

**ANALYZING CHANNEL DYNAMICS WITHIN THE DELAWARE BAY
ESTUARY: CONSTRAINTS FROM CHIRP SEISMIC PROFILES**

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the Bachelor of Arts in Geology with Distinction

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**ANALYZING CHANNEL DYNAMICS WITHIN THE DELAWARE BAY
ESTUARY: CONSTRAINTS FROM CHIRP SEISMIC PROFILES**

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ABSTRACT

In this senior thesis, chirp sub-bottom data were analyzed in order to place constraints on the dynamics of the Delaware River/Bay navigation channel. In 2003, the Delaware Estuary system (consisting of the Delaware River and Delaware Bay) was the 5th largest national waterborne area of commerce within the United States. Chirp profiles are a highly accurate type of seismic data that allow a user to observe bottom and sub-bottom features to a decimeter scale. This thesis is the product of a Delaware Department of Natural Resources and Environmental Control (DNREC) sponsored benthic mapping project in the Delaware Estuary. The goal of the Delaware Benthic Mapping Project was to provide constraints on the bottom and sub-bottom sediments to aid in better understanding, managing, and preserving the Delaware Estuary.

DNREC and University of Delaware scientists gathered chirp data using a vessel with a chirp towfish attached. The data collected were georeferenced with a GPS and were placed within SonarWiz5 and ArcGIS 10.1 to be analyzed. SonarWiz5 was utilized in order to view, edit, process and interpret the chirp profiles within the navigational channel of Delaware Geological Survey (DGS) ID sector Ge. Within SonarWiz5 features could be defined and measured. The navigation channel chirp profiles were also placed within a three-dimensional viewer in order to gain a better perspective on the navigational channel. The results were depictions of the navigation channel and its shape and sub-bottom structure. The figures and three-dimensional

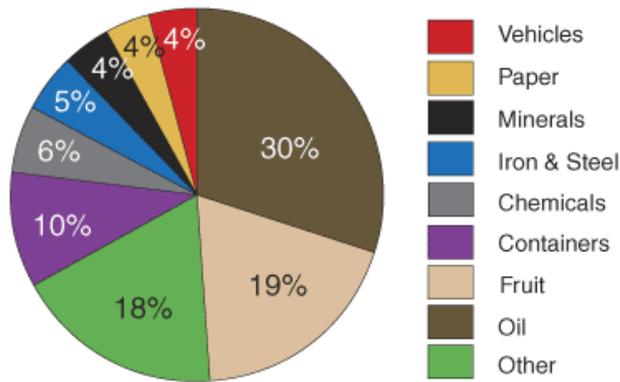
images were used to define areas of sediment accumulation, sediment wave structures, and the presence of subsurface paleochannels.

Chapter 1

BACKGROUND AND OBJECTIVES

The Delaware River and Bay comprise the Delaware Estuary located in the Northeastern to Middle-Atlantic portion of the United States. This 2,031 square kilometer body of water provides a pathway by which goods travel to and from the North American continent on a daily basis. The estuary is critical to economic success within not only Delaware and New Jersey, but nationally as well. According to the University of Delaware College of Earth Ocean & Environment (UD CEOE, 2004) and the National Oceanic and Atmospheric Administration (NOAA), in 2003 there were approximately 3,000 vessels that transited the estuary, and it was the fifth largest waterborne area of commerce within the United States (UD CEOE, 2003).

Almost 30% of all goods that travel through the Delaware Estuary are hydrocarbons which are refined at facilities along the Delaware River including the Delaware City Refinery operated by PBF Energy and located in Delaware City, Delaware (Figure 1). In an economic report released by the Delaware Sea Grant in 2012, it was reported that the total economic contributions of coastal related activity to Delaware alone were \$6.9 billion in revenue, 59,000 jobs supported, and \$711 million in additional local, state, and federal taxes (Delaware Sea Grant, 2012). Needless to say, the Delaware Estuary is a pivotal economic area on a state and national level. The dynamics of the estuary have been studied in the past, but in only a limited extent using geophysical techniques (e.g., Knebel and Circé, 1988; Knebel et al., 1988).



Other is Comprised of:
 General — 3%, Wood — 3%, Clothes — 2%, Food — 2%, Meat — 2%,
 Cocoa — 1%, Project — 1%, Juice — 1%, Miscellaneous — 1%,
 Passengers — 1%, Fertilizer — 1%

Figure 1 Distribution of goods and services by ships entering the Delaware Bay (data source from University of Delaware Sea Grant Program, 2004)

Previous work related to sedimentology has been done within the Delaware Bay including a study by Fletcher et al. (1990) (Figure 2). Their study, “Holocene Depocenter Migration and Sediment Accumulation in Delaware Bay: A Submerging Marginal Marine Sedimentary Basin”, concentrated on identifying the migration of the centers of sediment deposition along the bay using techniques including analyzing offshore core samples (Fletcher et al., 1990). Their project was important because it provided a framework for the types of sediments within the Delaware Bay and how these sediments were deposited over time (Fletcher et al., 1990). Their results indicate that there has been a large relatively recent rise in sea level over the past approximately nine thousand years (ka) (Fletcher et al., 1990). As seen in Figures 3 and 4 in response to this sea-level rise, sediment depocenters within the bay have moved their position from nearer to the New Jersey coast of the Delaware Bay, westward to their modern position, which is more proximal to the Delaware coast along the bay (Fletcher et al., 1990).

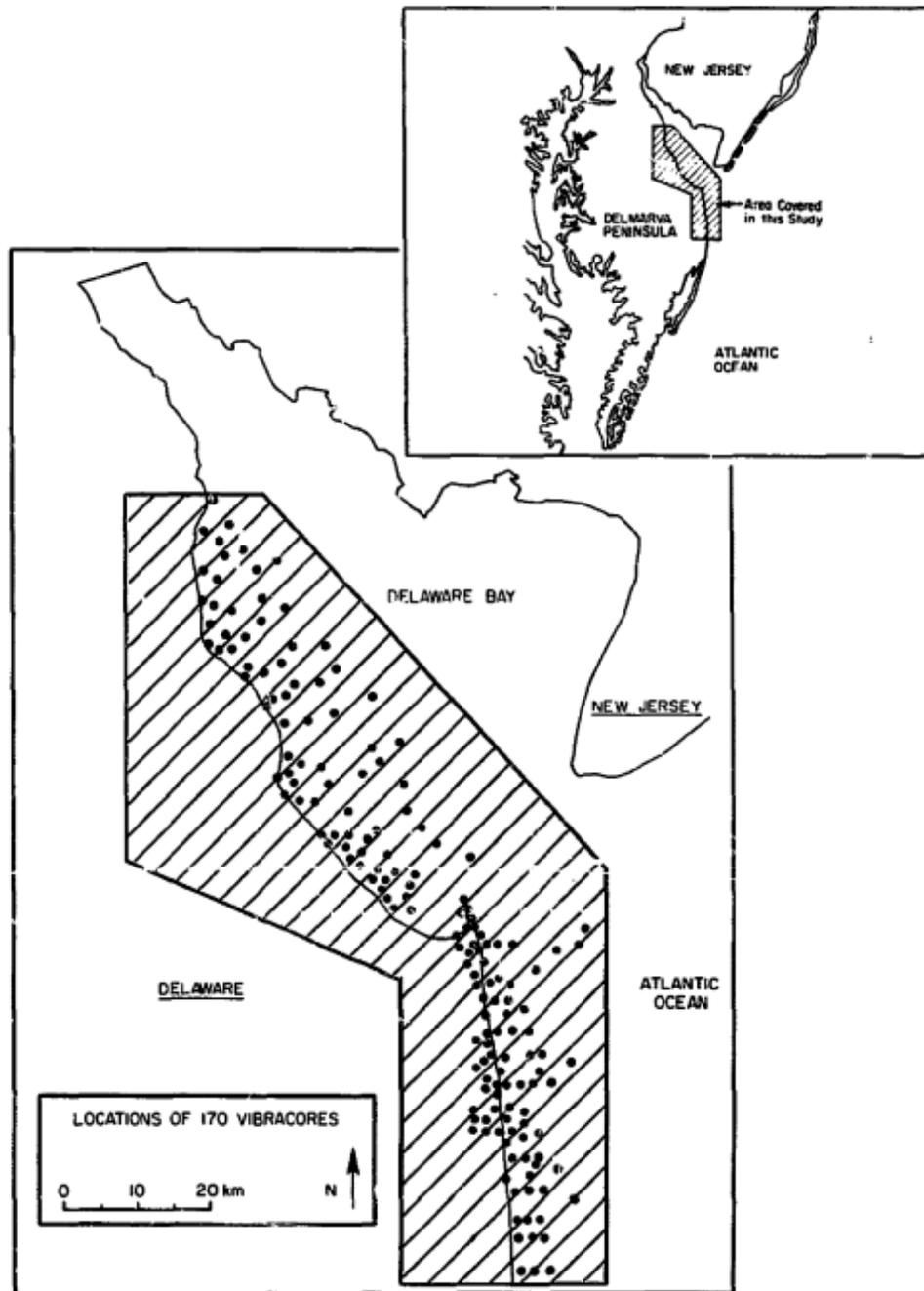


Figure 2 Study area of Fletcher et al. (1990). Coastline of Delaware and locations of 170 vibracore samples.

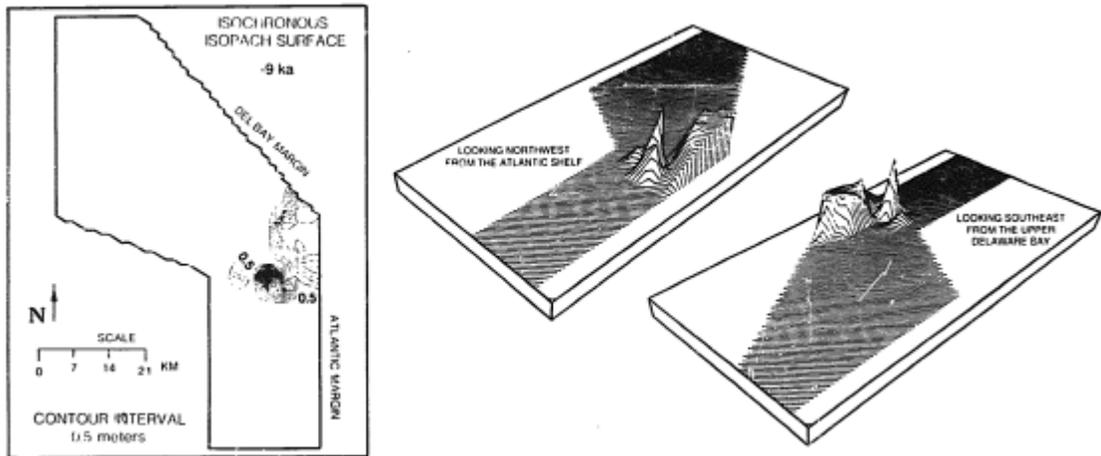


Figure 3 Depositional center of Delaware Bay approximately 9 ka. Results from Fletcher et al. (1990).

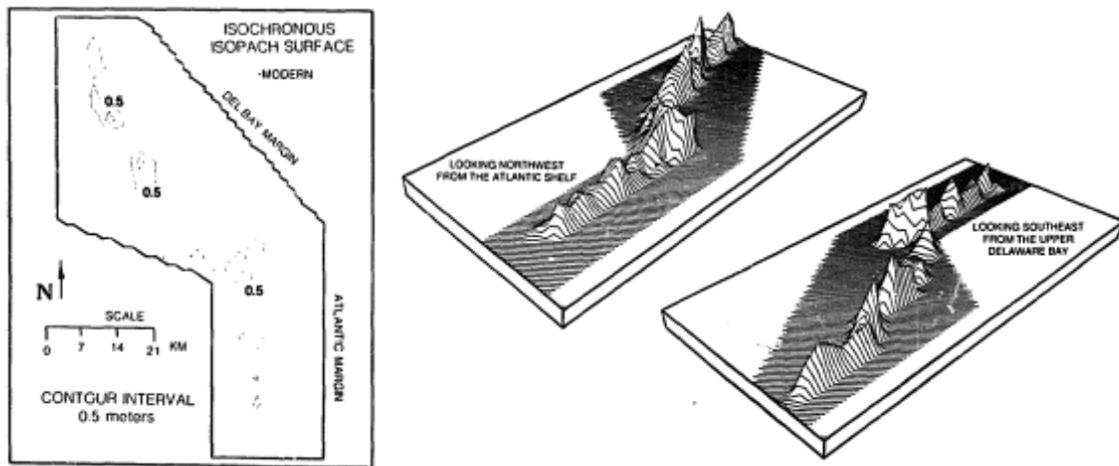


Figure 4 Depositional center of Delaware Bay in modern time. Results from Fletcher et al. (1990).

The research by Fletcher et al. (1990) was beneficial, but they were somewhat limited by the technologies that they were able to use. Their study was based primarily from 170 vibracore samples which were analyzed to form their conclusions (Figure 2). This senior thesis study uses recently collected high-resolution sub-bottom profiles to place additional constraints on the results from those who earlier studied the Bay such as Fletcher et al. (1990). The specific goal of this thesis is to take a closer look at the dynamics of the modern Delaware Bay/River channel within the Estuary to gain a better understanding of the surficial and shallow sub-surface sediments and structure of the channel, and to investigate the impacts that anthropogenic activities such as dredging have on sediments within, and in the vicinity of, the navigation channel.

Chapter 2

DATA ACQUISITION

Chirp sub-bottom data were collected from 2003 to 2013 as part of the Delaware Department of Natural Resources and Environmental Control (DNREC) Delaware Benthic Mapping Project, a benthic and sub-bottom mapping project conducted in the Delaware Estuary and the coastal Atlantic Ocean portion of Delaware (Madsen, 2014). The mission of the Delaware Benthic Mapping Project was to identify and map the benthic habitat and sub-bottom sediments of these areas, and to supply this information in a form decision makers and stakeholders could easily use that would aid them in their efforts to manage and conserve resources (Madsen, 2014).

As summarized in Madsen (2014), the chirp system used in the Delaware Benthic Mapping project is a sonar device that generates a high resolution (decimeters) cross-sectional image of the seafloor and sub-bottom over a range of depths from 5-20 meters (m). The chirp towfish transmits a wide-band frequency modulated (FM) sound pulse that is linearly swept over a full spectrum frequency range. The sound waves travel through the water column and seabed until some of their energy is reflected when they encounter a boundary where acoustic impedance changes (Figures 5 and 6). Acoustic impedance is the product of the sonic wave velocity times the density of the materials through which the waves are traveling (e.g., Madsen, 2014).

The sound waves are reflected off of this acoustic impedance boundary and travel back to the towfish and their amplitudes are recorded digitally (Figure 5). The boundaries of acoustic impedance almost always occur at interfaces of different

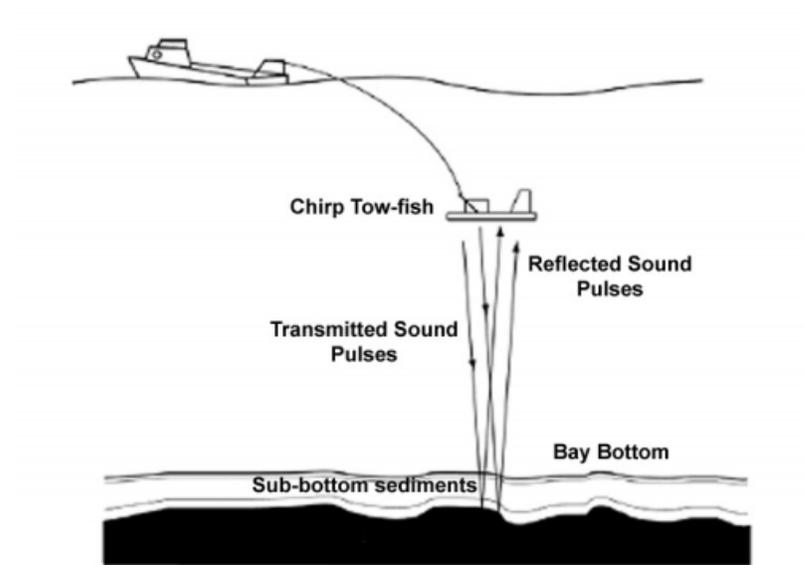


Figure 5 Schematic of chirp sub-bottom data gathering methods (Madsen, 2014).



Figure 6 Deployment of the chirp towfish into the Delaware Estuary.

geologic sediments or materials. The general structure and stratigraphy of sedimentary layers in the sub-surface may be inferred by imaging where the boundaries of acoustic impedance occur (e.g., Madsen, 2014).

As summarized by Madsen (2014), in the Delaware Benthic Mapping Project, an Edgetech X-Star chirp sonar system with a SB-216S towfish was used to collect the chirp data. The towfish was configured to emit a sound pulse with a swept frequency of 2-10 kilohertz (kHz) at an interval of 8 cycles per second. With this frequency, the vertical resolution between differing sub-surface sediment layers is estimated to be about 20-30 centimeters (cm). Given a sampling interval of 8 cycles per second while travelling at an average vessel speed of 5 knots (nautical miles per hour), the horizontal resolution of the chirp sonar was about 5-10 cm. Sonar reflections were observed to have penetrated to depths of about 20-30 m maximum below the bay bottom. Most of the penetration depths reached about 2-5 m below the bay and about

5-10 m beneath the ocean bottom. All chirp data were recorded with co-registered Global Positioning System (GPS)-determined locations (i.e., longitude, latitude) (Madsen, 2014).

Chapter 3

DATA PROCESSING

The chirp sub-bottom data collected in the Delaware Benthic Mapping Project were organized using the Delaware Geological Survey Identification (DGS ID) area grid system. Each DGS ID area is 5' by 5' latitude and longitude in size. For this particular study, DGS ID area Ge (75°30'0" W to 75°25'0" W and 39°25'0" N to 39°20'0" N) was used. Track lines along which chirp sub-bottom files were recorded within DGSID area Ge are shown in Figure 7.

Area Ge is located within the middle to middle-lower portion of the Delaware Estuary and the modern channel, roughly defined by water depths greater than 30 ft (~9.1 m; shown in white on Figure 7), runs roughly northwest to southeast across the area. The Delaware River/Bay navigation channel, the channel within which large ships transit to/from regional ports, is confined within the modern channel. The US Army Corps of Engineers maintains the depth of the navigation channel at a minimum of 35 ft (~10.7 m). The position of the navigation channel is defined by the dashed lines in Figure 7. Within the past five years, the Corps of Engineers has implemented a navigation channel deepening project in which the modern channel is being deepened via dredging to minimum depths of 40 ft (~12.2 m). The chirp sub-bottom files collected in the Delaware Benthic Mapping Project were collected prior to deepening. However, they do provide information on the types of sediments that will need to be removed (i.e., dredged) in order to deepen the navigation channel.

