Faculty of Science & Technology

Department of Geology

Study of the Late Cenozoic depositional environment and seismic anomalies on the Trøndelag Platform using 3D seismic data

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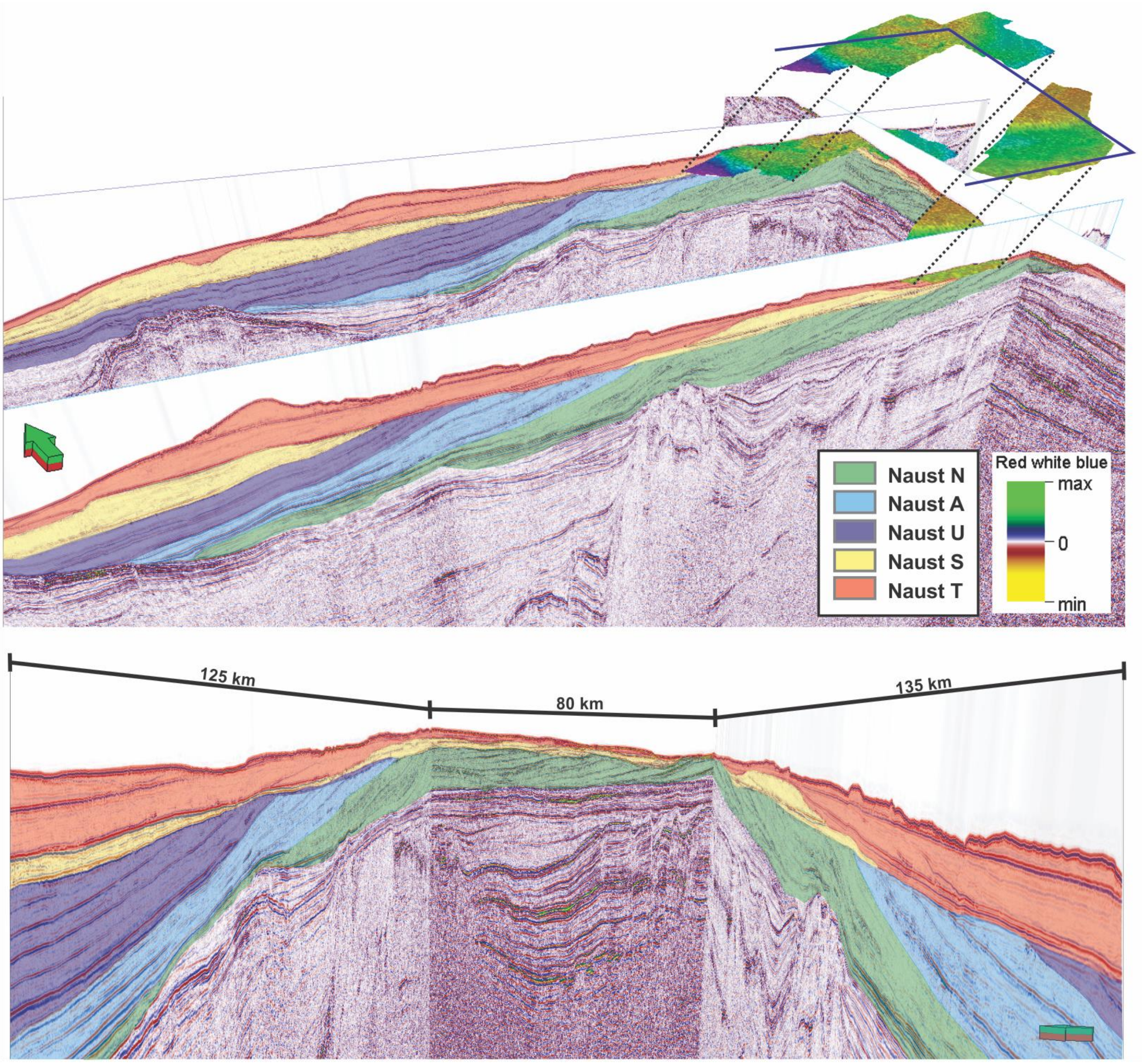

Abstract

This thesis has focused on the depositional environment during the development of the Naust Formation in order to improve our understanding of the glacial history of the mid-Norwegian continental shelf, using 3D-seismic data from the Trænabanken and Sklinnadjupet area along with regional 2D-lines. Seismic anomalies have also been investigated to increase our understanding of fluid migration affecting the Naust Formation. A seismic stratigraphy of the area has been established and correlated to earlier works in adjacent areas, resulting in 5 seismostratigraphic units, N (oldest), A, U, S and T (youngest). Naust N-U show a prograding reflection configuration while the S and T units include both an aggradational as well as progradational reflection configuration.

Eleven seismic horizons in different stratigraphic levels have been mapped for geomorphological features, identifying glacial features such as cross-shelf troughs, MSGL, flutes, hill-hole pairs and iceberg plough-marks. These features suggests a dynamic glacial history on the mid-Norwegian continental shelf over the past 2.8 Ma. Iceberg plough-marks have been identified early in Naust N time (1.5-2.8 Ma), which may indicate the presence of calving ice along the Norwegian coast. Morainal deposits along with an increase in deposition of debris flows suggest a change in depositional environment taking place during Naust N time, where glacial processes became more dominant. This may be the first indication of the ice sheet reaching the paleo-shelf edge within the study area. Cross-shelf troughs, MSGL and flutes have been located on the base of unit A, S and T as well as on the seafloor. This suggests the presence of several fast-flowing ice streams in the period from ~1.5 Ma to the last glacial maximum. The Vestfjorden paleo-ice stream appears to have reached all the way down to the Skjoldryggen area during the Elsterian glaciation. However, the buildup of Trænabanken probably resulted in a change in flow pattern during the two last glaciations, where the Vestfjorden paleo-ice stream drained throughout Trænadjupet while Sklinnadjupet was dominated by ice flowing from the east.

The massive loading by the thick glacial deposits of the Naust Formation resulted in polygonal faulting of the underlying Brygge Formation in the study area. This lead to dewatering, which may be the main source of fluids in the area along with fluids migrating through deep-seated faults from deeper sources. Vertical discontinuities in the seismic data suggests vertical fluid flow within pipes or through fractures created by overpressure within the Naust Formation, while some bright spots and paleo-pockmarks indicate that as the fluids encounter permeable layers the flow was freely following the stratigraphic boundaries of the prograding wedges.

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Etter 5 år med studier er det litt vemodig, men først fremst utrolig deilig at masteren endelig er på plass! Disse årene har gitt meg brei erfaring og jeg er nå klar for nye utfordringer og eventyr.

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André Frantzen Jensen

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1. Introduction and objectives

The objective with the thesis is to describe the Naust Formation on the mid-Norwegian continental margin using 3D-seismic data supplemented with available 2D-seismic, discuss the origin of the deposits as well as derive the paleo-climate of deposition.

During the last ca. 2.8 Ma, Fennoscandia has been subjected to several glacial-interglacial cycles where the ice sheets have reached the coast and all the way out to the continental shelf edge. The thick sequences of glacial sediments deposited on the mid-Norwegian margin during the Late Cenozoic make up the Naust Formation. Based on a stratigraphic analysis, the glacial deposits of the Naust Formation will be divided into seismic sequences. The sequence geometry and internal seismic facies as well as the morphology of buried surfaces on the continental shelf and slope will then be described and discussed. The formation will be further discussed in relation to glacial-history and contribute to increased knowledge about the evolution of continental margins during glacial periods, as well as help reconstruct the development of the Fennoscandian Ice Sheet. In addition, shallow seismic anomalies within the Naust Formation will be described and interpreted. These anomalies may represent fluid flow within the study area or important depositional features, which may be connected to the glacial history. There is also a possibly of shallow gas, which may be a potential geohazard during drilling operations.

2. Geological background

2.1 Study area

The study area for this thesis is located at the inner parts of Trænabanken and Sklinnadjupet along the mid-Norwegian continental margin. It consists of two 3D-surveys which covers an area of approximately 2000 km^2 (ST07M07) and 1200 km^2 (ST10013) that lies between 08°50’-10°50’E and 65°50’-66°50’N (Fig. 2.1.1). Parts of the ST07M07 3D-survey have previously been interpreted by Halvorsen (2012). However, this study will focuses on a larger area which is complimented by 2D-lines for a better regional understanding. This study will also consider seismic anomalies within the inner part of the Naust Formation.

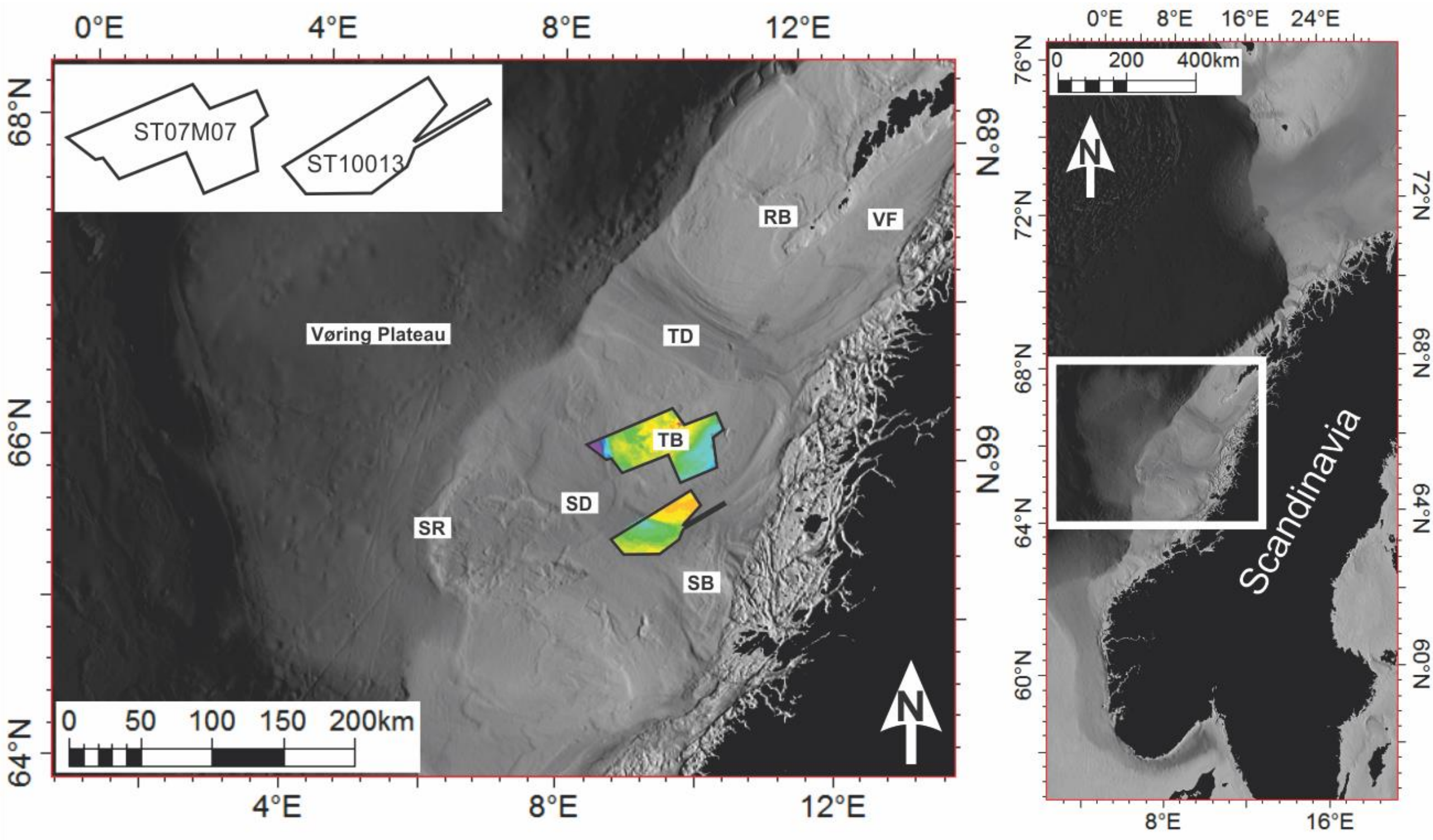


Figure 2.1.1 Bathymetry map of the mid-Norwegian continental shelf showing the study area which consist of the 3D-seismic survey ST07M07 located on Trænabanken and the 3D-seismic survey ST10013 located in Sklinnadjupet. RB: Røstbanken; VF: Vestfjorden; TD: Trænadjupet; TB: Trænabanken; SR: Skjoldryggen; SD: Sklinnadjupet; SB: Sklinnabanken.

2.2 Morphology of the mid-Norwegian continental margin

The mid-Norwegian continental margin consists of three main regions; Lofoten-Vesterålen to the north, Møre to the south and Vøring in the middle (Fig. 2.2.1). Each of these segments are approximately 400-500 km long (Faleide et al., 2008). The Lofoten-Vesterålen and Møre margins are particularly narrow with a minimum continental shelf width of 10 to 65 km. These narrow areas are also where the shallowest parts of the margin are found, with depths of less than 200 m. The area between Lofoten and Møre stretches much further out from the coast, reaching a width of up to 260 km and water depths of 250-500 m. The mid-Norwegian margin is made up of several shallow banks separated by transverse troughs going out to the shelf edge (Vorren et al., 1998). The depth of the shelf break is ranging between 280-410 m with the deepest areas located in the troughs and the shallow areas located at the banks (Dahlgren et al., 2002a).

The continental slope is steepest where the continental margin is narrow. Of the Lofoten margin, the slope gradient can be up to 5°. To the north of Trænadjupet the gradient decreases to 1,2°, while the gradient down to the central Vøring Plateau is less than 1° (Fig. 2.2.1) (Dahlgren et al., 2002a). The Vøring Plateau has a depth of 1200-1600 m and the outer plateau dip into the abyssal plain of the Lofoten Basin to the north, the Norwegian basin to the south as well as the Jan Mayen Fracture zone separating them. From the shelf break to the abyssal plain the water depth varies from 300-3000 m (Laberg et al., 2005a).

