Master Thesis

Stockholm University

Degree Project in Marine Geology 60 hp

Acoustic stratigraphy, seafloor morphology and bottom current influence along the NW Svalbard continental slope

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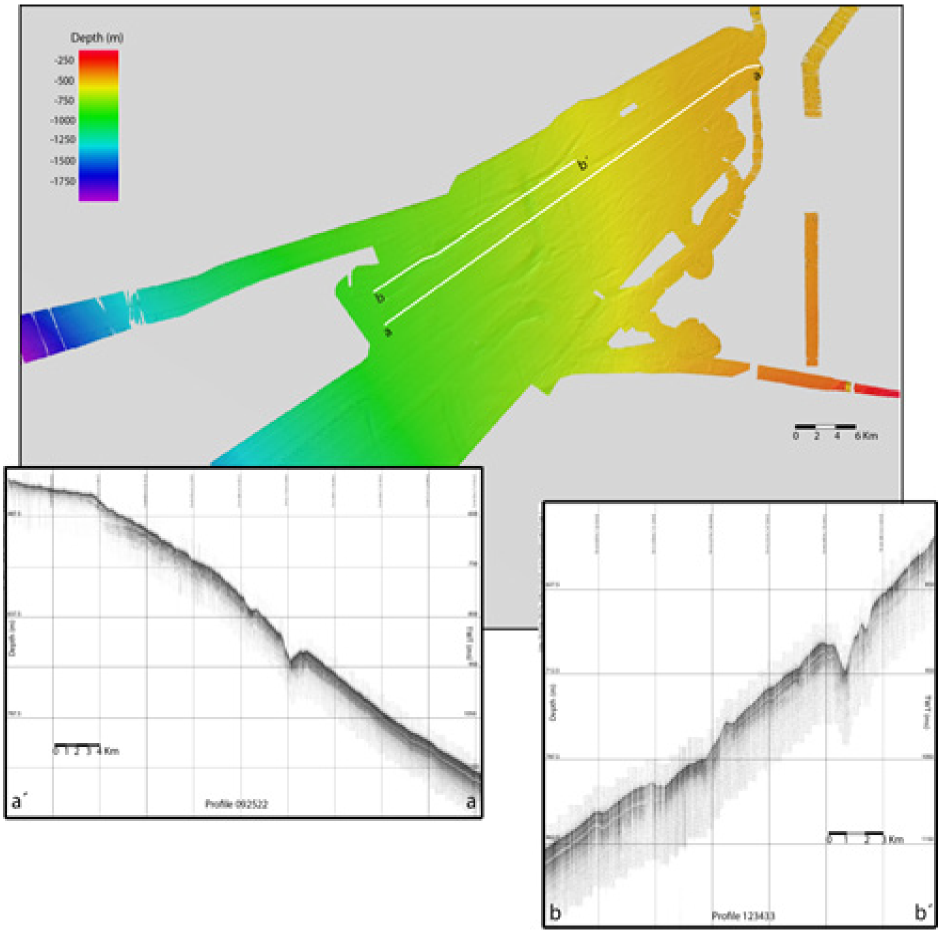

Stockholm 2014

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Abstract

Chirp subbottom acoustic profiling (2.5-7 kHz) along with multibeam swath bathymetry data has been used to map the submarine landforms and for interpretation of the acoustic stratigraphy on the northwest Svalbard continental slope. This region borders to the Fram Strait, which is the only deep gateway for the warm Atlantic water towards the cold Arctic Ocean, and most of the Atlantic inflow to the Arctic is carried by the West Spitsbergen Current.

The geophysical data sets are divided into two study areas based on the depth of the continental slope and their acoustic signatures. Area 1 comprises water depths between 400 to 1312 m along the continental slope. Submarine land forms in this area are dominated by 70-1200 m wide and 3-35 m deep linear to curvilinear ice berg ploughmarks with different orientations. The acoustic stratigraphy reveals four distinct units indicating different depositional environments. A zone of acoustic blanking is interpreted as gas-bearing sediments and debris flows. The dominant acoustic units exhibit undisturbed and continuous acoustic signatures in the lower sections of profiles while their acoustic patterns become chaotic and less significant in the upper sections due to bottom current activity, probably from the West Spitsbergen Current can be seen in the profiles as a condensed acoustic stratigraphy in a limited depth around 800 m. Acoustic profiles appear to be useful tools to determine the lowermost extension of the bottom currents along the continental slope.

Area 2 comprises the lower continental slope adjacent to the Molloy Deep (1200-2585 m). The most prominent feature is a symmetrical sediment drift controlled by bottom currents on the Vestnesa Ridge at the depth of 1238 m. This drift has been described in previous works, and a gravity core from the Vestnesa Ridge suggests that the sediments consist of contourites and turbidites. The crest of this drift consists of a < 450 m wide and 37 m vertically long acoustically featureless chimney with 6 m surficial depression along with down bent reflectors, interpreted as an acoustic pipe associated with pockmark formation. Below 2400 m water depth on the NE side of the Molloy Deep (MD), sediments display parallel and continuous acoustic signatures. The profile and multibeam data below 2500 m water depth show stair like features, interpreted as slump scars related to mass wasting on steep slopes in the Fram Strait. Gas hydrates and earthquake activities are the possible factors responsible for such phenomenon in this region.

Keywords:
Contourites, Fram Strait, Mass wasting, Molloy Deep, Pockmarks, Ploughmarks, Slump scars, Vestnesa Ridge, West Spitsbergen Current.

1. Introduction

The Yermak Plateau (YP) and the northern Svalbard continental margin lie on the eastern side of the Fram Strait and provide a spectacular site for the study of exchange of ice and water between the cold Arctic and North Atlantic Oceans during the Quaternary period (Dowdeswell et al., 2010a). The West Spitsbergen continental margin is sensitive to climatic changes as warm north Atlantic water flows as the West Spitsbergen Current (WSC) along this continental margin (Hald et al., 2004). The WSC is considered as the primary source of water and heat to the Arctic Ocean. A large portion of Atlantic water entering into the Arctic Ocean through the Fram Strait is assumed to be the primary source of salt and heat. In the Fram Strait it divides into the Yermak and Svalbard Branches. The Fram Strait separates Greenland from Spitsbergen, thus providing a deep passageway between the warm Atlantic and the cold Arctic Oceans (Cokelet et al., 2008; Howe et al., 2008).

The East Greenland Current (EGC) carries major outflow from the Arctic Ocean to the south while the West Spitsbergen Current (WSC) carries warm Atlantic water inflow to the north. The WSC follows the tract path of the continental slope which splits at the junction of the Yermak Plateau and the Spitsbergen continental shelf at 79°N. The Svalbard Branch of the WSC moves along the upper continental slope at about 400 m contour, whereas the Yermak Branch moves along the lower continental slope at about 1000 m contour and then rejoins the Svalbard Branch at the northeast of Spitsbergen. Recently, it has been observed that a second major inflow into the cold Arctic Ocean occurs through the Barents Sea, whereas this colder inflow rejoins the eastward extension of the WSC in the north of Kara Sea and they flow together along the Arctic Basin's rim and its oceanic ridges (Cokelet et al., 2008).

The western Svalbard margin comprises of glaciogenic debris flows in Trough Mouth Fans (TMFs), turbiditic, glaciomarine and hemiplegic sediments, whereas these sediments are partially reworked by along slope currents (Bunz et al., 2012). Trough Mouth Fans along the Norwegian - Barents Sea - Svalbard continental margin off the major fjords and troughs consist of glacier fed submarine sediments that are accumulated in front of ice streams of the former Barents Sea- Svalbard Ice Sheet, moreover these fans are the most important archives for the study of paleoclimate and the evolution of the Barents Sea ice sheet (Vorren et al., 2011; Ingólfsson et al., 2013). Previous marine geological and geophysical evidence reveal the presence of past grounded ice on the Yermak Plateau along with several submarine landforms on the seafloor produced by deep keeled icebergs (Dowdeswell et al., 2010a). Large ice berg ploughmarks exist between water depths of 600 to 800 m around the Yermak Plateau with smaller features at shallower depths (Dowdeswell et al., 2010a).

The Vestnesa Ridge is an elongate submarine sediment drift (SE-NW to E-W bending) on the western Svalbard, geographically located on the eastern part of the Molloy Ridge and contains gas hydrate systems, it is also considered as one of the shortest segments of the slow spreading North Atlantic Ridge system. The relatively warm and northward flowing West Spitsbergen Current is mainly responsible for affecting the morphology of the Vestnesa Ridge (Bunz et al., 2012). This drift consists of more than 2 km thick contourites, turbidites and hemipelagic sediments (Howe et al., 2008).

The physiography, sediments thickness and internal seismic structures of the Vestnesa Ridge reveal the fact that it is a sediment drift formed by bottom currents during the late Miocene and Pliocene (Vogt et al., 1994). Current controlled contourites provide a wealth of information regarding thermohaline circulation in the deep sea along the slope, whereas these sediments are very little studied on Arctic continental margins (Howe et al., 2008). The Vestnesa Ridge contains several gas escape features i.e. pockmarks and slump scars resulting from the decay of submarine organic matter within the drift (Howe et al., 2008).

In this thesis, high resolution geophysical data sets (subbottom profiles and multibeam bathymetry data) are used to interpret the shallow acoustic stratigraphy, bottom current (WSC) impact and submarine landforms resulted due to paleo climatic changes on the NW Svalbard continental slope between 78º N and 80º N and 3ºE and 10º E. In addition, the short gravity core 067 (Howe et al., 2008) is used to correlate with acoustic profile from the Vestnesa Ridge (Figure 1).

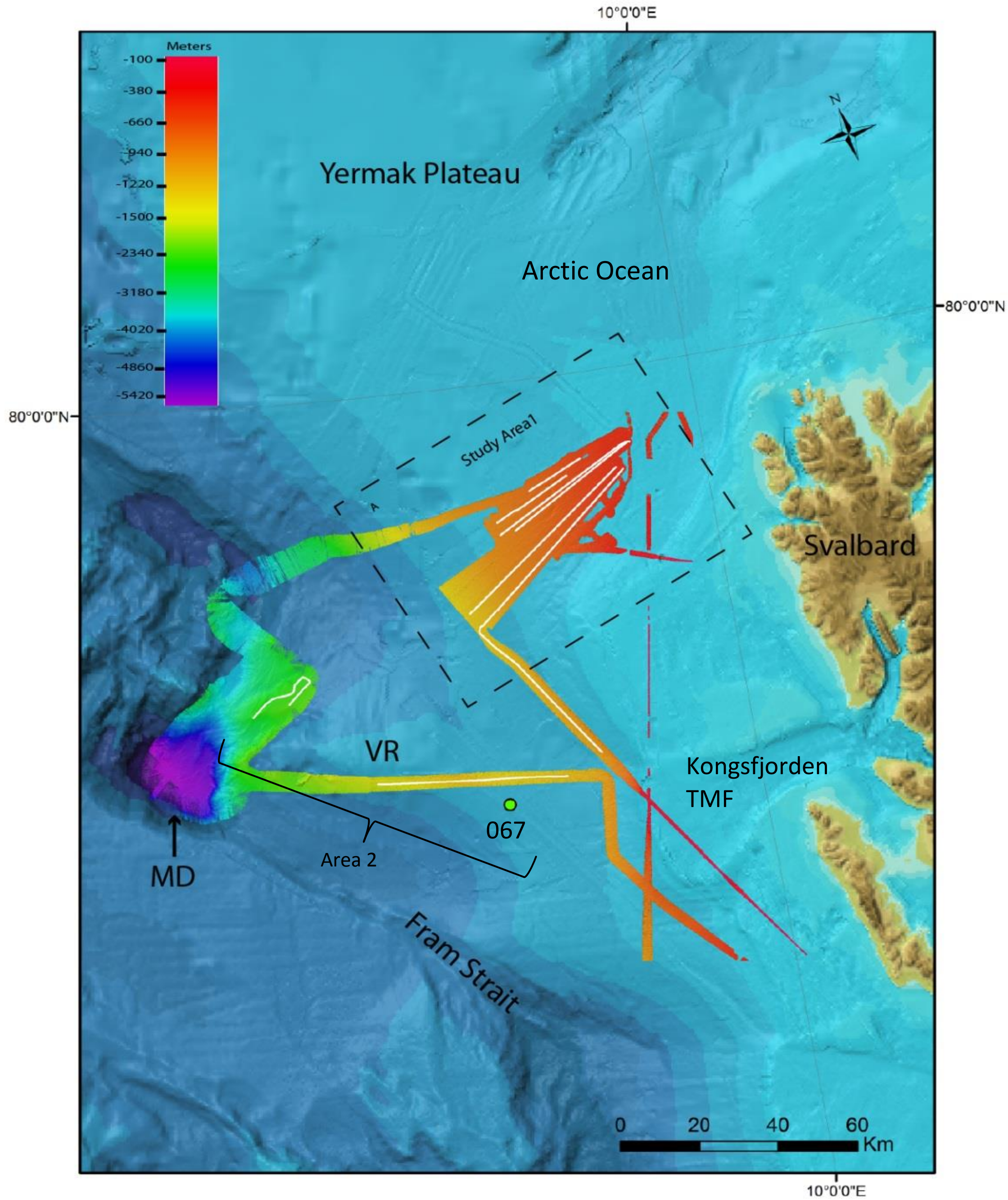


Figure 1. Multibeam Bathymetric map of the NW Svalbard continental slope (IBCAO- The International Bathymetric Chart of the Arctic Ocean, Jakobsson et al. 2008) along with selected ODEN 2009 track lines. Location of the landforms as shown in study area 1 (Figure 10 &18). MD= Molloy Deep. VR= Vestnesa Ridge. Location of core 067 (Howe et al., 2008) is marked by green dot.

2. Regional background of the study area

2.1. Regional setting

The Svalbard archipelago is located between 76° and 81° N in the high Arctic, currently it is almost 60% covered with glaciers and ice caps. A part from its high Arctic setting, its climate is enhanced by the West Spitsbergen Current (WSC), the northern extension of the North Atlantic Current (NAC), as shown in Figure 2. Svalbard's average annual winter temperature is about -12 °C on the western coast and the average July temperature is about 5 °C. The 15-20 km wide Hinlopen Strait separates Spitsbergen from Nordaustlandet Island (Ślubowska et al., 2005).

Spitsbergen is surrounded by the Arctic Ocean to the north, the Barents Sea to the south and east, and the Norwegian-Greenland Sea to the west. It is the largest island of Svalbard archipelago (Figure 2). The gradient of the continental slope is 4-5° steep. Quaternary and Tertiary sediments occur in submarine troughs on the shelf and as submarine fans on the slope (Hald et al., 2004).

The Nordic Seas along with the North Atlantic and Arctic Oceans are connected together through the 2600 m deep Fram Strait, which allows exchange of heat and fresh water between Greenland and Spitsbergen (Ślubowska et al., 2005). The warm and saline Atlantic Water (AW) passes through the eastern Fram Strait poleward with the help of West Spitsbergen Current (WSC) into the Arctic basin. The Atlantic water continues to flow north and west of the Yermak Plateau as the Yermak Branch. The Svalbard Branch carries these water masses eastward into the Arctic Ocean. The East Spitsbergen Current (ESC) carries cold water and sea ice from the Arctic Ocean to the south of the eastern Svalbard coast and then to the west around the Spitsbergen, joining WSC to the west as a result of this the north flowing warm AW becomes cooler and fresher. In the western part of the Fram Strait, the southward directed East Greenland Current (EGC) carries cold fresh water and sea ice along the Greenland continental slope and it is further divided into the two minor currents the Jan Mayen Current and the East Icelandic Current (Werner et al., 2011) (Figure 2). The seasonal sea ice distribution pattern of this particular area is controlled by the hydrography of the Fram Strait. The western part of the Fram Strait is perennially covered by sea ice, whereas the eastern part displays seasonally varying ice conditions. The warmer and relatively more saline Atlantic Water (AW) keeps large part of the west and north Svalbard ice free though out the year (Werner et al., 2011). In fact, the role of the Fram Strait is vital in terms of heat budget and sea ice extent of the Arctic (Werner et al., 2011).