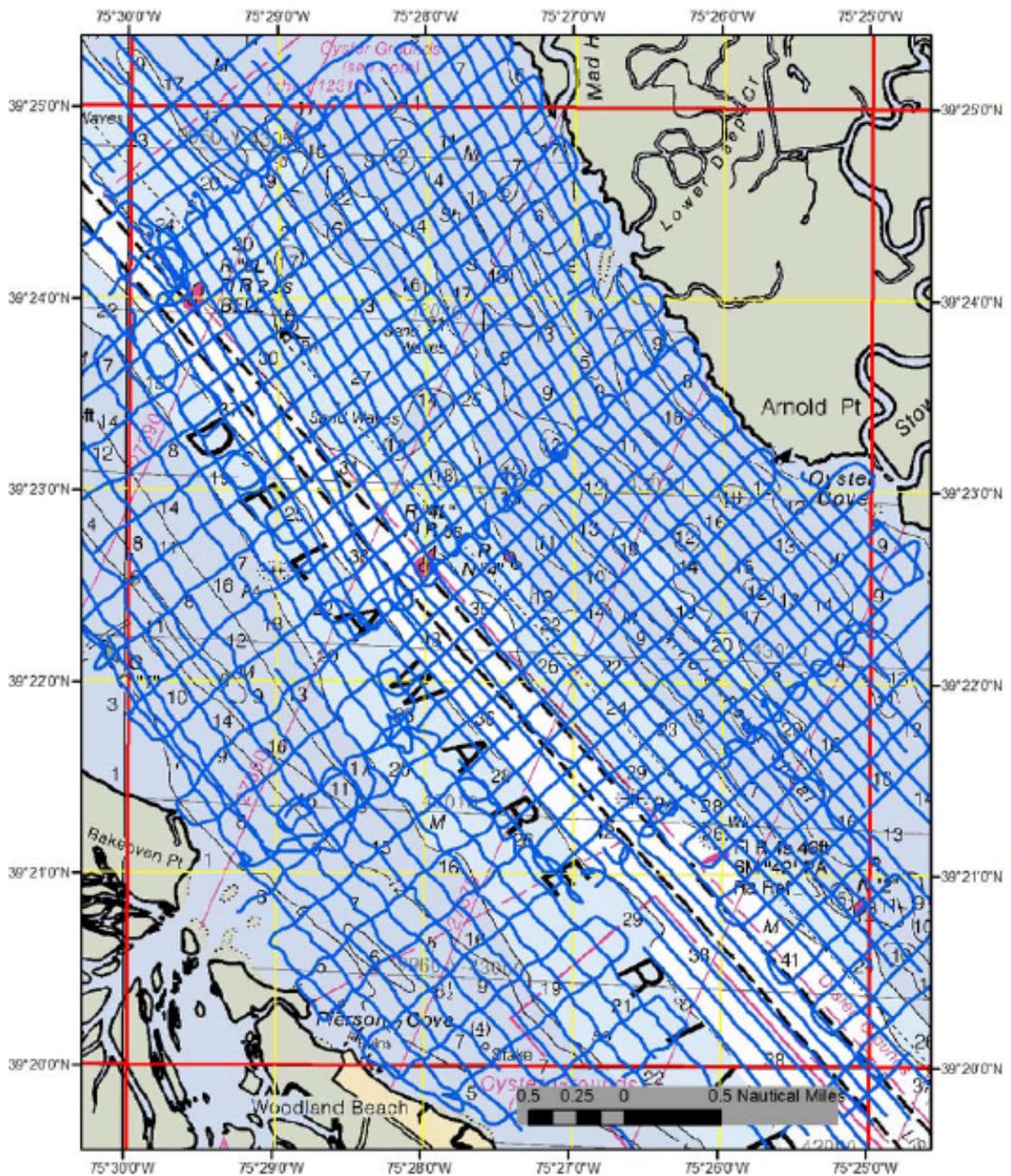


Figure 7 DGS ID area Ge with chirp tracklines shown in blue. Red lines outline the 5' by 5' DGS ID Ge area. Yellow lines indicate 1' by 1' sub-areas within Ge.

Since this thesis project was focused on the sediments in the modern, including the navigation, channel of the Delaware River/Bay, the survey tracklines within DGS ID area Ge that crossed, or ran along, the channel were of particular interest. Thirty nine chirp sub-bottom files from DGS ID area Ge were processed, analyzed and interpreted in this project. The locations of these files are shown in Figure 8.

Each of the files was uploaded into the software program SonarWiz5. Chesapeake Technology's SonarWiz5 is geophysical processing software that allows sonar data to be viewed, edited, processed and interpreted. Following the procedure used by University of Delaware graduate student Alia Ponte in her Master of Science thesis project using chirp data, the files were imported using a geographic projection of UTM 1983 18N and a manual scalar value of either 150, or 250 when unusually low amplitude returns were observed, on initial plots of the files (Ponte, 2016). The manual scalar is a multiplying factor applied to the sonar returns that scales them within a 16-bit integer range for optimal display (Chesapeake Technology, Inc., 2014). The larger the scalar, the greater the multiplication of return amplitudes (Chesapeake Technology, Inc., 2014). The 150 and 250 values used were determined by experimentation; varying the scalar between 1 and 500 and observing the strength (neither too faint (i.e., scalar too low) nor too dark (i.e., scalar too high) of the sonar returns shown on initial plots of the data (Ponte, 2016).

After the chirp files were imported, they were processed using the bottom-tracking function in the Digitizing View of SonarWiz5. For each "ping" of the chirp system, this function compares the amplitudes of successive data points, identifies when an initial large increase in amplitude occurs (e.g., a high amplitude signal is generated by the reflection of acoustic energy at the water-seafloor boundary where a

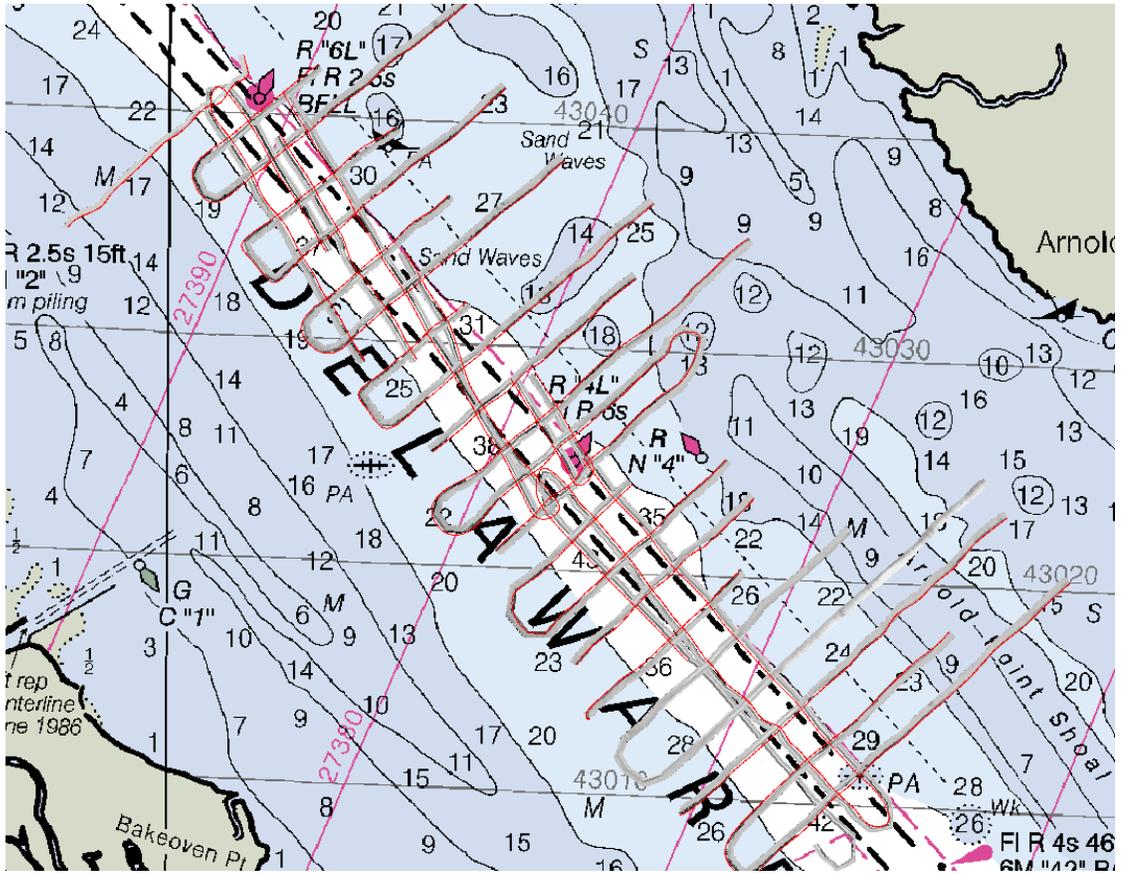


Figure 8 SonarWiz5 generated map display of chirp sub-bottom profiles within DGS ID area Ge used in this thesis project. Navigation channel is delineated by dashed black lines. White coloration shows depths greater than 30 feet (9.1 m); lighter blue shows depths between 20 and 30 feet (6.1 to 9.1 m); darker blue depths between 0 and 20 feet (0 to 6.1 m).

large change in acoustic impedance occurs) and defines this position as the seafloor, or bottom (e.g., Ponte, 2016).

Following the procedure used by Ponte (2016), after bottom tracking to enhance sub-bottom reflections (where changes in acoustic impedance occurred) automatic gain control (AGC) was applied to data occurring beneath the defined seafloor. AGC is a method to adjust (or gain) the amplitudes of time-varying signals relative to an average output level such that even if the amplitudes were continuously decreasing (e.g., due to spherical divergence and absorption), the output level would be maintained (Telford et al., 1990). AGC is performed by determining average signal amplitudes (resolution) within relatively short sample time periods, and adjusting applied gains (intensity) within the sample periods such that the output signal level is relatively constant (Telford et al., 1990). In the application of AGC in SonarWiz5, all amplitudes of signals were applied a resolution of 30 and an intensity of 25 with amplitudes above the seafloor set to zero, eliminating any “noise” within the water column (e.g., Ponte, 2016).

Chirp data are conventionally displayed in cross sectional profiles. In this thesis project, the profiles were displayed using horizontal distances of 1200 m to 1800 m and vertical distances (depths) of 15 to 20 m below the towfish. An example chirp sub-bottom profile that was imported into SonarWiz5, bottom-tracked and had AGC gain applied is shown in Figure 9. The profiles are shown with horizontal distance lines every 200 m; and with depth lines every 5 m (see Figure 9). The depths (i.e., 0, 5, 10 m) are relative to the towfish rather than the water surface. The towfish was generally towed at a depth of 1 m below the water surface.

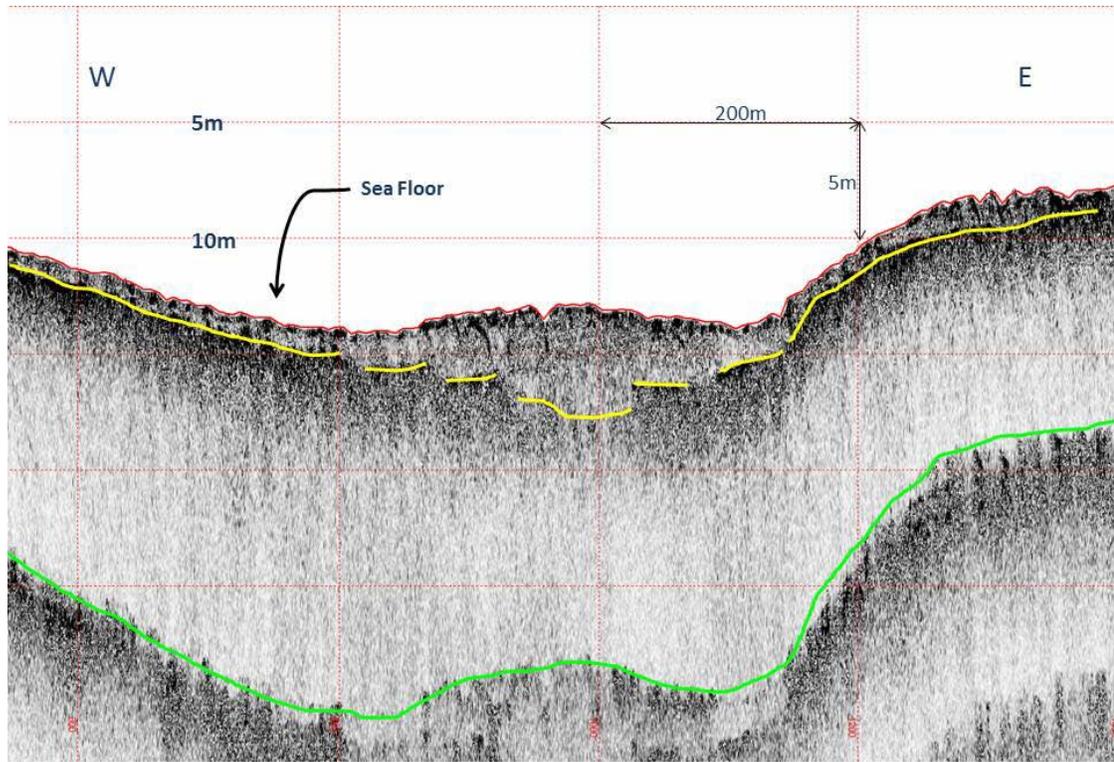


Figure 9 Example chirp sub-bottom profile cross-section. Red line denotes the position of the water-sediment boundary (i.e., the seafloor or bottom). Yellow line is an example of a boundary in acoustic impedance contrast within the sub-surface sediments. This boundary denotes the position (depth) where there is a change in the sub-surface sediment type. Green lines indicate multiples of the bottom reflection.

Colored lines were added to the profiles to highlight the boundaries where changes in acoustic impedance and resulting chirp reflections occurred (see Figure 9). In the chirp sub-bottom profile figures, red lines denote the seafloor, water-sediment boundary. Yellow lines are reflections in the subsurface that occur where there are changes in acoustic impedance. These reflections can be interpreted as subsurface boundaries where changes occur in the types of sediments. Green lines indicate the position of seafloor, or bottom, multiples. The multiples represent sound waves that have reflected off of the seafloor, travelled to the sea surface, been reflected back

down into the water column, reflected again off of the seafloor, and then recorded by the towfish. They essentially mirror the seafloor reflection, and occur at a depth that is twice the depth of the seafloor reflection plus the depth of the towfish below the sea surface (Figure 9).

Chapter 4

RESULTS

Shown in Appendix I are the chirp sub-bottom profiles that cross the Delaware River/Bay navigation channel within the DGS ID area Ge. Included with the profile images are ArcGIS-generated maps that show their location. Three major features were observed in the chirp sub-bottom profiles that were collected along the Delaware River/Bay navigation channel within DGS ID area Ge:

- Surficial mound-shaped deposits of sediment near the center of the channel. These deposits have thicknesses that vary between less than 1 to greater than 3 m,
- Sub-surface reflections, up to 5 m or more beneath the bay bottom, that may be associated with the boundaries of former river channels, or paleochannels, of the Delaware Estuary, and
- Sets of surficial sediment waves with average heights that vary between less than 1 to greater than 2 m, with average widths of approximately 10 to 25 m, respectively. These waves are due to bottom tidal currents and show the mobile-nature of sediments within the navigation channel.

These three major features are discussed in further detail, and shown by example figures, below.

Surficial Mound-Shaped Deposits of Sediment

In many of the chirp profiles that cross the navigation channel within area Ge, there is a notable mound-shaped deposit of sediment near the center of the channel. Chirp sub-bottom profiles (Ge14, Ge15, Ge16 and Ge19) prominently display mound-shape deposits. These profiles with their locations are shown in Figures 10 to 17. These features are most likely formed by deposition of sediment transported by bottom currents within the estuary. Sources for these deposits would include sediments within the water column that would settle out and/or sediments that would slump off the steepened sides of the navigation channel after dredging has occurred. These deposits provide evidence that as the deepening of the navigation channel to 40 ft (12.2 m) proceeds and is completed, it should be expected that deposition of sediment will resume and subsequent maintenance dredging will need to be carried out to maintain 40 ft (12.2 m) depths within the navigation channel.

Around the edges of the channel, surficial sediment thicknesses to the first zone of sub-surface acoustic impedance, or boundary between different sedimentary layers, range from approximately 0.6 to 2.0 m with an average of approximately 1.2 m. In contrast within the center of the navigation channel, zones of acoustic impedance associated with the boundary between surficial sediments and older, more consolidated, sediments below have a greater range and a larger maximum thickness with values of approximately 0.3 m to as high as approximately 3.0 m. The greater variability in thickness of the sediments within the modern (including the navigation) channel is likely due to the larger influence of bottom currents (both due to tidal and estuarine circulation) within the channel. The expression of deposition from these currents is seen by the mound-shaped features observed within the navigation channel.

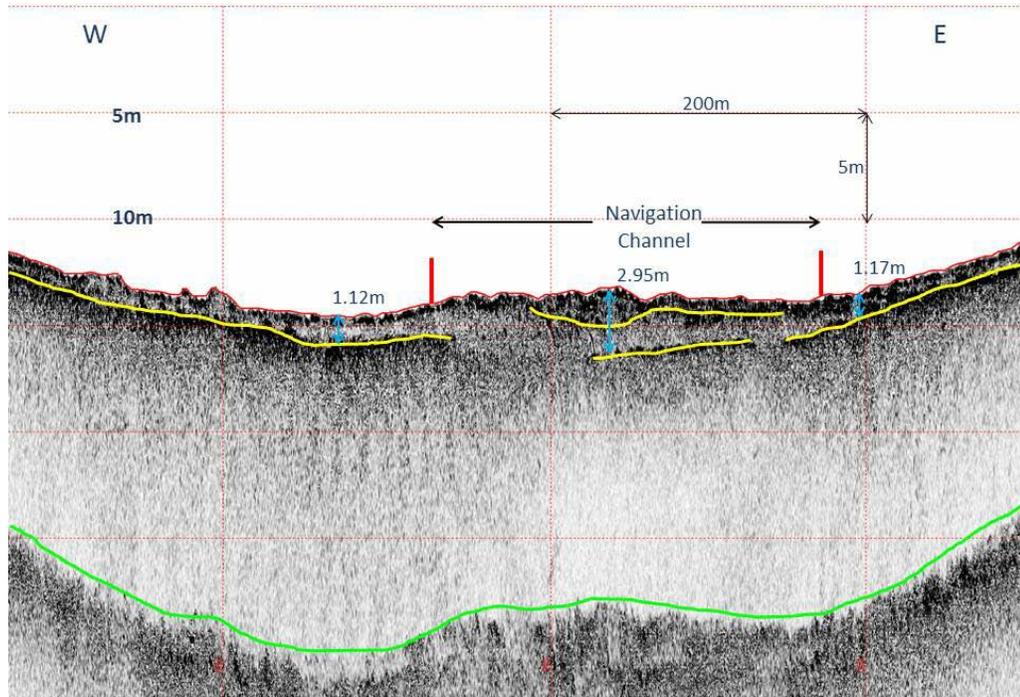


Figure 10 Chirp sub-bottom profile Ge14. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

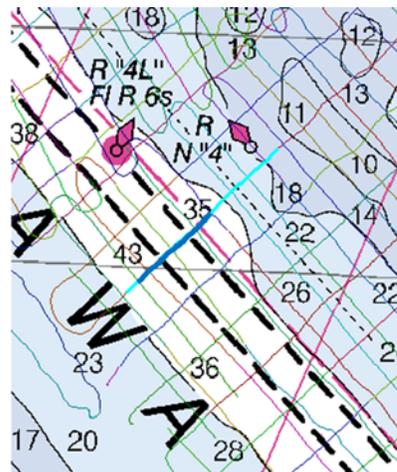


Figure 11 Location of chirp sub-bottom profile Ge14 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

