1	0.7	-1.278	2.43	N/A	504.9
4B	43 03.5584 N 070 42.1403 W	10.7	Sandy Pebble Gravel	BM	71.4	27.9	0.7	-2.326	5.01	1.28	291.7
5A	43 03.3477 N 070 41.9242 W	12.2	Slightly Granule Gravelly Fine Sand	UM	0.1	98.4	1.5	2.95	0.13	0.64	154.6
5B	43 03.3335 N 070 41.9220 W	12.2	Slightly Granule Gravelly Fine Sand	UM	0.7	97.8	1.5	2.928	0.13	0.73	136.0
15A	43 02.9809 N 070 42.3311 W	15.2	Slightly Granule Gravelly Medium Sand	UM	3.2	96	0.7	1.848	0.28	0.93	220.4
15B	43 02.9722 N 070 42.3316 W	15.2	Pebble Gravelly Medium Sand	BM	19.2	80.2	0.5	0.56	0.68	0.69	265.0
16A	43 02.5765 N 070 41.3415 W	17.7	Slightly Pebble Gravelly Very Fine Sand	UM	4.4	94.2	1.4	2.72	0.15	0.67	153.0
16B	43 02.5650 N 070 41.3437 W	17.7	Pebble Gravelly Fine Sand	BM	15.6	83.4	1	1.74	0.30	0.68	117.9
23A	43 03.3046 N 070 42.4685 W	15.2	Sandy Pebble Gravel	BM	76.7	22.7	0.6	-2.684	6.43	0.90	336.2
23B	43 03.2793 N 070 42.4885 W	15.2	Sandy Granule Gravel	BM	49.2	49.9	0.8	-0.801	1.74	0.70	363.5

Surficial Geology. Much of the Harbor Mouth seafloor is sandy gravel (which matches the Inner Harbor) (Figure 4-12). The exception is the apron of fine sand (referred to as the Sand Apron for this study) that starts in the Harbor Mouth and expands moving seaward. The entrance to Little Harbor and the western (left) side of the Harbor Mouth has the greatest seafloor diversity within the area, while the eastern (right) side of the Harbor Mouth is predominantly bedrock surrounded by gravel.

The western bank is dominated by bedrock outcrops (which are surrounded by patches of fine sand, medium to coarse sand, and gravel) and glacial moraines (assumed to be De Geer moraines). The highly variable seafloor is confirmed by station 15 (Figure 4-11). Sediment sample 15A, a unimodal medium sand (2 phi) is similar to the sand portion of sample 15B, but lacks the pebble gravel (-4 phi) fraction seen in 15B (Table 4-2; Appendix I).

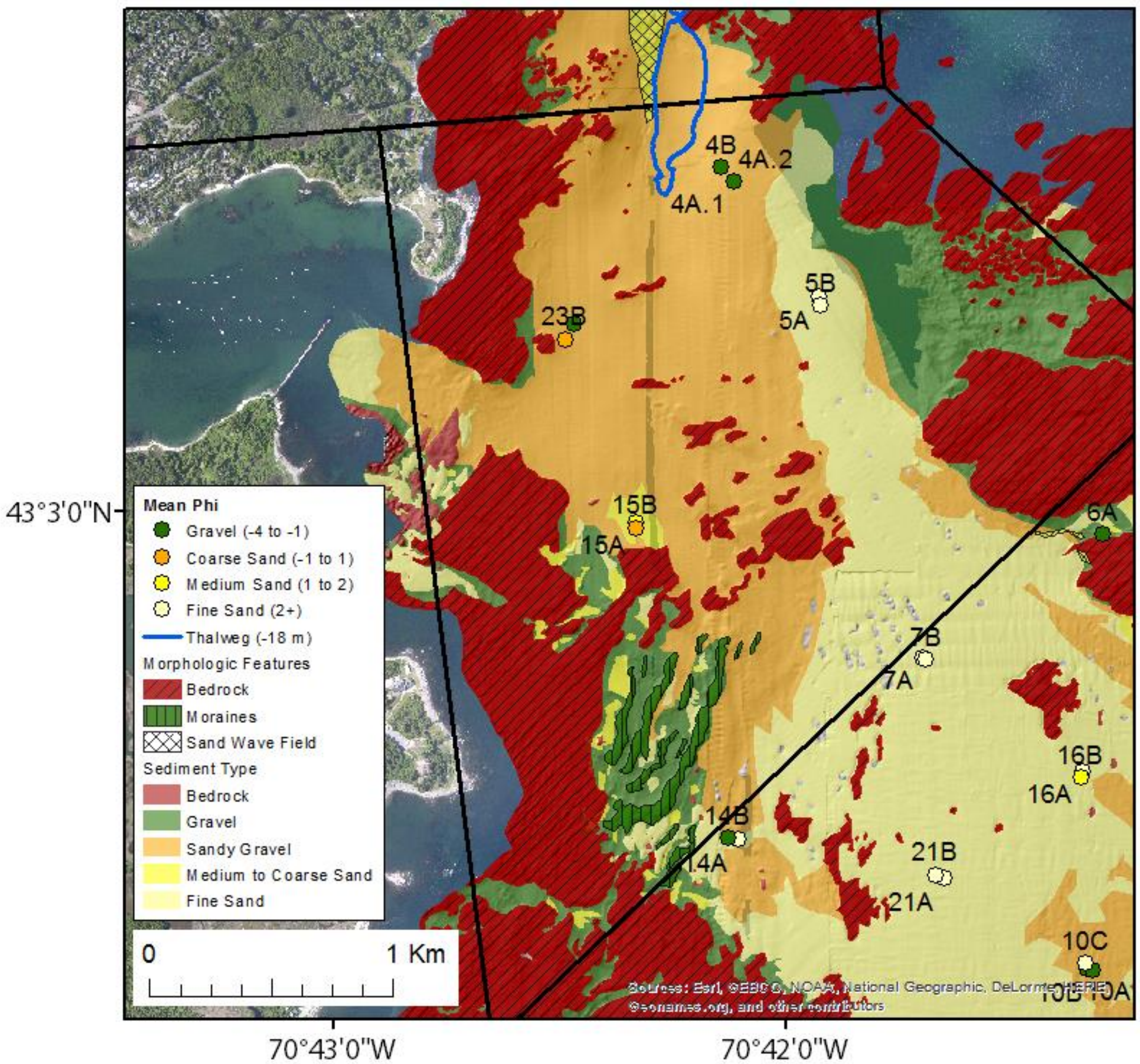

Figure 4-12: Surficial geology map of Harbor Mouth (location shown in Figure 4-1). Sediment sample locations shown by colored points. Channel Thalweg is represented by the -18 m bathymetry. Morphologic features (bedrock and sand wave fields) are shown in red and hash marks. De Geer moraines are shown by green with lines.

Seismic Stratigraphy. The Harbor Mouth contains 13 IKB survey seismic profiles, 8 cross-sections and 5 longitudinal profiles (Figure 4-13).

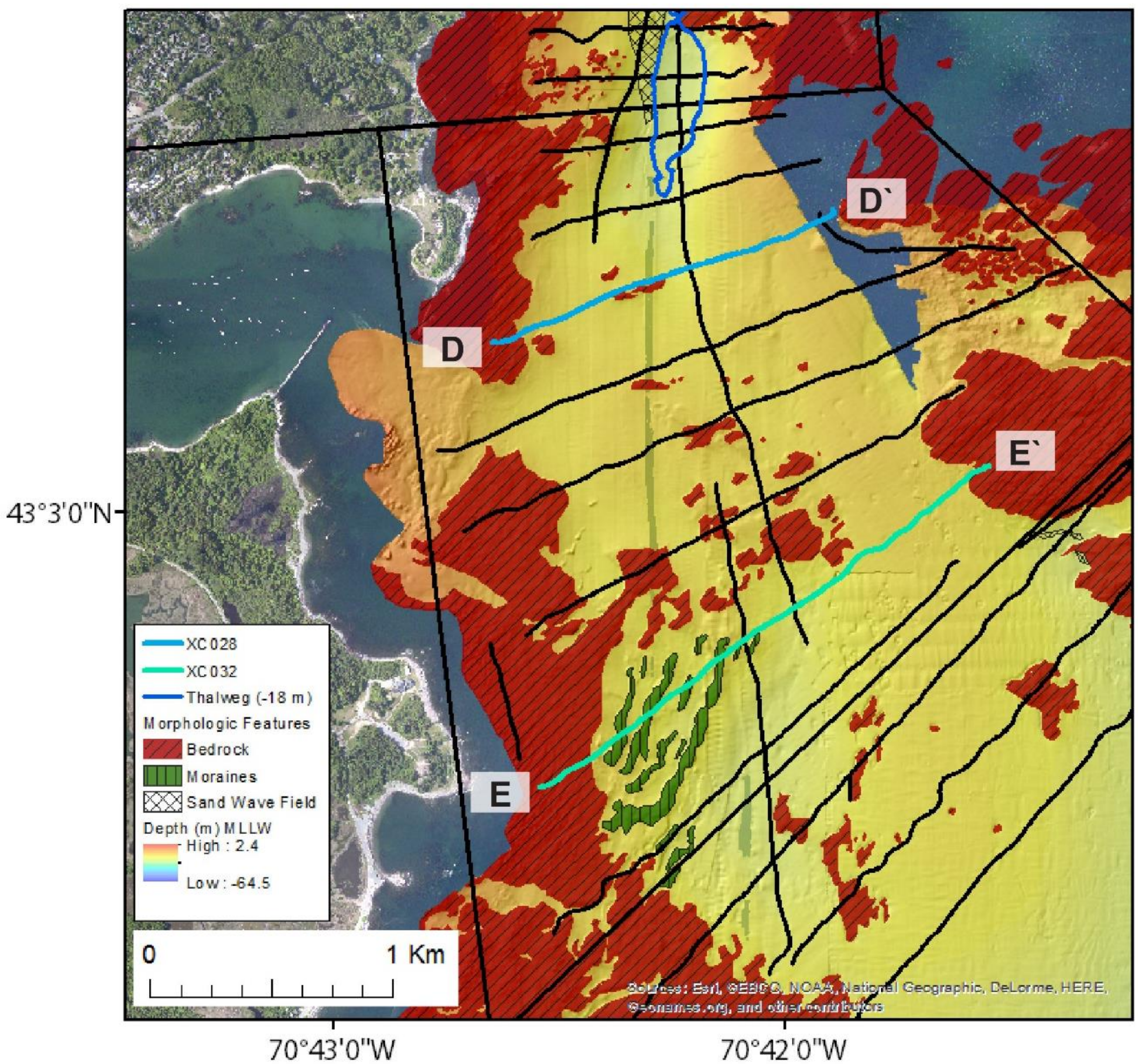

Figure 4-13: Seismic lines within the Harbor Mouth (location on Figure 4-1) over bathymetry (x10 vertical exaggeration) with morphologic features identified (sand wave fields, bedrock outcrops, moraines, and channel thalweg). Channel Thalweg represented by the -18 m bathymetry contour. Seismic profile XC028 shown in blue (D-D`) and XC032 (E-E`) shown in teal.

Seismic profile XC028 (Figure 4-14) provides an overview of the paleochannel and the channel fill sequence. There is a bedrock (Br) high in the middle of the cross-section, which separates two apparent paleochannels, or a paleochannel and a basin. On the left side of the profile (D) the bedrock dips down to a depression at ~27 m below psl, and shows a small channel or basin fill sequence. A slightly darker reflector crosses the depression at ~24 m below psl and is interpreted as an erosional unconformity (Un), separating the minimally stratified unit of glaciomarine sediments (Gm) from the overlying Holocene sediments (Hc).

The bedrock outcrop on the right side of the profile (D`) drops sharply downward to ~22 m below psl, and represents the eastern boundary of the eastern paleochannel. The western boundary of the eastern paleochannel drops sharply to ~30 m below psl. A very dark and chaotic reflector crosses about half of the paleochannel between 17 and 20 m below psl, and is interpreted as an erosional unconformity (Un). The chaotic stratified beds above the unconformity (Un) are interpreted as Holocene sediments (Hc).

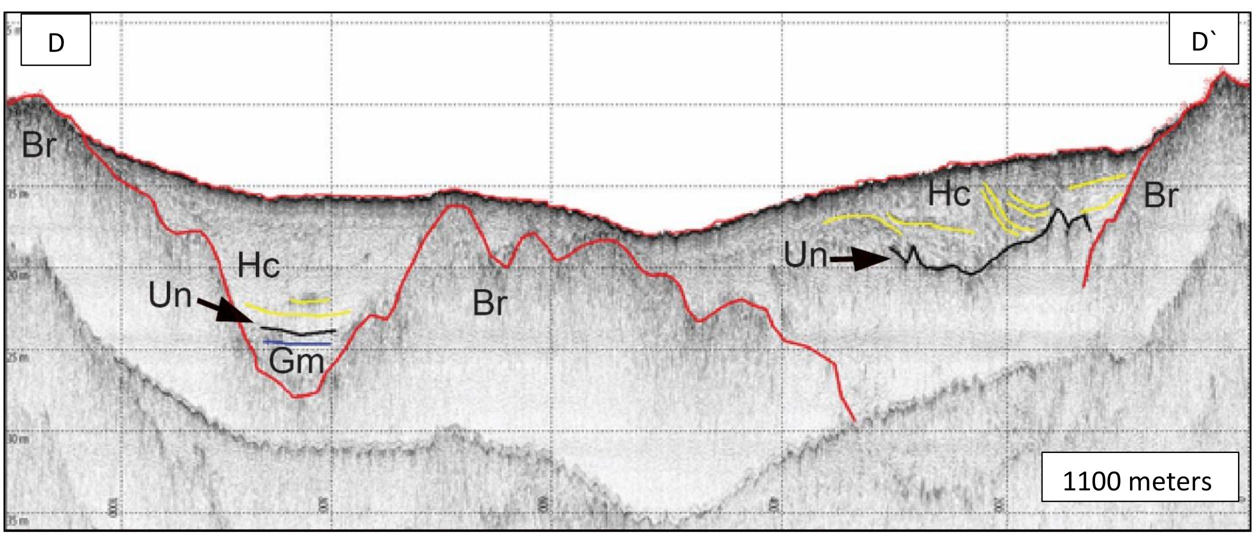

Figure 4-14: Seismic Profile XC028. View is upriver with New Hampshire bank on left (D) and Maine bank on right (D`). The vertical exaggeration is 10x. Holocene sediment (Hc) reflectors are shown in yellow and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red.

Seismic profile XC032 (Figure 4-15) includes the De Geer moraines at the western, seaward edge of the Harbor Mouth (E), a view of the paleochannel, the channel fill sequence, and a mounded seisimic unit. The bedrock (Br) on the right side (E`) of the profile drops to ~23 m below psl and represents the eastern boundary of the paleochannel. The western boundary of the paleochannel is interpreted as the bedrock outcrop in the middle of the profile. Stratified reflectors within the paleochannel are interpreted as Holocene sediments (Hc). A thin, mounded unit occurs at the surface of the paleochannel and caps the underlying stratified Holocene sediments. This is interpreted as the start of a feature referred to as the Sand Mound, a unit that corresponds with the Sand Apron identified in the surficial geology (Figure 4-12). Little to no seismic penetration is visible through the moraines on the left side of the profile (D), but the surficial shape of the features is clearly seen (Figure 4-15).

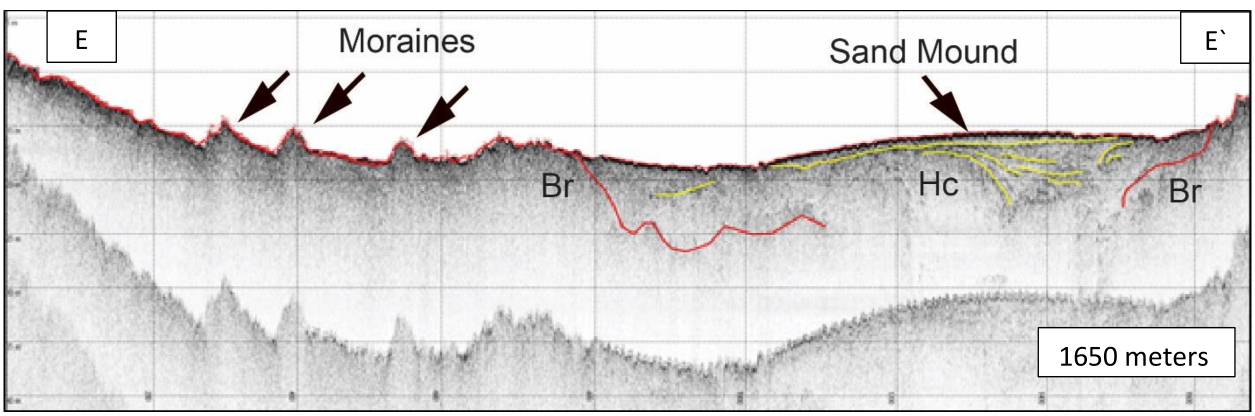

Figure 4-15: Seismic Profile XC032. View is upriver with New Hampshire bank on left (E) and Maine bank on right (E`). The vertical exaggeration is 10x. The Sand Mound and Holocene sediment (Hc) reflectors are shown in yellow. Bedrock (Br) is traced in red. Moraine and Sand Mound features are shown with arrows.

Inner Shelf

The Inner Shelf seafloor is highly diverse (Figure 4-16), with large bedrock outcrops, the expanded sand apron (originating in the Harbor Mouth), various bottom sediment types, and a moraine field hypothesized to be De Geer moraines (Sinclair, 2015). The seafloor diversity of the Inner Shelf area precludes any morphologic feature being dominant. However, areas of specific interest include the extension of the sand apron and the moraine field (Figure 4-17).

Large areas of bedrock outcrops dominate the seafloor on the Inner Shelf. These regions are referred to as the northern, southern, and offshore outcrops for this study (Figure 4-16). The northern outcrop is the total area of bedrock outcrops extending from the northeastern side of the Harbor Mouth across the Inner Shelf. The southern outcrop is the total area of bedrock outcrops extending along the western side of the Harbor Mouth. The offshore outcrop area is located at the seaward edge of the Inner Shelf area (~2.5 km from the shoreline) and is associated with the moraine field. The moraine field consists of multiple (~30) small moraines ranging in size from 100 to 400 m in length and 20 to 50 m in width.

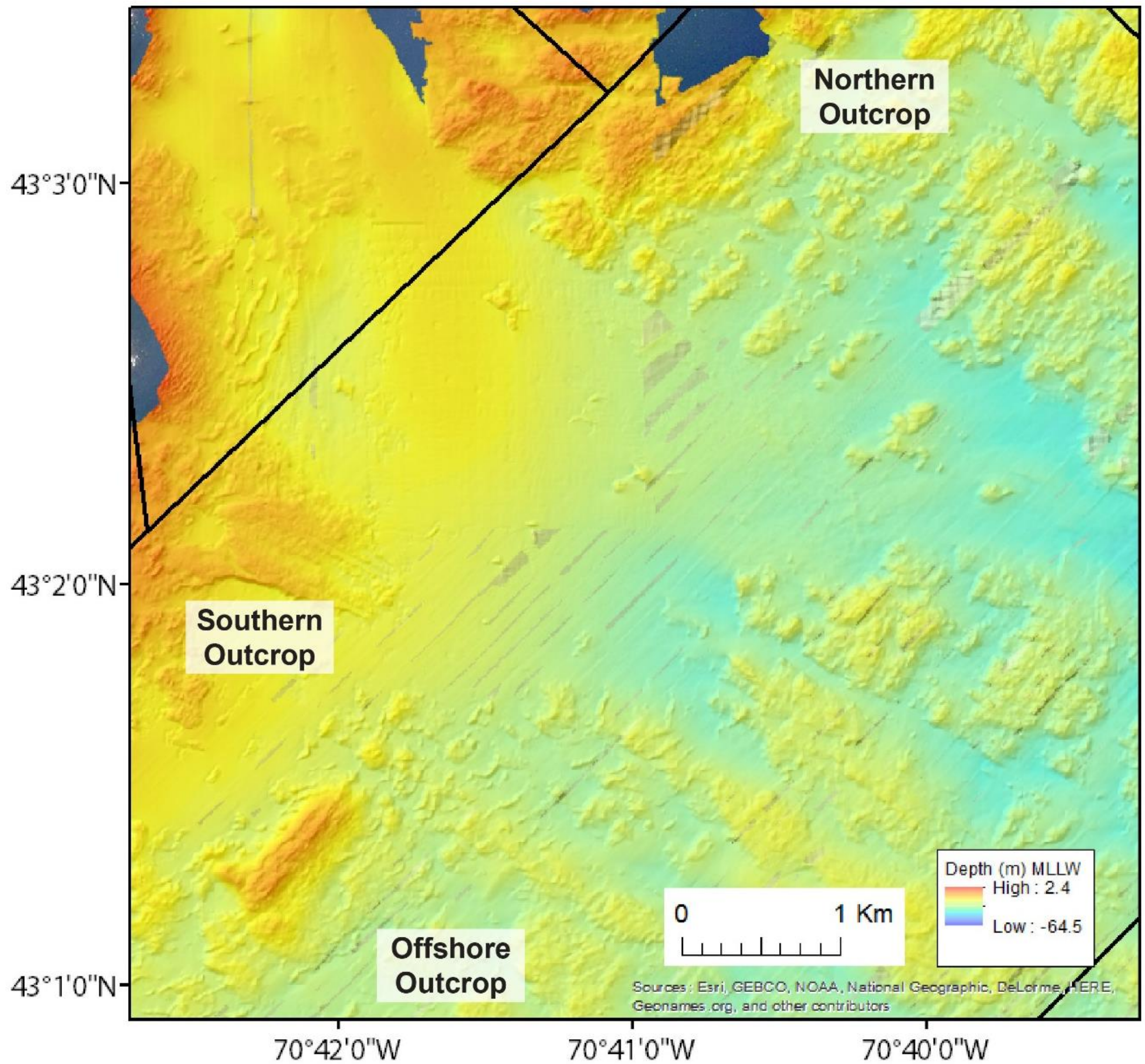

Figure 4-16: Bathymetry map of the Inner Shelf with vertical exageration of 10x (location shown in Figure 4-1). Showing locations of the regions of bedrock outcrops referred to as the northern, southern, and offshore bedrock outcrops for this study.

Backscatter and Bottom Sediment Classification. Overall, the backscatter intensity of the Inner Shelf (Figure 4-17) is lower than the Inner Harbor and Harbor Mouth (excluding the Sand Apron), indicating the seafloor of the Inner Shelf is primarily composed finer grained sediments.

A large portion of the Inner Shelf seafloor is an extension of the Sand Apron from the Harbor Mouth, a low backscatter intensity apron that extends offshore and to the south. Three sampling stations (7, 20, and 21) are located near the center of the Sand Apron. All samples from these stations are well sorted, unimodal, fine (3 phi) or very fine sand (3.5 phi) (Table 4-3, Appendix I). The Sand Apron connects to a second area of low backscatter intensity to the southwest. The two sediment samples from station 12, located within the second area, are also well sorted, unimodal fine sand (3 phi). At the eastern boundary of the Sand Apron, the backscatter intensity increases indicating the sediments become coarser. Stations 10 and 16 (located in this transitional area) are mostly poorly sorted, bimodal samples with modes at very find sand (3.5 phi) and pebble gravel (-3.5 phi or -4 phi) (Table 4-3, Appendix I). Samples 10C and 16A are the exceptions and lack the pebble gravel content.

Another transitional area of mixed low and high backscatter intensities is located just seaward of the moraine field in the Harbor Mouth. Station 14 confirmed the mixed environment. Sample 14A is a well sorted, unimodal fine sand (2.5 phi), and 14B is a poorly sorted, bimodal sample with modes of fine sand (2.5 phi) and pebble gravel (-2 phi) (**Table 4-3, Appendix 1)**.

The seafloor surrounding the northern bedrock outcrop is characterized by medium to high backscatter intensities. Only one sample from station 6 and one sample from station 17 were recovered, likely due to the proximity to the bedrock outcrops. Both samples are poorly sorted, bimodal samples with modes at medium sand (2 phi) and pebble gravel (-3 and -3.5 phi) (Table 4-3, Appendix I).

The medium to high backscatter intensity surrounding the northern outcrop appears to extend south to the offshore bedrock outcrop. Stations 8, 9, and 22 are within this region and are primarily poorly sorted, bimodal samples with modes at medium sand (2 and 2.5 phi) and pebble gravel (-

3 and -3.5 phi) (Table 4-3, Appendix I). Stations 11 and 19, located within the moraine field and the offshore bedrock outcrop, are similar being composed of poorly sorted, bimodal samples of coarse to medium sand (1 to 2 phi) and pebble gravel (-2.5 to -3.5 phi).

It should be noted the area between stations 9 and 11 at the seaward extent of the study area appears to have darker backscatter; however, this is due to loss of data and resultant errors in the backscatter lines and should not be considered real data (addressed in DISCUSSION). It is assumed the medium intensity backscatter (coarse sediments) continues across the seafloor from the northern bedrock outcrop to the southern offshore bedrock outcrop and moraine field.

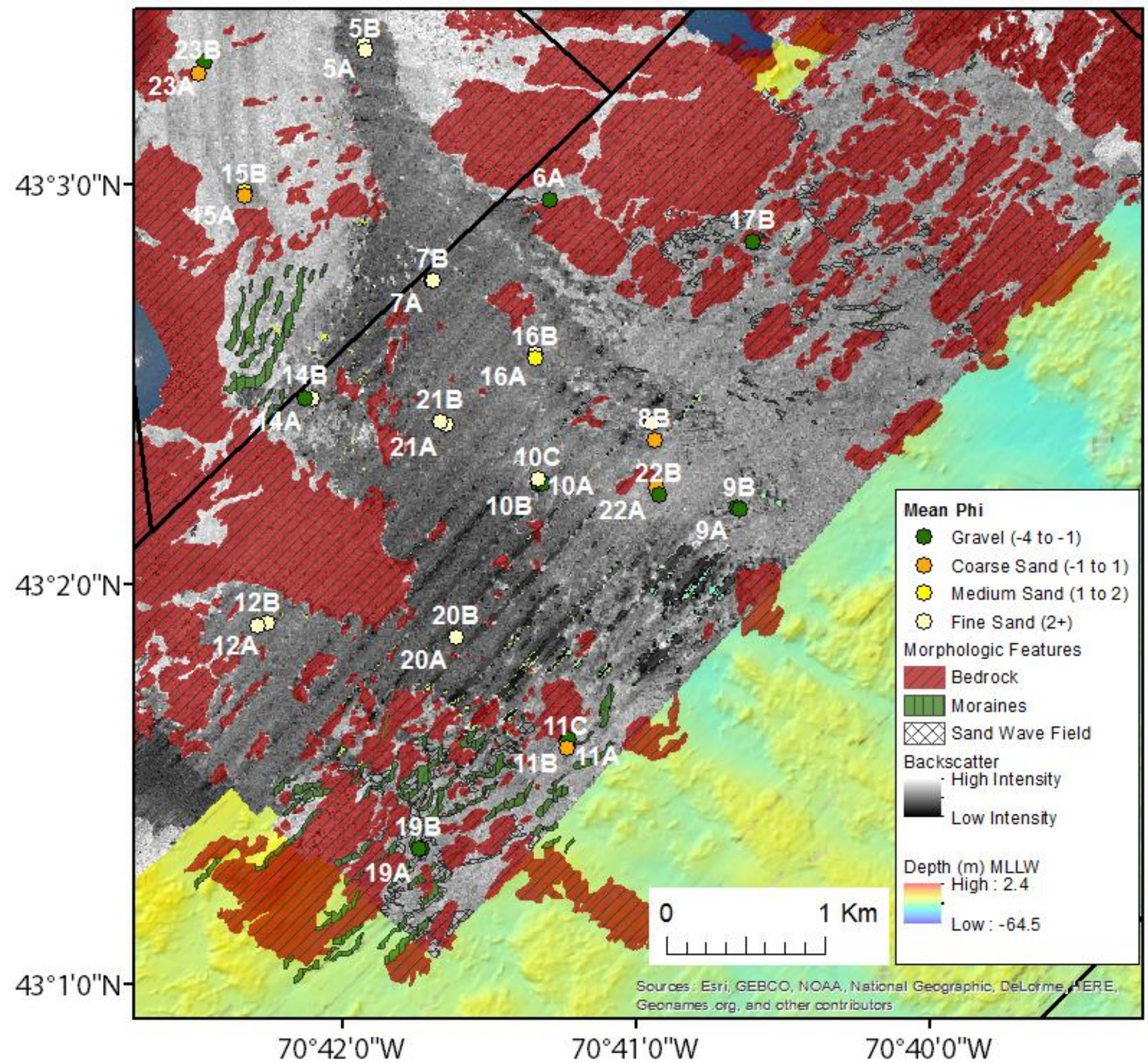

Figure 4-17: Backscatter map of the Inner Shelf over bathymetry with a vertical exageration of 10x (location shown in Figure 4-1). Sand wave fields are outline by black hash. Morphologic features (bedrock) are shown in red and the De Geer moraines are shown in green. Sediment samples are shown colored by mean phi size.

Table 4-3: Sediment grain size statistics for the Inner Shelf (sample locations shown in Figure 4-17).

Sediment Sample	Location (Lat/Long)	Depth (m)	Sediment Name (Wentworth)	Mode (unimodal or bimodal)	% Gravel	% Sand	% Mud	Mean Phi	Mean mm	LOI %	Sample Weight (g)
6A	43 02.9611 N 070 41.2952 W	18.3	Sandy Pebble Gravel	BM	62	37	1	-1.322	2.50	0.74	273.7
7A	43 02.7599 N 070 41.6940 W	14.6	Slightly Granule Gravelly Very Fine Sand	UM	0	98.7	1.3	2.996	0.13	0.72	66.7
7B	43 02.7584 N 070 41.6881 W	14.6	Slightly Pebble Gravelly Very Fine Sand	UM	0.3	98.3	1.4	3.011	0.12	0.66	197.5
8A	43 02.4030 N 070 40.9432 W	20.4	Slightly Granule Gravelly Fine Sand	UM	2.2	96.9	1	2.228	0.21	0.66	182.4
8B	43 02.3602 N 070 40.9362 W	20.4	Pebble Gravelly Medium Sand	BM	16.6	82.7	0.7	0.913	0.53	0.58	273.7
9A	43 02.1914 N 070 40.6543 W	24.4	Sandy Pebble Gravel	BM	48.1	51.3	0.5	-1.23	2.35	0.55	504.2
9B	43 02.1875 N 070 40.6465 W	24.4	Sandy Pebble Gravel	BM	49.1	50.4	0.5	-1.067	2.10	0.65	539.4
10A	43 02.2539 N 070 41.3308 W	18.9	Sandy Pebble Gravel	BM	67.5	31.5	1	-1.699	3.25	N/A	101.1
10B	43 02.2531 N 070 41.3178 W	18.9	Sandy Pebble Gravel	BM	64.2	34.2	1.6	-1.61	3.05	1.07	196.7
10C	43 02.2638 N 070 41.3334 W	18.9	Pebble Gravelly Fine Sand	UM	7.5	91.3	1.2	2.221	0.21	0.57	173.3
11A	43 01.6102 N 070 41.2332 W	24.4	Pebble Gravelly Medium Sand	UM	6.1	93	0.9	1.649	0.32	0.51	212.4
11B	43 01.6110 N 070 41.2278 W	24.4	Coarse Silty Sandy Pebble Gravel	BM	78.9	18.5	2.6	-2.294	4.90	0.80	40.3
11C	43 01.5904 N 070 41.2316 W	24.4	Sandy Pebble Gravel	BM	42	57.2	0.8	-0.351	1.28	0.97	348.2
12A	43 01.9036 N 070 42.2535 W	15.2	Slightly Granule Gravelly Fine Sand	UM	0.4	97.7	1.9	2.814	0.14	0.63	190.6
12B	43 01.8981 N 070 42.2880 W	15.2	Slightly Granule Gravelly Fine Sand	UM	0.1	97.8	2.2	2.816	0.14	0.61	185.3
14A	43 02.4642 N 070 42.1026 W	18.3	Slightly Granule Gravelly Fine Sand	UM	0.2	98.4	1.4	2.364	0.19	0.62	250.5
14B	43 02.4666 N 070 42.1263 W	18.3	Sandy Granule Gravel	BM	57.9	40.9	1.2	-1.14	2.20	0.76	285.4
17B	43 02.8568 N 070 40.6005 W	20.4	Pebble Gravel	BM	85.8	13.7	0.4	-2.724	6.61	1.35	408.2
19A	43 01.3377 N 070 41.7296 W	21.3	Sandy Pebble Gravel	BM	66.2	33.5	0.4	-1.608	3.05	1.52	401.8

Table 4-3 (continued): Sediment grain size statistics for the Inner Shelf (sample locations shown in Figure 4-17).

Sediment Sample	Location (Lat/Long)	Depth (m)	Sediment Name (Wentworth)	Mode (unimodal or bimodal)	% Gravel	% Sand	% Mud	Mean Phi	Mean mm	LOI %	Sample Weight (g)
19A	43 01.3377 N 070 41.7296 W	21.3	Sandy Pebble Gravel	BM	66.2	33.5	0.4	-1.608	3.05	1.52	401.8
19B	43 01.3377 N 070 41.7377 W	21.3	Sandy Granule Gravel	BM	73.5	26.1	0.4	-1.679	3.20	0.67	389.3
20A	43 01.8692 N 070 41.6099 W	17.7	Slightly Granule Gravelly Very Fine Sand	UM	0.2	97.6	2.2	2.956	0.13	0.47	98.0
20B	43 01.8680 N 070 41.6126 W	17.7	Slightly Granule Gravelly Very Fine Sand	UM	0.8	97.2	2	2.941	0.13	0.71	103.5
21A	43 02.4010 N 070 41.6455 W	15.2	Slightly Pebble Gravelly Fine Sand	UM	1.5	96.5	2	2.948	0.13	0.71	195.7
21B	43 02.4073 N 070 41.6671 W	15.2	Slightly Granule Gravelly Fine Sand	UM	0	97.4	2.5	2.904	0.13	0.78	113.3
22A	43 02.2436 N 070 40.9314 W	20.7	Sandy Pebble Gravel	BM	42.3	57.3	0.4	-0.265	1.20	0.52	381.7
22B	43 02.2236 N 070 40.9184 W	20.7	Sandy Pebble Gravel	BM	53.1	45.8	1.1	-1.159	2.23	0.59	432.3

Seafloor Geology. The overall lower backscatter intensity of the Inner Shelf (compared to the Inner Harbor and Harbor Mouth) indicating generally finer grained sediments, is somewhat misleading. The seafloor surrounding and connecting the northern and offshore bedrock outcrop is primarily sandy gravel (based on most of the stations that were located outside of the Sand Apron) (Figure 4-18). The Sand Apron originating from the Harbor Mouth remains a fine sand (based on several stations), and narrows moving south, wrapping around the southern bedrock outcrop and connecting to another region of fine sand (based on station 12). This second region of fine sand appears to be associated with the nearshore ramp extending from Wallis Sands New Hampshire State Beach. The seafloor around the offshore bedrock outcrop and moraine field is scattered with bedform areas (sand wave fields) and are assumed to be medium to coarse sand.

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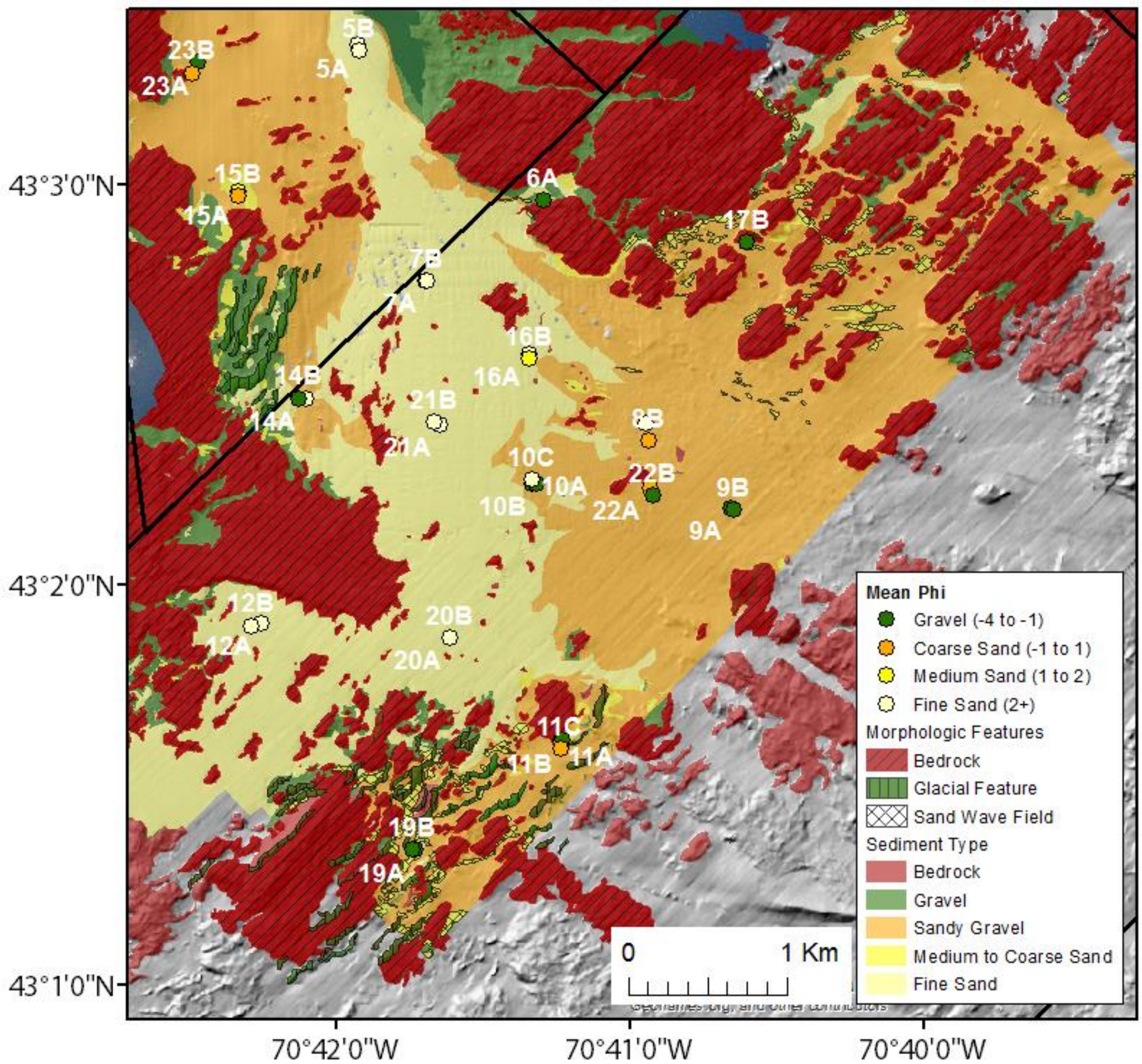

Figure 4-18: Surficial geology map of Inner Shelf (location shown in Figure 4-1). Sediment sample locations shown by colored points. Morphologic features (bedrock and sand wave fields) are shown in red and hash marks. De Geer moraines are shown by green with lines.

Seismic Stratigraphy. The Inner Shelf has a total of 17 seismic profiles, 5 profiles from the 2007 IKB survey and 12 profiles from the Birch survey, 9 shore parallel and 8 shore perpendicular (Figure 4-19).

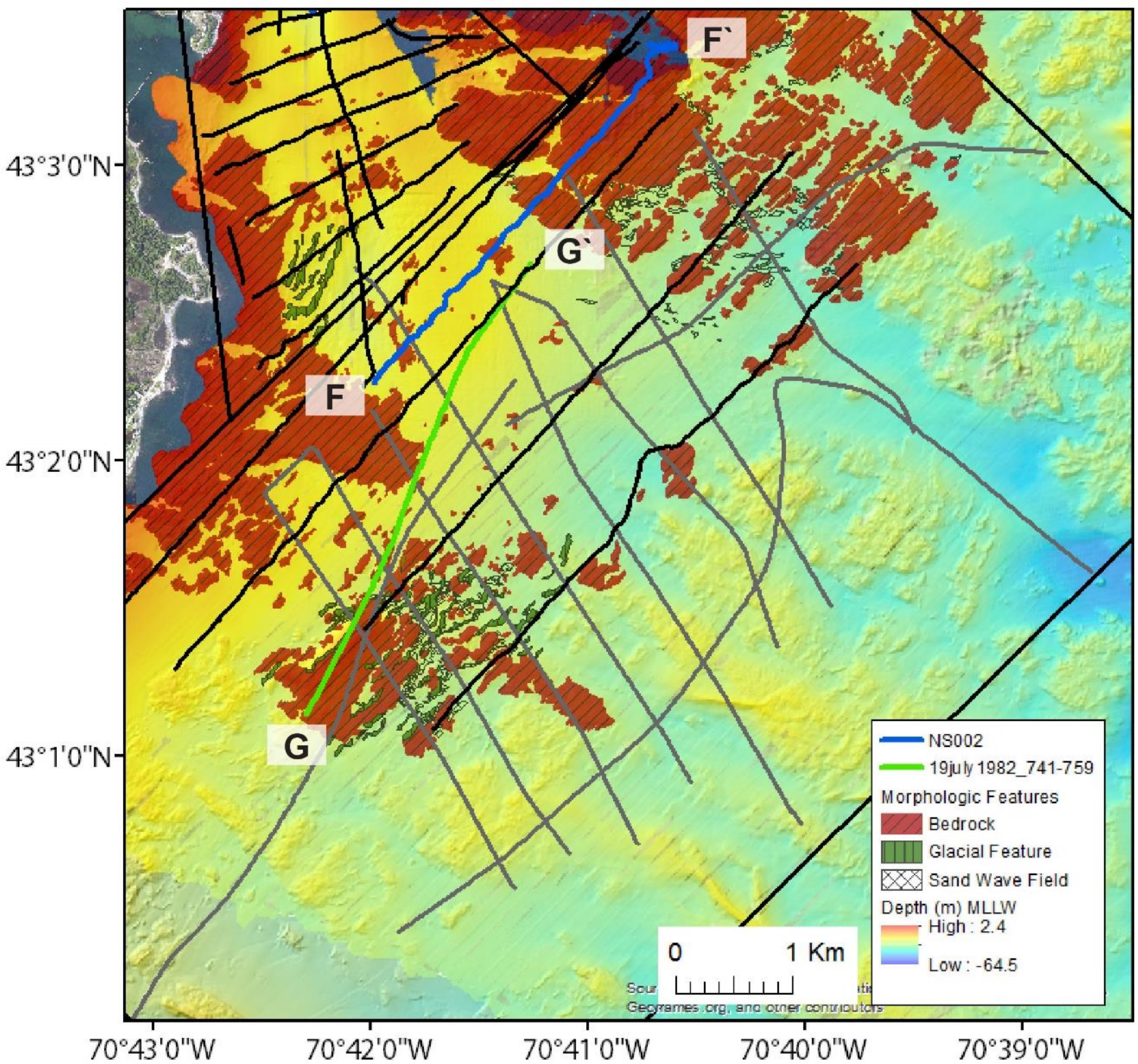

Figure 4-19: Seismic lines within the Inner Shelf (location on Figure 4-1) over bathymetry (x10 vertical exaggeration) with morphologic features identified (sand wave fields, bedrock outcrops, and moraines). IKB Seistec seismic profiles shown in black and Birch seismic profiles shown in grey. Seismic profile NS002 shown in blue (F-F`) and 19july1982_741-759 (G-G`) shown in green.

Seismic profiles NS002 (Figure 4-20) and 19july1982_741-759 (Figure 4-21) both provide similar overviews of the paleochannel, channel fill sequence, and sand mound. Both profiles show a large paleochannel with steep bedrock (Br) walls that drop sharply to ~40 to ~45 m below psl. The paleochannel is crossed by a dark reflector (~20 to ~24 m below psl) that is interpreted as an erosional Unconformity (Un). The underlying stratified unit filling the paleochannel is interpreted as glaciomarine (Gm) sediments (Figure 4-20 and 4-21). The stratified unit above the erosional unconformity, which mounds to cap the paleochannel fill sequence, is interpreted as Holocene sediments (Hc). Within seismic profile NS002 (Figure 4-20), the unconformity cuts ~3 m into the underlying glaciomarine sediments and appears to be the most focused evidence of downcutting during the sea-level lowstand, likely due to fluvial erosion.

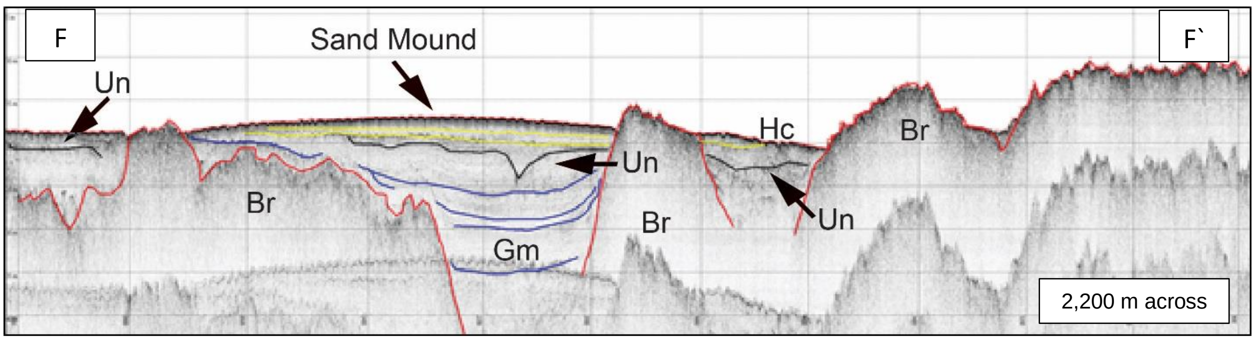

Figure 4-20: Seismic profile NS002. View is landward with New Hampshire on left (F) and Maine on right (F`). The vertical exaggeration is 10x. The Sand Mound and Holocene sediment (Hc) reflectors are shown in yellow and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red. Sand Mound feature shown with arrow.

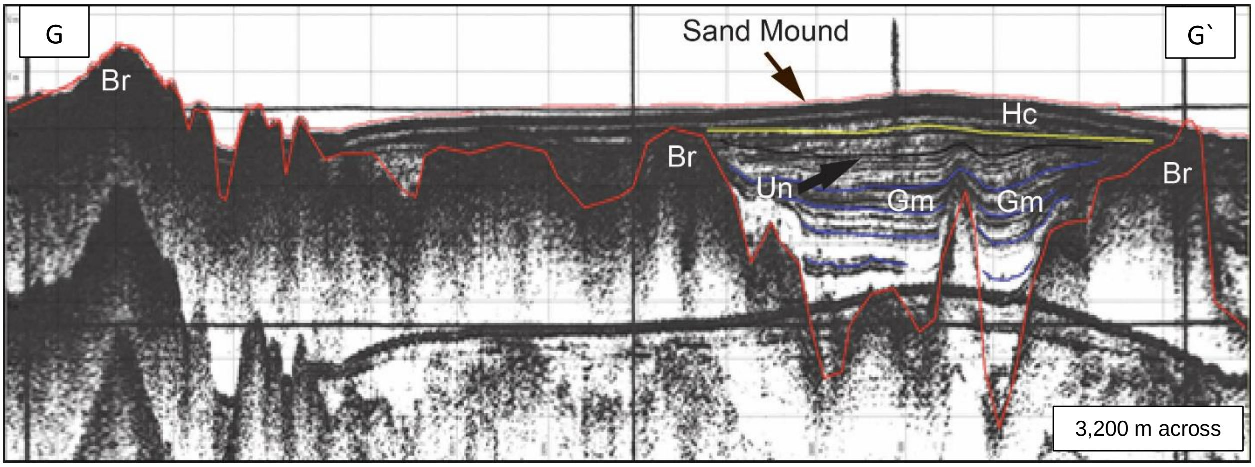

Figure 4-21: Seismic profile 19july1982_741-759. View is landward with New Hampshire on left (G) and Maine on right (G`). The vertical exaggeration is 10x. The Sand Mound and Holocene sediment (Hc) reflectors are shown in yellow and the Unconformity (Un) is highlighted in black. The Glaciomarine sediments (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red. Sand Mound feature shown with arrow.

Chapter 5

DISCUSSION

The surficial geology mapped and described in this study, coupled with the seismic stratigraphy of the major morphologic features and surrounding areas, reveal surficial and subbottom characteristics of each of the sections of the study area. Here, the morphologic features along with the associated seismic stratigraphy characteristics are summarized and related to the major forcings (sea-level fluctuations, glaciation, and marine or fluvial processes) that influenced the depositional history of Portsmouth Harbor and adjacent inner continental shelf.

Surficial Geology Map

The study area is extremely heterogeneous (Figure 5-1) as a result of the local bedrock geology and the influences of the Late Quaternary glaciation, sea-level fluctuations, and marine processes. Throughout the study area the bedrock has a major control on the surficial environments, forming extensive rocky outcrops and constricting the channel in Portsmouth Harbor. Glacial deposits, now extensively reworked by marine processes, provide sediments to the shelf resulting in large areas of very coarse grained sediments. The majority of the seafloor in the study area that is not bedrock is a sandy gravel mixture, which is likely a result of the erosion of local bedrock, reworking of glacial deposits, and a low sediment input from the Piscataqua River. Clearly, the seafloor was modified during the present transgression and fine sediments were likely winnowed and deposited further offshore. The exceptions to the general overall coarseness of the sediment of Portsmouth Harbor and the inner shelf are the large sand wave field within the inner harbor and the apron of fine sand that extends seaward from the harbor mouth.