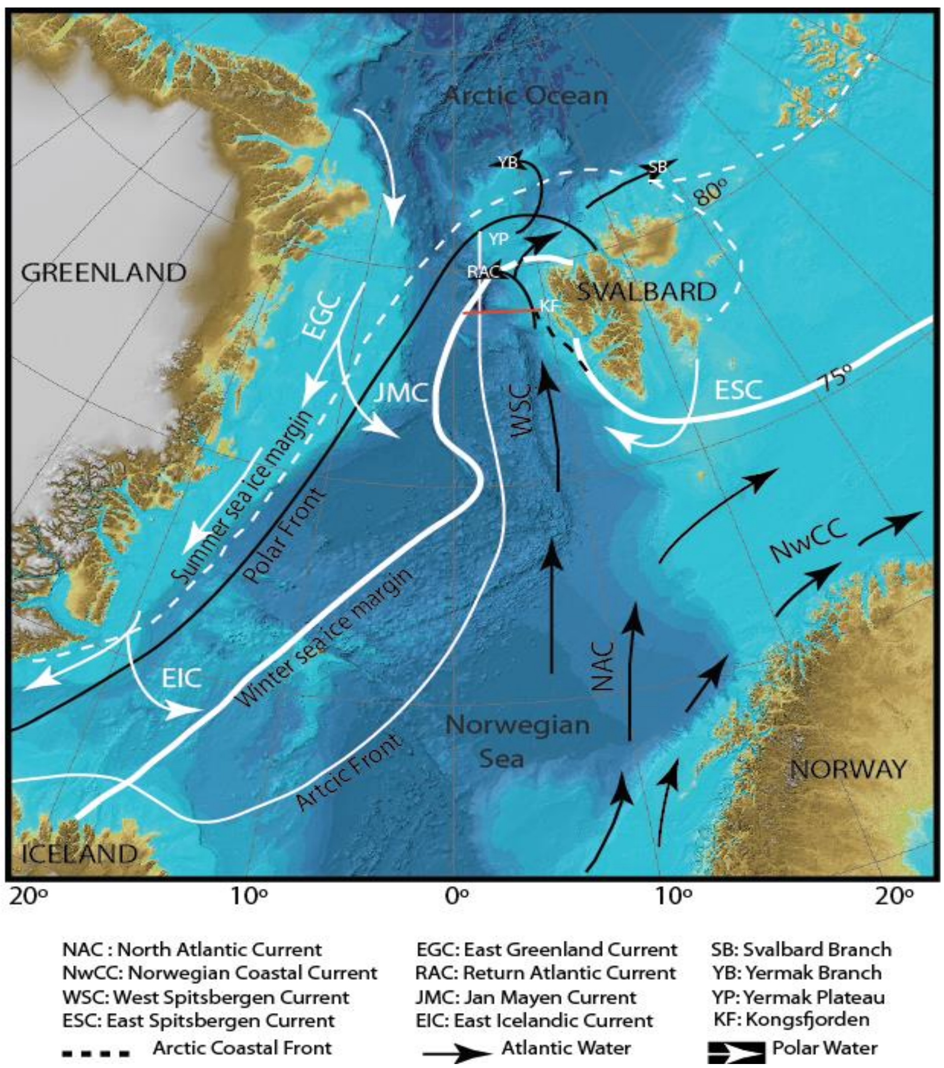


Figure 2. Bathymetric map (IBCAO-The International Bathymetric Chart of the Arctic Ocean by Jakobsson et al. 2012) of the Norwegian–Greenland Sea with respect to the major currents and the hydrography of the Fram Strait (modified after Werner et al., 2011). The orange line shows the position of the salinity and temperature section 1 (Figure 21) by Cokelet et al (2008).

2.2. Oceanography

Two main currents, the warm and saline West Spitsbergen Current (WSC) which forms the continuation of the North Atlantic Current (NAC) and the East Greenland Current (EGC) which follows the East Greenland margin and drives the polar water southward to the North Atlantic Ocean, meet in the Fram Strait. The EGC is considered the largest of export path of sea ice from the Arctic Ocean through the Fram Strait. The Atlantic water, Atlantic Intermediate water and Norwegian Sea Deep Water are transported by the WSC and it is the main source of warm and saline water flowing towards the Arctic (Ślubowska et al., 2005; Howe et al., 2008).

The northern part of Spitsbergen is covered by Arctic ice throughout the years with the minimum flow in the month of August and September. The entire Svalbard archipelago may be surrounded by ice pack between November and April. The cold Arctic water transports the ice pack southward along the eastern side of Svalbard, whereas the WSC carries warm Atlantic water northward to the western part of Svalbard (Hald et al., 2004).

Cokelet (2008) presented five oceanographic sections of the WSC along the western Svalbard continental slope. Atlantic water can be found in the upper 500 m of all the sections (Cokelet et al., 2008). Due to ice melting the surface water freshens between oceanographic sections. Relatively less saline water can be found above the Atlantic Water due to near surface water that has exited the Arctic Ocean via the East Greenland Current and recirculated in the Nordic Seas and the Fram Strait. River runoff, ice melt and the Pacific Ocean inflow through the Bering Strait are the sources that keep the upper layers of Arctic Ocean relatively fresh. The Arctic Ocean forms dense water that flows into the basin because of freezing condition and brine rejection on the continental shelf, attaining a density level between the Atlantic Water and the surface. The warm Atlantic Water is kept away from direct contact with sea ice by the cold halocline in the central Arctic Ocean, thus reducing ice melting and strong heat loss to the atmosphere (Cokelet et al., 2008).

The Sea ice distribution is mainly affected by the relatively warm Atlantic water flowing northward and it is the source of heat advection towards the cold Arctic. Increase in air temperature and decrease of sea ice cover are the evidence for rapid warming in the Arctic (Spielhagen et al., 2011). The warm Atlantic water (AW) with a temperature of 2° to 6°C and salinities of > 35.0% at 50 to 600 m depth in the eastern Fram Strait is the main carrier of oceanic heat to the cold Arctic, as a result of this flow of warm water there is an ice free condition along the eastern Fram Strait (Spielhagen et al., 2011). The Fram Strait is the only deep passageway for the warm and saline Atlantic Water (AW) to the north of cold Arctic Ocean (Werner et al., 2011).

The WSC submerges in the Fram Strait at 78°N and forms the Atlantic layer (AL), characterized by a temperature of 0°- 2°C and salinities of 34.7- 35%, which passes into Arctic Ocean along the northern continental slope of Svalbard. It is obvious from several studies that current moves along the bathymetry of sea floor and its topography intensifies the tidal force activities. This phenomenon also applies to the WSC moving over the upper continental slope at nearly 79.5° N, where the slope isobaths separates and the WSC divides into two branches. The Yermak branch moves northwest towards the Yermak Plateau and loses its Atlantic water qualities rapidly, while the Svalbard branch supplies a major part of the Atlantic water in the form of the Atlantic layer into Arctic Ocean (Figure 2). The Atlantic layer is between 100-200 and 600-800 m deep with temperature fluctuations in its main core from 3°C to 4.5°C at 100 to 400 m water depth (Ślubowska et al., 2005). The velocity of the WSC along the margin (500-1500 m) ranges between 9 to 16 cm/sec, whereas the Yermak Slope Current (YSC) ranges between 1 to 3 cm/sec (Howe et al., 2008). According to one survey 55% of the Atlantic water transported by the WSC enters into the Arctic Ocean, while the remaining 45% recirculates in the Fram Strait (Teigen et al., 2011).

2.3. Geological background

The Northeast Greenland was separated from the Svalbard as a result of large scale strike slip fault during the Cenozoic time. The submarine Yermak Plateau lies between the sheared western and rifted northern Svalbard continental margins and plays vital role in the evolution of the deep Frame Strait (Geissler et al. 2008). The Spitsbergen Archipelago is located in the NW of the Barents Sea and surrounded by the Norwegian-Greenland Sea and Eurasian Basins, thus representing the NW limit of the Eurasian Plate. Tectonically the Spitsbergen Continental margin is considered to be a passive margin, with divergent boundary in the northern part and strike slip fault in the western part**.** The Yermak plateau in the north and the Spitsbergen (Vestnesa) in the west are two plateaus on the continental margin. The Yermak Plateau has a structure similar to most marginal plateaus on passive margins, with its main part underlain by continental crust, and formed as a result of stretching during the rifting phase, whereas the Spitsbergen Plateau is mainly underlain by oceanic crust and formed in response to accumulative processes during the drift phase (Baturin et al., 1994).

The Norwegian margin comprises of a continental shelf and slope is the result of continental breakup followed by opening of the Norwegian-Greenland Sea in the early Cenozoic. It consists of the rifted volcanic margin offshore mid Norway (62°-72° N) and the sheared margin along the western Barents Sea and Svalbard (70°-82° N) (Faleide et al., 2008). The continental slope gradient varies from less than 1° in the southern part to ~ 4° close to the Isfjorden on Svalbard (Faleide et al., 1996).

The western Barents Sea- Svalbard margin consists of two shear segments and a central rifted margin segment southwest of Bjørnøya associated with volcanic activity (Figure 3). The southern shear segment along the western Barents Sea is the Senja Fracture Zone (SFZ). The Vestbakken Volcanic Province (VVP) connects the north and south sheared segments at a rifted margin segments SW of Bjørnøya (Figure 3) (Faleide et al., 2008).

Faleide et al (2008) subdivided the continental margin north of Bjørnøya (74.30° N–81°N) into three segments:

1. A sheared margin from Bjørnøya to Sørkapp (southernmost tip of Spitsbergen, 74.30°-76°N)

2. A pre sheared and then rifted margin west of Svalbard from Sørkapp to Kongsfjorden

(76°-79°N)

3. Both sheared and rifted margin associated with volcanic activity along the NW Svalbard and SW Yermak Plateau (79°-81°N).

Crustal thickness varies significantly from 30 km for continental crust on the Svalbard to oceanic crust 2-6 km in the Greenland Sea (Figure 4; profiles 1-3). Tectonically the Spitsbergen Fold and Thrust Belt evolved as the Greenland slid past the Svalbard margin during the Paleocene and Eocene (Figure 4; Profile 3). A foreland basin was created as a result of uplifted parts of the fold and thrust belt in the western part on the Spitsbergen during the early Cenozoic (Figure 4; Profile 3). The continental crust becomes thin to the west of the fold and thrust belt across the Svalbard margin. The Fram Strait was opened as a North Atlantic –Arctic gateway in the Miocene and has great influence on the ocean water circulation (Faleide et al., 2008). The Hovgård Ridge (HR) may be considered as rifted part of the Barents Sea-Svalbard margin, removed as a result of tensional processes during second evolutionary stage (Figure 4; Profile 2) (Faleide et al., 2008; Baturin et al., 1994). The Hornsund Fault Zone (HFZ) was formed in response to tectonic deformation when the Greenland slid away along the Spitsbergen (Baturin et al., 1994). Along the coast of the NW Spitsbergen and SW Yermak Plateau there are several N-S trending graben like structural features with maximum width of 30 km as shown in figure 3 and 4. Significant submarine fans were deposited during the middle Eocene in the SW Barents Sea (Sørvestsnaget Basin). The Continent-Ocean transition along the western part of Svalbard margin is close to the present plate boundary at the Molly Ridge as shown in profile 1 (Figure 4) (Faleide et al., 2008). Tectonic uplifting and glacial erosion of the Barents shelf and subsequent deposition of large volumes of glacial deposits as submarine fans along the margin during the Plio- Pleistocene resulted in the regional tilting of the margin (Faleide et al., 2008). Most of the unlithified sediments in the Barents Sea are glacial and glaciomarine diamictons deposited during the Late Weichselian, in addition there are indications for a grounded Late Weichselian glacier over the western parts of the Barents Sea margin (Faleide et al., 1996).

Thick sedimentary cover of approximately 10 km and relatively high heat flow along the west Spitsbergen margin are favorable signs for the transformations of organic matter into oil and gas as compared to the northern part of Spitsbergen margin (Baturin et al., 1994).

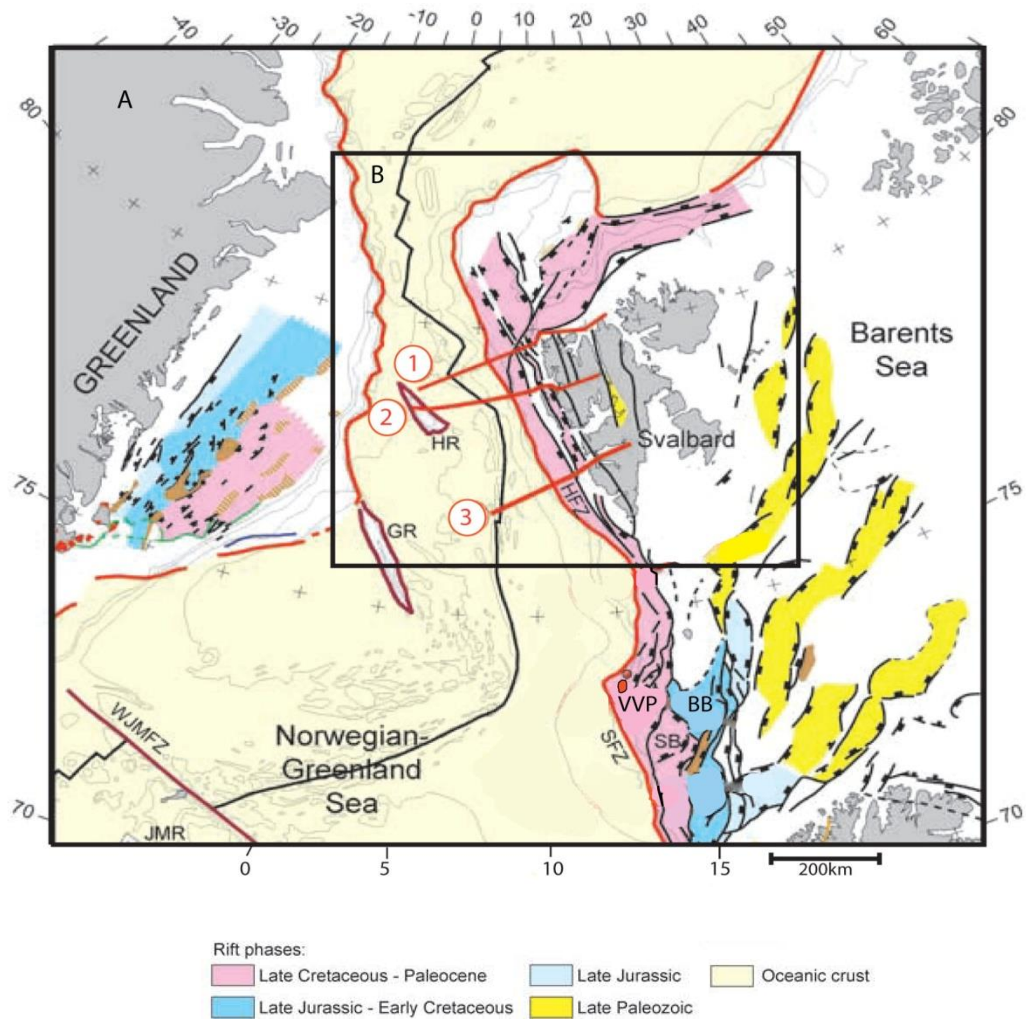


Figure 3. (A) Part of the Structural map of the Norwegian continental margin, with focus on NW Barents Sea- Svalbard margin (B) Study area with location of margin transects in Figure 4. BB: Bjørnøya Basin, GR: Greenland Ridge, HR: Hovgård Ridge, HFZ: Hornsund Fault Zone, JMR: Jan Mayen Ridge, SFZ: Senja Fracture Zone, SB: Sørvestsnaget Basin, VVP: Vestbakken Volcanic Province, WJMFZ: West Jan Mayen Fracture Zone (Modified after Faleide et al., 2008)

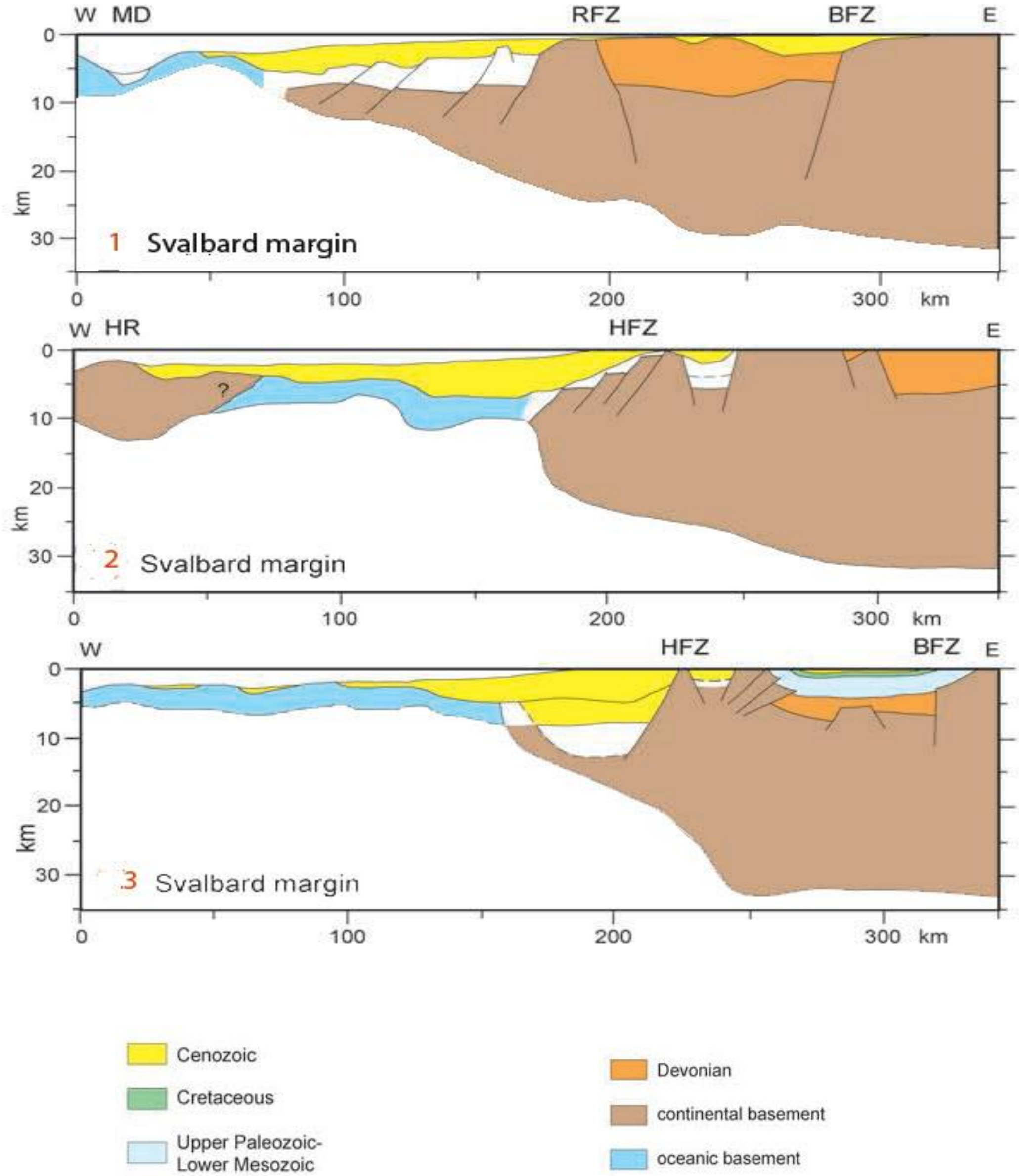


Figure 4. Crustal transects across the mainly sheared western Barents Sea-Svalbard margin. Location of profiles in figure 1. BFZ: Billefjorden Fault Zone, HR: Hovgård Ridge, HFZ: Hornsund Fault Zone, MD: Molloy Deep, RFZ: Raudfjorden Fault Zone (Modified after Faleide et al., 2008)

3. Data and Methods

The geophysical datasets used in this study were acquired using the Icebreaker ODEN's hull mounted Kongsberg multibeam sonar and subbottom profiler during the expedition SAT (Sea Acceptance Test) in July 2009.