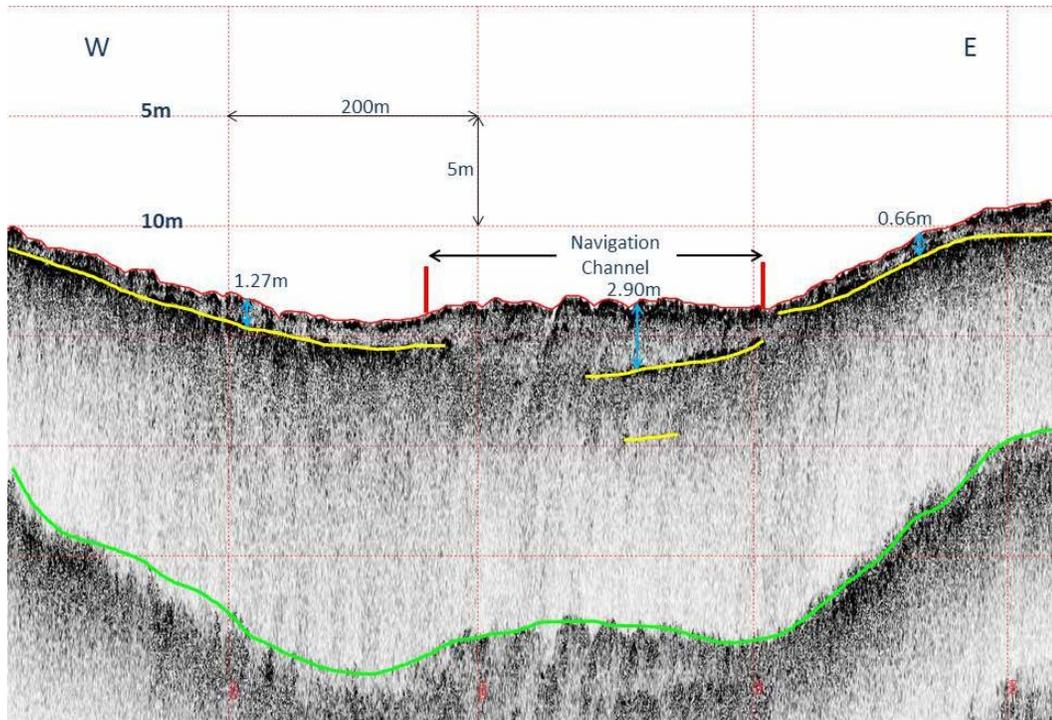


Figure 12 Chirp sub-bottom profile Ge15. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 13 Location of chirp sub-bottom profile Ge15 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

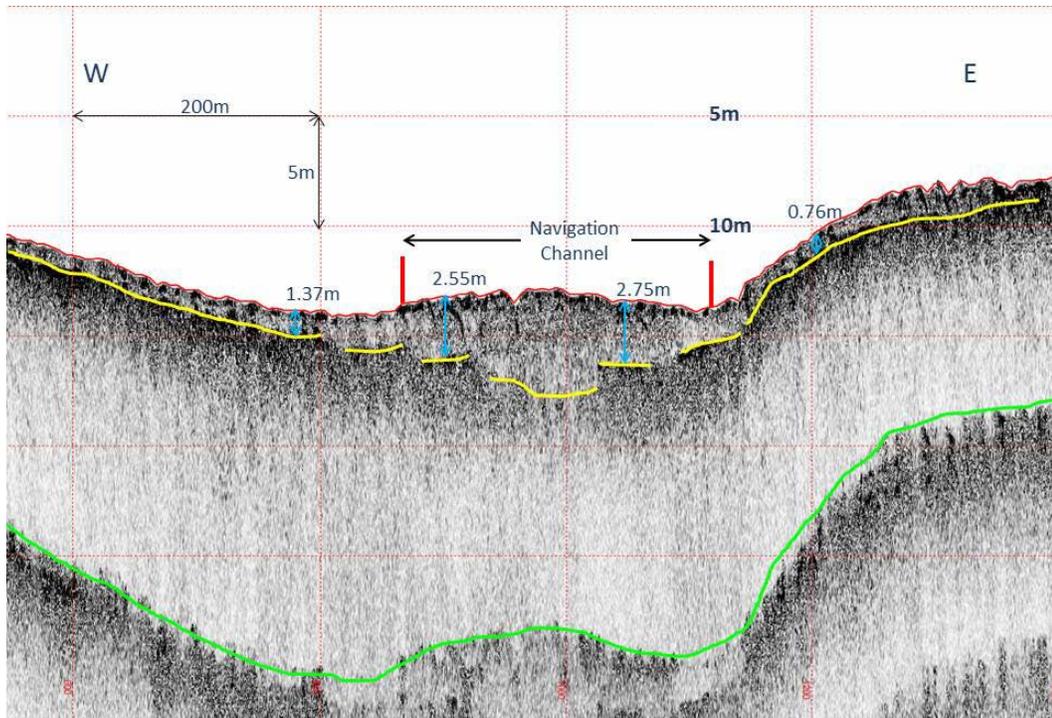


Figure 14 Chirp sub-bottom profile Ge16. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

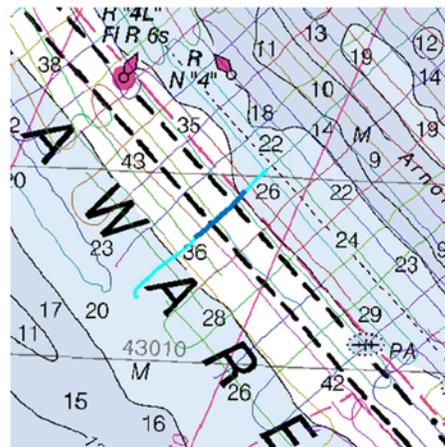


Figure 15 Location of chirp sub-bottom profile Ge16 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

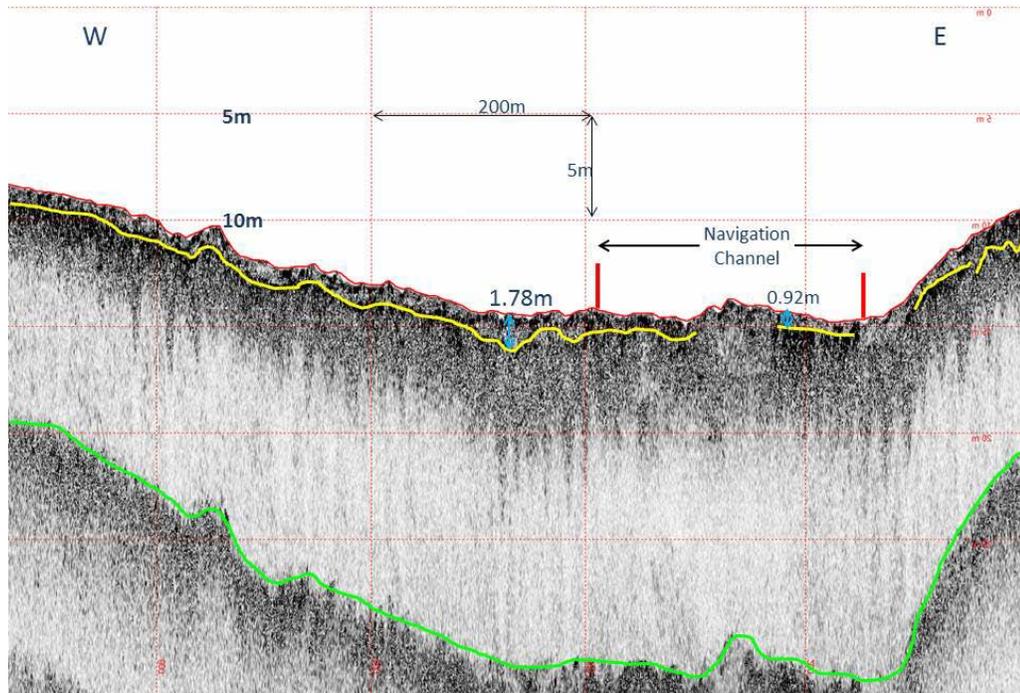


Figure 16 Chirp sub-bottom profile Ge19. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

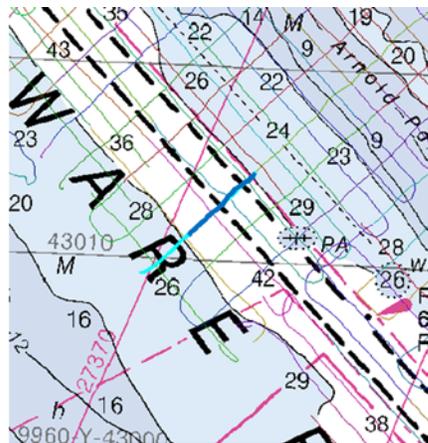


Figure 17 Location of chirp sub-bottom profile Ge19 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

The along-channel variation in the distribution and size of the mound-shaped deposits can be seen in the various series of chirp profiles that are displayed as three-dimensional views in Figures 18 to 22.

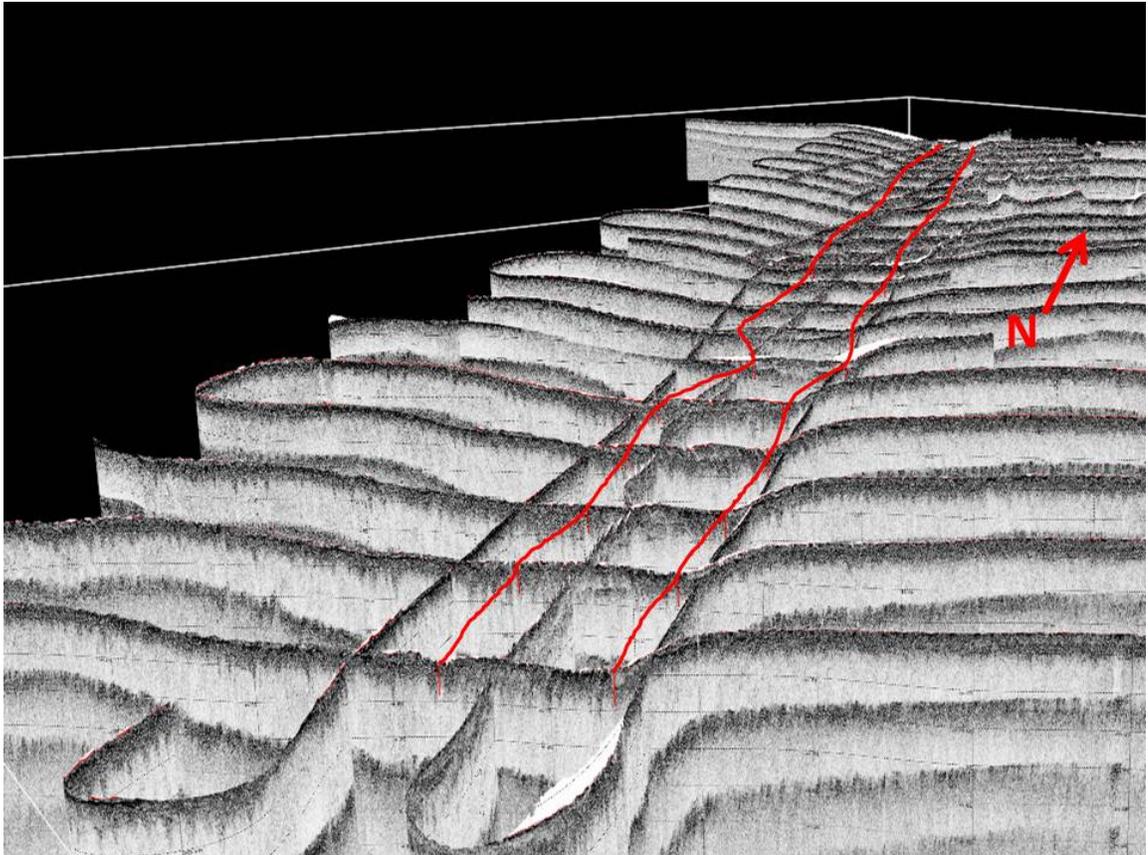


Figure 18 Three-dimensional view of chirp profiles looking from the south towards the north within DGS ID area Ge. Thick red lines indicate location of the navigation channel.

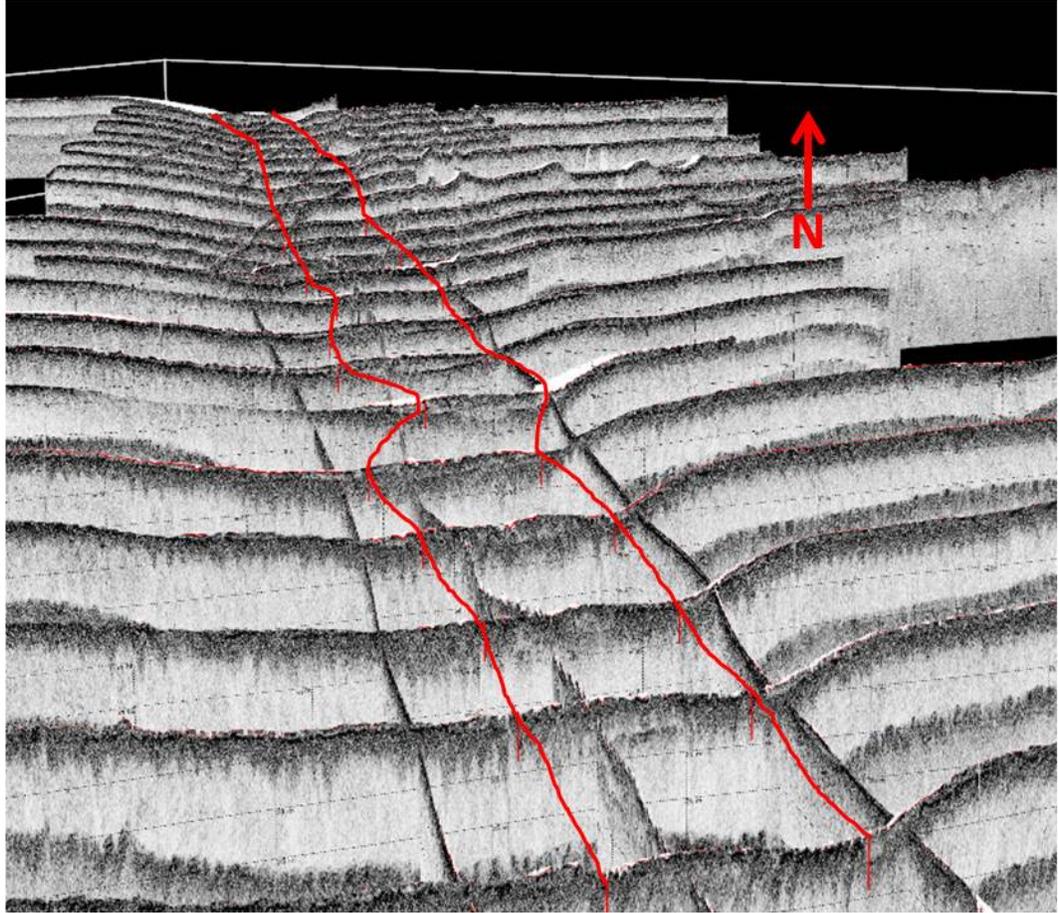


Figure 19 Three-dimensional view of chirp profiles looking southeast to northwest within DGS ID area Ge. Thick red lines indicate the location of the navigation channel.

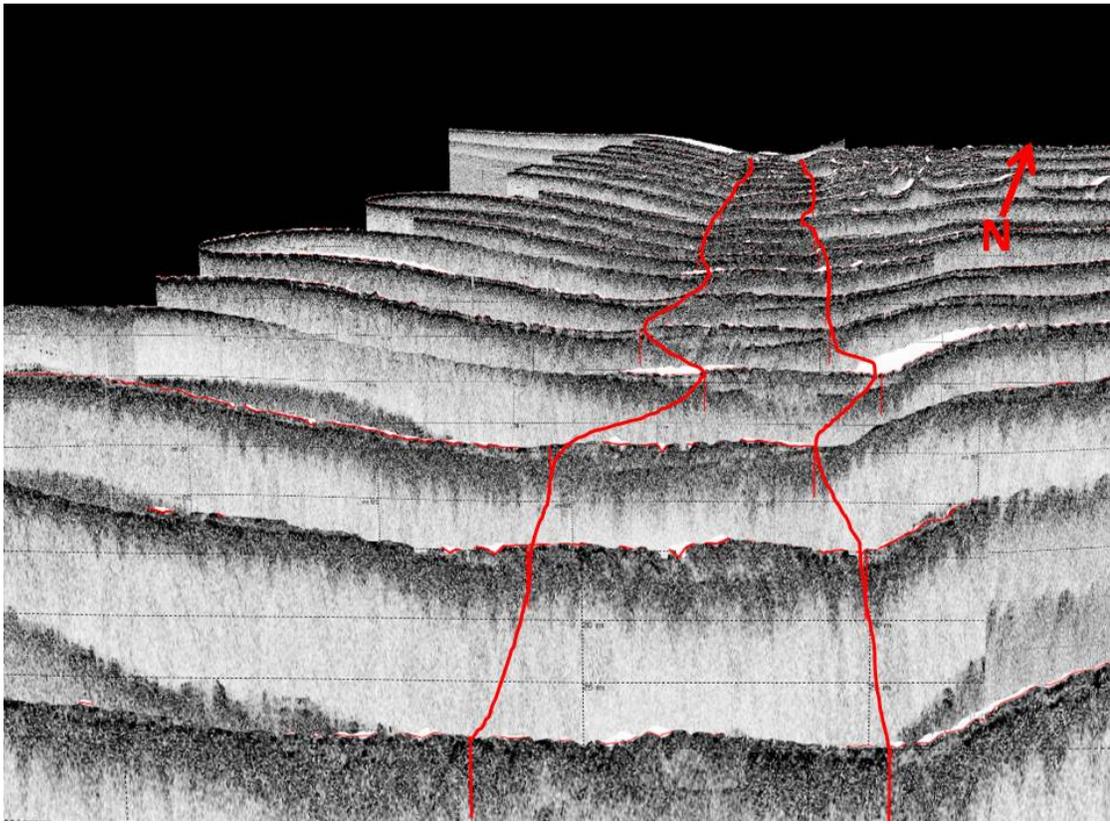


Figure 20 Three-dimensional view of chirp profiles looking from the southeast towards the northwest within DGS ID area Ge. The north-south trending profiles are not shown in this figure to highlight the mound-like feature within the navigation channel. Thick red lines indicate channel path.

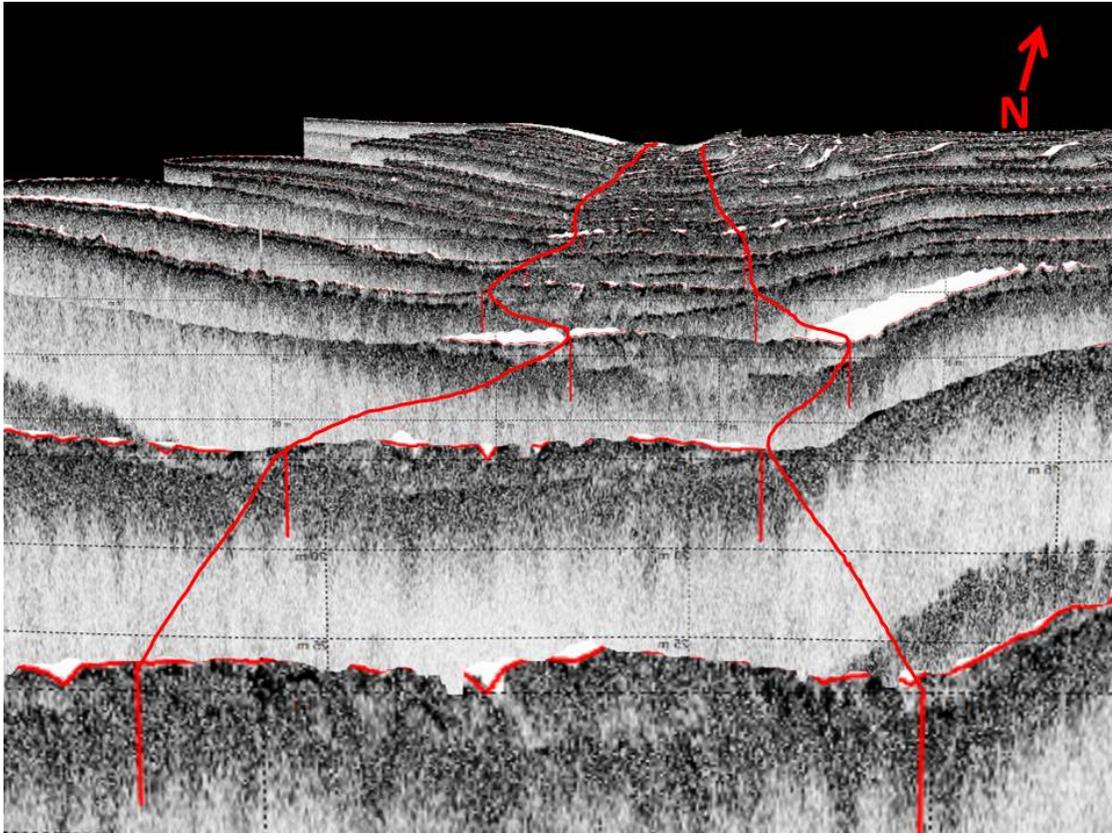


Figure 21 Three-dimensional view of chirp profiles looking southeast to northwest within DGS ID area Ge. Thick red lines indicate channel path. N-S trending chirp profiles removed for visibility of channel trend.