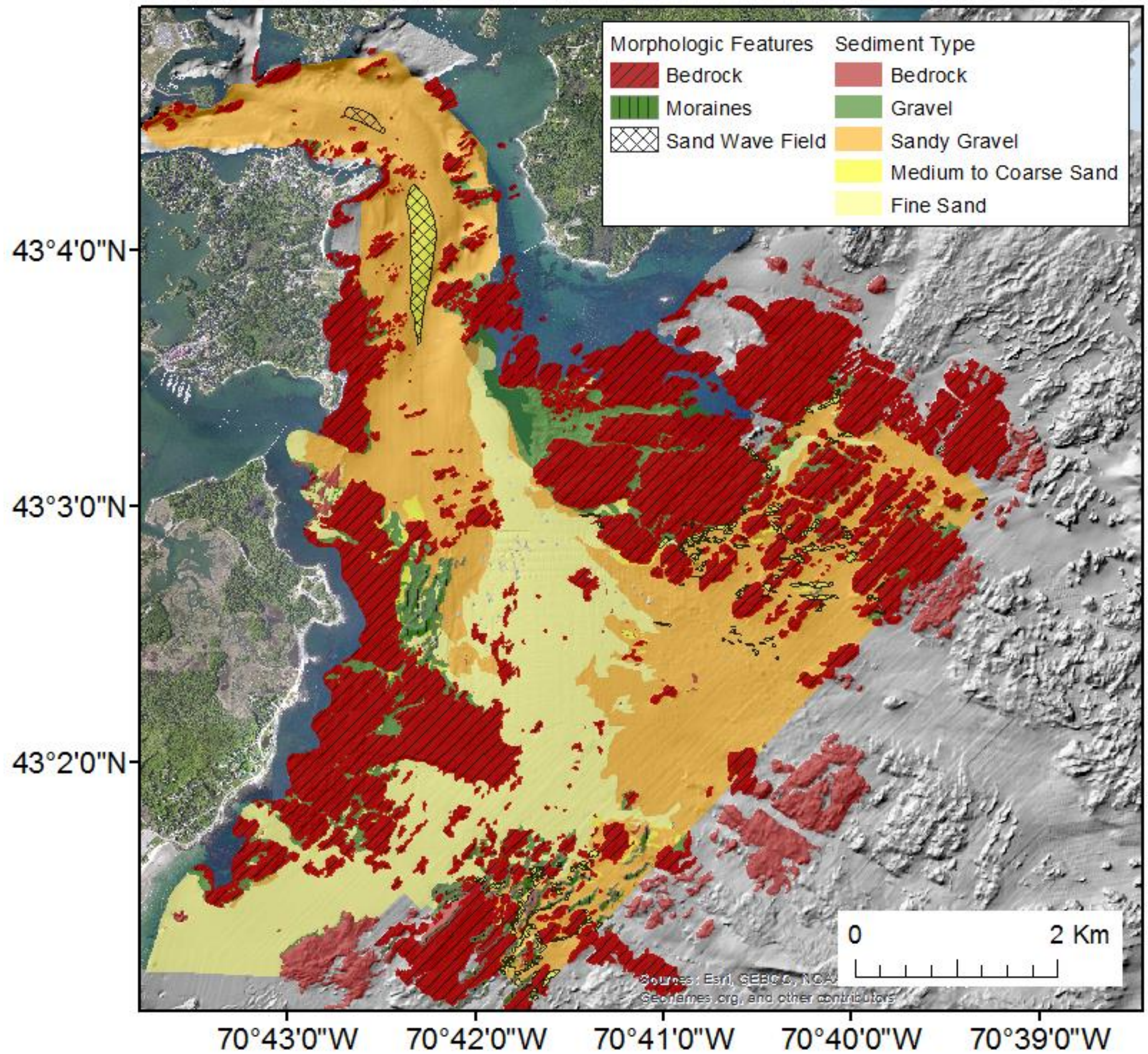

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Figure 5-1: Surficial geology map of Portsmouth Harbor and the adjacent inner shelf showing morphologic features and sediment type.

Seismic Stratigraphy

Paleochannel and Channel Fill Sequence. One of the most prominent features in the seismic stratigraphy is a paleochannel that runs through the entire study area. The previously untraced paleochannel was likely shaped (e.g. steepening of channel walls) during the advance of the Laurentide Ice sheet (Pratt and Schlee, 1969; Ives, 1978; Barnhardt et al., 1997; Schnitker et al., 2001).

A depth to bedrock surface was created to trace the path of the paleochannel through the harbor and onto the inner shelf using the depths of visible bedrock reflectors from both seismic surveys (Figure 5-2). The paleochannel is first seen prior to the bend in the river channel running along the right bank (Maine). After the bend, the paleochannel moves towards the center of the present river channel before again shifting slightly towards the right bank (Maine) in the Harbor Mouth. Once on the Inner Shelf, the paleochannel appears to curve slightly north before continuing offshore.

In Figure 5-2, the paleochannel appears to shallow at the mouth of the harbor. However, this shallowing is an artifact of the methodology used to define the paleochannel. The bedrock reflectors in the Harbor Mouth were not traceable below ~25 m (Appendix II). In the Harbor Mouth seismic profiles, the bottom of the channel is assumed to be deeper than ~25 m, but the bedrock reflector was covered by multiples and was not visible. Therefore, the true depth of the paleochannel was not traced throughout the entire survey area. Figure 5-2 is based on the depths of the observed bedrock. It is assumed that the paleochannel remains at a similar depth (~35 to 40 m depth) throughout Portsmouth Harbor and deepens (>40 m depth) moving offshore.

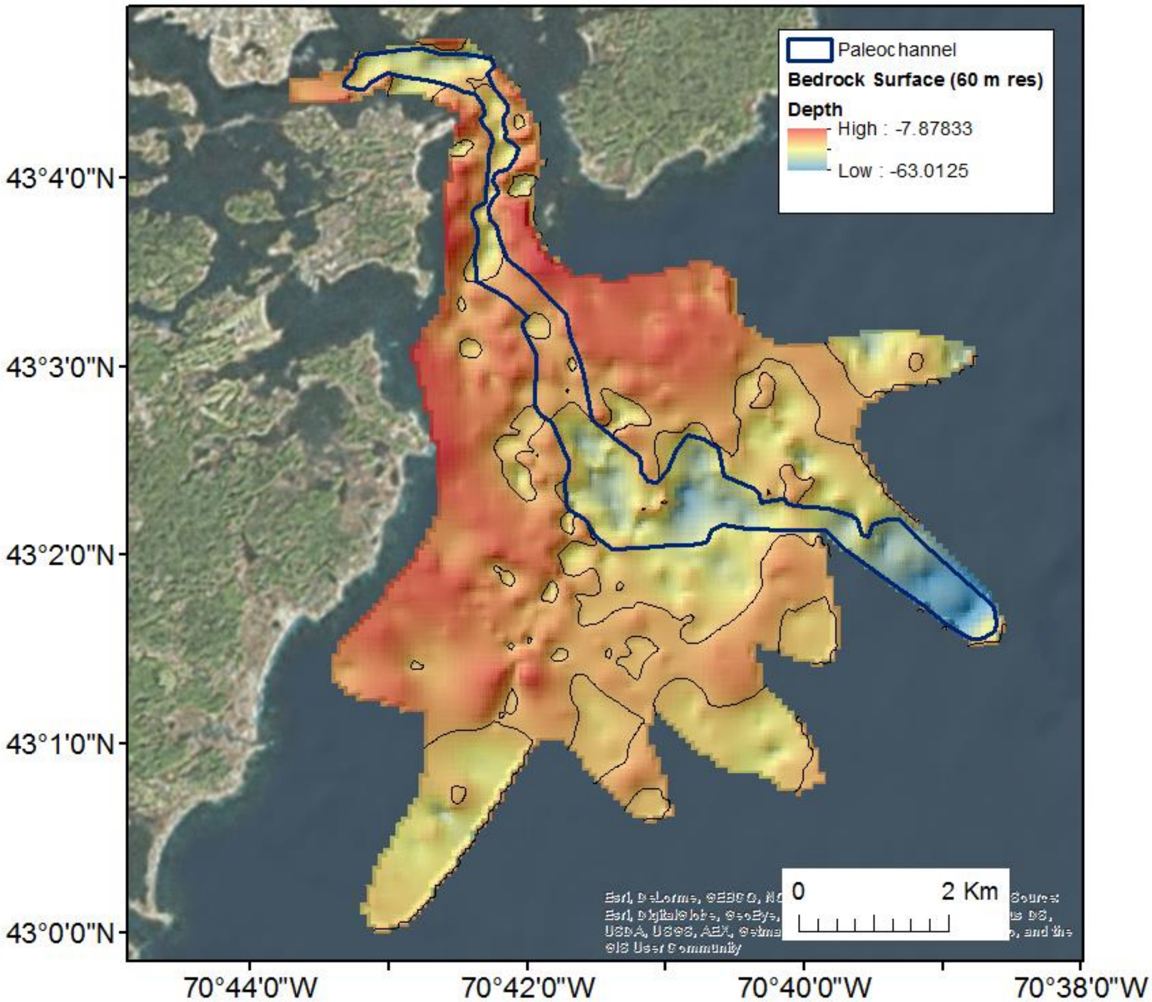

Figure 5-2: Depth to bedrock surface based on all of the seismic data analyzed for this study. Bedrock paleochannel location outlined in dark blue.

Offshore (the Inner Shelf) the paleochannel fill sequence provides the most direct view of the changes in depositional environments (Figure 5-3; Appendices II & III). The glaciomarine sediments (Gm) were deposited during the sea-level highstand that followed the retreat of the ice front (Birch, 1984; Barnhardt et al., 1997). The subsequent sea-level lowstand exposed the glaciomarine sediments to subaerial erosion including fluvial processes within the study area (Oldale et al., 1983; Birch, 1984; Belknap et al., 1987; Kelley et al., 1989; Shipp et al., 1991). It is likely that the glaciomarine sediments within the Piscataqua River paleochannel were eroded during the sea-level lowstand and the beginning of the present transgression. This erosional period is marked by the unconformity (Un) seen throughout the study area (Appendices II & III). The present transgression submerged the inner shelf and corresponds to the start of Holocene sediment (Hc) deposition, observed overlying the unconformity in the paleochannel and bedrock depressions. The Sand Mound that caps the paleochannel fill sequence is included in the Holocene sediment unit.

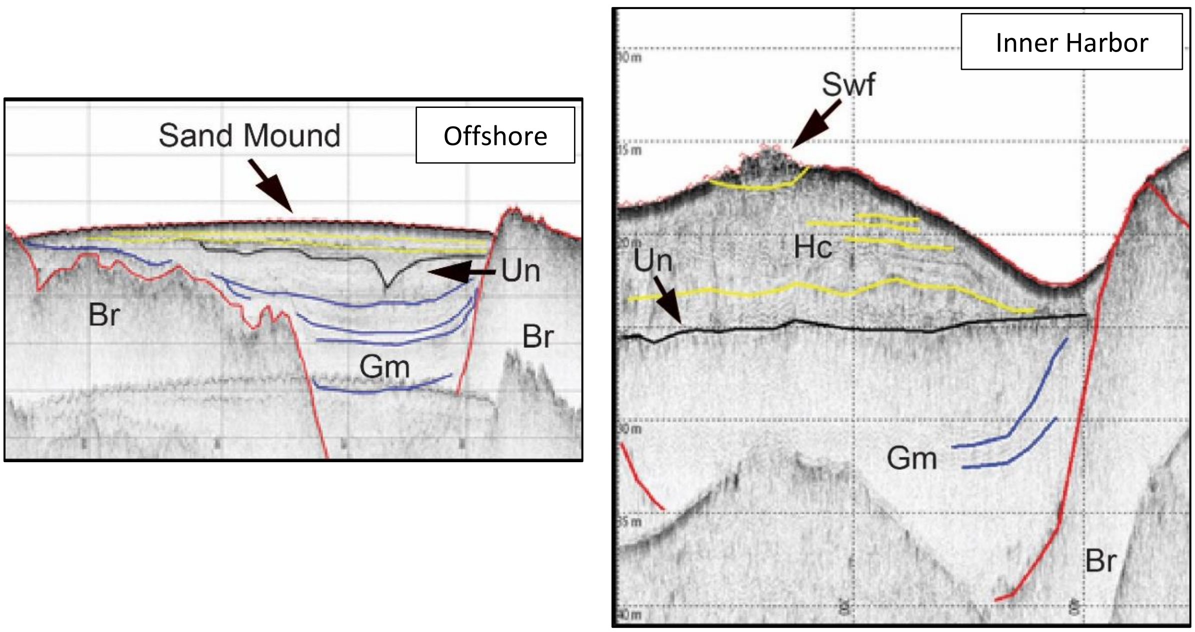

Figure 5-3: View of paleochannel fill sequence on the Inner Shelf (left box) from seismic profile NS002 and in the Inner Harbor (right box) from seismic profile XC010. Holocence sediments (Hc), which include the Sand Mound and Sand Wave Field (Swf), shown in yellow. Unconformity (Un) highlighted by black. Glaciomarine sediments (Gm) in blue and bedrock (Br) highlighted in red.

The Inner Harbor paleochannel fill sequence is similar to the Inner Shelf and the Harbor Mouth (Figure 5-3; Appendices II & III); however, the overall channel fill sequence shows increased variability due to evidence of an estuarine point bar that may represent the influence of the slowstand on the system. Above the erosional unconformity (Un) at the channel bend, a unit of layered, downward dipping beds potentially indicate estuarine point bar deposition (Figure 5-4). Since the point bar deposit is above the unconformity, which is assumed to represent the transition from lowstand to the present transgression, it is assumed that the point bar was deposited after the initial flooding of the system and during a period of slower sea-level rise, the slowstand. The depth of the point bar (~23 to ~18 m below psl) corresponds to the sea-level slowstand around 11,500-8,000 yr B.P. (based on the Maine relative sea-level curve).

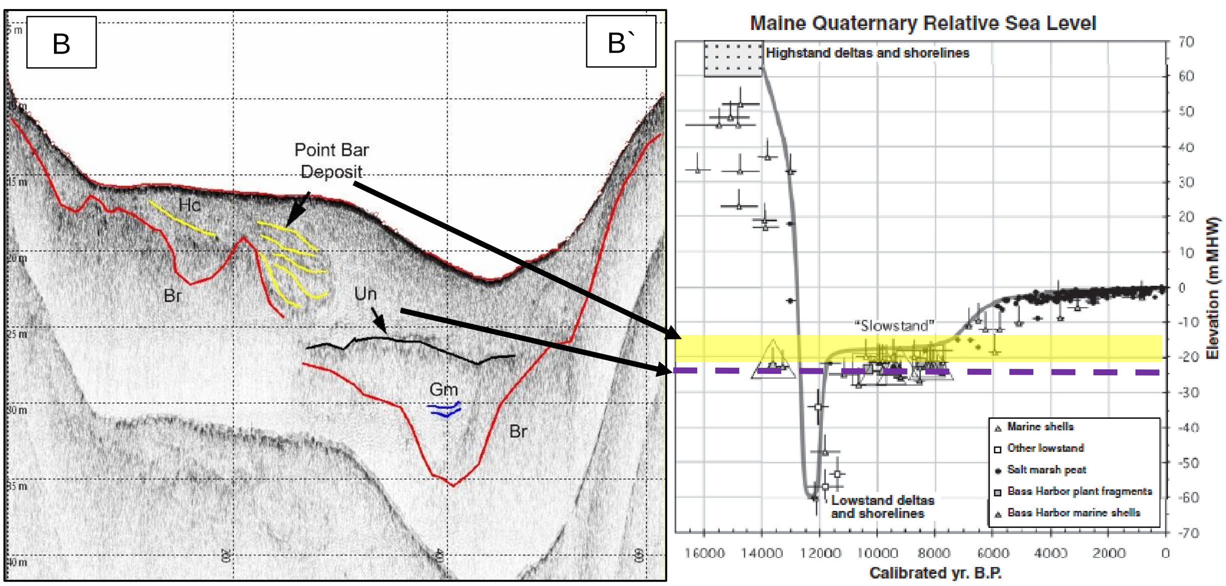

Figure 5-4: Seismic Profile UNH013 (left), location shown in Figure 4-6. View is upriver with New Hampshire on left (B) and Maine on right (B`). The vertical exaggeration is 10x. Holocene sediment (Hc) reflectors and estuarine Point Bar Deposit are shown in yellow, and the Unconformity (Un) is highlighted in black. The Glaciomarine sediment (Gm) reflectors are shown in blue and Bedrock (Br) is traced in red. Maine Quaternary Relative Sea Level curve (right) (from Kelley et al., 2010) with the following depths highlighed: 25 m below psl (purple dashed line) and 23 to 16 m below psl (yellow). Note the relationship between the depth of the unconformity (Un) (25 m bsl) and the depth of the point bar deposit (~24 to 17 m bsl) to the relative sea-level curve.

Moraine Fields. The glacial moraines on the Inner Shelf and within the Harbor Mouth reflect one of the features of the late Quaternary glaciation in the study area (Figure 5-5). These features are assumed to be De Geer moraines based their apparent morphology. De Geer moraines are widely recognized features of ice margin retreat in coastal regions and were recently identified in New Hampshire (Sinclair, 2015), based on shaded-relief LiDAR digital elevation models (analogous to the bathymetry and hillshade used in this study). The inland moraines are clusters of regularly-spaced, narrow ridges with an average length of 885 m, width of 30 m, and height of 1.2 m. This agrees with the morphology of the two moraine fields within this study (Figure 5-5). The moraine field offshore shows an average spacing of ~75 m and an average height of ~1.5 m (Figure 5-6). No internal structure could be determined from the seismic profiles used in this study. It is likely the finer grained sediments were winnowed out of the surficial sediments of the offshore moraines due to their exposure and re-submergence during to sea-level changes.

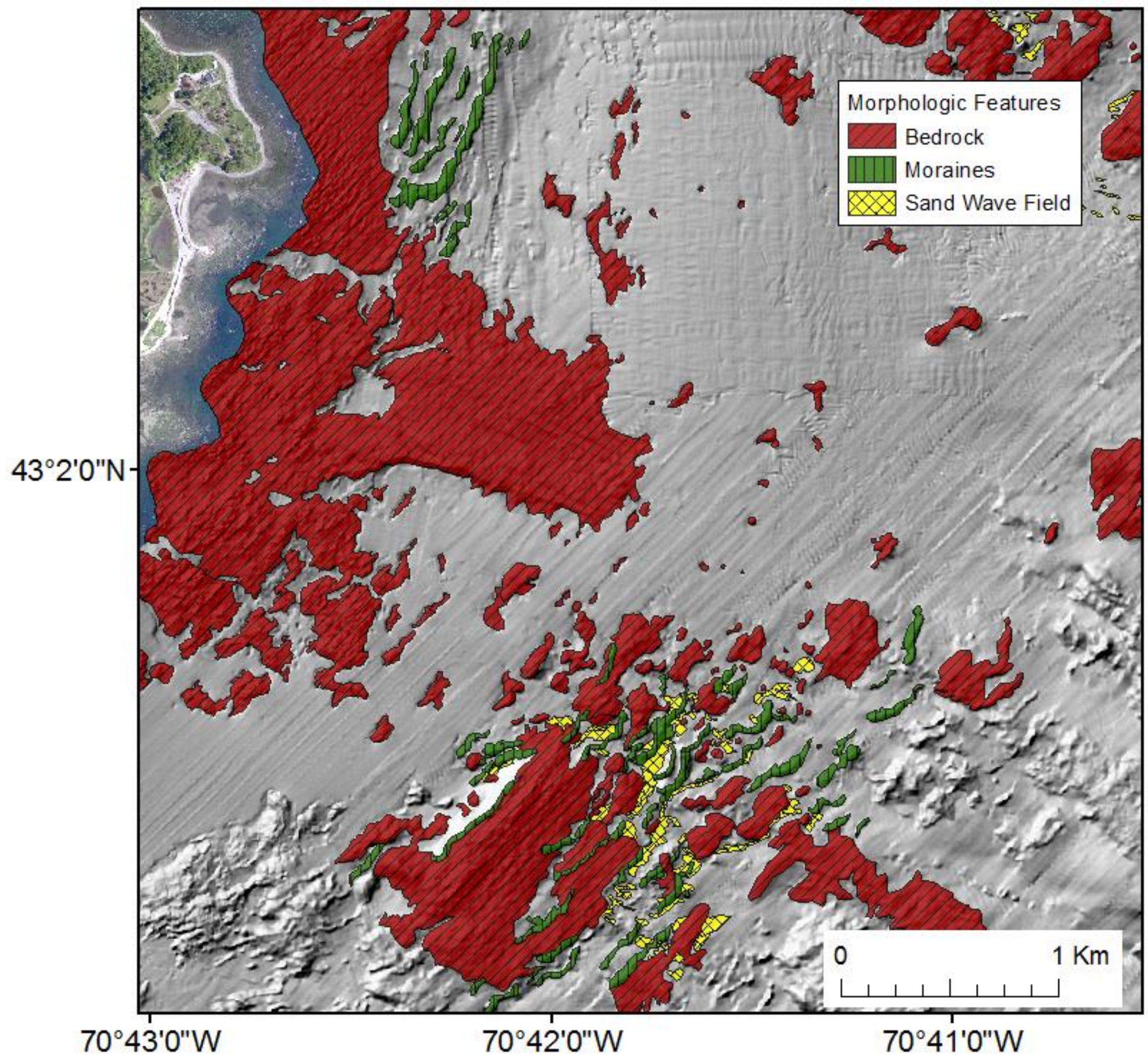

Figure 5-5: Location map of glacial moraines within Portsmouth Harbor and on the adjacent inner continental shelf. Moraines are highlighed by green.

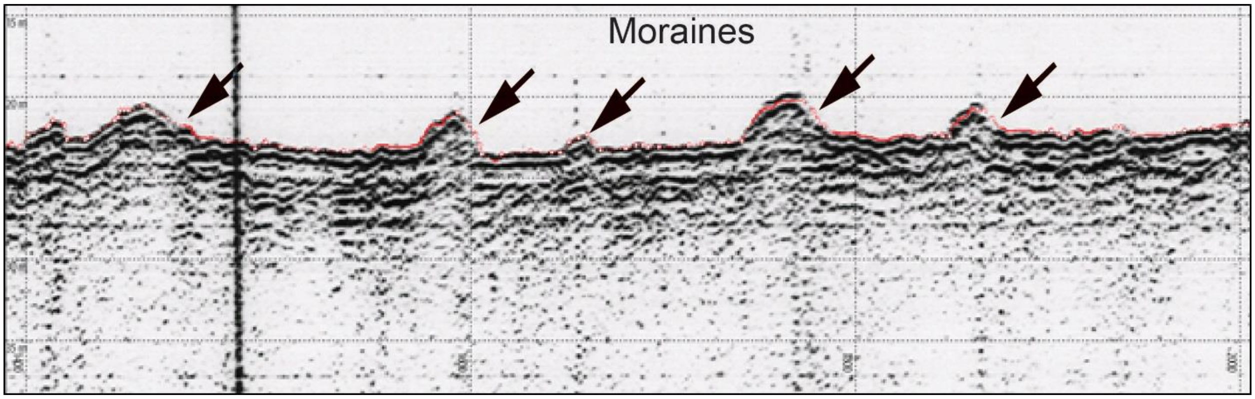

Figure 5-6: Seismic profile 16july1985_816-915, crossing over Inner Shelf De Geer moraine field. General spacing between moraines is between ~50 to 100 m and generaly height is ~1-2 m tall.

Sand Mound. The seismic unit identified as the Sand Mound is assumed in this study to be the subsurface expression of the Sand Apron feature identified in the backscatter. The characteristics of the Sand Mound unit is mounded unit ranging from 0.5 to 3 meters in the middle that thins on either side (Appendix II & III). A comparison of the paleochannel, Sand Mound, and Sand Apron locations (Figure 5-7) shows a correlation of the three within the Harbor Mouth, but a divergence of the Sand Mound and Sand Apron from the paleochannel moving offshore. Offshore the Sand Apron expands beyond the Sand Mound, likely due reworking of the sediments from tidal currents and storm waves. Unfortunately, the data in this study offers little explanation on the formation of the Sand Mound. It is assumed that the initial deposition of the Sand Mound occurred within the paleochannel since it represented a bathymetric low. However, this does not explain why the Sand Mound diverges from the paleochannel moving offshore. The divergence could be explained if deposition of the Sand Mound is ongoing, since the offshore paleochannel is filled and no longer represents a bathymetric low.

It is unclear from the work done in this study if the Sand Mound is a relic depositional feature that is being reworked, or is an area of ongoing sediment deposition. If the Sand Mound and Sand

Apron is an area of ongoing deposition, it could represent a potential renewable sand resource on the New Hampshire inner continental shelf. Further work is needed to define the sedimentary composition and thickness of the sand mound in order to determine if this feature is a sand resource.

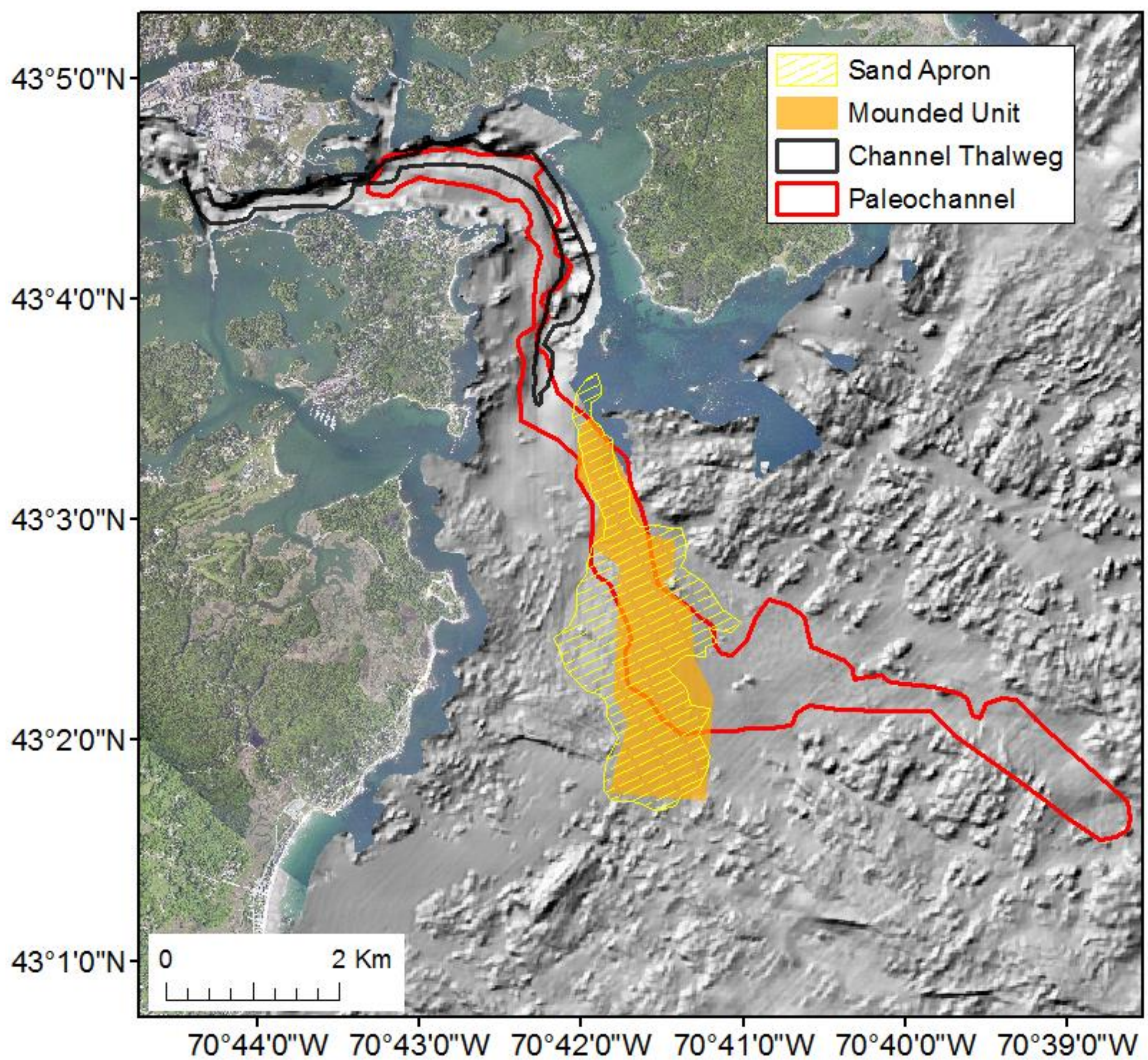

Figure 5-7: Location of the bedrock paleochannel (red), the present channel thalweg (black), the Sand Apron (yellow dashes), and the Sand Mound seismic unit (orange). Vertical exageration of 10x (hillshade).

Further Considerations

Acoustic backscatter, the return of the acoustic signal from the seafloor, is affected by a number of factors including the characteristics of the water column and the seafloor. Backscatter is also affected by the frequency and the angle at which the acoustic signal interacts with the seafloor (Weber and Ward, 2015). Therefore, interpreting the seafloor sediments based solely on backscatter intensity can be misleading. For example, within this study, the backscatter intensity from the EdgeTech 4600 survey did not always agree with the ground-truth data. One area where this is apparent is the Portsmouth Harbor channel thalweg, which contains a lower backscatter intensity signature and disagrees with the bottom image of a gravelly seafloor (Figure 5-8). This indicates that something other than the grain size and bottom roughness affected the backscatter intensity signal. Archived sediment samples from Ward (1995) cover the general area of the channel thalweg and have mean grain sizes that range from fine sand (>2 phi) to gravel (-1 to -4 phi). However, the actual locations of the sampling sites from the Ward (1995) survey is somewhat ambiguous due the use of Loran-C navigation. Nevertheless, the general sense from the available data is that the channel thalweg within Portsmouth Harbor has higher gravel content (Figure 5-8) than is interpreted from the backscatter intensity.

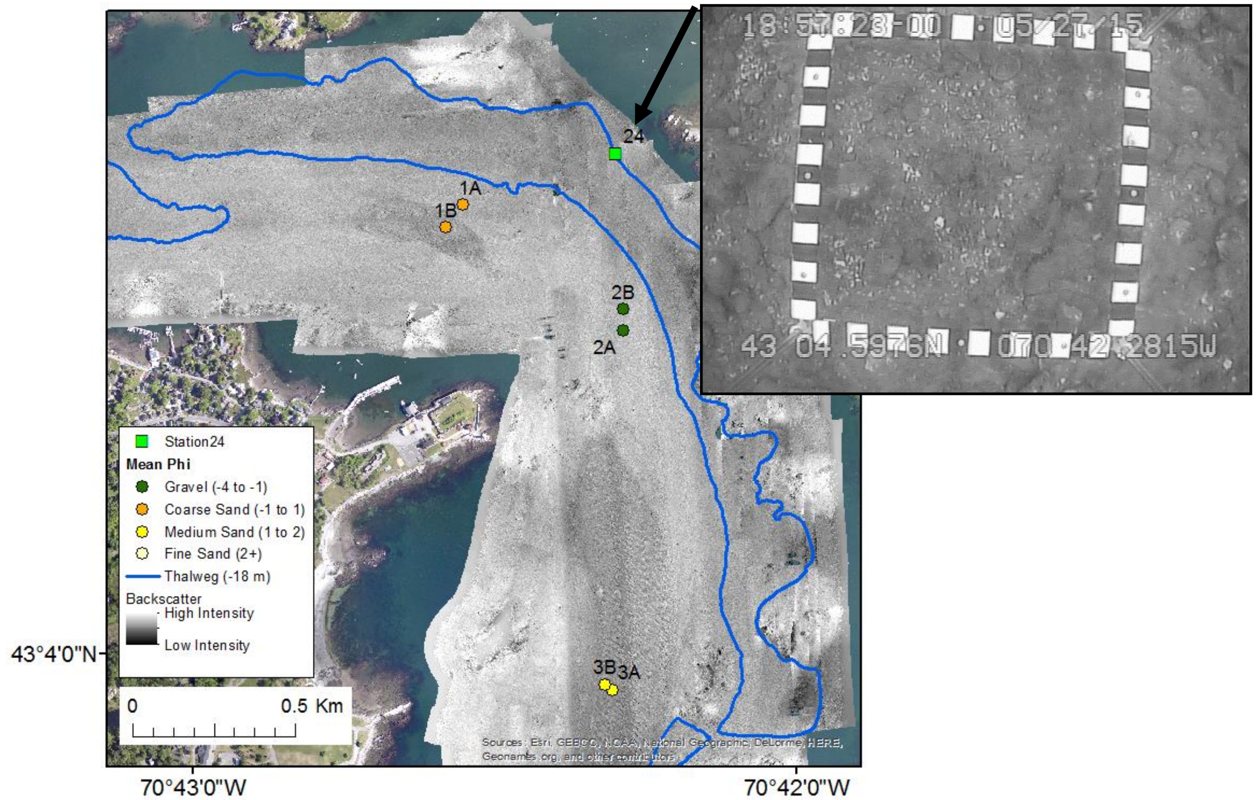

Figure 5-8: Backscatter map of Inner Harbor (location in Figure 4-1) with channel thalweg shown in blue and sediment samples showen by mean phi size. Station 24 shown by green square with bottom video image.

This highlights the importance of ground-truth with both sediment samples and bottom images. The bottom image for station 24, when no sediment sample was recovered, provided the necessary data to interpret the backscatter intensity data (Figure 5-8).

Another consideration is how the EdgeTech 4600 backscatter map was created. The data from the whole study area, which was highly diverse, was mosaicked in Fledermaus Geocoder to create the map. This means that a single intensity range (grayscale) was used to represent the entire study area. It is possible that creating separate backscatter maps for each section (Inner Harbor, Harbor Mouth, and Inner Shelf), which would only consider the backscatter intensity range for that specific region of the study area, would have allowed the differences in backscatter intensities for each section to be better highlighted.

Chapter 6

CONCLUSION

The surficial geology of Portsmouth Harbor and the adjacent shelf is highly variable, including bedrock outcrops, gravel fields, areas of coarse sand to gravel, and a fine sand apron. Much of the study area is composed of a mixture of sand and gravel, indicative of reworked glacial sediments. A Sand Apron that extends offshore and corresponds to a Sand Mound identified in the seismic stratigraphy represents a possible future sand resource for beach nourishment efforts. However, further study should be done to determine the origin of the Sand Mound (e.g. relic deposit or actively forming feature). Other major morphologic features include two sand wave fields within the Inner Harbor and two moraine fields. The moraine fields are assumed to be De Geer moraines, which are formed close to the ice front and were recently identified inland of the study area (Sinclair, 2015).

The advance of the Laurentide Ice Sheet modified the underlying bedrock and likely steepened the channel walls of the bedrock paleochannel identified in this study. Evidence of the sea-level highstand is seen within the paleochannel as highly stratified seismic units, which are presumed to be the glaciomarine sediments identified as the Presumpscot Formation. Downcutting into the glaciomarine sediments in a seismic profile from the inner shelf provides an example of fluvial erosion within the study area during the lowstand. However, this is the only clear evidence of fluvial erosion. Erosion during the lowstand and subsequent transgression is represented in the majority of the study area as an erosional unconformity that separates the underlying glaciomarine sediments from the Holocene sediments deposited during the present transgression. A possible estuarine point bar deposit found at the channel bend within the Inner Harbor is likely related to the slowstand that occurred around 11,500 – 8,000 yr B.P.

Further areas of study related to this work include tracing the paleochannel path as it continues across the continental shelf, determining the origins of the Sand Apron and Sand Mound, and an assessment of the Sand Mound as a viable sand resource.

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APPENDIX I

Shown here are the detailed grain size analysis results for all sediments samples collected during this study. The locations are shown in Figure I-1. Table I-1 shows the number of samples collected at each station. Table I-2 shows the percentage of gravel, sand, mud, and the mean phi/mm of each sample processed. Figures I-2 through I-22 show the detailed grain size analysis and pictures of each sample by station.

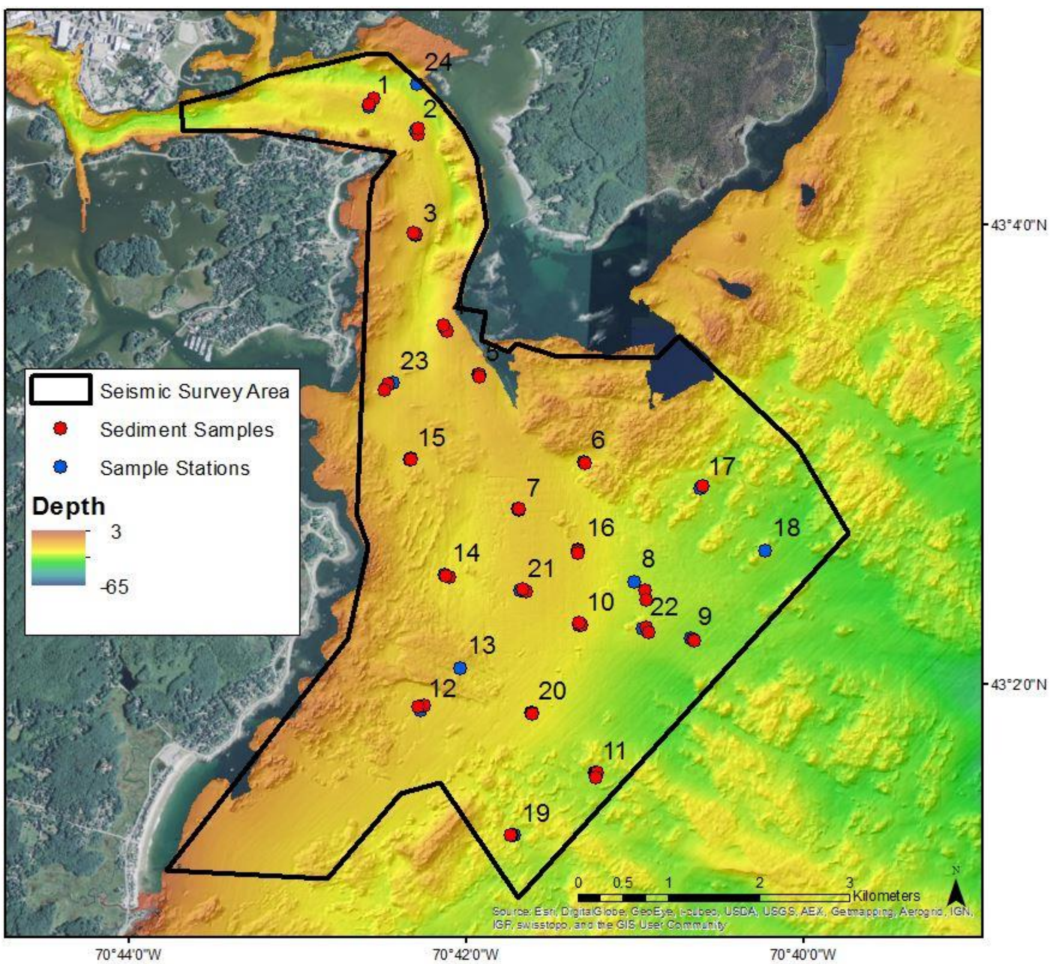


Figure I-1: Bottom video (blue) and sediment sample locations (red). Bathymetry is from the Western Gulf of Maine Bathymetry and Backscatter Synthesis (http://ccom.unh.edu/project/wgom-bathbackscatter), with vertical exageration of 6x.

Table I-1: Number of sediment samples and bottom photographs (from bottom videos)

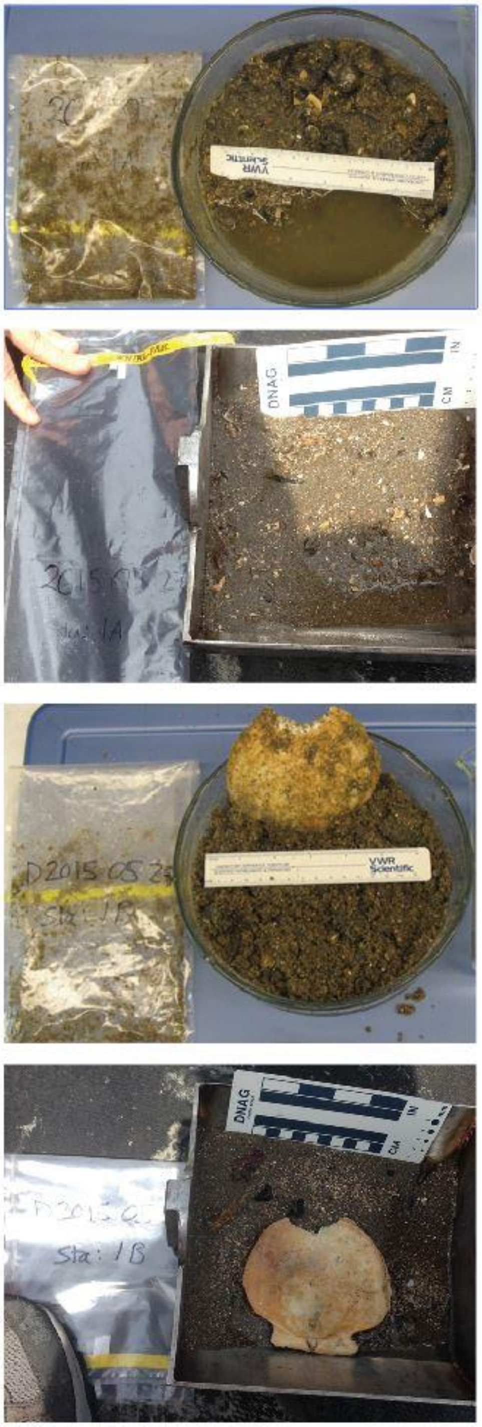
Sampling Station	Sediment Samples Analyzed	Bottom Photographs
1	2	6
2	2	11
3	2	7
4	3 - 4A Run Twice	8
5	2	10
6	2	9
7	2	9
8	2	5
9	2	6
10	3	9
11	3	9
12	2	9
13	0 - No Sample Recovered	6
14	2	8
15	2	10
16	2	10
17	1 - 17B Too Small	4
18	0 - No Sample Recovered	8
19	2	9
20	2	7
21	2	9
22	2	9
23	2	8
24	0 - No Sample Recovered	6

Table I-2: Sediment sample grain size analysis and LOI results

Sediment Sample	Location (Lat/Long)	Depth (m)	Sediment Name (Wentworth)	Mode (unimodal or bimodal)	% Gravel	% Sand	% Mud	Mean Phi	Mean mm	LOI %	Sample Weight (g)
1A	43 04.5451 N 070 42.5531 W	15.2	Sandy Pebble Gravel	BM	39.5	59.6	0.9	-0.278	1.21	0.89	265.4
1B	43 04.5182 N 070 42.5806 W	15.2	Sandy Pebble Gravel	BM	37.2	62.5	0.3	-0.462	1.38	3.18	259.8
2A	43 04.3922 N 070 42.2874 W	15.2	Sandy Pebble Gravel	BM	77.9	21.6	0.5	-2.696	6.48	N/A	725.9
2B	43 04.4187 N 070 42.2874 W	15.2	Sandy Pebble Gravel	BM	69.6	29.7	0.7	-2.226	4.68	1.89	539.3
3A	43 03.9563 N 070 42.3047 W	12.2	Slightly Granule Gravelly Medium Sand	UM	2.3	96.6	1.1	1.127	0.46	1.46	158.4
3B	43 03.9630 N 070 42.3164 W	12.2	Slightly Granule Gravelly Medium Sand	UM	0.6	98.5	0.9	1.638	0.32	0.92	263.8
4A-1	43 03.5354 N 070 42.1144 W	10.7	Sandy Pebble Gravel	BM	59.6	39.9	0.5	-1.407	2.65	0.79	279.0
4A-2	43 03.5354 N 070 42.1144 W	10.7	Sandy Pebble Gravel	BM	53.2	46.1	0.7	-1.278	2.43	N/A	504.9
4B	43 03.5584 N 070 42.1403 W	10.7	Sandy Pebble Gravel	BM	71.4	27.9	0.7	-2.326	5.01	1.28	291.7
5A	43 03.3477 N 070 41.9242 W	12.2	Slightly Granule Gravelly Fine Sand	UM	0.1	98.4	1.5	2.95	0.13	0.64	154.6
5B	43 03.3335 N 070 41.9220 W	12.2	Slightly Granule Gravelly Fine Sand	UM	0.7	97.8	1.5	2.928	0.13	0.73	136.0
6A	43 02.9611 N 070 41.2952 W	18.3	Sandy Pebble Gravel	BM	62	37	1	-1.322	2.50	0.74	273.7
6B	43 02.9477 N 070 41.2979 W	18.3	Coarse Silty Sandy Pebble Gravel	BM	55.1	39.6	5.2	-0.565	1.48	N/A	4.6
7A	43 02.7599 N 070 41.6940 W	14.6	Slightly Granule Gravelly Very Fine Sand	UM	0	98.7	1.3	2.996	0.13	0.72	66.7
7B	43 02.7584 N 070 41.6881 W	14.6	Slightly Pebble Gravelly Very Fine Sand	UM	0.3	98.3	1.4	3.011	0.12	0.66	197.5
8A	43 02.4030 N 070 40.9432 W	20.4	Slightly Granule Gravelly Fine Sand	UM	2.2	96.9	1	2.228	0.21	0.66	182.4
8B	43 02.3602 N 070 40.9362 W	20.4	Pebble Gravelly Medium Sand	BM	16.6	82.7	0.7	0.913	0.53	0.58	273.7
9A	43 02.1914 N 070 40.6543 W	24.4	Sandy Pebble Gravel	BM	48.1	51.3	0.5	-1.23	2.35	0.55	504.2

Sediment Sample	Location (Lat/Long)	Depth (m)	Sediment Name (Wentworth)	Mode (unimodal or bimodal)	% Gravel	% Sand	% Mud	Mean Phi	Mean mm	LOI %	Sample Weight (g)
9B	43 02.1875 N 070 40.6465 W	24.4	Sandy Pebble Gravel	BM	49.1	50.4	0.5	-1.067	2.10	0.65	539.4
10A	43 02.2539 N 070 41.3308 W	18.9	Sandy Pebble Gravel	BM	67.5	31.5	1	-1.699	3.25	N/A	101.1
10B	43 02.2531 N 070 41.3178 W	18.9	Sandy Pebble Gravel	BM	64.2	34.2	1.6	-1.61	3.05	1.07	196.7
10C	43 02.2638 N 070 41.3334 W	18.9	Pebble Gravelly Fine Sand	UM	7.5	91.3	1.2	2.221	0.21	0.57	173.3
11A	43 01.6102 N 070 41.2332 W	24.4	Pebble Gravelly Medium Sand	UM	6.1	93	0.9	1.649	0.32	0.51	212.4
11B	43 01.6110 N 070 41.2278 W	24.4	Coarse Silty Sandy Pebble Gravel	BM	78.9	18.5	2.6	-2.294	4.90	0.80	40.3
11C	43 01.5904 N 070 41.2316 W	24.4	Sandy Pebble Gravel	BM	42	57.2	0.8	-0.351	1.28	0.97	348.2
12A	43 01.9036 N 070 42.2535 W	15.2	Slightly Granule Gravelly Fine Sand	UM	0.4	97.7	1.9	2.814	0.14	0.63	190.6
12B	43 01.8981 N 070 42.2880 W	15.2	Slightly Granule Gravelly Fine Sand	UM	0.1	97.8	2.2	2.816	0.14	0.61	185.3
14A	43 02.4642 N 070 42.1026 W	18.3	Slightly Granule Gravelly Fine Sand	UM	0.2	98.4	1.4	2.364	0.19	0.62	250.5
14B	43 02.4666 N 070 42.1263 W	18.3	Sandy Granule Gravel	BM	57.9	40.9	1.2	-1.14	2.20	0.76	285.4
15A	43 02.9809 N 070 42.3311 W	15.2	Slightly Granule Gravelly Medium Sand	UM	3.2	96	0.7	1.848	0.28	0.93	220.4
15B	43 02.9722 N 070 42.3316 W	15.2	Pebble Gravelly Medium Sand	BM	19.2	80.2	0.5	0.56	0.68	0.69	265.0
16A	43 02.5765 N 070 41.3415 W	17.7	Slightly Pebble Gravelly Very Fine Sand	UM	4.4	94.2	1.4	2.72	0.15	0.67	153.0
16B	43 02.5650 N 070 41.3437 W	17.7	Pebble Gravelly Fine Sand	BM	15.6	83.4	1	1.74	0.30	0.68	117.9
17B	43 02.8568 N 070 40.6005 W	20.4	Pebble Gravel	BM	85.8	13.7	0.4	-2.724	6.61	1.35	408.2
19A	43 01.3377 N 070 41.7296 W	21.3	Sandy Pebble Gravel	BM	66.2	33.5	0.4	-1.608	3.05	1.52	401.8
19B	43 01.3377 N 070 41.7377 W	21.3	Sandy Granule Gravel	BM	73.5	26.1	0.4	-1.679	3.20	0.67	389.3
20A	43 01.8692 N 070 41.6099 W	17.7	Slightly Granule Gravelly Very Fine Sand	UM	0.2	97.6	2.2	2.956	0.13	0.47	98.0
20B	43 01.8680 N 070 41.6126 W	17.7	Slightly Granule Gravelly Very Fine Sand	UM	0.8	97.2	2	2.941	0.13	0.71	103.5

Sediment Sample	Location (Lat/Long)	Depth (m)	Sediment Name (Wentworth)	Mode (unimodal or bimodal)	% Gravel	% Sand	% Mud	Mean Phi	Mean mm	LOI %	Sample Weight (g)
21A	43 02.4010 N 070 41.6455 W	15.2	Slightly Pebble Gravelly Fine Sand	UM	1.5	96.5	2	2.948	0.13	0.71	195.7
21B	43 02.4073 N 070 41.6671 W	15.2	Slightly Granule Gravelly Fine Sand	UM	0	97.4	2.5	2.904	0.13	0.78	113.3
22A	43 02.2436 N 070 40.9314 W	20.7	Sandy Pebble Gravel	BM	42.3	57.3	0.4	-0.265	1.20	0.52	381.7
22B	43 02.2236 N 070 40.9184 W	20.7	Sandy Pebble Gravel	BM	53.1	45.8	1.1	-1.159	2.23	0.59	432.3
23A	43 03.3046 N 070 42.4685 W	15.2	Sandy Pebble Gravel	BM	76.7	22.7	0.6	-2.684	6.43	0.90	336.2
23B	43 03.2793 N 070 42.4885 W	15.2	Sandy Granule Gravel	BM	49.2	49.9	0.8	-0.801	1.74	0.70	363.5

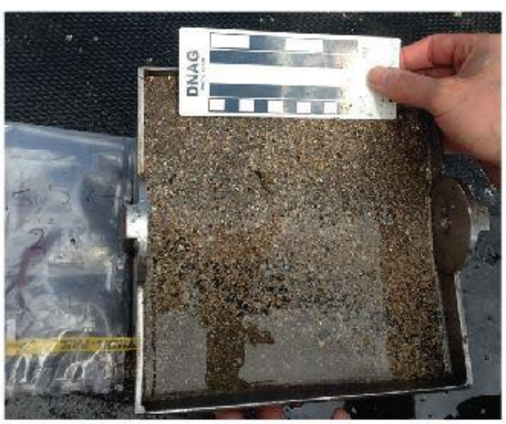


	Sample 1A	Sample 1B
Textural Group (Gradistat)	sG	sG
Sediment Name (after Folk 1954)	spG	spG
Sediment Name (from Gradistat)	scG	scG
Sorting	VPS	VPS
Modes	BM	BM
%G	39.5	37.2
%S	59.6	62.5
%M	0.9	0.3
Mean - phi	-0.35	-0.59
Mean - mm	1.27	1.50
Sorting - phi	2.48	2.70
Skew ness	-0.441	-0.508
Kurtosis	1.706	1.444
D10 - phi	-4.13	-4.41
D50 - phi	0.78	1.07
D90 - phi	2.17	1.91
D10 - microns	222.3	266.7
D50 - microns	582.60	477.60
D90 - microns	17,454.70	21,191.20
Total Sample Wt - gms	255.1	257.1
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	4.0	7.0
-4.0	8.2	18.0
-3.5	4.6	6.1
-3.0	6.5	2.3
-2.5	4.6	2.1
-2.0	4.2	0.7
-1.5	4.0	0.5
-1.0	3.4	0.5
-0.5	2.9	0.6
0.0	2.2	0.8
0.5	2.5	1.7
1.0	5.1	6.8
1.5	11.3	21.3
2.0	22.7	26.5
2.5	10.5	4.4
3.0	1.6	0.3
3.5	0.6	0.1
4.0>	0.1	0.0
4<(silt)	0.9	0.3

Figure I-2: Station 1 grain size analysis results.