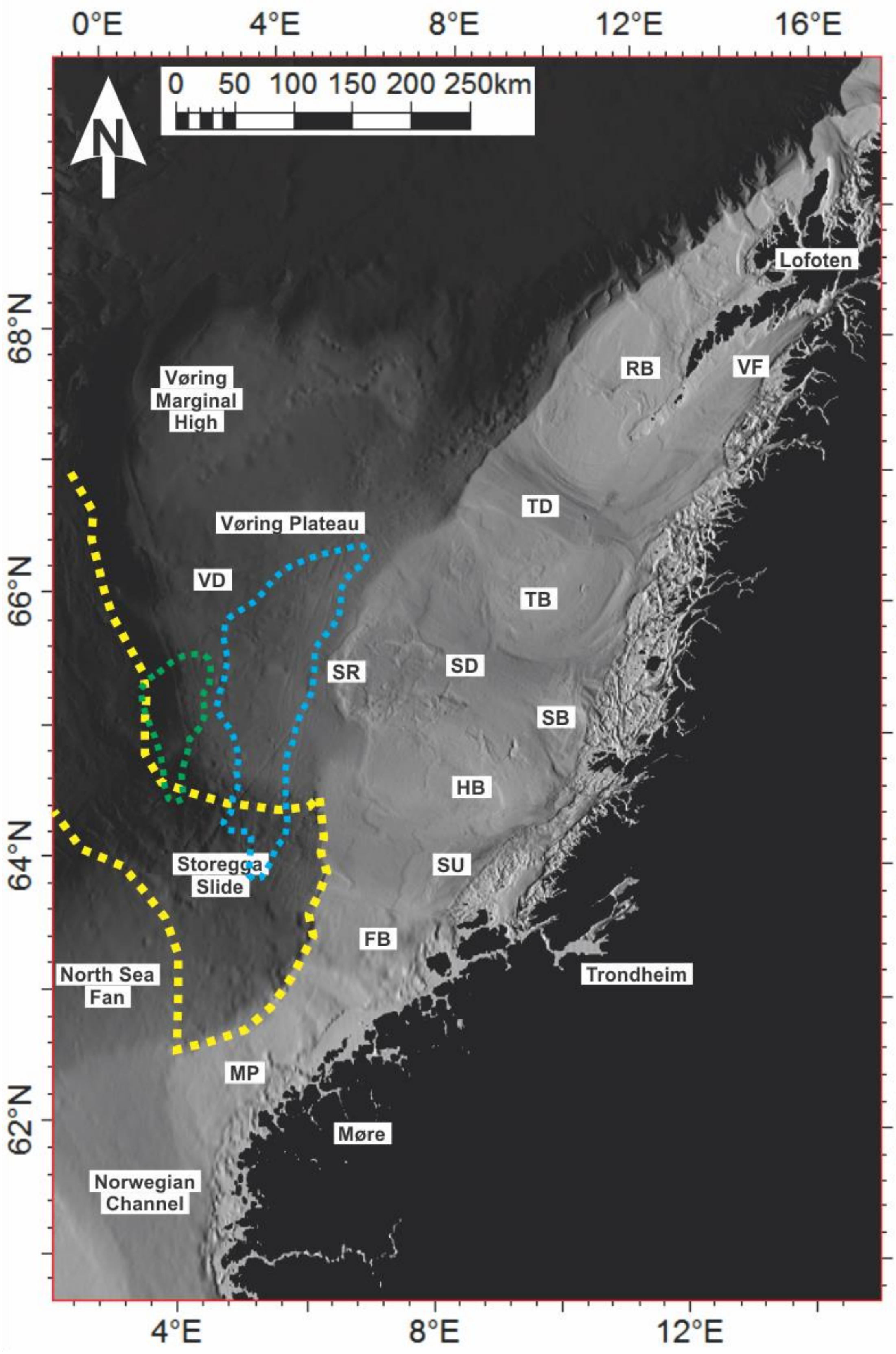


Figure 2.2.1 Overview map of the mid-Norwegian continental margin. RB: Røstbanken; VF: Vestfjorden; TD: Trænadjupet; TB: Trænabanken; VD: Vigrid depression; SR: Skjoldryggen; SD: Sklinnadjupet; SB: Sklinnabanken; HB: Haltenbanken; SU: Suladjupet; FB: Frøyabanken; MP: Måløy Plateau. Yellow stippled line indicates outline of the Storegga Slide. Blue stippled line outlines the Helland Hansen Arch. Green stippled line outlines the Modgunn Arch.

2.3 Pre-glacial history

The pre-glacial history of the mid-Norwegian continental margin has been dominated by two major tectonic events. The Caledonian Orogeny and the break-up of the North Atlantic divided the tectonic history into three main epochs:

1) The pre-Late Devonian epoch that resulted in the final closure of the Iapetus Ocean. This happened during the Late Silurian and Early Devonian time when the Caledonian Orogeny took place (Blystad et al., 1995).
2) The Late Devonian to Paleocene epoch was dominated by episodic extensional deformation which reached a climax with the continental separation of Eurasia and Greenland at the Paleocene-Eocene boundary (Blystad et al., 1995).
3) The epoch from Earliest Eocene to Present has been a period of active sea-floor spreading between Eurasia and Greenland (Fig. 2.3.1) (Blystad et al., 1995).

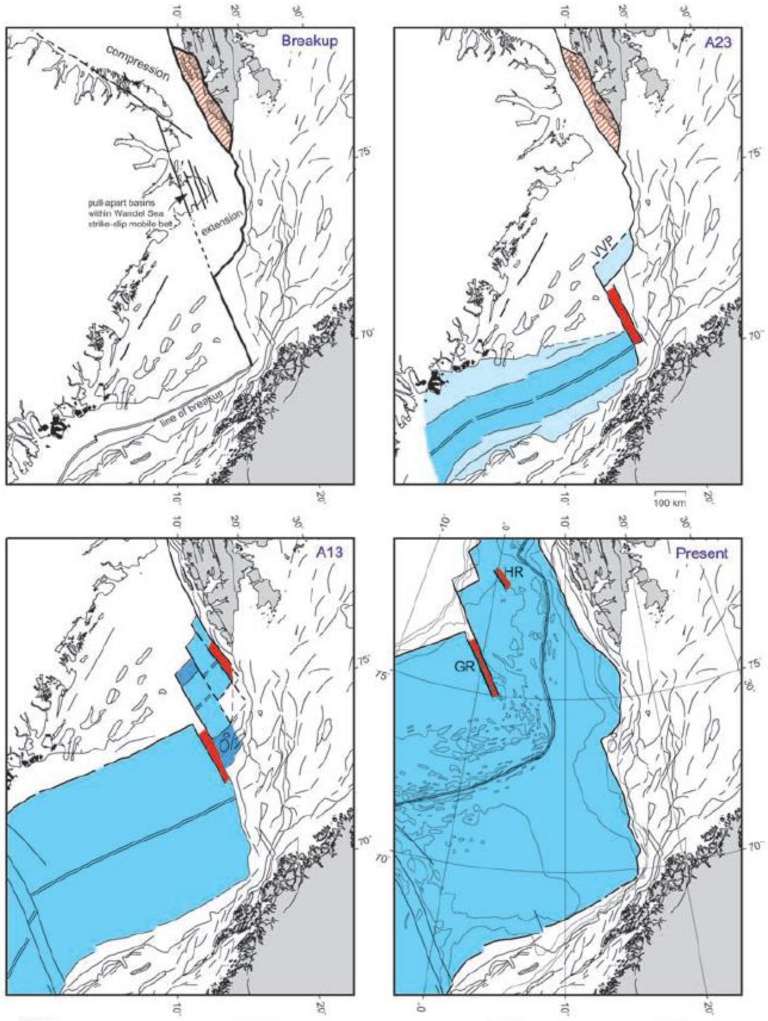


Figure 2.3.1 Cenozoic plate tectonic evolution resulting in the opening of the Norwegian-Greenland Sea. GR: Greenland Ridge, HR: Hovgård Ridge, VVP: Vestbakken Volcanic Basin. Figure was added from Faleide et al. (2008)

The mid-Norwegian continental margin has developed in an area that has been affected by sequential episodes of regional lithospheric extension, taking place after the Devonian period and the post-Caledonian orogenic collapse. These periods of extension were followed by subsidence leading to the development of several sedimentary basins during the Cretaceous. Basins such as the Møre and Vøring basins of the mid-Norwegian coast (Fig. 2.3.2) as well as the Harstad, Tromsø, Sørvestsnaget and Bjørnøya basins located in the SW Barents Sea (Eldholm et al., 2002).

The breakup in the NE Atlantic was initiated by rifting in the Late Cretaceous to the Paleocene. During the rifting, an epicontinental sea opened up between Greenland and NW Europe in the places that had been weakened by earlier rifting. The main faulting has been suggested to take place in the Campanian age resulting in low angle detachment structures. This was followed by small-scale activity towards the breakup (Faleide et al., 2008).

At the Paleocene to Eocene transition (~55-54 Ma) the final lithospheric breakup took place along the Norwegian continental margin. In a period of 3-6 Ma there was massive magmatic activity as a result of the breakup and onset of early sea-floor spreading (Faleide et al., 2008). The sea-floor spreading reached Spitsbergen in the end of Eocene followed by a plate tectonic reorganization in Early Oligocene that moved Greenland in a westerly direction with respect to Eurasia. In the Mid Eocene time, the mid-Norwegian margin developed into a passive rifted margin bordering the oceanic Norwegian-Greenland Sea (Fig. 2.3.1). The margin experienced regional subsidence and the sedimentation was modest until Late Pliocene where a transition to glacial sediments took place. In the Late Miocene there is increasing evidence for an outbuilding of the inner continental shelf as a result of regional uplift (Faleide et al., 2008).

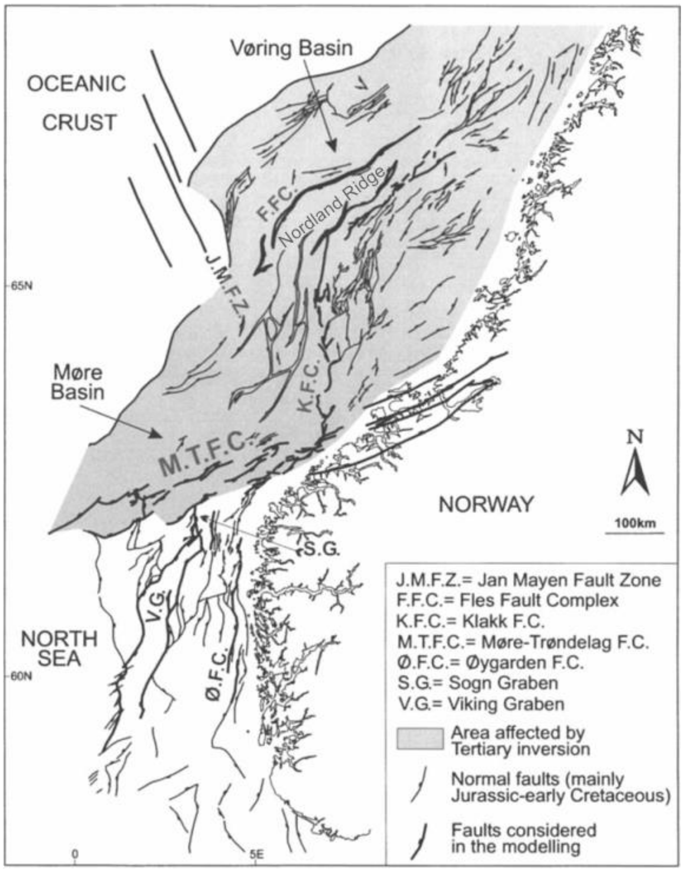


Figure 2.3.2 Simplified structural map of the mid-Norwegian margin and the northern North Sea showing basins and faults along parts of the Norwegian coast. Figure modified from Pascal and Gabrielsen (2001).

2.4 Glacial history

The direct action of ice is responsible for the main differences in depositional environment between glacial margins and lower latitude, non-glacial margins. Low latitude margins are characterized by regression, subaerial exposure, and fluvial erosion/deposition. Glacial margins are defined by Solheim et al. (1998) as continental margins affected by ice sheets, which at regular intervals have been grounded on the continental shelf. This can be margins present to regions that are glaciated today (Greenland) or regions that are deglaciated during interglacial time like the mid-Norwegian continental margin. Subglacial deposits mainly dominate these glacial margins (Solheim et al., 1998).

The repeated glacial cycles have eroded most of the evidence from past glaciations on land. The most complete records of these glaciations will therefore be found in the sedimentary record at the glacial continental margins (Mangerud et al., 2011). The earliest glacial deposits found on the mid-Norwegian shelf are glacially abraded coarse-grained particles. These have been dated to the late Mid Miocene (~15 Ma) and could be an indication that ice caps existed over Scandinavia at this point of time. However, tills and glacimarine diamicts were deposited at the eastward continental margin of Greenland, indicating the expansion of the ice sheet beyond the coastline. Meaning that the deposits most likely are ice-rafted debris (IRD) brought from Greenland to the mid-Norwegian margin by oceanic currents (Hjelstuen et al., 2005).

There was a dramatic increase of IRD at ca. 2.7 Ma on the mid-Norwegian continental margin. The increase was most likely related to a significant expansion of the ice volume around the Nordic seas as a result of the onset of the Northern Hemisphere glaciations. The size of the ice sheets were however modest until the climate conditions changed around 1.1 Ma which led to prolonged glacial cycles with warmer interglacials (Hjelstuen et al., 2005). This is supported by Dahlgren et al. (2005) which concluded that glacigenic wedge-growth began at 2.74 Ma reflecting smaller mountain-centered ice sheets. However, only a small portion of the sediment volume reached as far as the Helland-Hansen Arch in the time between 2.8-0.8 Ma, distributed from the south by the Atlantic Current (Rise et al., 2010).

Studies of cores with glacigenic debris flows (GDFs) as well as seismic profiles suggest that the first major ice sheet expansion onto the mid-Norwegian continental shelf took place around 1.1 Ma which marks the change in climate conditions. This has been known as the Fedje Glaciation (Hjelstuen et al., 2005). Dahlgren et al. (2005) documented a change in sediment transport routes taking place at 0.9-1-1 Ma supporting a change in glaciation style. During the last 1.1 Ma the mid-Norwegian continental shelf has been covered by grounded ice at least five times. The Fedje Glaciation was followed by a period of normal marine sedimentation, which lasted throughout Early Pleistocene time. During the next glacial and interglacial periods, the Scandinavian ice sheet did not expand onto the mid-Norwegian continental shelf. Only depositing marine sediments characterized by the different phases of seawater temperature and sea-level change (Fig. 2.4.1) (Haflidason et al., 1991).