3.1. Data acquisition

3.1.1. Oden multibeam and subbottom profiling systems

A Kongsberg EM120 (1°x1°) multibeam echo sounder along with integrated subbottom profiler SPB 120 (3°x3°) was installed on ODEN in 2007. The EM 120 was replaced by EM 122 in spring 2008. A Schematic illustration of these geophysical components installed on Oden is given in Figure 7 and their technical specification is described in table 1. The transmission arrays for both SBP 120 and EM 122 are mounted parallel to each other, while receiving array is similar for both of them and located perpendicular to the source arrays (Oden Mapping Data Repository).

The SBP120 images the uppermost layers of sediments below the seafloor, whereas the EM122 multibeam echo sounder maps the seafloor surface to full ocean depth ~ 11000 m (Oden Southern Ocean 0910 Cruise report). A chirp subbottom profiler generates a swept signal that is usually several kilo hertz wide and capable to penetrate up to 100 meters (Henkart, 2006). These acoustic pulses generated by the sonar transducer are wide across track lines and narrow along tract angular sector (Penrose et al., 2005). In order to increase the resolution, a shorter pulse is required, whereas in order to increase the penetration, more energy in the pulse is needed. This is a problem, because delivering high energy during short time is limited by the electrical system and the transducer material. By increasing the length of the outgoing signal (by making it a frequency modulated chirp) the power of the outgoing signal can be increased (Henkart., 2006). The frequency modulated (FM) chirp is matched with its replica, and through signal processing step called matched filtering, shorter duration wavelets are achieved (Figure 5), thus long pulses with more energy can be utilized (Mosher and Simpkin, 1999).

Henkart (2006) summarized the path followed by the chirp signal as;

- Transducer emits chirp signals
- These signals are reflected form various acoustic boundaries
- Reflected signals are detected by receiving transducer
- These signals are digitized and processed
- Finally, it is recorded to some storage medium before display

Chirp sonar is considered as the latest sonar technology capable of generating wide band, frequency modulated (FM) pulses from a resonant source, thus producing very high resolution profiles. The vertical resolution of ~ 5 cm can be achieved by Chirp sonar resulting in relatively artifacts free subbottom profiles up to 100 meters depth (Schock et al., 1989; Mosher and Simpkin, 1999).

The acoustic refraction in the water column with depth dependent sound velocity can badly affect the acoustic ray trajectories and resultant bathymetry images (Penrose et al., 2005). A Conductivity Temperature Depth (CTD) probe from Sea-Bird Electronics (Model SBE 9) was used in the multibeam system setup for the measurement of sound velocity in the water column. Additionally, a probe mounted just close to multibeam receiving transducer array is used to measure directly the sound velocity. For protection of the transducers from the impact of ice, pure titanium plates are used due to its better acoustic and less resistive nature than other materials (Oden Mapping Data Repository).

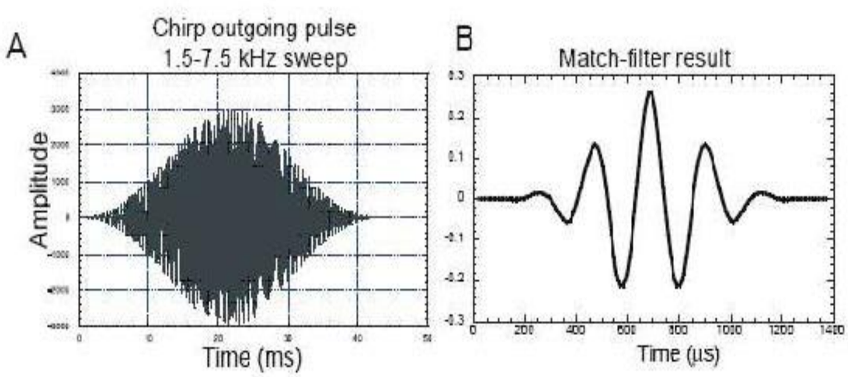


Figure 5. (A) A chirp sonar 1.5-7.5 kHz swept outgoing pulse and (B) Same source function after Match filtering (Mosher and Simpkin 1999).

3.1.2. Seismic reflection theory

In marine seismic work the acoustic signals emitted by the source penetrate the seafloor after passing through water column. Some of the acoustic pulses reflect back from the seafloor while the remaining signals penetrate down into the sediment layers. The reflection of sound waves occurs at a boundary (reflector) of two different geological media representing difference in acoustic impedances (Figure 6). Acoustic impedance (I) is the product of bulk density (ρ) and compressional velocity (V) in a particular medium (Mosher and Simpkin 1999; Penrose et al., 2005). The reflected wave from the acoustic boundary is proportional to the amplitude of the sound impulse emitted by the source and the reflection coefficient (μ). The reflection coefficient is given by equation;

$$\mu = \frac{I_2 - I_1}{I_2 + I_1} = \frac{V_2\rho_2 - V_1\rho_1}{V_2\rho_2 + V_1\rho_1}$$

High reflection coefficient represents high contrasts in geological layers. Scattering phenomena affects the reflection coefficient and may occur due to roughness of the geological boundary. The scattered energy transmits through the lower boundary into underlying sedimentary sequences (Mosher and Simpkin 1999). In general the upper-most medium in marine geophysics is always invariably water supporting the transducers (sources and receivers) with lower underlying complex geological sequences. The factors involved in detection of the reflected waves at the receiver are: source impulse amplitude, receiver and detector arrangement and sensitivity, scattering and absorption, the amplitude of reflection coefficient series represented by sediment column and background noise level at detector (Mosher and Simpkin 1999).

High resolution marine seismic reflection studies differ from the deep seismic exploration performed in oil industry due to the use of low source energy, small acoustic impedance changes, wide bandwidths, low signal to noise ratios and high signal attenuation (Mosher and Simpkin 1999).

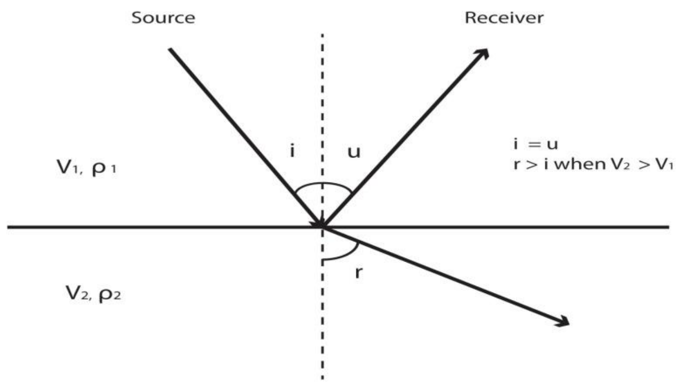


Figure 6. Seismic reflection principle, i = incident ray, u = reflected ray and r = refracted ray

Table 1. EM120, EM122 and SBP120 technical specifications (Oden Mapping Data Repository).

EM120 (1°)	Depth range: 20 to 11000 m Swath width: up to 5 times water depth (ice protection windows reduce this to ca 4 times the water depth) Beam width: 150°x1° Beams: 191 covering a sector up to 150° Frequency: 12 kHz
EM122 (1°)	Depth range: 20 to 11000 m Swath width: up to 25% better than EM120 Beam width: 150°x1° Beams: 288 simultaneous beams covering a sector up to 150° Frequency: 12 kHz (chirp mode and dual swath capability)
SBP120 (3°)	Frequency range: 3-7 kHz, chirp Vertical resolution: 0.35 ms Horizontal resolution: 3°x3° Integrated with EM120 by using the same receiving transducer array
Positioning and motion sensor	Seapath 200 MRU5 (motion reference unit) Heading accuracy: 0.05 RMS (4 m baseline) Roll and pitch accuracy: 0.03 RMS for ±5° amplitude. Heave accuracy: 5 cm or 5% whichever is highest Positioning accuracy: (best case) 0.15 m RMS or 0.4 m (95% CEP)

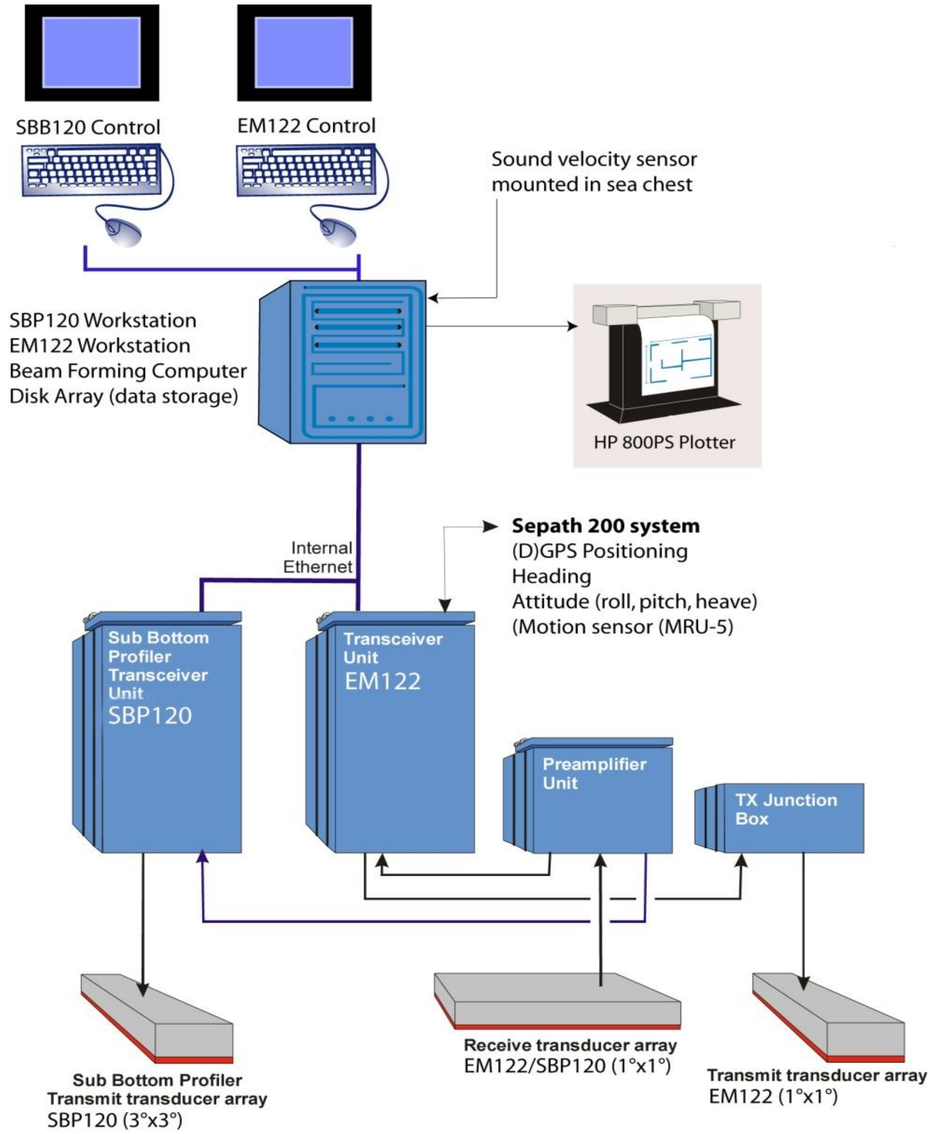


Figure 7. Schematic illustration of the EM122/SBP120 system installed on the Oden. The drawings are modified versions of Kongsberg's original (Oden Mapping Data Repository)

3.2. Data processing and interpretation

The raw data were exported from Kongsberg's RAW-format into a readable SEG format using Kongsberg's TOPAS software SBP 120v1.4.6 after processing of the profiles by adjusting various parameters i.e**.** gain, time variable gain (TVG), trace width, scale etc (Figure 8). The profiles were then converted to SEGY, DAT and DXF using the Read-SGY program (SEGY file reader, Tom Flodén) for all five beams (-2, -1, 0, +1 and +2). MeriData 5.1 (SView and MDPS) was used for interpretation of the profiles. Two way travel time (TWT) 100 milliseconds were selected for majority of profiles in TOPAS SBP 120v1.4.6, as 100 ms represents 75 meters depth assuming a sound velocity of 1500 m/s. The zero (Vertical) beams were used extensively for processing and interpretation of acoustic profiles, while in some cases, where the continental slope was quite steep negative or positive beams were used.

A 3 dimensional software Fledermaus Version 7.3.1a was used for interpretation of multibeam bathymetry data after adjusting different parameters. The DAT files were exported in Quantum GIS (1.7.4) for the display of trace lines. For the final presentation, the IBCAO (The International Bathymetric Chart of the Arctic Ocean) map by Jakobsson., et al (2012 was used as base map in ArcGIS 10.0 and Global Mapper 13 environment by using polar stereographic projection and WGS84 datum. Surface multibeam bathymetry data for selected study areas were exported as Geo Tiff files from Fledermaus to ArcGIS. Finally, all selected profiles and maps were cropped and fitted with scale bars and labeled using Adobe Photoshop CS4 and Adobe Illustrator CS5.

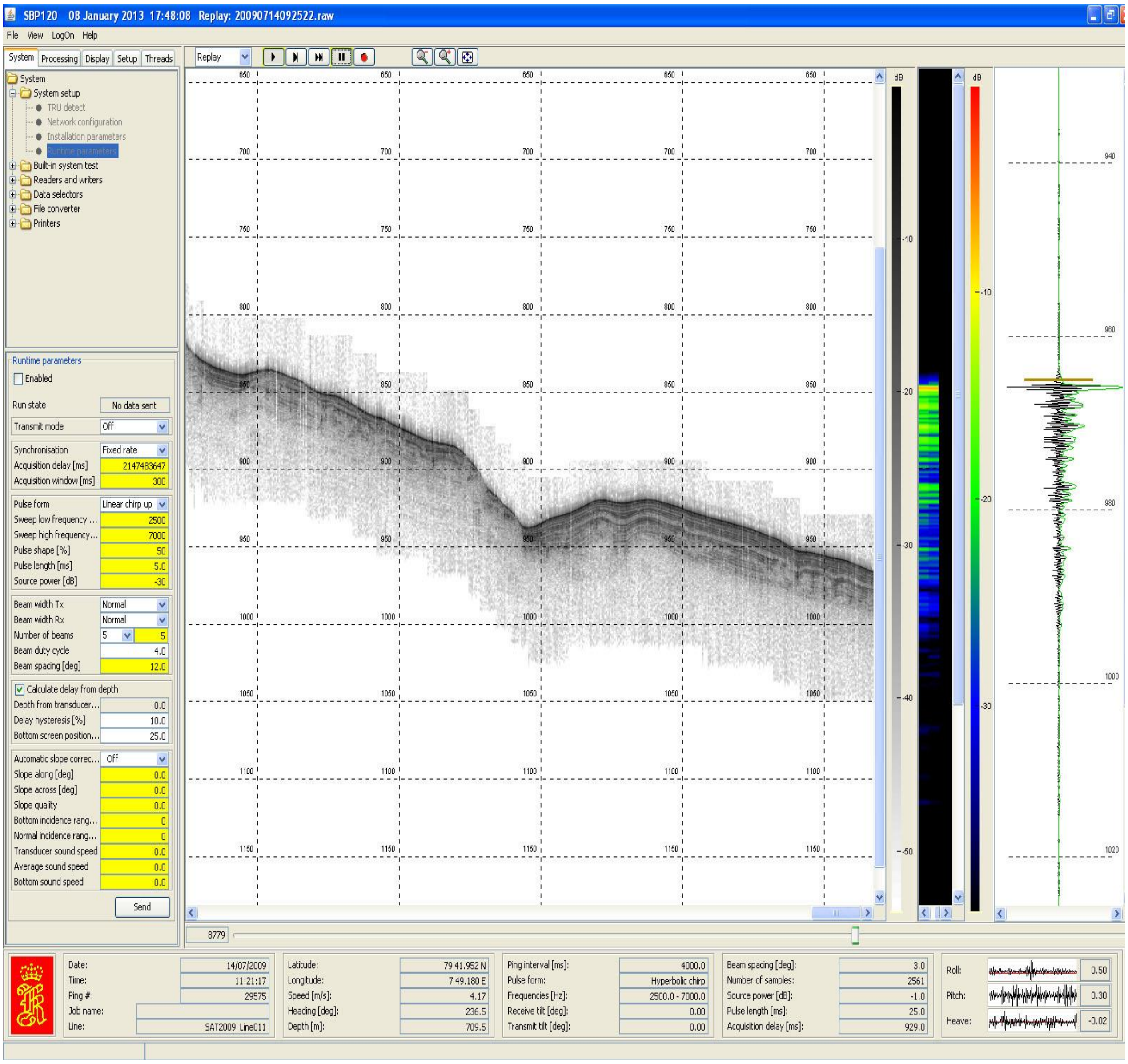


Figure 8. Screen dump of Kongsberg's SBP120v1.4.6 with system settings used for processing of subbottom profiles. A Chirp 2.5-7.5 kHz was used during SAT (Sea Acceptance Test) expedition 2009.