	Sample 2A	Sample 2B
Textural Group (Gradistat)	sG	sG
Sediment Name (after Folk 1954)	spG	spG
Sediment Name (from Gradistat)	scG	scG
Sorting	VPS	VPS
Modes	BM	BM
%G	77.9	69.6
%S	21.6	29.7
%M	0.5	0.7
Mean - phi	-3.01	-2.30
Mean - mm	8.03	4.94
Sorting - phi	2.51	2.63
Skew ness	1.159	0.670
Kurtosis	2.876	1.969
D10 - phi	-5.17	-5.05
D50 - phi	-4.12	-3.37
D90 - phi	1.57	1.76
D10 - microns	336.9	294.6
D50 - microns	17,364.50	10,307.00
D90 - microns	36,013.90	33,210.30
Total Sample Wt - gms	708.1	539.3
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	16.0	11.7
-4.5	21.1	10.0
-4.0	17.0	17.1
-3.5	12.5	8.8
-3.0	3.4	9.9
-2.5	3.4	4.1
-2.0	1.7	3.6
-1.5	1.5	2.6
-1.0	1.3	2.0
-0.5	1.1	1.5
0.0	1.0	1.4
0.5	1.3	1.8
1.0	2.6	3.5
1.5	5.0	6.7
2.0	7.4	10.3
2.5	2.4	3.6
3.0	0.4	0.5
3.5	0.2	0.3
4.0>	0.1	0.1
4<(silt)	0.5	0.7

Figure I-3: Station 2 grain size analysis results.

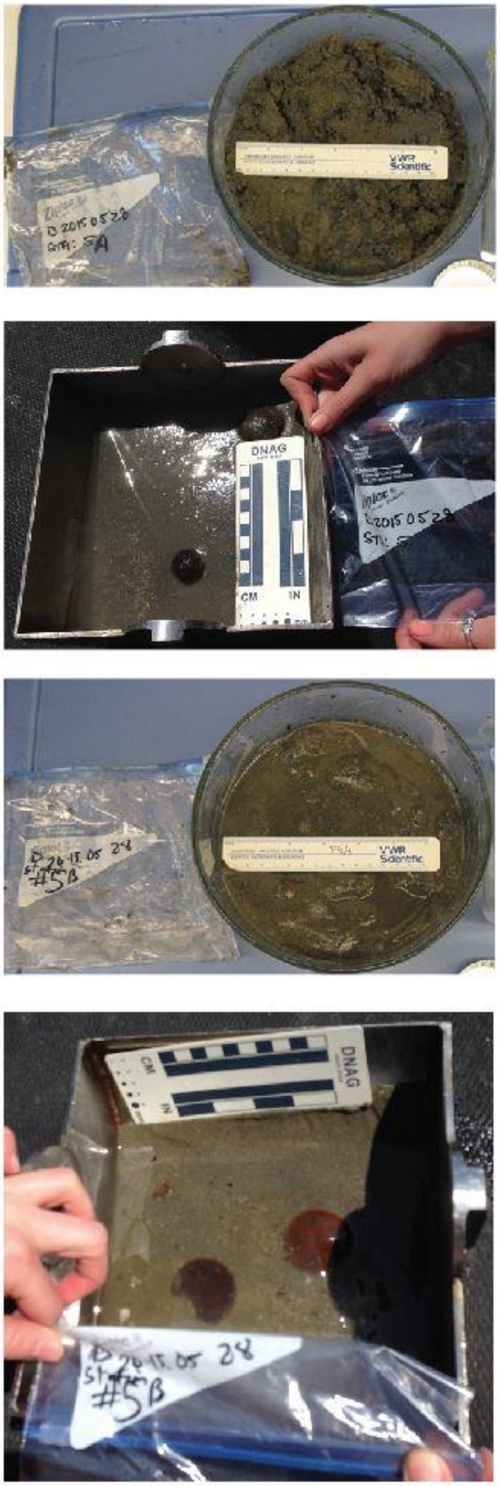


	Sample 3A	Sample 3B
Textural Group (Gradistat)	slgS	slgS
Sediment Name (after Folk 1954)	slggmS	slggmS
Sediment Name (from Gradistat)	slvfgmS	slvfgmS
Sorting	MS	MWS
Modes	UM	UM
%G	2.3	0.6
%S	96.6	98.5
%M	1.1	0.9
Mean - phi	1.13	1.62
Mean - mm	0.46	0.33
Sorting - phi	0.94	0.67
Skew ness	-0.360	-1.204
Kurtosis	4.833	14.080
D10 - phi	-0.20	0.95
D50 - phi	1.30	1.70
D90 - phi	2.00	2.25
D10 - microns	250.9	210.8
D50 - microns	406.00	308.70
D90 - microns	1,150.40	517.00
Total Sample Wt - gms	146.2	261.4
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	---	---
-3.5	---	---
-3.0	---	0.2
-2.5	0.1	0.0
-2.0	0.3	0.1
-1.5	0.4	0.1
-1.0	1.5	0.2
-0.5	3.8	0.6
0.0	6.8	1.2
0.5	8.6	2.2
1.0	14.8	6.0
1.5	22.7	18.5
2.0	31.4	52.4
2.5	7.6	16.4
3.0	0.6	0.9
3.5	0.3	0.2
4.0>	0.1	0.1
4<(silt)	1.1	0.9

Figure I-4: Station 3 grain size analysis results.

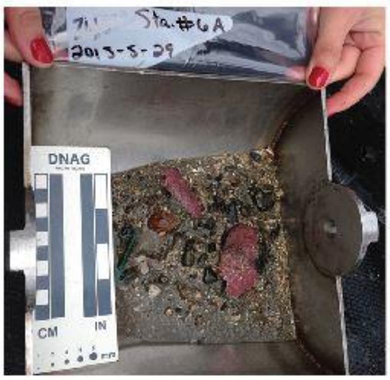
	Sample 4A-1	Sample 4A-2	Sample 4B
Textural Group (Gradistat)	sG	sG	sG
Sediment Name (after Folk 1954)	spG	spG	spG
Sediment Name (from Gradistat)	smG	scG	scG
Sorting	VPS	VPS	VPS
Modes	BM	BM	BM
%G	59.6	53.2	71.4
%S	39.9	46.1	27.9
%M	0.5	0.7	0.7
Mean - phi	-1.30	-1.10	-2.383
Mean - mm	2.46	2.15	5.2164
Sorting - phi	2.45	2.73	2.69
Skew ness	0.380	0.135	0.757
Kurtosis	1.629	1.449	2.116
D10 - phi	-4.05	-4.36	-4.857
D50 - phi	-2.13	-1.58	-3.588
D90 - phi	1.94	2.23	1.801
D10 - microns	260.6	213.4	287
D50 - microns	4,366.50	2,989.20	12,022.90
D90 - microns	16,528.60	20,552.10	28,978.70
Total Sample Wt - gms	279.0	491.1	291.6526
Class % of Size Distribution (phi)			
-5.5	---	---	---
-5.0	---	---	---
-4.5	---	6.6	40.9
-4.0	11.1	13.2	7.4
-3.5	15.1	12.7	2.2
-3.0	11.5	5.5	4.0
-2.5	7.9	5.3	4.3
-2.0	5.9	4.1	4.2
-1.5	4.9	3.3	4.8
-1.0	3.2	2.6	3.7
-0.5	2.5	2.1	2.4
0.0	2.1	1.9	1.6
0.5	2.2	2.1	1.4
1.0	3.4	3.9	2.3
1.5	7.1	8.0	6.2
2.0	14.9	16.6	7.8
2.5	3.5	4.6	2.4
3.0	2.5	3.2	1.8
3.5	1.4	3.3	1.8
4.0>	0.2	0.4	0.2
4<(silt)	0.5	0.7	0.7

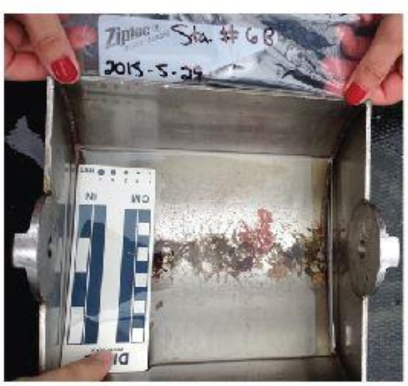
Figure I-5: Station 4 grain size analysis results.



	Sample 5A	Sample 5B
Textural Group (Gradistat)	slgS	slgS
Sediment Name (after Folk 1954)	slggfS	slggfS
Sediment Name (from Gradistat)	slvfgfS	slfgfS
Sorting	WS	WS
Modes	UM	UM
%G	0.1	0.7
%S	98.4	97.8
%M	1.5	1.5
Mean - phi	2.93	2.87
Mean - mm	0.13	0.14
Sorting - phi	0.47	0.66
Skew ness	-1.318	-4.234
Kurtosis	14.360	35.770
D10 - phi	2.49	2.43
D50 - phi	2.96	2.93
D90 - phi	3.40	3.40
D10 - microns	94.7	95.0
D50 - microns	128.70	131.70
D90 - microns	178.40	186.20
Total Sample Wt - gms	154.0	136.0
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	---	---
-3.5	---	---
-3.0	---	0.2
-2.5	---	0.3
-2.0	---	0.1
-1.5	0.0	0.1
-1.0	0.0	0.1
-0.5	0.0	0.1
0.0	0.1	0.1
0.5	0.1	0.1
1.0	0.2	0.3
1.5	0.4	0.6
2.0	2.3	2.8
2.5	5.7	5.9
3.0	44.7	46.0
3.5	43.1	40.0
4.0>	1.8	1.9
4<(silt)	1.6	1.5

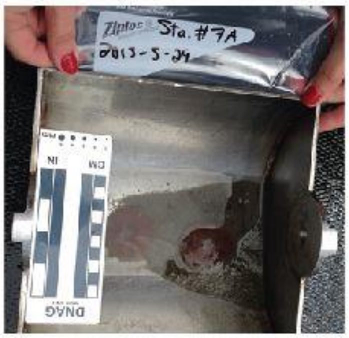
Figure I-6: Station 5 grain size analysis results.





	Sample 6A	Sample 6B
Textural Group (Gradistat)	sG	msG
Sediment Name (after Folk 1954)	spG	csspG
Sediment Name (from Gradistat)	smG	vcssfG
Sorting	VPS	VPS
Modes	BM	BM
%G	62.0	55.1
%S	37.0	39.6
%M	1.0	5.2
Mean - phi	-1.32	-5.08
Mean - mm	2.49	1.42
Sorting - phi	2.10	2.13
Skew ness	0.657	0.961
Kurtosis	2.309	2.724
D10 - phi	-3.62	-2.45
D50 - phi	-1.93	-1.28
D90 - phi	1.83	3.01
D10 - microns	282.0	123.8
D50 - microns	3,814.50	2,432.40
D90 - microns	12,284.90	5,463.00
Total Sample Wt - gms	273.7	4.6
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	---	---
-3.5	13.5	---
-3.0	15.0	---
-2.5	12.7	7.7
-2.0	7.8	31.1
-1.5	7.7	7.5
-1.0	5.3	8.8
-0.5	4.9	9.3
0.0	4.2	3.9
0.5	4.5	3.5
1.0	4.8	2.4
1.5	4.9	2.8
2.0	7.3	7.8
2.5	4.2	3.3
3.0	0.8	1.8
3.5	1.1	3.3
4.0>	0.4	1.5
4<(silt)	1.0	5.3

Figure I-7: Station 6 grain size analysis results.



	Sample 7A	Sample 7B
Textural Group (Gradistat)	slgS	sgS
Sediment Name (after Folk 1954)	slggvfS	pgvfS
Sediment Name (from Gradistat)	svfgvfS	slmgvfS
Sorting	WS	WS
Modes	UM	UM
%G	0.0	0.3
%S	98.7	98.3
%M	1.3	1.4
Mean - phi	2.97	2.98
Mean - mm	0.13	0.13
Sorting - phi	0.52	0.60
Skew ness	-1.380	-3.387
Kurtosis	8.942	31.270
D10 - phi	2.30	2.36
D50 - phi	3.08	3.09
D90 - phi	3.43	3.45
D10 - microns	92.6	91.8
D50 - microns	118.30	117.60
D90 - microns	202.90	194.50
Total Sample Wt - gms	66.7	197.5
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	---	---
-3.5	---	---
-3.0	---	0.2
-2.5	---	0.0
-2.0	---	0.0
-1.5	0.0	0.0
-1.0	0.0	0.0
-0.5	0.0	0.0
0.0	0.1	0.1
0.5	0.2	0.1
1.0	0.4	0.3
1.5	0.9	0.7
2.0	3.1	2.7
2.5	8.4	7.5
3.0	28.0	28.4
3.5	53.6	53.0
4.0>	4.1	5.4
4<(silt)	1.3	1.4

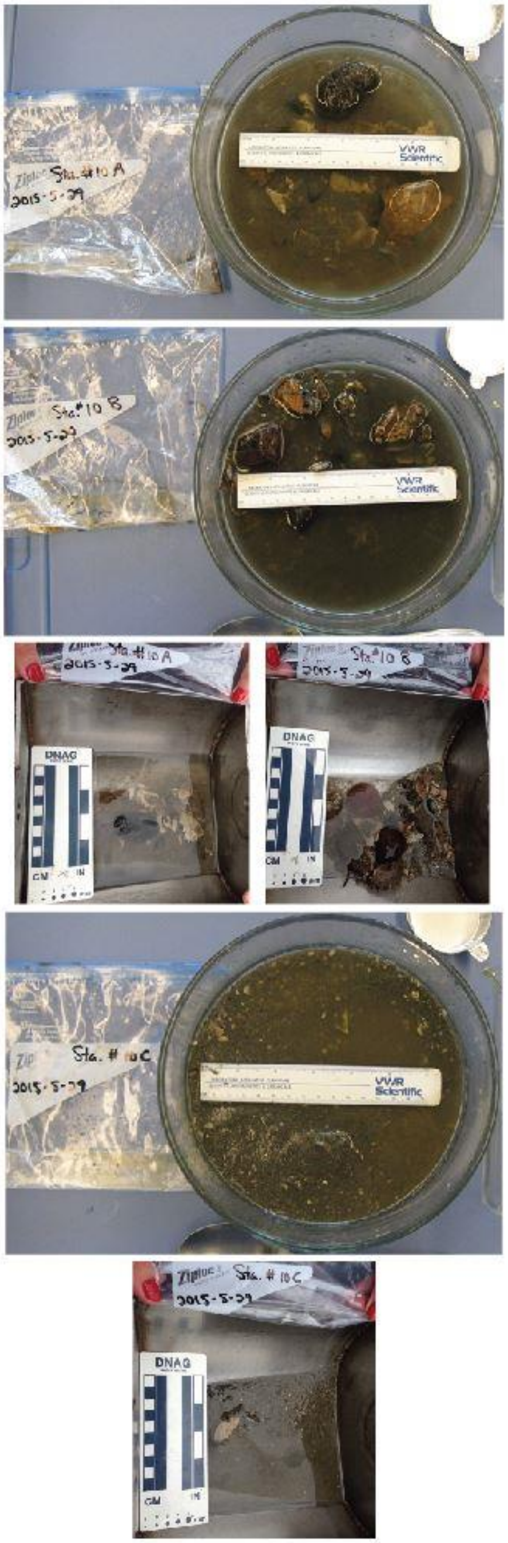
Figure I-8: Station 7 grain size analysis results.

	Sample 8A	Sample 8B
Textural Group (Gradistat)	slgS	gS
Sediment Name (after Folk 1954)	slggfS	pgmS
Sediment Name (from Gradistat)	slfgfS	mgmS
Sorting	MS	PS
Modes	UM	BM
%G	2.2	16.6
%S	96.9	82.7
%M	1.0	0.7
Mean - phi	2.13	0.96
Mean - mm	0.23	0.52
Sorting - phi	0.99	2.04
Skew ness	-2.455	-1.434
Kurtosis	13.850	3.850
D10 - phi	1.26	-3.33
D50 - phi	2.23	1.69
D90 - phi	3.06	2.58
D10 - microns	120.2	167.3
D50 - microns	212.70	310.00
D90 - microns	417.60	10,078.60
Total Sample Wt - gms	182.1	270.3
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	---	2.1
-3.5	0.3	7.1
-3.0	0.4	2.5
-2.5	0.4	2.0
-2.0	0.5	1.1
-1.5	0.3	0.8
-1.0	0.3	0.9
-0.5	0.3	0.9
0.0	0.4	1.1
0.5	1.1	2.5
1.0	2.7	6.6
1.5	6.4	12.6
2.0	20.9	25.2
2.5	32.6	22.8
3.0	22.3	8.5
3.5	9.1	2.3
4.0>	1.0	0.3
4<(silt)	1.0	0.7

Figure I-9: Station 8 grain size analysis results.

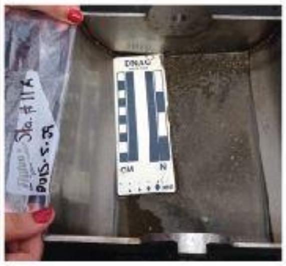
	Sample 9A	Sample 9B
Textural Group (Gradistat)	sG	sG
Sediment Name (after Folk 1954)	spG	spG
Sediment Name (from Gradistat)	scG	smG
Sorting	VPS	PS
Modes	BM	BM
%G	48.1	49.1
%S	51.3	50.4
%M	0.5	0.5
Mean - phi	-1.23	-1.07
Mean - mm	2.35	2.10
Sorting - phi	2.58	1.99
Skew ness	-0.201	-0.065
Kurtosis	0.654	0.664
D10 - phi	-4.67	-3.62
D50 - phi	-0.71	-0.93
D90 - phi	1.92	1.43
D10 - microns	264.7	371.7
D50 - microns	1,637.80	1,899.50
D90 - microns	25,421.20	12,255.00
Total Sample Wt - gms	504.2	539.4
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	15.9	---
-4.0	3.3	4.5
-3.5	5.9	7.3
-3.0	8.9	13.2
-2.5	5.6	7.1
-2.0	3.7	6.6
-1.5	2.7	5.3
-1.0	2.2	5.0
-0.5	3.3	6.4
0.0	4.9	7.4
0.5	7.6	9.2
1.0	10.6	11.0
1.5	9.4	8.0
2.0	7.1	4.7
2.5	4.8	2.3
3.0	2.5	0.9
3.5	0.8	0.4
4.0>	0.1	0.1
4<(silt)	0.6	0.5

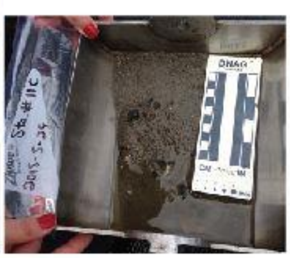
Figure I-10: Station 9 grain size analysis results.



	Sample 10A	Sample 10B	Sample 10C
Textural Group (Gradistat)	sG	sG	gS
Sediment Name (after Folk 1954)	spG	spG	pgfS
Sediment Name (from Gradistat)	smG	scG	mgfS
Sorting	VPS	VPS	PS
Modes	BM	BM	UM
%G	67.5	64.2	7.5
%S	31.5	34.2	91.3
%M	1.0	1.6	1.2
Mean - phi	-1.70	-1.61	2.22
Mean - mm	3.25	3.05	0.21
Sorting - phi	3.17	3.13	1.411
Skew ness	0.652	0.695	-0.384
Kurtosis	0.506	0.520	1.445
D10 - phi	-4.79	-4.65	0.33
D50 - phi	-3.40	-3.43	2.359
D90 - phi	3.22	3.33	3.386
D10 - microns	107.5	103.7	95.62
D50 - microns	10,522.00	10,748.20	194.90
D90 - microns	27,744.80	25,027.90	795.60
Total Sample Wt - gms	101.1	196.7	173.3
Class % of Size Distribution (phi)			
-5.5			
-5.0			
-4.5	26.9	14.8	
-4.0	1.9	20.2	
-3.5	18.8	13.9	2.2
-3.0	13.2	8.8	1.3
-2.5	1.9	2.9	0.5
-2.0	2.3	1.1	1.1
-1.5	1.4	1.3	1.3
-1.0	1.3	1.2	1.0
-0.5	0.7	1.0	0.8
0.0	0.4	0.6	0.7
0.5	0.5	0.6	1.5
1.0	0.8	1.4	4.9
1.5	1.2	2.2	9.4
2.0	2.3	3.0	14.2
2.5	3.8	3.4	14.6
3.0	7.0	6.0	16.4
3.5	12.6	13.2	24.6
4.0>	2.2	2.7	4.2
4<(silt)	1.0	1.6	1.3

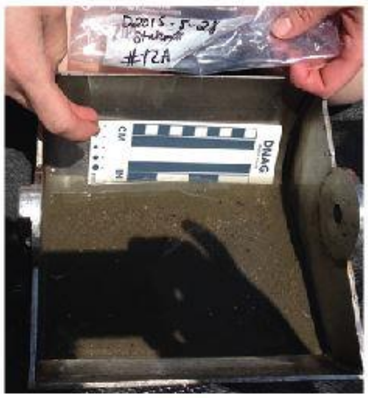
Figure I-11: Station 10 grain size analysis results.

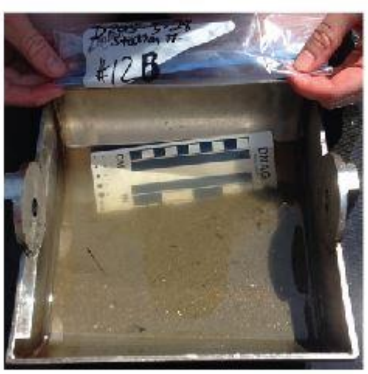




	Sample 11A	Sample 11B	Sample 11C
Textural Group (Gradistat)	gS	msG	sG
Sediment Name (after Folk 1954)	pgmS	csspG	spG
Sediment Name (from Gradistat)	mgmS	vcsscG	smG
Sorting	PS	VPS	VPS
Modes	UM	BM	BM
%G	6.1	78.9	42
%S	93.0	18.5	57.2
%M	0.9	2.6	0.8
Mean - phi	1.65	-2.29	-0.35
Mean - mm	0.32	4.90	1.28
Sorting - phi	1.02	2.28	2.368
Skew ness	-0.305	0.639	-0.422
Kurtosis	2.260	1.185	0.599
D10 - phi	0.34	-4.36	-3.742
D50 - phi	1.69	-3.30	0.555
D90 - phi	2.43	1.60	2.251
D10 - microns	185.7	331.0	210.1
D50 - microns	309.40	9,870.60	680.90
D90 - microns	791.30	20,499.90	13,377.00
Total Sample Wt - gms	212.4	40.3	348.2
Class % of Size Distribution (phi)			
-5.5	---	---	---
-5.0	---	---	---
-4.5	---	---	---
-4.0	---	38.0	3.1
-3.5	0.5	5.2	13.7
-3.0	2.2	18.2	8.0
-2.5	0.7	8.2	8.5
-2.0	1.3	4.2	3.6
-1.5	0.7	3.3	2.8
-1.0	0.7	1.8	2.2
-0.5	1.2	1.3	1.8
0.0	1.3	1.0	1.8
0.5	2.1	1.7	3.3
1.0	5.6	2.6	9.1
1.5	19.0	3.6	14.6
2.0	37.5	4.3	13.9
2.5	19.0	1.9	6.6
3.0	5.0	0.7	3.6
3.5	1.8	0.9	2.0
4.0>	0.4	0.4	0.4
4<(silt)	0.9	2.6	0.8

Figure I-12: Station 11 grain size analysis results.



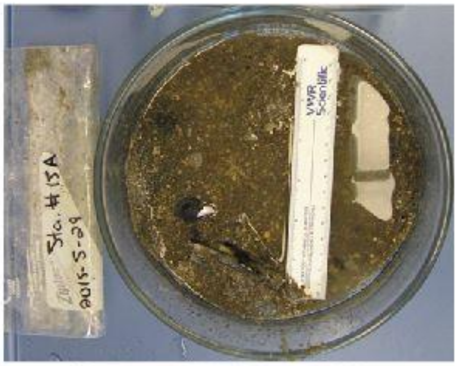


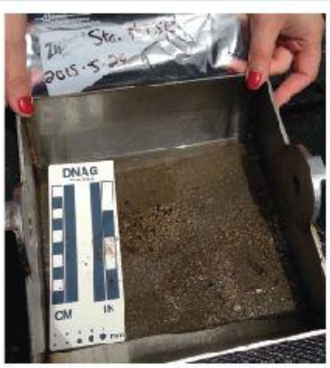
	Sample 12A	Sample 12B
Textural Group (Gradistat)	slgS	slgS
Sediment Name (after Folk 1954)	slggfS	slggfS
Sediment Name (from Gradistat)	slvfgfS	slvfgfS
Sorting	WS	WS
Modes	UM	UM
%G	0.4	0.1
%S	97.7	97.8
%M	1.9	2.2
Mean - phi	2.81	2.82
Mean - mm	0.14	0.14
Sorting - phi	0.47	0.45
Skew ness	-0.048	0.044
Kurtosis	1.151	1.154
D10 - phi	2.16	2.20
D50 - phi	2.80	2.79
D90 - phi	3.38	3.38
D10 - microns	95.9	95.8
D50 - microns	143.60	144.50
D90 - microns	224.40	218.40
Total Sample Wt - gms	190.6	185.3
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	---	---
-3.5	---	---
-3.0	---	---
-2.5	---	---
-2.0	0.1	---
-1.5	0.1	0.0
-1.0	0.2	0.1
-0.5	0.2	0.1
0.0	0.2	0.1
0.5	0.3	0.2
1.0	0.6	0.4
1.5	1.2	0.9
2.0	2.7	2.4
2.5	13.3	14.2
3.0	50.3	52.6
3.5	25.8	23.6
4.0>	3.1	3.3
4<(silt)	1.9	2.2

Figure I-13: Station 12 grain size analysis results.

	Sample 14A	Sample 14B
Textural Group (Gradistat)	slgS	sG
Sediment Name (after Folk 1954)	slggfS	sgG
Sediment Name (from Gradistat)	slvfgfS	sfG
Sorting	MWS	VPS
Modes	UM	BM
%G	0.2	57.9
%S	98.4	40.9
%M	1.4	1.2
Mean - phi	2.36	-1.14
Mean - mm	0.19	2.20
Sorting - phi	0.57	2.69
Skew ness	0.033	0.232
Kurtosis	1.382	0.775
D10 - phi	1.62	-4.54
D50 - phi	2.32	-1.65
D90 - phi	3.03	2.58
D10 - microns	122.1	167.8
D50 - microns	199.70	3,138.10
D90 - microns	324.80	23,308.90
Total Sample Wt - gms	250.5	285.4
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	11.3
-4.0	---	3.4
-3.5	---	5.3
-3.0	---	7.2
-2.5	0.0	7.7
-2.0	0.0	9.7
-1.5	0.1	8.0
-1.0	0.1	5.4
-0.5	0.2	4.7
0.0	0.4	3.9
0.5	0.8	3.9
1.0	1.9	4.5
1.5	3.5	3.8
2.0	11.7	3.8
2.5	45.8	6.4
3.0	25.0	5.3
3.5	8.0	3.6
4.0>	1.2	0.9
4<(silt)	1.4	1.2

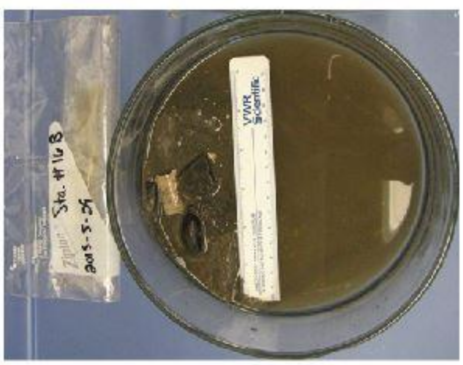
Figure I-14: Station 14 grain size analysis results.





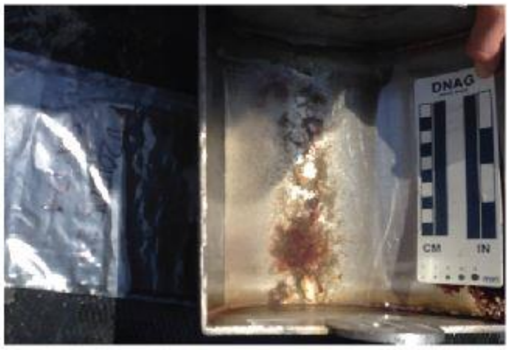
	Sample 15A	Sample 15B
Textural Group (Gradistat)	slgS	gS
Sediment Name (after Folk 1954)	slggmS	pgmS
Sediment Name (from Gradistat)	slvfgmS	cgmS
Sorting	MWS	VPS
Modes	UM	BM
%G	3.2	19.2
%S	96.0	80.2
%M	0.7	0.5
Mean - phi	1.85	0.56
Mean - mm	0.28	0.68
Sorting - phi	0.69	2.17
Skew ness	-0.313	-0.769
Kurtosis	1.796	1.784
D10 - phi	0.87	-4.03
D50 - phi	1.90	1.72
D90 - phi	2.42	2.38
D10 - microns	186.5	192.4
D50 - microns	269.00	303.00
D90 - microns	548.40	16,326.40
Total Sample Wt - gms	220.4	265.0
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	---	10.6
-3.5	0.7	3.0
-3.0	0.3	0.8
-2.5	0.4	1.1
-2.0	0.4	1.2
-1.5	0.5	1.2
-1.0	0.9	1.3
-0.5	1.1	1.6
0.0	1.3	1.6
0.5	1.8	2.0
1.0	3.4	3.2
1.5	8.3	8.1
2.0	39.0	31.7
2.5	35.8	28.3
3.0	4.0	2.8
3.5	1.3	0.8
4.0>	0.1	0.1
4<(silt)	0.7	0.5

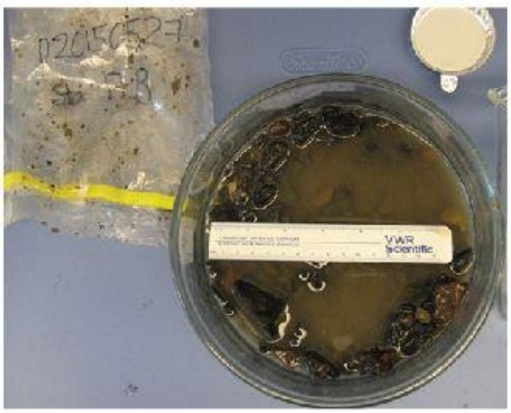
Figure I-15: Station 15 grain size analysis results.



	Sample 16A	Sample 16B
Textural Group (Gradistat)	slgS	gS
Sediment Name (after Folk 1954)	slpgvfS	pgfS
Sediment Name (from Gradistat)	slcgvfS	mgfS
Sorting	MS	VPS
Modes	UM	BM
%G	4.4	15.6
%S	94.2	83.4
%M	1.4	1.0
Mean - phi	2.72	1.74
Mean - mm	0.15	0.30
Sorting - phi	0.96	2.14
Skew ness	-0.463	-0.689
Kurtosis	1.655	2.030
D10 - phi	1.52	-3.72
D50 - phi	2.88	2.57
D90 - phi	3.44	3.40
D10 - microns	92.2	95.0
D50 - microns	136.00	168.60
D90 - microns	348.00	13,177.30
Total Sample Wt - gms	153.0	117.9
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	1.4	6.1
-3.5	0.4	7.2
-3.0	1.0	0.2
-2.5	0.3	0.7
-2.0	0.4	0.2
-1.5	0.5	0.6
-1.0	0.4	0.6
-0.5	0.5	0.6
0.0	0.4	0.4
0.5	0.6	0.7
1.0	0.6	1.3
1.5	3.1	4.4
2.0	7.7	9.6
2.5	14.1	13.6
3.0	24.3	20.9
3.5	37.0	27.3
4.0>	5.8	4.5
4<(silt)	1.5	1.1

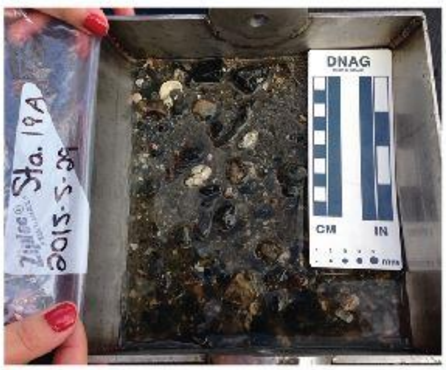
Figure I-16: Station 16 grain size analysis results.





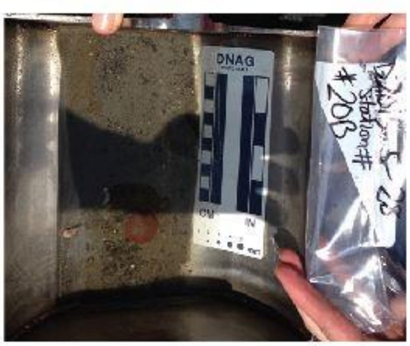
	Sample 17B
Textural Group (Gradistat)	G
Sediment Name (after Folk 1954)	pG
Sediment Name (from Gradistat)	mG
Sorting	PS
Modes	BM
%G	85.8
%S	13.7
%M	0.4
Mean - phi	-2.72
Mean - mm	6.61
Sorting - phi	1.61
Skew ness	0.474
Kurtosis	1.592
D10 - phi	-3.99
D50 - phi	-3.09
D90 - phi	-0.14
D10 - microns	1,098.3
D50 - microns	8,523.60
D90 - microns	15,921.20
Total Sample Wt - gms	408.2
Class % of Size Distribution (phi)	
-5.5	---
-5.0	---
-4.5	6.0
-4.0	3.7
-3.5	22.4
-3.0	22.1
-2.5	13.0
-2.0	8.4
-1.5	6.3
-1.0	4.0
-0.5	2.9
0.0	1.7
0.5	1.3
1.0	1.0
1.5	1.4
2.0	2.2
2.5	2.1
3.0	0.6
3.5	0.4
4.0>	0.2
4<(silt)	0.4

Figure I-17: Station 17 grain size analysis results.



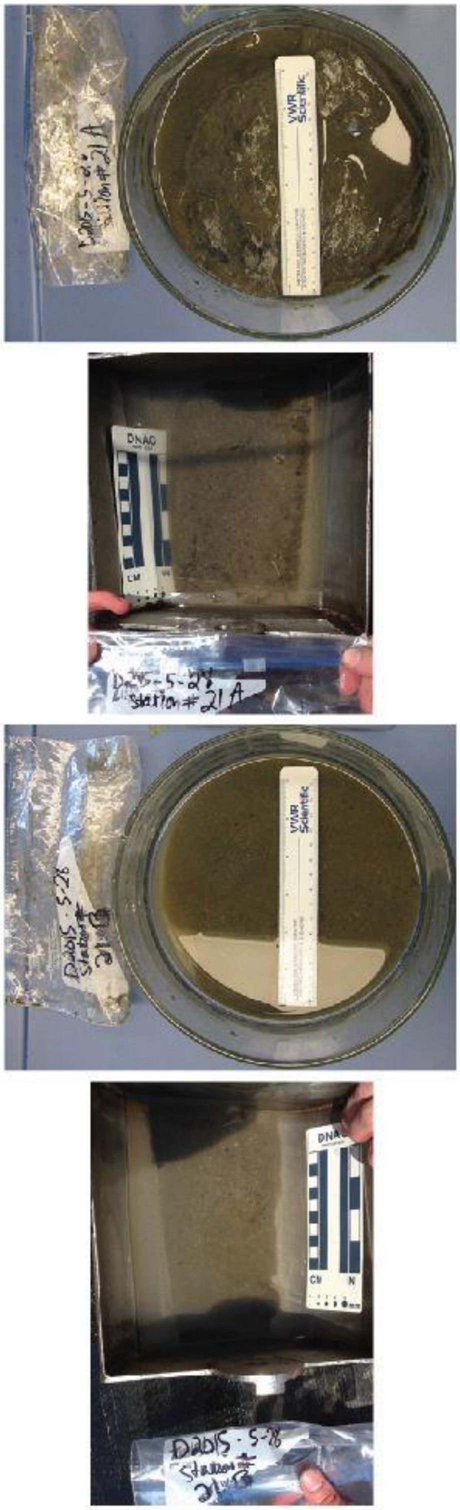
	Sample 19A	Sample 19B
Textural Group (Gradistat)	sG	sG
Sediment Name (after Folk 1954)	spG	sgG
Sediment Name (from Gradistat)	smG	sfG
Sorting	PS	PS
Modes	BM	BM
%G	66.2	73.5
%S	33.5	26.1
%M	0.4	0.4
Mean - phi	-1.61	-1.68
Mean - mm	3.05	3.20
Sorting - phi	1.99	1.63
Skewness	0.435	0.418
Kurtosis	0.722	1.057
D10 - phi	-3.73	-3.35
D50 - phi	-2.26	-2.12
D90 - phi	1.41	0.97
D10 - microns	375.3	509.8
D50 - microns	4,788.00	4,353.80
D90 - microns	13,284.00	10,198.90
Total Sample Wt - gms	401.8	389.3
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	3.1	---
-3.5	13.2	5.9
-3.0	20.2	14.9
-2.5	9.5	17.3
-2.0	8.8	16.0
-1.5	6.3	11.4
-1.0	5.2	8.1
-0.5	4.6	5.6
0.0	3.9	3.3
0.5	4.2	3.2
1.0	5.9	4.6
1.5	6.2	4.1
2.0	4.9	2.7
2.5	2.1	1.2
3.0	0.9	0.7
3.5	0.6	0.6
4.0>	0.1	0.2
4<(silt)	0.4	0.4

Figure I-18: Station 19 grain size analysis results.



	Sample 20A	Sample 20B
Textural Group (Gradistat)	slgS	slgS
Sediment Name (after Folk 1954)	slggvfS	slggvfS
Sediment Name (from Gradistat)	slvfgvfS	slvfgvfS
Sorting	MWS	MWS
Modes	UM	UM
%G	0.2	0.8
%S	97.6	97.2
%M	2.2	2.0
Mean - phi	2.96	2.94
Mean - mm	0.13	0.13
Sorting - phi	0.57	0.57
Skew ness	-0.286	-0.275
Kurtosis	1.252	1.259
D10 - phi	2.10	2.10
D50 - phi	3.05	3.02
D90 - phi	3.47	3.47
D10 - microns	90.1	90.6
D50 - microns	120.80	122.90
D90 - microns	232.90	234.00
Total Sample Wt - gms	98.0	103.5
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	---	---
-3.5	---	---
-3.0	---	---
-2.5	---	---
-2.0	---	0.3
-1.5	0.1	0.3
-1.0	0.2	0.2
-0.5	0.1	0.2
0.0	0.2	0.3
0.5	0.3	0.4
1.0	0.8	0.7
1.5	1.6	1.4
2.0	4.7	4.3
2.5	9.3	9.4
3.0	28.1	30.3
3.5	44.7	43.1
4.0>	7.7	7.2
4<(silt)	2.2	2.0

Figure I-19: Station 20 grain size analysis results.

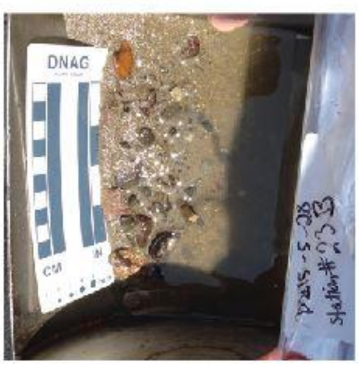


	Sample 21A	Sample 21B
Textural Group (Gradistat)	slgS	slgS
Sediment Name (after Folk 1954)	slpgfS	slggfS
Sediment Name (from Gradistat)	slmgfS	slvfgfS
Sorting	WS	WS
Modes	UM	UM
%G	1.5	0.0
%S	96.5	97.4
%M	2.0	2.5
Mean - phi	2.95	2.90
Mean - mm	0.13	0.13
Sorting - phi	0.45	0.43
Skew ness	-0.027	0.088
Kurtosis	1.104	1.126
D10 - phi	2.48	2.47
D50 - phi	2.94	2.86
D90 - phi	3.44	3.41
D10 - microns	92.5	93.9
D50 - microns	130.40	137.50
D90 - microns	179.70	180.90
Total Sample Wt - gms	195.7	113.3
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	---	---
-4.5	---	---
-4.0	---	---
-3.5	1.1	---
-3.0	0.1	---
-2.5	0.0	---
-2.0	0.1	---
-1.5	0.1	---
-1.0	0.1	0.0
-0.5	0.1	0.0
0.0	0.1	0.1
0.5	0.1	0.1
1.0	0.1	0.2
1.5	0.3	0.5
2.0	2.0	2.4
2.5	5.5	6.8
3.0	45.5	54.0
3.5	37.8	29.7
4.0>	4.8	3.6
4<(silt)	2.0	2.6

Figure I-20: Station 21 grain size analysis results.

	Sample 22A	Sample 22B
Textural Group (Gradistat)	sG	sG
Sediment Name (after Folk 1954)	spG	spG
Sediment Name (from Gradistat)	smG	smG
Sorting	VPS	VPS
Modes	BM	BM
%G	42.3	53.1
%S	57.3	45.8
%M	0.4	1.1
Mean - phi	-0.27	-1.16
Mean - mm	1.20	2.23
Sorting - phi	2.65	2.60
Skew ness	-0.292	0.210
Kurtosis	0.656	0.653
D10 - phi	-4.51	-4.20
D50 - phi	0.27	-1.60
D90 - phi	2.70	2.40
D10 - microns	154.3	189.5
D50 - microns	827.70	3,029.40
D90 - microns	22,759.20	18,357.90
Total Sample Wt - gms	381.7	432.3
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	4.5	---
-4.5	5.7	8.6
-4.0	0.0	2.4
-3.5	4.2	14.2
-3.0	11.6	11.2
-2.5	7.7	7.1
-2.0	3.5	4.3
-1.5	2.8	2.8
-1.0	2.2	2.4
-0.5	2.3	2.6
0.0	2.9	3.2
0.5	4.5	5.0
1.0	6.7	7.0
1.5	7.5	6.7
2.0	9.8	7.2
2.5	10.6	6.1
3.0	7.9	4.6
3.5	4.2	2.7
4.0>	0.8	0.6
4<(silt)	0.4	1.1

Figure I-21: Station 22 grain size analysis results.



	Sample 23A	Sample 23B
Textural Group (Gradistat)	sG	sG
Sediment Name (after Folk 1954)	spG	sgG
Sediment Name (from Gradistat)	scG	sfG
Sorting	VPS	VPS
Modes	BM	BM
%G	76.7	49.2
%S	22.7	49.9
%M	0.6	0.8
Mean - phi	-2.68	-0.80
Mean - mm	6.43	1.74
Sorting - phi	2.96	2.67
Skew ness	0.819	0.023
Kurtosis	1.046	0.582
D10 - phi	-5.32	-4.21
D50 - phi	-4.64	-0.88
D90 - phi	2.23	2.50
D10 - microns	212.7	176.8
D50 - microns	24,852.10	1,836.30
D90 - microns	40,053.80	18,554.50
Total Sample Wt - gms	336.2	363.5
Class % of Size Distribution (phi)		
-5.5	---	---
-5.0	30.6	---
-4.5	27.9	6.0
-4.0	2.0	7.2
-3.5	7.6	9.0
-3.0	2.9	4.7
-2.5	2.7	8.9
-2.0	1.2	6.6
-1.5	1.0	3.8
-1.0	0.8	3.2
-0.5	0.6	3.2
0.0	0.6	2.9
0.5	0.7	3.2
1.0	1.2	3.4
1.5	1.7	3.3
2.0	4.0	8.0
2.5	9.1	16.5
3.0	3.5	6.9
3.5	1.1	2.3
4.0>	0.2	0.4
4<(silt)	0.6	0.8

Figure I-22: Station 23 grain size analysis results.

APPENDIX II

IKB Seismic Profiles

An IKB-Seistec Marine Sediment Profiler (Figure II-1) was used to collect 48 seismic profiles on the University of the New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center's Research Vessel *Cocheco*, July 18-20, 2007. Positioning was collected by attaching a Garmin GPS antenna to the Seistec catamaran (Figure II-2). The catamaran supports both a boomer transducer and a line-in-cone receiver. The boomer produces a single positive peak pressure impulse with a primary pulse width of ~120 µs, and emits frequencies in the 1-10 kHz range (Blatzer et al., 2005).

Figure II-1: IKB-Seistec marine sediment profiler catamaran on dock prior to deployment.

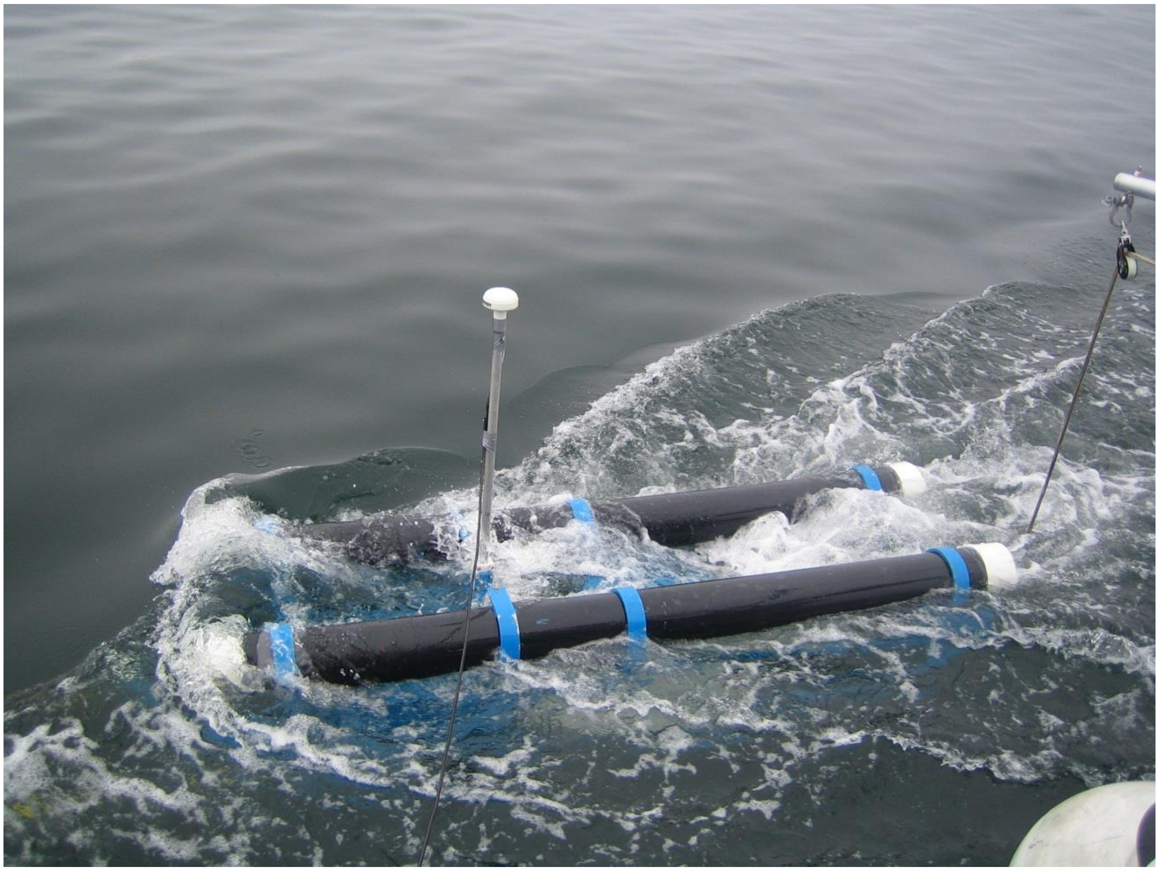


Figure II-2: IKB-Seistec marine sediment profiler catamaran being towed, showing attached Garmin GPS antenna.

All seismic profiles, both uninterrupted and interpreted, from the IKB-Seistec survey are shown below. Locations of all profiles can be seen in Figure II-3. Seismic profiles are separated into SHORE PARALLEL and SHORE PERPENDICULAR, with both groups starting with most inland profile and moving offshore. Interpreted profiles show highlighted seismic reflectors as: bedrock (red), till (green), glaciomarine sediment (blue), erosional unconformity (black), and Holocene sediments (yellow).

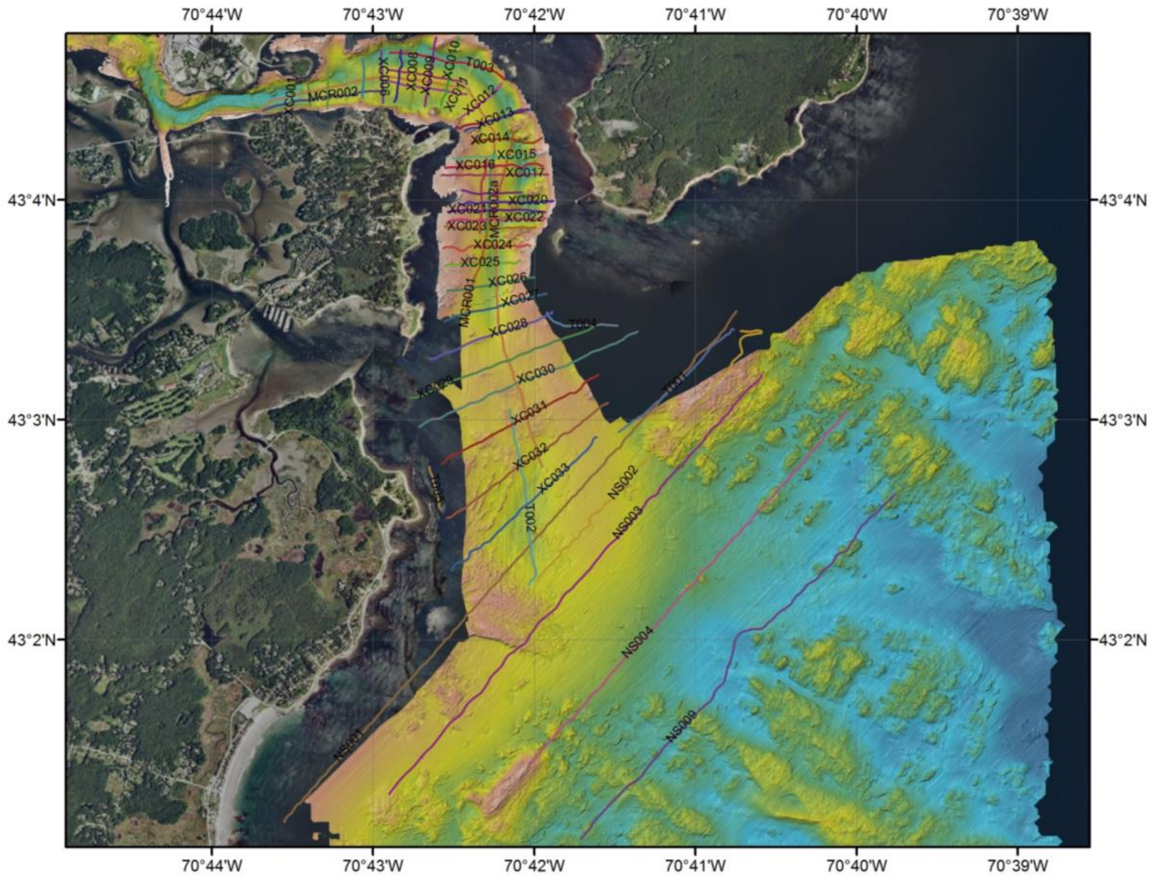


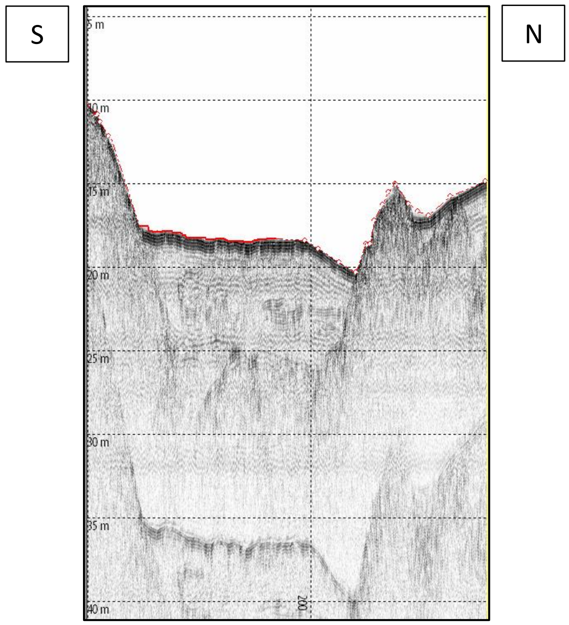
Figure II-3: Location of all IKB-Seistec profiles. Credit to Larry Ward.