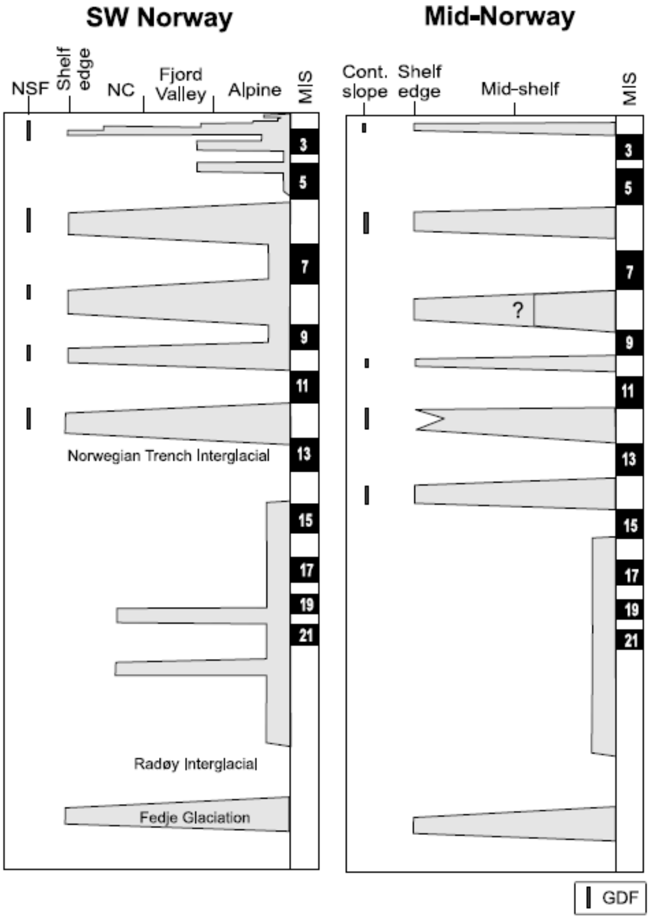


Figure 2.4.1 Curves showing the extent of the ice sheet on the SW Norwegian margin and the mid-Norwegian margin the past 1.1 Ma. MIS: marine isotope stage; NC: Norwegian channel; NSF: North Sea Fan; GDF: glacigenic debris flow. Modified from Sejrup et al. (2005).

In cores from the North Sea Fan there are four glacigenic debris flows dated to Middle Pleistocene that can be correlated to marine isotope stage 12, 10, 8 and 6. This indicated that the ice stream reached the shelf edge each time and the North Sea Fan had now become the main depo-center of glacial sediments for southern Scandinavia (Mangerud et al., 2011). Studies by Dahlgren et al. (2002a) from further north concluded that the Fennoscandian Ice Sheet probably reached the shelf break during marine isotope stage 2, 6, 10, 12 and 14, while only reaching to the inner shelf during marine isotope stage 8. The reach of the ice sheet during marine isotope stage 8 is still a topic under discussion. The time difference from the first shelf edge glaciations in this period between the two areas may be related to more extensive glaciation in the north during marine isotope stage 14 (Fig. 2.4.1) (Sejrup et al., 2005).

There is little evidence of the ice sheet reaching the shelf edge during the Early and Middle Weichselian. Cores indicate that the high sedimentation rate on the mid-Norwegian continental margin started during the Late Weichselian. Marine isotope stage 5-3 therefore probably had a limited ice sheet. During the Late Weichselian, several ice sheet oscillations took place. Changes from maximum glacial to open marine conditions may possibly have taken place in as little as a few hundred years. Last glacial maximum (LGM) (Fig. 2.4.2) is assumed to have taken place at different times along the Norwegian coast. At the south Vøring margin the LGMI has been dated to ca. 22,000 yr ^{14}C BP followed by an ice free period up to 18,900 yr ^{14}C BP. Then a ca. 4000 year long readvance known as Tampen (LGMII) once again covered the south Vøring margin (Hjelstuen et al., 2005; Mangerud et al., 2011).

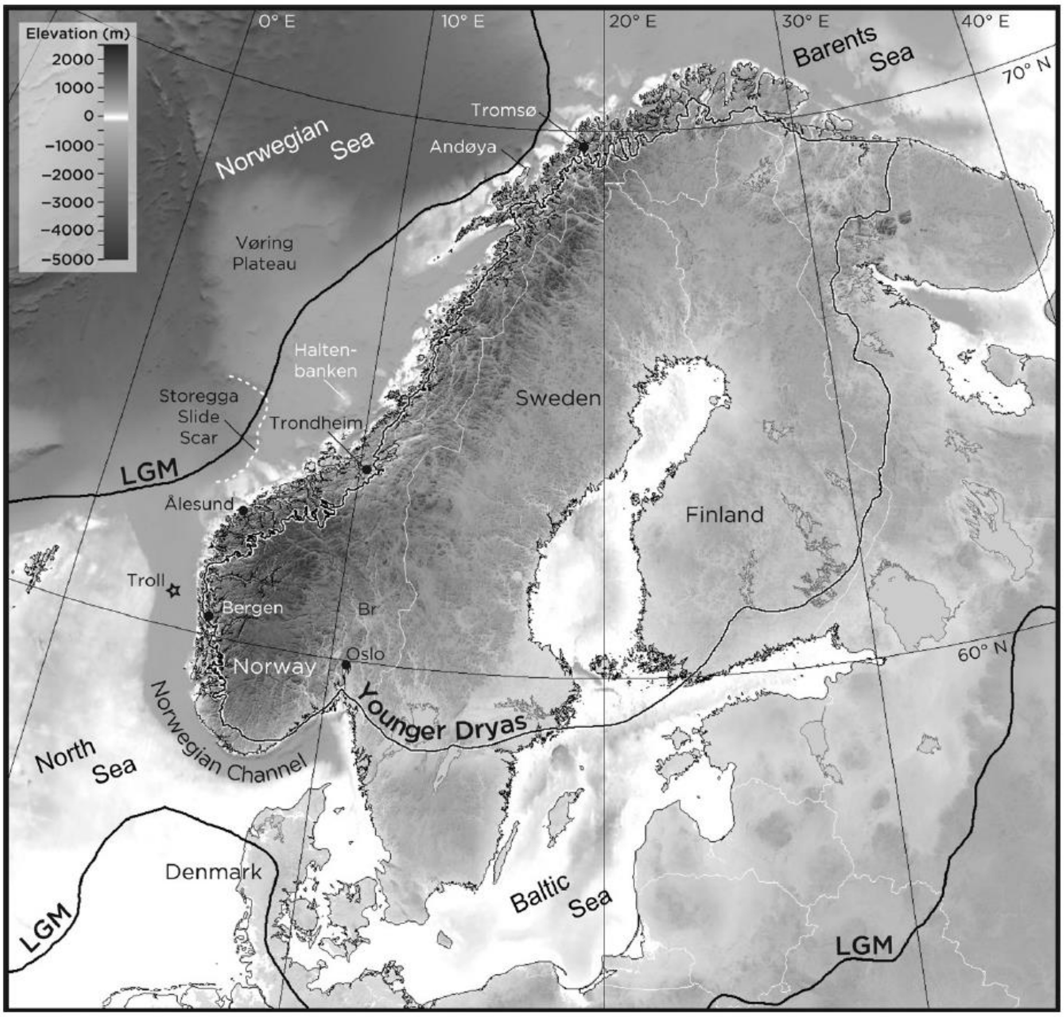
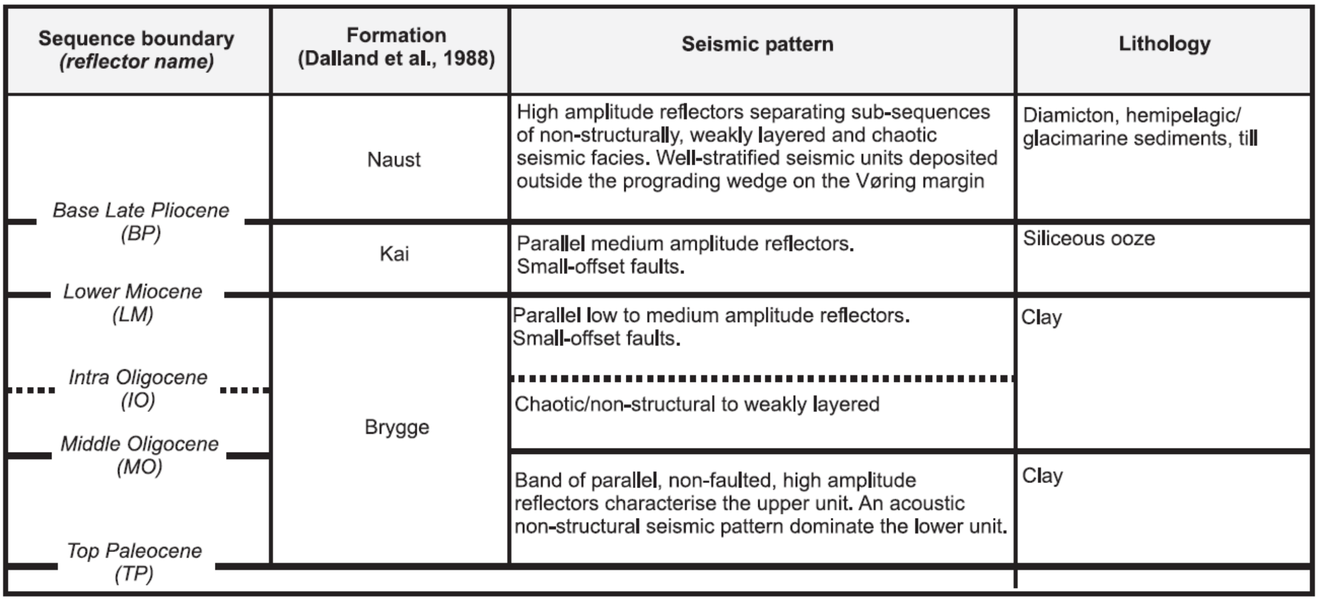


Figure 2.4.2 Map showing Last Glacial Maximum (LGM) and the Younger Dryas moraines of Scandinavia and the adjacent lands and seas. With the main mountain range starting in central south Norway and continues northeastwards. Br is the Brumunddal site. Figure was added from Mangerud et al. (2011).

2.5 Stratigraphy

The sedimentary layers deposited after the opening of the Norwegian-Greenland sea have been divided into three main sequences: The Brygge, Molo/Kai- and Naust Formation which have been given an age estimate and described by Dalland et al. (1988) (Fig. 2.5.1). The age estimate has later been revised by Eidvin et al. (2014) (Fig. 2.5.2) among others.



Sequence boundary *(reflector name)*	**Formation** (Dalland et al., 1988)	**Seismic pattern**	**Lithology**
Base Late Pliocene (BP)	Naust	High amplitude reflectors separating sub-sequences of non-structurally, weakly layered and chaotic seismic facies. Well-stratified seismic units deposited outside the prograding wedge on the Vøring margin	Diamicton, hemipelagic/ glacimarine sediments, till
Lower Miocene (LM)	Kai	Parallel medium amplitude reflectors. Small-offset faults.	Siliceous ooze
Intra Oligocene (IO)	Brygge	Parallel low to medium amplitude reflectors. Small-offset faults.	Clay
Middle Oligocene (MO)		Chaotic/non-structural to weakly layered	
Top Paleocene (TP)		Band of parallel, non-faulted, high amplitude reflectors characterise the upper unit. An acoustic non-structural seismic pattern dominate the lower unit.	Clay

Figure 2.5.1 Identified boundaries between the Brygge, Kai and Naust Formation, including description of seismic facies characteristic and lithology. Figure was added from Hjelstuen et al. (2004).

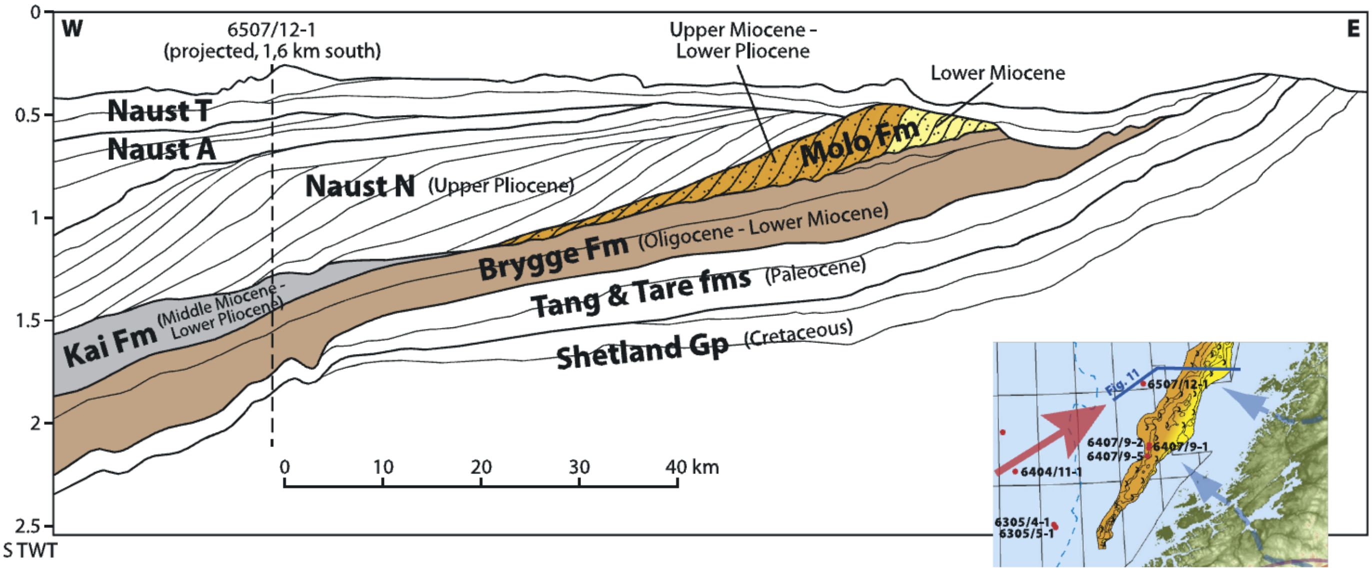


Figure 2.5.2 Geoseismic cross section showing the location and age estimate of the Molo and Kai formation with respect to each other, and the underlying Brygge Formation with the Mid Miocene unconformity in-between. Figure was added from Eidvin et al. (2014).