4. Results

The study areas contain high resolution shallow acoustic subbottom profiles and multibeam bathymetry data to describe the acoustic stratigraphy and submarine landforms on the NW Svalbard continental slope. The thickness 100 ms TWT in profiles corresponds to 75 m, assuming acoustic velocity of 1500 m/s. A 3.80 m short gravity core 067 (Howe at el., 2008) is used to correlate with established acoustic stratigraphy from the Vestnesa Ridge (Figure 9). The investigated area has been subdivided into area 1 and area 2 respectively based on the nature of continental slope and their acoustic signatures.

4.1. Study area 1

4.1.1. Description

All selected track lines in this study area run almost parallel to each other approximately NE-SW across the NW Svalbard continental slope except profile 111110-131811 (Figure 9). These profiles display shallow acoustic signatures in a water depth range from 400 to 1312 m along the continental slope. Two profiles 092522 and 123433 represent the best shallow acoustic subbottom profiles showing the slope disturbed by iceberg ploughmarks, as well as features related to the bottom water current (WSC) as indicated by Dowdeswell et al (2010a) and shown in multibeam bathymetry image (Figure 10). Along these profiles stratified to unstratified sequences containing several acoustic units can be recognized.

The shallow acoustic stratigraphy of this region is defined by the following acoustic units which have been summarized in table 2.

1. An acoustically transparent homogeneous Unit (U)
2. A thick sequence containing three identifiable acoustic Units (U1,U2,U3)

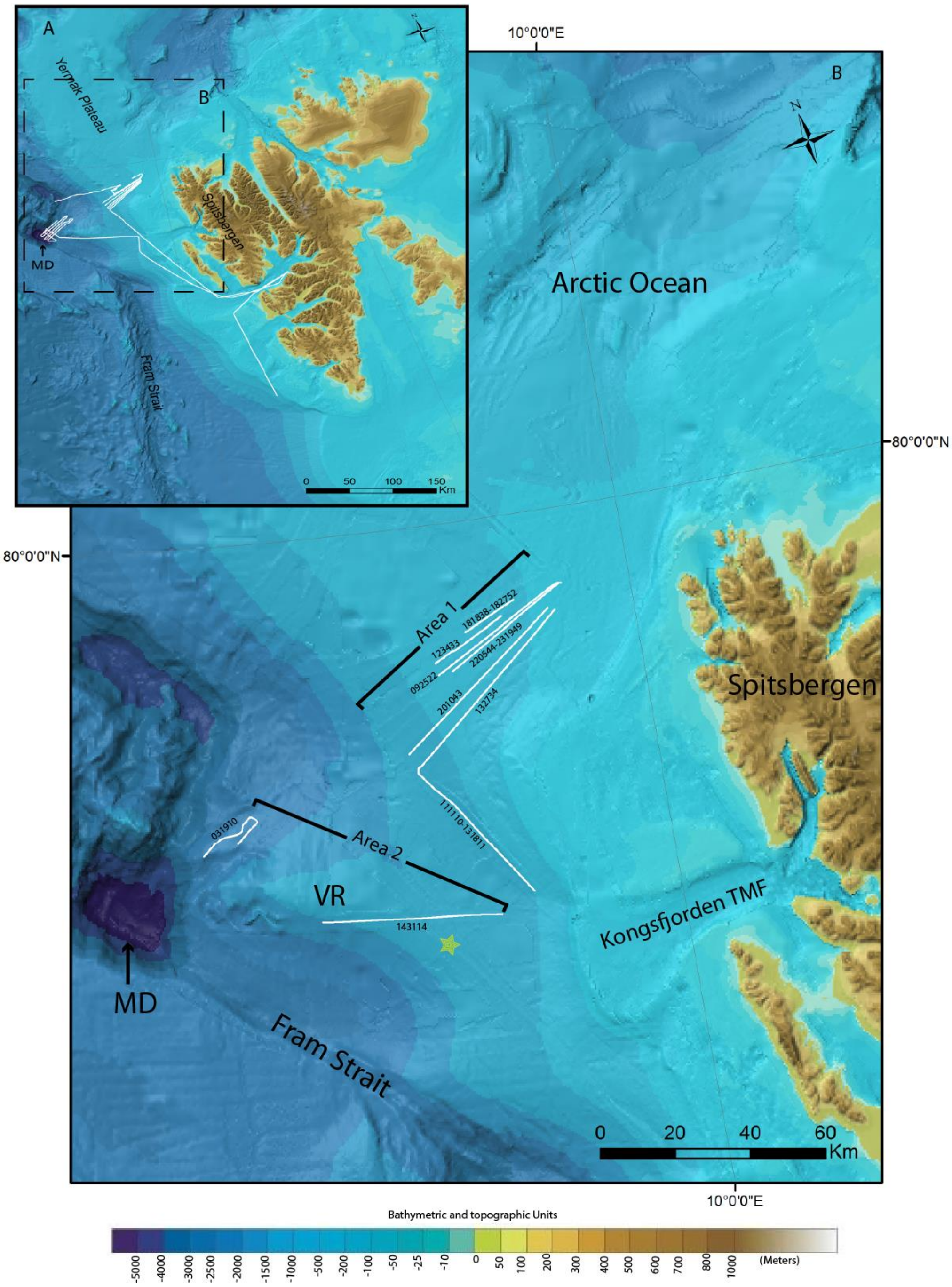


Figure 9. (A) Bathymetric map of the Svalbard (IBCAO- The International Bathymetric Chart of the Arctic Ocean, Jakobsson et al. 2012) with ODEN 2009 track lines. (B) Location of the selected ODEN 2009 acoustic profiles with investigated area 1 and 2 used in this study. MD: Molloy Deep, VR: Vestnesa Ridge, ✶: Core 067 by Howe et al (2008).

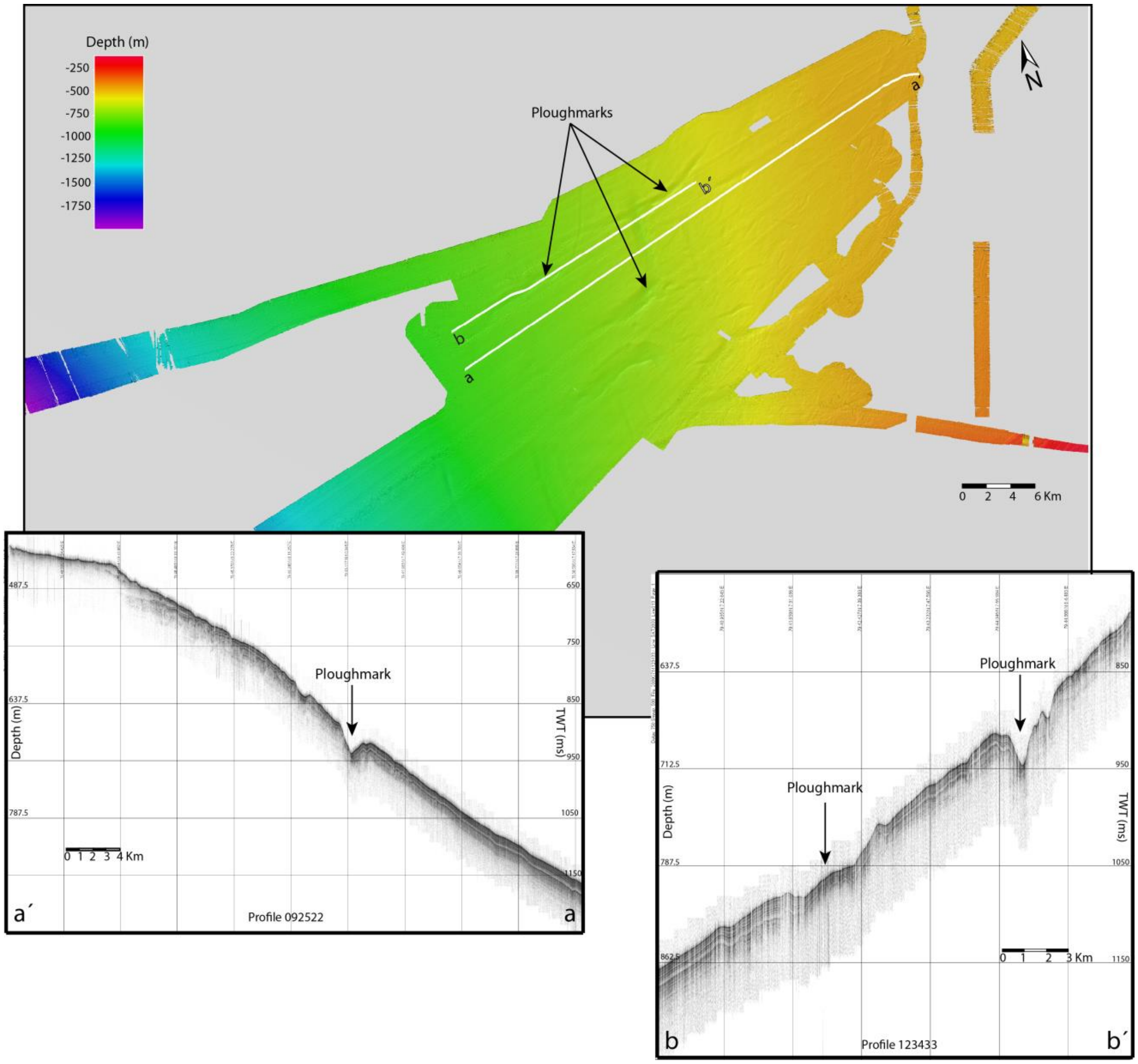


Figure 10. Multibeam bathymetry data along with selected subbottom profiles showing the submarine landforms (ploughmarks) in the study area 1. The profiles are briefly described in figures 11 and 12. For location of map see figure 1.

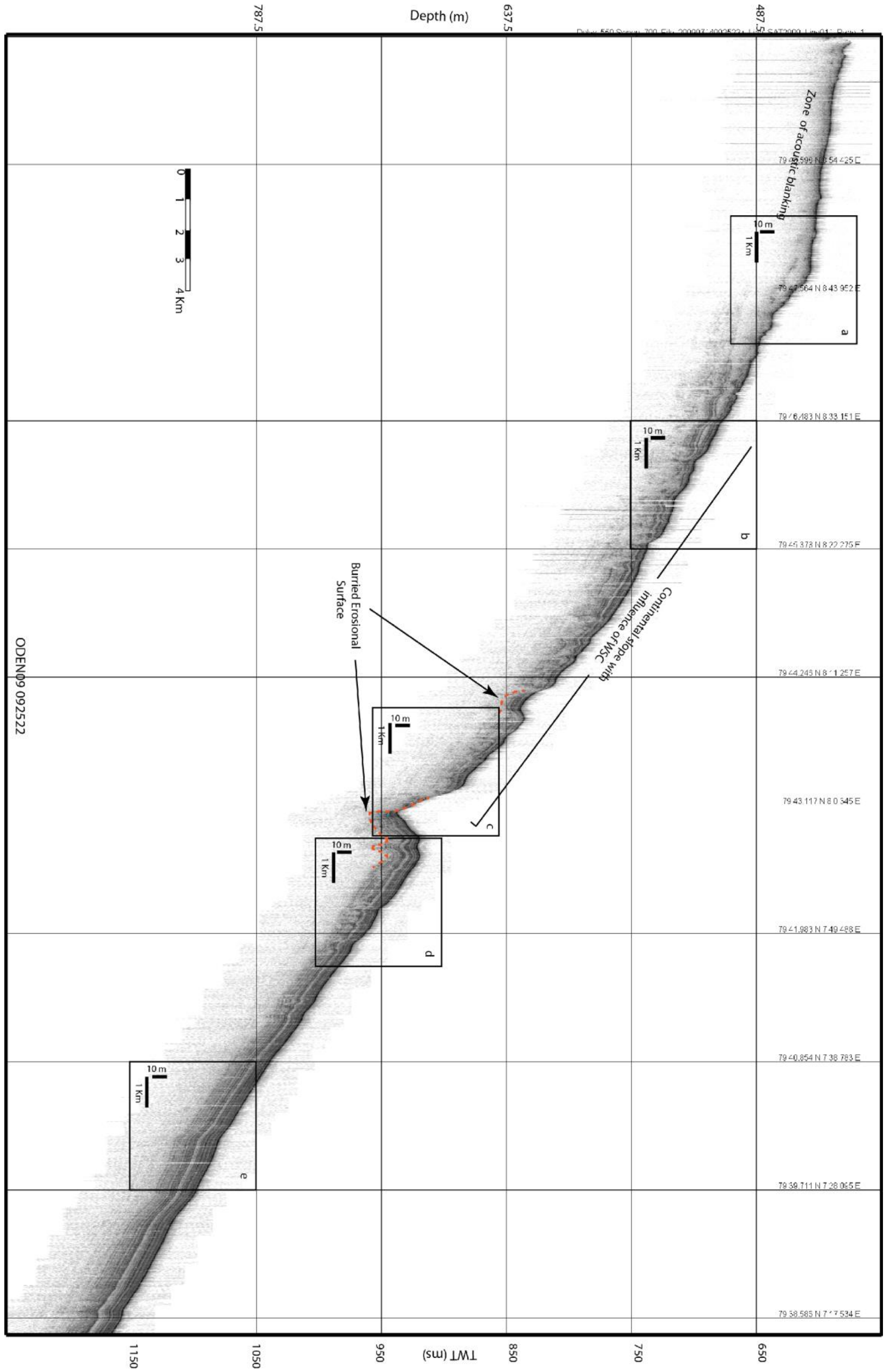


Figure 11. ODEN09-092522 subbottom profile. Note that small boxes (a to e) represent different acoustic signatures and distinguished facies described in the table 2. The orange dashed line shows the buried erosional surface created by mega iceberg.

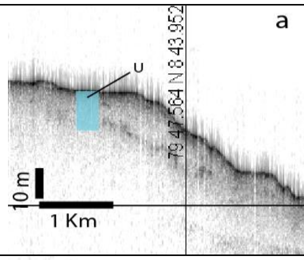
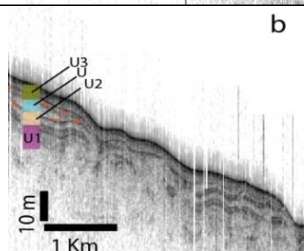
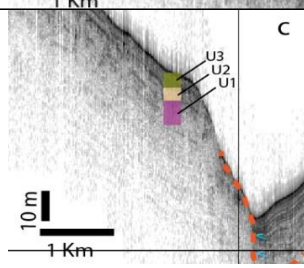
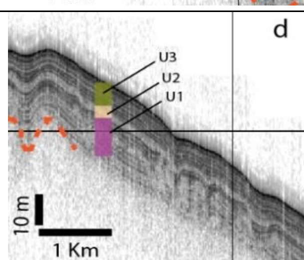
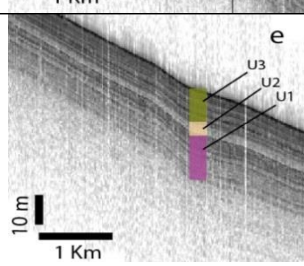
<table>
<tr><th colspan="2">Acoustic Units</th><th>Acoustic signatures</th><th>Description</th></tr>
<tr><td>Acoustic sequence 2</td><td>U</td><td>
</td><td>Acoustically homogenous sediments with absence of any significant internal reflectors while the seafloor reflector is distinct and irregular. This acoustic signature can be seen between~431-495 m.</td></tr>
<tr><td rowspan="4">Acoustic sequence 1</td><td>U3
U
U2
U1</td><td>
</td><td>Strong and irregular seafloor reflector with internally deformed (wavy) patterns. An acoustically transparent lenticular unit bounded by moderate strength reflectors (U facies part of extension of acoustic sequence 2 exists only in upper part). Such reflector patterns are visible between 495-607 m</td></tr>
<tr><td>U3
U2
U1</td><td>
</td><td>Limited and disturbed internal reflectors, the reflectors display acoustically chaotic pattern in deeper parts. The seafloor surface is relatively irregular. The depth for such patterns ranges ~ 607-712 m. The blue arrows show onlapping pattern of reflectors.</td></tr>
<tr><td>U3
U2
U1</td><td>
</td><td>The internal reflectors are parallel - sub parallel to the slightly irregular seafloor surface. The internal reflectors show slightly wavy pattern in most parts. This pattern is visible between ~ 698-750 m of the profile. The dashed line is interpreted as buried erosional surface created by mega icebergs.</td></tr>
<tr><td>U3
U2
U1</td><td>
</td><td>Acoustically well stratified reflectors that are parallel to the seafloor surface. The sea floor surface is relatively regular and undisturbed; this pattern can be observed below 750 m in profile.</td></tr>
</table>

Table 2. Acoustic signatures for the profile 092522 along with distinguished acoustic units, representative for most profiles in study area 1. Locations are shown in figure 11.

Profile 123433

This acoustic profile runs parallel to the above discussed profile-092522 and contains parallel to sub parallel internal reflectors. The thickness decreases where ploughmarks occur towards the upper continental slope. The deepest ploughmarks with depth ~37 m and width ~1 km exits at the depth between 684–712 m (Figure 12). The direction of past iceberg movement was sub perpendicular to this profile, as shown in figure 10.