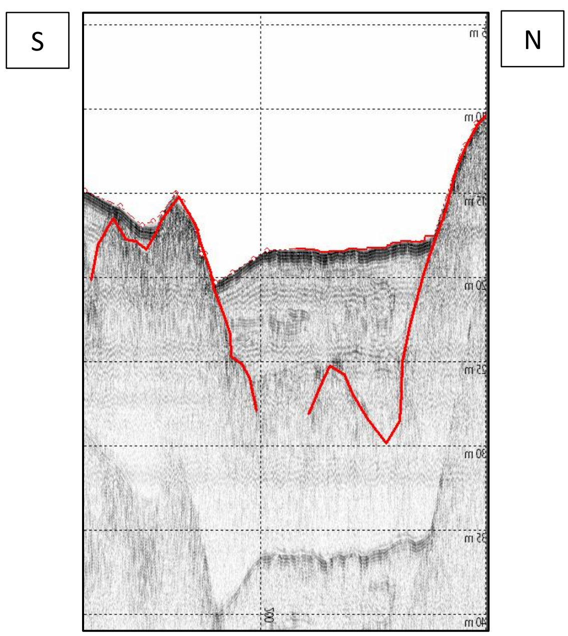
Reference

Baltzer, A., Tessier, B., Nouzé, H., Bates, R., Moore, C., Menier, D., 2005. "Seistec seismic profiles: A tool to differentiate gas signatures." *Marine Geophysical Researches* 26: 235 - 245.

SHORE PARALLEL

SC003





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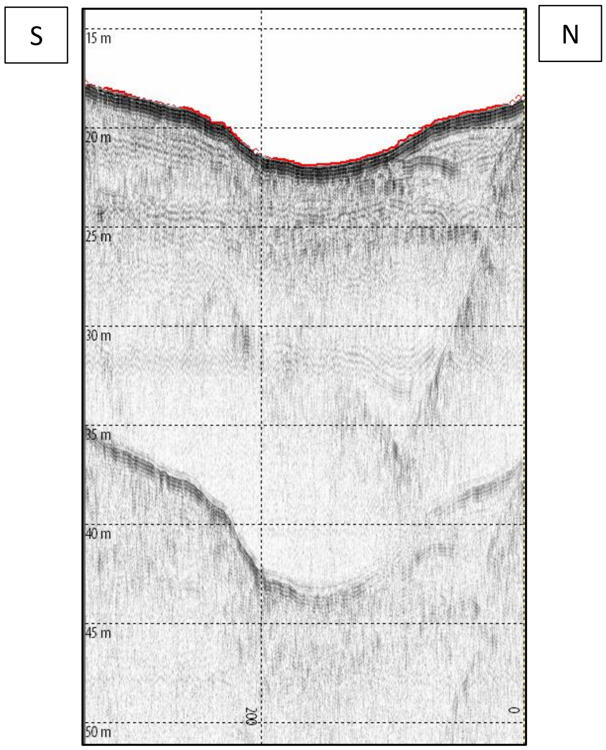
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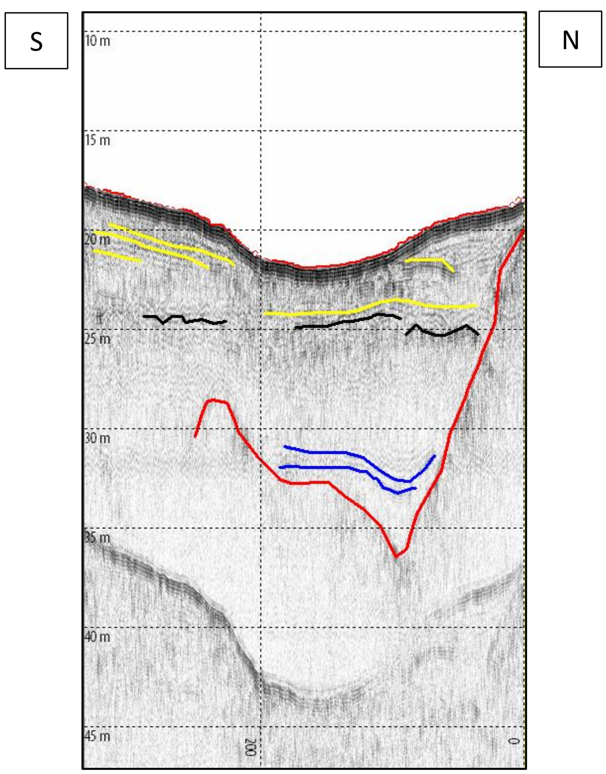
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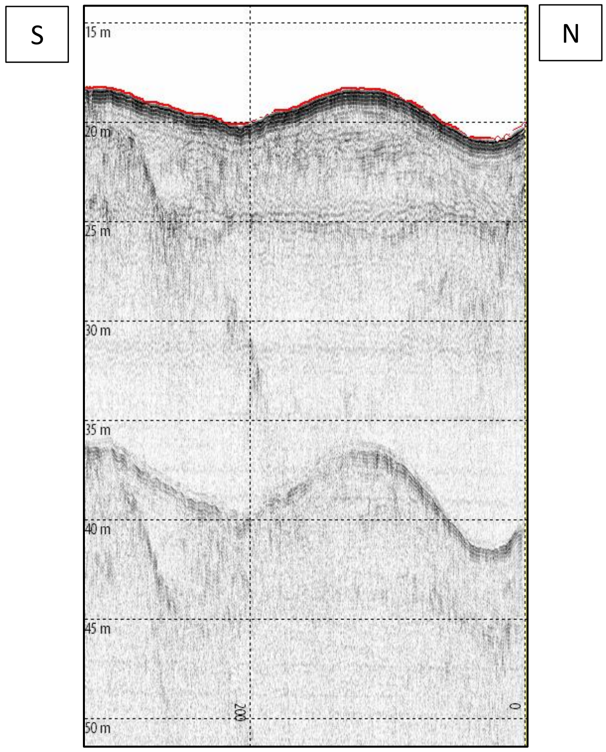
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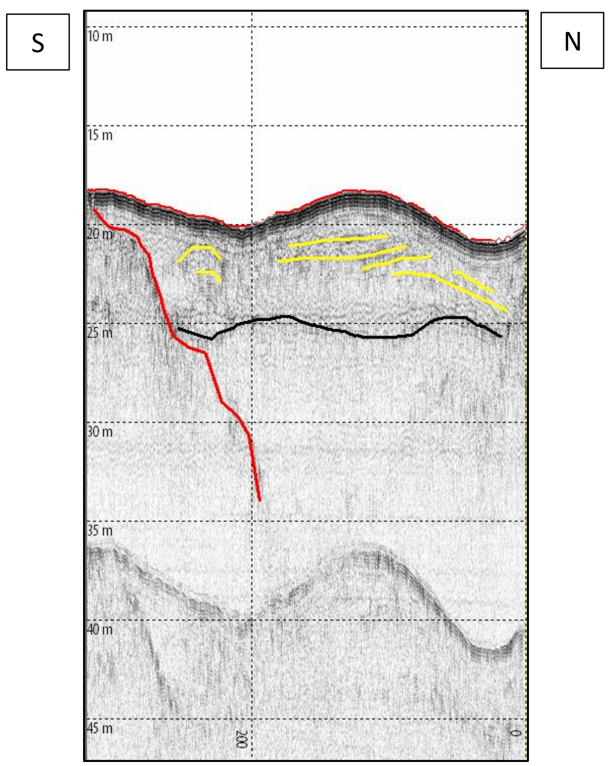
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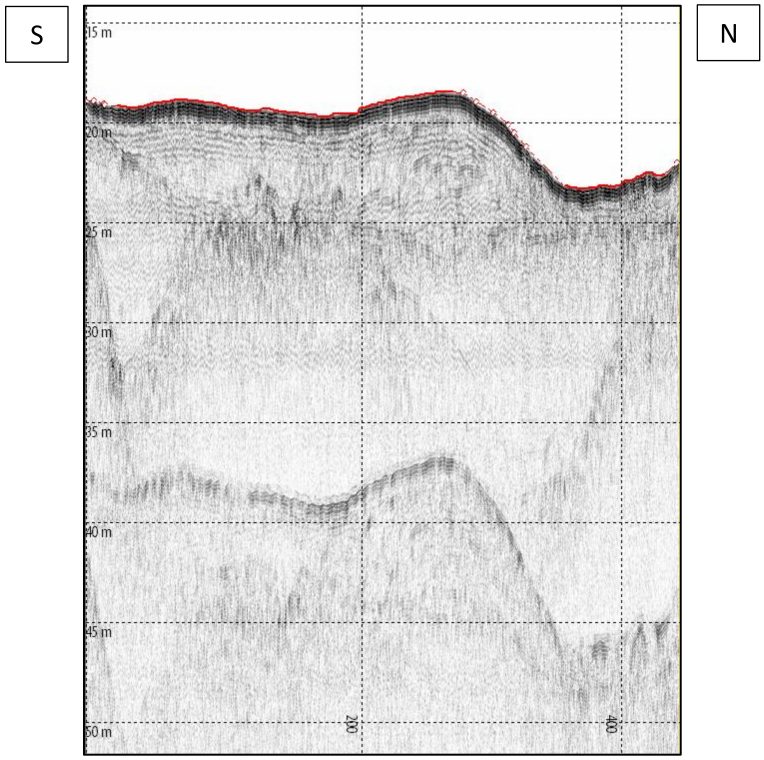
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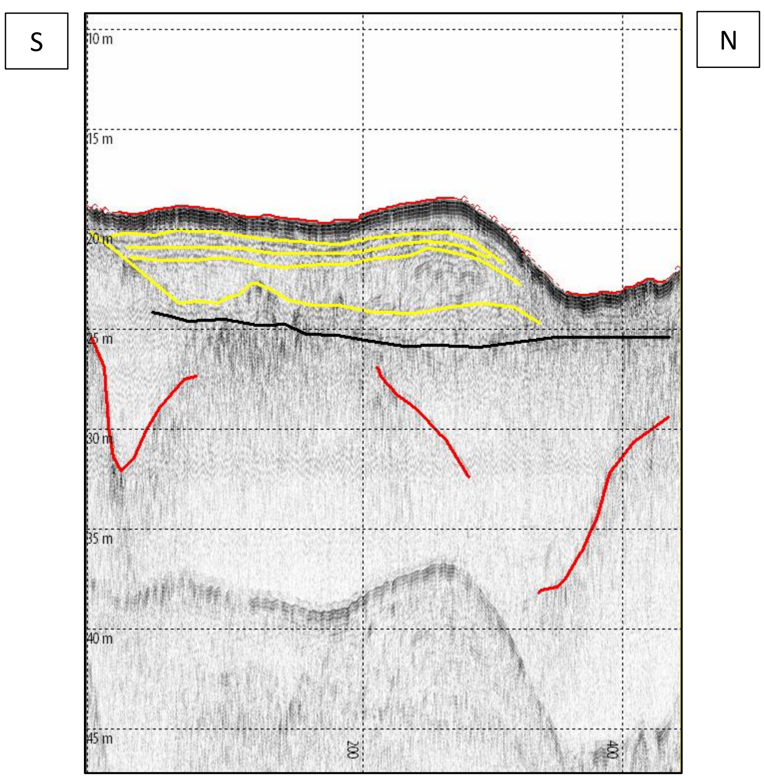
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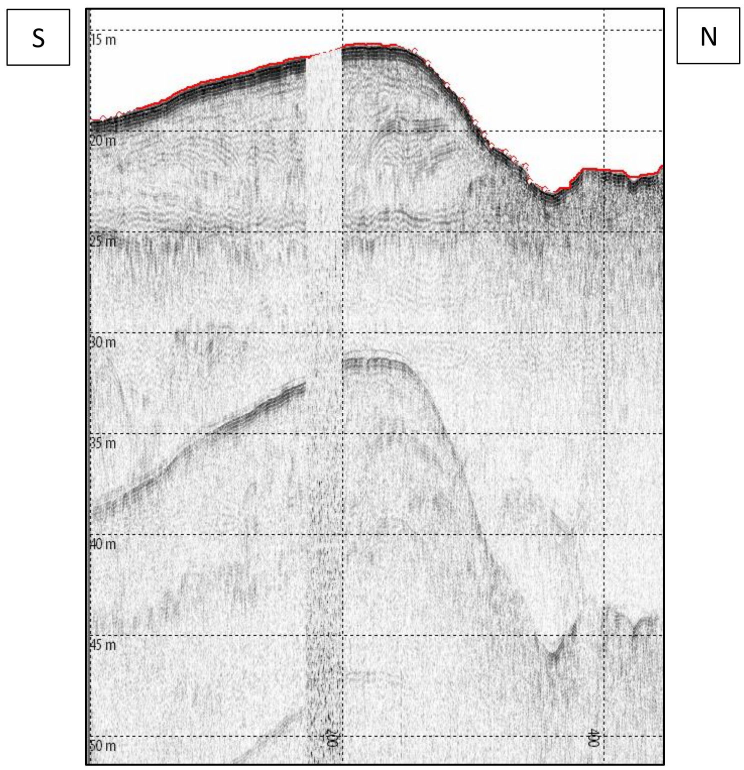
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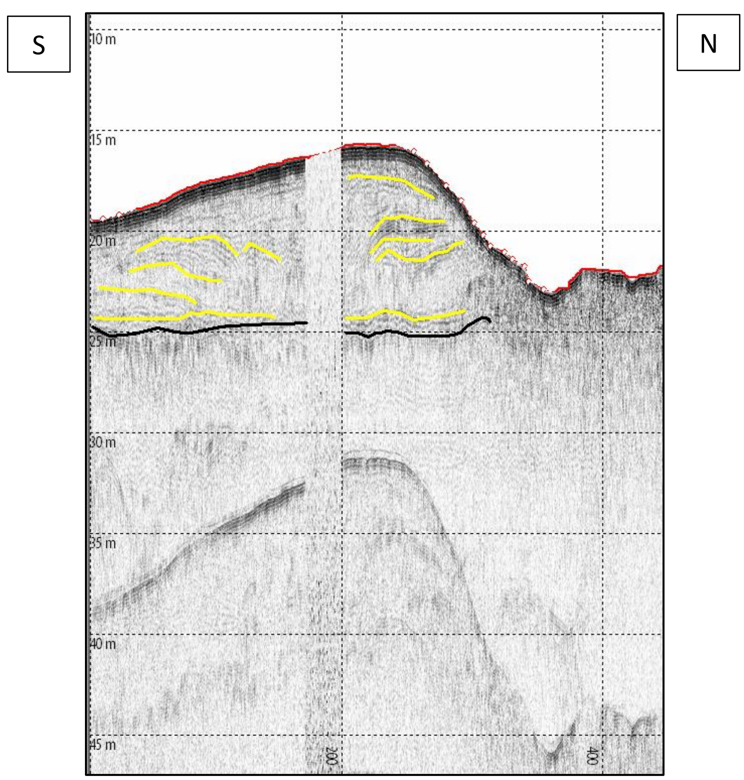
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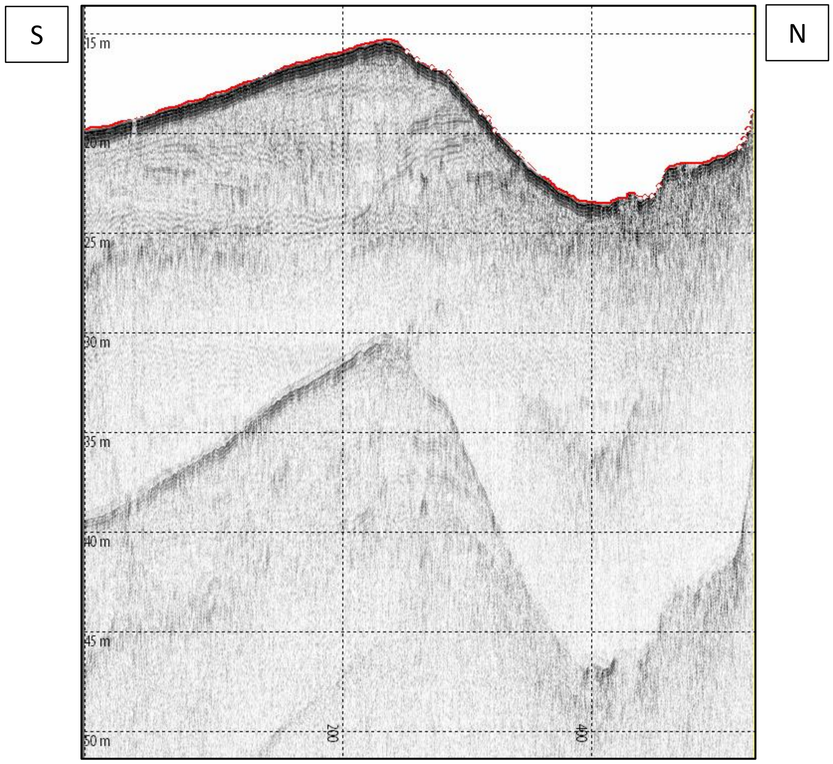
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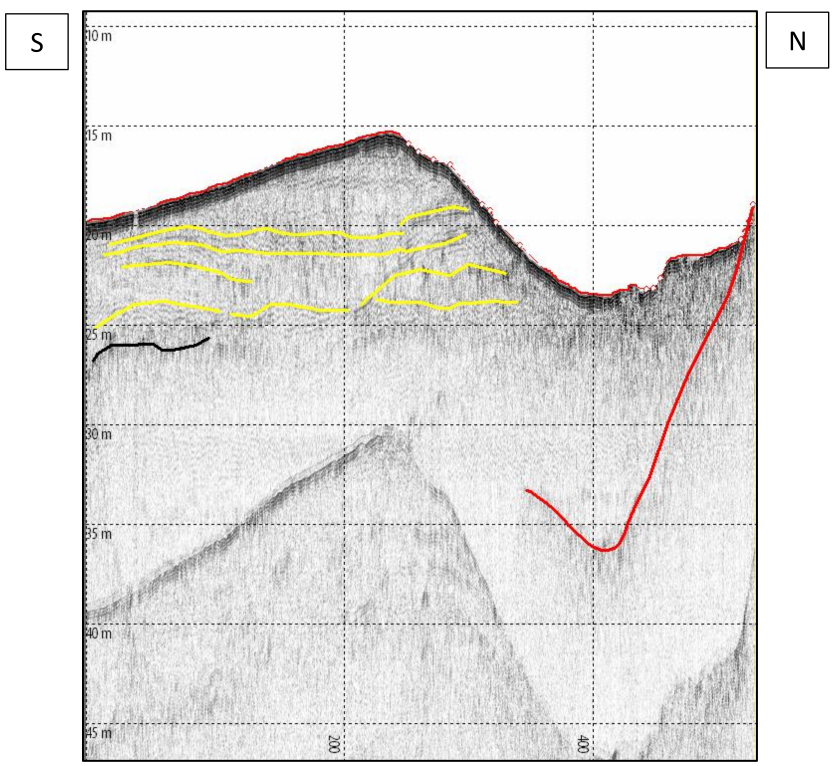
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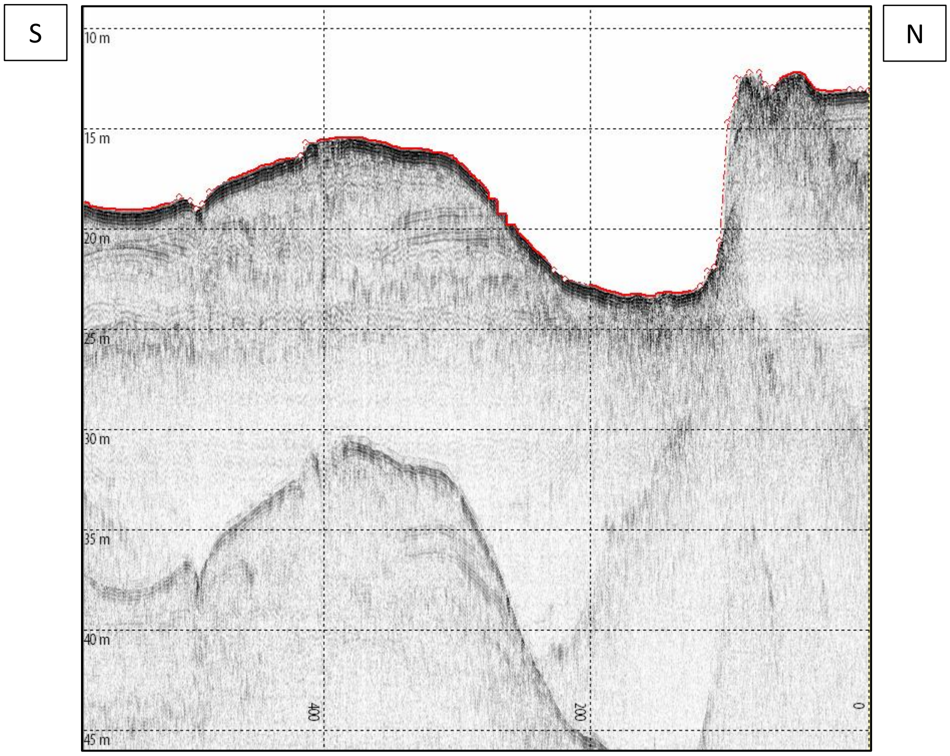
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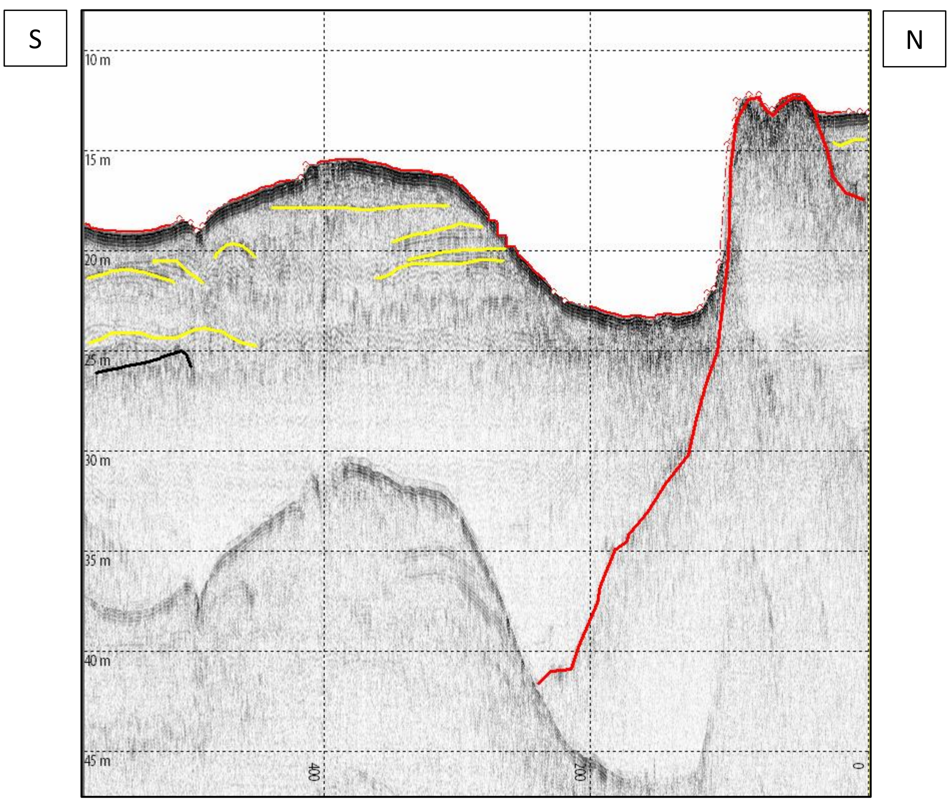
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XC010

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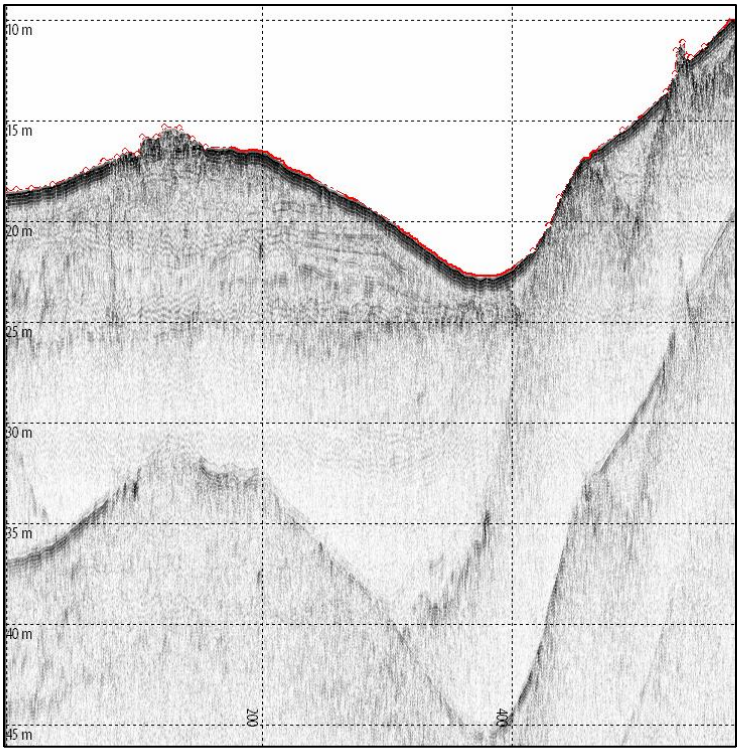
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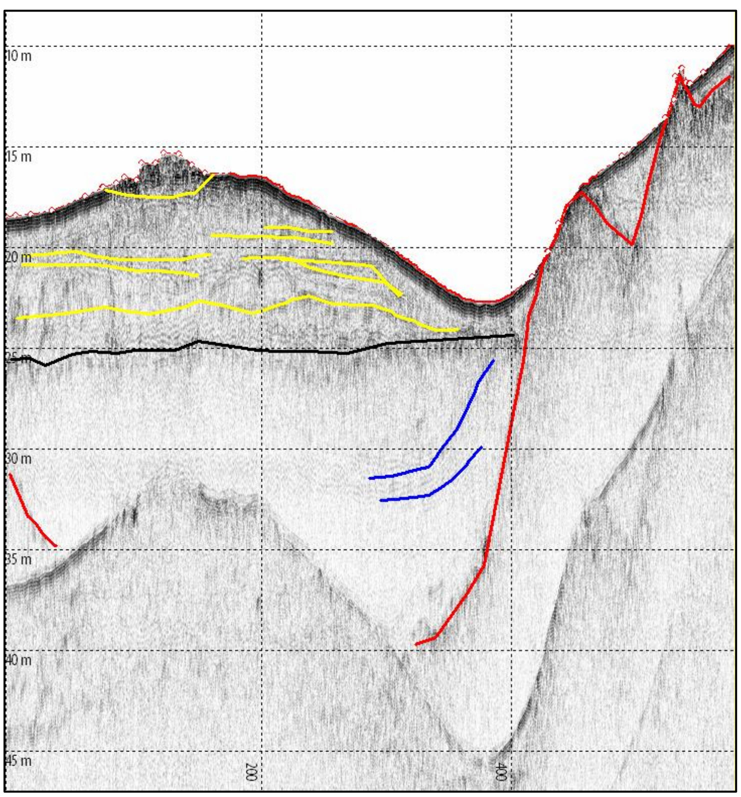
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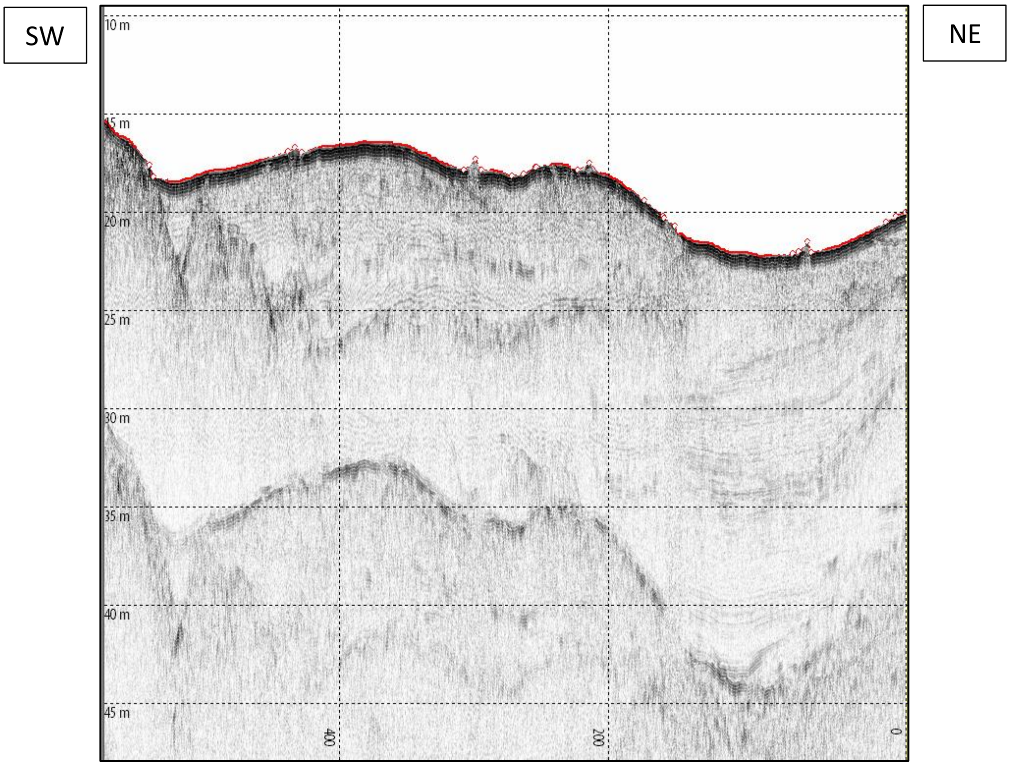
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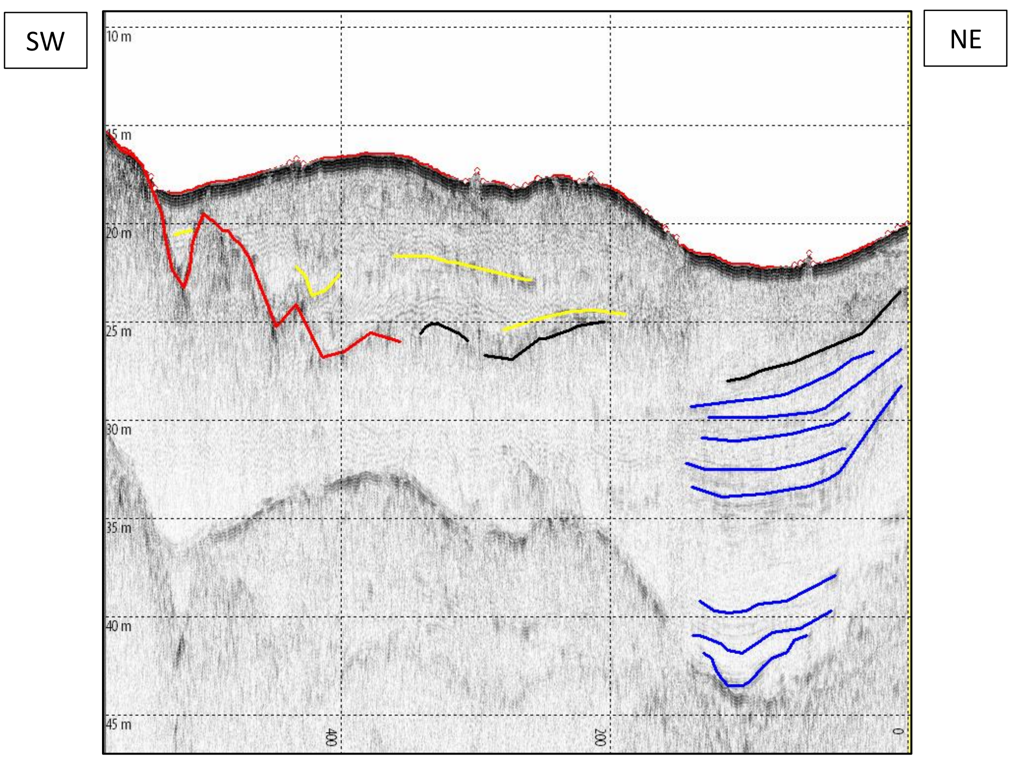
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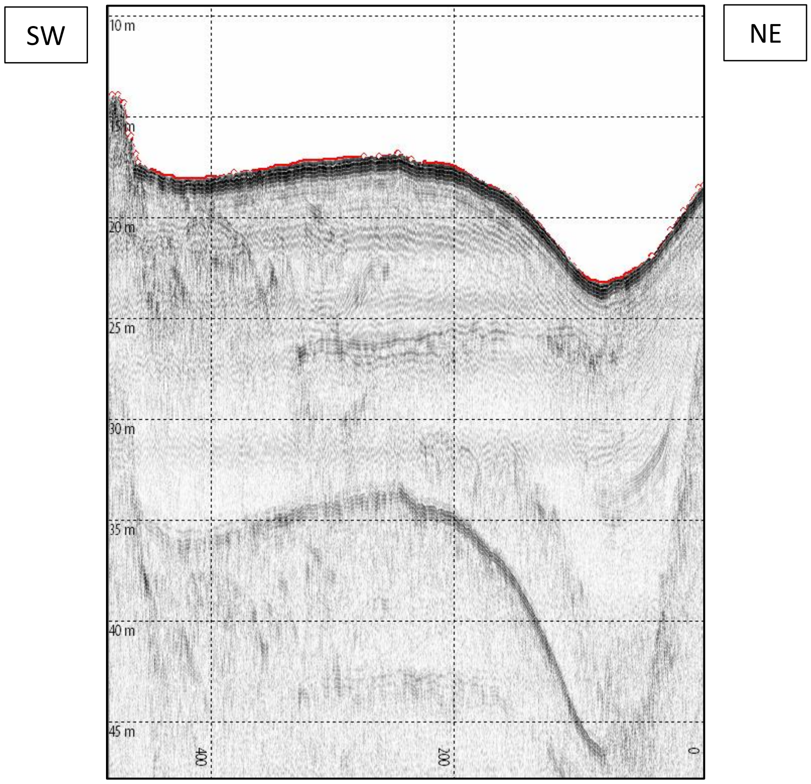

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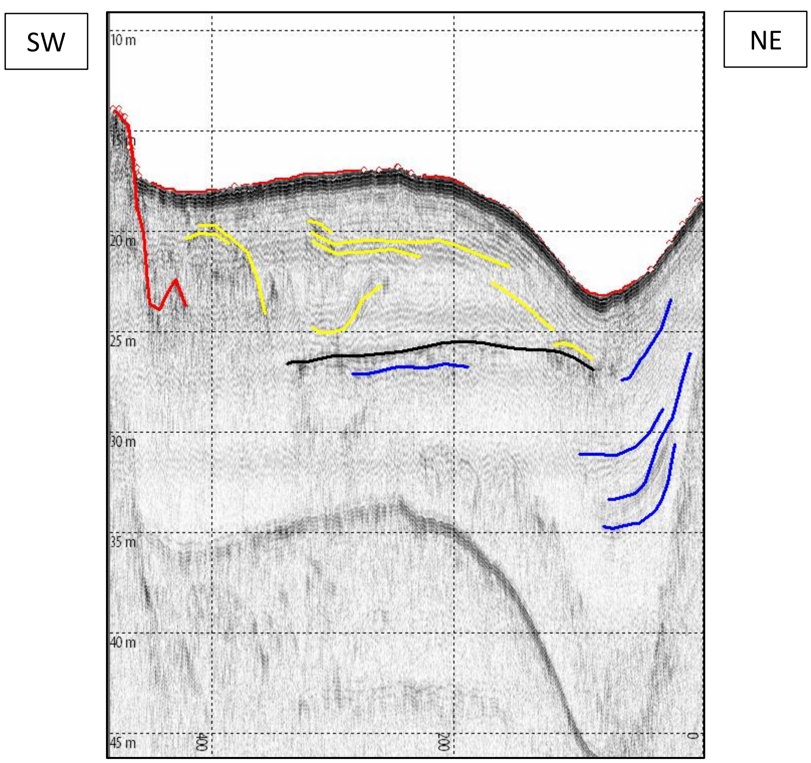