2.5.1 The Brygge Formation

The Brygge Formation is the oldest of the three sequences and was deposited after the margin subsided and the sea transgressed. Therefore, the sediments were deposited in a marine environment where the present day shelf is clay-dominated and the deep marine areas are ooze-dominated. The deposition was concentrated in the Møre Basin (thicknesses: 600-1000 m) and the outer part of the Vøringen Basin (thicknesses: 500-700 m) (Fig. 2.3.2) (Eidvin et al., 2007). The ooze deposits show small-scale faulting interpreted to be caused by compaction and water escaping trough the sediments. In the sediments along the paleo-slope, sliding is observed while the basins are more subjected to mounding and diapirism. Reactivation of the Brygge Formation deposits have most likely taken place during or after deposition of the glacial sediments from the Naust Formation. The Brygge Formation is ended by an unconformity caused by uplift that culminated in the Mid Miocene (Fig. 2.5.2) (Eidvin et al., 2007). The Brygge Formation has a lateral extent reaching across Haltenbanken and belongs to the Hordaland Group, but is absent on the crest of the Nordland Ridge (Fig. 2.3.2) (Dalland et al., 1988) (Eidvin et al., 2007). On the outer parts of the slope on the Vøring Marginal High, Laberg et al. (2005a) have correlated ocean-current-influenced deposits to the Brygge Formation, implying that much of the sediments on the outer margin probably are of contouritic origin.

2.5.2 The Molo/Kai Formation

The Molo/Kai Formation lies on top of the Mid Miocene unconformity. The Kai Formation that is located on the outer part of the shelf is clay dominated while the Molo Formation, which is located on the middle/inner part of the shelf is sand-dominated (Fig. 2.5.2). The Kai Formation has been dated to Middle Miocene-Early Pliocene while the Molo Formation has been dated to Early Miocene-Early Pliocene, making them approximately the same age (Fig. 2.5.2) (Eidvin et al., 2014). The clay-dominated deposits of the Kai Formation contain ooze in the basinal part with polygonal faults that have some similarity to the Brygge Formation (Eidvin et al., 2007). The Kai Formation represents a deep marine depositional environment effected by contourite drift. This leads to a distinct sediment distribution pattern where layers vary from thin or absent to contouritic deposits over 1000 m thick (Hjelstuen et al., 2004; Bryn et al., 2005).

During the time of the Molo deposition there is clear evidence of forced regression. The lowering of the sea level is most likely due to the Mid Miocene uplift. The Formation is dominated by sandy prograding clinoforms which indicates a relatively high energy costal environment (Eidvin et al., 2007). This is supported by *In situ* fossils from the Draugen Field. These sandy sediments were probably eroded from the coastline exposed after the uplift, before being redistributed by the waves and long-shore currents. The Molo/Kai Formation belongs to the Nordland Group (Eidvin et al., 2007).

2.5.3 The Naust Formation

The Naust Formation is the youngest of the three sequences, being deposited the last ca. 2.8 Ma (Rise et al., 2010). During this time, mainland uplift and the onset of major glaciations in Scandinavia resulted in increased erosion, which led to a huge rise in sediment supply to the mid-Norwegian continental margin. The eroded sediments transported to the margin was deposited as extensive prograding wedges and flat-lying sheet like units of mainly glacial origin (Ottesen et al., 2009; Rise et al., 2010). During the extensive progradation the shelf break migrated up to 150 km westward in the Haltenbanken-Trænabanken region. The narrow Møre shelf only migrated to the extent of 30-50 km due to a steeper slope leading down to a deeper basin. The Naust Formation has a large lateral extent and belongs to the Nordland Group (Rise et al., 2005; Eidvin et al., 2007; Rise et al., 2010).

The Naust Formation is more than 1000 m thick in extensive areas of the outer shelf and uppermost slope. Low-angle, wedge formed sediment layers prograde into a ca. 500-1000 m deep basin westward of the Molo Formation. The layers thin out as they continue west, down-lapping onto the underlying Kai Formation (Rise et al., 2010). The sedimentation rate increased dramatically during Naust time, being at least one magnitude higher than in Brygge and Molo/Kai time. The mean sedimentation rate has been calculated to ca. 25 cm per 1000 years offshore mid-Norway. The sediments were mainly deposited in a glacimarine environment on the paleo shelf-with the possibility of being redistributed over the paleo-shelf break by gravity-driven processes (Rise et al., 2010). During interglacial time contouritic and hemipelagic depositional processes dominated and even during glacial time bottom-current control upon hemipelagic/contouritic sedimentation is evident (Dahlgren et al., 2002a; Rise et al., 2005).

Rise et al. (2006) subdivided the Naust Formation into five depositional sequences N (oldest), A, U, S and T (youngest) (Fig. 2.5.3), replacing the older terminologies. The age of the different sequences are poorly constrained due to the relatively high deposition rate. Few cores have been obtained from the area and deficiency of index fossils as well as the extensive reworking of fossil faunas have been problematic. Therefore, the suggested age for the sequences (especially N, A and U) must be considered as provisional (Eidvin et al., 2007; Ottesen et al., 2009).

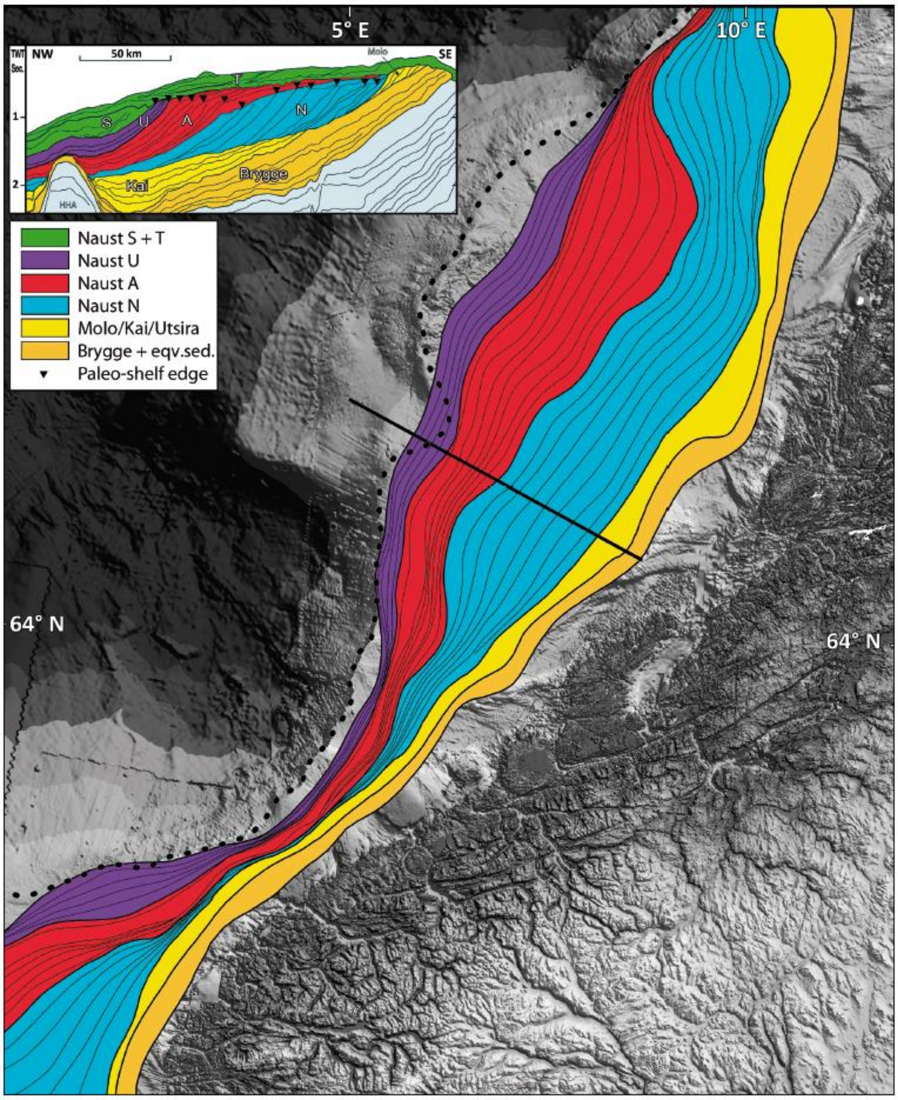


Figure 2.5.3 Progradational pattern of the palaeo-shelf break through the Naust Formation. Black line indicats the profile across Haltenbanken shown in upper left corner. Yellow area indicates subcrop of the Molo Formation and equivalent sediments; orange area indicates subcrop of the Brygge Formation; black dotted line indicates present day shelf edge. Figure was added from Ottesen et al. (2009).

Naust units N and A

Naust N is suggested to be approximately 1.5-2.8 Ma and is the oldest sequence in the Naust Formation while Naust A is suggested to be approximately 0.8-1.5 Ma (Fig. 2.5.4). They are mostly made up of westerly prograding, wedge-formed units with the most massive units occurring in the east (Rise et al., 2010). On the inner and middle shelf the upper part of the clinoforms are often worn down by glacial erosion which may be a result of inner shelf uplift (Ottesen et al., 2009). Naust N has some units that probably were deposited by glacial debris flows redistributing sediments beyond the paleo-shelf break during massive shelf glaciations.

Contouritic deposits are also observed along flanks or highs as well as areas of elevation changes such as slide scars and craters where deep ocean currents are reduced. The depositional patterns of Naust A resembles that of Naust N, only with a lower sediment thickness. During Naust N and A time the mean sedimentation rate was ca. 0.17-0.18 m per 1000 year where only 5% of the total thickness was of hemipelagic origin (Fig. 2.5.1) (Dowdeswell et al., 2010; Rise et al., 2010).

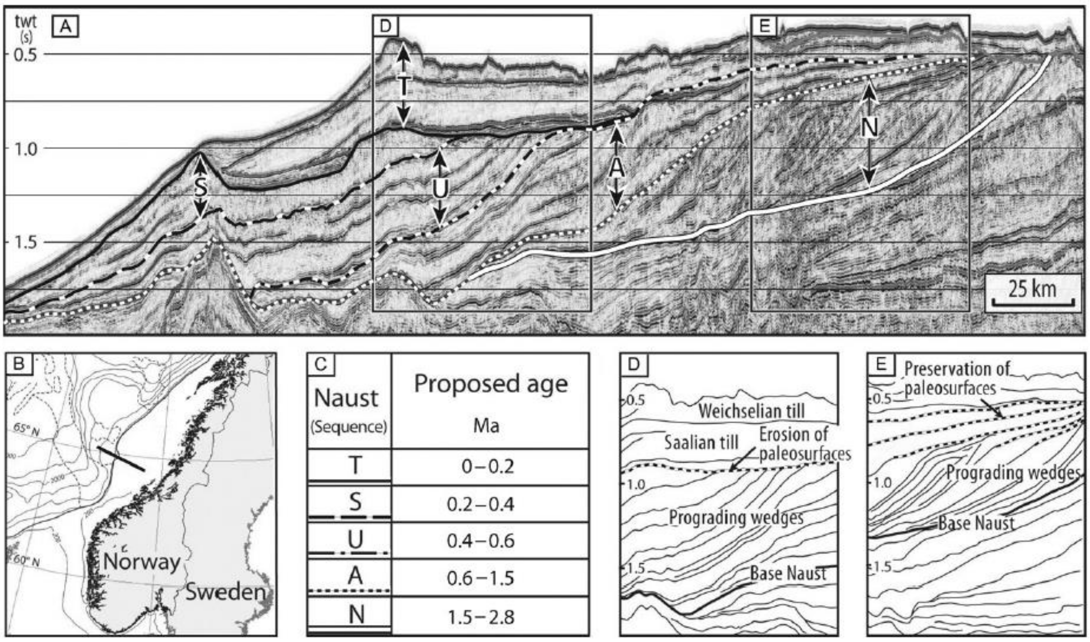
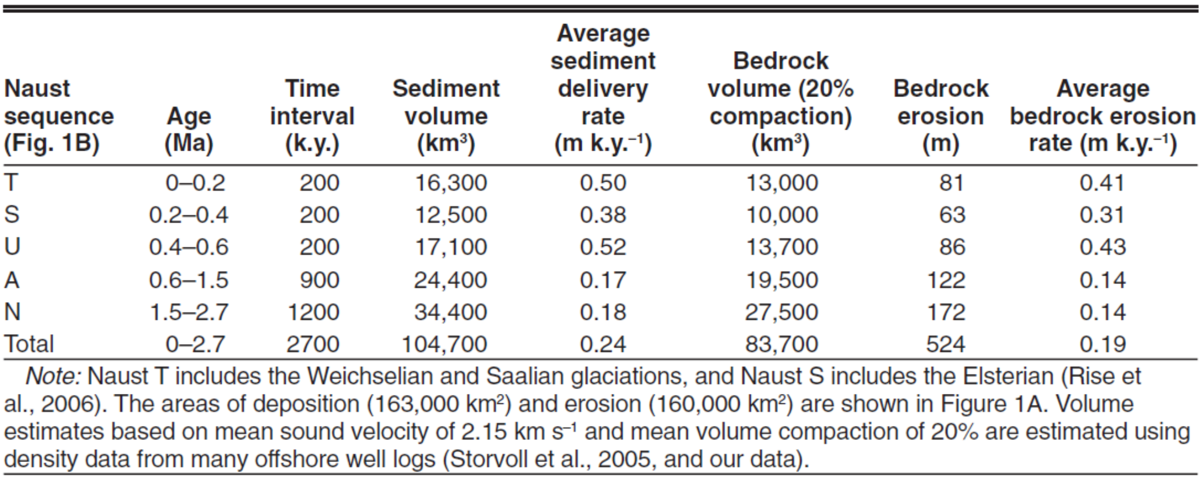


Figure 2.5.4 A) Seismic stratigraphic section across the Naust Formation on the mid-Norwegian continental margin. The subunits of the formation are marked with letters N, A, U, S and T. Twt indicates two-way travel time where 1s equals ~1000 m of sediment thickness. (B)Location of the cross section. (C) Proposed ages of the different sequences, marked with a variation of lines in (A). (D) Interpreted part of the cross section showing truncation of prograding wedges and paleo-shelf surfaces. (E) Interpreted part of the cross section showing preserved wedges and paleo-shelf surfaces. Location is indicated on (A). Figure was added from Mangerud et al. (2011).



Naust sequence (Fig. 1B)	Age (Ma)	Time interval (k.y.)	Sediment volume (km³)	Average sediment delivery rate (m k.y.⁻¹)	Bedrock volume (20% compaction) (km³)	Bedrock erosion (m)	Average bedrock erosion rate (m k.y.⁻¹)
T	0–0.2	200	16,300	0.50	13,000	81	0.41
S	0.2–0.4	200	12,500	0.38	10,000	63	0.31
U	0.4–0.6	200	17,100	0.52	13,700	86	0.43
A	0.6–1.5	900	24,400	0.17	19,500	122	0.14
N	1.5–2.7	1200	34,400	0.18	27,500	172	0.14
Total	0–2.7	2700	104,700	0.24	83,700	524	0.19

Note: Naust T includes the Weichselian and Saalian glaciations, and Naust S includes the Elsterian (Rise et al., 2006). The areas of deposition (163,000 km²) and erosion (160,000 km²) are shown in Figure 1A. Volume estimates based on mean sound velocity of 2.15 km s⁻¹ and mean volume compaction of 20% are estimated using density data from many offshore well logs (Storvoll et al., 2005, and our data).