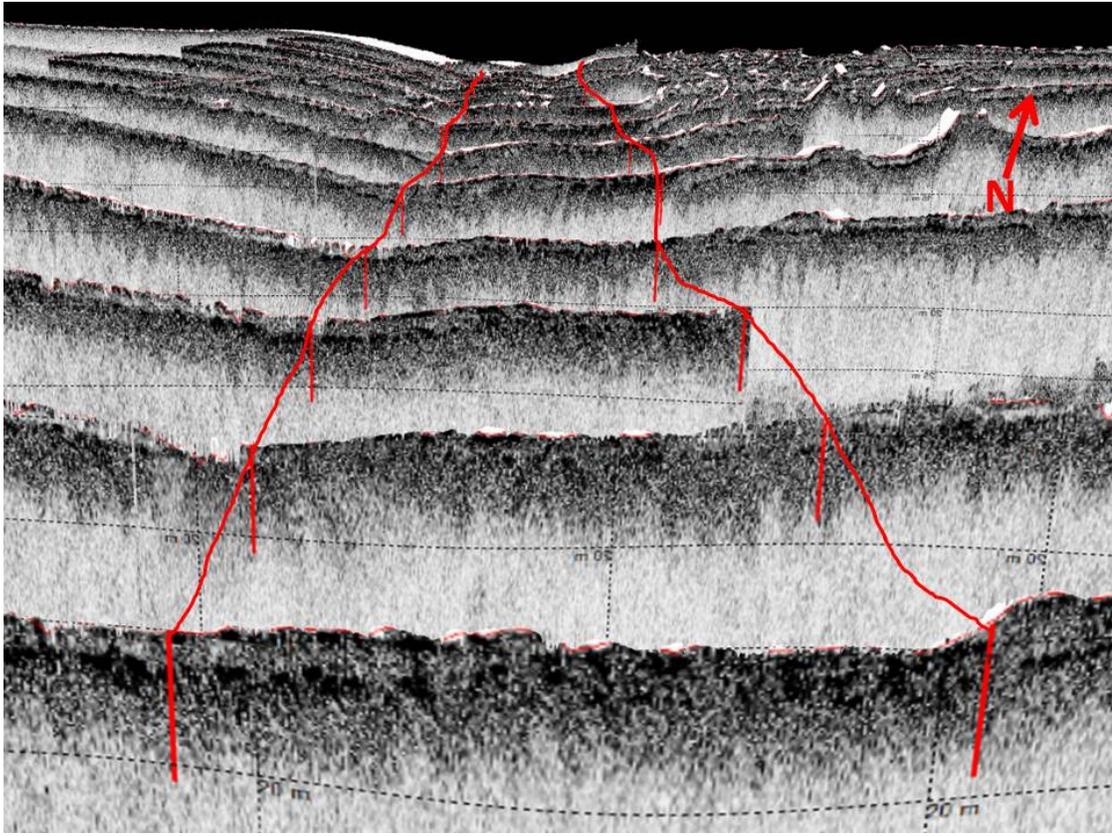


Figure 22 Three-dimensional view of chirp profiles looking southeast to northwest within DGS ID area Ge. Thick red lines indicate channel path. N-S trending figures removed for visibility of channel trend.

Sub-Surface Reflections and Paleochannels

Sub-surface features within the chirp profiles include deeper (up to 5 m or more beneath the bay bottom) reflections that are associated with changes in acoustic impedance. These changes in acoustic impedance are most likely associated with changes in sediment types with depth beneath the surface. Some of these reflections may be associated with the boundaries of former river channels of the Delaware Estuary. These features are commonly called paleochannels. Examples of reflections that may be associated with paleochannels are illustrated in chirp profiles Ge01, Ge02, Ge03 and Ge04. These chirp profiles with their locations within area Ge are shown in Figures 23 to 30.

The paleochannels are formed during time periods when global sea level is lower and the region that is currently under water was exposed as a land surface and river systems flowed across these land surfaces. Paleochannels associated with the Delaware Estuary have been mapped within the Delaware Bay and the adjacent Atlantic Ocean continental shelf in several past studies (e.g., Twichell et al., 1977; Knebel and Circé, 1988; Murphy, 1996; Childers, 2014).

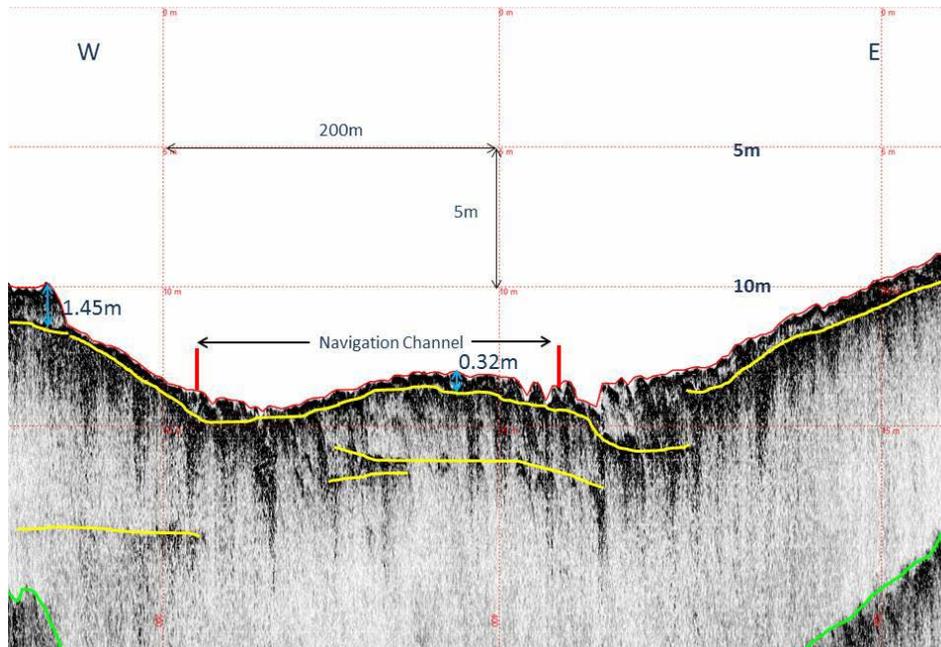


Figure 23 Chirp sub-bottom profile Ge01. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 24 Location of chirp sub-bottom profile Ge01 indicated by thick dark blue trackline. Thick red lines indicate boundaries of DGS ID areas. DGS ID area Ge is the largest area shown in this image.

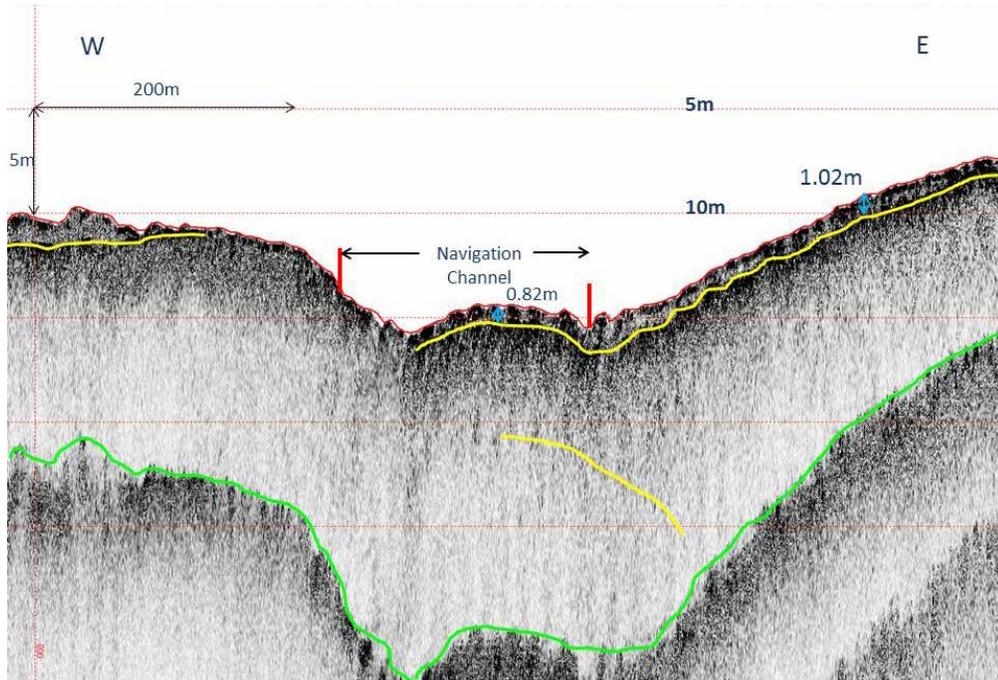


Figure 25 Chirp sub-bottom profile Ge02. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 26 Location of chirp sub-bottom profile Ge02 indicated by thick dark blue trackline. Thick red lines indicate boundaries of DGS ID areas. DGS ID area Ge is the largest area shown in this image.

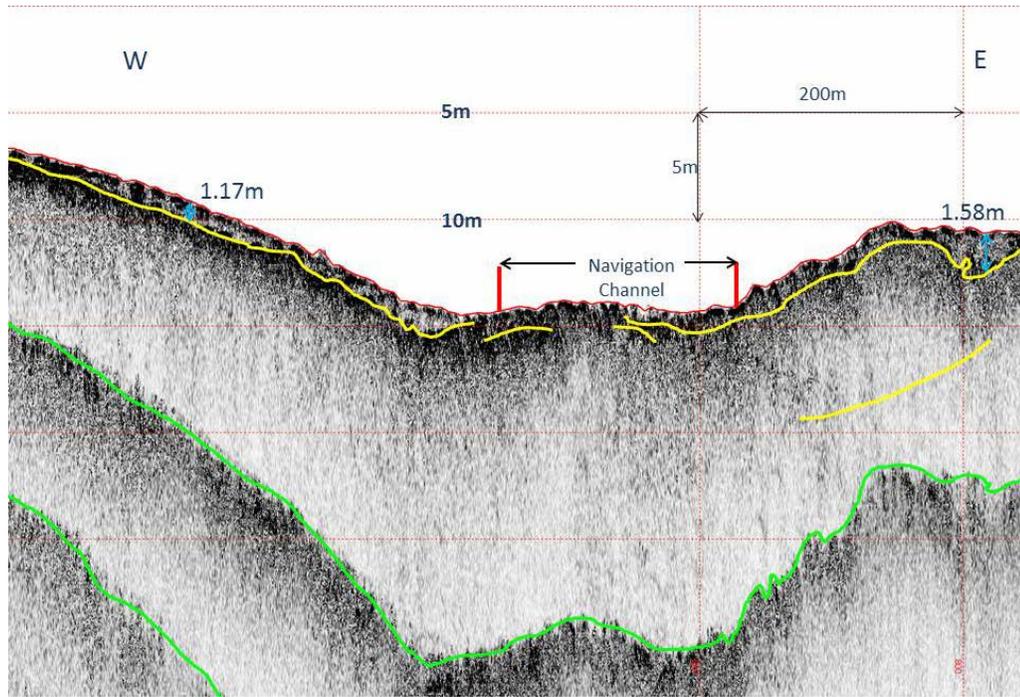


Figure 27 Chirp sub-bottom profile Ge03. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 28 Location of chirp sub-bottom profile Ge03 indicated by thick dark blue trackline. Thick red lines indicate boundaries of DGS ID areas. DGS ID area Ge is the largest area shown in this image.

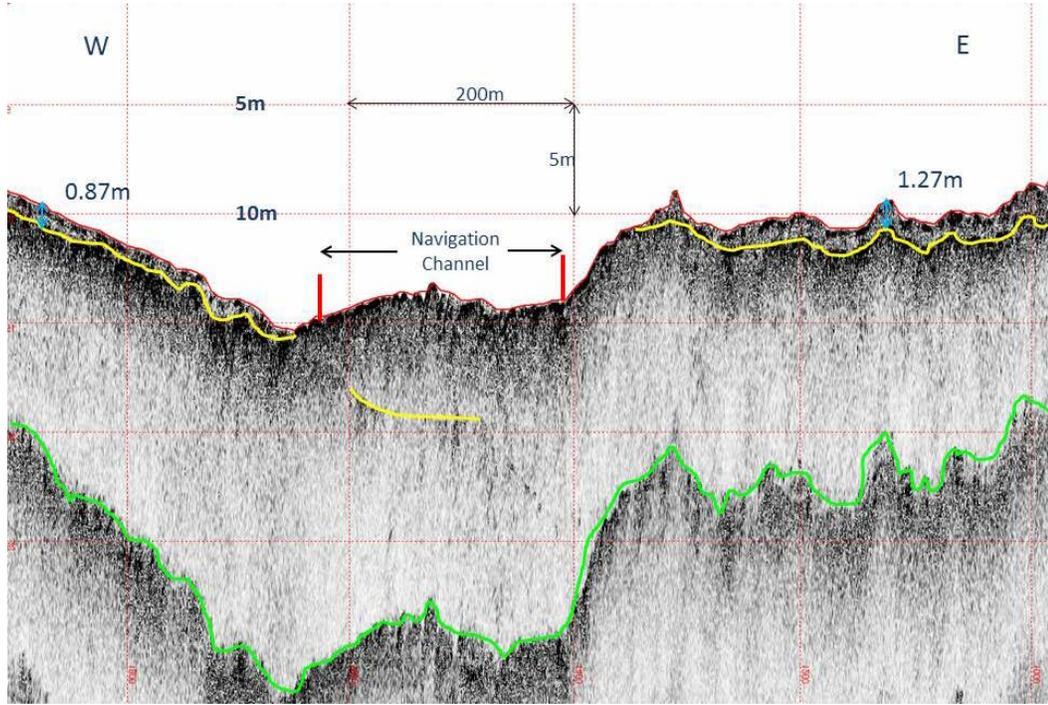


Figure 29 Chirp sub-bottom profile Ge04. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 30 Location of chirp sub-bottom profile Ge04 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

Surficial Sediment Waves

Along some of the north-south trending tracklines within the navigation channel pronounced surficial sediment waves were observed. Example chirp profiles with their locations are shown in Figures 31 to 40. Figure 31 shows asymmetrical sediment waves with an average height of approximately 1 m and an average width of approximately 10 m. In contrast in Figure 33, the sediment waves are much larger with an average of approximately 2 m height and 25 to 28 m wide. The asymmetric nature of these sand waves suggests that they are created by tidal currents, and the orientation of the steep- versus gently-sloping sides can be used to determine the direction of the tidal currents at the time that these profiles were collected. The steeper sides of the waves align in the direction that the tidal current is flowing. For example, in both Figures 31 and 33, the tidal currents are flowing “up-the-estuary” and would thus would have been generated by the flood tide that was occurring at the time that the chirp sub-bottom profiles were collected.

Shown in Figures 41 and 43 are unusual surficial sediment features within DGS ID area Ge that are found outside of the navigation channel along the eastern-side of Delaware Bay. Shown in Figure 41, the features are symmetric with steep slopes on both sides of these “pointed-shape” structures. These features are found within an area that is denoted as “sand waves” on the navigation chart for the Delaware Bay. Due to their non-tidal orientation (i.e., the orientation of the peaks and intervening troughs are generally east-west, rather than north-south), these features are most likely due to bottom currents that reflect general estuarine water circulation patterns within the Bay. Further research is needed to confirm this hypothesis.

To the northwest of the “pointed” structures shown in Figure 41, are much larger dome- and intervening trough-structures that are also located outside of the

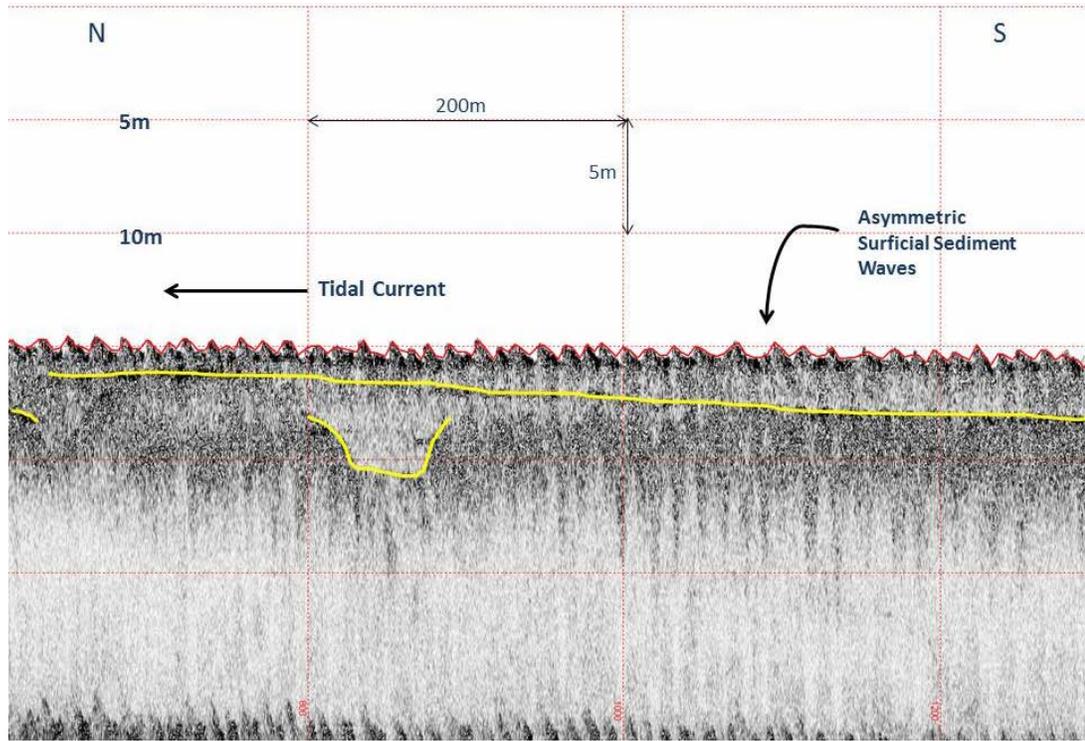


Figure 31 Chirp sub-bottom profile Ge22. Red line denotes position of the sea floor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Asymmetric surficial sediment waves formed due to northward tidal current.