Profiles 201043 and 132734

These profiles are almost parallel and close to each other; therefore the imaged structures are similar. Both profiles display well stratified semi convex homogenous sedimentary cover on the lower continental slope below ~850 m water depths. The internal reflectors are parallel and continuous, thus indicating no major deformation as compared to the moderate to highly deformed reflector patterns in the upper part. These profiles contain a zone of acoustic blanking and ploughmarks (Figures 13 & 14).

Profile 181838-182752

This profile displays variation in internal reflector patterns i.e. the upper reflections are sub parallel to irregular seafloor surface, while the reflections become chaotic in the deeper part between 562 to 675 m. Below 675 m the signal penetration become more with parallel to sub parallel upper internal reflectors overlying the lower hummocky pattern reflections (Figure 15). Thickness increases down slope just like other profiles.

Profile 111110-131811

This particular profile is oriented SE -NW along the continental slope while its upper part is close to the Kongsfjorden Trough Mouth Fans (TMF); sediment source (Figure 9). The seafloor surface is highly deformed and displays ridges and grooves between 1000-1100 m water depths. Its upper continental part consists of moderate to low relief wavy internal reflectors, while these internal reflectors vanish in sediments creating zone of acoustic blanking at water depths between 1050-1088 m. The reflectors are extremely compacted at the water depths of ~1220-1225 m. In the deepest part below 1237 m the reflectors become continuous and parallel-subparallel to the seafloor surface with higher acoustic penetration of ~23 m (Figure 16).

Profile 220544-231949

Just like most of the profiles in study area 1 this profile consists of continuous, parallel to sub parallel reflections in the lower most part which turns into wavy and chaotic in the upper part. The uppermost part between 437-498 m is acoustically featureless with sharp and uneven seafloor surface. A 19 m depression on seafloor surface is visible at the water depth of 675-693 m and this morphology represents past iceberg ploughing action (Figure 17).

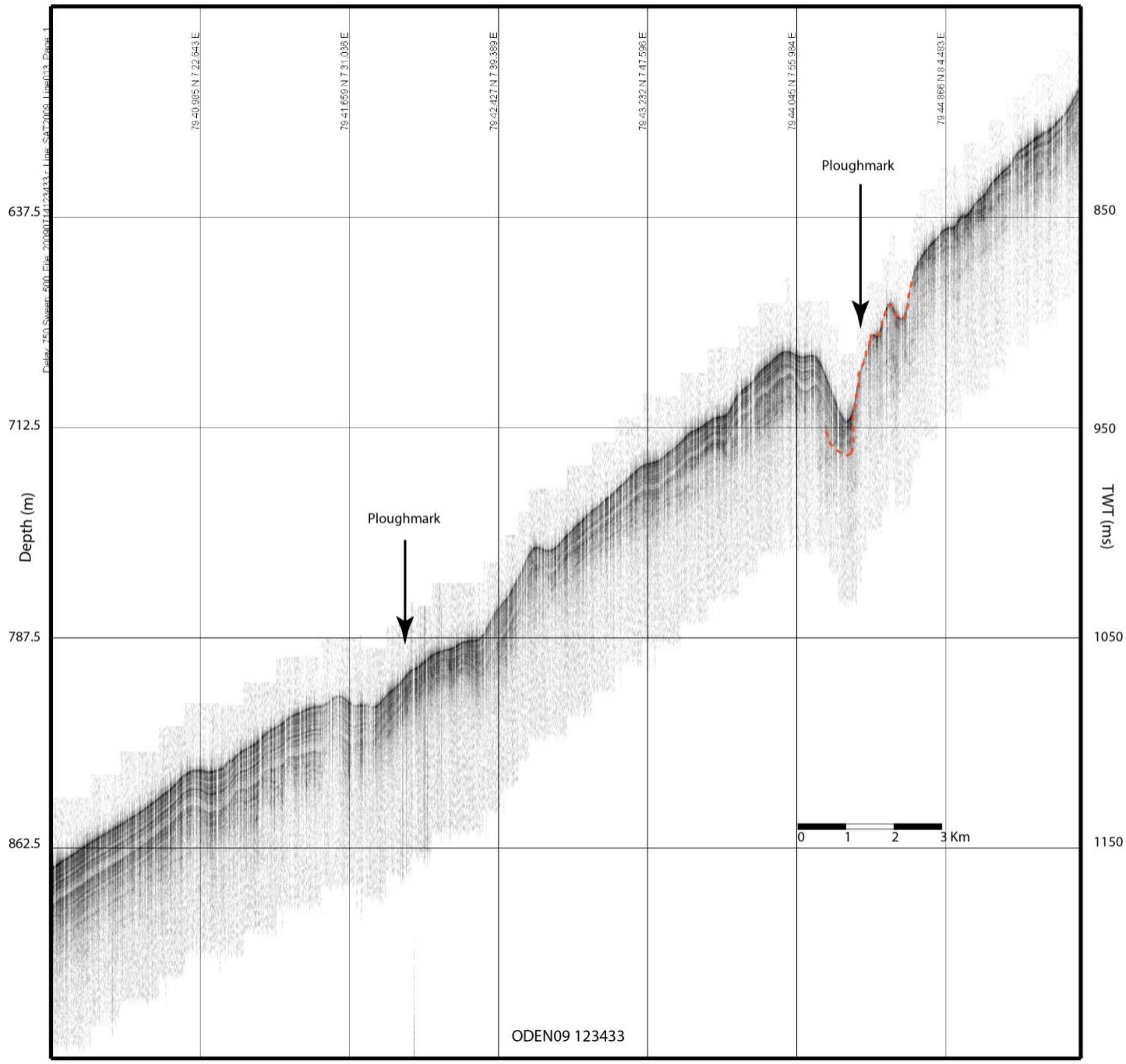


Figure 12. ODEN09-123433 subbottom profile. The orange dashed line shows the erosional surface created by ploughmarks. For location of the profile see figure 9.

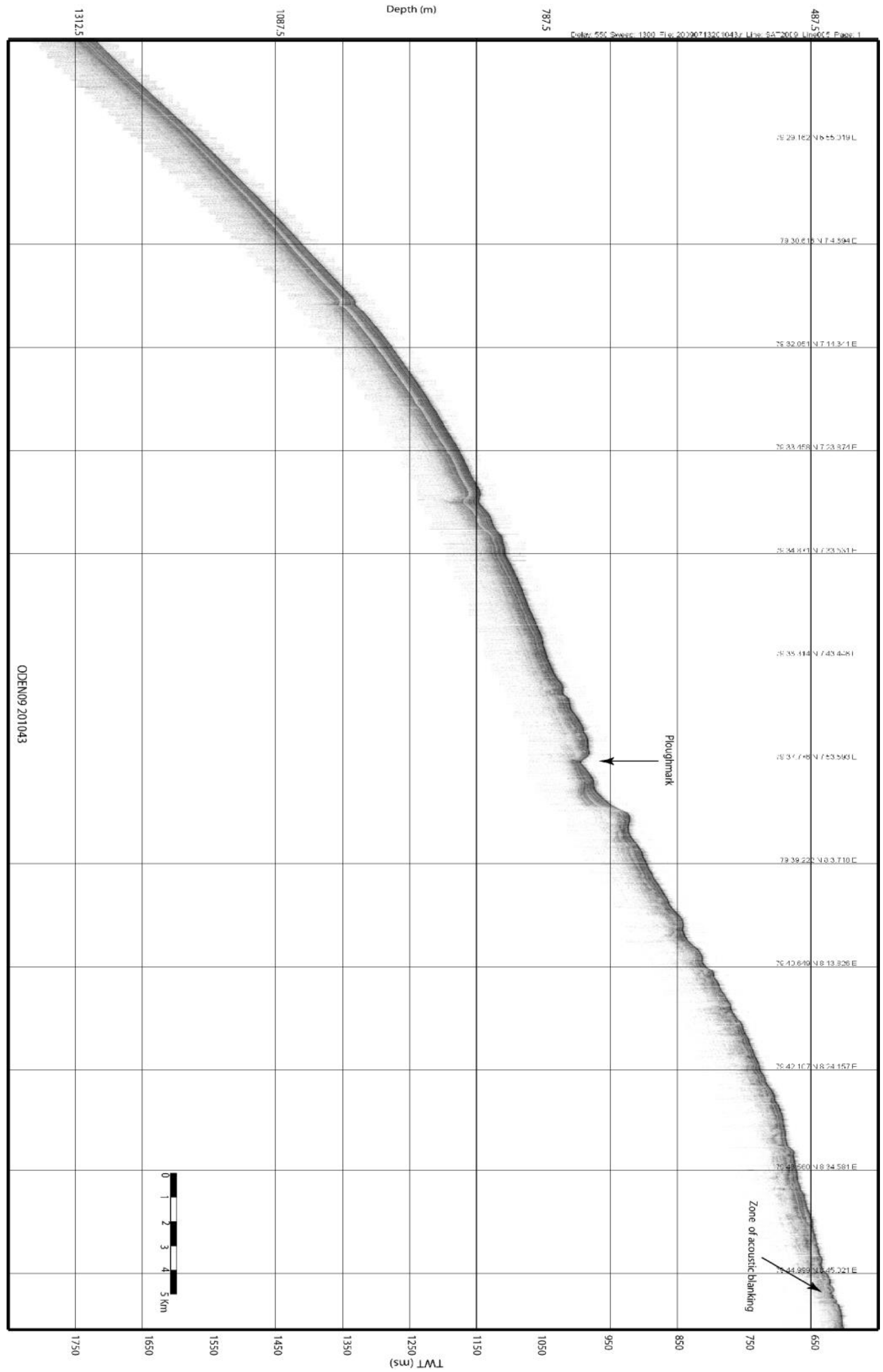


Figure 13. ODEN09-201043 subbottom profile showing ploughmark and zone of acoustic blanking. For location of the profile see figure 9.

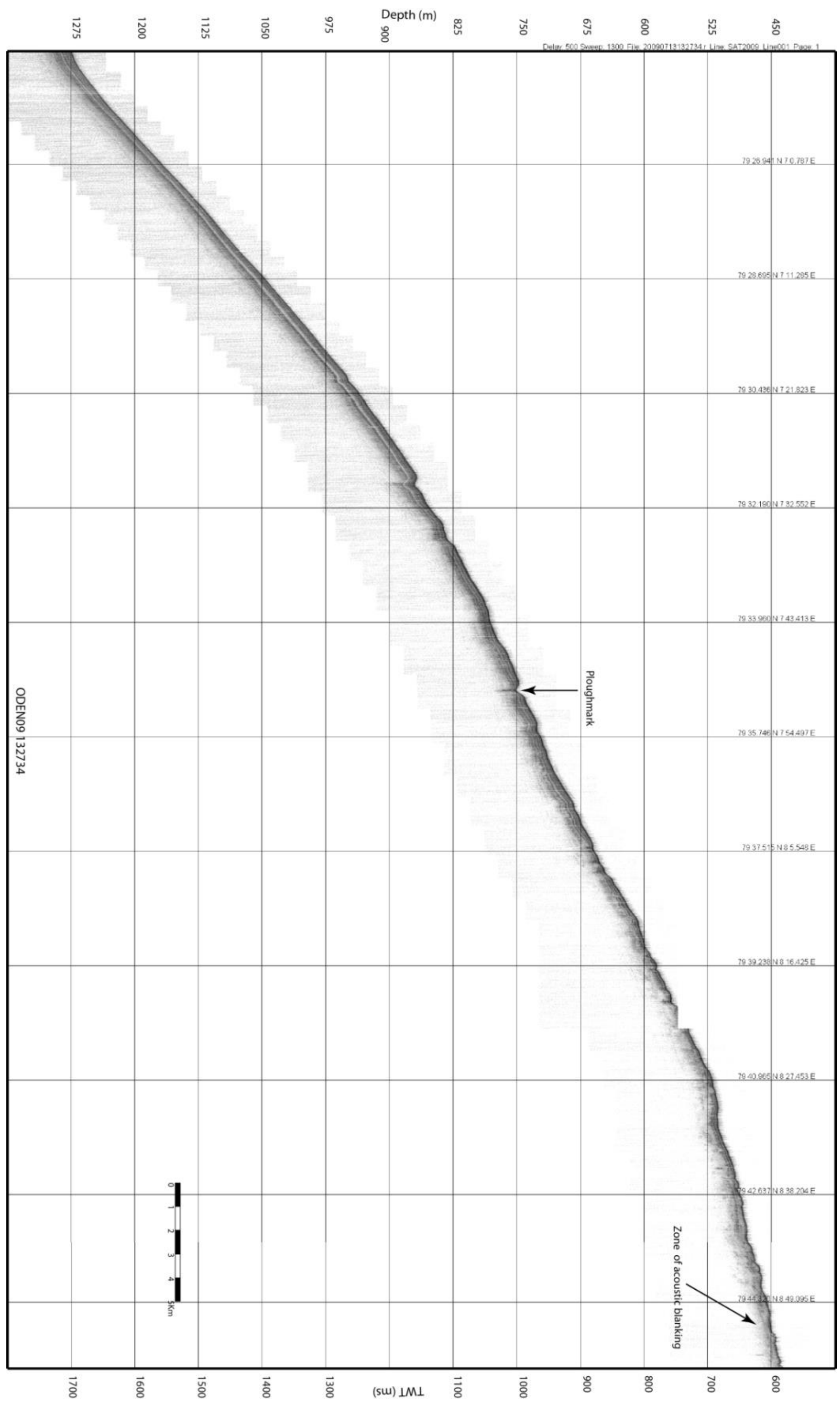


Figure 14. ODEN09-132734 subbottom profile showing ploughmark and zone of acoustic blanking. For location of the profile see figure 9.

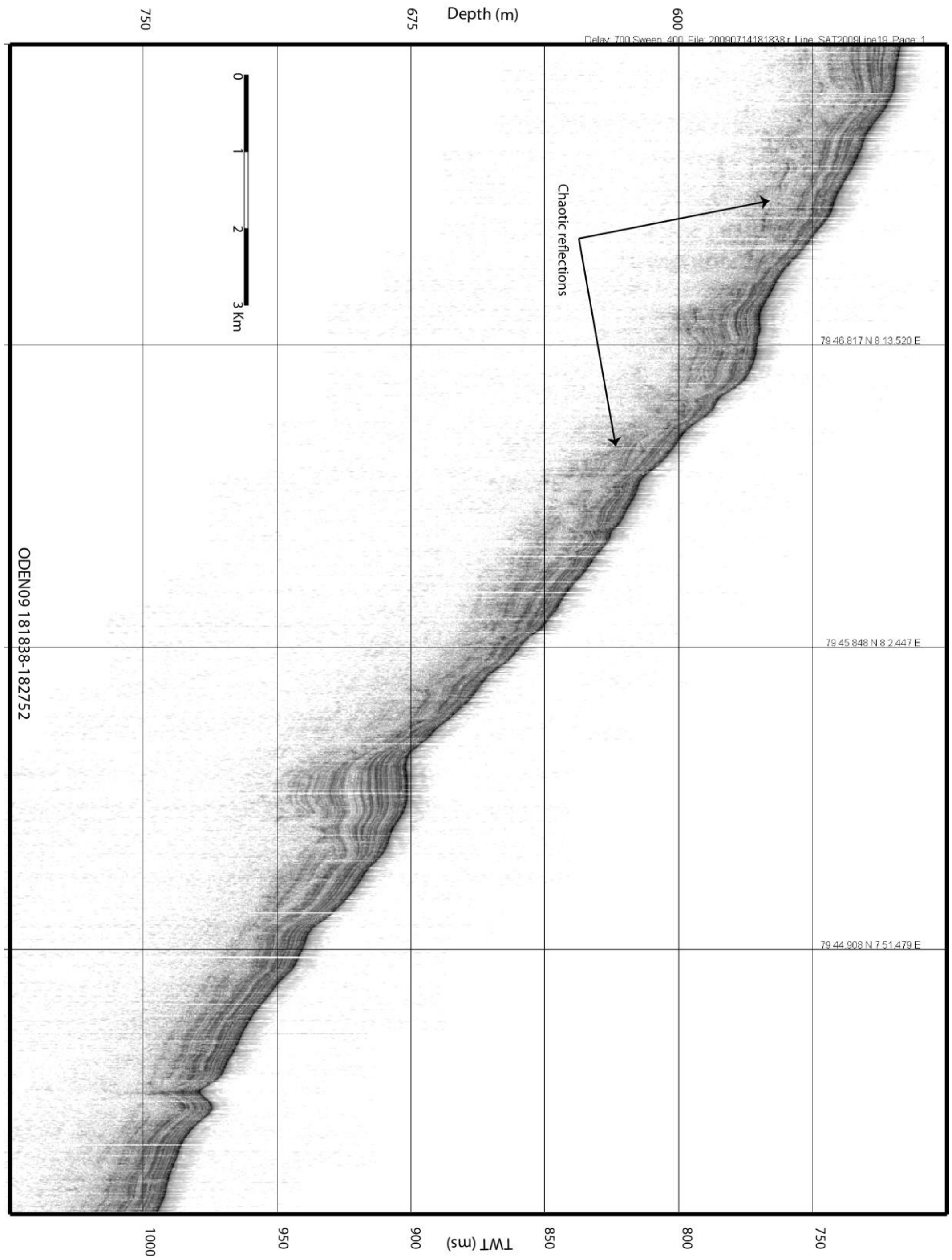


Figure 15. ODEN09 181838-182752 subbottom profile. For location of the profile see figure 9.