Figure 2.5.5 The estimated ages for the five different sequences of the Naust Formation as well as sediment volume, sedimentation rate and catchment erosion on the mid-Norwegian margin (63°–68°N). Figure was added from Dowdeswell et al. (2010).

Naust U

Naust U is suggested to be approximately 0.4-0.8 Ma and have the highest mean sedimentation rate of the five sequences (ca. 0.52 m per 1000 year) (Fig. 2.5.5) (Dowdeswell et al., 2010; Rise et al., 2010). It consists of several aggradational and slope-building units which are likely to represent several glacial-interglacial cycles (Ottesen et al., 2009). During this time, the prograding sediments buried the Helland Hansen Arch and the Modgunn Arch (Fig. 2.2.1). Therefore the youngest units of Naust U could be distributed beyond the shallow part of Helland Hansen Arch, extending further westward into the Vigrid depression, making them the first widely distributed glacial debris sediment unit on the slope west of Helland Hansen Arch (Fig. 2.2.1) (Rise et al., 2010).

Naust S

Naust S is proposed to be approximately 0.2-0.4 Ma and was mainly deposited westward of the present shelf edge (Ottesen et al., 2009; Rise et al., 2010). Naust S time contains the Elsterian glaciation (300,000-400,000 years ago) which probably was the largest glaciation located in continental Europe in the Late Cenozoic (Ottesen et al., 2009). During this time the paleo-shelf migrated to its westerly position possible covering the shallow crest of the HHA with more than 200 m of sediments. The glacial debris were distributed to the shelf edge by ice streams focused through the Sklinnadjupet paleo-trough (Rise et al., 2010). In the Skjoldryggen region (Fig. 2.2.1), a prominent depocenter is located with up to 400 m of glacial sediments. The depocenter is split apart into two sections by the buried Sklinnadjupet Slide, which occurred at the end of Elsterian or immediately following the retreat of the ice sheet. In the southern parts of the mid-Norwegian ridge, up to 500 m of glacial sediments were deposited on sections of the North Sea Fan (Ottesen et al., 2009; Rise et al., 2010). During Naust S time the mean sedimentation rate was ca. 0.38 m per 1000 year (Fig. 2.5.5) (Dowdeswell et al., 2010).

Naust T

Naust T is the youngest sediment sequence of the Naust Formation and is proposed to be approximately <0.2 Ma. The base is located on top of an erosional surface created by the Elsterian Ice Sheet. It comprises mainly of two flat-lying units of massive till and glacial debris. These layers were deposited during the last two glaciations, the Saalian (140,000-300,000 years old) and Weichselian (10,000-115,000 years old) (Ottesen et al., 2009; Rise et al., 2010). Fast-flowing ice streams deposited up to 700 m of sediments on the North Sea Fan, which demonstrates that the Norwegian channel was very active during the last glaciations. In the same area, the approximately 130,000 year old Tampen Slide is located, which most likely removed a large part of the Saalian deposits. Fast-flowing ice streams were also active in the Skjoldryggen region during Naust T time, where 300-400 m of sediments makes up the main Skjoldryggen Ridge and adjacent areas (Fig. 2.2.1) (Ottesen et al., 2009; Rise et al., 2010). During this time, numerous wedges of glacial debris prograded into the deep Sklinnadjupet paleo-trough, and by the end of Saalian glacial debris flowed into the eastern part of the Sklinnadjupet Slide (Rise et al., 2010). During Naust T time the mean sedimentation rate was ca. 0.50 m per 1000 year (Fig. 2.5.5) (Dowdeswell et al., 2010).

Continental margin subsidence

There is evidence that suggest that the outer mid-Norwegian continental shelf has been affected by subsidence. The seaward tilting of the Upper Regional Unconformity (URU) as well as the gradually deeper buried paleo-shelf breaks are uncommon features of glacial shelves, which usually are over-deepened. This indicates that the shelf has been prone to tectonic tilting after the deposition took place (Dahlgren et al., 2002a). Dahlgren et al. (2002a) suggested a subsidence rate of ca. 1.2 m/ka since ca. 350 ka BP, but with local differences. Sediment loading is probably one of the main factors contributing to the subsidence, explaining the local differences as the most affected areas appear to be depocenters consisting of thick sediment deposits.

2.6 Oceanographic conditions

The mid-Norwegian margin may have been influenced by bottom-currents as early as the opening of the Norwegian-Greenland Sea during Late Eocene-Early Oligocene time (Bryn et al., 2005; Faleide et al., 2008). However, it was not until Mid Miocene the thermohaline circulation system that is known today was established (Laberg et al., 2005b). The Norwegian Atlantic Current (NAC) brings warm and saline Atlantic surface water to the north where the temperature and salinity decreases and the water sinks to form Norwegian Sea Deep Water and Norwegian Sea Arctic Intermediate Water (Bryn et al., 2005; Laberg et al., 2005b). The NAC consists of two different northward-flowing branches of the mid-Norwegian shelf. The currents are topographically guided from the Iceland-Faroe Front, throughout the Nordic Seas toward the Fram Strait with one branch cutting off into the Barents Sea. The eastern branch passes over the upper part of the Storegga Slide area and continues east of the Vøring Plateau, while the western branch passes over the lower escarpments of the Storegga Slide area and continues along the outer parts of the Vøring Plateau (Fig. 2.6.1) (Orvik & Niiler, 2002; Bryn et al., 2005; Laberg et al., 2005a)

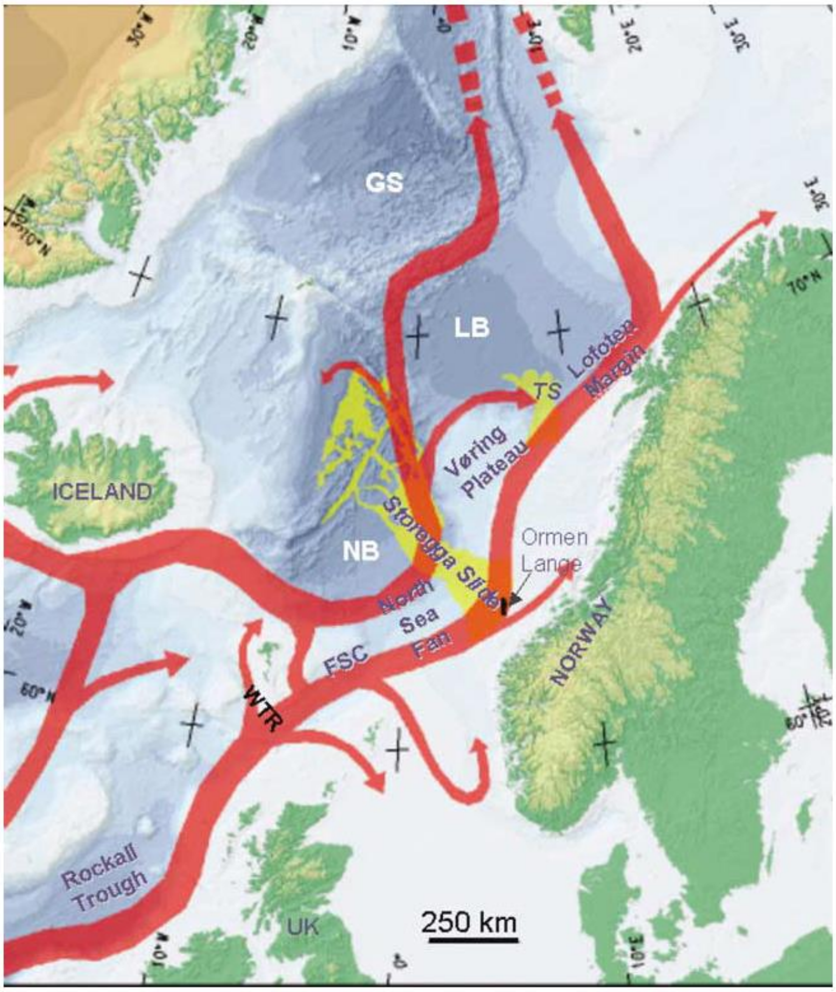


Figure 2.6.1 The Norwegian Atlantic Current direction along the Norwegian margin (red arrows). WTR: Wyllie Thomson Ridge; FSC: Faroe–Shetland Channel; TS: Trænadjupet Slide; NB: Norwegian Basin; LB: Lofoten Basin. Figure was added from Bryn et al. (2005).

In the Norwegian-Greenland Sea, the NAC is turned into Norwegian Sea Deep Water as the water temperature decreases and get denser. The Norwegian Sea Deep water returns to the Atlantic Ocean through deep-water pathways over the Greenland-Scotland Ridge (GSR) such as the Faroe Conduit. However, the deepest levels of the Norwegian Sea Deep Water may be unable to traverse the shallower levels of the Faroe Conduit and might be deflected back north (Bryn et al., 2005; Laberg et al., 2005a).

The NAC dominates the upper water column, which stretches down to a depth of 500-700 m. At this depth a strong thermocline is located where the water temperature drops form 5-6 to less than 0 ° C, a transition from NAC to Norwegian Sea Arctic Intermediate Water (Fig. 2.6.2). Above the thermocline, the currents are variable because of the influence of atmospheric forces while the Norwegian Sea Arctic Intermediate Water have a more stable current speed and direction following the seabed topography (Bryn et al., 2005). Current speeds of over 1 m/s have been registered in the NAC while the Norwegian Sea Arctic Intermediate Water has a measured speed of 0.5-0.6 m/s. Therefore, the thermocline is an important sedimentation boundary keeping sediments in suspension where the current velocity is high (Bryn et al., 2005). During glacial times the currents were considerably reduced, since surface waters were characterized by sea ice and iceberg drift (Bryn et al., 2005).

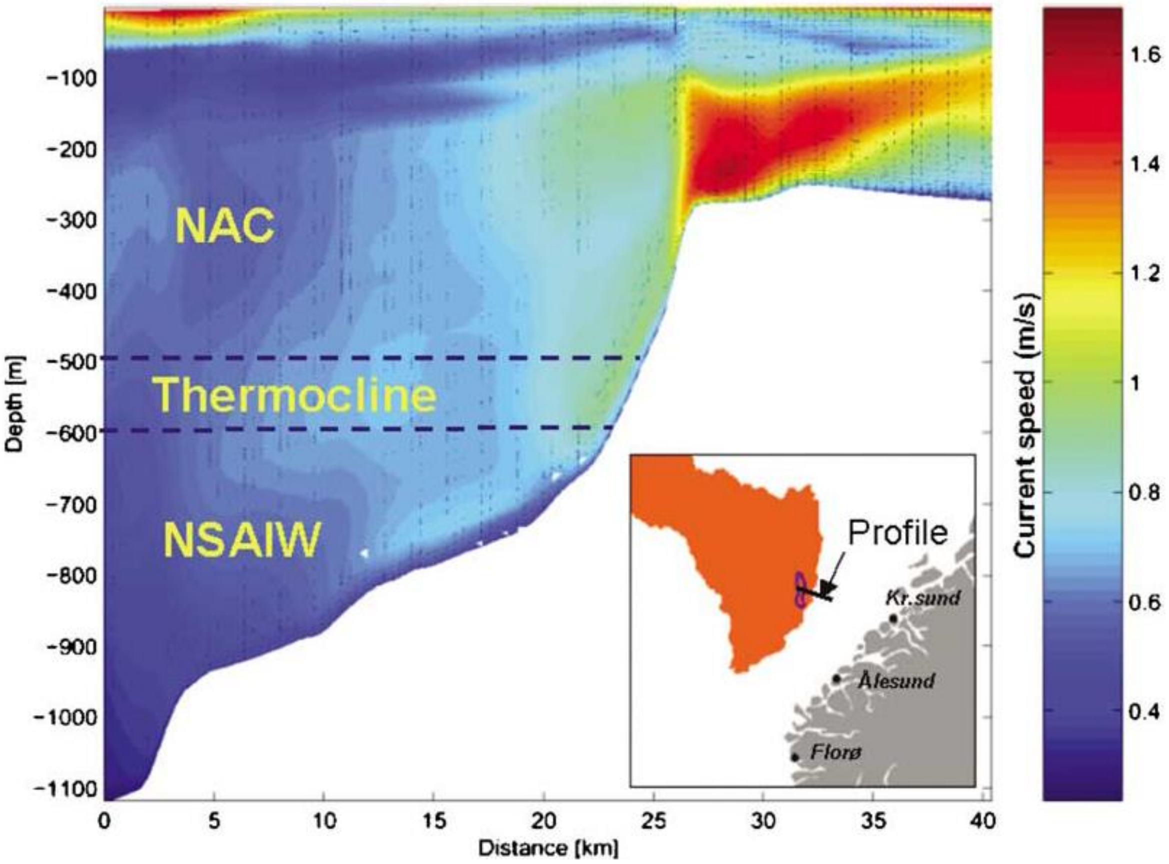


Figure 2.6.2 Results from a numerical ocean model showing increase in current velocities around the shelf break in the Storegga Slide area. The color bar shows current velocity in m/s. NAC: Norwegian Atlantic Current; NSAIW: Norwegian Sea Arctic Intermediate Water. Figure was added from Bryn et al. (2005).

2.7 Contourites

Contourites consists of sediments deposited or significantly affected by bottom currents. They can have a wide range of compositions depending on the sediment supply resulting in sediment facies with muddy to gravel-lag characteristics. While sediment drifts are a general term for sediments accumulated by currents, contourite drifts are a specific term for sediments deposits that have been formed mainly, though not necessarily exclusively, by bottom currents at depths below 300 m. Similar deposits from 300-50 m water depth may be referred to as shallow water drifts (Stow et al., 2002). Stow et al. (2002) describes six main classes of contourite deposits divided by their overall morphology and setting: contourite sheet drifts; (ii) elongate mounded drifts; (iii) channel- related drifts; (iv) confined drifts; (v) infill drifts; and (vi) modified drift-turbidite systems. However, hybrids between the different types also occur.