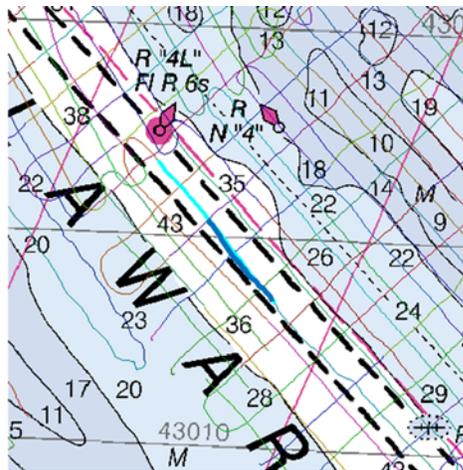


Figure 32 Location of chirp sub-bottom profile Ge22 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

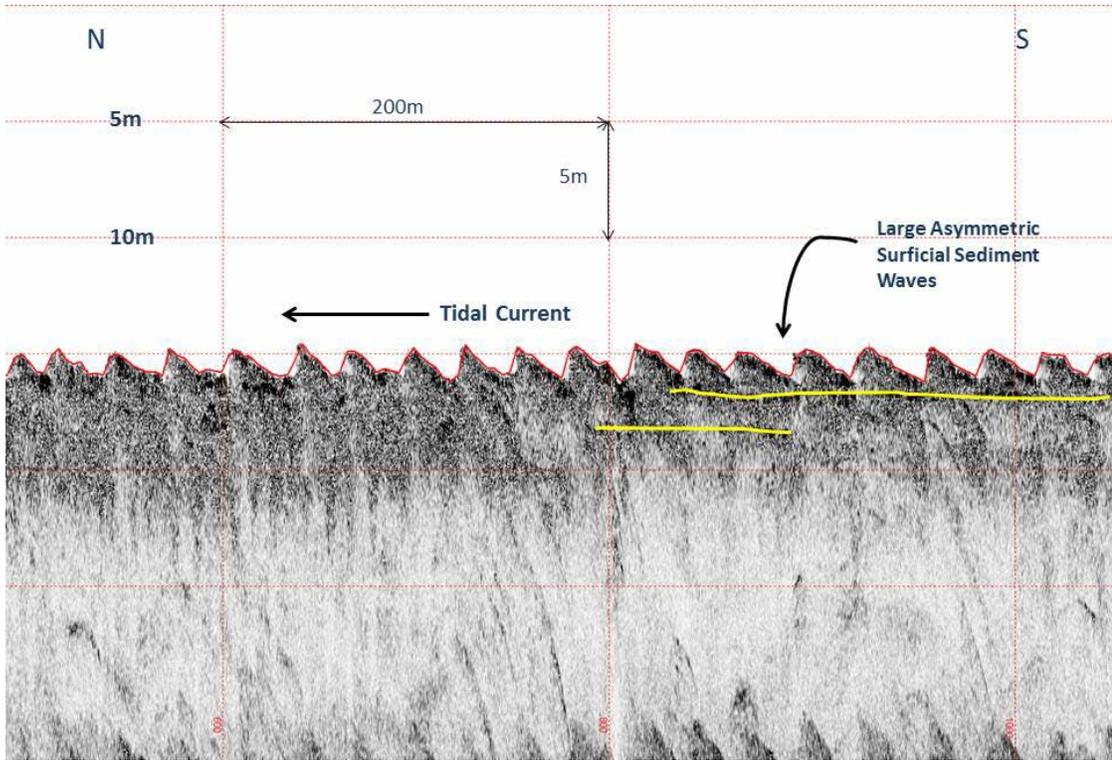


Figure 33 Chirp sub-bottom profile Ge23. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Asymmetric surficial sediment waves formed due to northward tidal current.

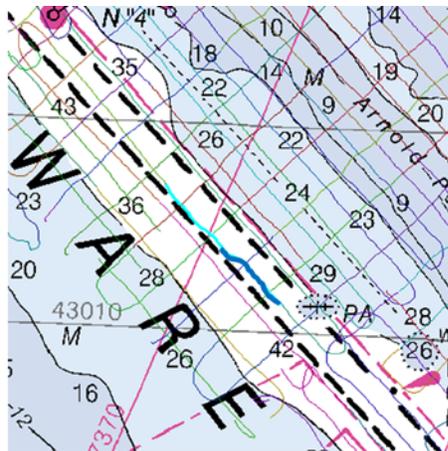


Figure 34 Location of chirp sub-bottom profile Ge23 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

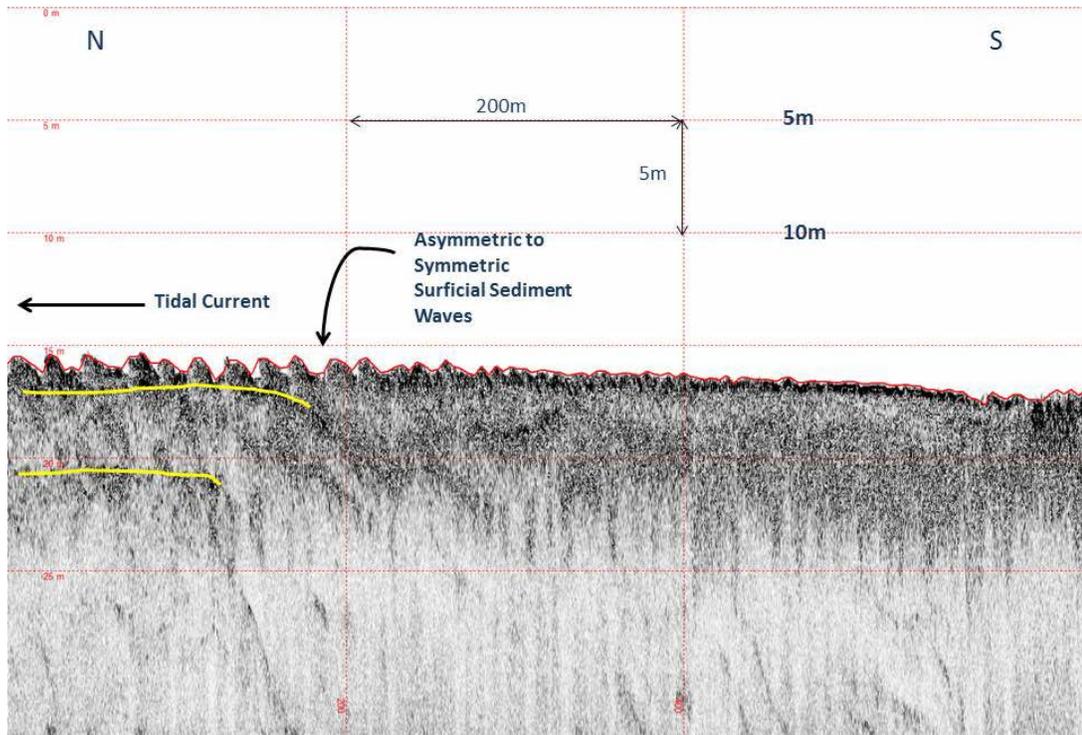


Figure 35 Chirp sub-bottom profile Ge24. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Asymmetric surficial sediment waves formed due to northward tidal current.

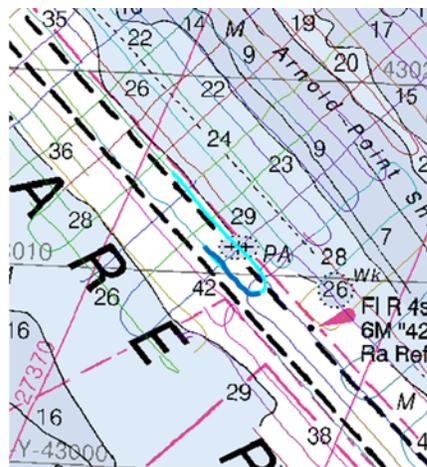


Figure 36 Location of chirp sub-bottom profile Ge24 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

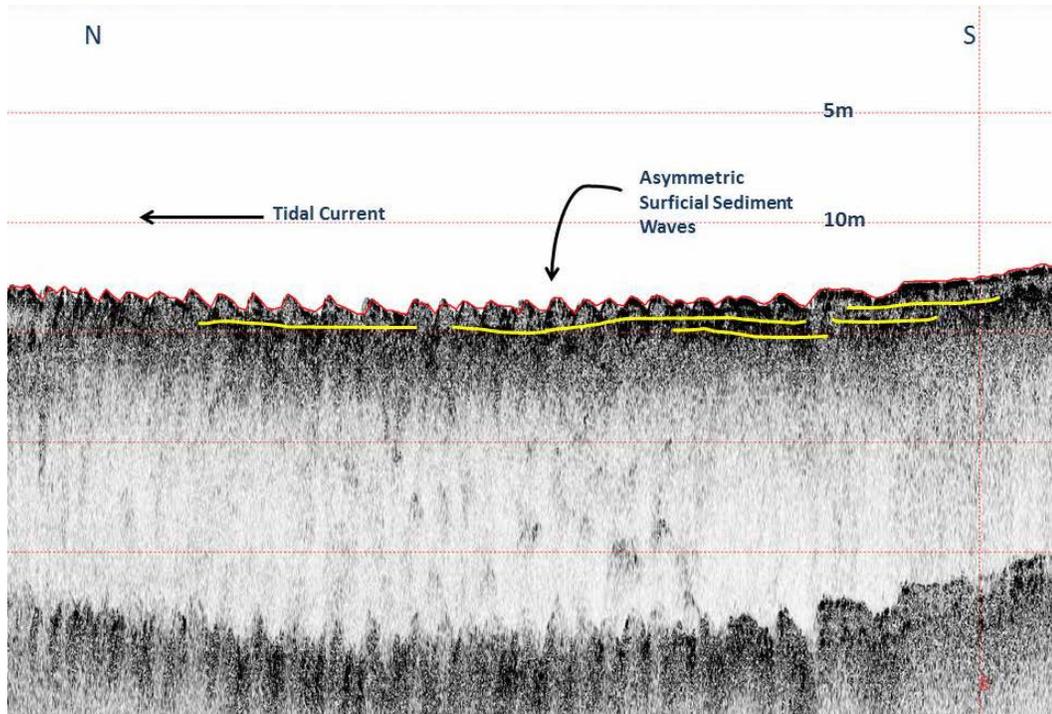


Figure 37 Chirp sub-bottom profile Ge25. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Asymmetric surficial sediment waves formed due to northward tidal current.

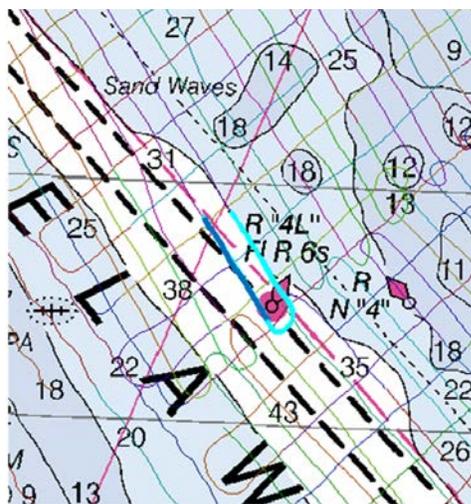


Figure 38 Location of chirp sub-bottom profile Ge25 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

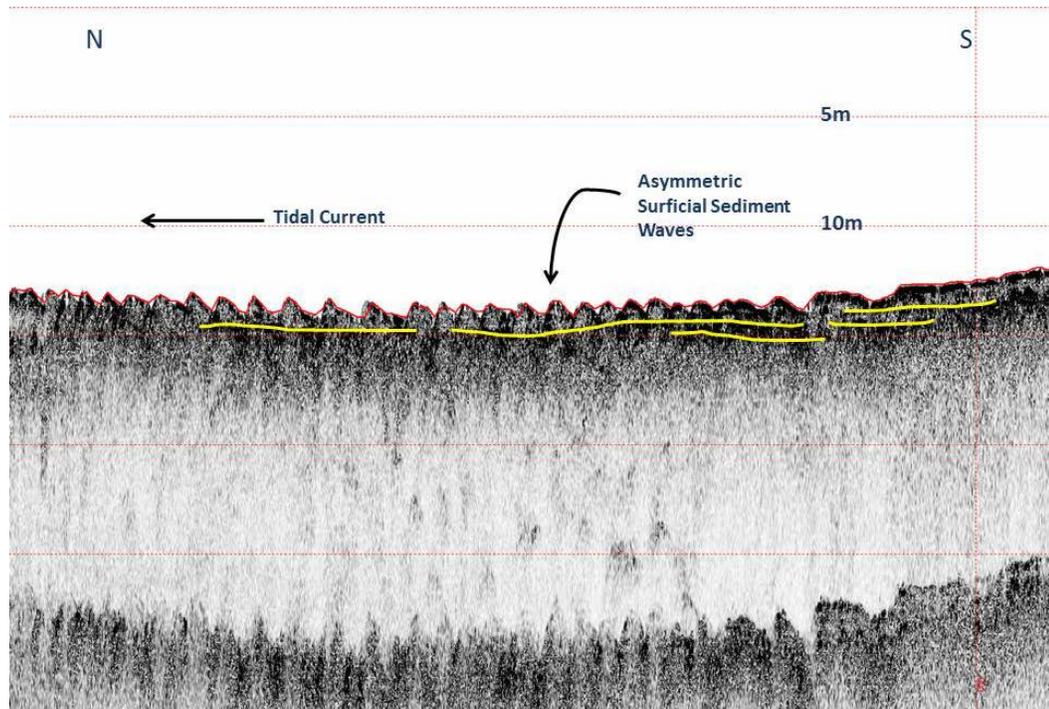


Figure 39 Chirp sub-bottom profile Ge26. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Asymmetric surficial sediment waves formed due to northward tidal current.

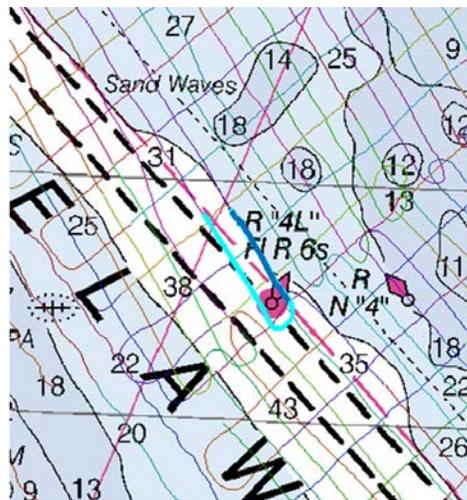


Figure 40 Location of chirp sub-bottom profile Ge26 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

navigation channel (Figure 43). These large dome-shaped structures have average heights of approximately 3 m and widths of approximately 100 m. The troughs between each of these “domes” range from 150 m to 200 m in width. Due to the general east-west trends of these ridge and trough structures, they also are not likely formed as the result of tidal currents within the Bay. As with the smaller “pointed” surficial features, the large “dome” structures could be a reflection of the general estuarine circulation patterns within the bay. However, their large dimensions suggests significant movement (erosion and deposition) of sediment. Further research is also needed to better constrain the origin and evolution of these features.

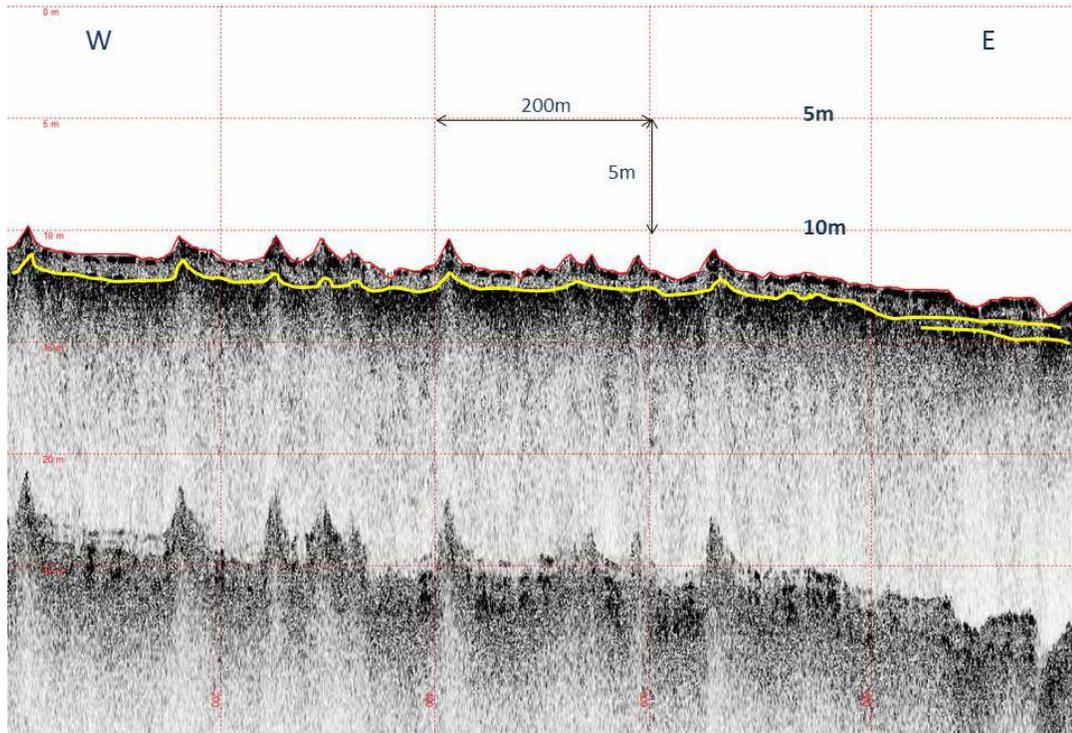


Figure 41 Chirp sub-bottom profile Ge27. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance.



Figure 42 Location of chirp sub-bottom profile Ge27 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

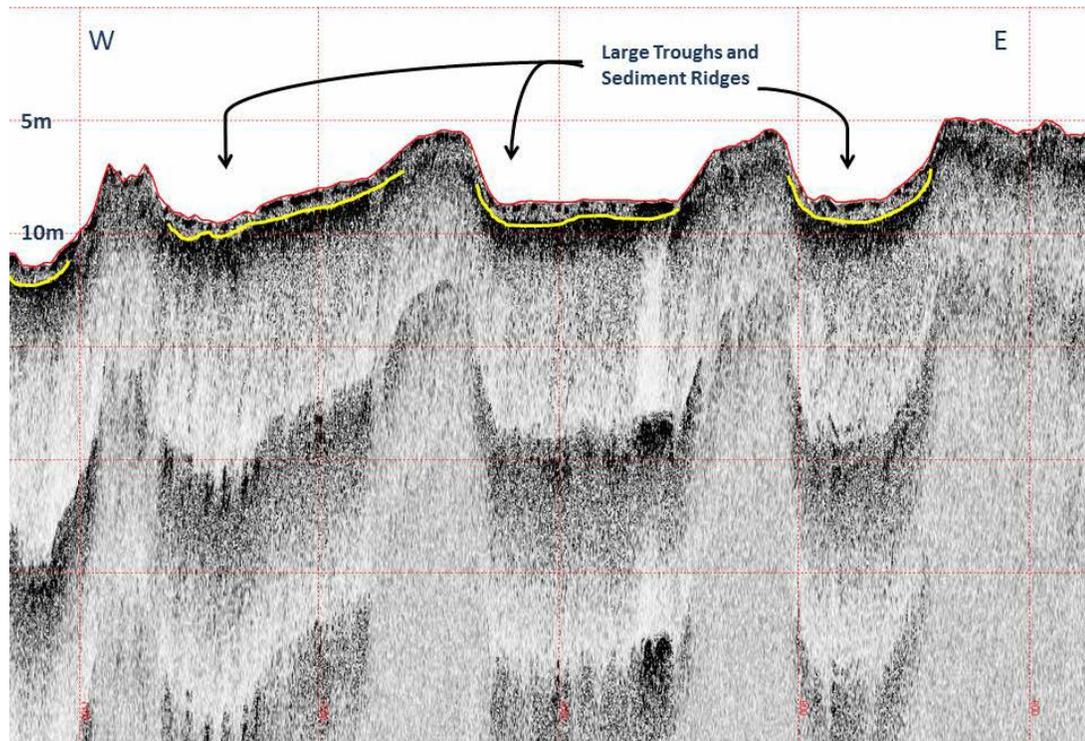


Figure 43 Chirp sub-bottom profile Ge28. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance.

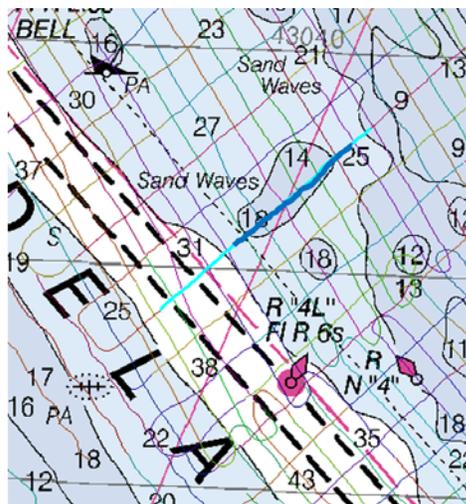


Figure 44 Location of chirp sub-bottom profile Ge27 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

CONCLUSIONS

In this senior thesis project, chirp sub-bottom data that were collected for the DNREC sponsored Delaware Benthic Mapping Project were analyzed to place constraints on the structure and overall characteristics of the bay sediments within the Delaware Bay/River navigation channel. A method was developed to organize and sort the data that had been collected previously. This method involved utilizing SonarWiz5 seismic processing software and ArcGIS mapping to process (e.g. geolocation, bottom tracking, digitizing features, and creating three-dimensional views) these chirp files. Specifically, the navigation channel within DGS ID area Ge, located in the middle to middle-lower portion of the Delaware Estuary, was studied.