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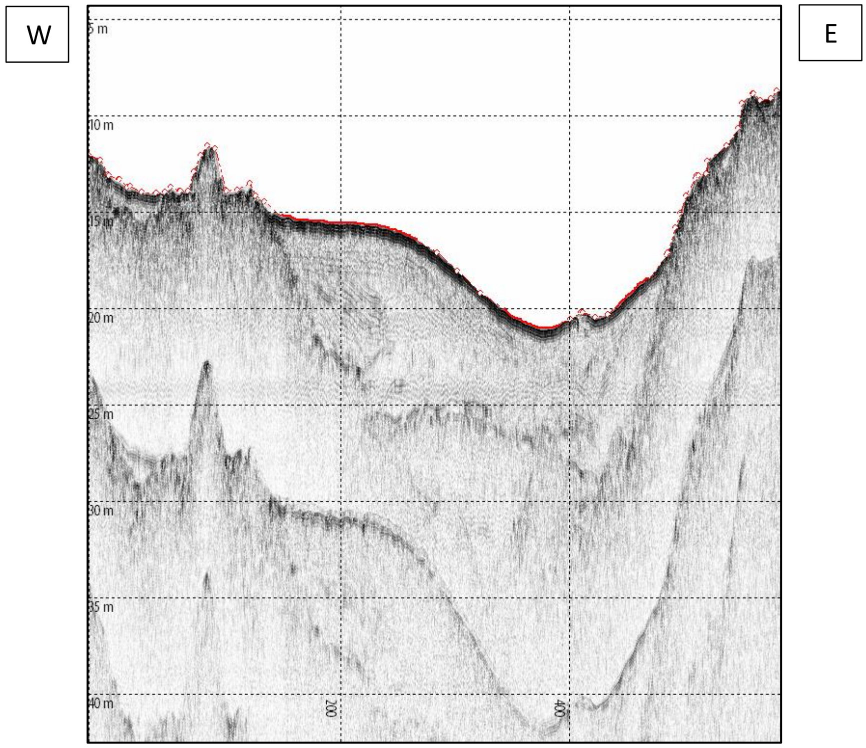
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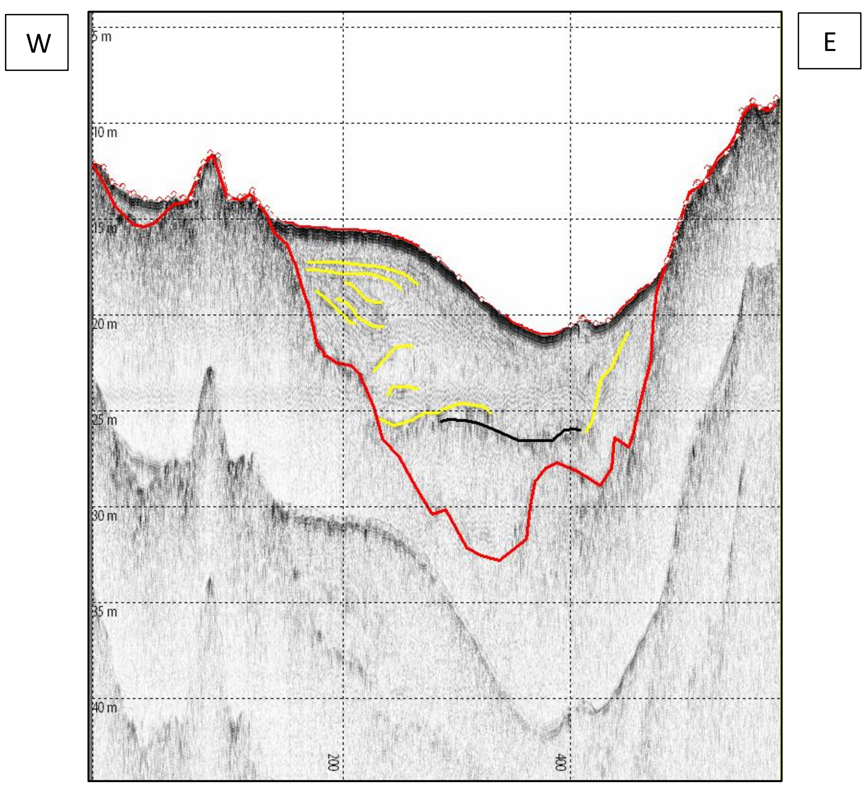
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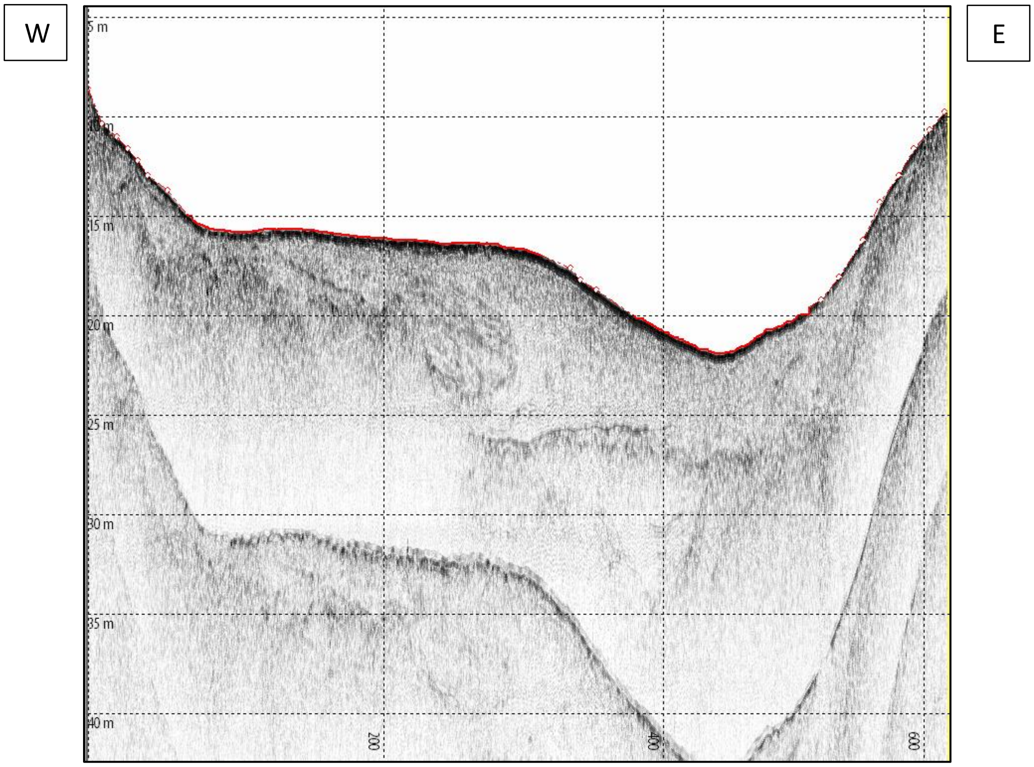
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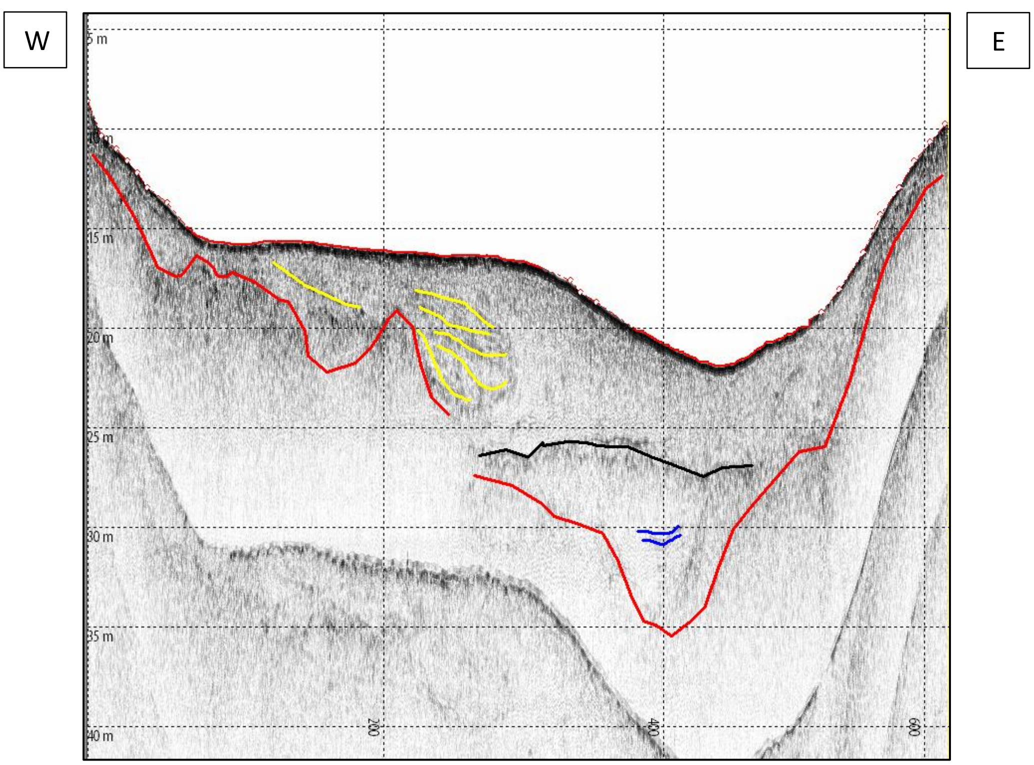
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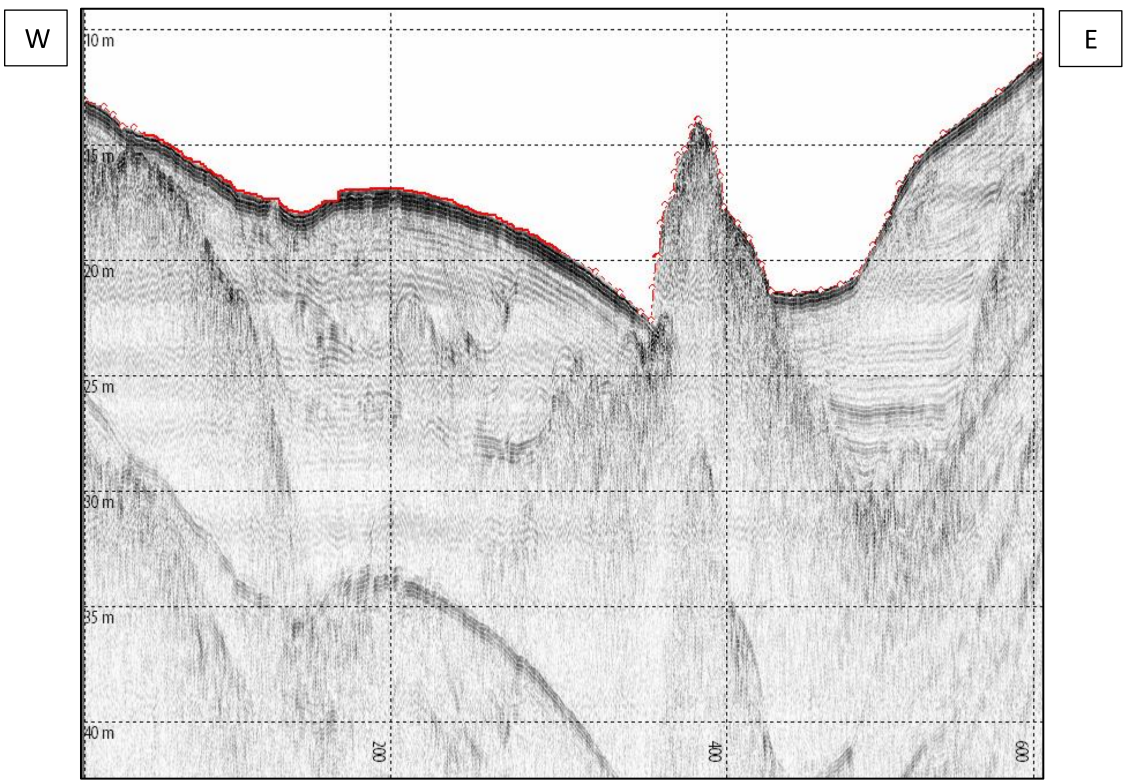
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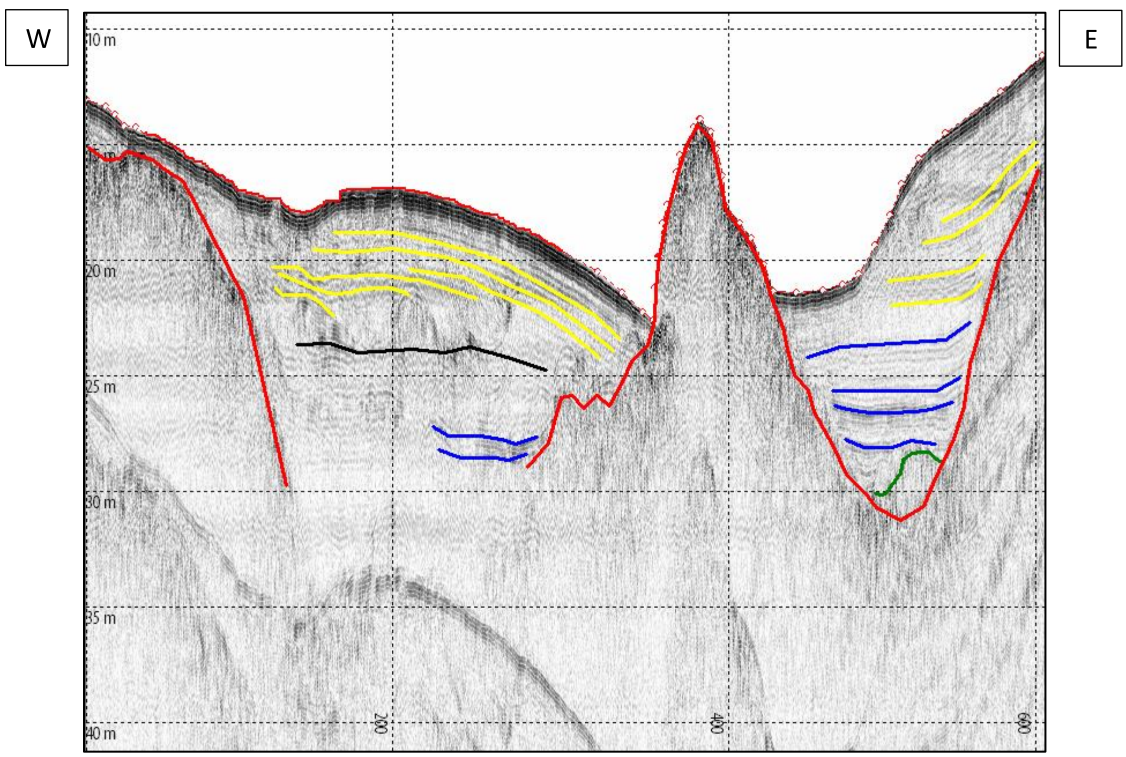
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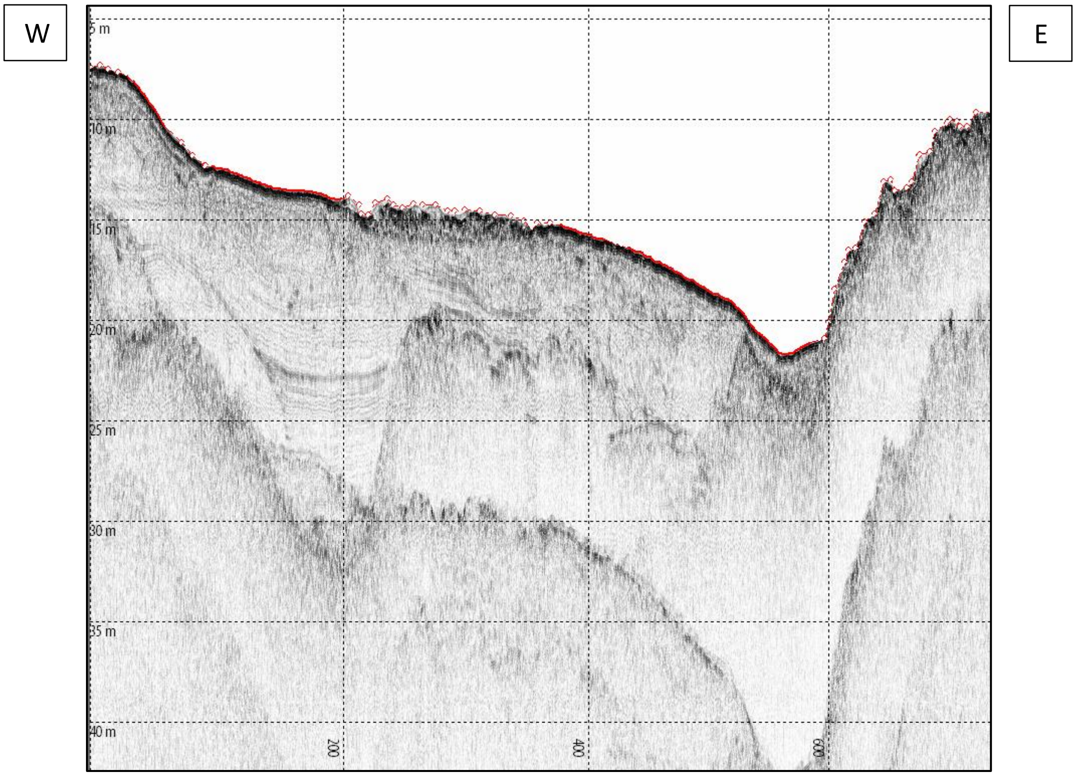
XC015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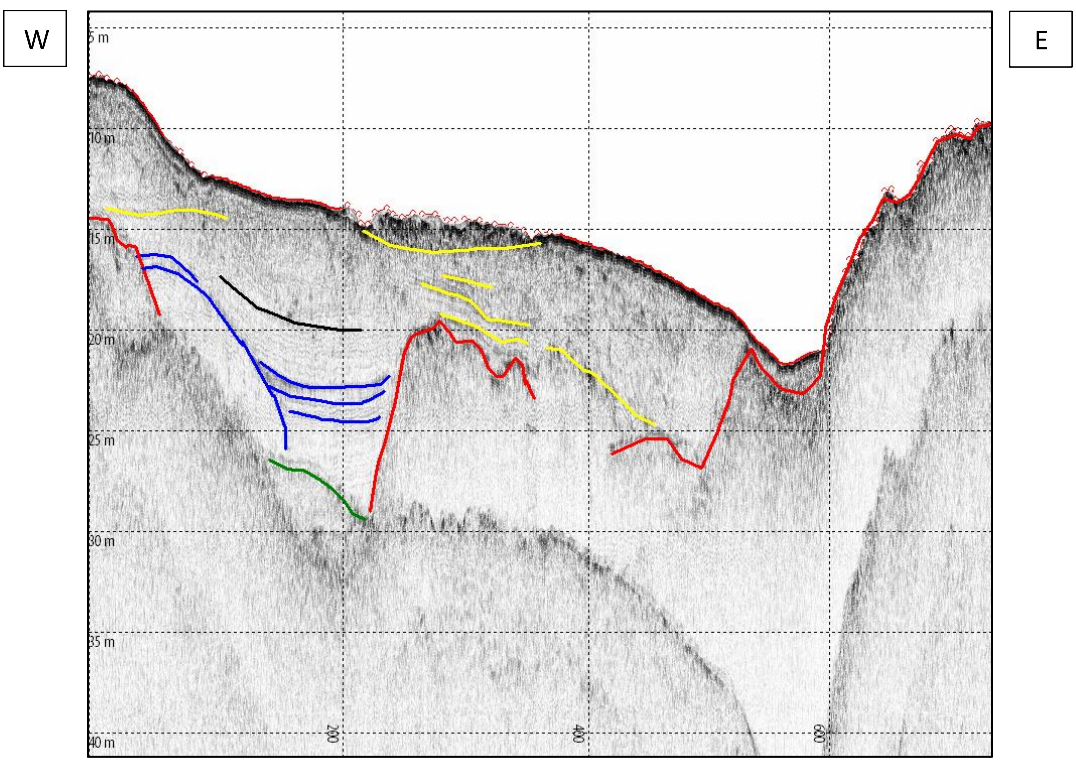
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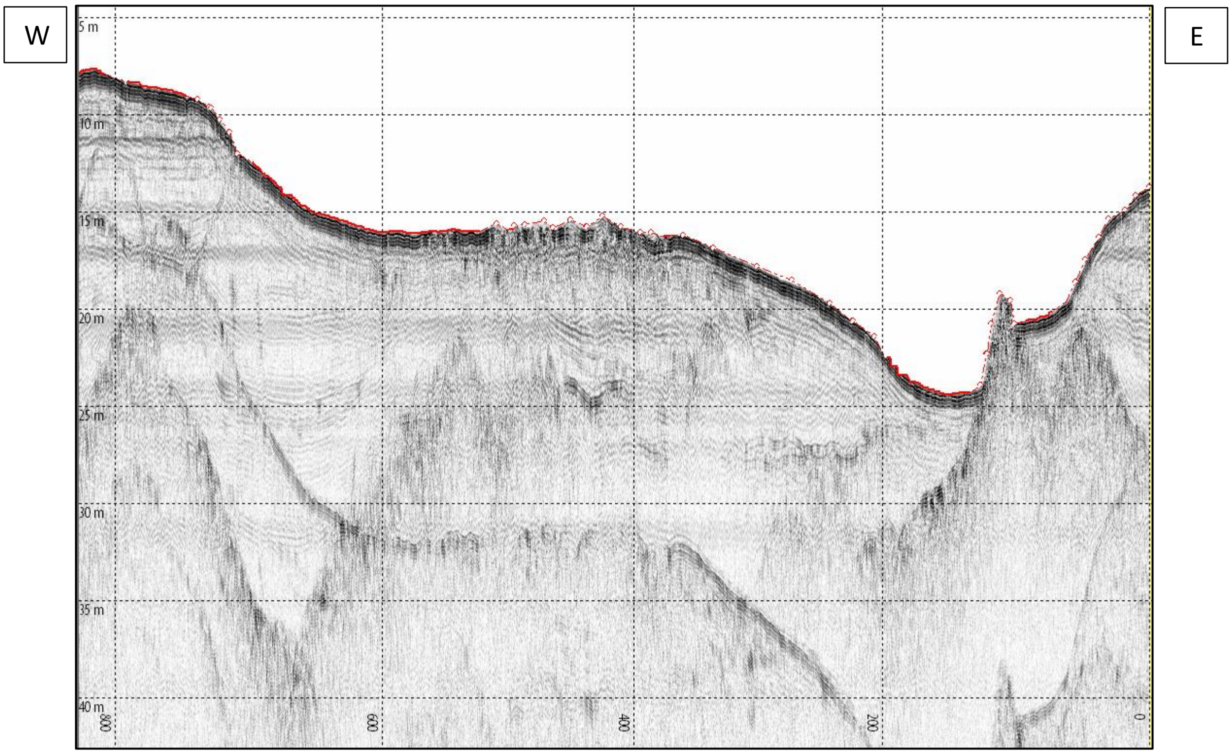
XC016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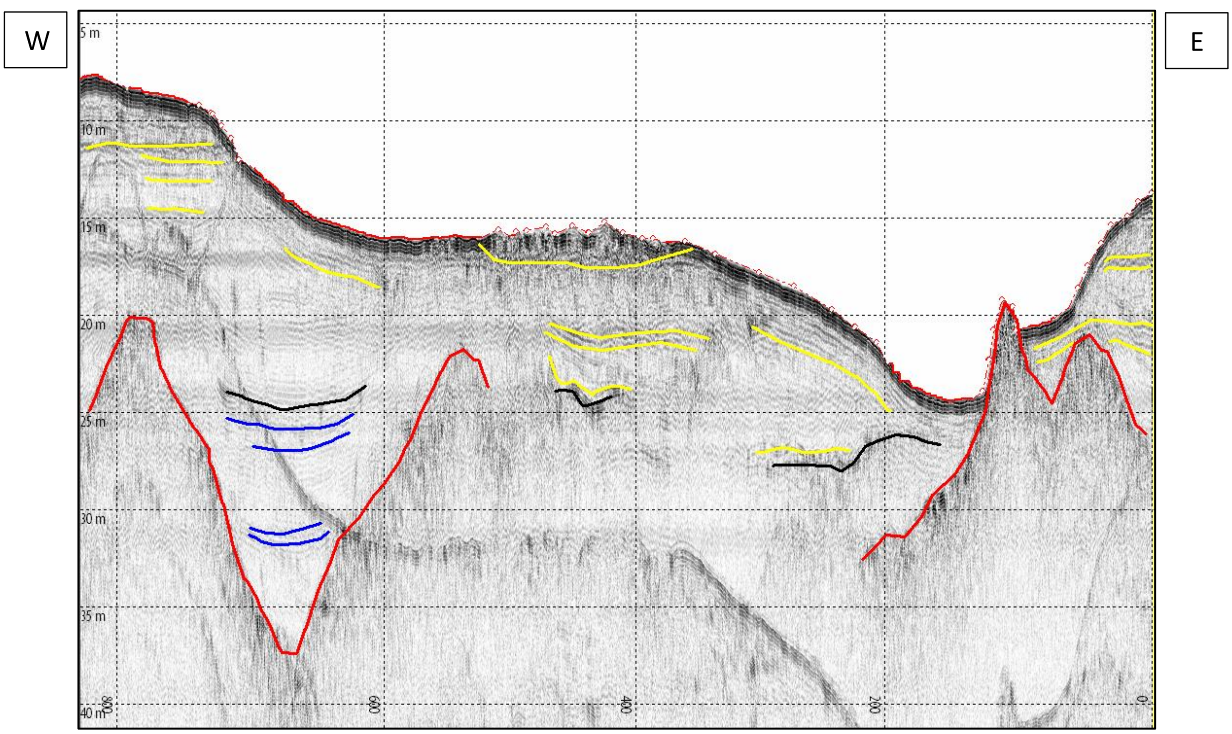
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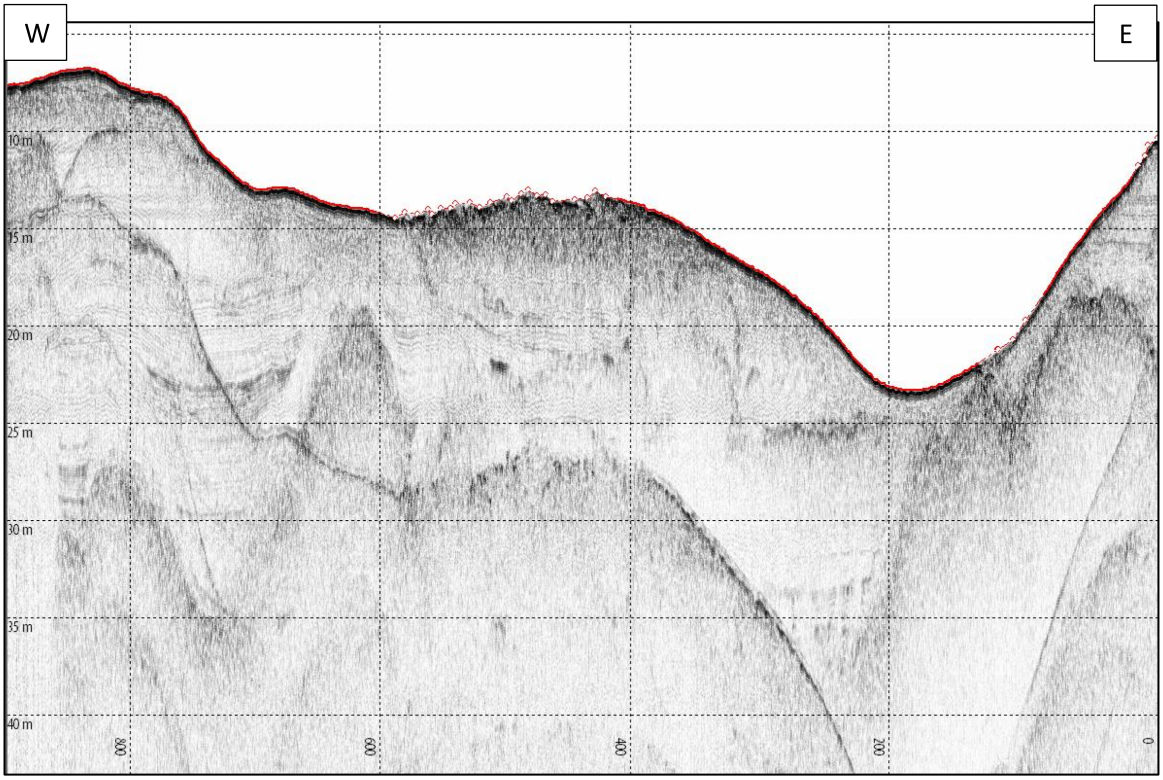
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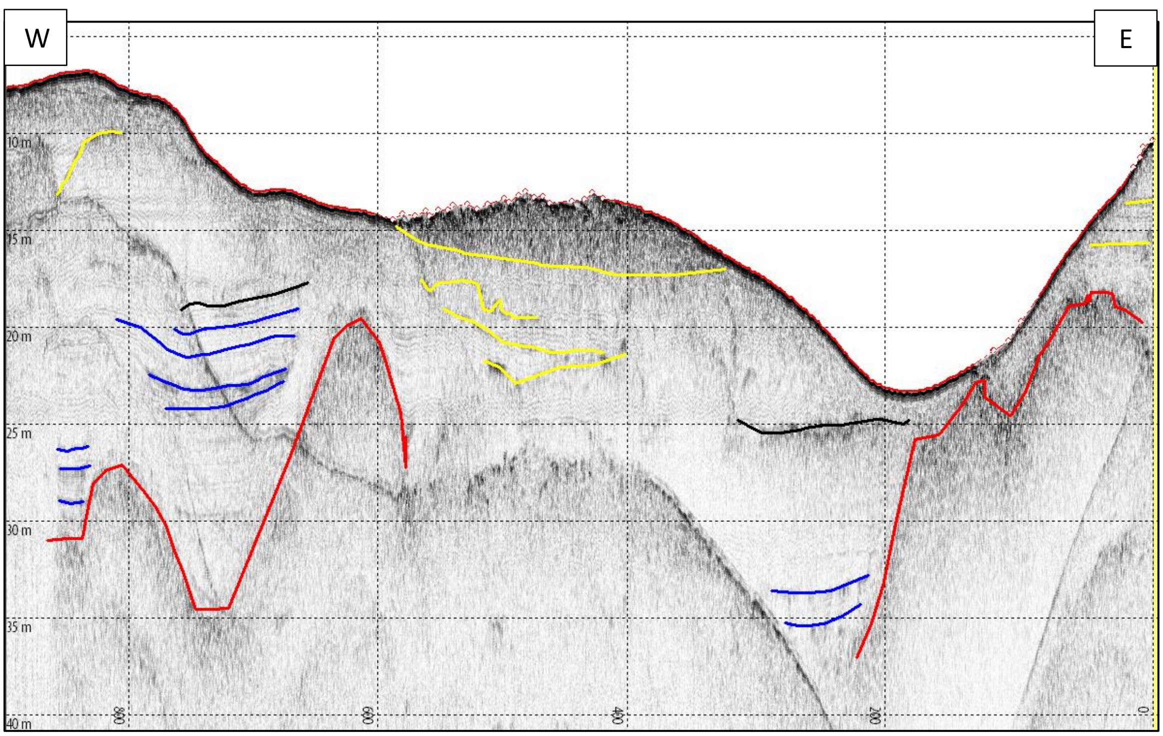
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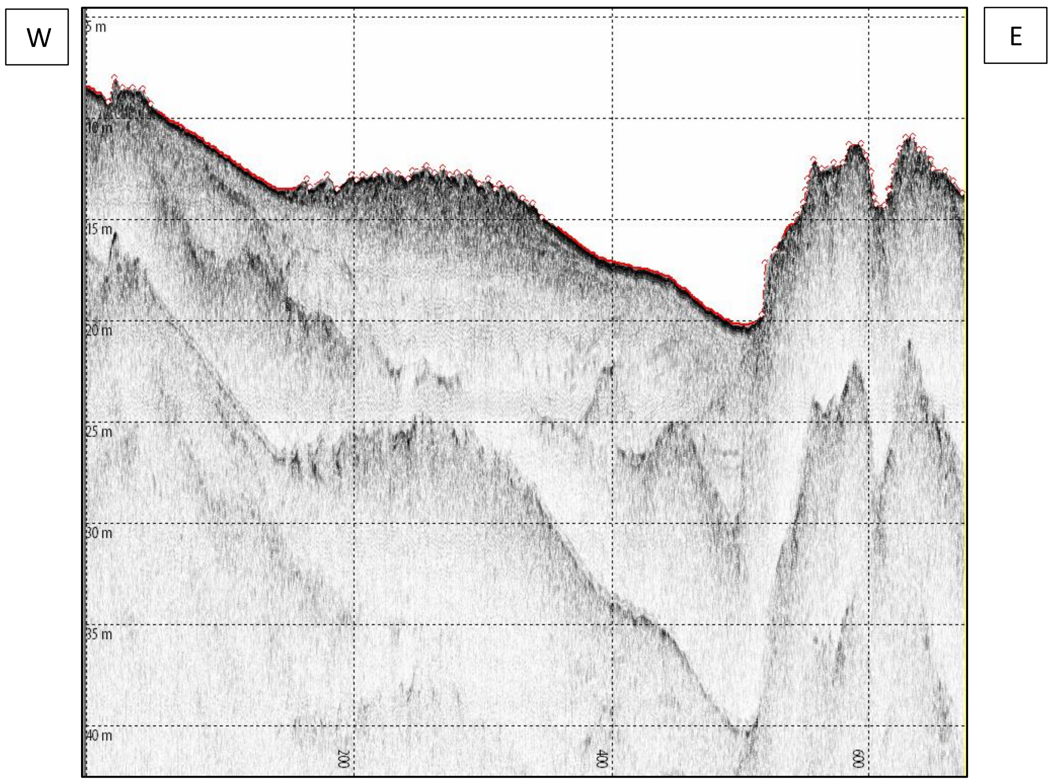
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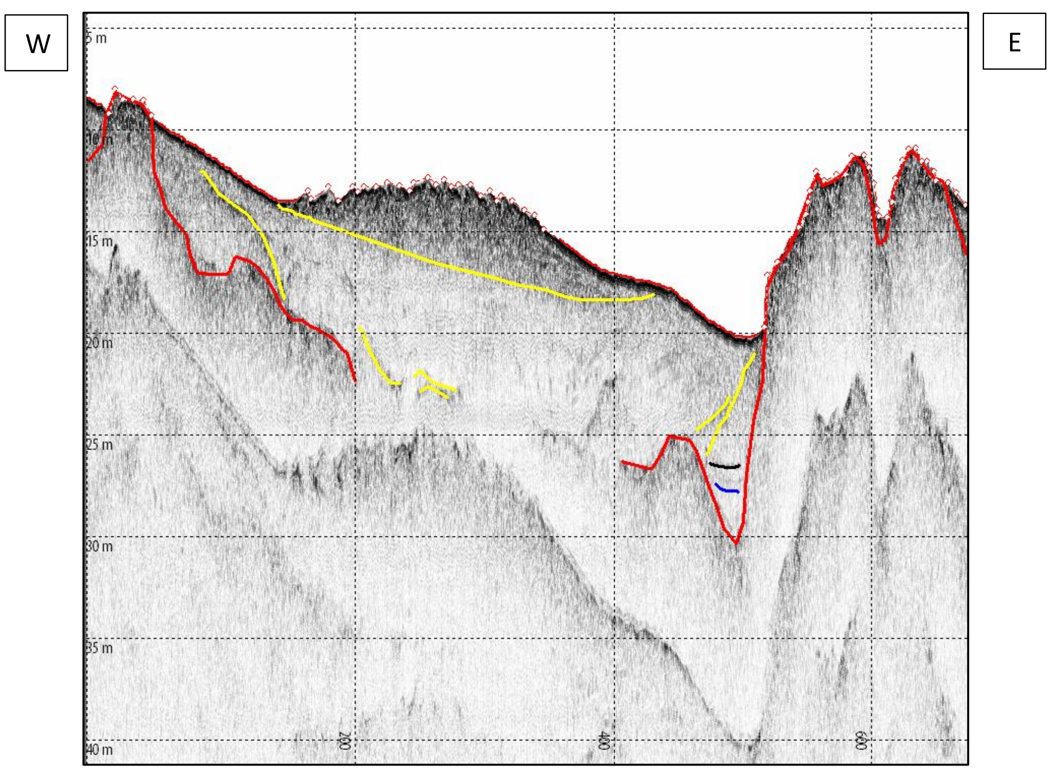
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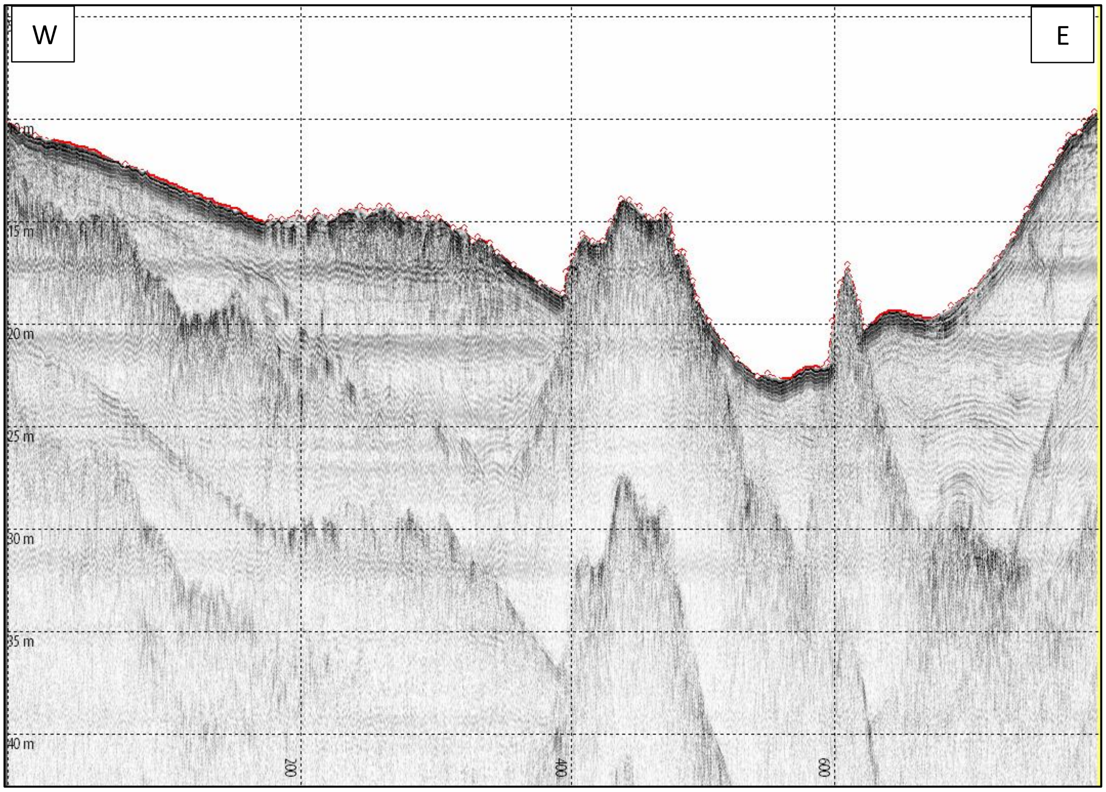
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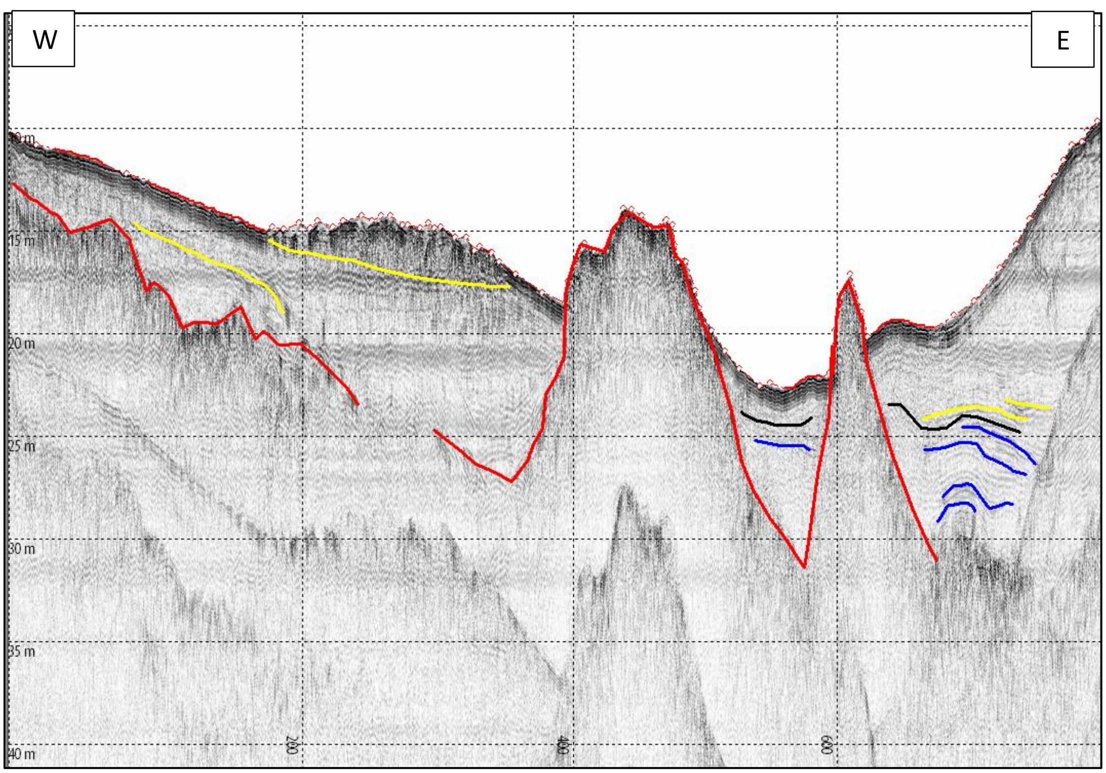
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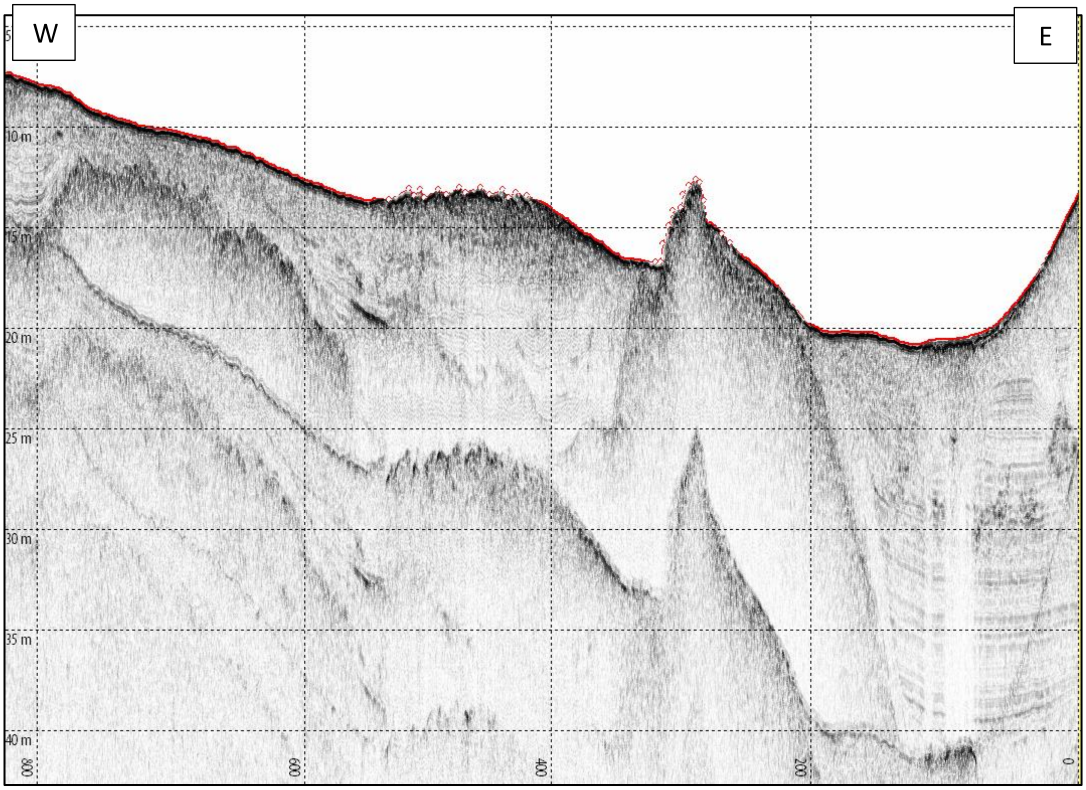
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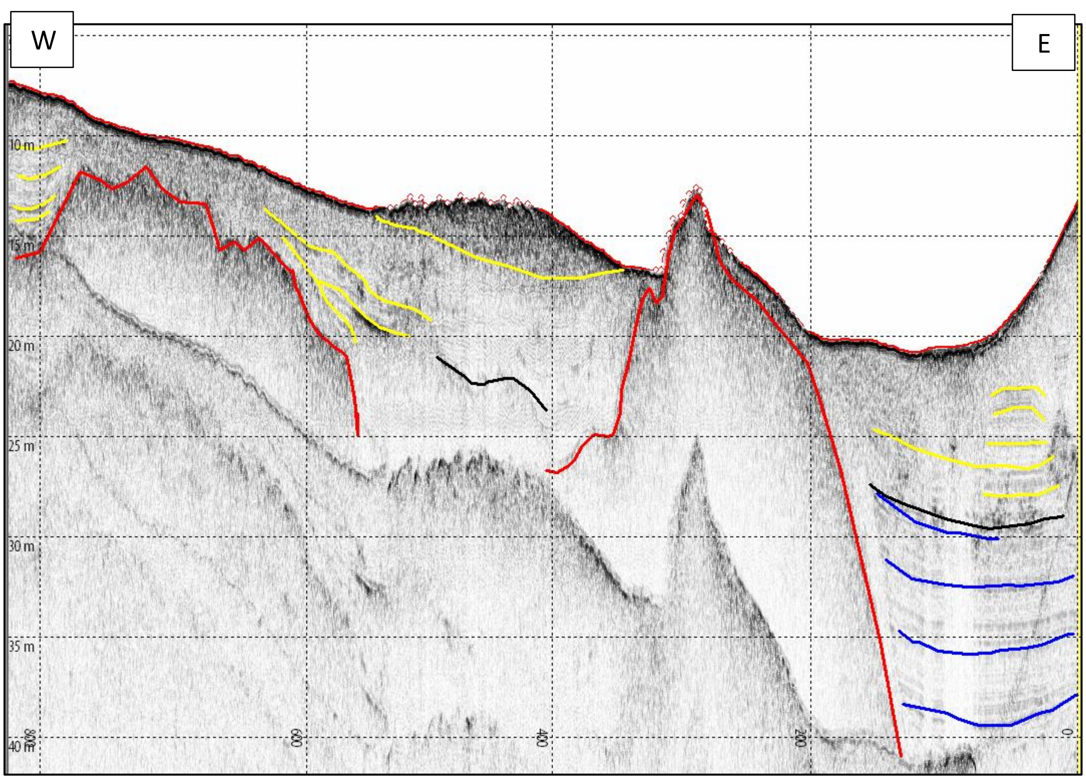
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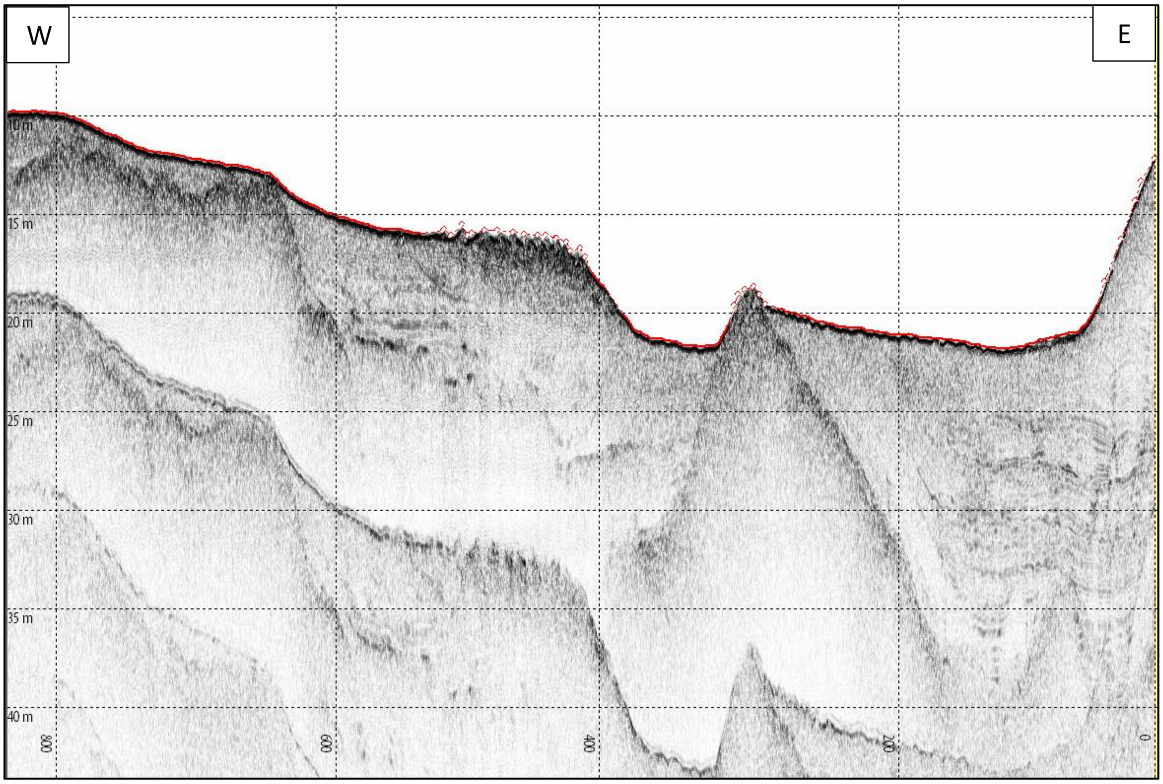
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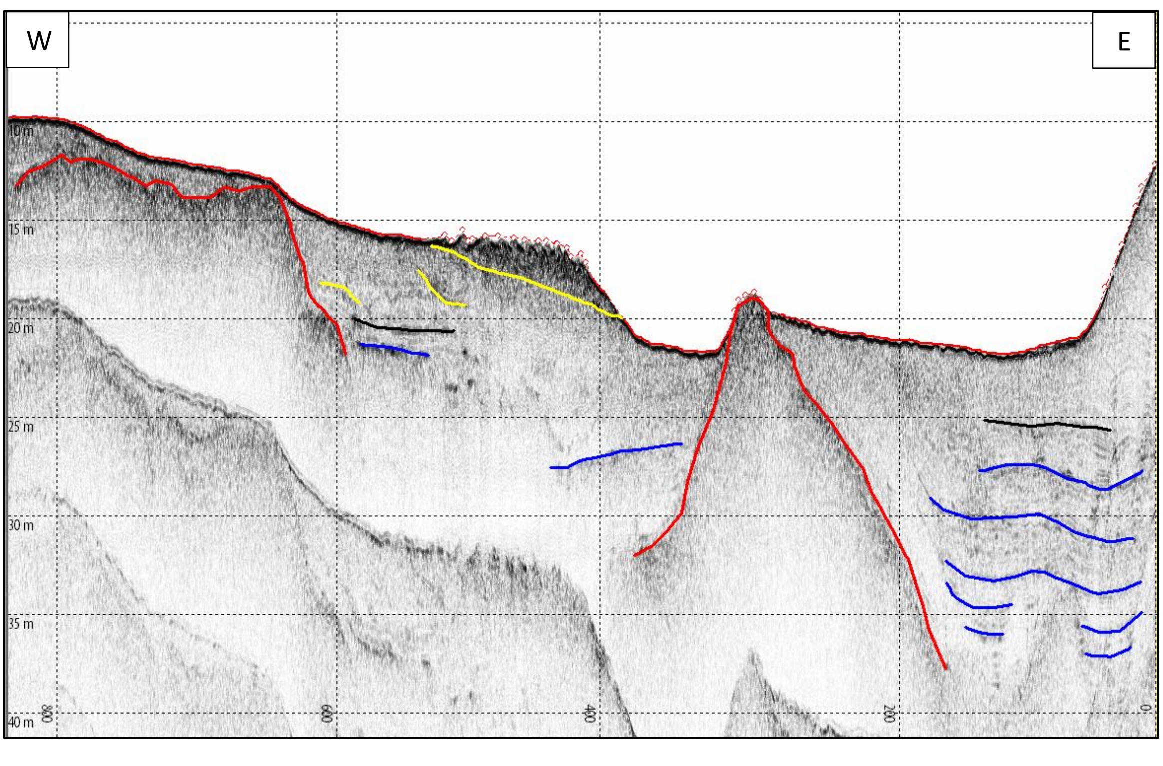
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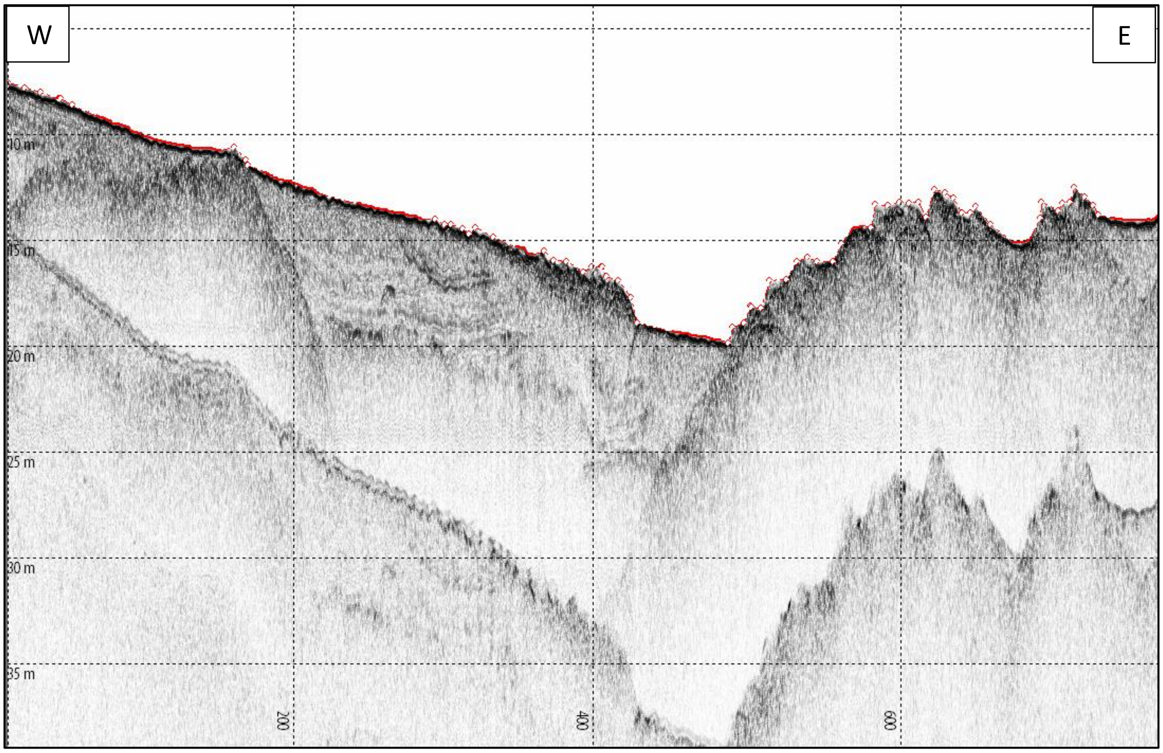
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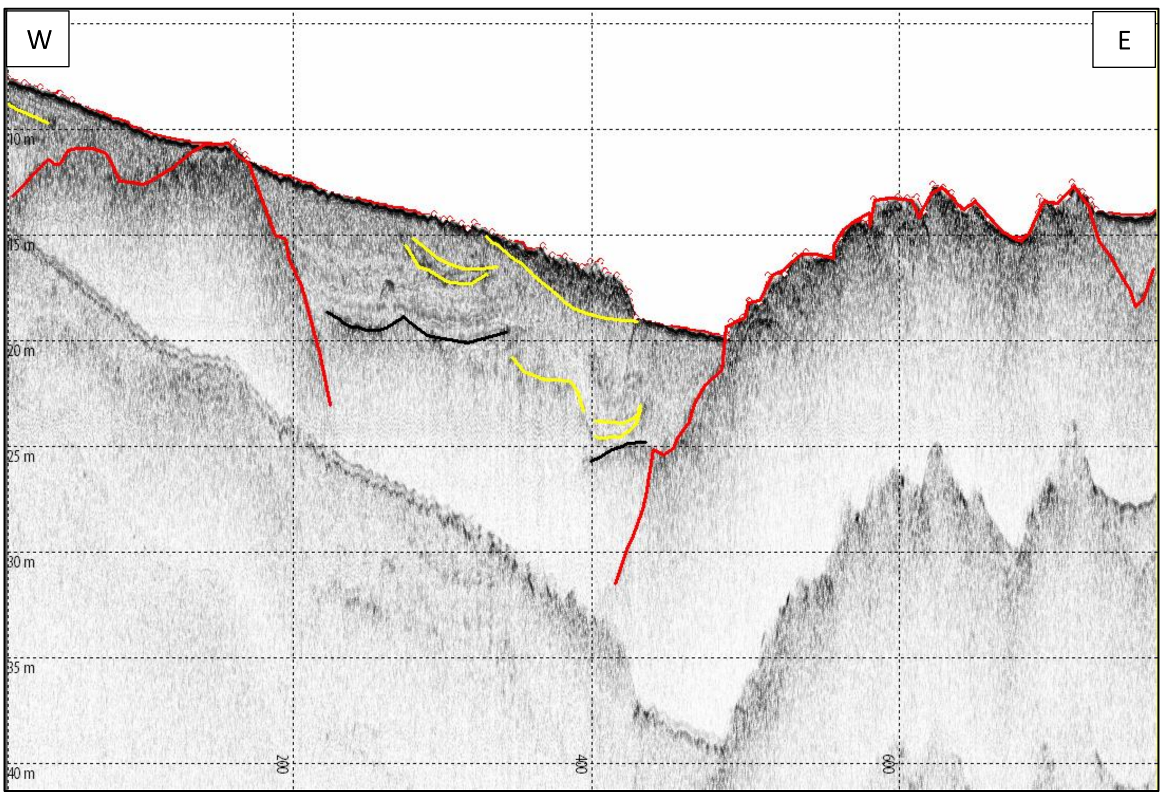
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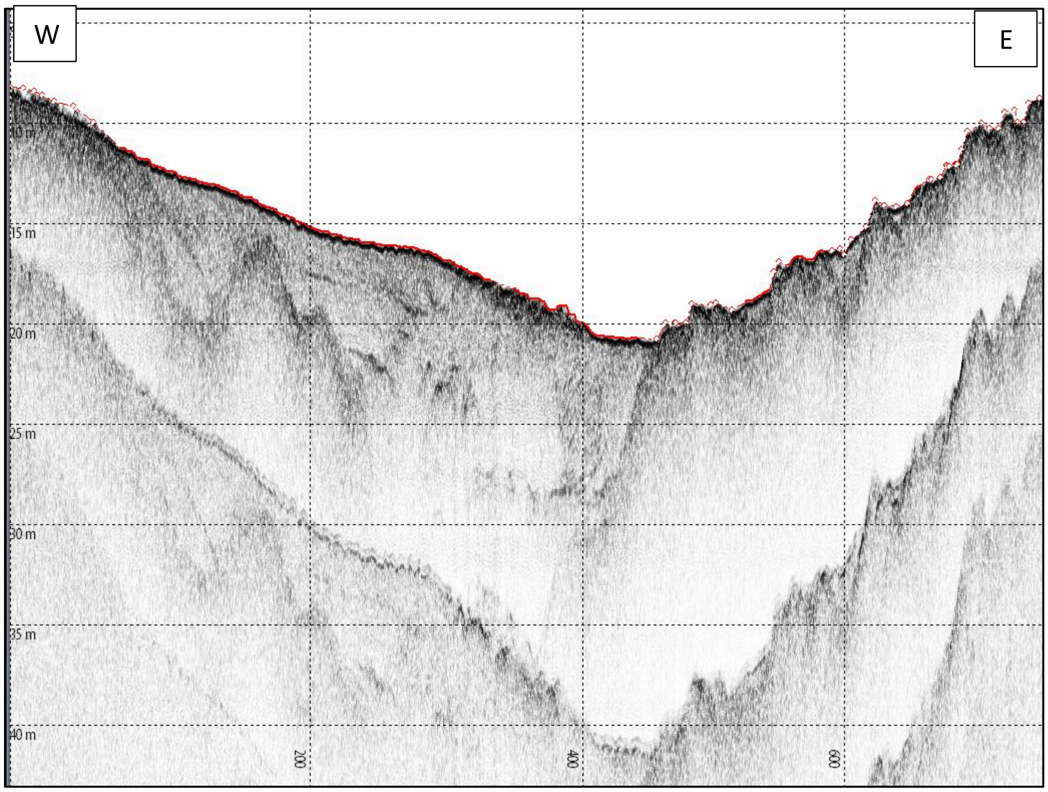
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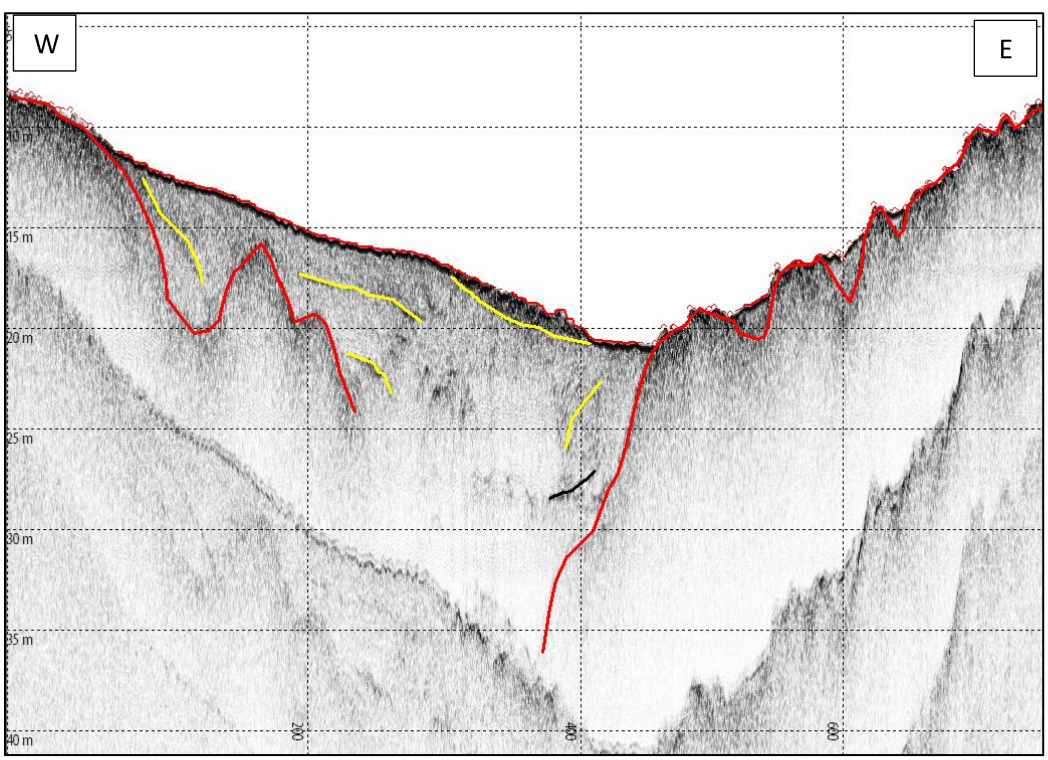
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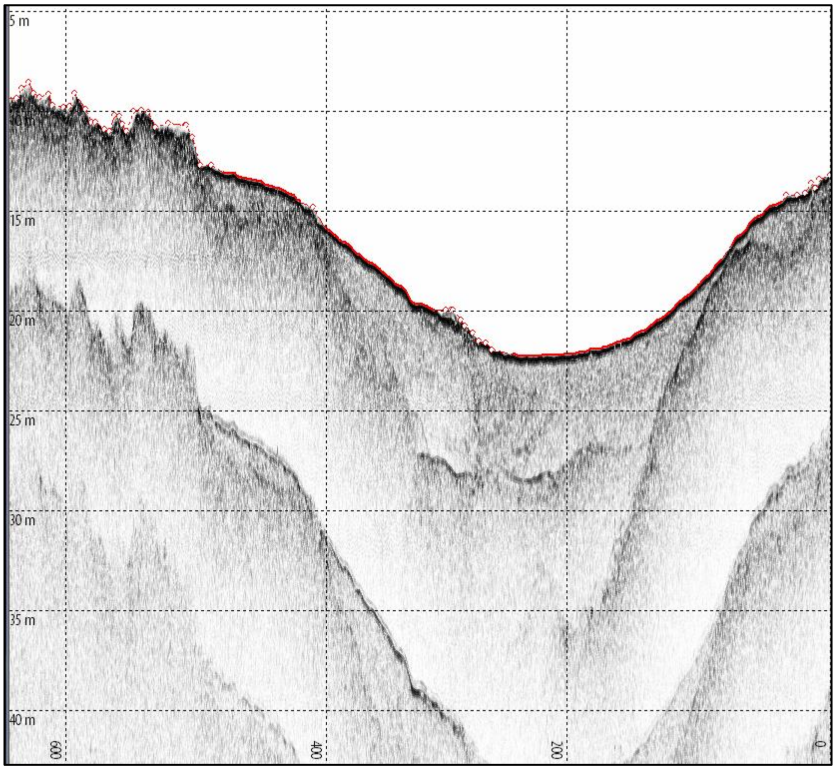
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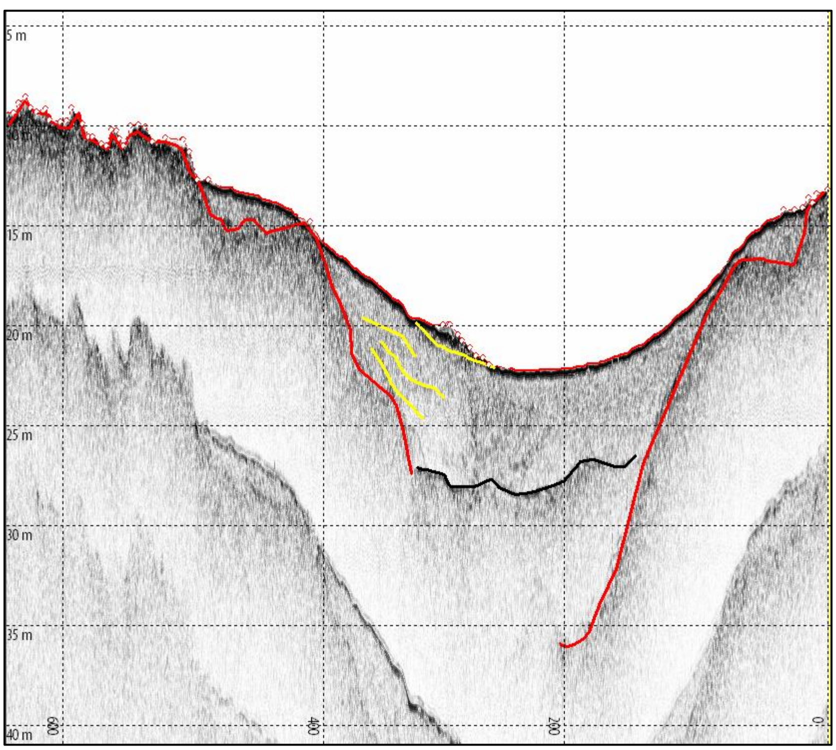
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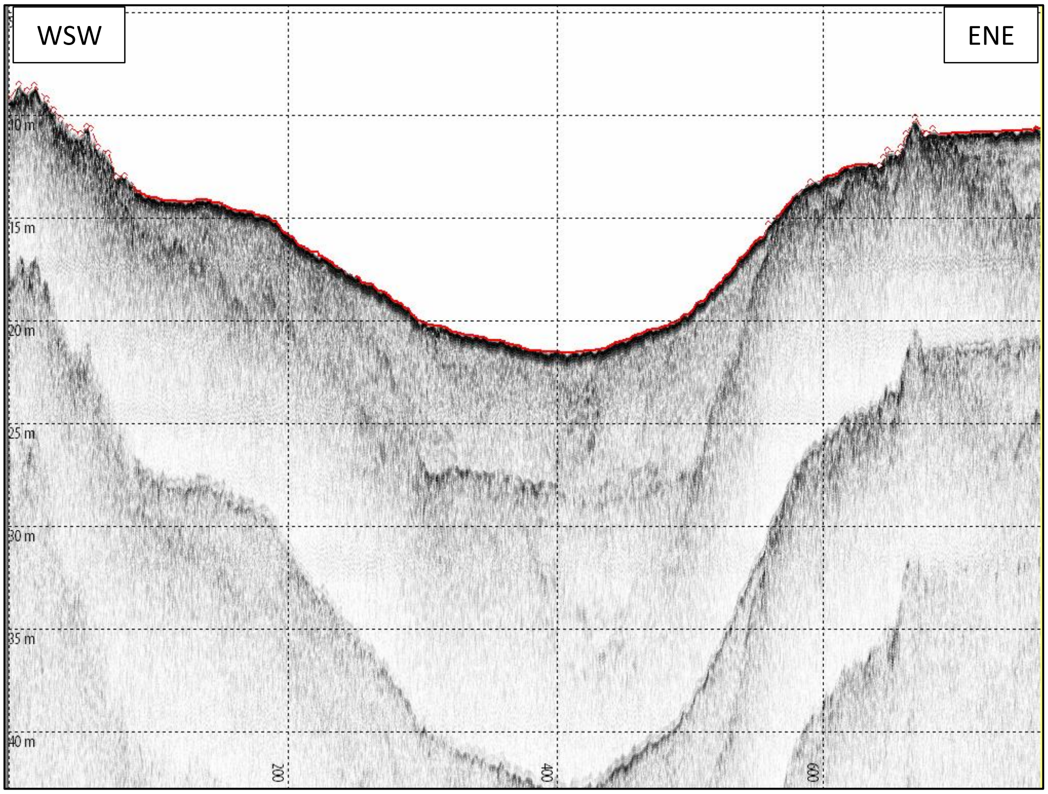
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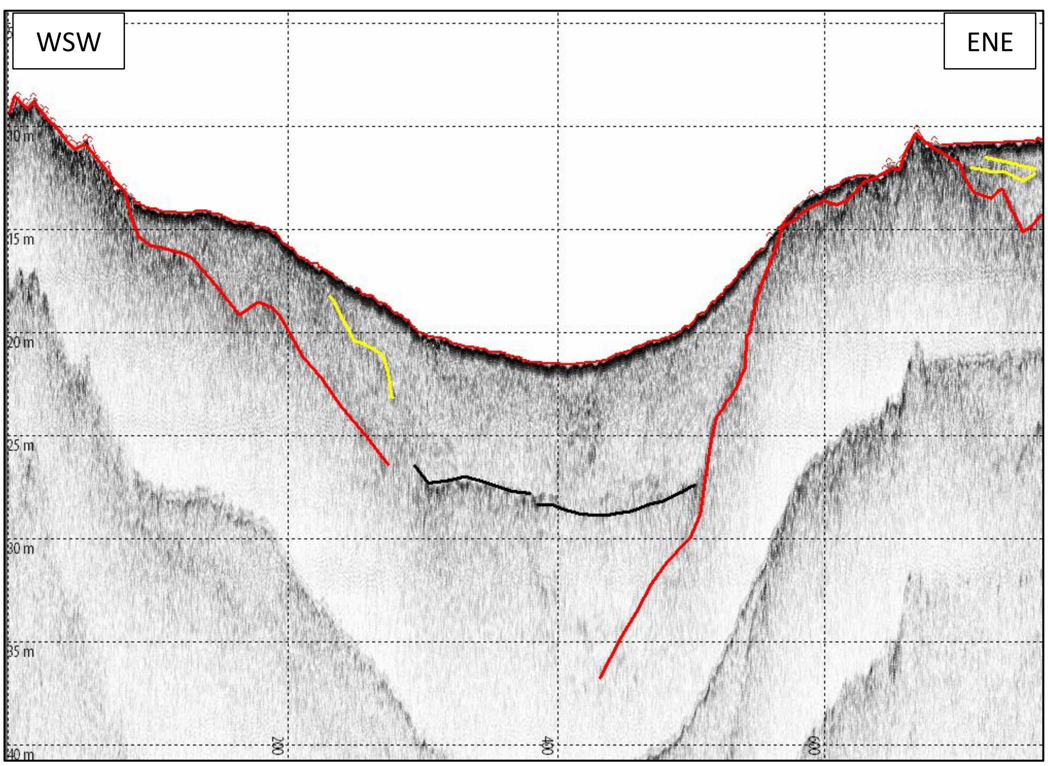
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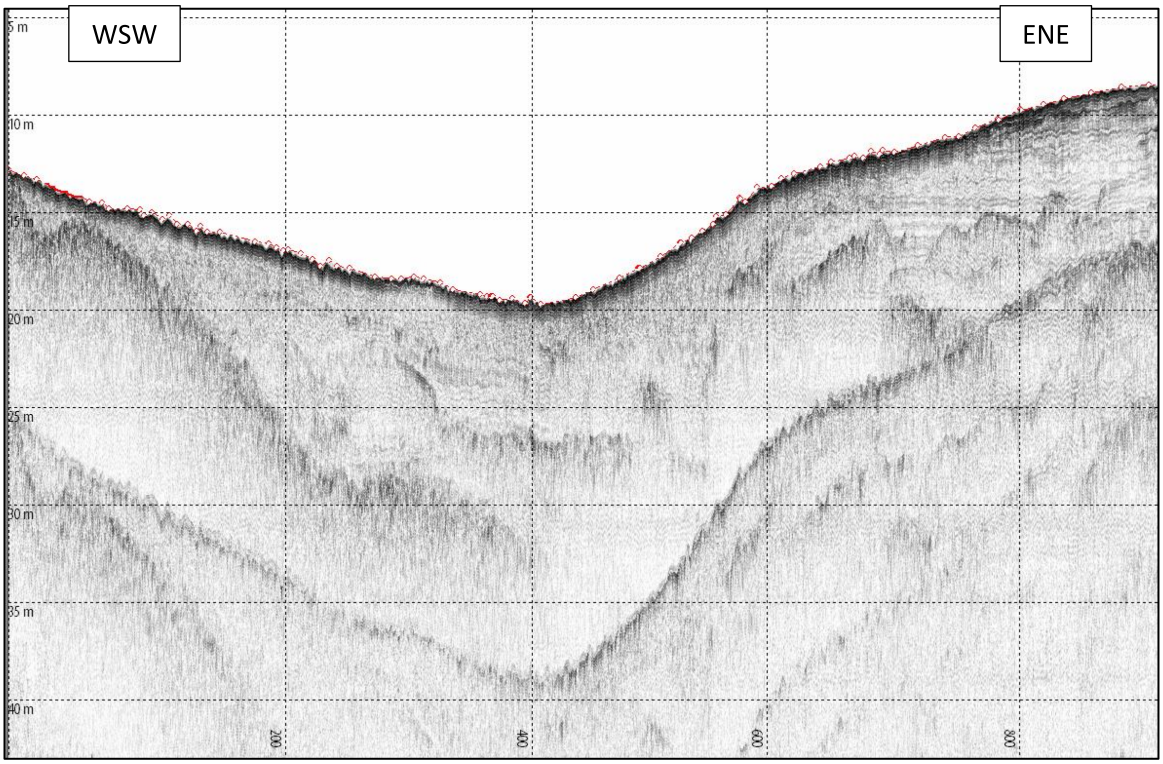
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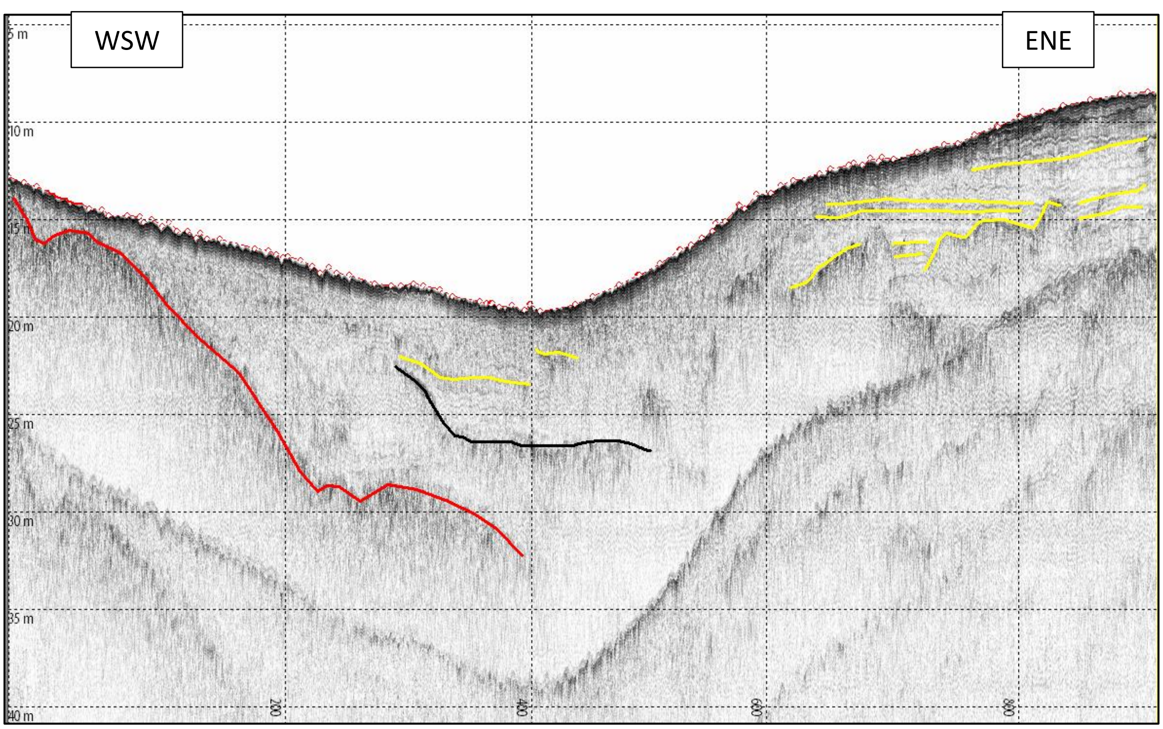
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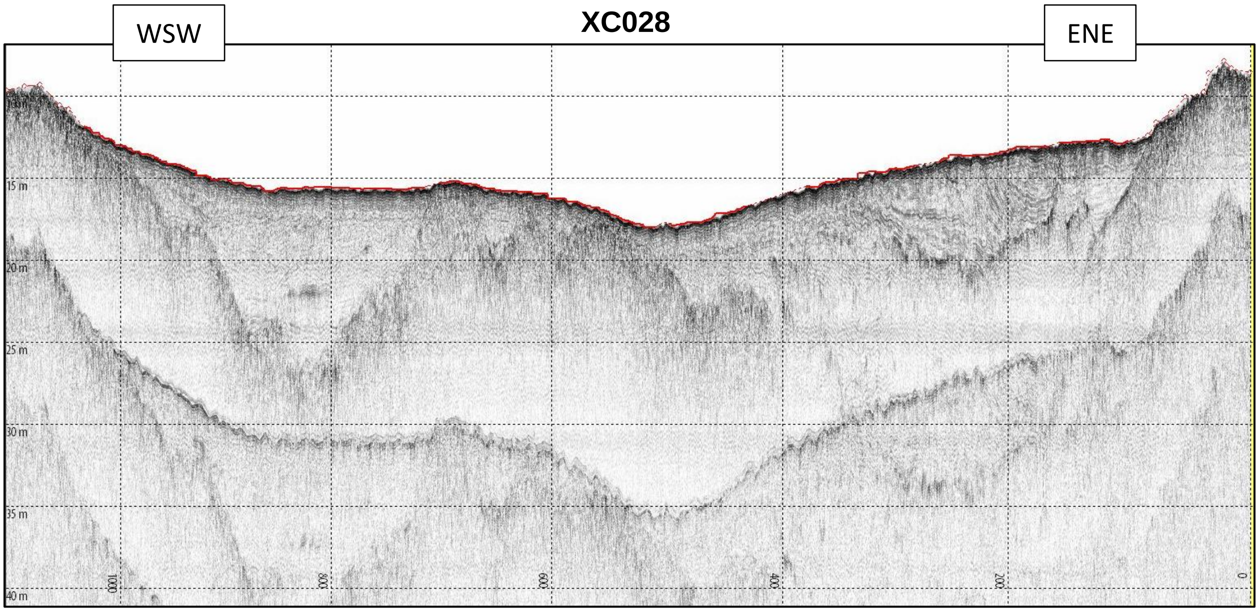