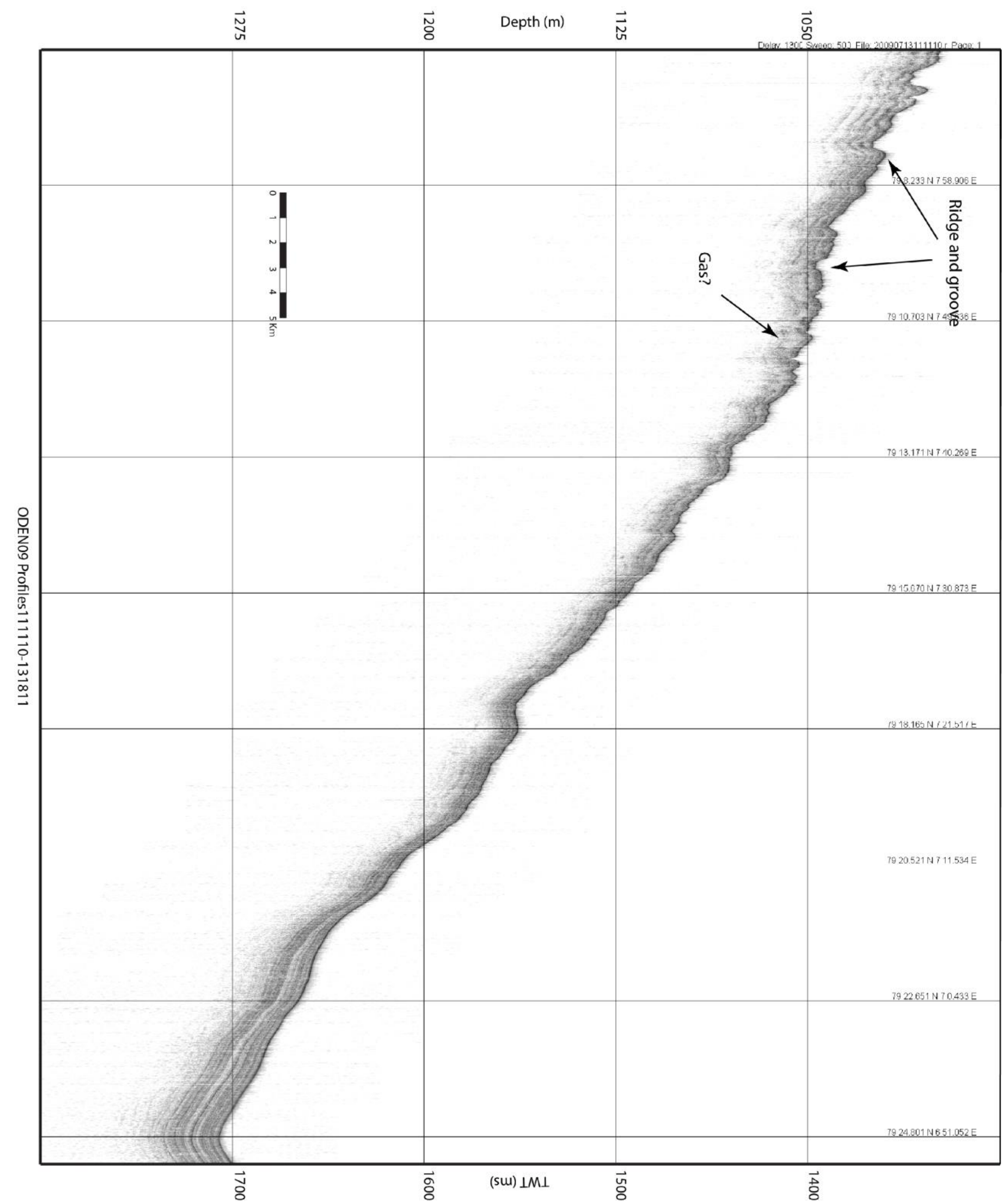


Figure 16. ODEN09 111110-131811 subbottom profile showing ridge and groove features. For location of the profile see figure 9

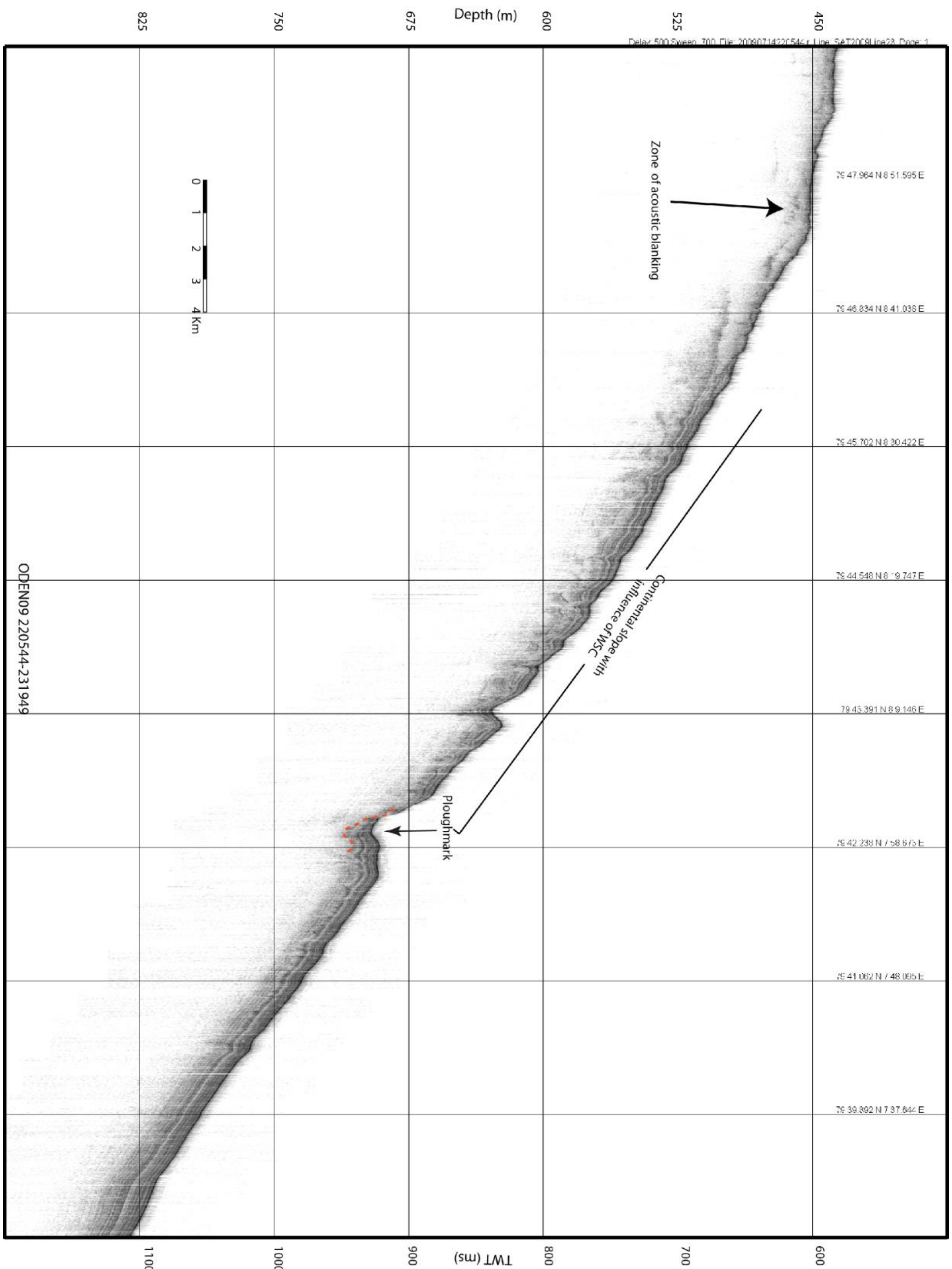


Figure 17. ODEN09 220544-231949 subbottom profile showing ploughmark and zone of acoustic blanking. For location of the profile see figure 9.

4.1.2. Acoustic units' description

4.1.2.1. Acoustic sequence 1

Unit U1

Unit U1's acoustic facies in the lower continental slope is distinguished by parallel-subparallel reflectors and continuous stratification, while the stratification becomes deformed and diffuse above approximately 760 m in most of the profiles. This unit is bounded by upper moderate strength reflector and weak bottom reflector. It is assumed that its lower boundary may have buried erosional surface of past ploughmarks as shown in profile 092522 at a depth of 712-718 m. This acoustically stratified unit thickens down slope and various from 5 to 15 m. In upper part of the continental slope this unit lacks the internal stratification and the reflectors become chaotic (Table 2).

Unit U2

This particular unit consists of acoustically transparent facies sandwiched between upper unit U3 and lower unit U1 and bounded by sharp strength reflectors in the lower continental slope. In middle part of the continental slope this unit becomes faint, less prominent and hard to trace out as the bounding reflectors are rarely visible, while in the upper part of the slope the bounding reflectors turn sharp and wavy. This unit becomes more evident in all profiles except profile 111110-131811. Thickness for this acoustic unit varies from 2 to 5 m.

Unit U3

The facies in unit U3 in the lower continental slope is characterized by continuous, well stratified and parallel reflectors bounded by a smooth to irregular seafloor reflector at the top and moderate strength reflector of unit U2 at the bottom. This unit is about 10 m thick in the lower part of the slope while the thickness reduces to ~2 m in the upper part where the internal reflectors become less prominent with distinct and uneven seafloor reflector. This unit fills in the pre-existing topography (graben) and its uppermost surface represents the recent sea floor at the water depth of 627-637 m in profile 092522.

4.1.2.2. Acoustic sequence 2

Unit U

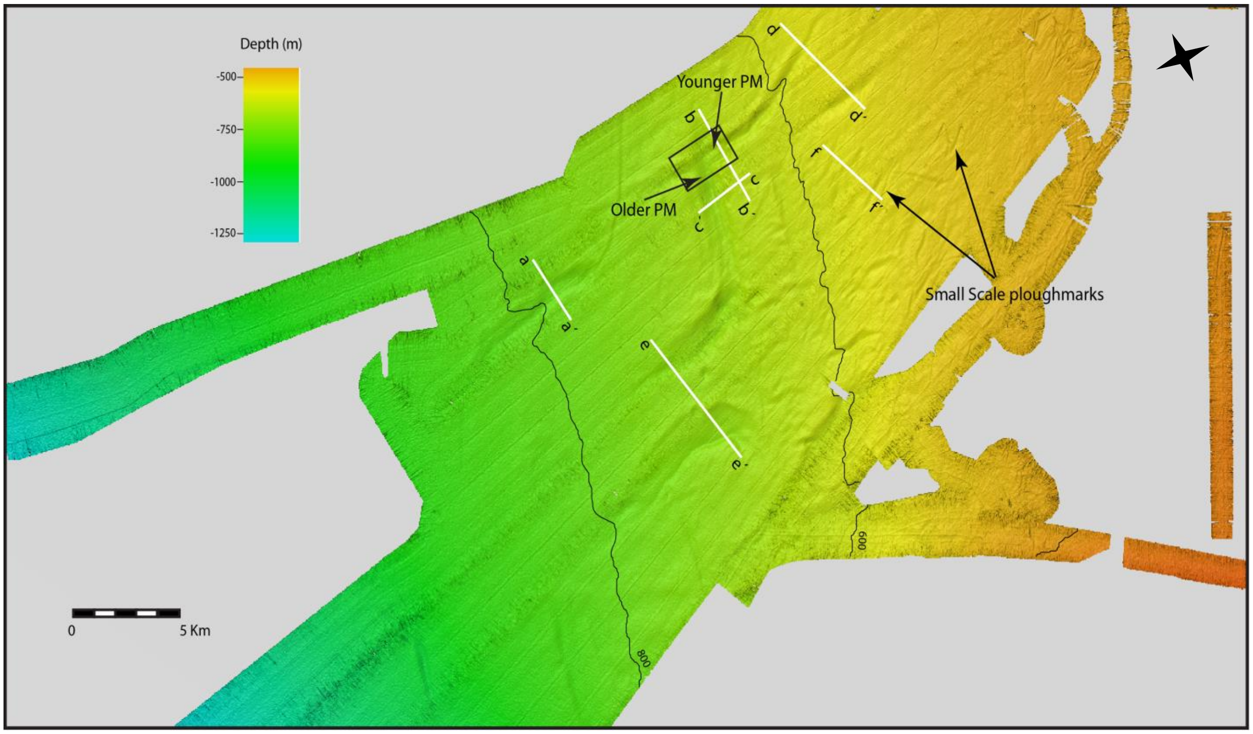
This unit represents acoustically homogenous facies with no significant internal reflectors and blanks out the underlying stratigraphy. This unit can be seen in almost all profiles present in the study area 1 except in profiles 123433 and 181838-182752. The penetration ranges from 18 to 11 m. However, minor internal reflectors are visible in some part of this facies. This unit is bounded by an irregular seafloor reflector with several small mounds at the top, whereas its lower boundary is unknown. The lense shaped extension of this particular facies can be seen in upper part of profiles 092522 and 220544-231949. This particular facies occurs as semitransparent unit with internally well deformed reflectors in the uppermost part of the profile 111110-131811, while these reflectors are invisible between the depths of 1050-1088 m as shown in figure 16.

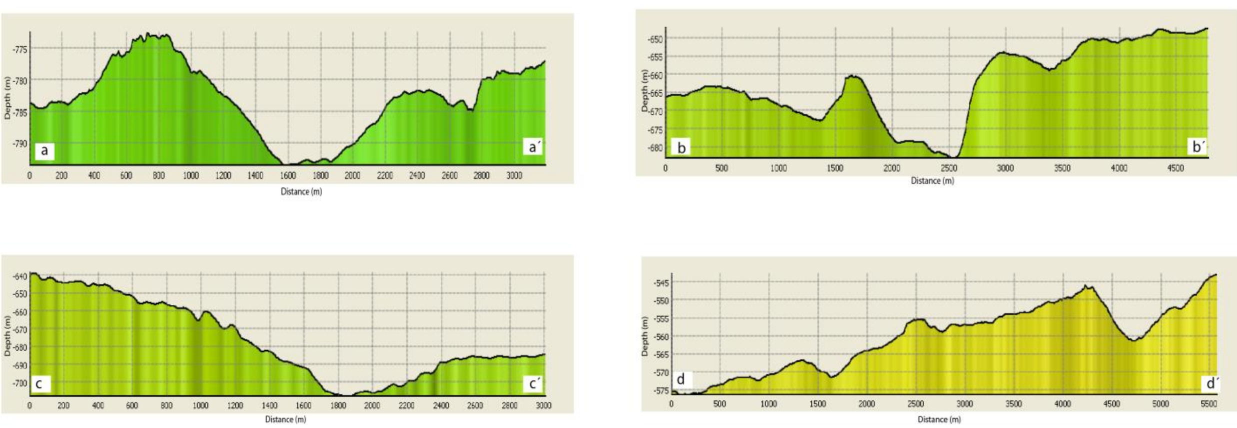
4.1.3. Submarine landforms

4.1.3.1. Description

The submarine landforms of various dimensions in area 1 are interpreted as ploughmarks created by paleo mega icebergs as shown in high resolution multibeam bathymetry data (Figure 18). These are of two types; large scale ploughmarks and several small-scale linear to curvilinear features present on shallower depth. Widths are generally less than 1200 m and relief is usually less than 35 m, whereas small-scale features are 70 to 250 m wide and 3 to 8 m deep with different orientations (Figure 18). These submarine landforms are present between the water depths of 400 to 1000 m as shown in multibeam data (Figure 18). These ploughmarks are overprinted by recent sediments. Most of subbottom profiles are running across these features and reveal subsurface acoustic signatures. It is obvious from several subbottom profiles in area 1 that the ploughmarks display almost similar dimensions as in multibeam data with maximum depth ~35 m and width ~1100 m (Figures 11 & 12).

Based on high resolution swath bathymetry data, Dowdeswell et al (2010a) described four types of submarine landforms identified on northwest and north Svalbard seafloor e.g lineations, iceberg ploughmarks, moats and largely featureless seafloor (hemipelagic deposits). Large ploughmarks exist between water depths of 600 to 800 m around the Yermak Plateau with smaller features at shallower depths (Dowdeswell et al., 2010a).
Study area 1 on northwestern part of Svalbard also displays same features (Large and small- scale ploughmarks) as shown in figure 18 and also discussed by Dowdeswell et al (2010a). Some of these features cross cut the older ones, thus representing a relatively younger ploughing event (Dowdeswell et al., 2010a).





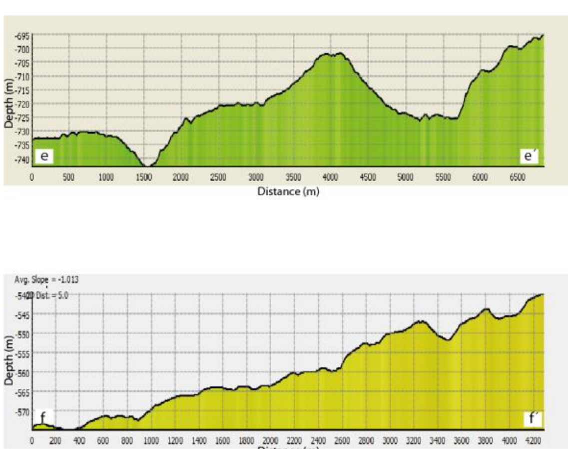


Figure 18. Submarine landforms; large ploughmarks along with small-scale linear to curvilinear features (ploughmarks) on the NW Svalbard continental slope as seen from multibeam data. Note that the younger ones cross cut the older ones, suggesting relative younger age as shown in the black box. PM; Ploughmark. Sea floor depth profiles along the line a-a´, b-b´, c-c´, b-b´, e-e´ and f-f´ are shown below the multibeam image. For location map see figure 1.