Multiple aspects of channel structures could be studied such as the thickness of the surficial sediments, defined as the depth between the bay bottom and the first sub-bottom zone of acoustic impedance, the presence of mound-shaped deposits of sediments that were centered, and thickest, in the middle portions of the navigation channel, the occurrence of paleochannels, and sediment waves produced by tidal currents along the navigation channel. Building upon the work completed during this senior thesis project, further research is needed to develop a better understanding of how the mound-shaped deposits and sediment waves are formed and evolve within the navigational channel. An integration of grab samples and sediment cores collected would invaluablely assist in understanding the dynamics of sediment flow including deposition, and erosion, along the channel.

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Appendix A

CHIRP SUB-BOTTOM PROFILES AND LOCATIONS WITHIN

DGS ID AREA Ge

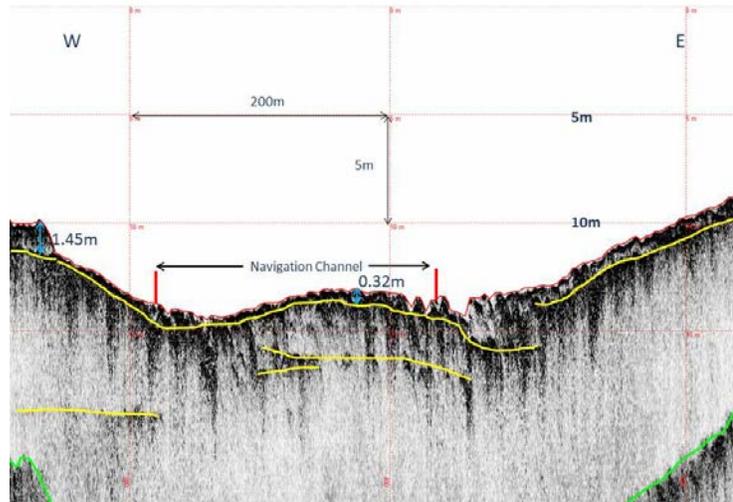


Figure 45 Chirp sub-bottom profile Ge01. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

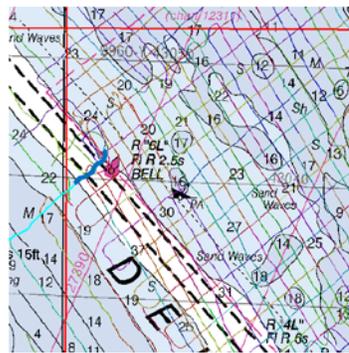


Figure 46 Location of chirp sub-bottom profile Ge01 indicated by thick dark blue trackline. Thick red lines indicate boundaries of DGS ID areas. DGS ID area Ge is the largest area shown in this image.

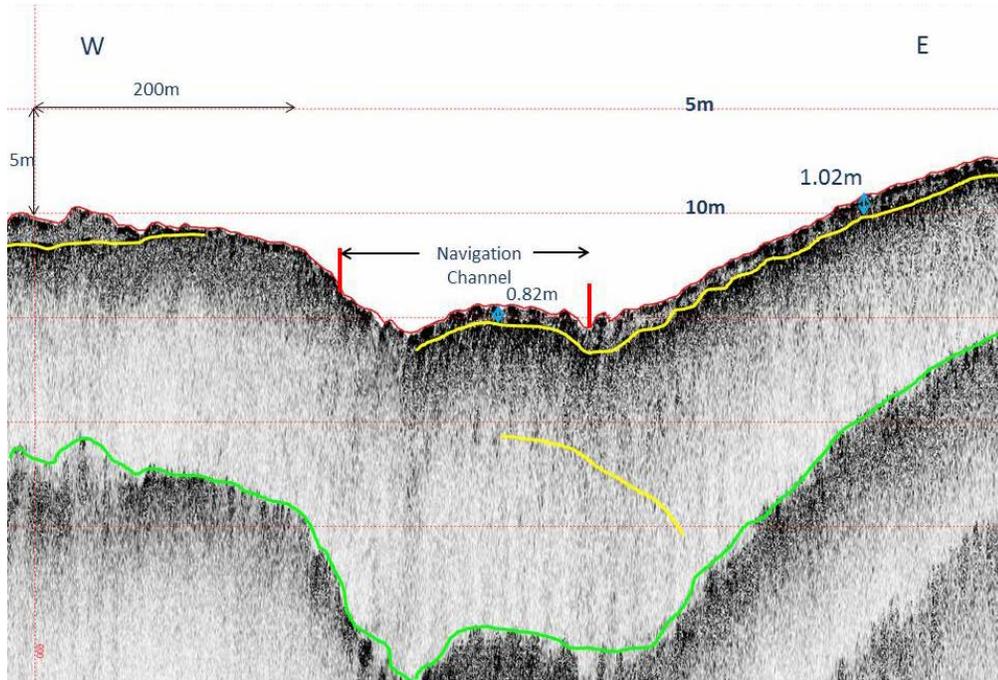


Figure 47 Chirp sub-bottom profile Ge02. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 48 Location of chirp sub-bottom profile Ge02 indicated by thick dark blue trackline. Thick red lines indicate boundaries of DGS ID areas. DGS ID area Ge is the largest area shown in this image.

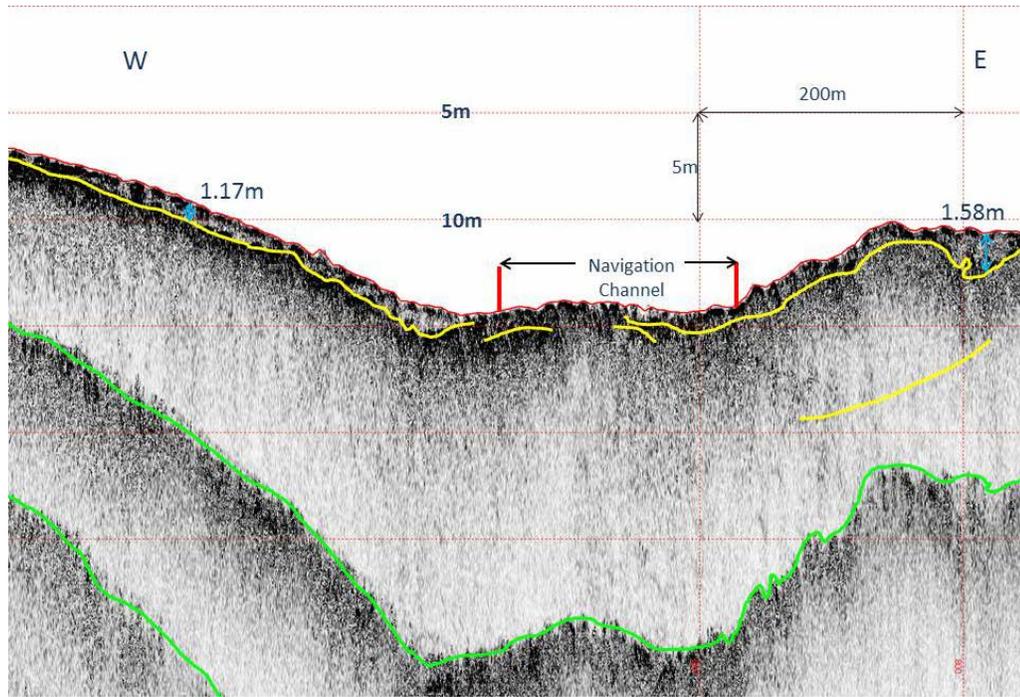


Figure 49 Chirp sub-bottom profile Ge03. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 50 Location of chirp sub-bottom profile Ge03 indicated by thick dark blue trackline. Thick red lines indicate boundaries of DGS ID areas. DGS ID area Ge is the largest area shown in this image.

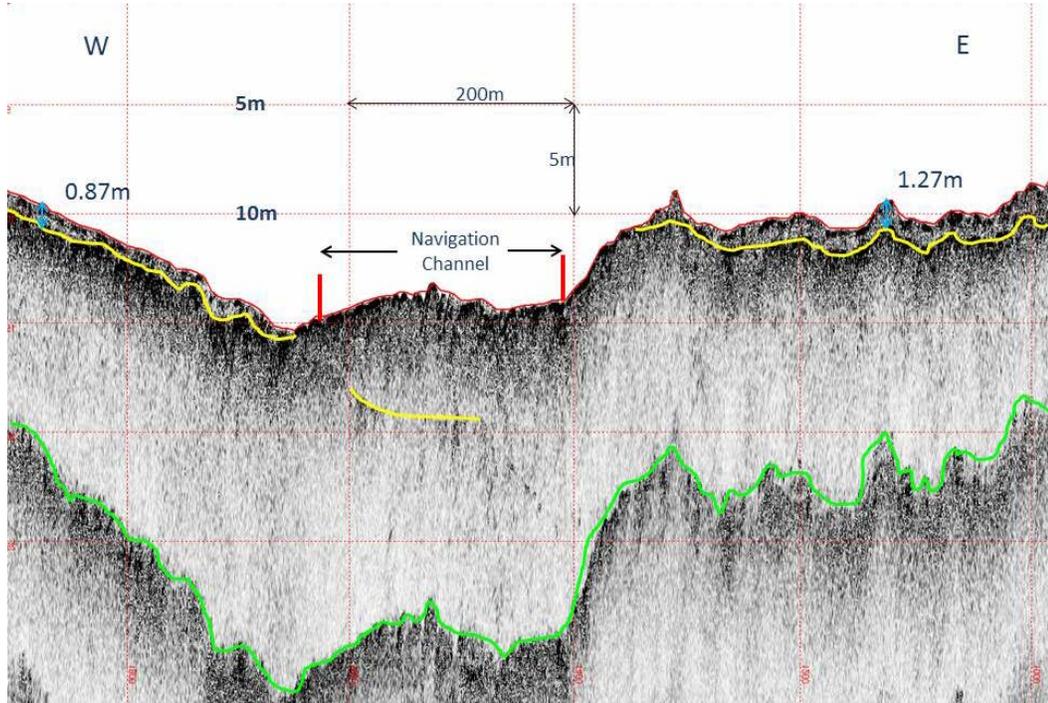


Figure 51 Chirp sub-bottom profile Ge04. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

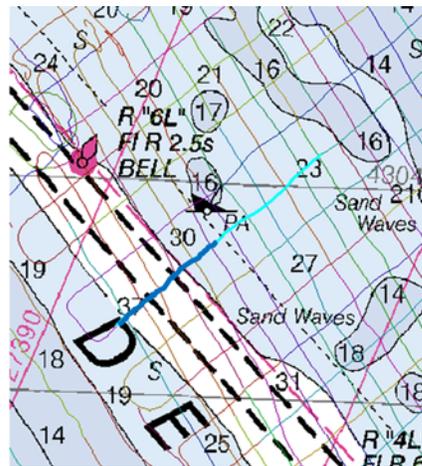


Figure 52 Location of chirp sub-bottom profile Ge04 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

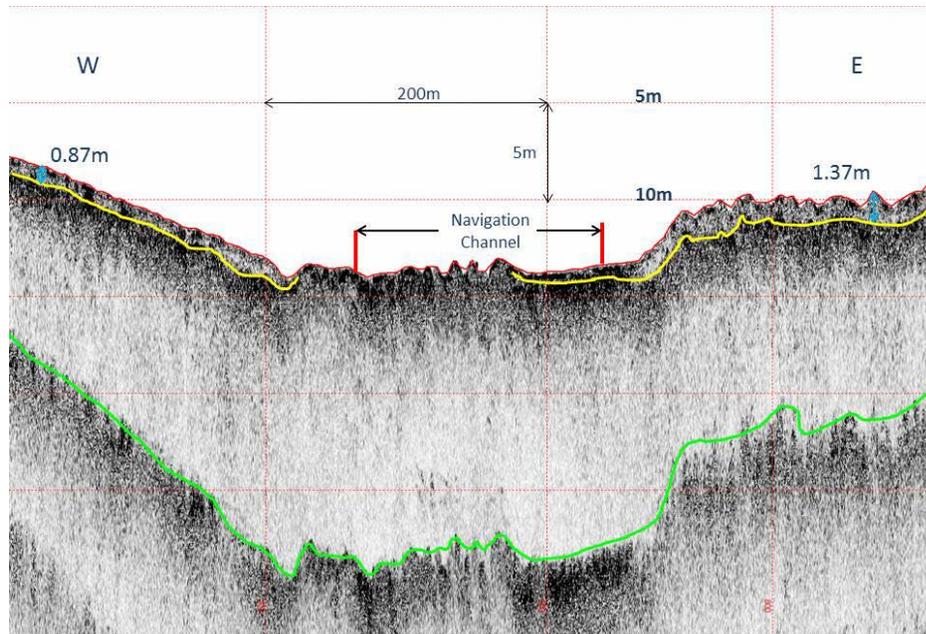


Figure 53 Chirp sub-bottom profile Ge05. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 54 Location of chirp sub-bottom profile Ge05 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

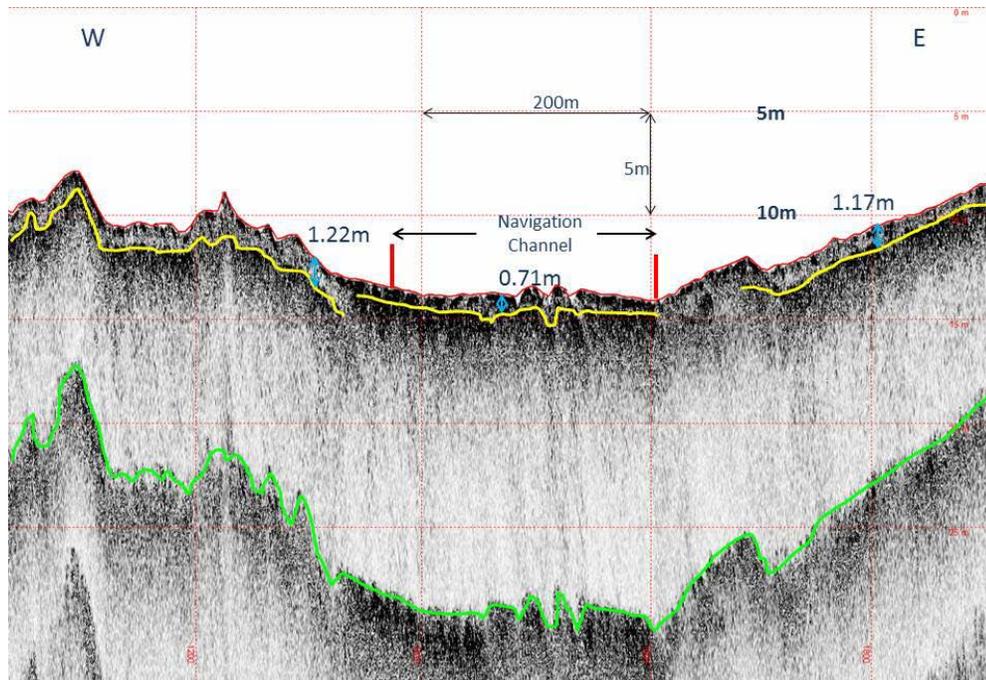


Figure 55 Chirp sub-bottom profile Ge06. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 56 Location of chirp sub-bottom profile Ge06 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

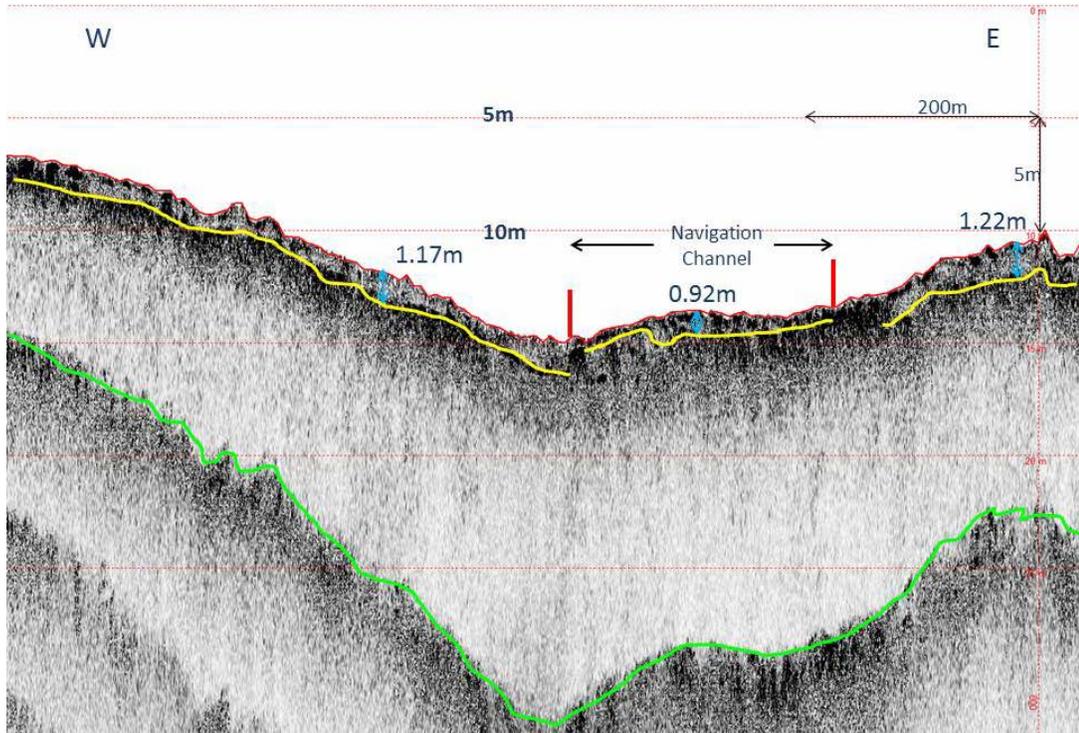


Figure 57 Chirp sub-bottom profile Ge07. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

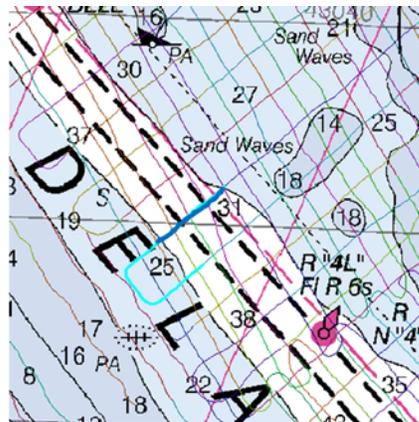


Figure 58 Location of chirp sub-bottom profile Ge07 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