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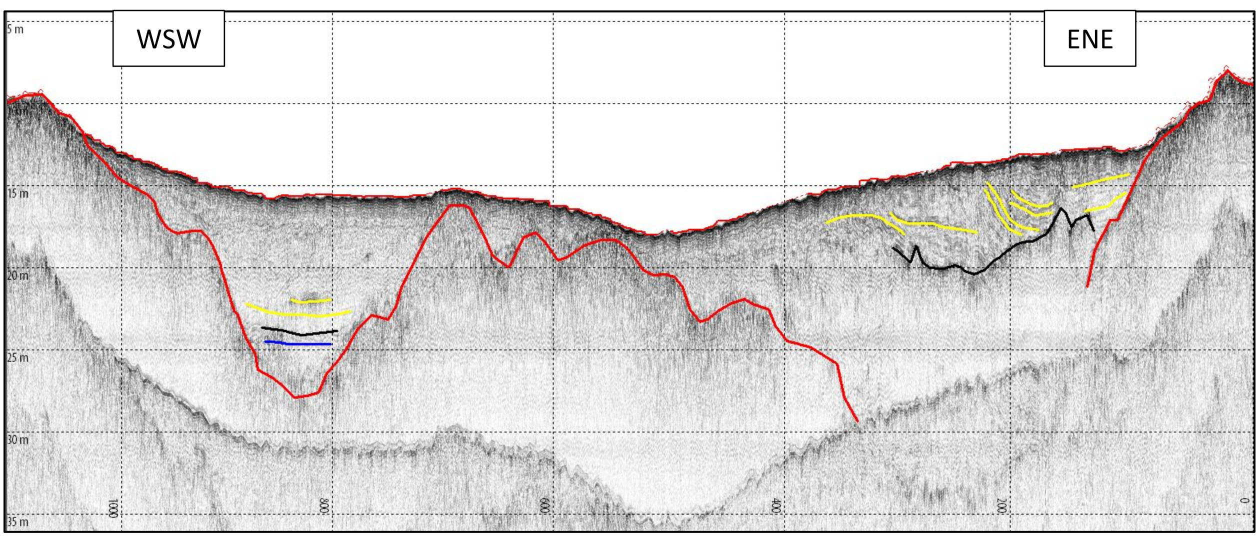

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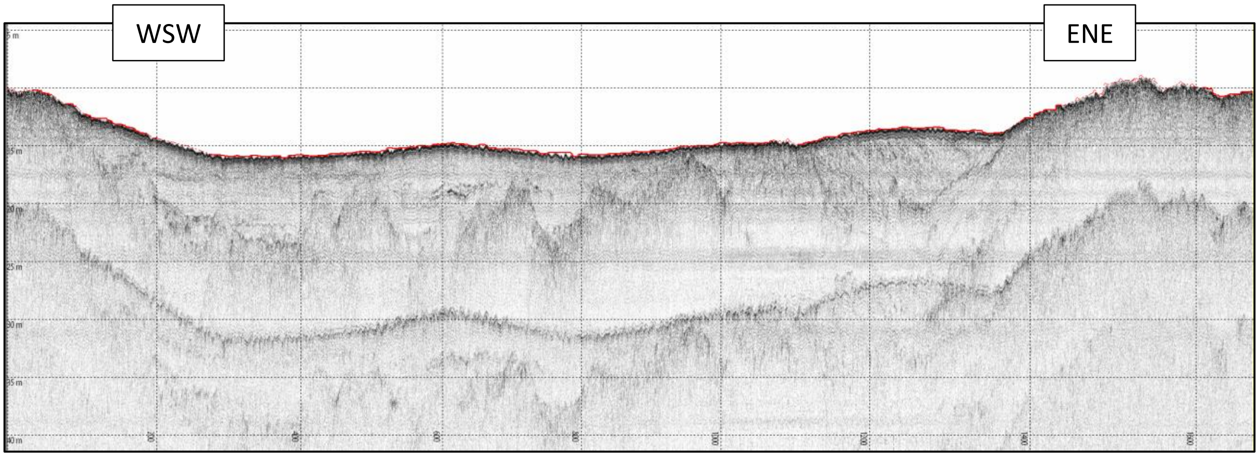

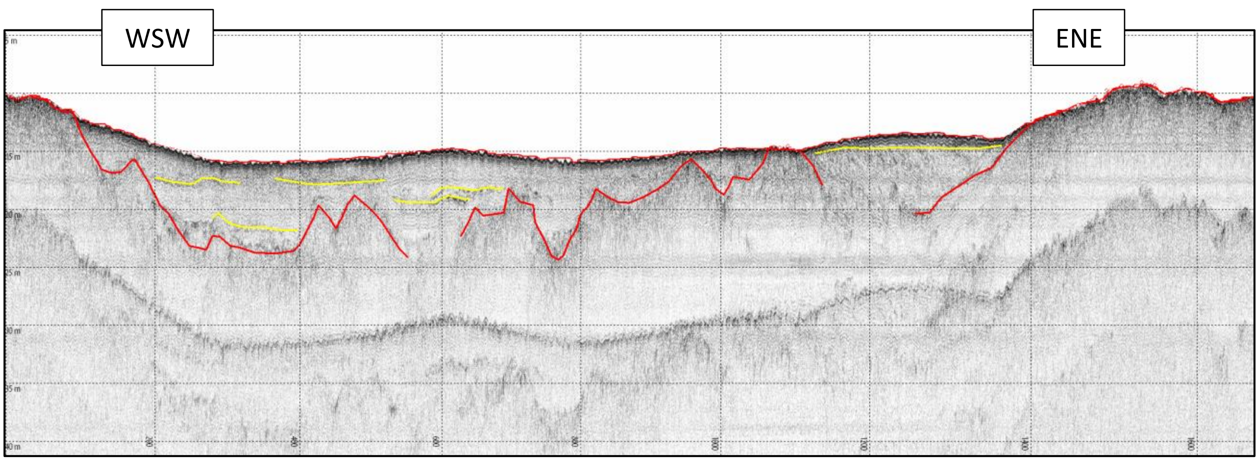

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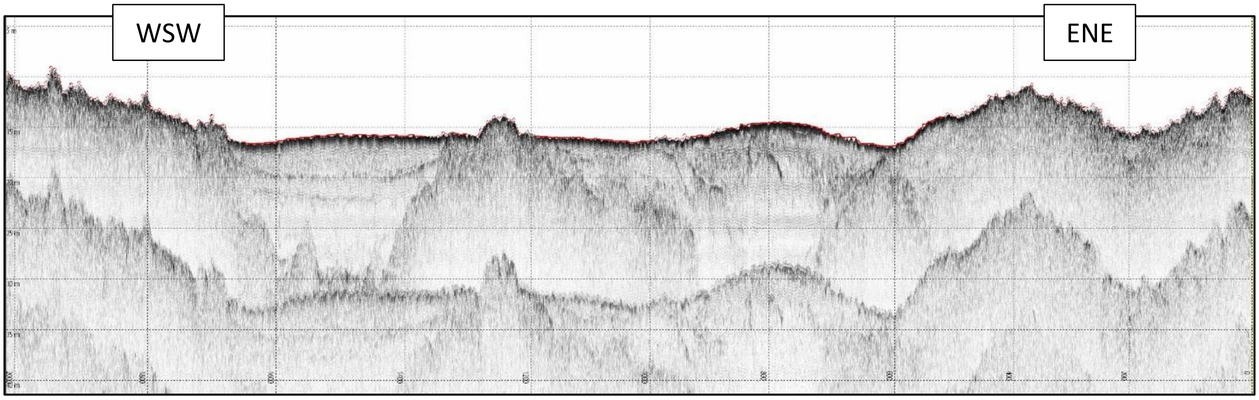

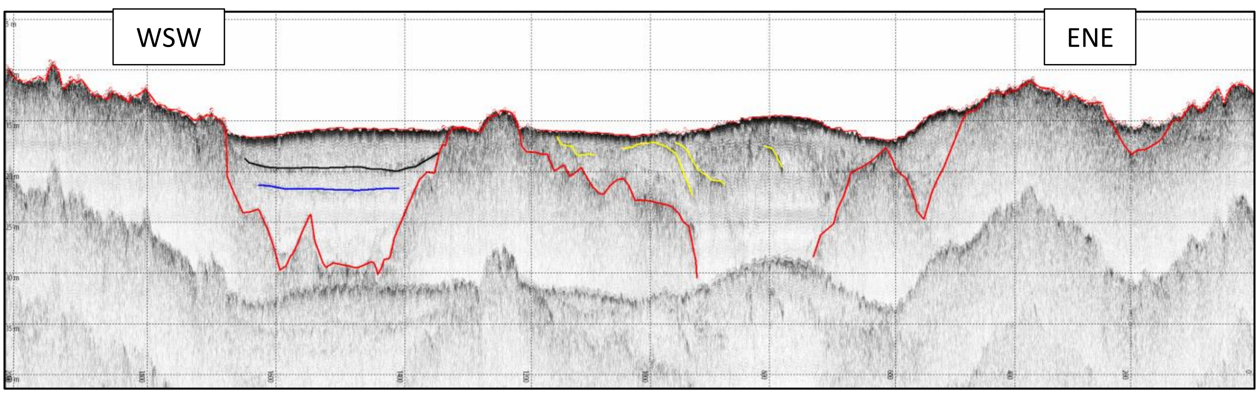

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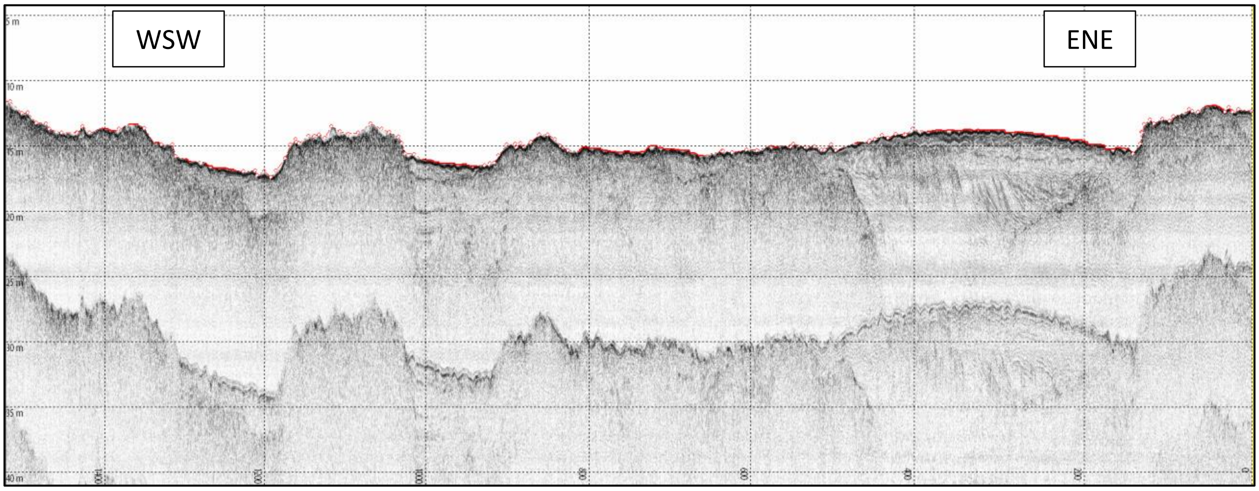

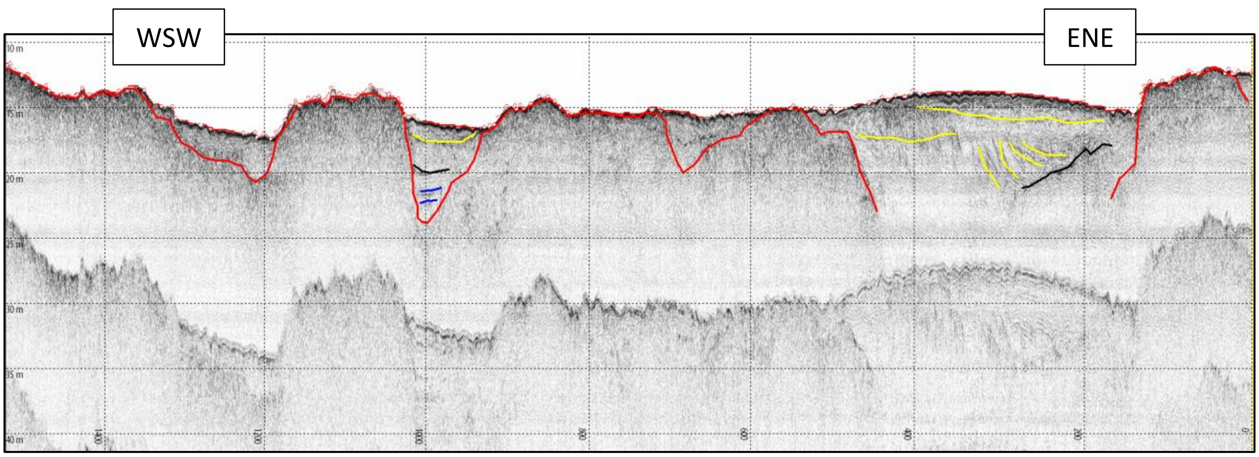

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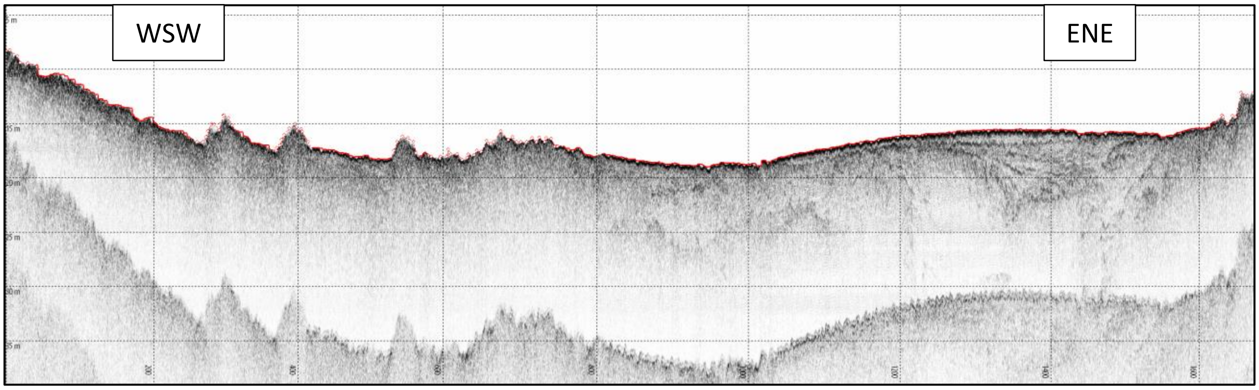

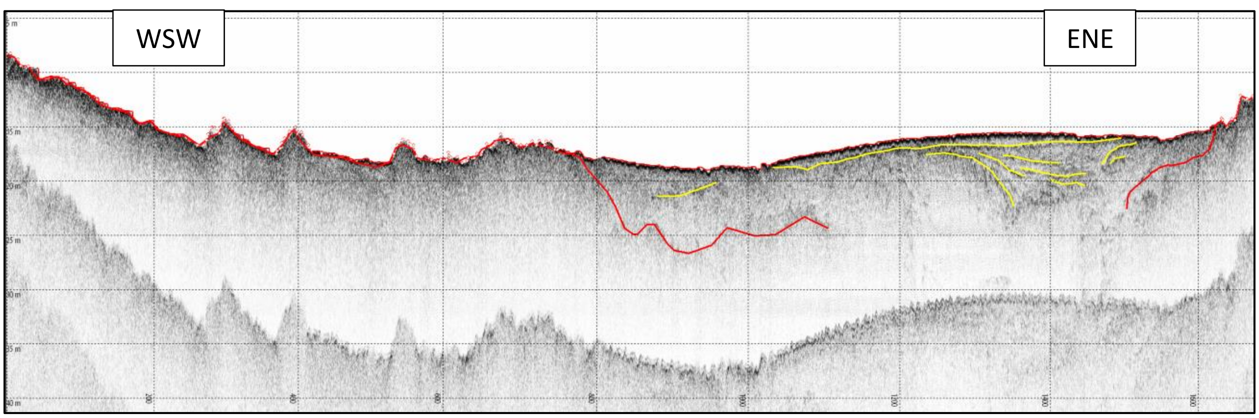

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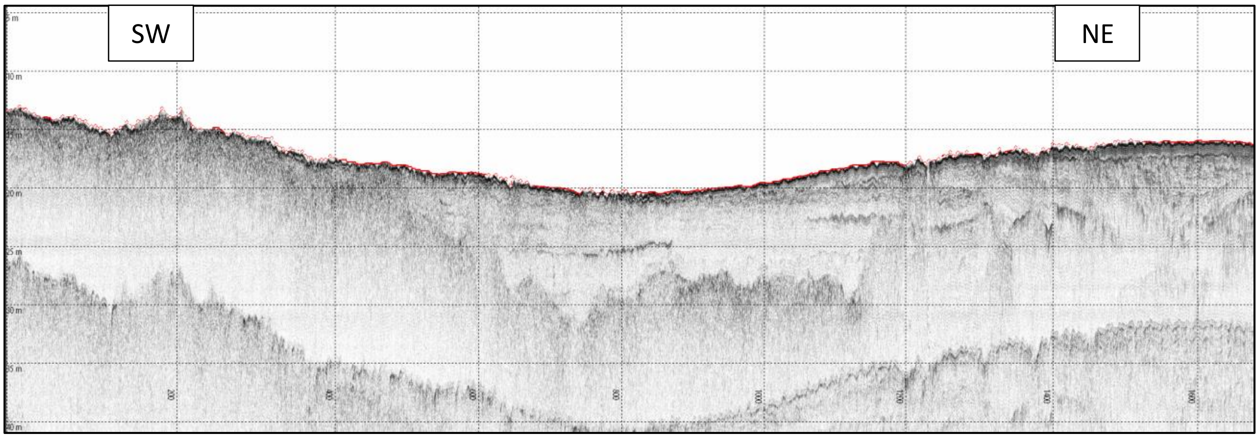

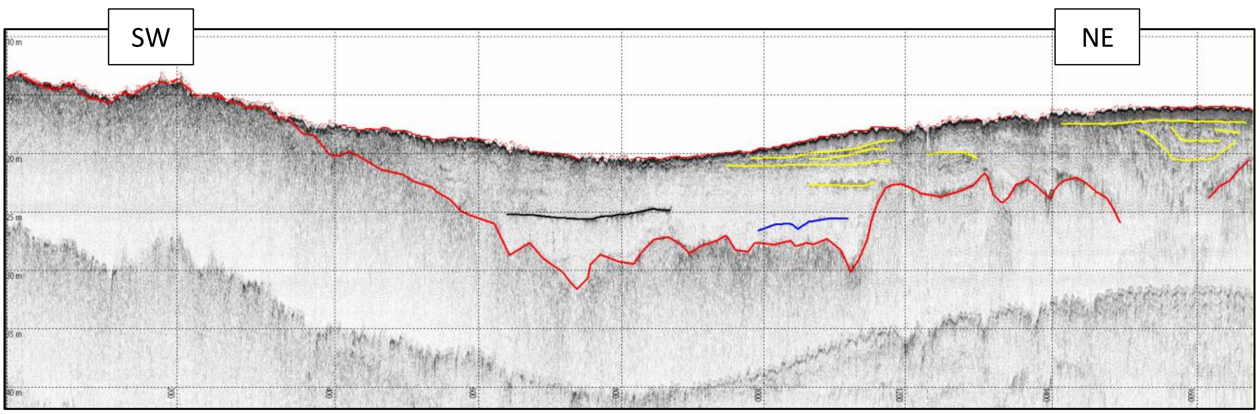

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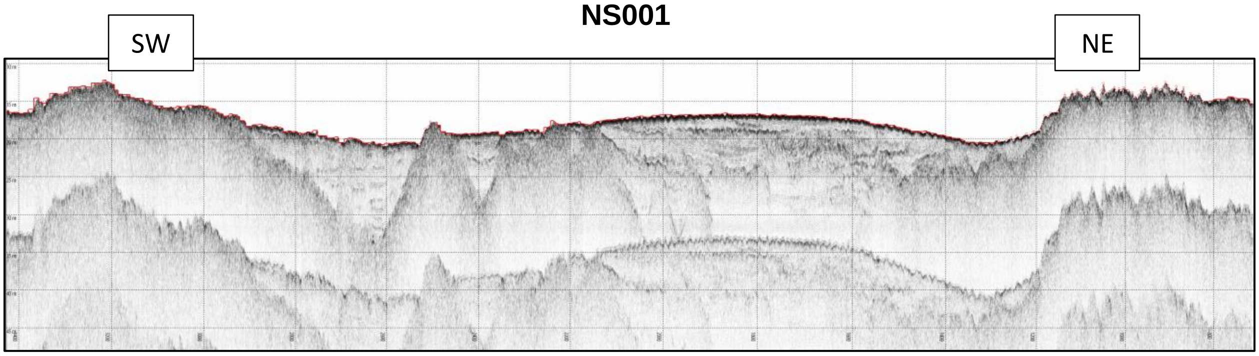

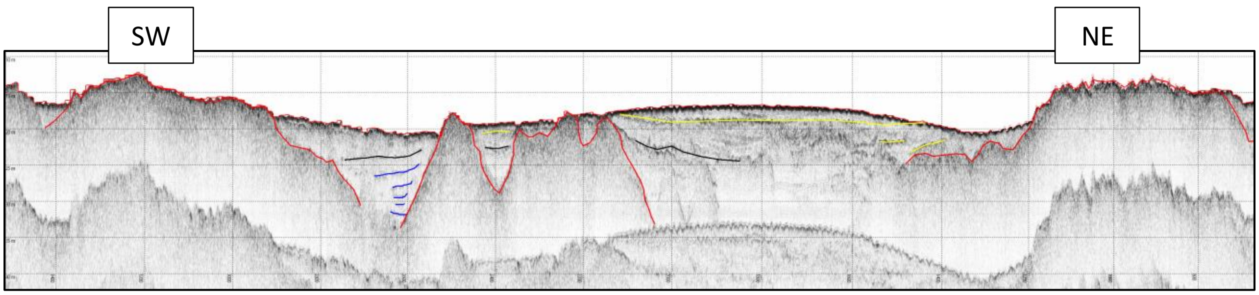

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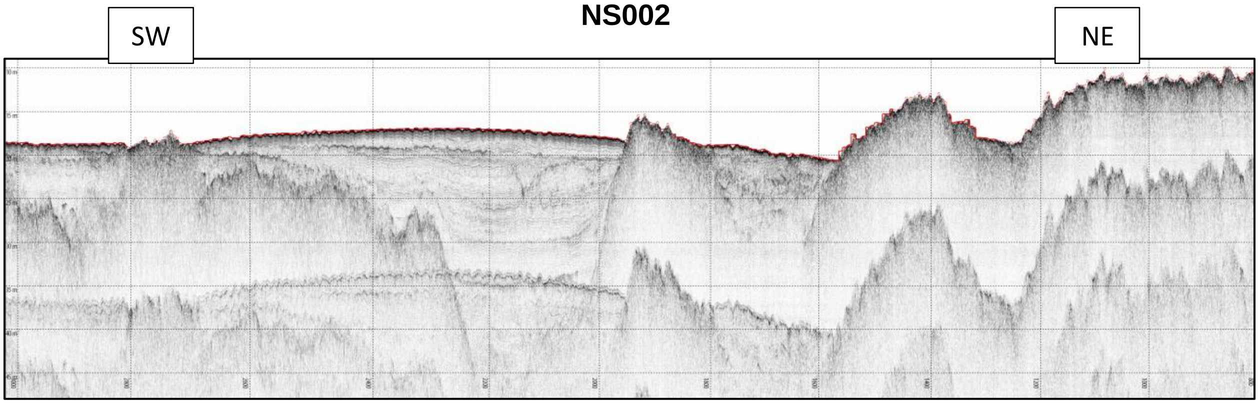

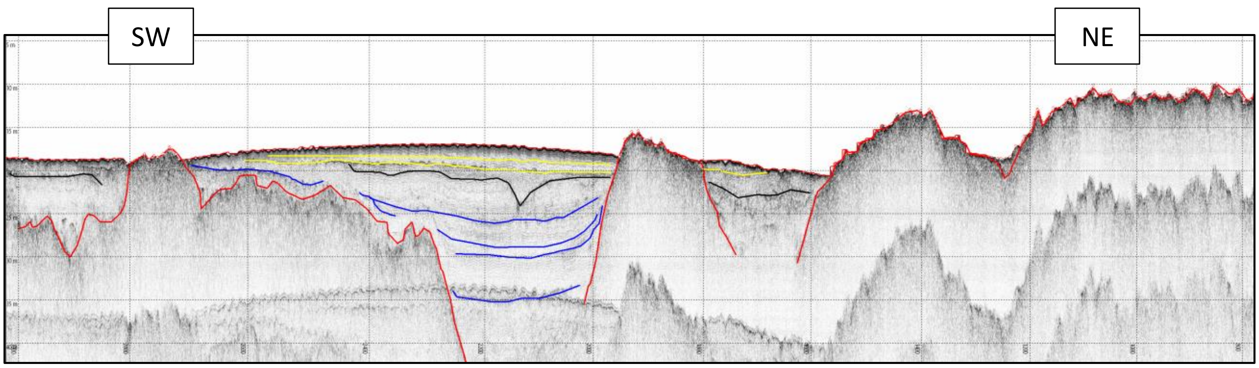

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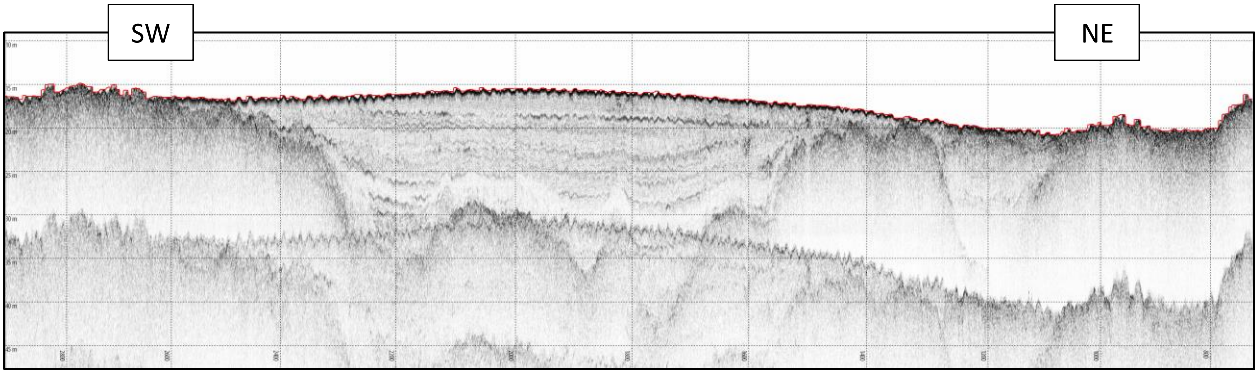

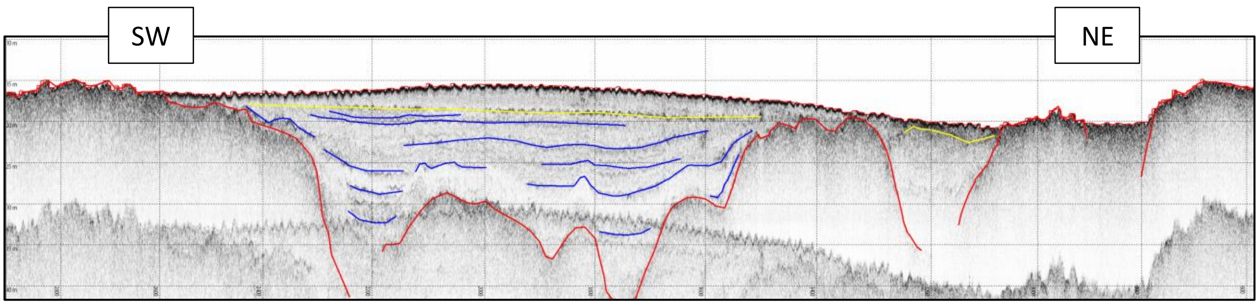

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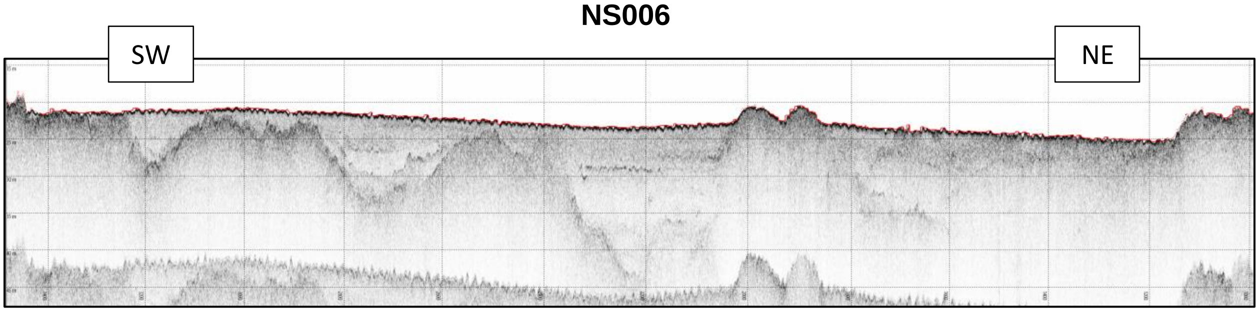

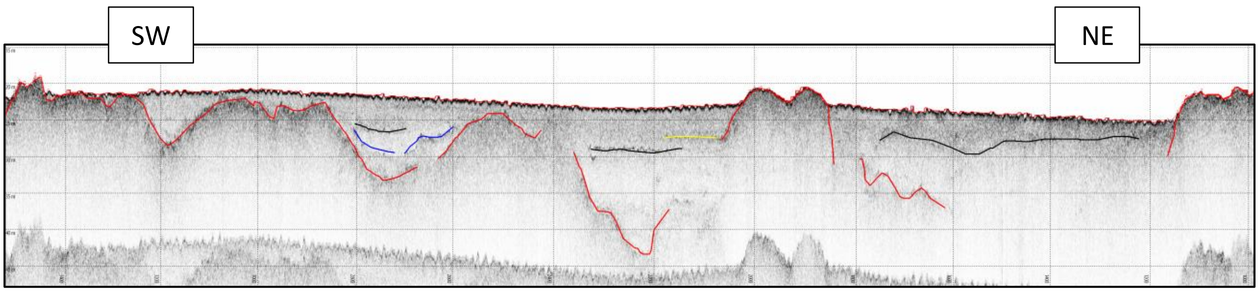

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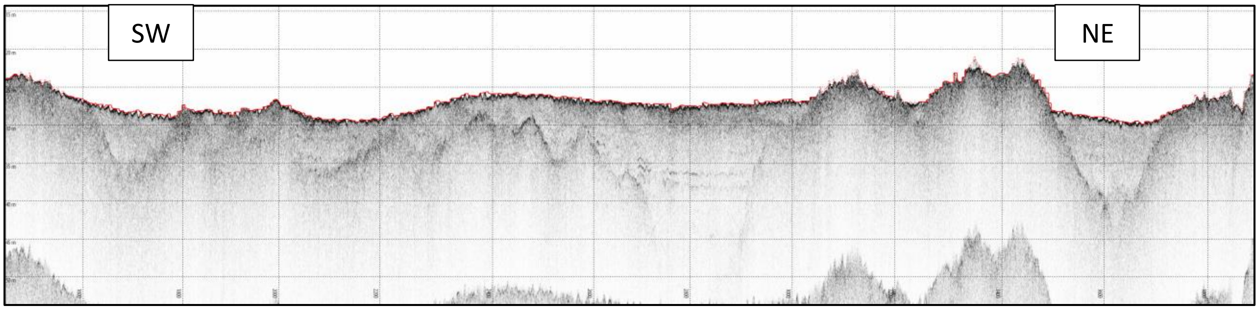

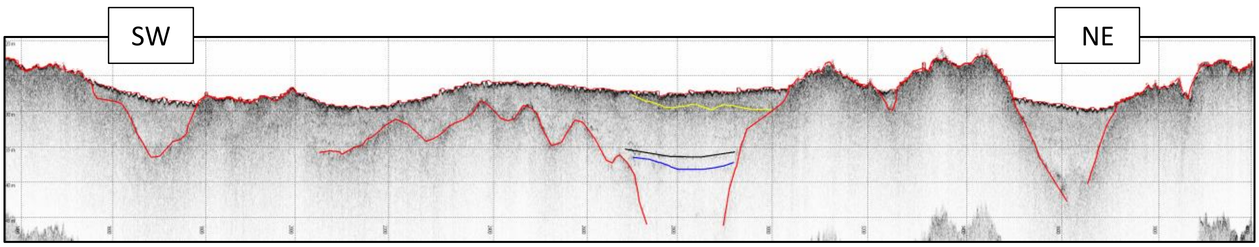

SHORE PERPENDICULAR

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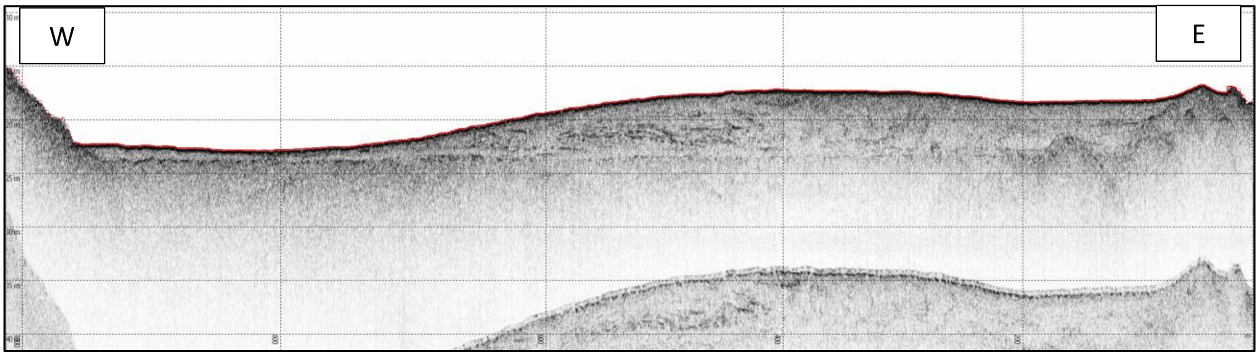