4.2. Study area 2

4.2.1. Description

The data consists of two selected profiles 143144 and 031910, oriented towards the deepest part of the Fram Strait, the Molloy deep (1200-2585 m) along the NW Svalbard continental slope (Figure 9). Profile 143114 is aligned almost E-W on the Vestnesa Ridge. This profile displays internally stratified sediments with sub parallel reflectors to the seafloor. The surface reflector is irregular and wavy. The acoustic penetration becomes limited internally between 1218 and 1350 m water depths at the upper continental slope. The sediment thickness varies i.e. thicker at the crests and troughs (~34 m) and thinner at the deepest part of the section as well as on the upper continental slope (~18 m) as shown in figure 19. Low amplitude sediment mounds (wave length~3 km, amplitude ~9 m) can be observed between the water depths of 1275-1350 m on the upper slope where seafloor reflector is relatively convex and further below internal reflectors become less significant with very low relief. At water depths of 1237 to 1284 m the internal reflectors are bent downward with a depression of 6 m on the seafloor. A pipe or chimney like feature is recognizable on the crest of sediment drift at the Vestnesa ridge. This acoustic pipe is about 37 m vertically long and < 450 m wide in profile (Figure 19). The reflectors are convergent at the upper continental slope and divergent down slope between 1350 to 1387 m. On the other hand at depths below 1235 m from the crest (Figure 19) the reflector pattern is inverse i.e. divergent at the crest of sediment drift and convergent down slope.

Profile 031910 consists of uneven seafloor topography with parallel and continuous subbottom internal reflectors. This profile lies on the deepest part of the continental slope towards the Molloy Deep (MD) as shown in figure 9. Stairs like reflectors at the deepest section (2531-2569 m) of this profile reveal slump scars resulted from mass movement. These slump scars are clearly visible on adjoining multibeam bathymetry data (Figure 20).

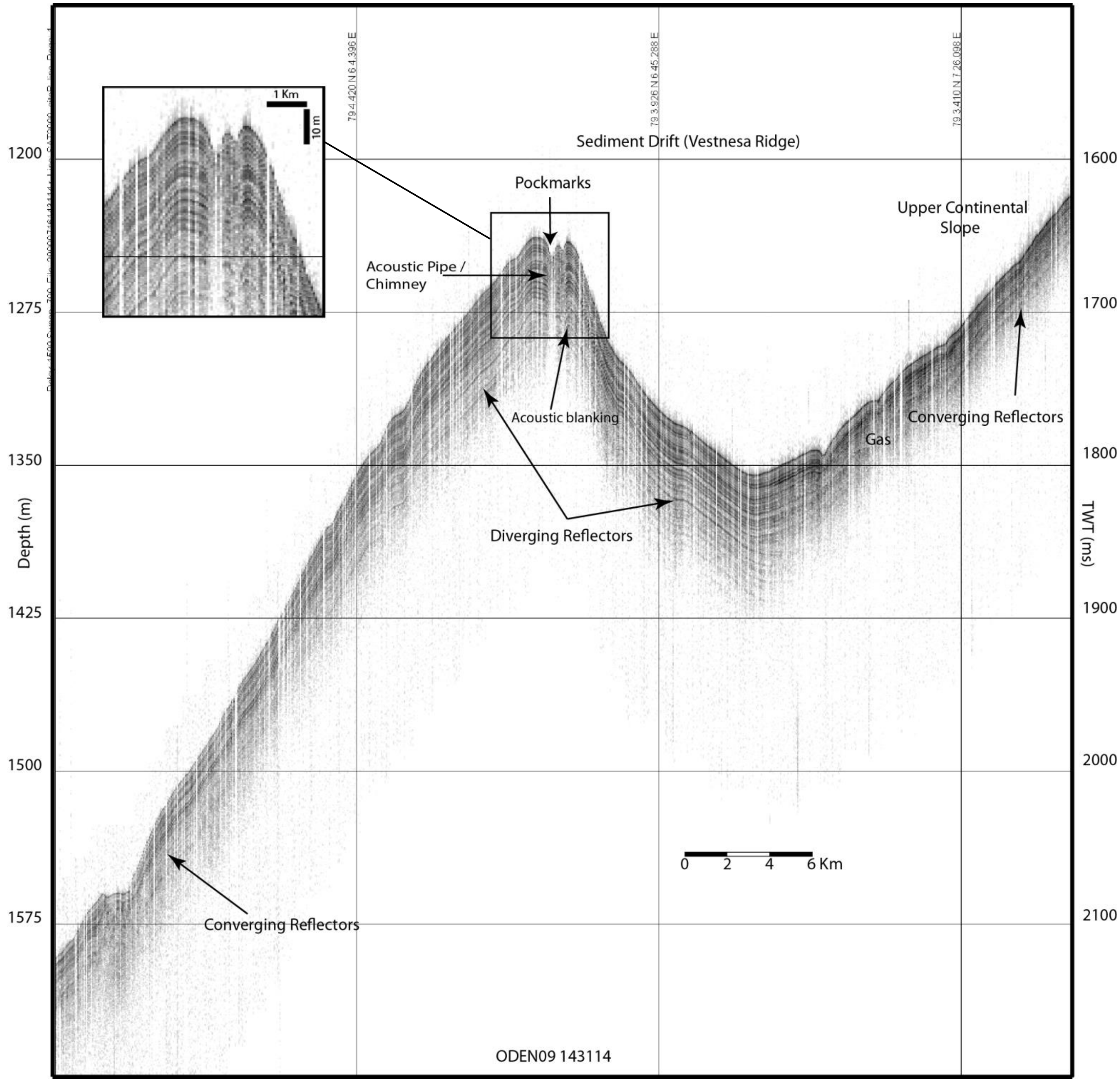


Figure 19. ODEN09- 143114 Subbottom profile across the Vestnesa Ridge, NW Svalbard continental slope. For location of the profile see figure 9.

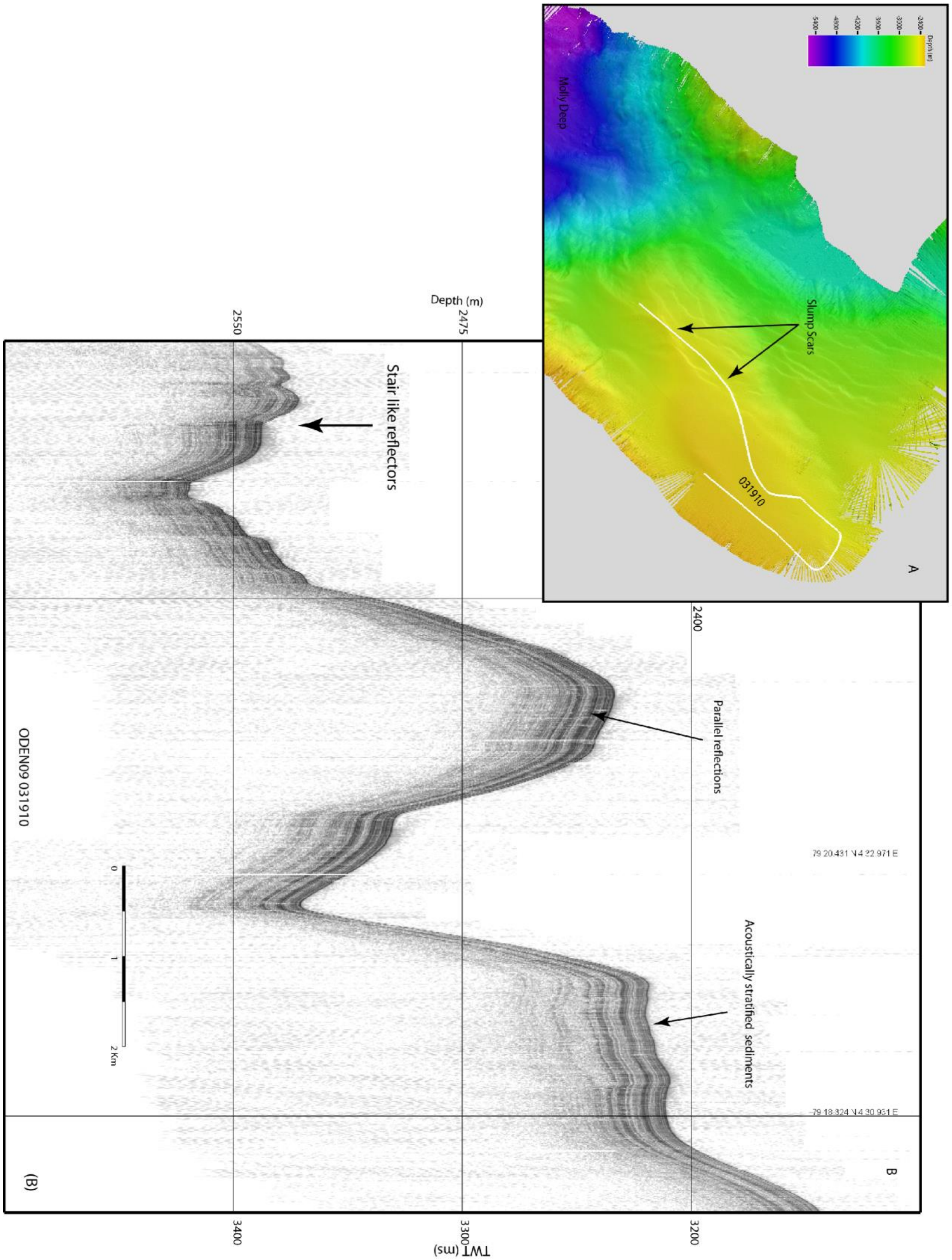


Figure 20. A: Location of the profile 031910 along with multibeam bathymetry data showing slump scars. B: Subbottom profile displaying acoustically stratified sediments and stair like reflectors. For location of the profile see figure 9.

5. Discussion

5.1. Acoustic interpretation for area 1

Units U1, U2 and U3 dominate all acoustic profiles in study area 1 and these facies display a homogeneous acoustic signature in the deepest part of the continental slope towards the Fram Strait, while in the upper continental slope their acoustic patterns are quite disturbed. The penetration depth of the acoustic pulses is limited to a maximum depth of about 50 meter. The lower part of the unit U1 is assumed to include buried erosional surface created by paleo mega icebergs (orange lines in figures 11 and 12) although due to limited penetration these features are not visible in any profiles. The internal reflector patterns of the above mentioned facies show onlapping geometry with buried erosional surfaces (Figures 11). Similar acoustic signatures on chirp data at the depth below 1000 m from central arctic ocean has been described by Jakobsson (1999), where acoustically transparent unit is sandwiched by stratified units, thus representing similar low energy environment for units U1, U2 and U3 at the lower continental slope.

5.1.1. Bottom current influence

Units U1 and U3 consist of chaotic reflections at the upper continental slope which become faint and less evident (Figure 11), representing an unstable environment i.e. sedimentation remained under the influence of bottom currents, whereas acoustically transparent unit U2 can be traced out in this region with uneven reflector pattern and represents hemiplegic sediments. Besides, the distortion in reflector patterns and the fact that the thickness of each facies decrease in the upper continental slope suggests that this part of the slope remained under the influence of bottom currents (WSC). Sediments on the eastern part of the Fram Strait are mainly under the influence of ongoing down faulting and bottom current activity (Geissler et al., 2011). The WSC plays vital role in this region with great impact on sedimentation.

The interpreted lower extension of the WSC along the continental slope has been illustrated in figure 22 with small arrows. Using acoustic limits A, B and C from the studied profiles several curve lines have been drawn between them on multibeam data, each curve line represents the change in acoustic signature along the slope (Figure 22). Relatively warm and northward flowing current (WSC) is mainly responsible for affecting the morphology of the Vestnesa Ridge (Bunz et al., 2012). The lower extension of the WSC most likely follows the bathymetry contours between 650-1200 m in the studied areas as shown in figure 22 (the curve line between acoustic limits B and C). Moreover the interpreted depth for the lower boundary of the WSC is well in line with the oceanographic cross section 1 (out of 5) of Cokelet et al (2008) which has been obtained using CTD (conductivity, temperature, depth) casts from the USCGC Healy during October to November 2001 and shown in figure 21. These sections show a sequence of potential temperature (θ_0) following the Svalbard Branch as it flows into the Arctic Ocean from section 1 in the south to section 5 in the northeast. At the right side of the section 1 the Atlantic water's warm core is concentrated over the continental slope (Figure 21). The Atlantic Water (AW) carried by the WSC can be distinguished from the Arctic water on the basis of its relatively high temperature and salinity ($\theta_0 \geq 2$°C, S $\geq$ 34.88 psu). Comparatively cold and fresh water has been observed both below and above the AW. Surface water cools as a result of ice melting and atmospheric heat exchange (Cokelet et al., 2008).

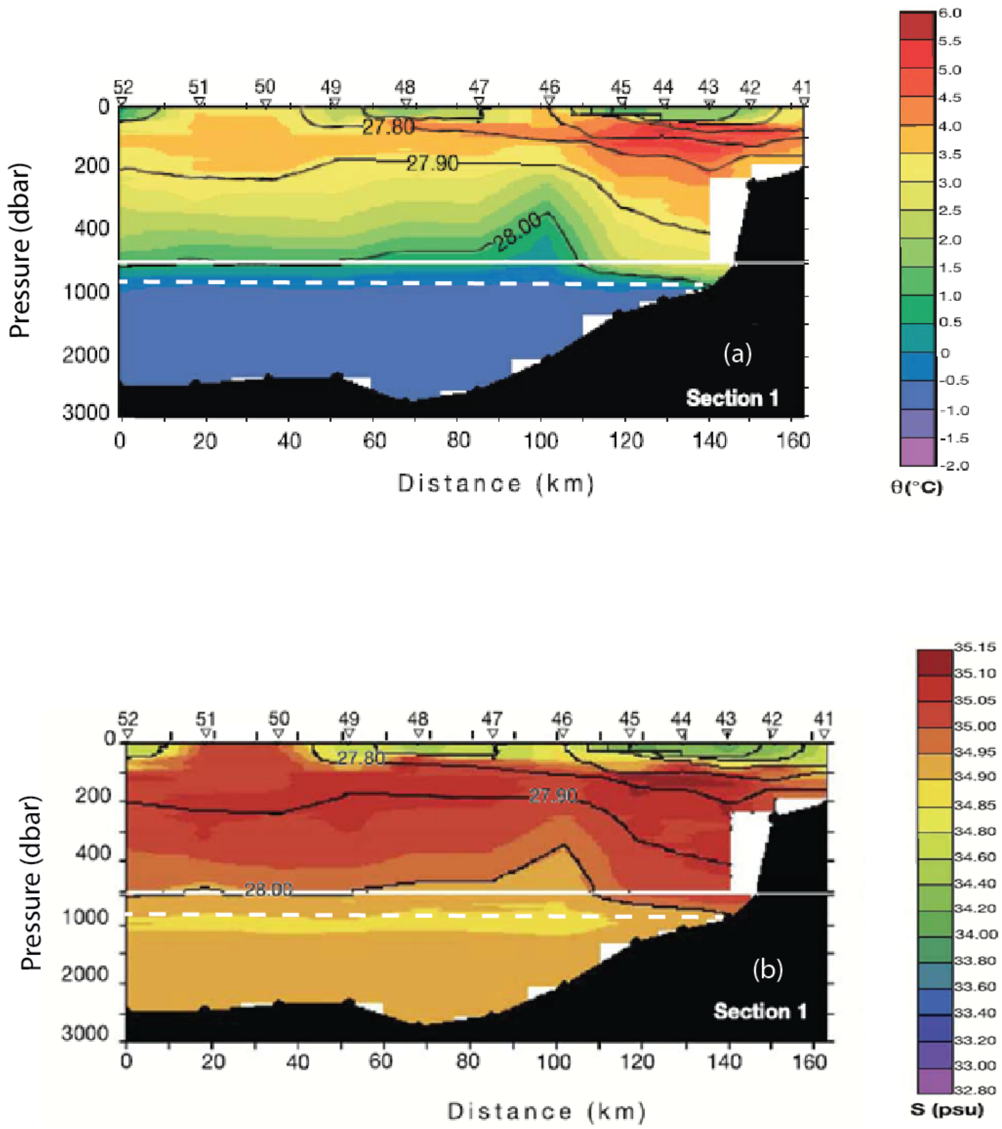


Figure 21. Section 1 by Cokelet et al (2008) showing a) potential temperature (θ_0 °C referred to 0 dbar pressure), and b) salinity (psu) variations across the path looking downstream in the WSC on the slope 11 October to 2 November 2001 (Modified after Cokelet et al., 2008). Warm and saline Atlantic Water flows along the right edge of the section 1 that stretches from deep water on the left, over the continental slope to the shelf break at about 200 dbar (≈200 m). For location of the section see figure 2. Note the break in the scale below 500 dbar (solid white line). The maximum detected depth of WSC at about 800 m is marked by a dashed white line.

5.1.2. Presence of gas

Facies U represents the uppermost sediment unit in profiles. There could be several interpretations for this acoustic featureless unit e.g. the presence of the gas trapped in sediments along the upper part of the continental slope give rise to such acoustically transparent feature. Similar acoustic behavior of gas masking has been illustrated by Jakobsson (1999) using chirp data from Lomonosov ridge slope in the central Arctic ocean, where reflectors below 1025 m water depth dies out due the presence of gas in marine sediments. The limited penetration of unit U and its irregular surface reflector in acoustic sequence 2 can be correlated to the reflector pattern and acoustic facies (Unit B) discussed by Dowdeswell et al (2010a) across the crest of the Yermak Plateau. They interpreted that the low acoustic penetration might be due to the high acoustic impedance of diamictic or glacially disturbed sediments. Several small-scale submarine features are identified on multibeam bathymetry data where this acoustic unit exits (Figure 18). Meanwhile, irregular seafloor reflector of unit U in profiles 132734 and 201043 confirms these small-scale features. Moreover, this transparent acoustic unit (U) is similar to the transparent facies (Unit C) from the southwestern Yermak Plateau discussed by Dowdeswell et al (2010a), interpreted as debris flows which suggests that reworking of pre-existing sediment occurred.