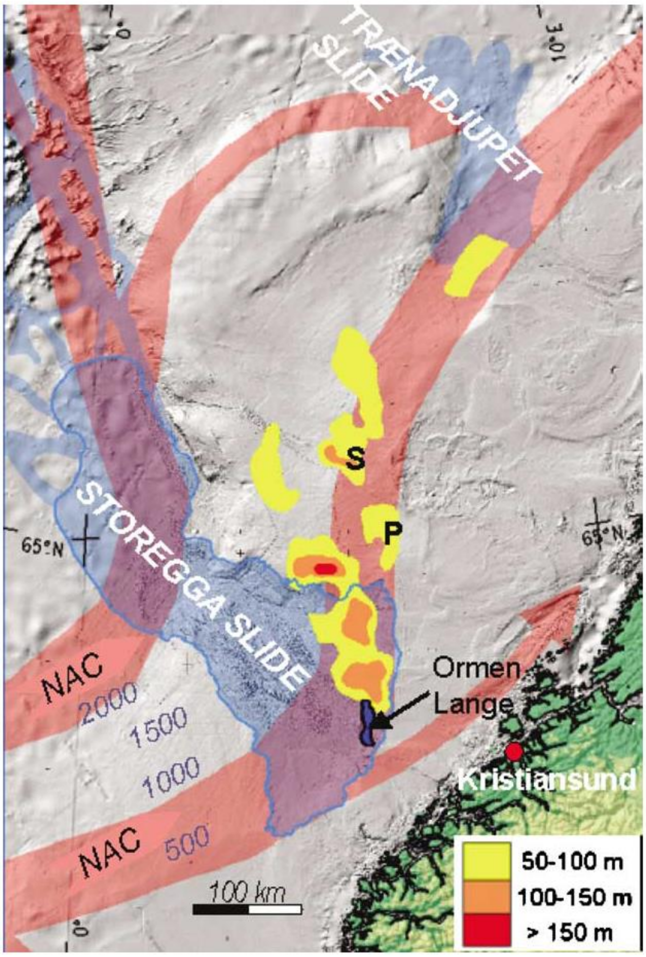


Figure 2.7.1 Thickness showing the main contourite drifts within the Naust S sequence. The two depo-centers within the Storegga Slide represent infill drifts in the scars from the paleo-slide R. S: infill drifts in the Sklinnadjupet paleo-slide. P: possible meltwater plume deposits. NAC: Norwegian Atlantic Current. Figure was added from Bryn et al. (2005).

Bottom current activities, which have affected the mid-Norwegian continental margin, have been deposited after the Mid Miocene as the thermohaline circulation system was established. The growth of the contourites are controlled by two main factors, water circulation and sediment supply. They are normally located on water depths between 600 and 1200 m and the largest accumulations are up to 1000 m thick (Laberg et al., 2001; Bryn et al., 2005). On the mid-Norwegian continental margin there have been described contourite sheet drifts in the Møre basin by Evans et al. (2002), infilling drifts associated with the slide-scar in the Storegga area by Bryn et al. (2005); Solheim et al. (2005) and infilling drifts associated with Sklinnadjupet paleo-slide as well as elongate mounded drifts (Lofoten-,Vesterålen- and Nyk Drift) on the Vøringen and Lofoten margins described by Laberg et al. (2001) (Fig. 2.7.1).

2.8 Slides

Seven different large-scale slides from pre-Holocene have been located on the mid-Norwegian continental margin. The large-scale of these slides make them important features in the formation of the margin. The Storegga Slide which occurred 8100 cal. years B.P., alone resulted in the movement of 3500 km^3 of material and effected a total area of 90,000 km^2 (Haflidason et al., 2005; Solheim et al., 2005). With the exception of the Vigrid- and Sklinnadjupet slides, they are all located in the Storegga area or on the immediately adjacent North Sea Fan. All of the slides except one are younger than 0.5 Ma, and although older slides exist the main sliding activity took place as the continental margin repeatedly was covered by the Fennoscandian Ice Sheet (Fig. 2.8.1) (Solheim et al., 2005).

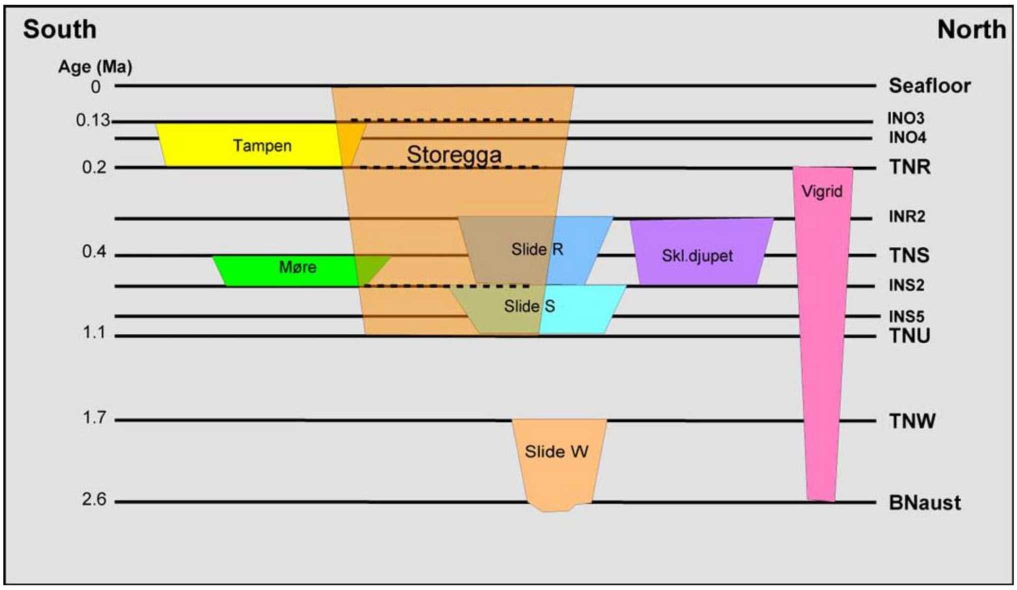


Figure 2.8.1 Schematic slide stratigraphy of the mid-Norwegian margin. Stippled lines within the Storegga Slide indicates the most important slide planes for this Holocene slide. Figure added from Solheim et al. (2005)

All the seven slides, with the exception of the Vigrid Slide which is located above the Kai Formation, are located within the Naust Formation and display a number of similar features. They have glide planes parallel to the stratigraphy, large sediment blocks in close proximity to the slide scar and the headwalls appear to be stable enough for the slide scare to fill up over time (Solheim et al., 2005). The slides appear to be a result of the relationship between contourite drift and glacial debris flows. Where the instability is caused by pore pressure build-up in the contourite deposits as they are buried under thick glacial deposits, which then most likely are triggered by large earthquakes. In the Vigrid Slide which has a deeper glide plane, fine-grained and partly biogenic ooze may be the cause of the instability instead of contourites (Solheim et al., 2005).

2.9 Fluid flow and seismic anomalies

Seismic anomalies of the Naust Formation, interpreted to be due to fluid flow have mainly been studied along the outer part of the mid-Norwegian continental shelf. The Naust Formation on the outer shelf is generally underlain by the Kai Formation, which has been affected by polygonal faulting due to the abrupt sediment loading of thick glacigenic deposits of the Naust Formation (Fig. 2.9.1) (Hustoft et al., 2007; Chand et al., 2011). The Miocene oozes of the Kai Formation have been suggested to be the main source of biogenic methane in this area as it is located within the biogenic zone of gas generation (Chand et al., 2011). The fluid flow upward in the strata and into the low-permeability layers of the Naust Formation may be a result of manufacturing self-enhanced permeability. Such hydraulically generated fractures lead to zones where vertical fluid migration can take place and are often referred to as pipes (Fig. 2.9.1) (Hustoft et al., 2007). These pipe-structures are associated with acoustic masking, pull-down and bright spots. The pull-down, together with pockmarks on the seafloor and shallow gas hydrates suggest a presently active fluid flow (Hustoft et al., 2007). Bottom simulating reflectors indicating deeper gas hydrates have mainly been documented in the Nyegga area east of the Modgunn Arch and west of the present shelf edge, within the Naust A and U sequences (Fig. 2.9.1) (Chand et al., 2011). This is in the same area as the Nyegga pockmark field. Hjelstuen et al. (2010) however, was not able to find any close relations between the geological settings and the development of the pockmarks. Hovland et al. (2005) suggested that the pockmarks were formed by a sudden catastrophic burst of fluids, followed by micro-seepage (Fig. 2.9.1).

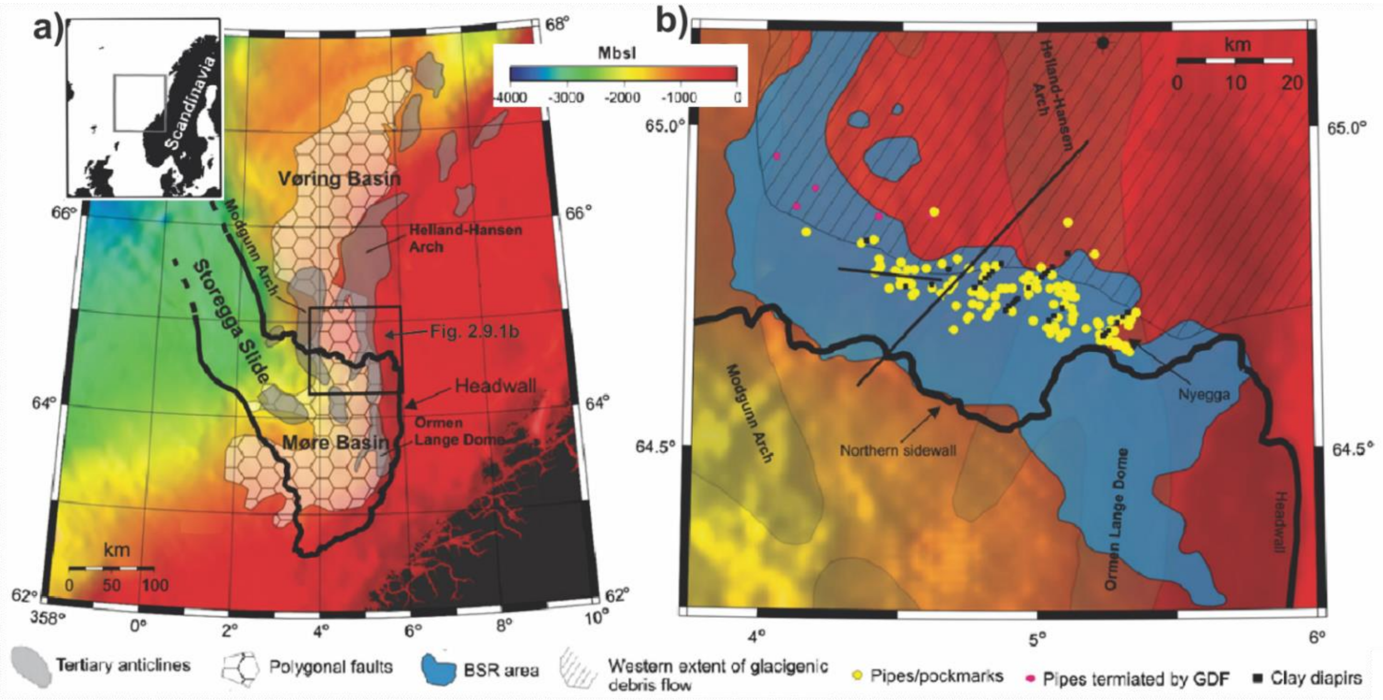


Figure 2.9.1 a) Shaded relief map of the mid-Norwegian margin indicating areas of polygonal faults and tertiary anticlines. b) Zoom-in of the Nyegga where features such as pipes/pockmarks and bottom simulating reflectors have been located. The figure has been modified from Hustoft et al. (2007).

Some shallow areas with high gas content have been located on the mid-Norwegian continental shelf. These generally consist of strings of sandy sediments located within the glacigenic sediments of the Naust Formation (Ottesen et al., 2012). These shallow gas layers are generally avoided during exploration drilling, as they are potential geohazards. This was proven when the West Vanguard rig drilled trough a shallow gas horizon on Haltenbanken, resulting in a catastrophic blowout (Ottesen et al., 2012). On the western side of Trænabanken, gas-bearing contourites located above the base of Naust have been identified as potential hydrocarbon (gas) prospects. However, the play is rather uncertain as the contourites most likely are fine-grained and make rather poor reservoirs. The prospect would also depend on a stratigraphic seal, as well as a good top and basal seal (Ottesen et al., 2012). Only one commercial discovery has been made in the shallow glacial sediments of the mid-Norwegian continental shelf. This was the Peon gas field which was located in glacifluvial sands in the outer part of the Norwegian Channel (Ottesen et al., 2012).

3. Data and methods

3.1 Dataset

This study is primarily based on the two 3D-surveys ST10013 and ST07M07. 2D-seismic surveys have also been used to correlate the two 3D-cubes as well as getting a regional understanding of the study area (Fig. 3.1.1).

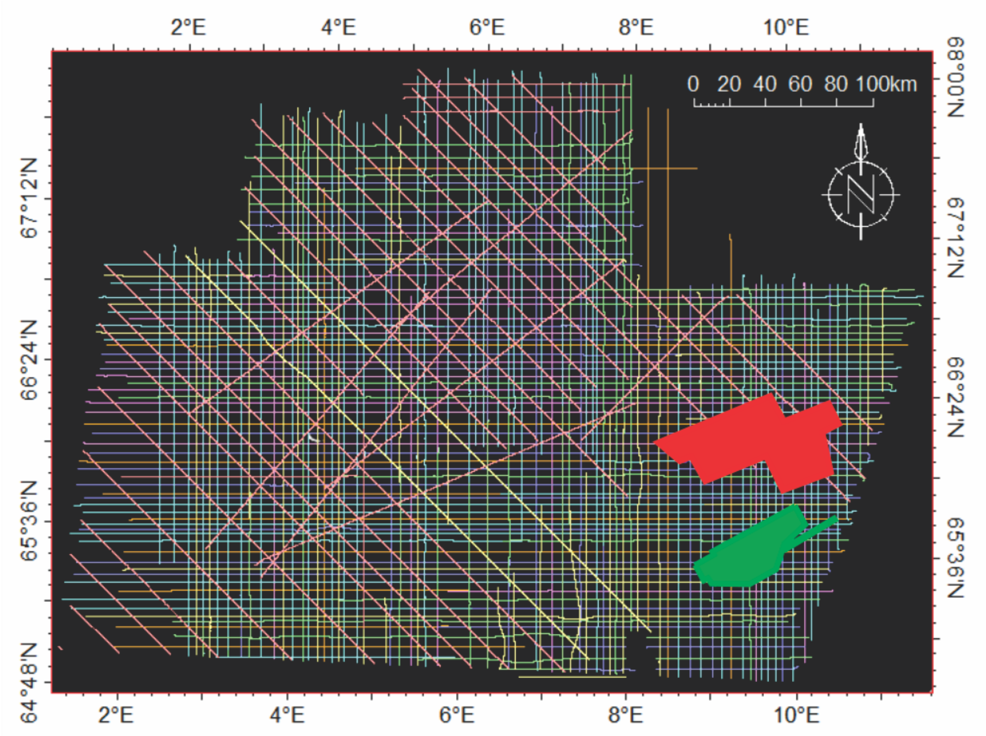


Figure 3.1.1 The location of the seismic data used in the study. Polygons indicated the ST07M07 (red) and ST10013 (green) 3D-seismic surveys. Lines indicated the 2D-surveys MNR05 to MNR11.