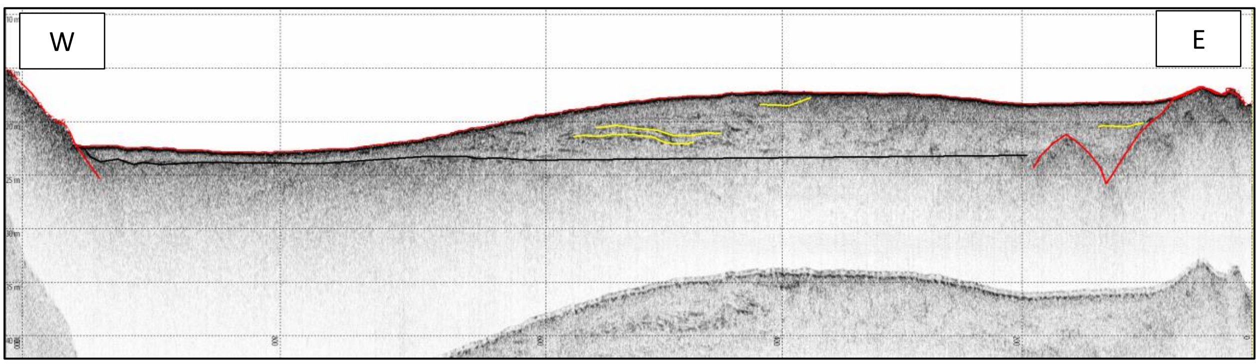

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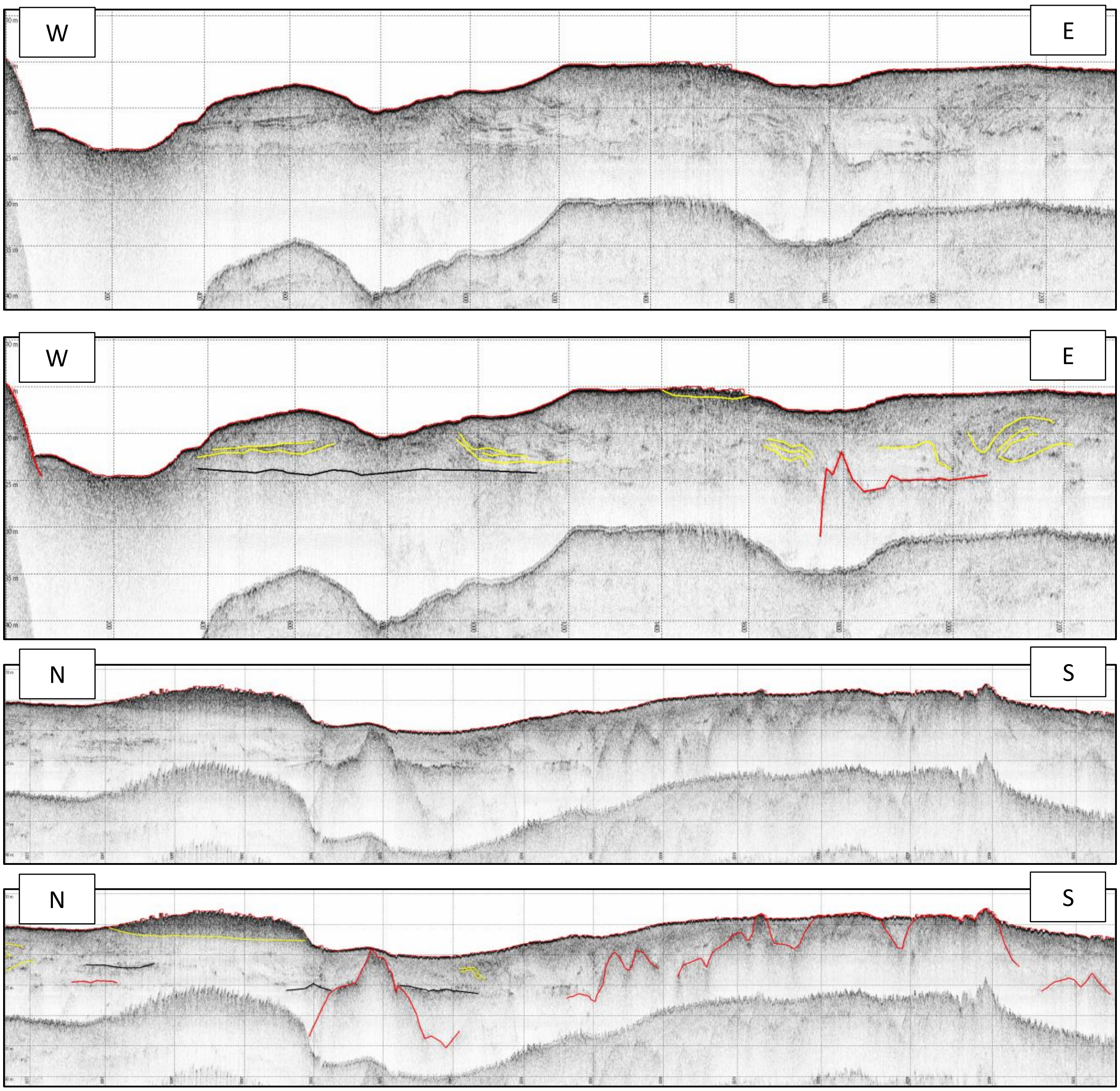

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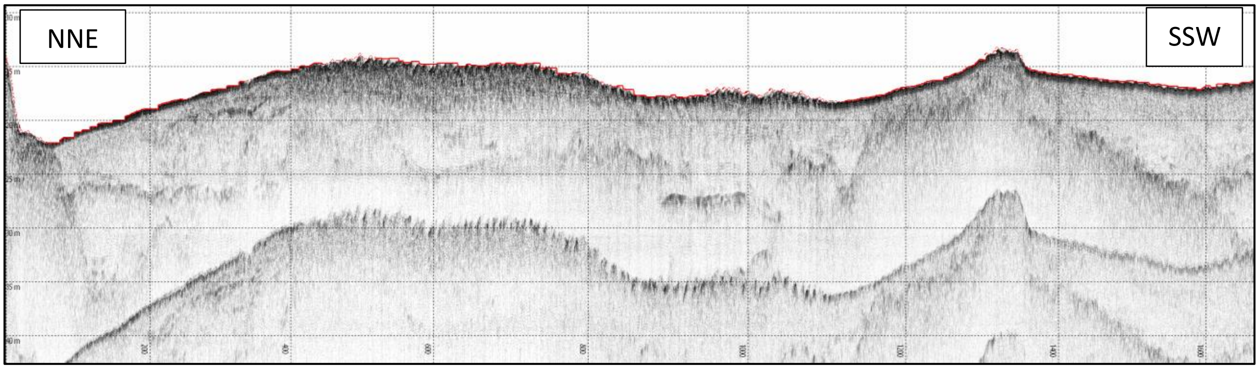

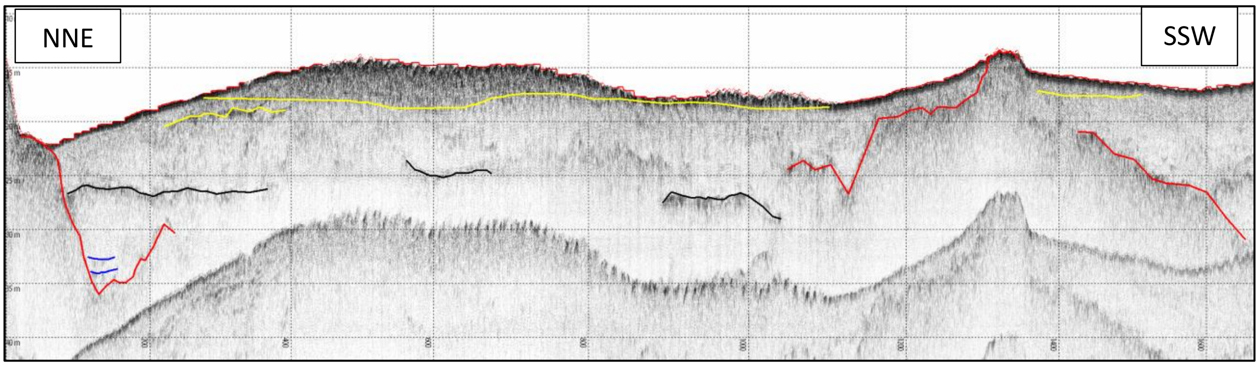

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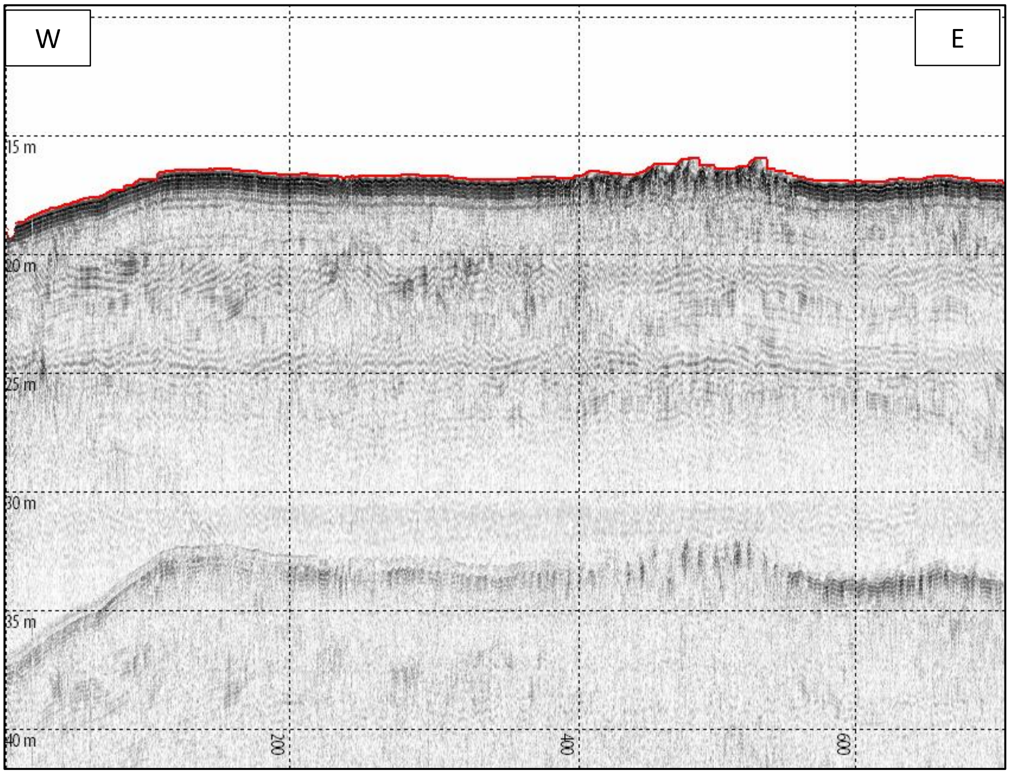
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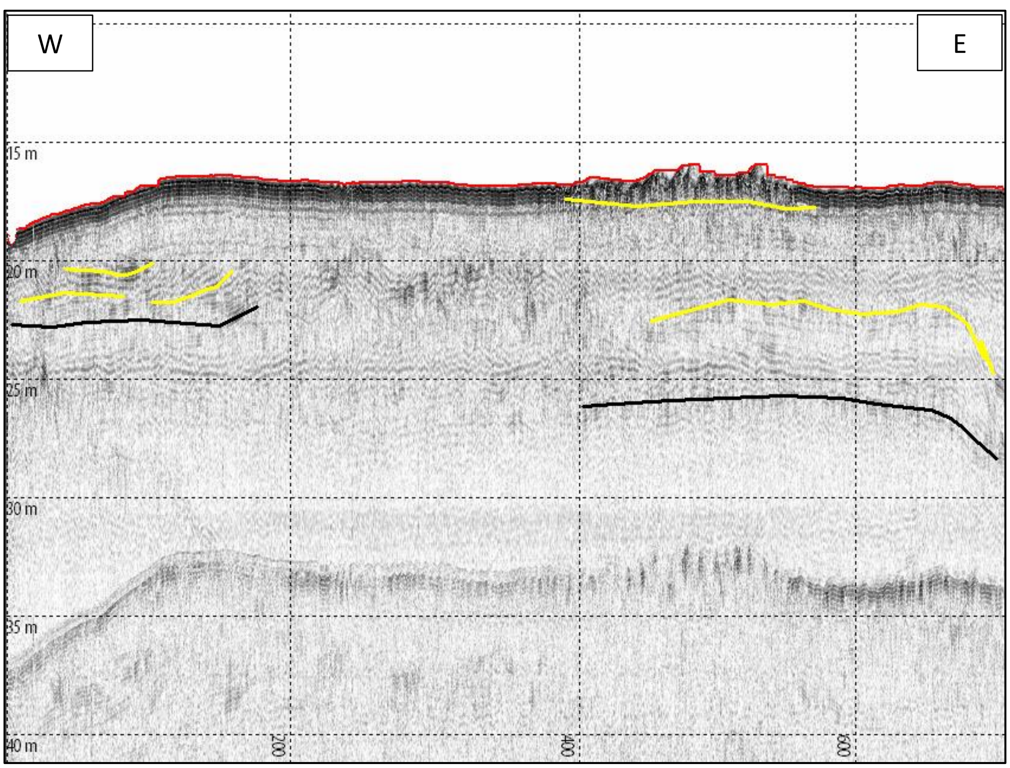
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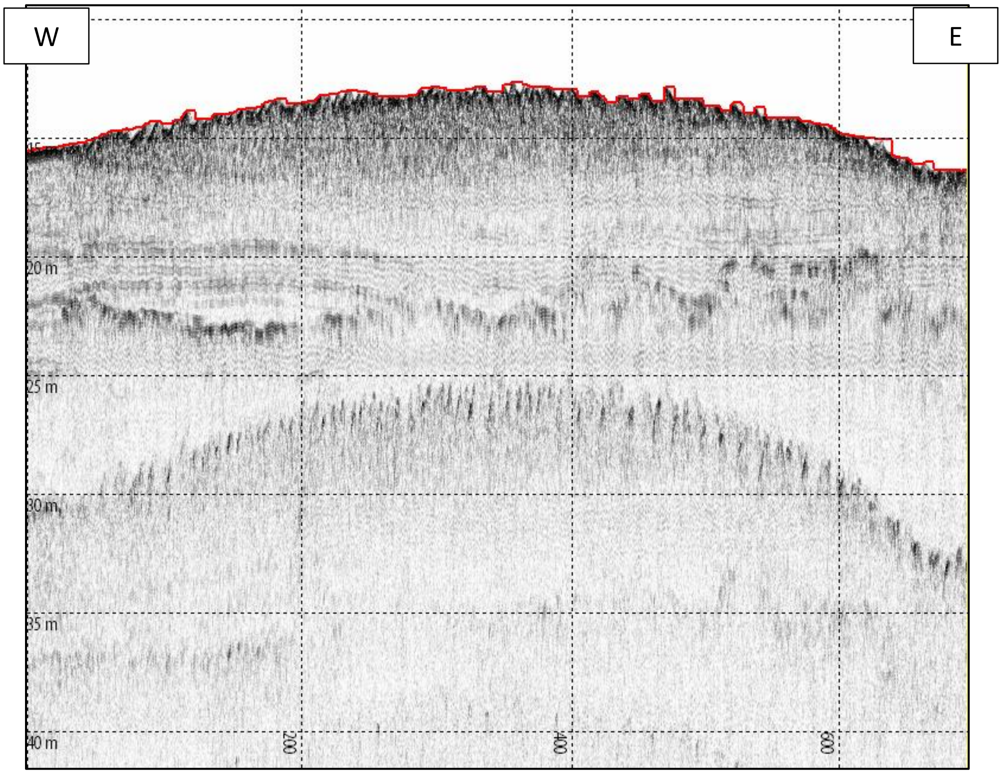
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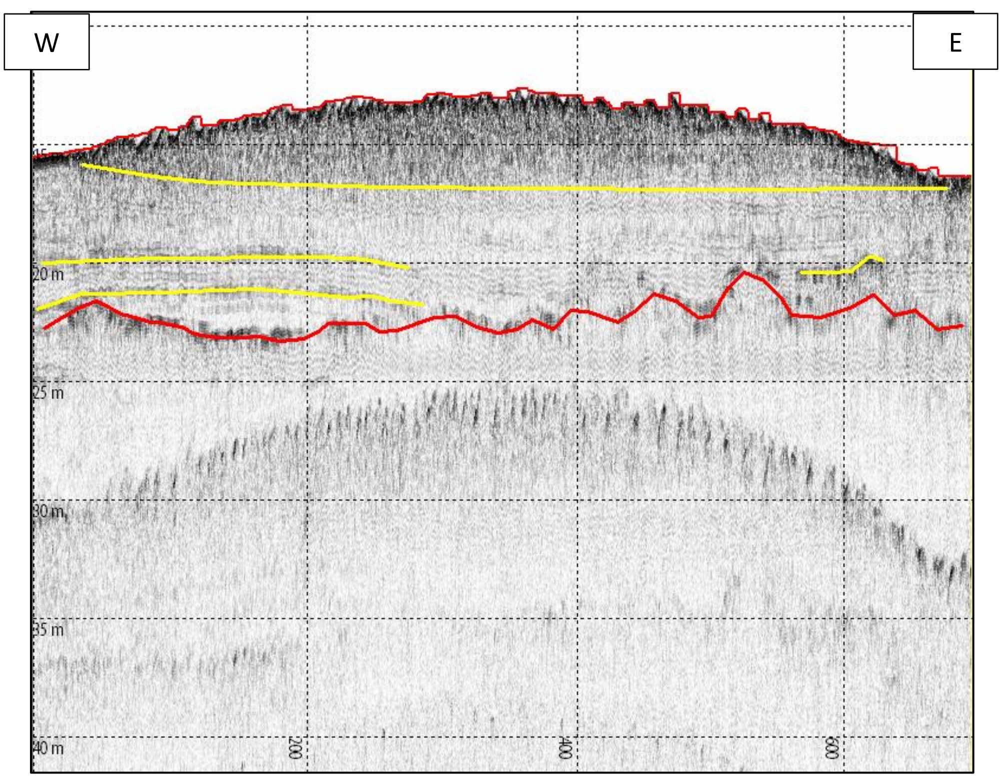
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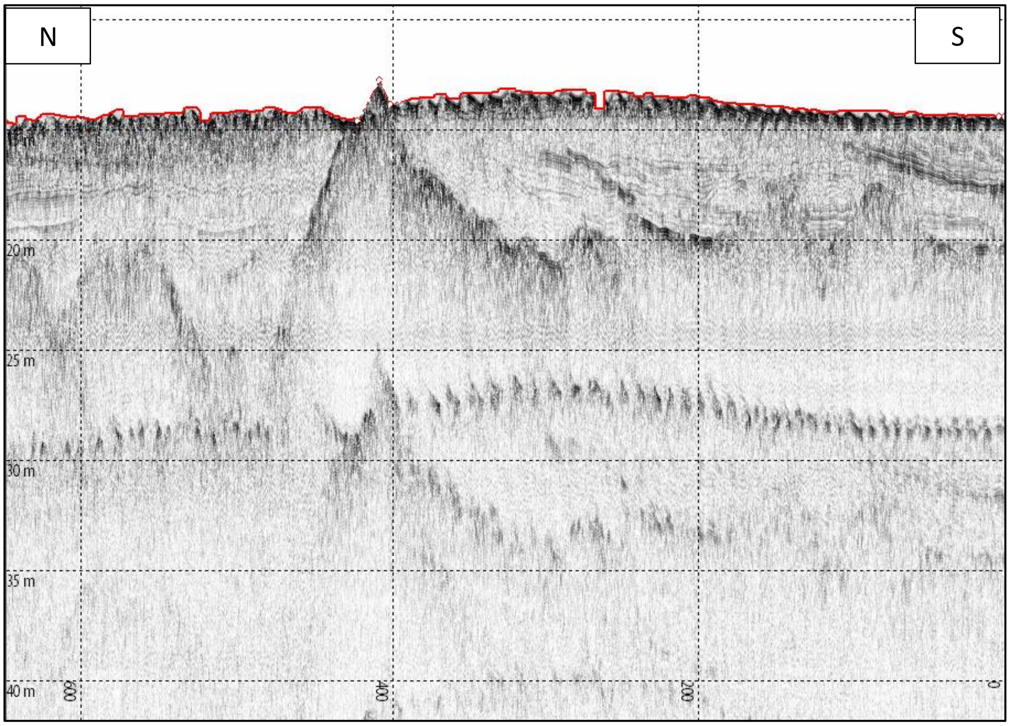
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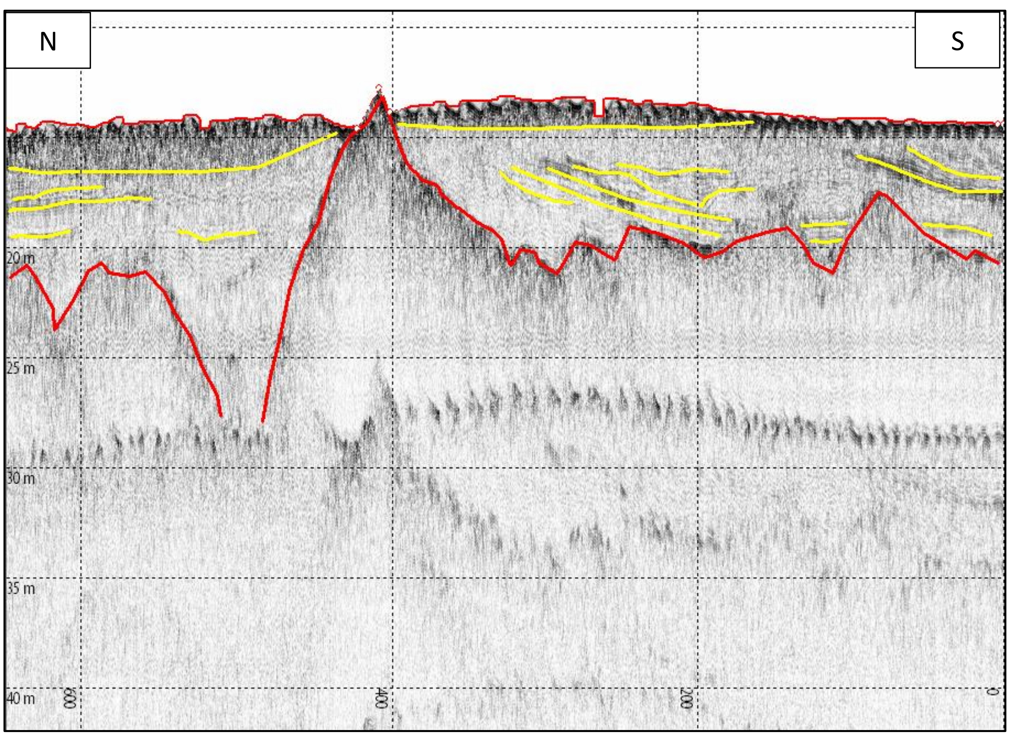
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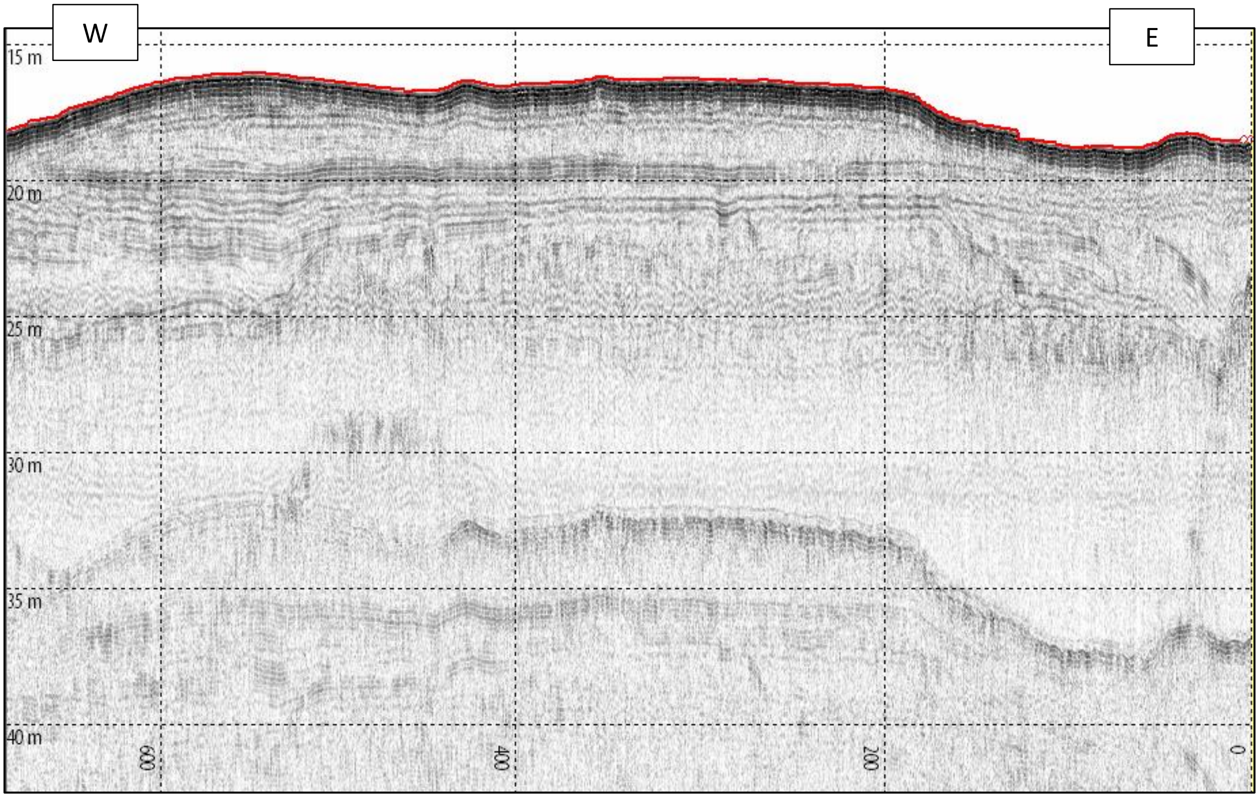
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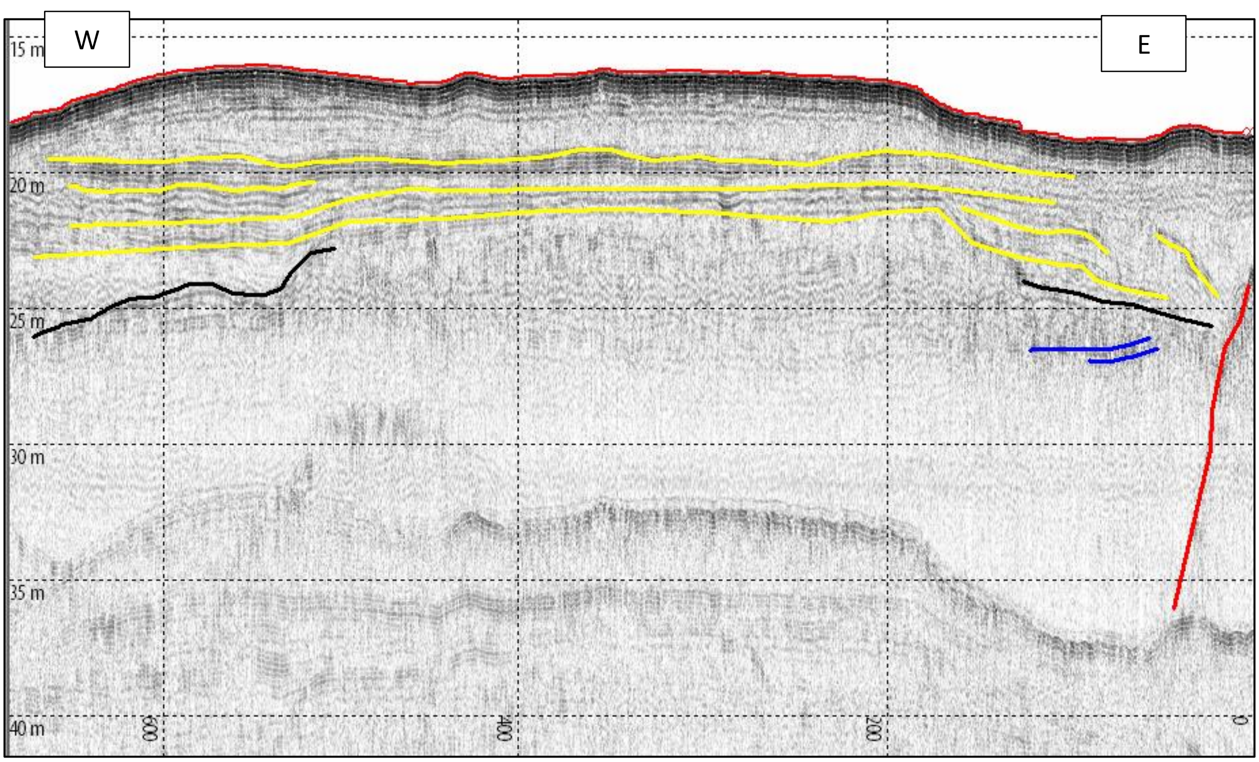
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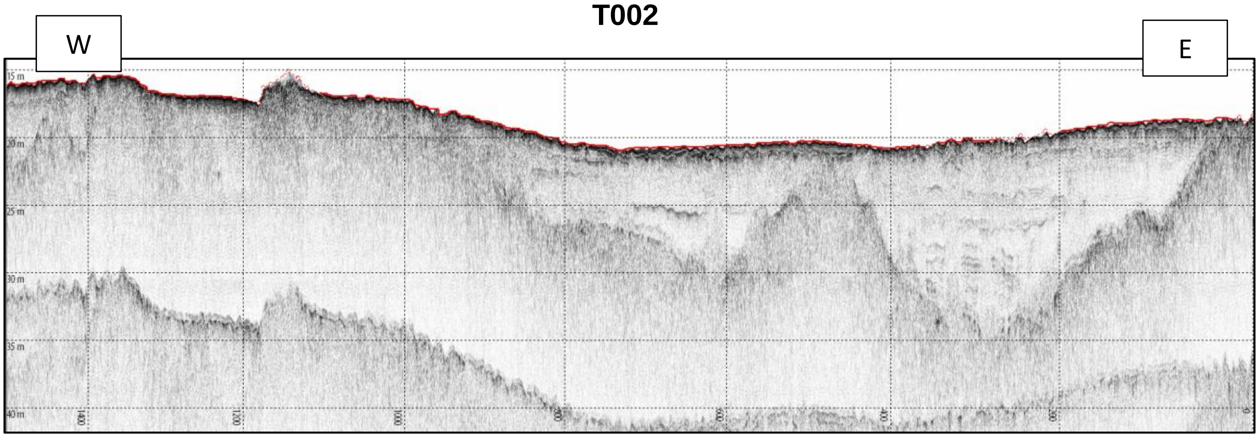

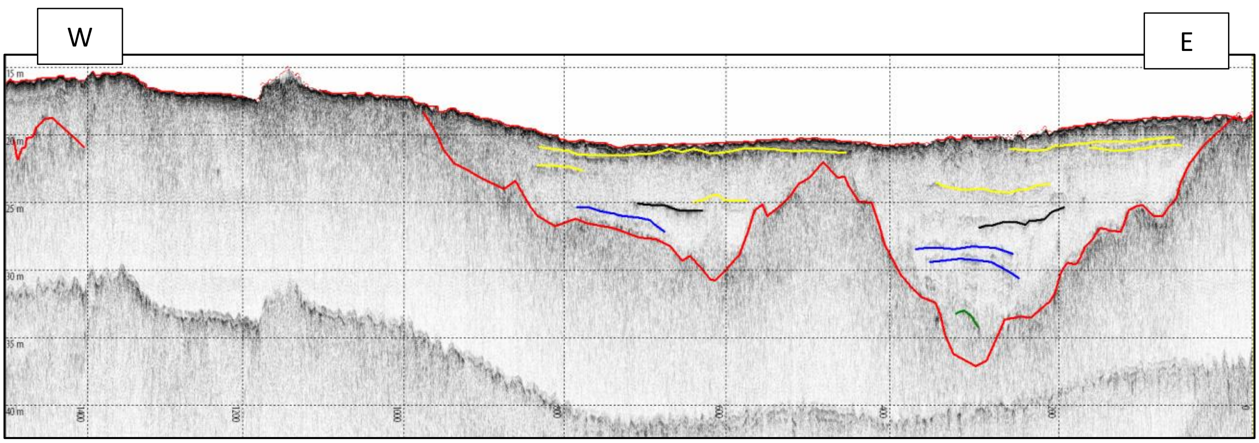

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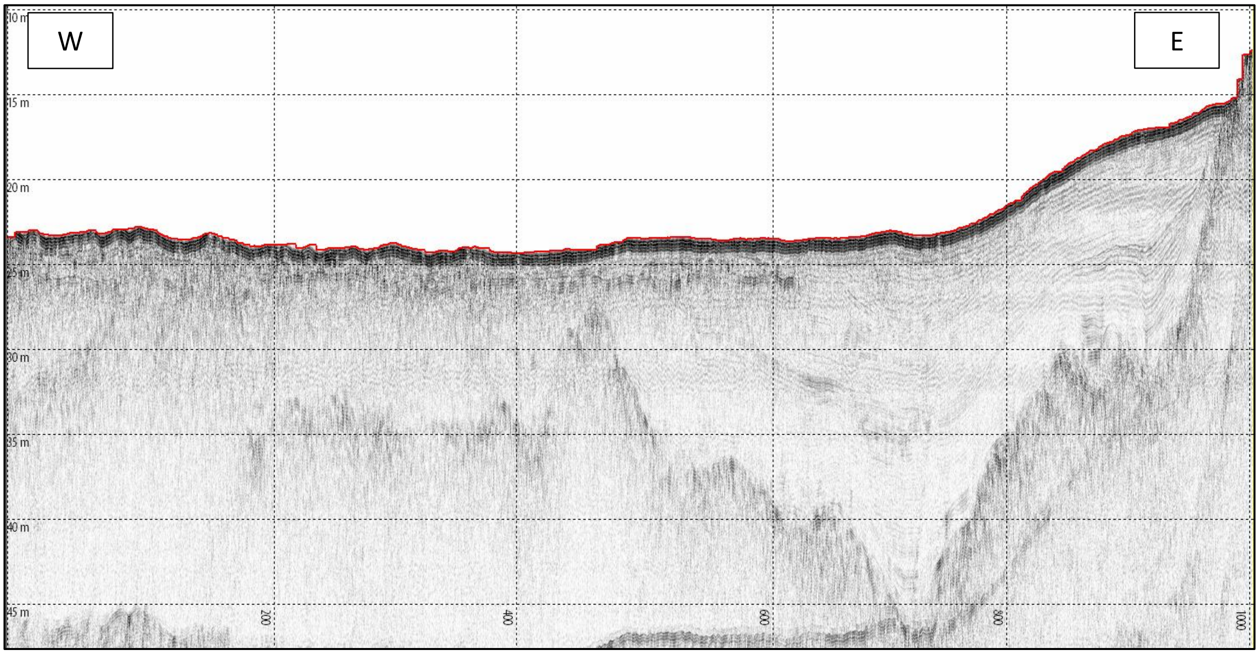
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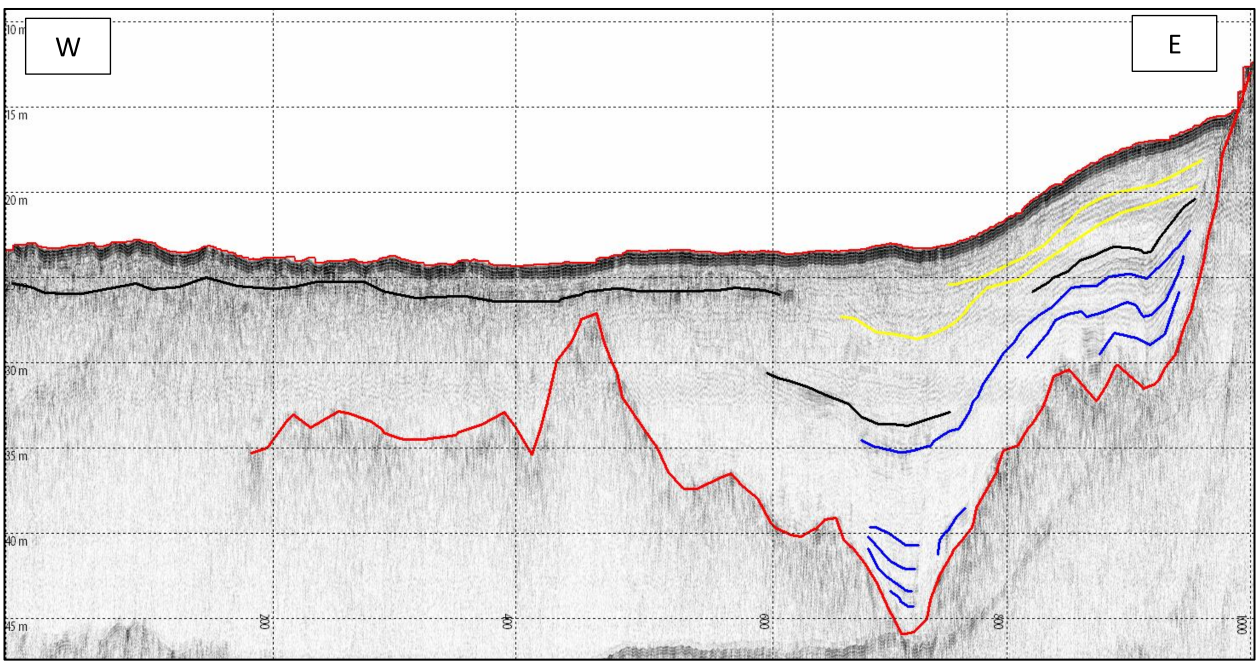
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APPENDIX III

Birch Seismic Profiles

All seismic profiles, both un-interpreted and interpreted, from the Birch survey are shown below. Locations of all profiles can be seen in Figure III-1. Seismic profiles are separated into SHORE PARALLEL and SHORE PERPENDICULAR, with both groups starting with most inland profile and moving offshore. Several profiles were broken into multiple sections to fit onto the page. Any profiles in multiple sections go from top image to bottom image. Interpreted profiles show highlighted seismic reflectors as: bedrock (red), till (green), glaciomarine sediment (blue), erosional unconformity (black), and Holocene sediments (yellow).

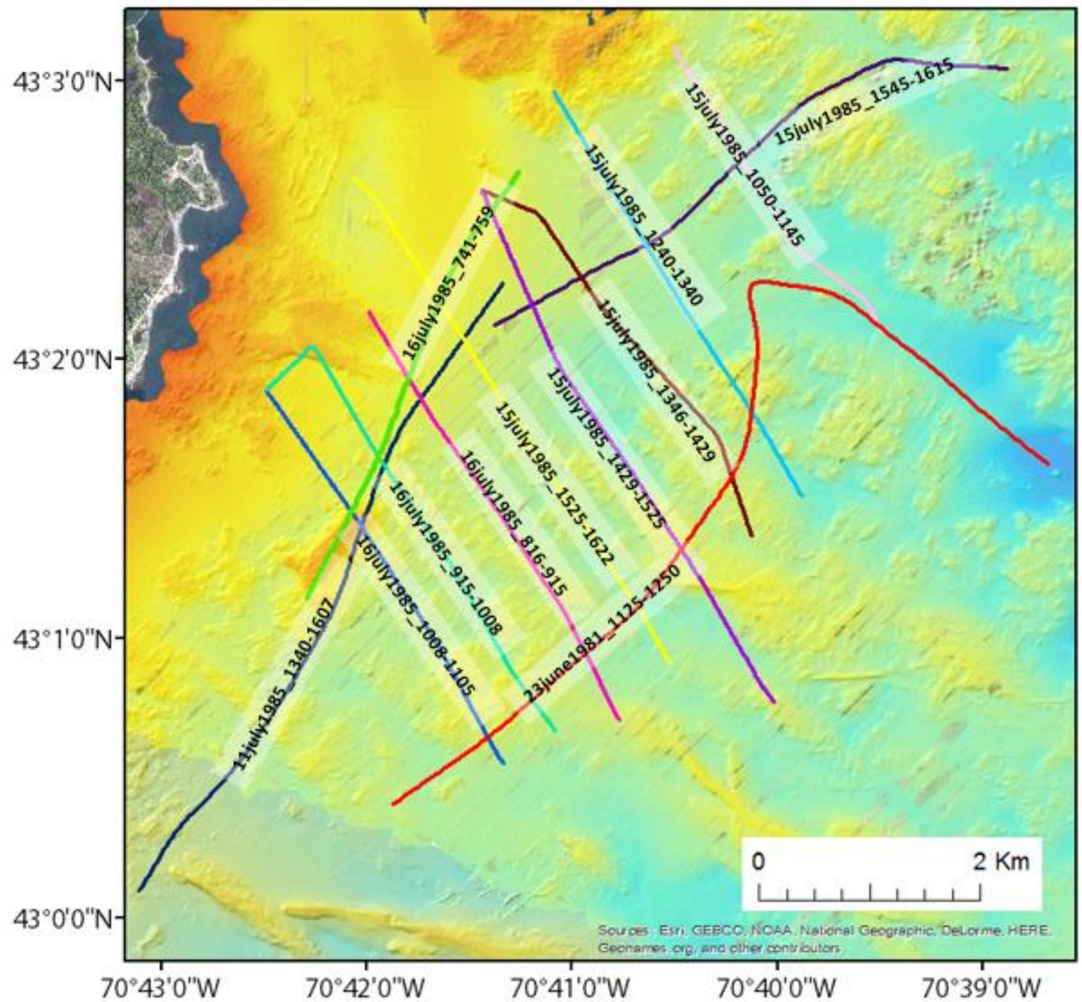
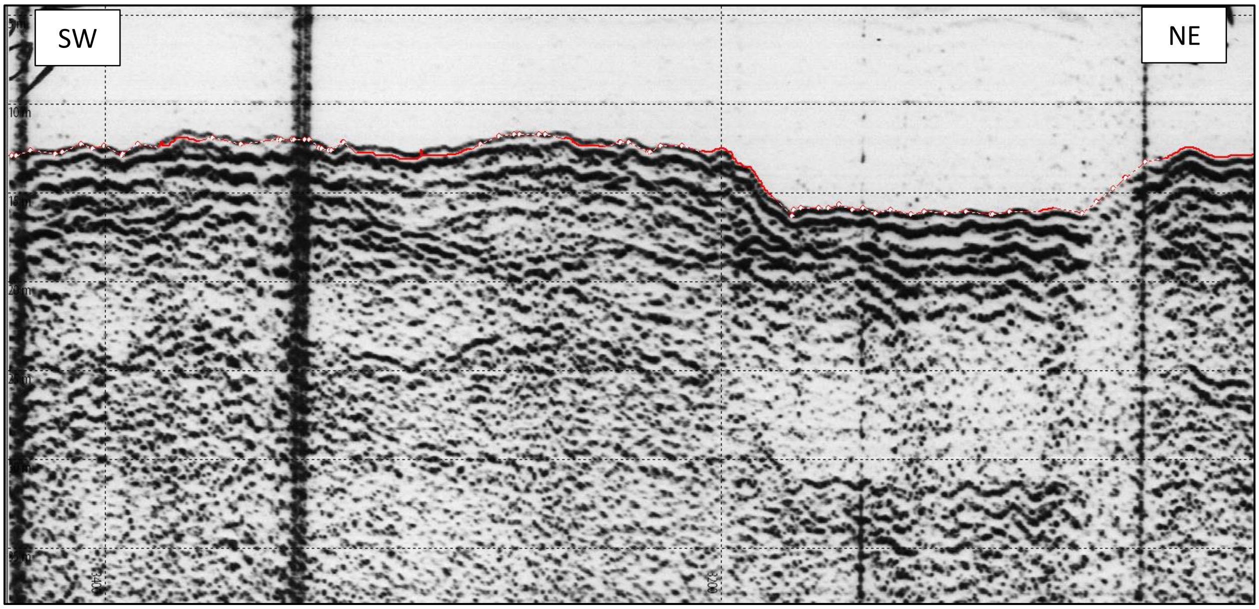
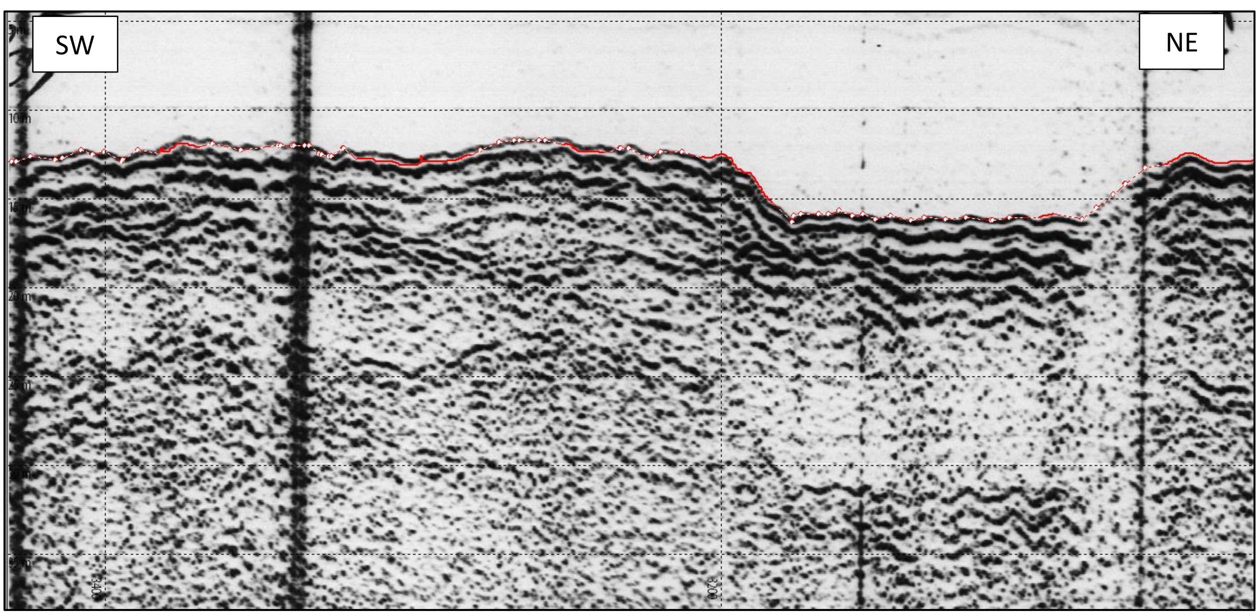


Figure III-1: Location of Birch seismic lines.