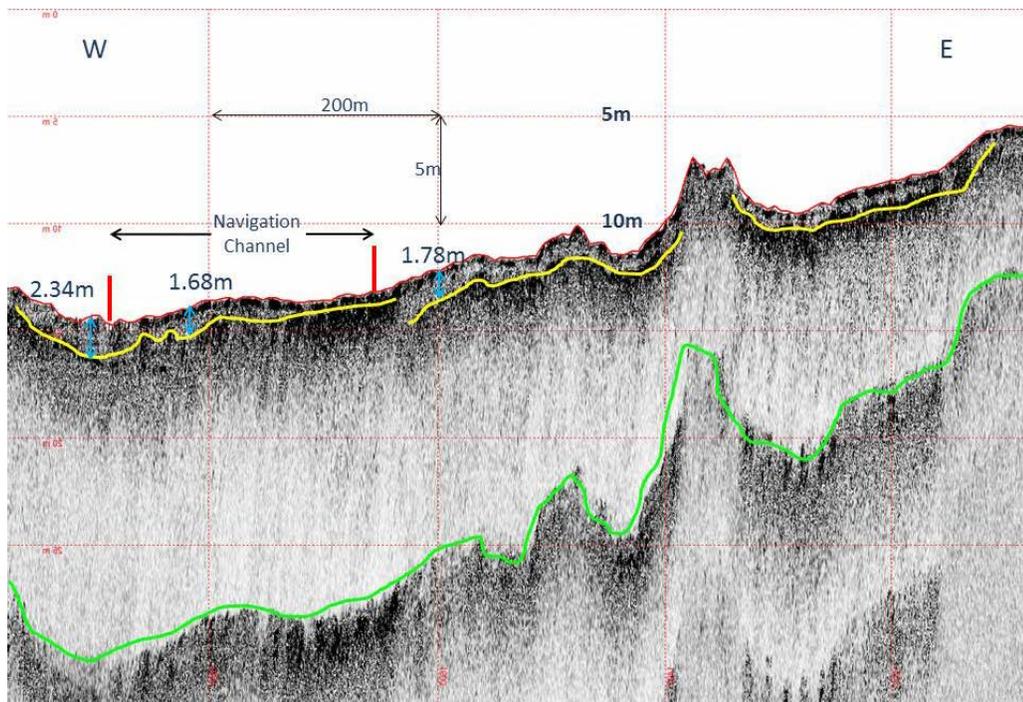


Figure 59 Chirp sub-bottom profile Ge08. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 60 Location of chirp sub-bottom profile Ge08 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

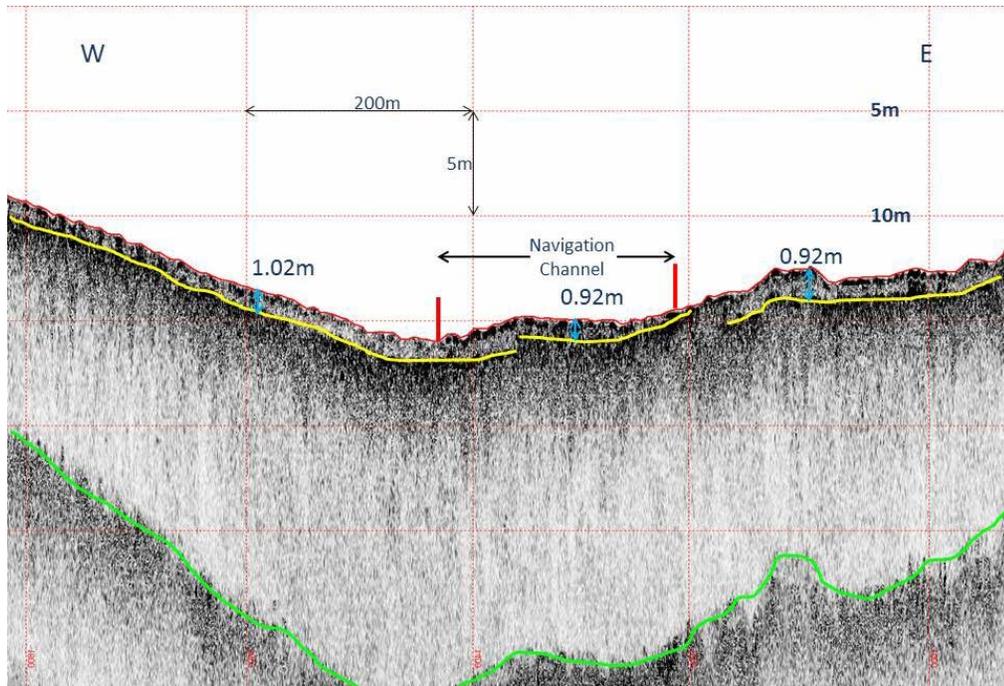


Figure 61 Chirp sub-bottom profile Ge09. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

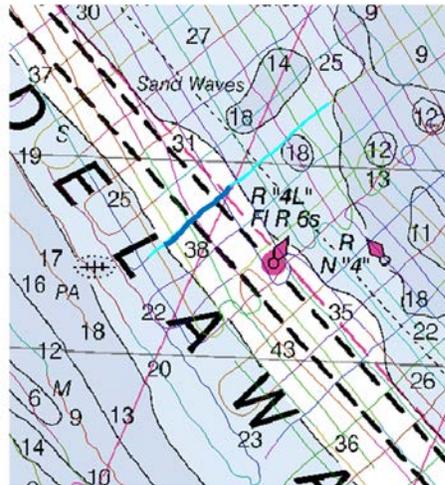


Figure 62 Location of chirp sub-bottom profile Ge09 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

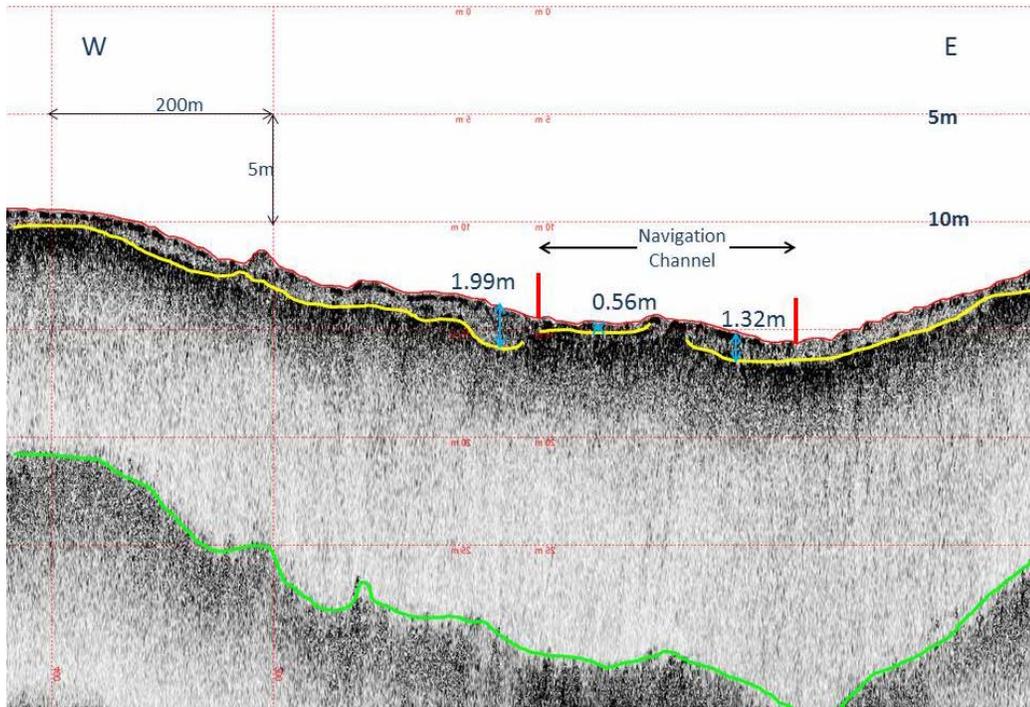


Figure 63 Chirp sub-bottom profile Ge10. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

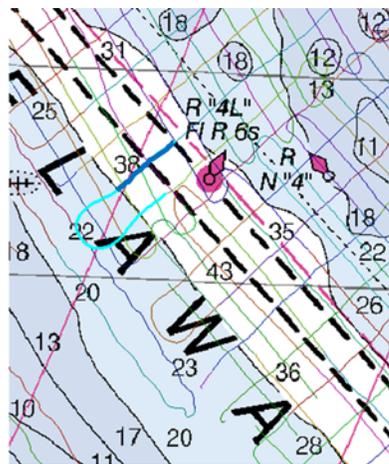


Figure 64 Location of chirp sub-bottom profile Ge10 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

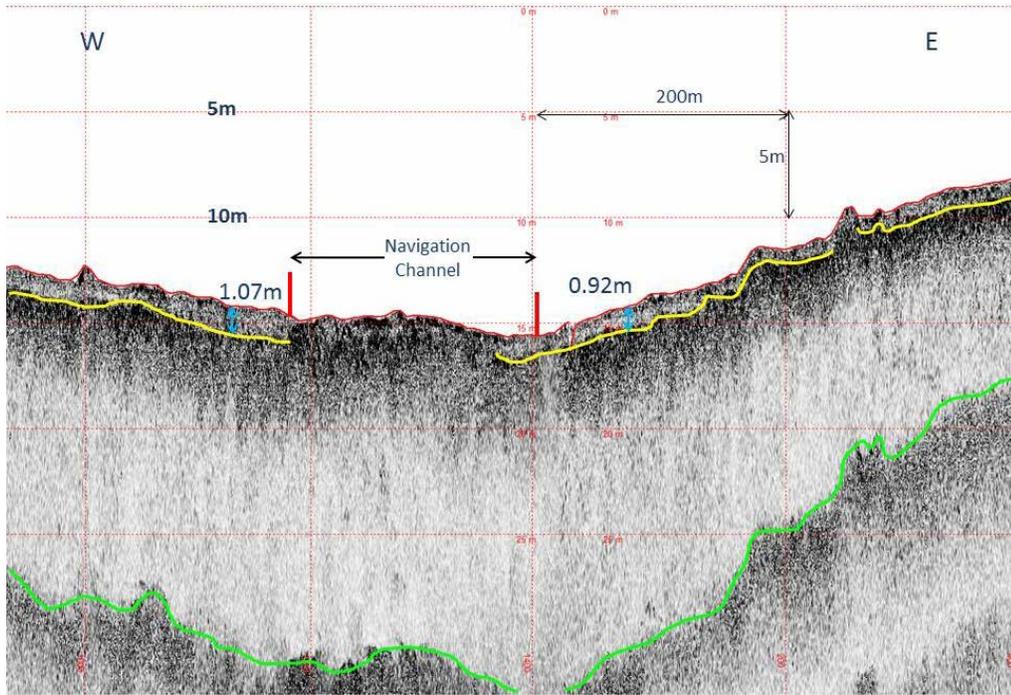


Figure 65 Chirp sub-bottom profile Ge11. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

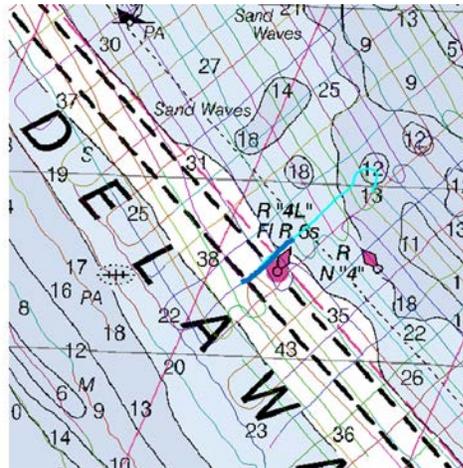


Figure 66 Location of chirp sub-bottom profile Ge11 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

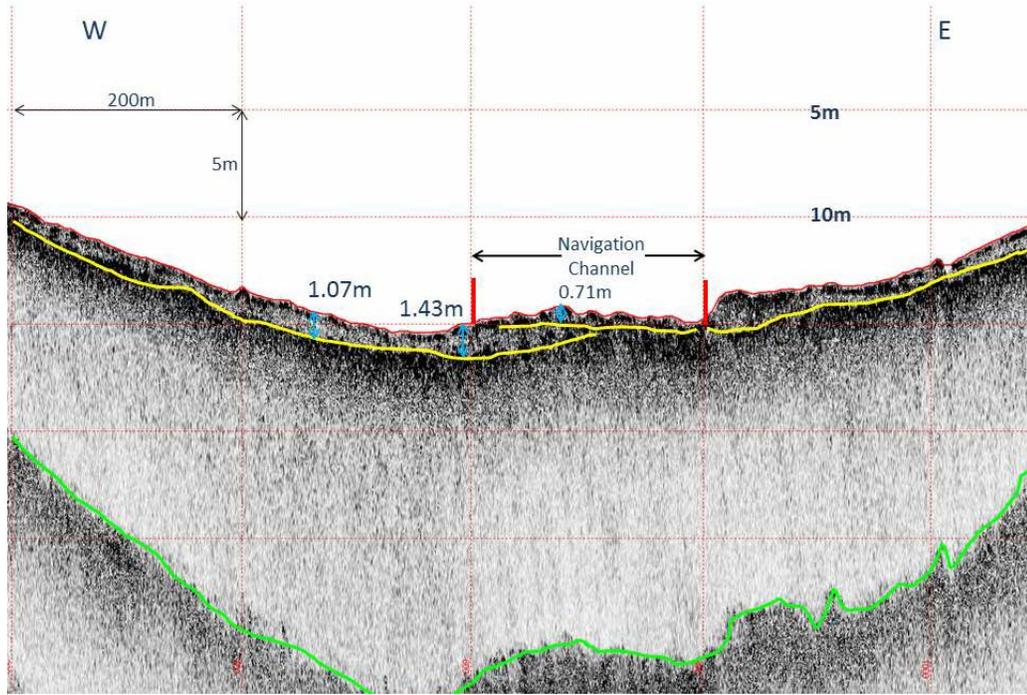


Figure 67 Chirp sub-bottom profile Ge12. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

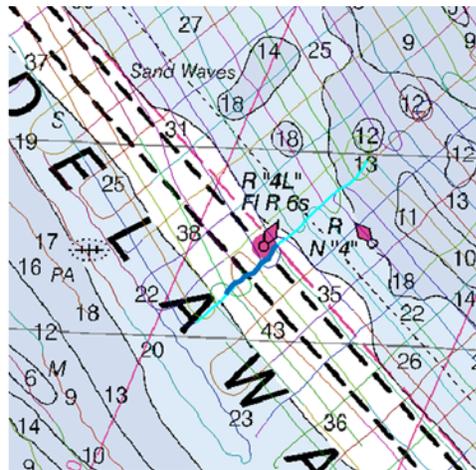


Figure 68 Location of chirp sub-bottom profile Ge12 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

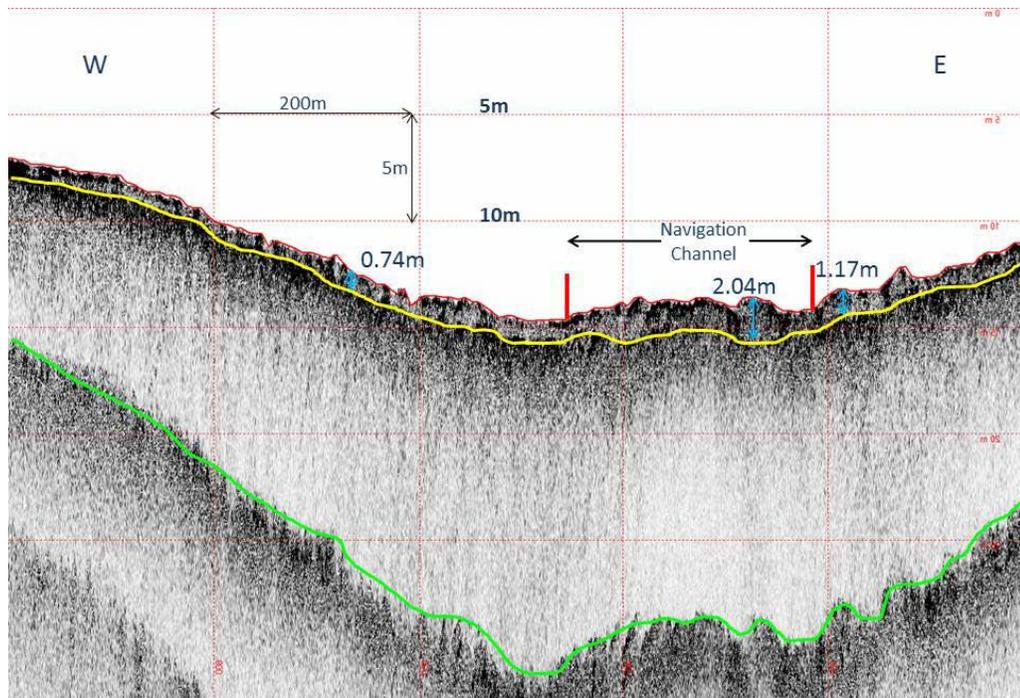


Figure 69 Chirp sub-bottom profile Ge13. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

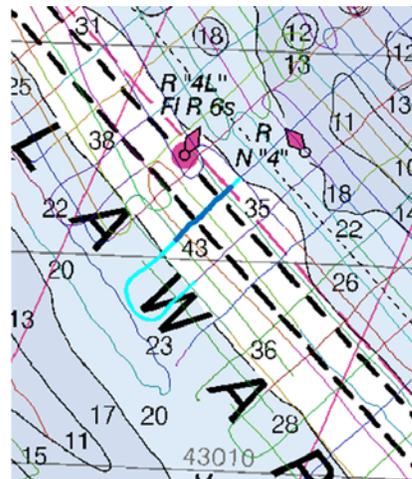


Figure 70 Location of chirp sub-bottom profile Ge13 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

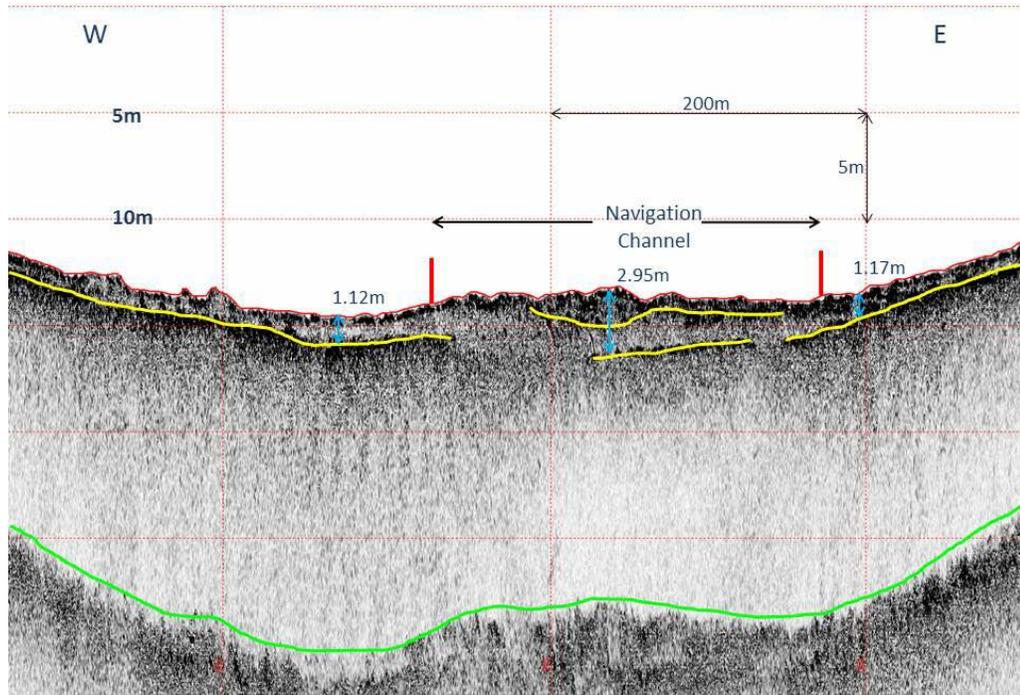


Figure 71 Chirp sub-bottom profile Ge14. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

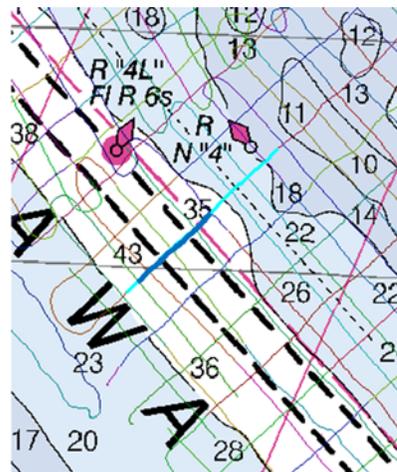


Figure 72 Location of chirp sub-bottom profile Ge14 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