3.1.1 3D-surveys

The two 3D-surveys have been provided by Statoil, the ST10013 survey was gathered in 2010 and the ST07M07 survey was gathered in 2007. The phase and polarity of the seismic datasets can be determined by looking at the seafloor. This is because there is always an increase in acoustic impedance at the interface between water and the seafloor reflection (fluid-solid interface). In variable wiggle display, the traces show a strong peak between two smaller troughs (Fig. 3.1.2). Using the SEG polarity standard of Sheriff (2006) it can be concluded that both the ST10013 and ST07M07 3D-surveys have been processed to zero-phase signal, normal polarity. The distance between the seismic lines can also be determined by looking at the seafloor in variable wiggle display. As there are 125 m every tenth trace (Fig. 3.1.2), the distance between each seismic line must be 12.5 m.

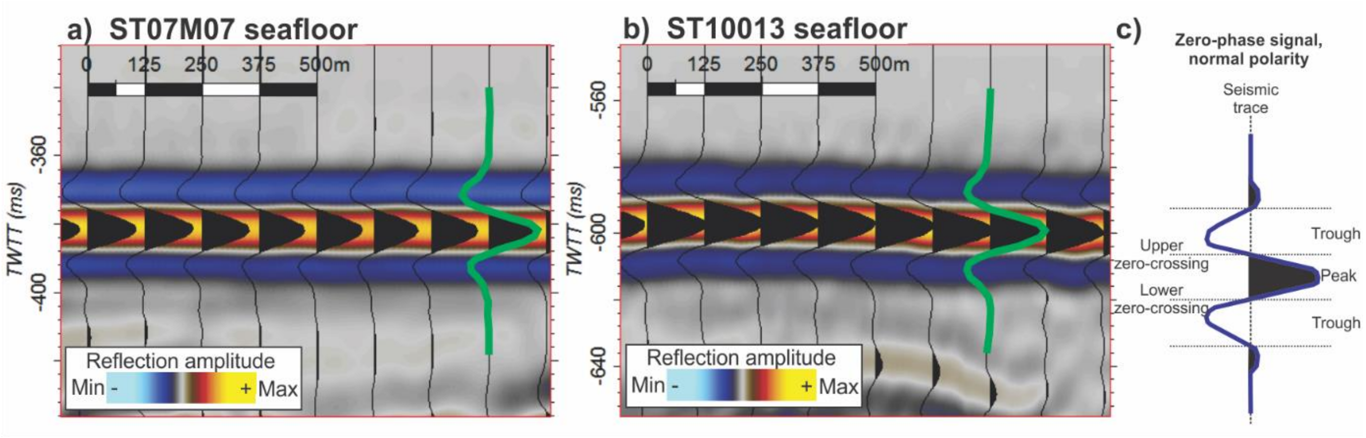


Figure 3.1.2 a) Seismic cross section showing variable wiggle display of the seafloor from the ST07M07 survey. b) Seismic section showing the seafloor of the ST10013 survey as variable wiggle display. c) Model of seismic trace showing zero-phase signal, normal polarity using SEG polarity standard of Sheriff (2006). The green lines indicate that both surveys have zero-phase signal, normal polarity. As every tenth seismic trace are shown in a) and b), the scale indicates a distance of 12.5 m between the seismic lines.

Spectral analyses from both 3D-surveys have been conducted to find the dominant frequency of the seismic interval covering the Naust Formation. From some chosen seismic lines, both surveys appear to peak between 30-40 Hz and the frequency spectrum is located between approximately 10-70 Hz (Fig. 3.1.3).

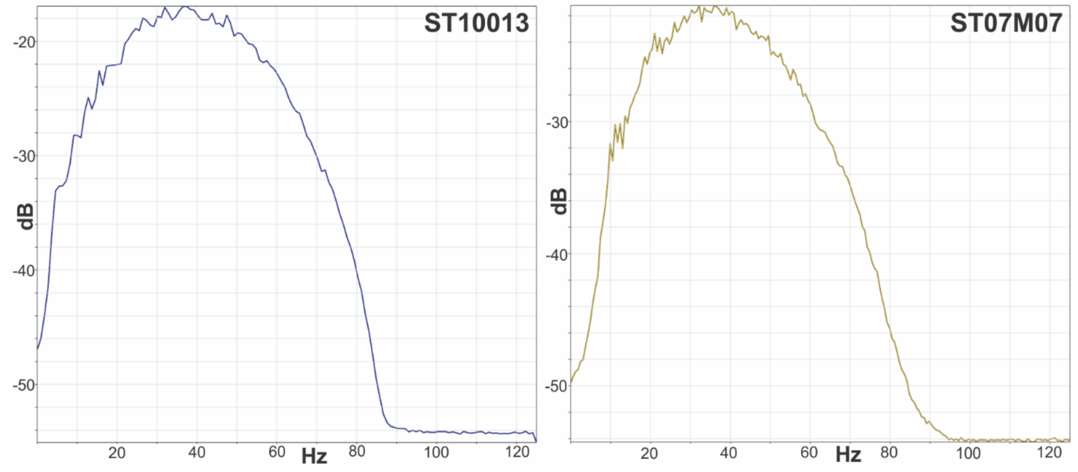


Figure 3.1.3 Spectral analyses from chosen seismic sections of the Naust Formation. The seismic sections have been obtained from both the ST10013 and ST07M07 surveys. The surveys peak at a dominant frequency between 30 and 40 Hz.

3.1.2 2D-surveys

The 2D-lines used in this study have been obtained from the MNR05 to MNR11 datasets, which have been provided by TGS. The datasets consists of over 250 separate 2D-lines of different quality. The dominating frequency of these seismic lines differ, but appears to generally lie between 30 to 40 Hz.

3.2 Seismic resolution

The vertical and horizontal resolution of the seismic data is important as it gives an understanding of how large structures must be to register within the data. The resolution depends on two factors, the velocity and the frequency. Together, these factors define the wavelength of the seismic signal. The seismic resolution decreases proportionally with depth while the wavelength increases. This is because older and deeper rocks become more compacted, which increases the seismic velocity. In addition to this, the high frequencies will decreases faster than low frequencies as they are more easily absorbed with increasing depth (Fig. 3.2.1) (Brown, 1999).

3.2.1 Vertical resolution

The vertical resolution is defined as the minimum thickness a layer must have to appear as a separate layer in seismic sections. This minimum thickness is determined by the wavelength (λ) which is a function of frequency (f) and velocity (v) (equation 1) (Fig. 3.2.1) (Badley, 1985). The thickness must be at least $^1/_4$ of the wavelength for layers to appear as separate structures (equation 2). If the layer is thinner than $^1/_4\ \lambda$, reflections from different layers will begin to merge. This continues all the way down to $^1/_{30}\ \lambda$ where the layer would not appear in the seismic all together (Badley, 1985; Brown, 1999).

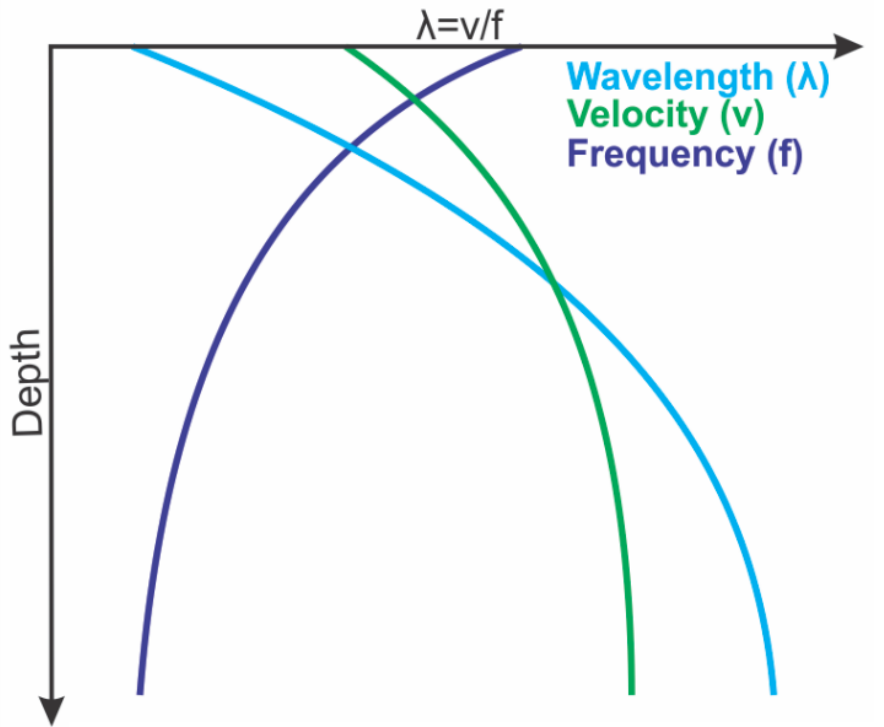


Figure 3.2.1 The relation between the frequency, velocity and wavelength of the seismic signal as it travels downwards in the strata. The figure has been modified from Brown (1999).

Equation 1

$$Wawelength: \lambda = \frac{v}{f}$$

Equation 2

$$Vertical\ resolution: \lambda\frac{1}{4}$$

λ = Wavelength (m), f = dominating frequency (Hz), v = velocity (m/s).

3.2.2 Horizontal resolution

The Fresnel Zone (equation 3) defines the horizontal resolution for unmigrated seismic data (Fig. 3.2.2). The Fresnel Zone represents the smallest distance two reflection points must have to appear as two separate objects in the seismic data. This is because the seismic wave front propagate downward as a sphere, and everything within this sphere results in the energy that is reflected to the hydrophones. Therefore, vertical structures must be larger than the Fresnel Zone to appear as separate structures. The Fresnel Zone will increase with depth because of attenuation and increasing velocity (Badley, 1985). The vertical resolution can be significantly improved by migration, decreasing the size of the Fresnel Zone. 2D-seismic can only be migrated along the seismic line, resulting in an ellipse perpendicular to the sampling direction (Fig. 3.2.2). 3D-seismic can be migrated in all directions resulting in a Fresnel zone with a smaller radius. If the migration is optimal the radius will decrease to as little as λ/4 (equation 4) (Fig. 3.2.2) (Badley, 1985; Brown, 1999).

Equation 3

$$Fresnel\ Zone\ before\ migration: rf = \frac{V}{2}\left(\frac{t}{f}\right)^{1/2}$$

Equation 4

$$Fresnel\ Zone\ after\ migration: \frac{\lambda}{4} = \frac{\mathrm{V}}{4f}$$

rf = radius of Fresnel Zone (m),

V = average velocity (m/s),

t = two way travel time (s),

f = dominant frequency (Hz)

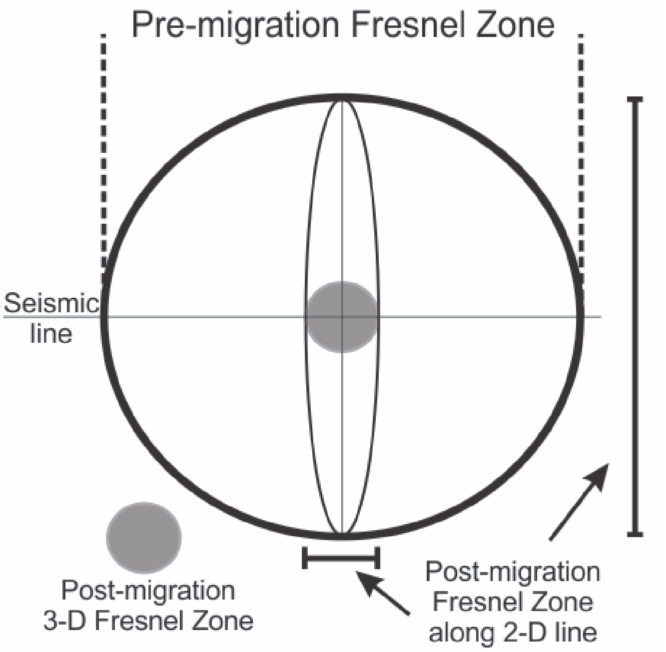


Figure 3.2.2 Illustration of the Fresnel Zone before and after migration for both 3D- and 2D-seismic data. The large cercal represent the data before migration. The ellipse represent the Fresnel Zone of 2D-seismic data after migration. The gray circle represents the Fresnel Zone for 3D-seismic data after migration. The figure has been modified from Brown (1999).

3.2.3 Resolution of the 3D-seismic surveys

Using the velocity model from the Haltenbanken area by Storvoll et al. (2006) (Fig. 3.2.3), and the dominating frequency from the spectral analyses the resolution from the 3D-seismic surveys have been calculated. For simplicity, the velocity has been set to 1800 m/s for Naust S and T, while the deeper sequences have been given a velocity of 2100 m/s.