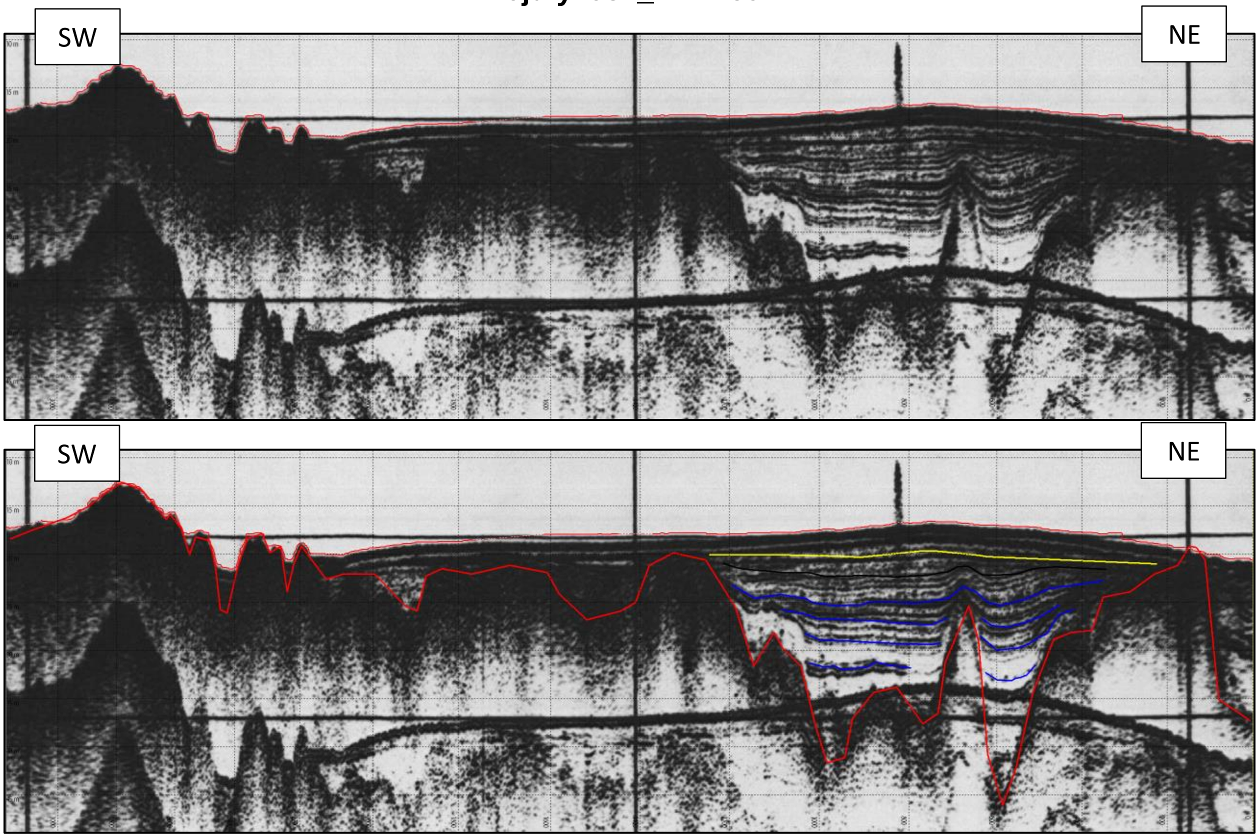
SHORE PARALLEL

16july1985_915-1008 (shore parallel section)

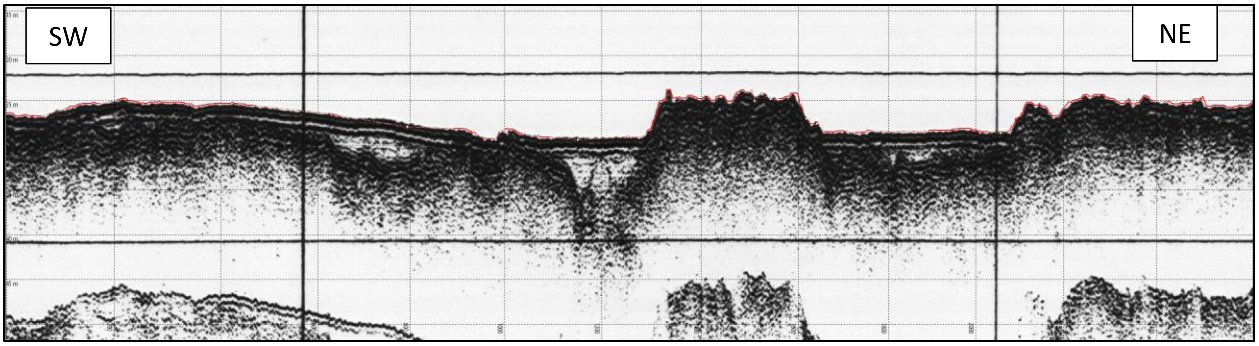


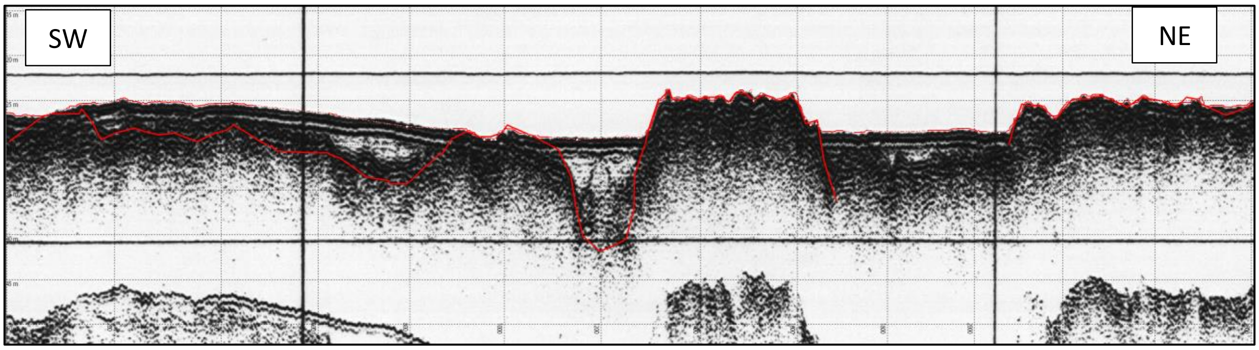


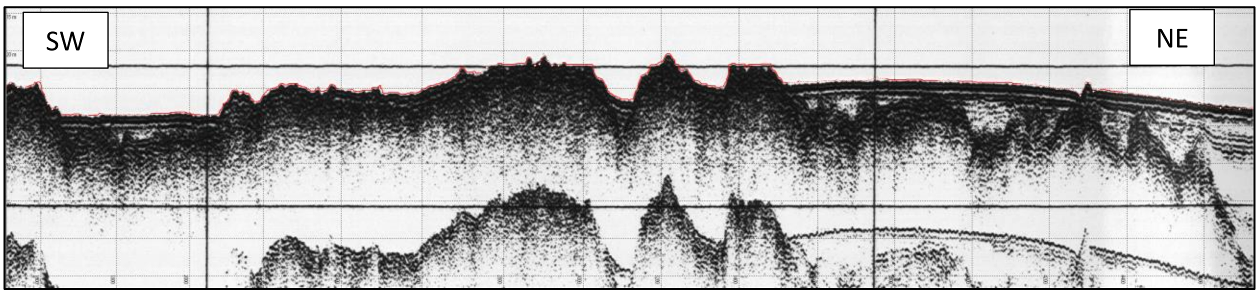
19july1982_741-759

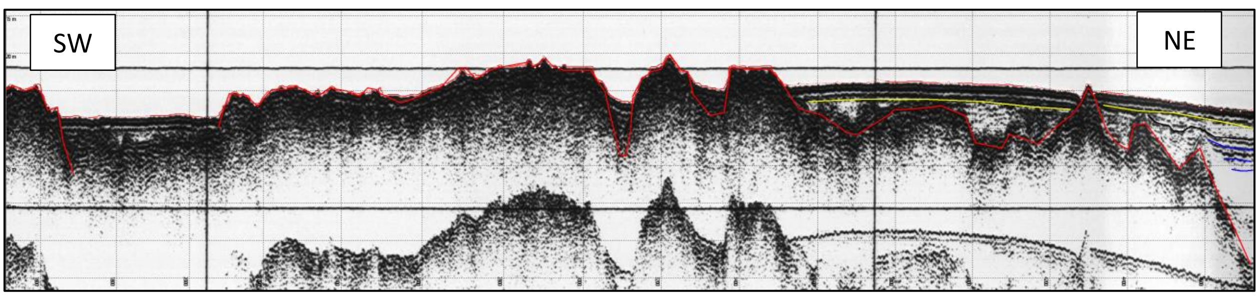


11july1982_1340-1607

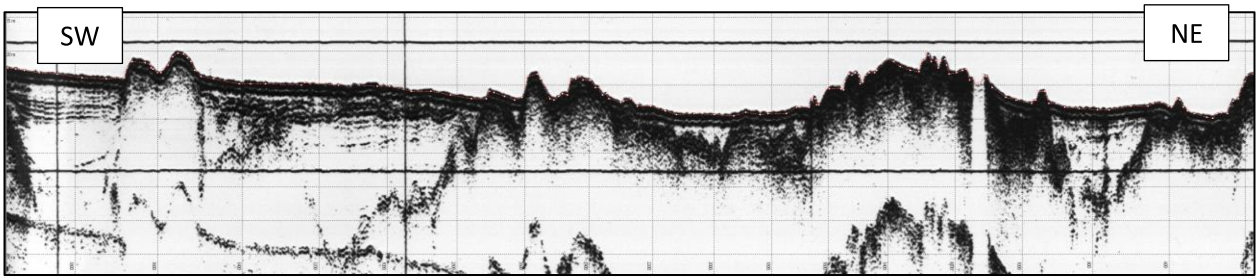


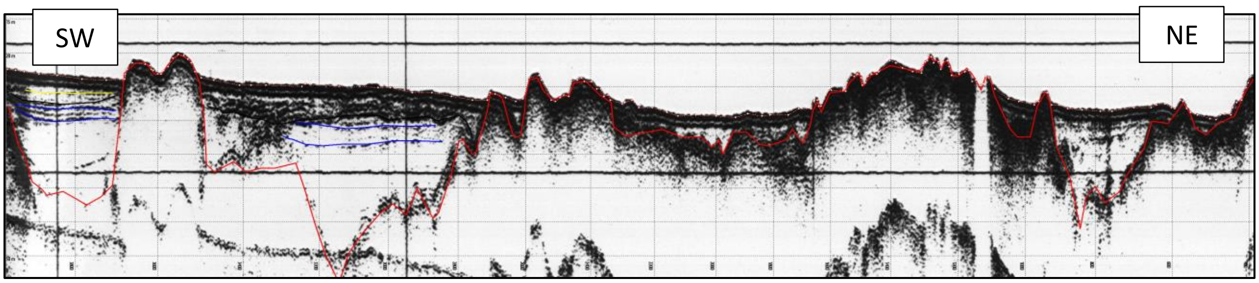






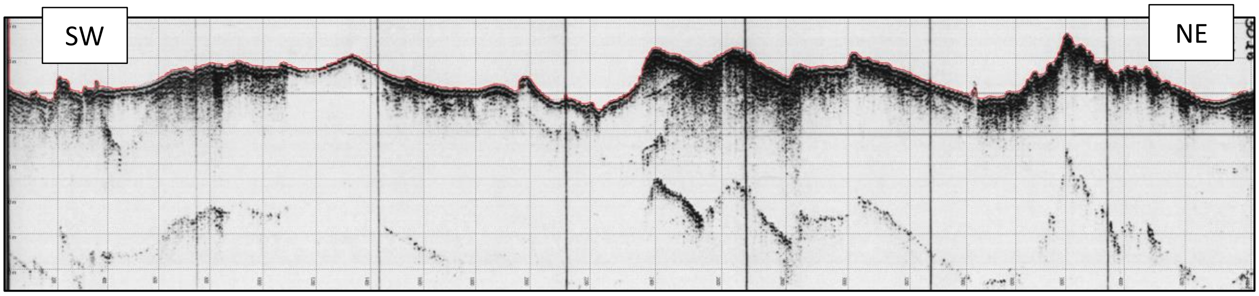
15july1982_1545-1615

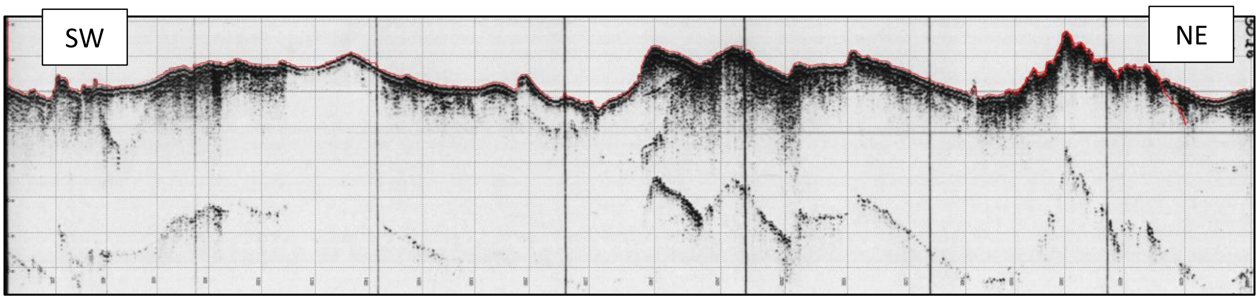




23june1981_1125-1250

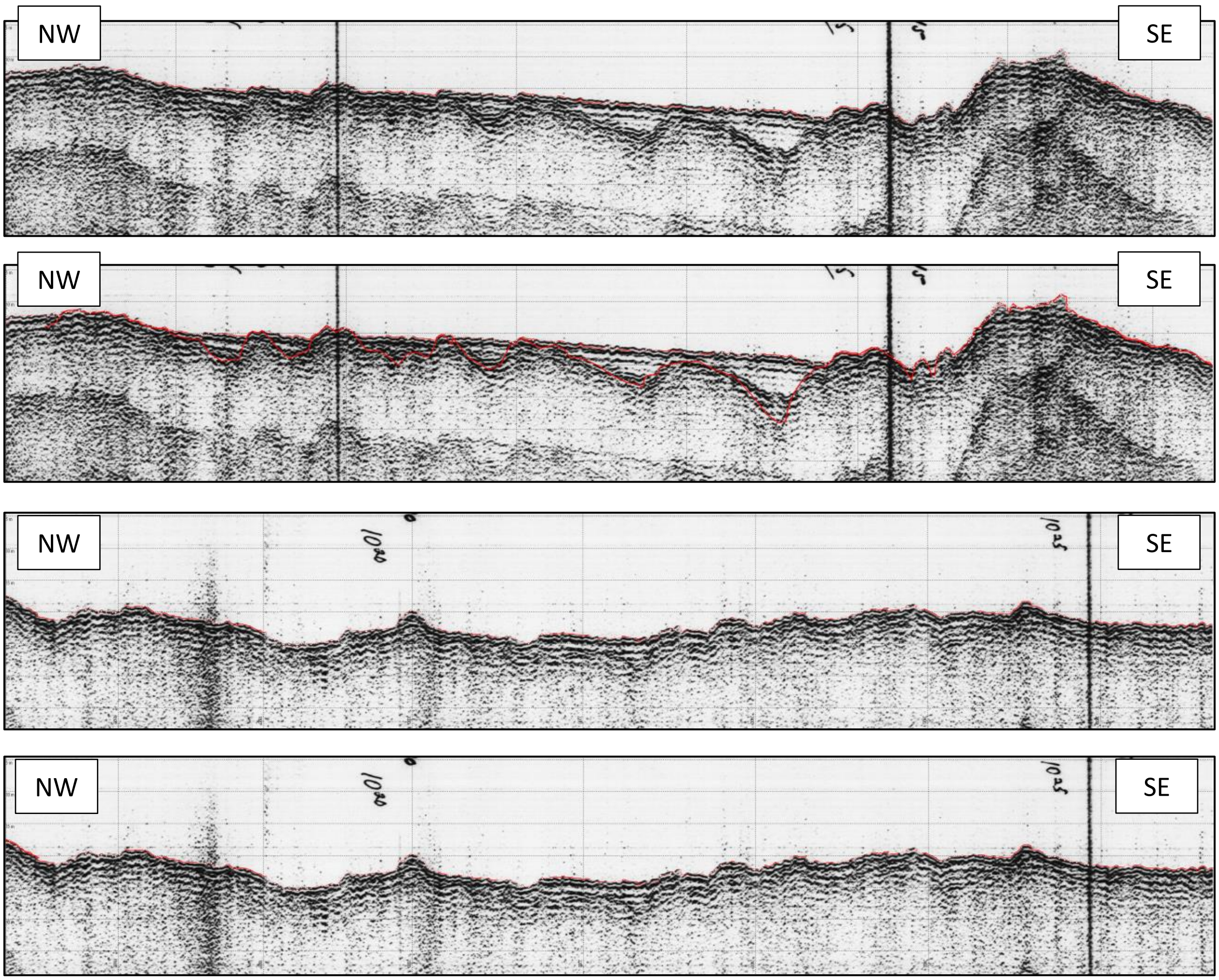
(shore parallel section)



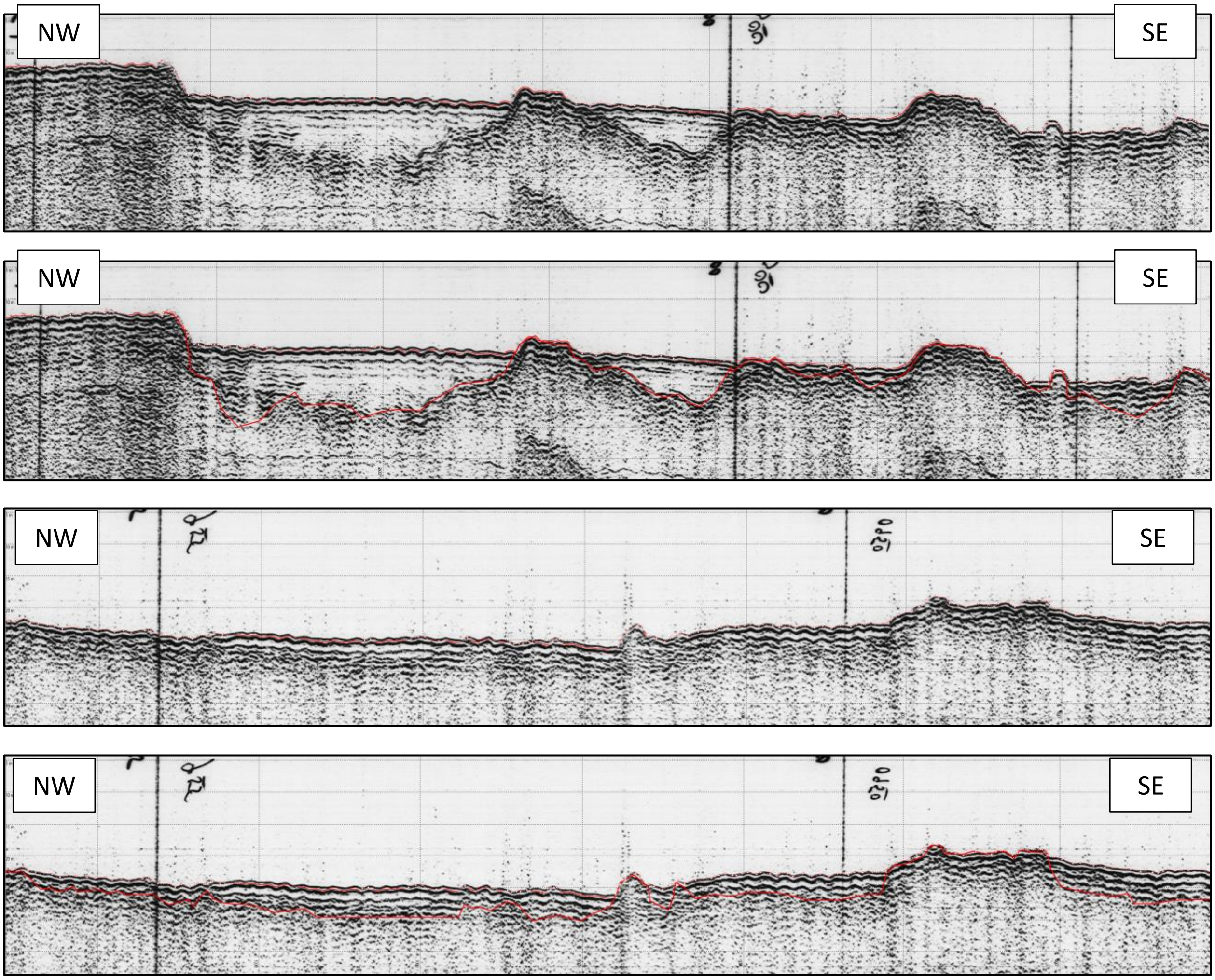


SHORE PERPENDICULAR

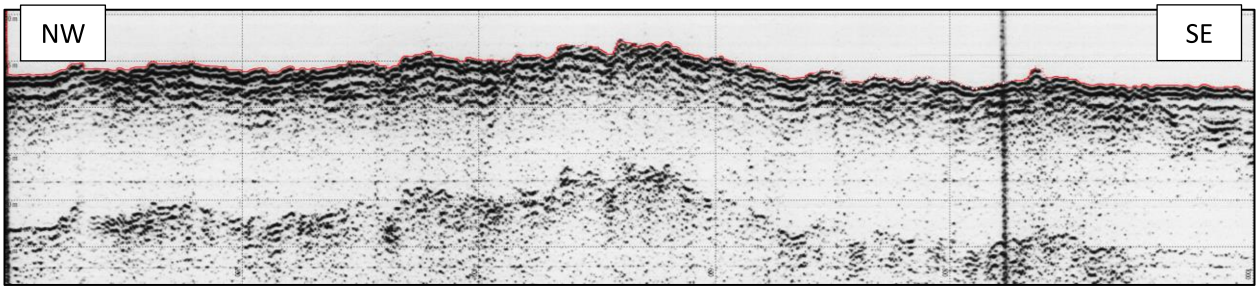
16july1985_1008-1105

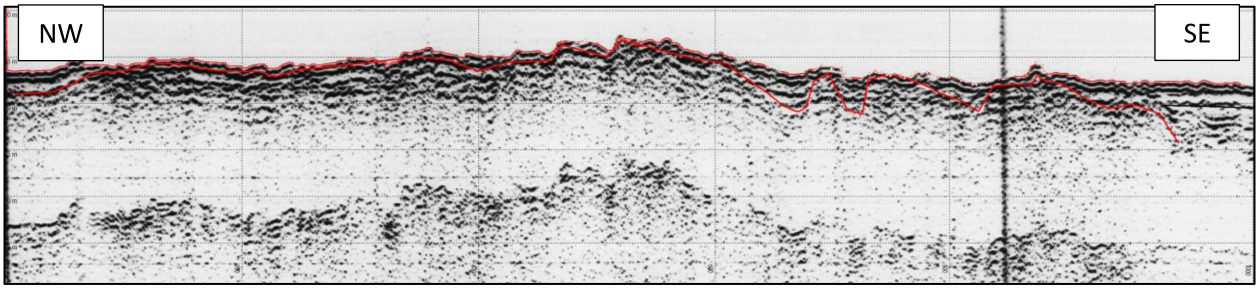


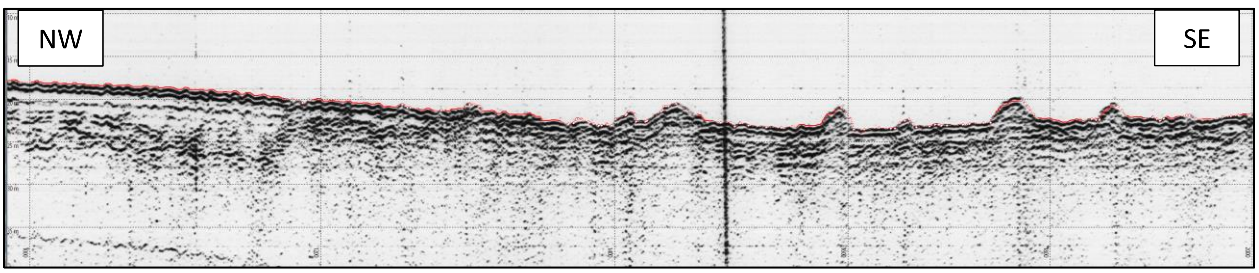
16july1985_915-1008

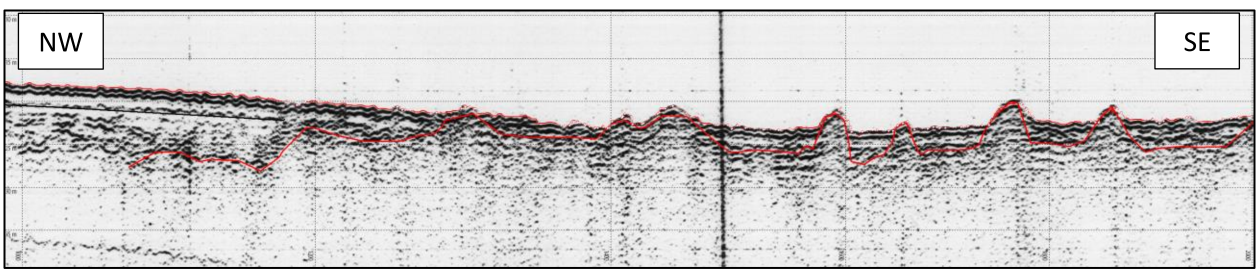


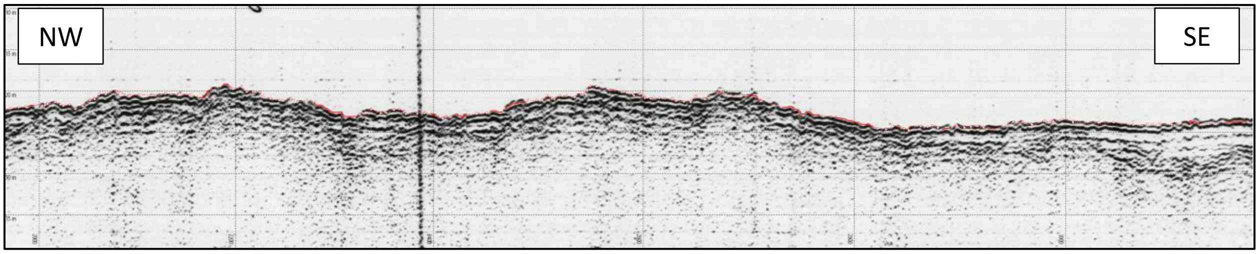
16july1985_816-915







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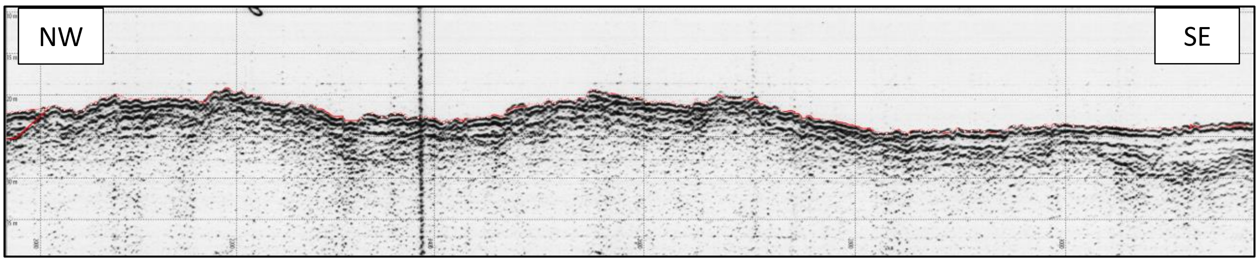
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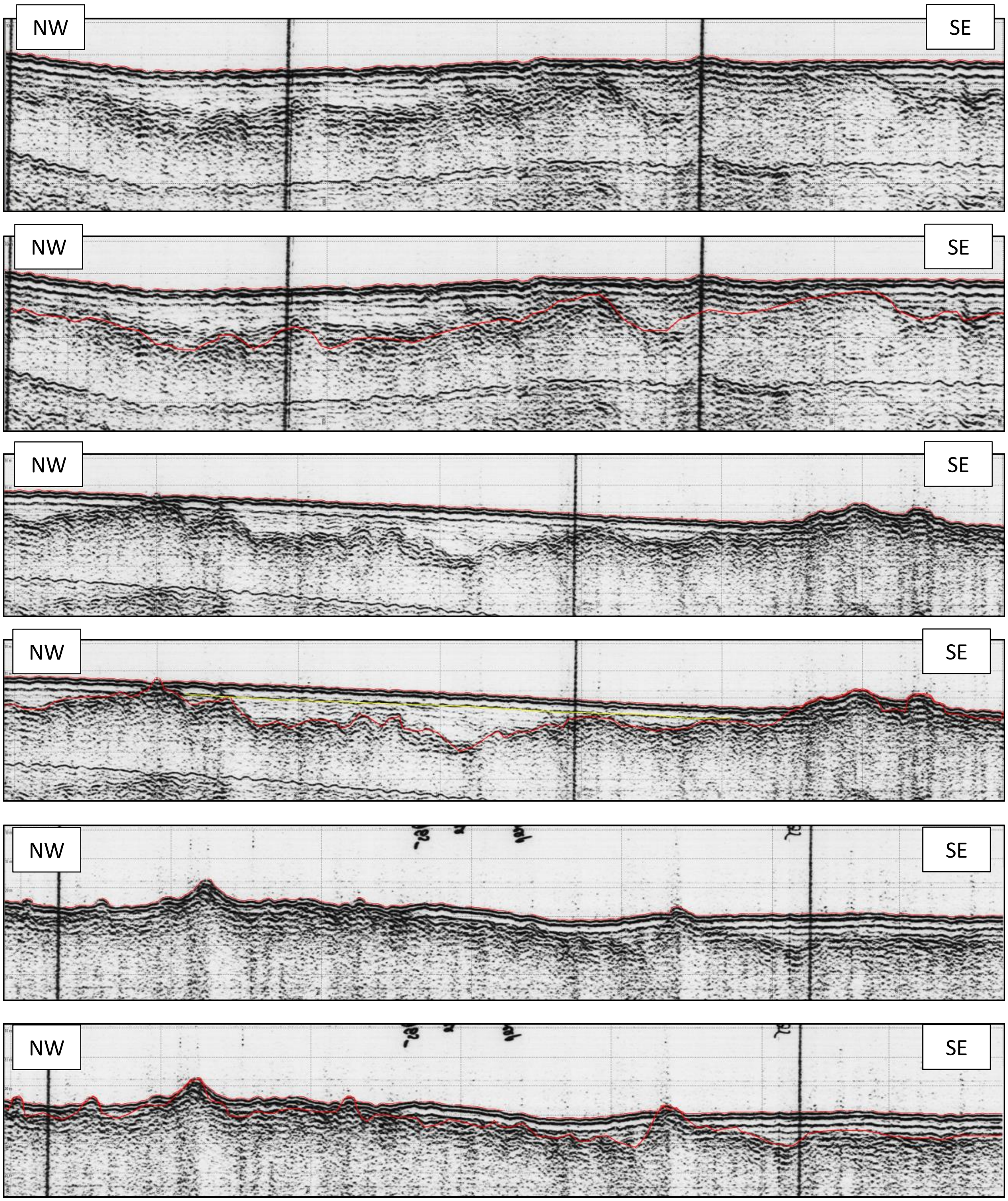
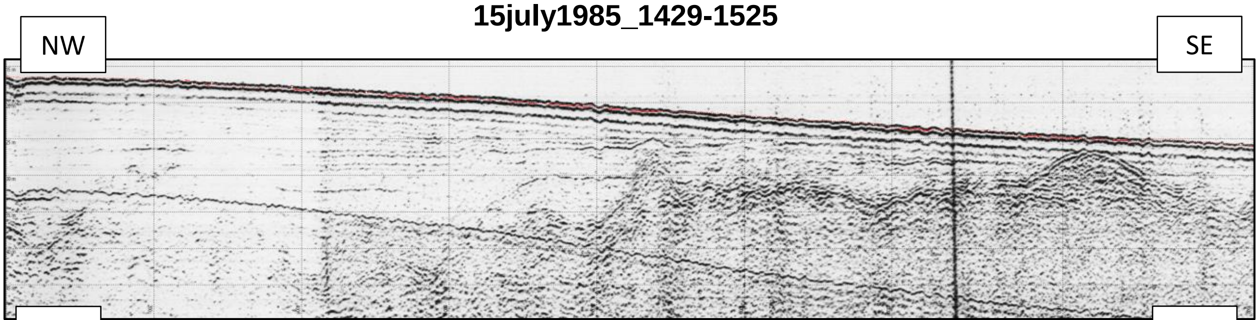
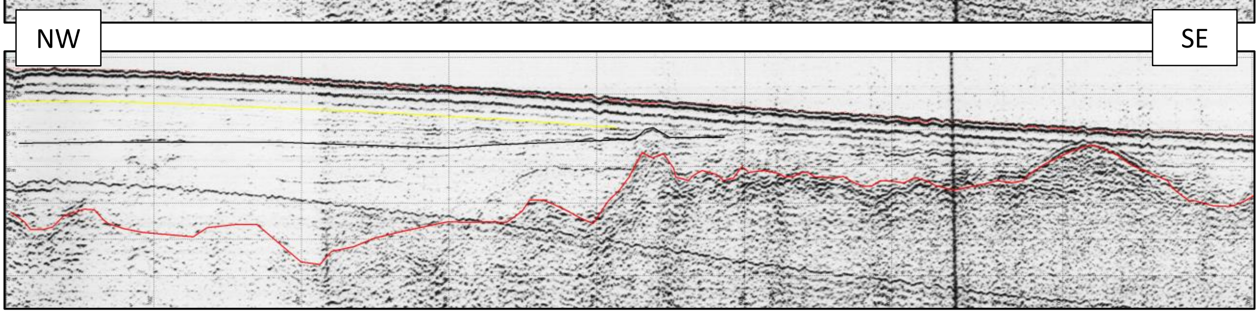
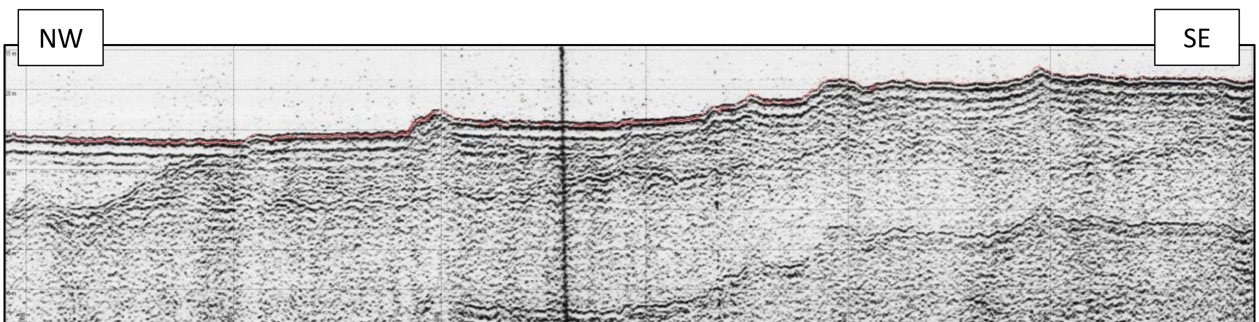
15july1985_1525-1622

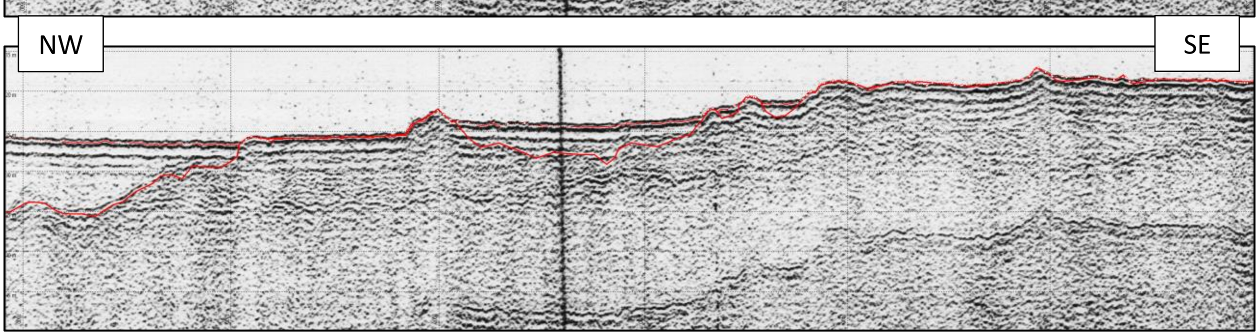


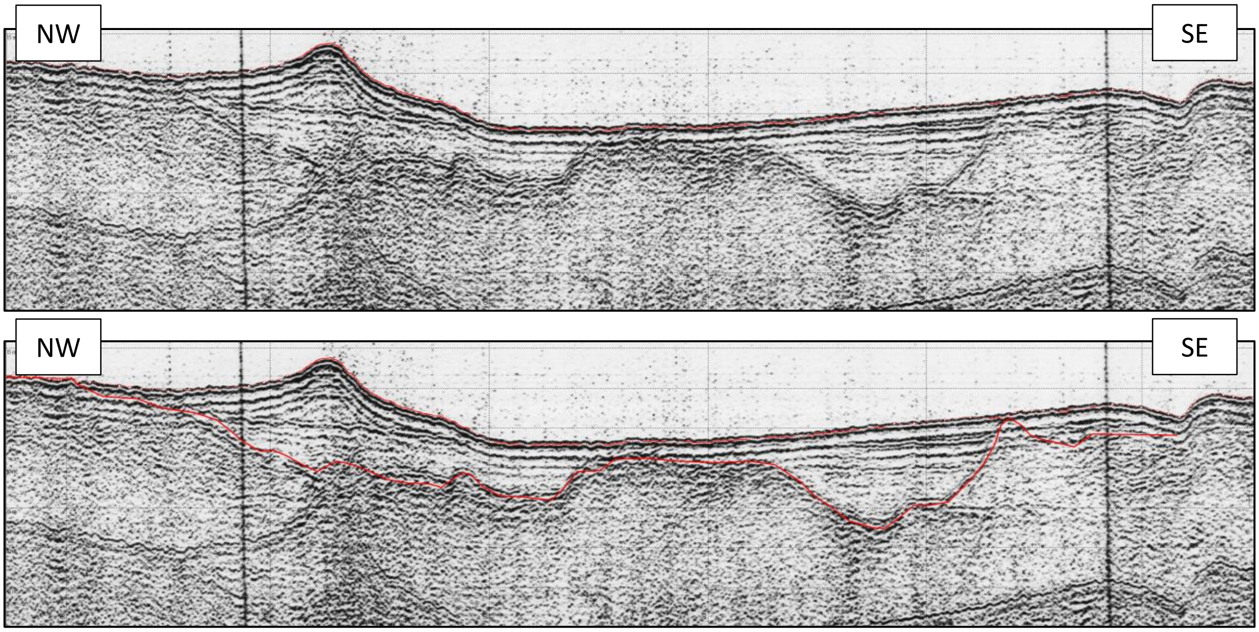
15july1985_1429-1525







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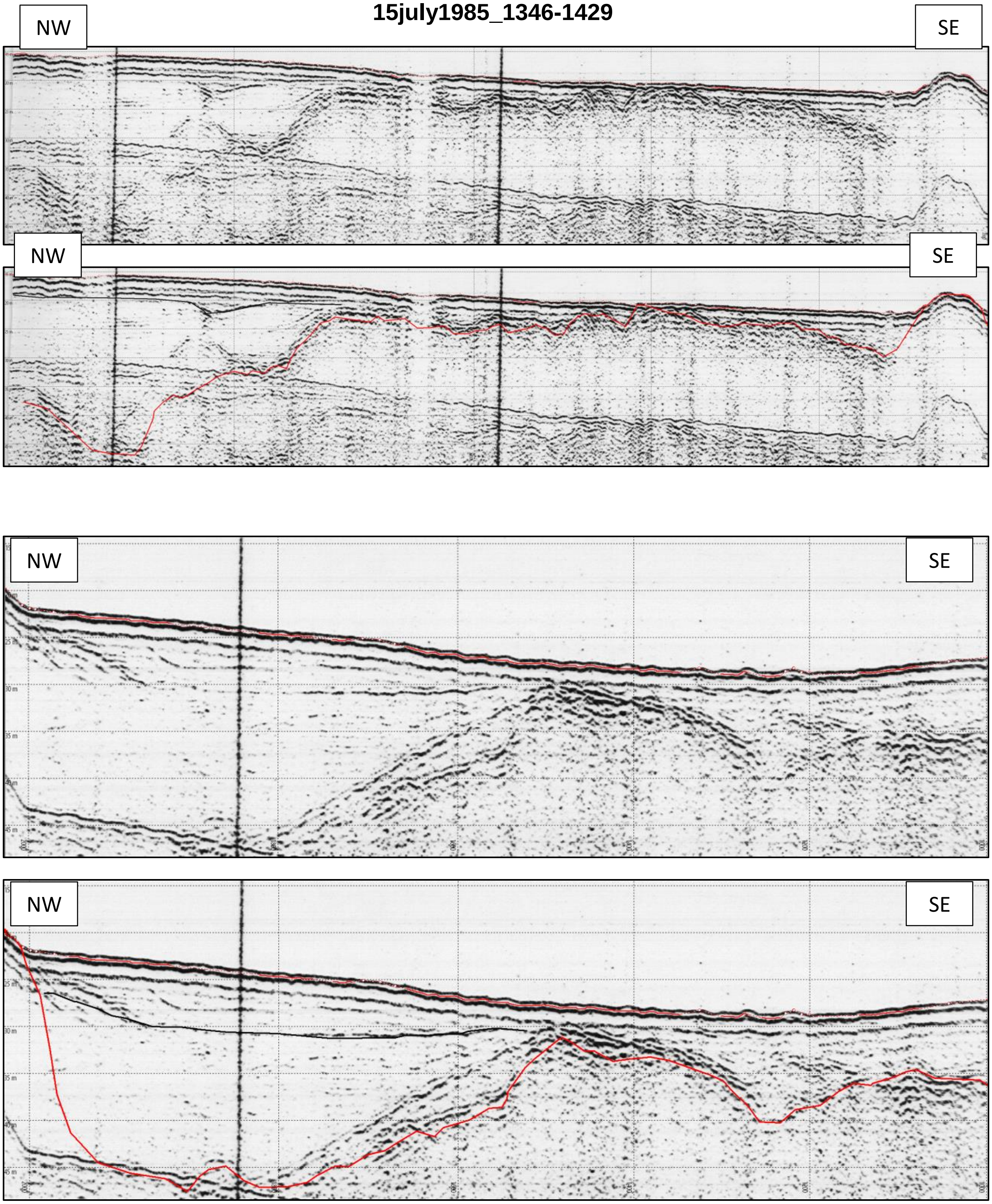
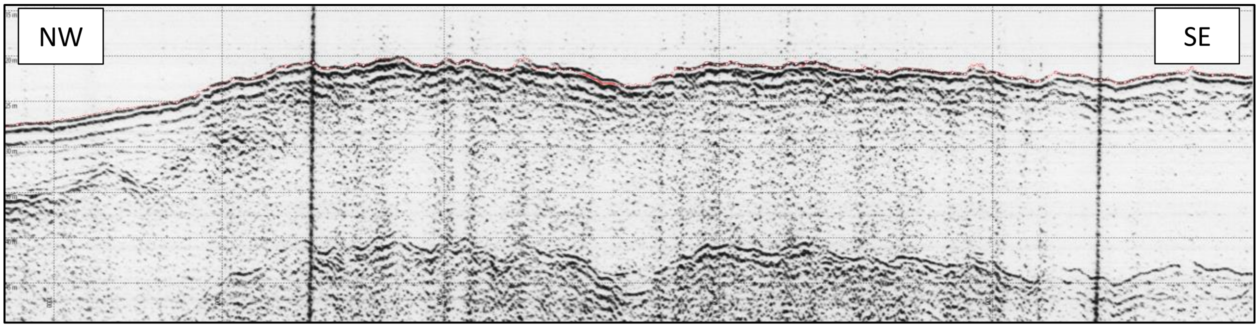
15july1985_1346-1429

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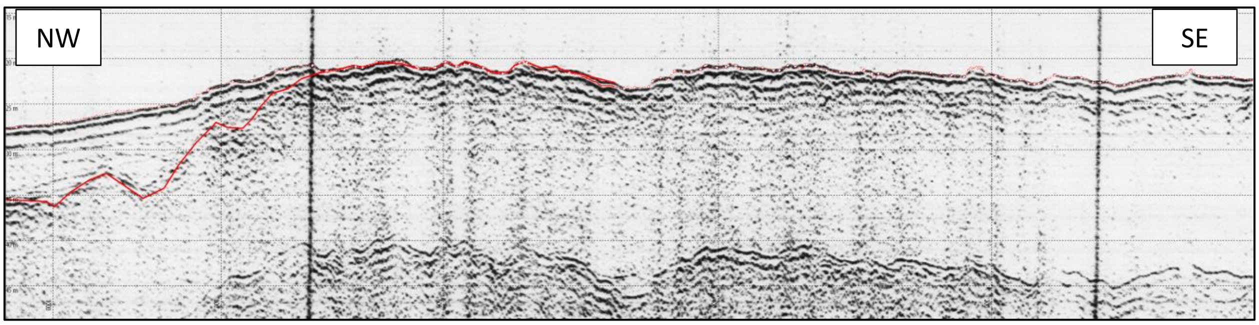
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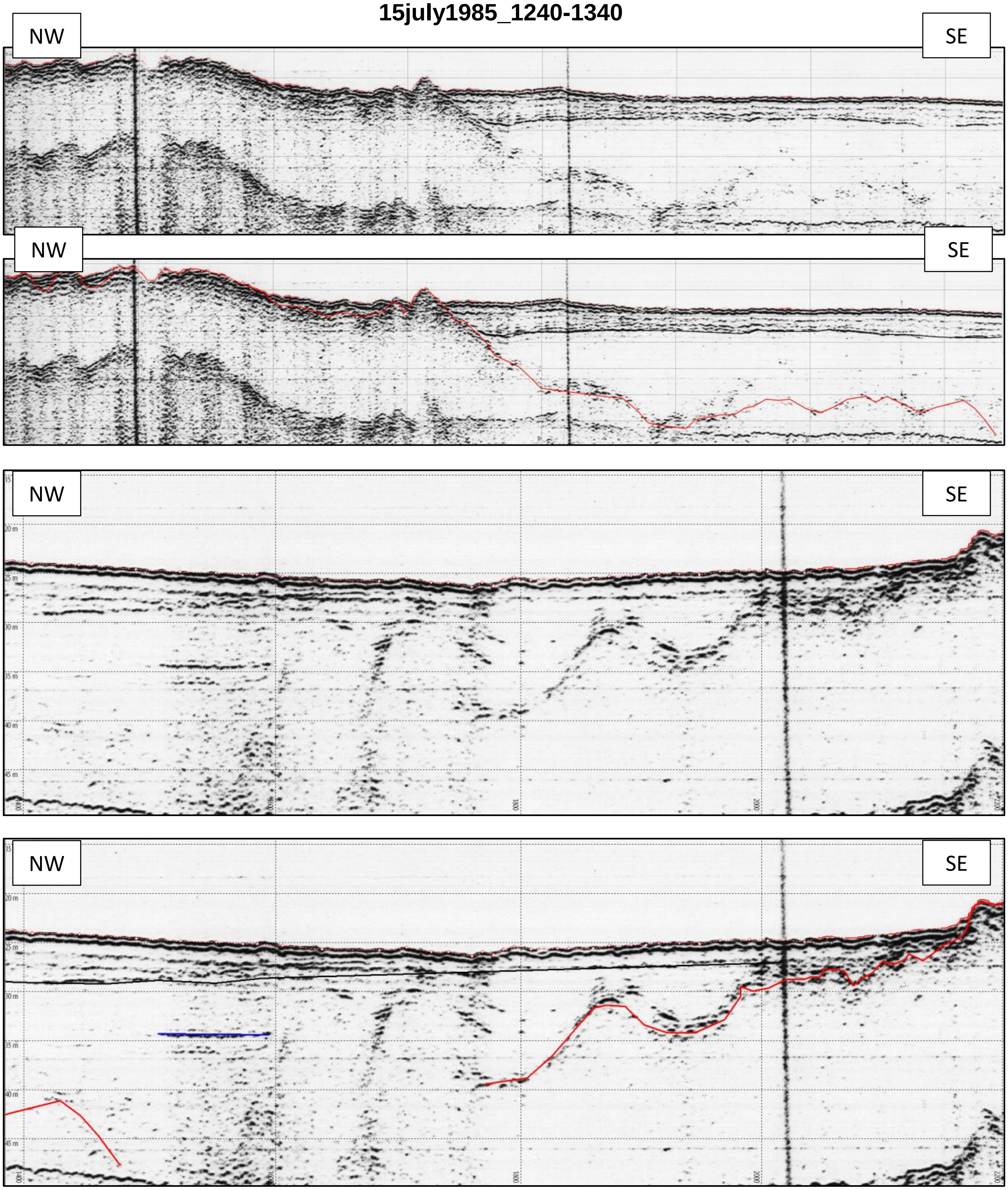
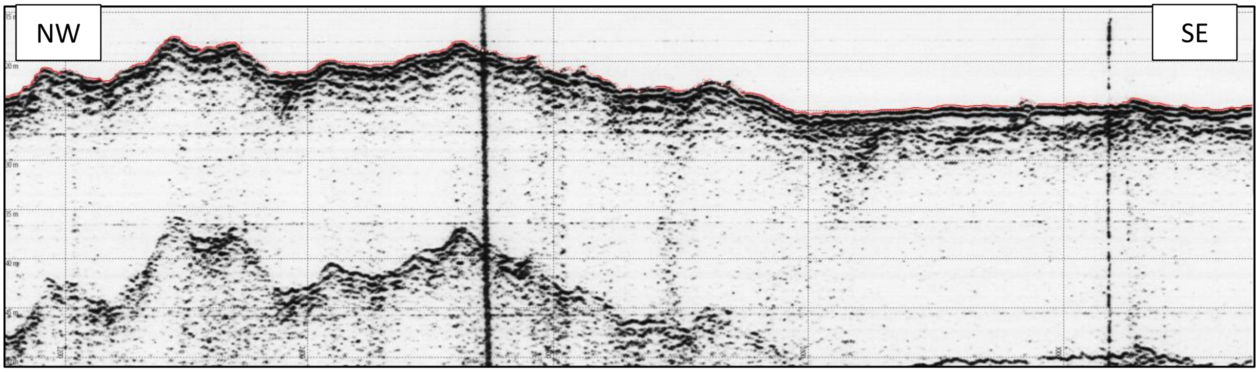
15july1985_1240-1340

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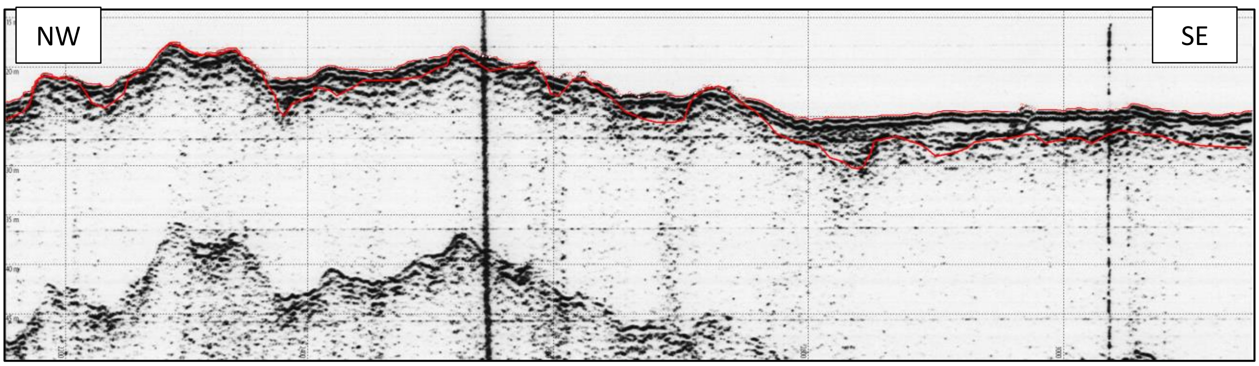
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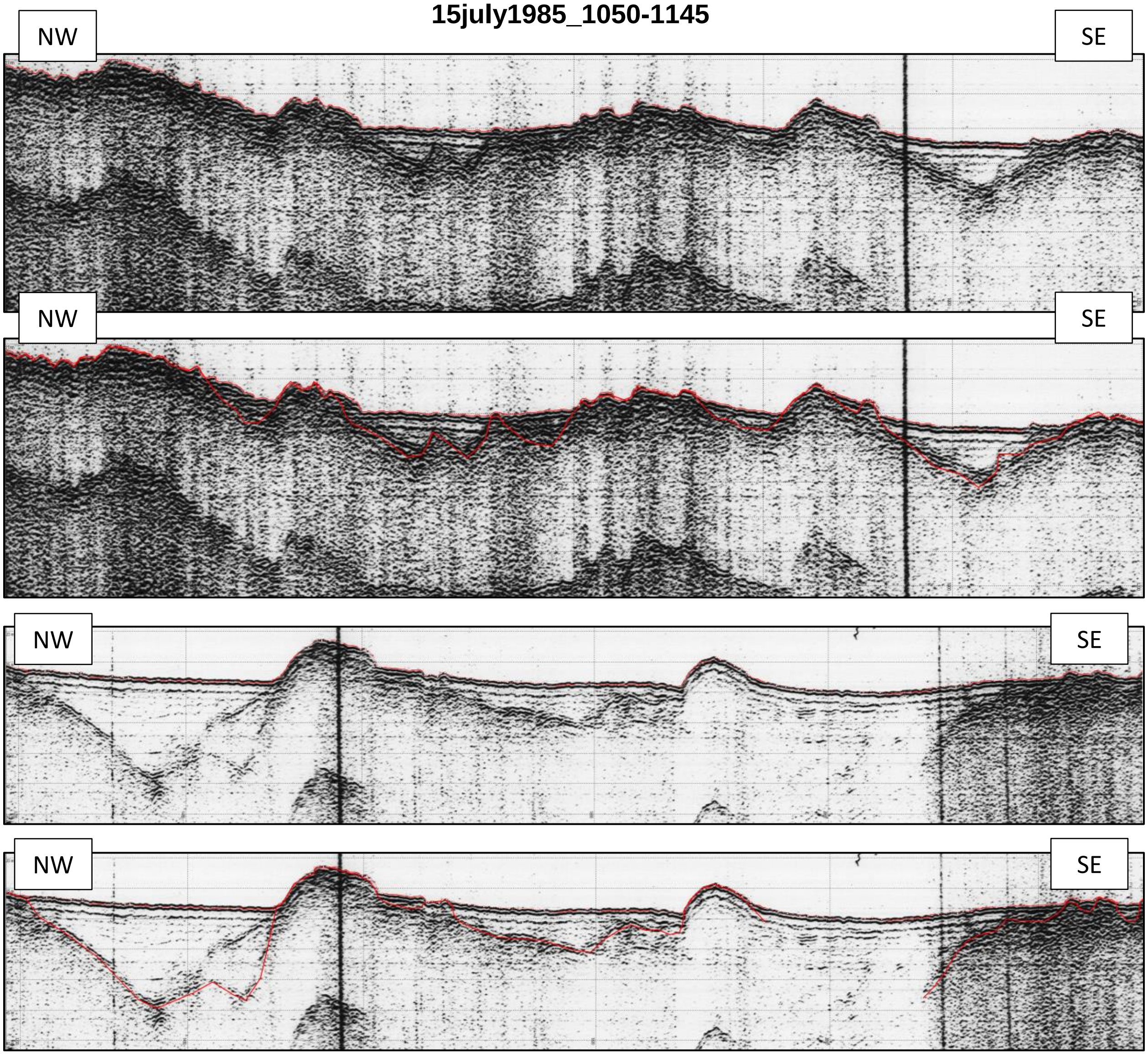
15july1985_1050-1145



23june1981_1125-1250

(shore perpendicular section)