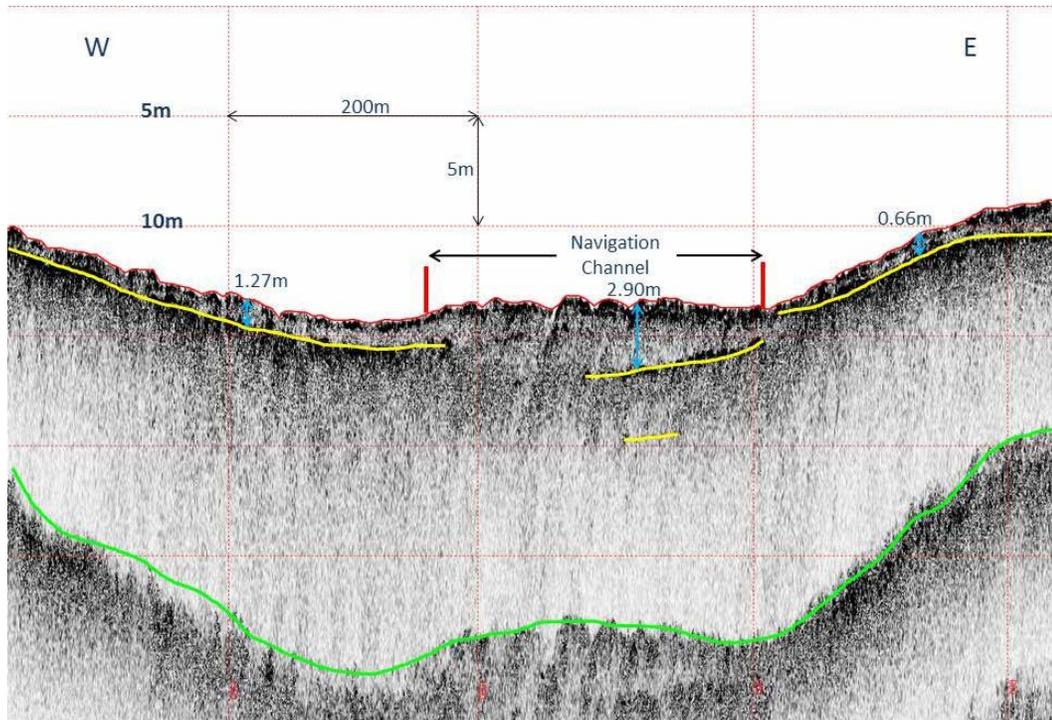


Figure 73 Chirp sub-bottom profile Ge15. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 74 Location of chirp sub-bottom profile Ge15 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

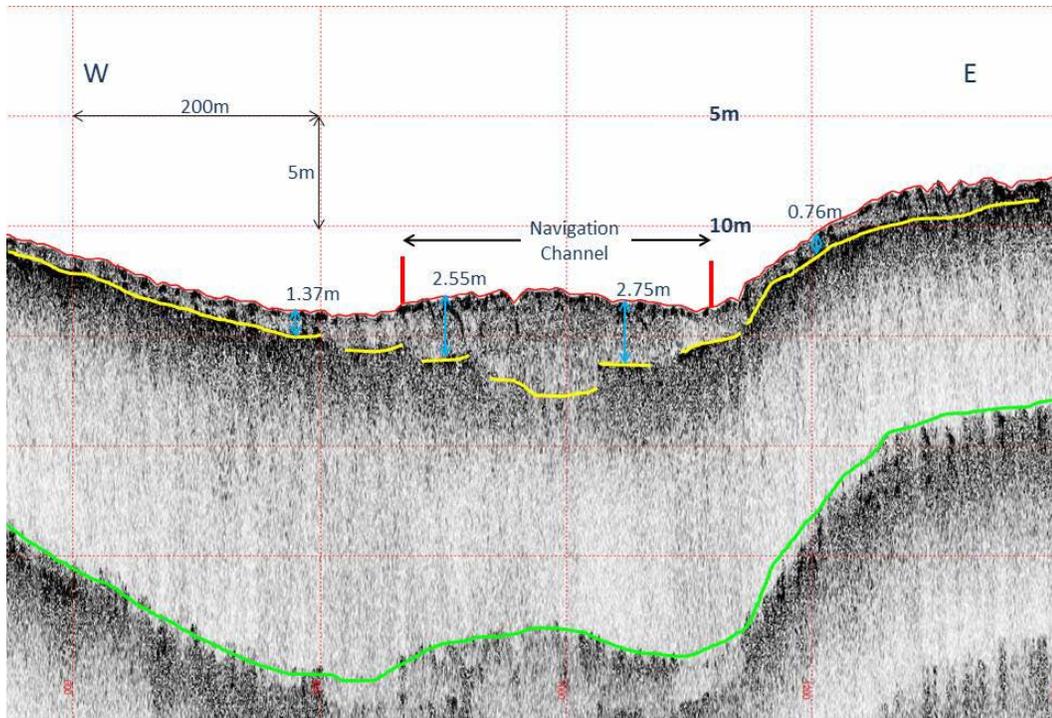


Figure 75 Chirp sub-bottom profile Ge16. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

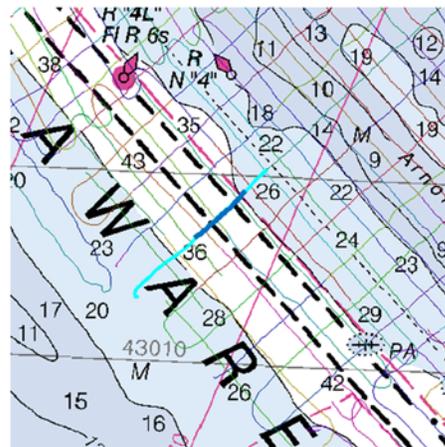


Figure 76 Location of chirp sub-bottom profile Ge16 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

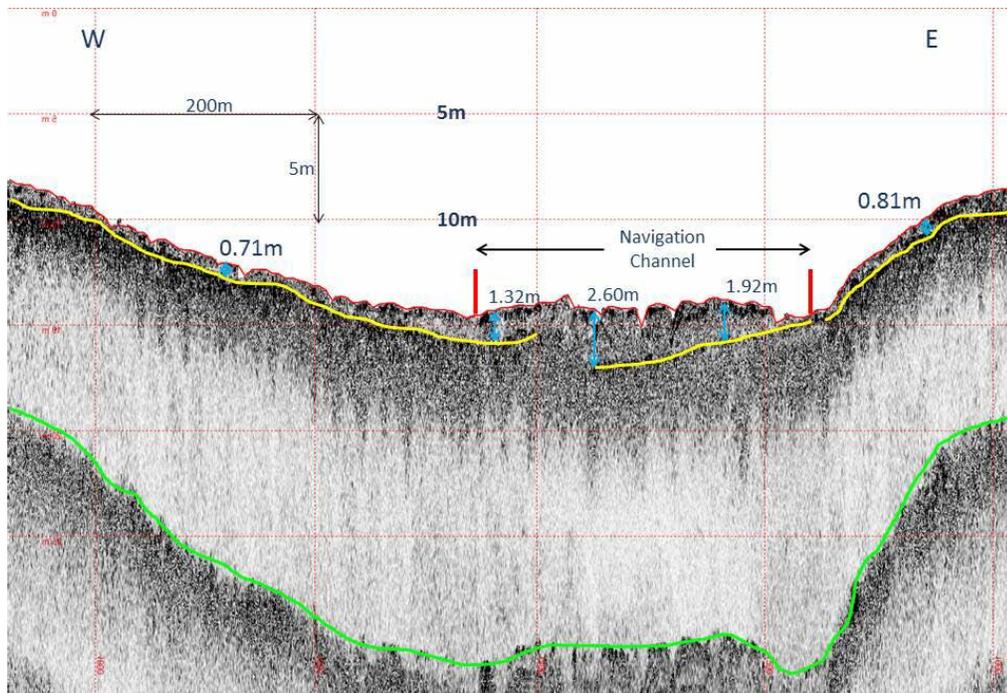


Figure 77 Chirp sub-bottom profile Ge17. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

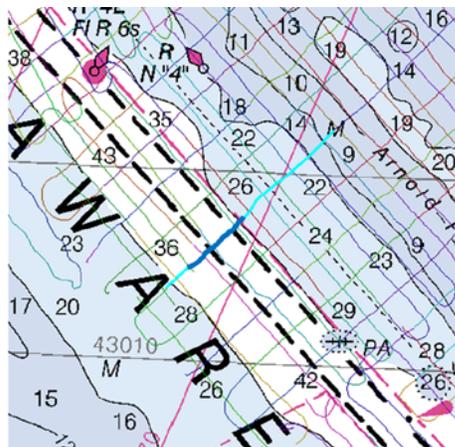


Figure 78 Location of chirp sub-bottom profile Ge17 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

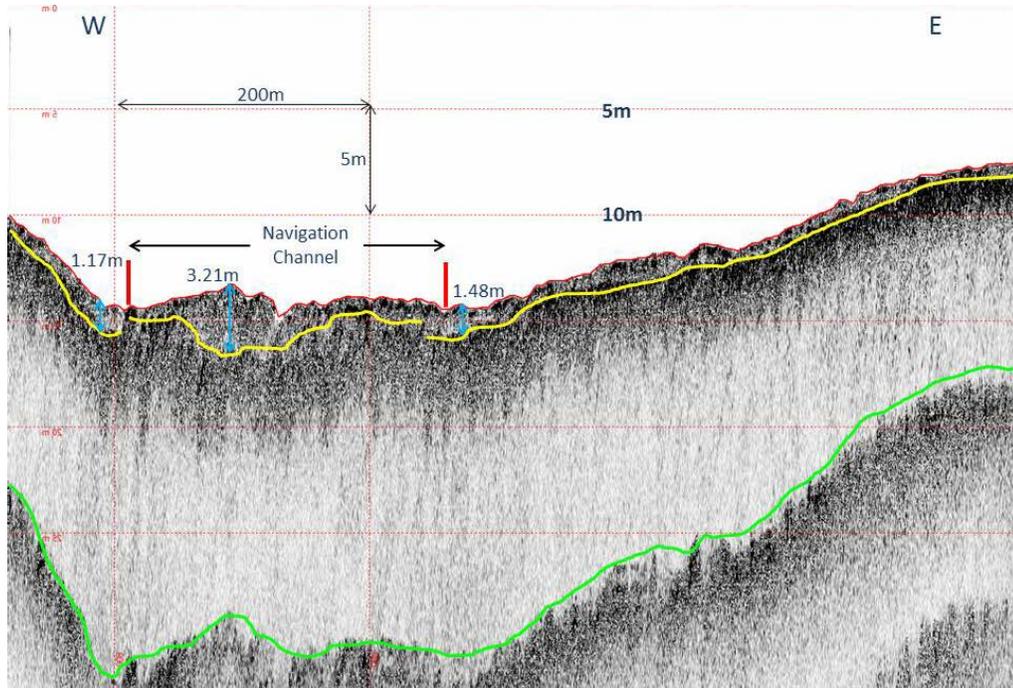


Figure 79 Chirp sub-bottom profile Ge18. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

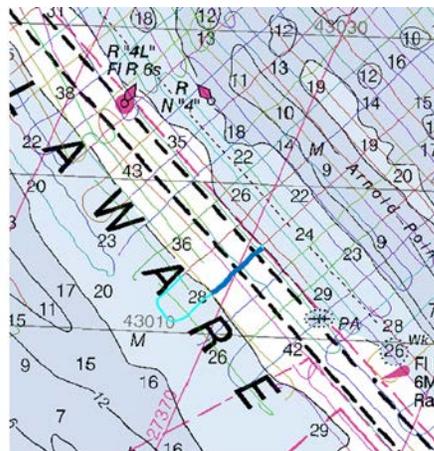


Figure 80 Location of chirp sub-bottom profile Ge18 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

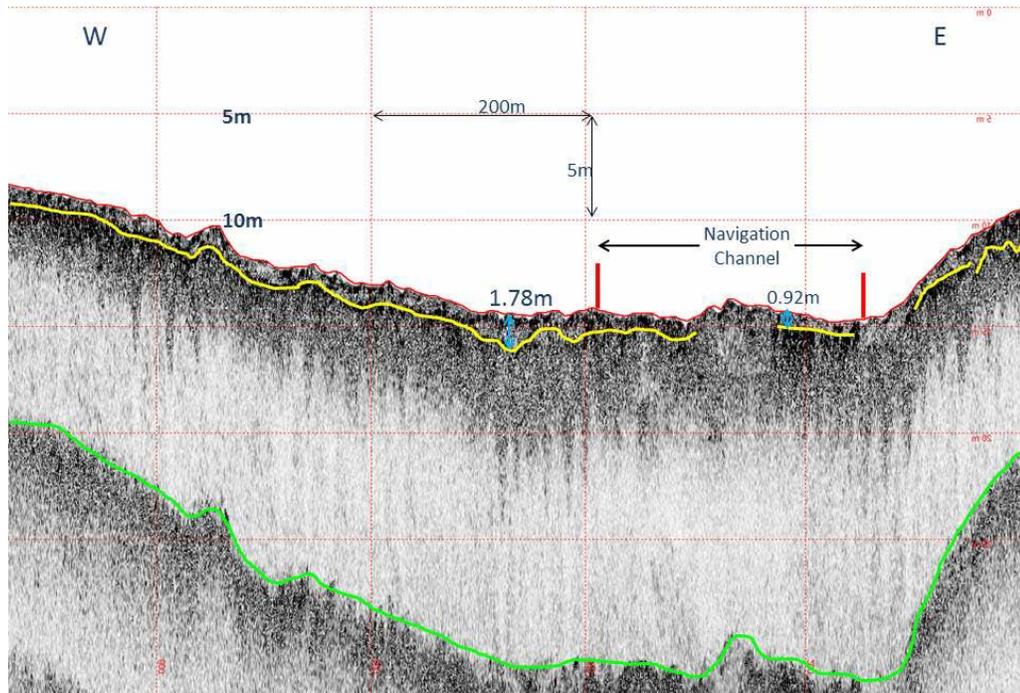


Figure 81 Chirp sub-bottom profile Ge19. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 82 Location of chirp sub-bottom profile Ge19 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

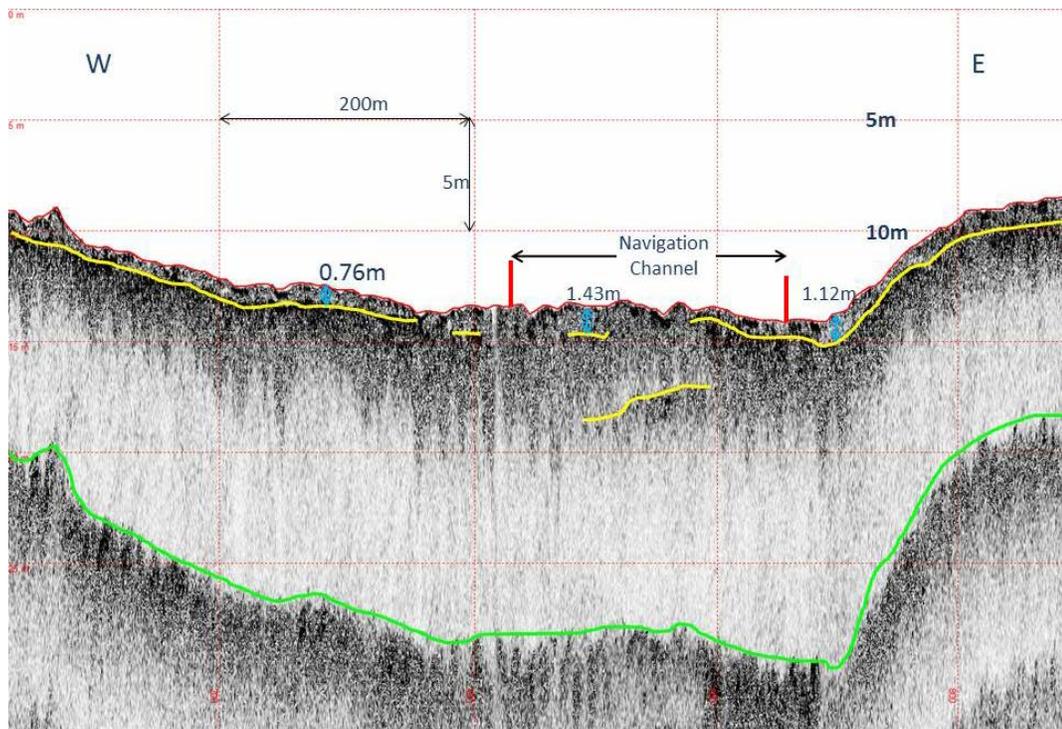


Figure 83 Chirp sub-bottom profile Ge20. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.



Figure 84 Location of chirp sub-bottom profile Ge20 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.

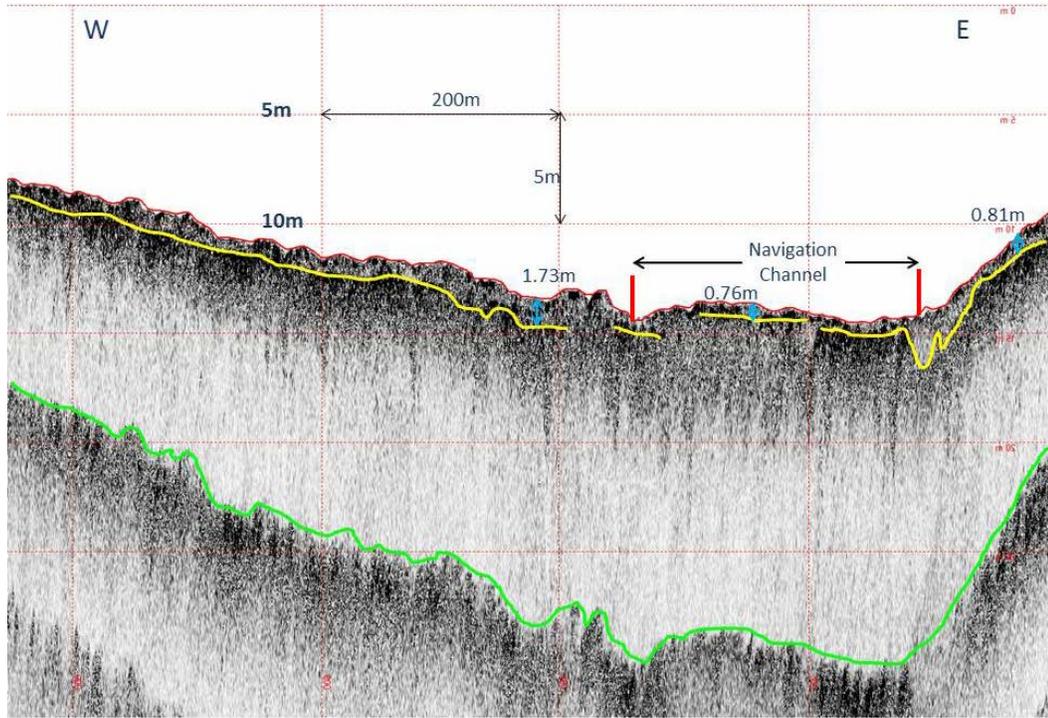


Figure 85 Chirp sub-bottom profile Ge21. Red line denotes position of the seafloor. Yellow lines indicate position of shallow sub-surface reflections due to change in acoustic impedance. Green lines indicate multiples of the bottom reflection. Measurements of surficial sediment thickness were made in the center of the navigation channel and channel edge.

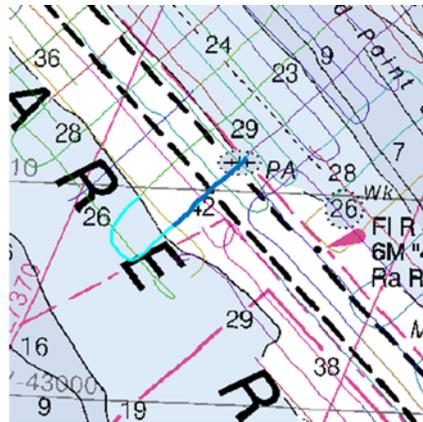


Figure 86 Location of chirp sub-bottom profile Ge21 indicated by thick dark blue trackline. DGS ID area Ge is the largest area shown in this image.