The lens shaped extension of unit U in the upper most part of the slope in profile 092522 as illustrated in table 2 suggests debris flow. In addition similar transparent acoustic features were also identified on acoustic records by Dowdeswell (2010b) on the Kangerlussuaq slope from the East Greenland at water depths of 1850 m, which were also interpreted as debris flows. Debris flows are considered a significant part of the sedimentary architecture of trough mouth fans (TMFs) around the Norwegian- Greenland Sea and are largely composed of dimictic material derived from glacially eroded sediments in fast flowing ice streams (Dowdeswell et al., 2010b).

Based on the above mentioned acoustic observations we can interpret that this unit (U) consists of sediments with trapped gas and debris flow.

5.1.3. Morphologic features in area 1

The combination of acoustic subbottom profiles along with multibeam bathymetry data provides good visualization for detailed study of submarine landforms. The width of these large surficial features are less than 1200 m while the relief is generally less than 35 m, whereas small scale features are 80-250 m wide and 4-12 m deep (Figure 18). The linear to curvilinear landforms shown in multibeam data can be interpreted as iceberg ploughmarks. In addition, the acoustic subbottom profiles provide pictures of subsurface structures along with seafloor morphology, thus the dimensions for these ploughmarks are very close to dimensions of landforms observed in their associated multibeam data (Figures 11 and 12).

Dowdeswell et al (2010a) described two types of submarine landforms i.e. large and small-scale linear to curvilinear features based on their dimensions and orientation from the Yermak Plateau and the northern Svalbard margin at water depth less than 800 m and these features are interpreted as iceberg ploughmarks.

1. Large and curvilinear ploughmarks on the southern flank of the Yermak Plateau (600 m wide and 20 m deep), while on the northern Svalbard these features are 1 km wide and over 80 m deep.
2. Small-scale highly irregular ploughmarks on the northern Svalbard shelf and oriented 90 ^{o} to large ones. These features are 100 m wide and 10 m deep.

These ploughmarks cross cut each other when they occur together and suggest relative age. The deepest ploughmark is about 100 m deep relative to the seafloor and observed on multibeam bathymetry data from the northern Svalbard margin with orientation NNE-SSW (Dowdeswell et al., 2010a).

The ploughmarks identified in the study area 1 have been summarized in figure 22 are the same as those described by Dowdeswell et al (2010a). The subbottom profiles confirm these features and provide subsurface acoustic signatures.

Landforms created by ice on the seafloor may be preserved on the sea floor if the bottom currents keep removing subsequent sediments from settling (Dowdeswell et al., 2010a). The deepest iceberg ploughmarks from the central Arctic Ocean are mapped by Jakobsson et al (2010) in south of Lomonosov Ridge off Greenland at a water depth down to 1045 m on multibeam imaging from Morris Jesup Rise. Furthermore, sediment cores from ice grounded regions reveal MIS 6 age for the events i.e. deepest ploughmarks on the Morris Jesup Rise, central and southern Lomonosov Ridge and formation of Mega Scale Glacial Lineation (MSGL) on the Chukchi Borderland and the Yermak Plateau (Jakobsson., et al 2010). Dowdeswell et al (2010a) suggested a Saalian (MIS 6) age for the ice produced lineations on the ridge crest of the Yermak Plateau, further referring to the mapping work done by Ottesen and Dowdeswell (2009) regarding subglacial lineations and the grounding wedge zone on the shelf edge of northwestern part of the Spitsbergen and interpreted the Late Weichselian ice sheet on the Svalbard. The orientation of these lineations and past ice flow is different by 45º as compared to the lineations on the Yermak Plateau. The ice was less extended at the Last Glacial Maximum when it reached the shelf edge in the northwest Svalbard, whereas during an earlier glacial phase the extension of ice was about 80 km further offshore where lineations exist on southern part of the Yermak Plateau (Dowdeswell et al., 2010 a). Several ploughmarks created by deep keels of mega bergs have been observed on the seafloor along the flanks of the Yermak Plateau. The timing for this ploughing action is not easy to construct directly as bergs create erosional landforms, however these ploughmarks cross cut Saalian lineations on Yermak Plateau, indicating a Weichselian age (Dowdeswell et al., 2010a). Large ploughmarks exist between water depths of 600 to 800 m around the Yermak Plateau with smaller features at shallower depth (Dowdeswell et al., 2010a). According to Dowdeswell et al (2010a) these ploughmarks are either the result of multiple keels of a single megaberg or by several ice bergs trapped together within multiyear sea ice.

5.2. Acoustic interpretation for area 2

5.2.1. Vestnesa Ridge and current impact

The symmetrical mound like feature in profile 143114 at water depths between 1238-1355 m is interpreted as sediment drift controlled by along slope currents, thus supports the interpretations of Howe et al (2008) and Bunz et al (2012). The width of this mound is 15 km and the relief is~113 m. The acoustic penetration within this mound ranges from 17 to 38 m (Figure 19). Howe et al (2008) interpreted similar mound like feature based on a TOPAS subbottom profile from the Vestnesa Ridge as a current controlled sediment drift (1120-1360 m). The drift deposits formed due to bottom currents resulting from thermohaline circulations in the deep oceans are termed as contourite drifts (Faugères et al., 1999). Moreover, gravity core 067 from the crest of the drift studied by Howe et al (2008) suggests that the sediments consist of contourites and turbidites.

The Vestnesa ridge is an elongate submarine sediment drift (SE-NW to E-W bending) on the western Svalbard, geographically located on eastern part of the Molloy Ridge and contains gas hydrate systems. It is also considered as one of the shortest segments of the slow spreading North Atlantic Ridge system. The relatively warm and northward flowing West Spitsbergen Current is mainly governing the morphology of the Vestnesa Ridge (Bunz et al., 2012). The physiography, sediments thickness (>2 km) and internal seismic structures of the Vestnesa Ridge indicate that it is a sediment drift formed by bottom currents during the late Miocene and Pliocene (Vogt et al., 1994).

A Gravity core 067 with recovery of 3.80 m from the Vestnesa Ridge drift (79º 00' 01" N and 06º 56' 84" E) at water depth of 1226 m has been studied by Howe et al (2008). This core is divided into following three facies S1-S3 by Howe et al (2008):
S1: consist of poorly sorted homogenous mud with scattered sub angular clasts and shelly debris. Howe et al (2008) interpreted this facies as glaciomarine muddy silty contourites deposited from the persistent flow of the bottom current (WSC), whereas the sub angular clasts are interpreted as ice rifted debris (IRD). S2: consists of moderate to well sorted

finely laminated silts with limited sub angular clasts. This facies is interpreted as fine grained muddy turbidites interbedded with glaciomarine hemipelagites. S3: consists of moderate to well sorted muddy sands with abundant angular to sub angular clasts and interpreted as sandy turbidite with IRD.

5.2.2. Morphologic features in area 2

A featureless vertical chimney at the crest of the Vestnesa Ridge sediment drift as shown in figure 19 is interpreted as an acoustic pipe associated with pockmarks. The same vertical fluid flow features (acoustic pipe) has been illustrated by Bunz et al (2012) on the crest of the Vestnesa Ridge along with significant gas accumulation using 2D Seismic data from the eastern onset of the Vestnesa Ridge.

Pockmarks are the results of escaping methane formed by decomposition of marine organic matter in the Vestnesa Ridge sediments (Vogt et al., 1994**).** According to the hypothesis of Vogt et al (1994) the methane gas generated at the depth below the Vestnesa Ridge, migrates along the base of the hydrates layer and collects below the anticline geometry of the ridge. Generally a biogenic origin has been suggested for these marine gas hydrates along the western Svalbard margin (Bunz et al., 2012). Pockmarks are interlinked with pipe or chimney like features in the subsurface, whereas on seismic data these features vertically crosscut the host sedimentary strata (Bunz et al., 2012). The crest of the Vestnesa Ridge consists of several pockmarks of various shape (circular, oval etc) and sizes (up to 700 m) while these features are absent on the flanks of the Vestnesa Ridge as well as adjacent to western continental slope (Bunz et al., 2012).

The Vestnesa Ridge is located close to the slow spreading axis of mid oceanic ridge and its hydrothermal circulations have great impact on the dynamics of gas hydrate and free gas system trapped in sediments (Bunz et al., 2012). Bunz et al (2012) suggested that the gas hydrates reduce the permeability of the marine sediments on the flanks of the ridge, thus affecting fluid flow and these gas hydrates prevent the vertical flow of gas to the seafloor at the flanks, while fluids migrate laterally and upwards to the slope in hydrate bearing sediments. On the other hand lateral migration of fluids cease at the crest of the ridge, consequently an overpressure gas trap is formed below hydrate bearing sediments. In response, either new chimneys are formed or former chimneys are used to release these pressures at the crest (Bunz et al., 2012). Several chimneys display acoustically blanked vertical columnar features originating from deeper subsurface and this effect could be the consequence of strong loss of acoustic energy within the chimneys (Bunz et al., 2012). Further studies of 3D seismic data revealed an inactive and buried pockmark along with others active pockmarks on the eastern part of Vestnesa Ridge. The seafloor of this inactive pockmark is relatively smooth due to infilling of recent sediments (Bunz et al., 2012).

The stair like features in profile 031910 at the depth below 2531 m along with chaotic topography associated with erosive scars on multibeam data (Figure 20) are indication of slides or slumps triggered by mass wasting phenomena on relatively steep slopes towards the Molloy Deep. The Vestnesa Ridge is characterized by features like pockmarks and slumps resulted from the decaying action of organic matter within drift (Howe et al., 2008). Slump deposits along the margins of the Vestnesa Ridge and northeast of Molly ridge might be the consequences of tectonic activity and methane hydrates (Vogt et al., 1994).

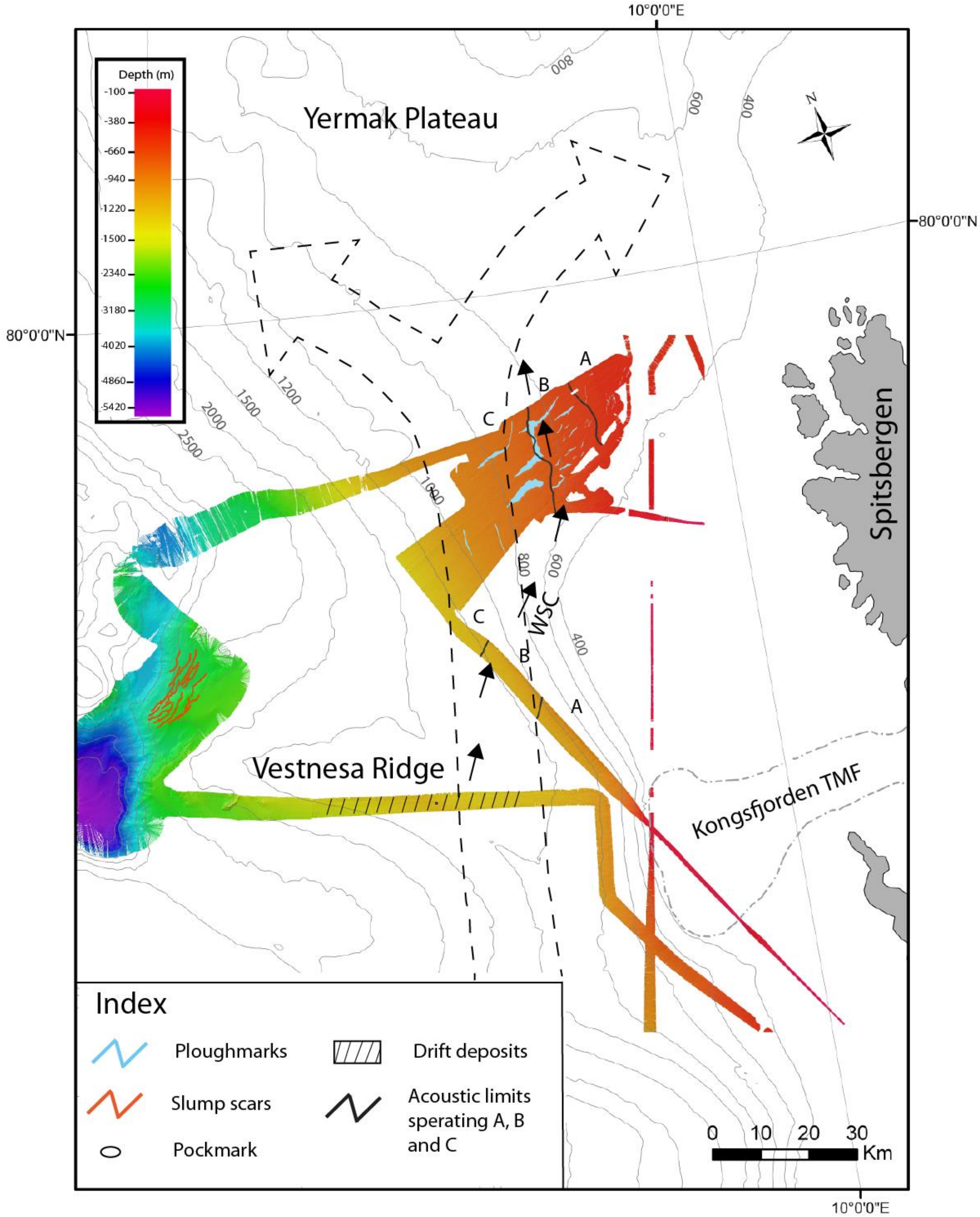


Figure 22. Submarine landforms distribution in the study areas along the NW Spitsbergen continental slope. The black small arrows are the interpreted lower extension of the WSC along the slope, whereas the dashed arrow is the general path way followed by the WSC shown by Cokelet et al (2008).

A: Acoustically transparent unit, B: Unstratified/ Semi stratified units, C: Acoustically stratified units.

6. Conclusions

The NW Svalbard continental slope between 78º N and 80º N and 3º E and 10º E has been investigated using geophysical data sets (Figure 1). Acoustic subbottom chirp profiling (2.5-7 KHz) and multibeam bathymetry data are used for the analysis of upper and lower continental slope offshore Svalbard (Figure 1). Shallow acoustic stratigraphy and submarine landforms are discussed as follows;

1. In study area 1 two acoustic subbottom profiles reveal high resolution images for shallow marine sediments (Figure 10). Acoustic units (U, U1, U2 & U3) represent different submarine environments with significant change in their acoustic signatures (Table 2). Acoustically featureless unit U represents sediments with entrapped gas and debris flow. Facies U1, U2 and U3 are the dominant and well established units in the lower continental slope representing stable environment while their acoustic patterns become less significant in the upper continental slope due to influence of bottom currents. The interpreted lowermost extension of the bottom currents (WSC) along the NW Spitsbergen continental slope in the study areas can be marked using acoustic profiles as shown with small arrows following the bathymetry contours between 650-1200 m (Figure 22). Hence subbottom profiles can be considered as useful tool to determine the bottom currents extension along the continental slopes.

2. Several large and small-scale linear to curvilinear iceberg ploughmarks of various dimensions are the distinct seafloor landforms in the study area 1 (Figure 18). These ploughmarks are also mapped by Dowdeswell et al (2010a). The widths of these large ploughmarks are < 1200 m and depths are generally < 35 m, whereas small- scale ploughmarks are in the range of 70 to 250 m wide and 3 to 8 m deep with different orientations (Figure 18). In addition subbottom profiles provide the subsurface acoustic signatures of these submarine landforms. The erosional surfaces created by these ploughmarks are buried under recent sediments and not clearly visible in studied profiles due to limited acoustic penetration (>50 m).

3. The geophysical data sets in area 2 along the deepest part of the continental slope adjacent to the Molloy Deep (MD) images the presence of a ~113 m high and 15 km wide symmetrical sediment mound on the Vestnesa Ridge (1238 m) containing ~38 m thick acoustically laminated sediments. It is interpreted as a drift deposits formed as a result of bottom current activity of the West Spitsbergen Current along the continental margin. Previous geophysical studies along with core samples by Howe et al (2008) suggest that the sediments consist of contourites and turbidites. Moreover, the presence of a <450 m wide and 37 m vertically long featureless chimney on the anticlinal geometry of this drift can be interpreted as an acoustic pipe associated with pockmark (Figure 19).

4. Below 2400 m water depth, acoustically parallel and continuous sediment layers along with stair like topography between the depths of 2531-2569 m reveal slump scars (Figure 20). These features are related to the mass movements on the steep slope of the Fram Strait towards the Molloy Deep. Presence of gas hydrates and tectonic activity may be the possible factors that cause mass movements in the deepest part of the continental slope.

Acknowledgements

I would like to thank my supervisor Dr. Richard Gyllencreutz and assistant supervisor professor Martin Jakobsson. I also appreciate the useful guidance provided by docent Tom Flodén, Francis Freire, Akkaneewut, Daniele, Hamad, Oscar, Martina and other PhD scholars from Geological Science department, Stockholm University.

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Link sources:

Oden Mapping Data Repository (http://oden.geo.su.se/mb.html)

The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0 (http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/ibcaoversion3.html)