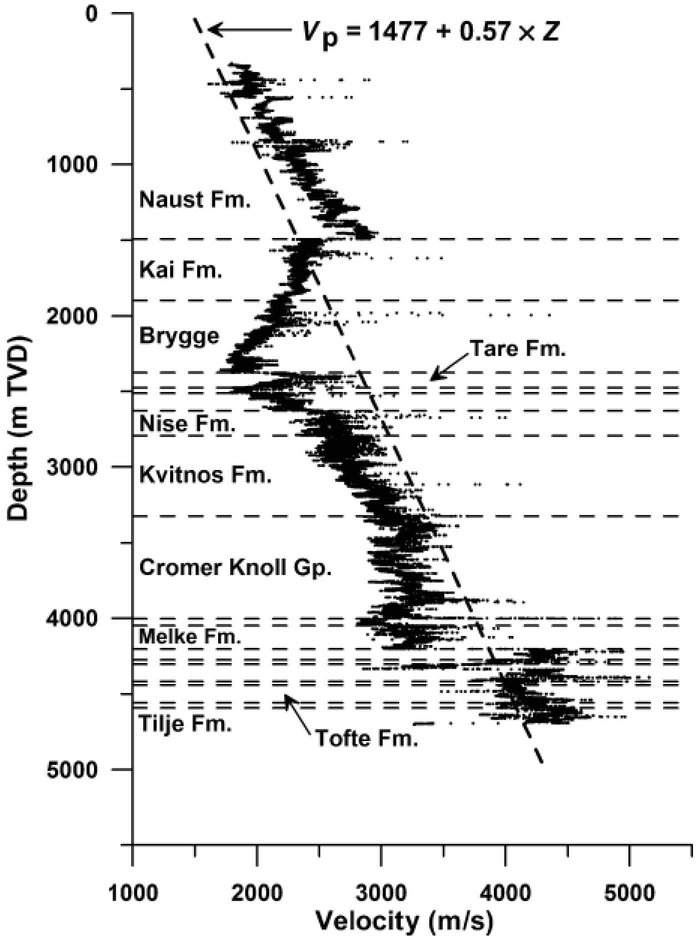


Figure 3.2.3 Velocity model based on one of the studied wells from the Haltenbanken area as well as a linear trend line based on data from various publications. The figure was added from Storvoll et al. (2006).

Resolution of Naust S and T

$$Wawelength\text{: } \lambda = \frac{1800\,\frac{m}{s}}{35\ Hz} = 51.4\ m \qquad Vertical\ resolution\text{: } 51.4\ \mathrm{m} \times \frac{1}{4} = 12.9\ m$$

$Fresnel\ Zone\ before\ migration$:

$$radius\ of\ Fresnel\ Zone\ = \frac{1800\,\frac{m}{s}}{2}\left(\frac{0.6\ s}{35\ Hz}\right)^{\frac{1}{2}} = 117.8\ m$$

$$Fresnel\ Zone\ after\ migration\text{: } \frac{\lambda}{4} = \frac{1800\ \mathrm{m/s}}{4 \times 35\ Hz} = 12.9\ m$$

In summary, the vertical resolution is 12.9 m, the radius of the Fresnel Zone is 117.8 m before and 12.9 m after migration.

Resolution of Naust N-U

$$Wawelength\text{: } \lambda = \frac{2100\,\frac{m}{s}}{35\ Hz} = 60.0\ m \qquad Vertical\ resolution\text{: } 60.0\ \mathrm{m} \times \frac{1}{4} = 15.0\ m$$

$Fresnel\ Zone\ before\ migration$:

$$radius\ of\ Fresnel\ Zone\ = \frac{2100\,\frac{m}{s}}{2}\left(\frac{1\ s}{35\ Hz}\right)^{\frac{1}{2}} = 177.5\ m$$

$$Fresnel\ Zone\ after\ migration\text{: } \frac{\lambda}{4} = \frac{2100\ \mathrm{m/s}}{4 \times 35\ Hz} = 15.0\ m$$

In summary, the vertical resolution is 15.0 m, the radius of the Fresnel Zone is 177.5 m before and 15.0 m after migration.

3.3 Artefacts

Artefacts have been observed in both of the 3D-seismic surveys. These artificial features probably appear in the seismic data as a result of seismic acquisition noise. Both surveys display lineations parallel to the sampling direction that can be found throughout the datasets (Fig. 3.3.1). These lineations have been interpreted to be noise which are the results of the difficulties to acquire identical rates for the collected lines (Bulat, 2005). The artefacts can be reduced by adjusting the light source. Hoverer, if the light source is directed perpendicular to the sampling direction the noise will be highlighted (Fig. 3.3.1). The artefacts are important to keep in mind when interpreting the seismic, so that they are not mistaken for real features.

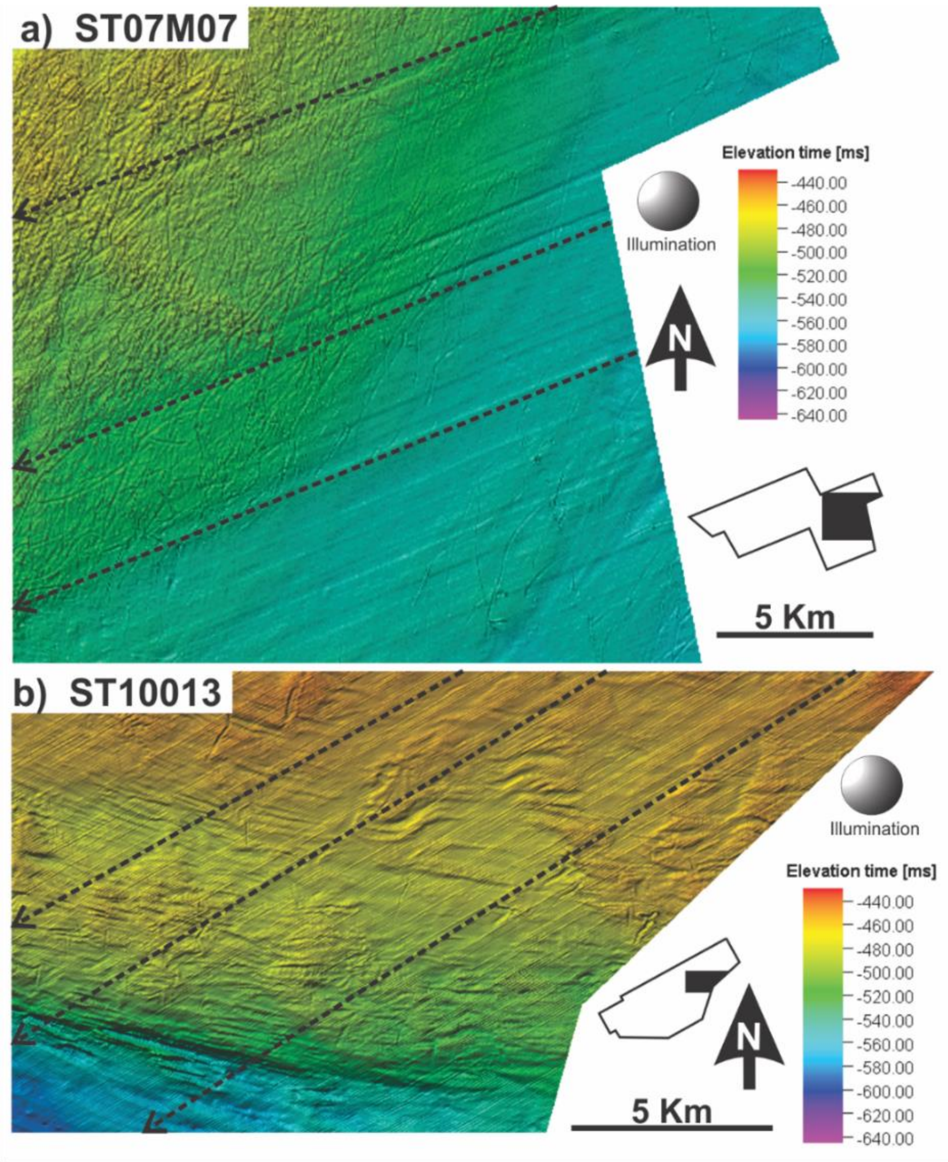


Figure 3.3.1 a) Display of the ST07M07 seafloor showing linear artefacts following the sampling direction (black stippled arrows) b) Artefacts on the ST10013 survey consisting of lineations parallel to the sampling direction (black stippled arrows).

3.4 Methods

In this study, the Petrel 2013 software from Schlumberger has been used as an interpretation- and visualization-tool. The software contains several tools that can be used to do a number of seismic analyses and interpretations. In this study "seismic interpretation" has been used to visualize surfaces within the 3D-seismic data. Surface and volume attributes have also been used to enhance different features of the seismic signal. The depth of the seismic data has been presented in two-way travel time (TWTT) where values under sea level have been given negative signs (e.g. -2100 ms TWTT). The figures of the study have been made and modified using the vector graphics editor software, CorelDRAW X6 from the Corel Corporation.

3.4.1 Interpretation of the seismic data

Before the interpretation was started the seismic volume of the two 3D-surveys were cropped in the z domain as the study mainly focuses on the relatively shallow Naust Formation. This allowed the interpretation work to proceed more efficient. The seismic horizons of this study have been interpreted using the "seismic interpretation tool". "Seeded 2-D autotracking" and "Guided autotracking" was used to pick points along the reflector that the interpretation would follow. This could be done using four different settings: upper zero-crossing, lower zero-crossing, peak and/or trough (Fig. 3.1.2c). In this study, the seafloor horizons have been interpreted on upper zero-crossing while the buried horizons have been interpreted on peak. This was done as the zero-crossing appear to give a more detailed surface, but can be difficult to track along the buried surfaces.

After a number of inlines and crosslines had been interpreted, the "Paintbrush" was used to fill in the areas in between. The number of lines varied as chaotic and complex seismic areas require more reference points. On the chaotic areas, strict interpretation parameters where also set to ensure the best possible interpretation result.

When looking at the surfaces, which have been created from the interpreted horizons, vertical exaggeration was used to enhance the geomorphological features. The exaggeration was normally set to between 10 and 20 times the normal value.

Mainly two different types of seismic display were used in the study. Changing the seismic display may give a different view and understanding of the seismic lines. Red-white-blue modified to display the strong amplitudes in green and yellow was used to interpret geomorphological structures (Fig. 3.4.1). Seismic (default) was used to interpret amplitude anomalies as it gives a good view of the amplitude specter (Fig. 3.4.1). In the ongoing chapters, the simplified templates (Fig. 3.4.1b) will be used for simplicity. Note that the yellow color represent the trough in one color scale (Red white blue) and the peak in the other (Seismic (default)).

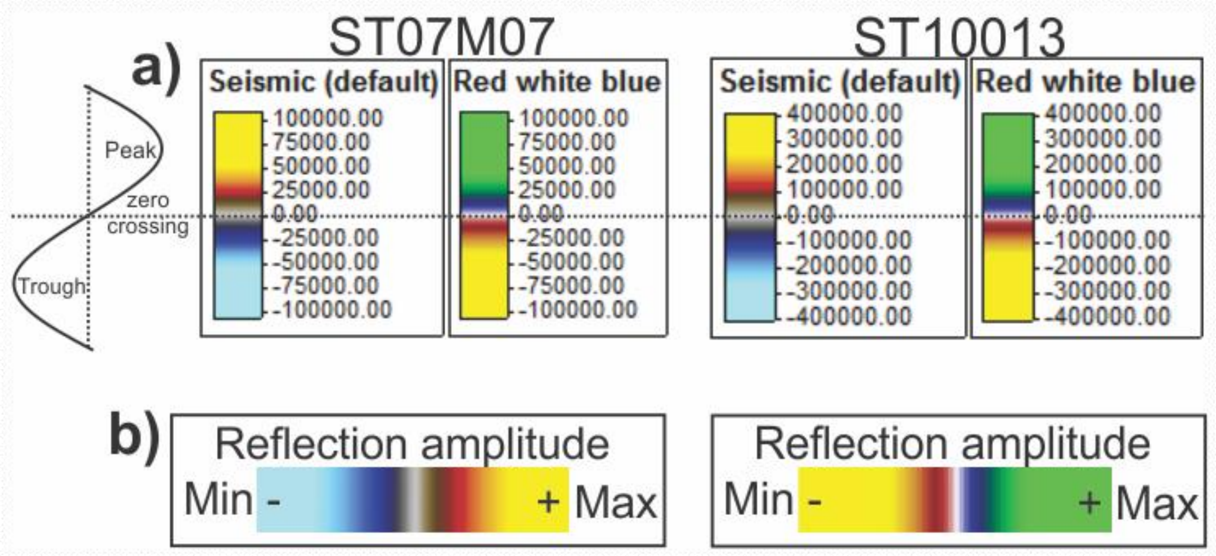


Figure 3.4.1 a) Templates showing the color scale of the different seismic displays used in the study. The templates have been compared to a model of the seismic signal with maximum, minimum and lower zero-crossing defined. c) Simplified templates, which are used in the study.

3.4.2 Seismic attributes

Seismic attributes can be useful tools when certain seismic characteristics are of interest. They can be used to map out specific geometry or physical parameters, and therefore increase the geological understanding of the study area (Chopra & Marfurt, 2005). The attributes can be volume-based (e.g. variance) where the attribute is generated for the whole 3D-cube or surface-based (e.g. RMS amplitude and minimum amplitude) where the attribute is generated from a specific surface or interval window. In this study, attributes were used to map out faults and amplitude anomalies. Some of these attributes where also combined on the same surface to see if any correlation between the faults and amplitude anomalies could be identified.

Variance (edge method)

Variance cubes are useful for edge detection as it estimates the local variance of the seismic signal. Such discontinuities of amplitude in the horizontal continuity may represent different geomorphological features (Daber et al., 2010). In this study, the variance cubes have been used to locate faults, pipes and paleo-pockmarks at different depths.

RMS amplitude map

RMS amplitude maps calculates the root mean square amplitudes divided by the number of samples (Daber et al., 2010). This highlights strong amplitudes, both positive and negative, for the chosen interval window and displays them along a surface. The RMS maps have been used to document amplitude anomalies within the study area.

Minimum amplitude map

Minimum amplitude maps measures the reflectivity within an interval window and highlights only the strong negative amplitudes within the selected interval window (Daber et al., 2010). The minimum amplitude attribute is a good tool to locate bright spots, as they consist of strong negative amplitudes, and is therefore a useful in the search of hydrocarbon indicators.

4. Results

The results presented in this chapter are based on the 3D-seismic surveys ST10013 and ST07M07. Several 2D-lines were also used to connect the two surveys and to get more insight into the regional stratigraphy surrounding them. After the stratigraphy of the study area is presented, different surfaces within the Naust Formation and their geomorphology will be described and interpreted. The first interpreted surface is the seafloor before gradually moving down into the subsurface. Then seismic anomalies within the sediment sequences will be described and interpreted. All the results will be discussed in chapter 5.

4.1 Stratigraphy

The seismic stratigraphy of the Naust Formation in the study area has been correlated using the works of Ottesen et al. (2009); Rise et al. (2010); Ottesen et al. (2012); Eidvin et al. (2014) Rise et al. (2006). The stratigraphy is displayed using 2D-lines moving through the 3D-surveys (Fig. 4.1.1). The purpose of the correlation is to connect the different seismic reflectors to the different sediment sequences within the Naust Formation and establishing an age estimate that can be compared to glacial cycles of the same period. The age model used is that of Rise et al. (2010) which is a revised model from Rise et al. (2006). The stratigraphy has been described using the standards of Veeken (2007).

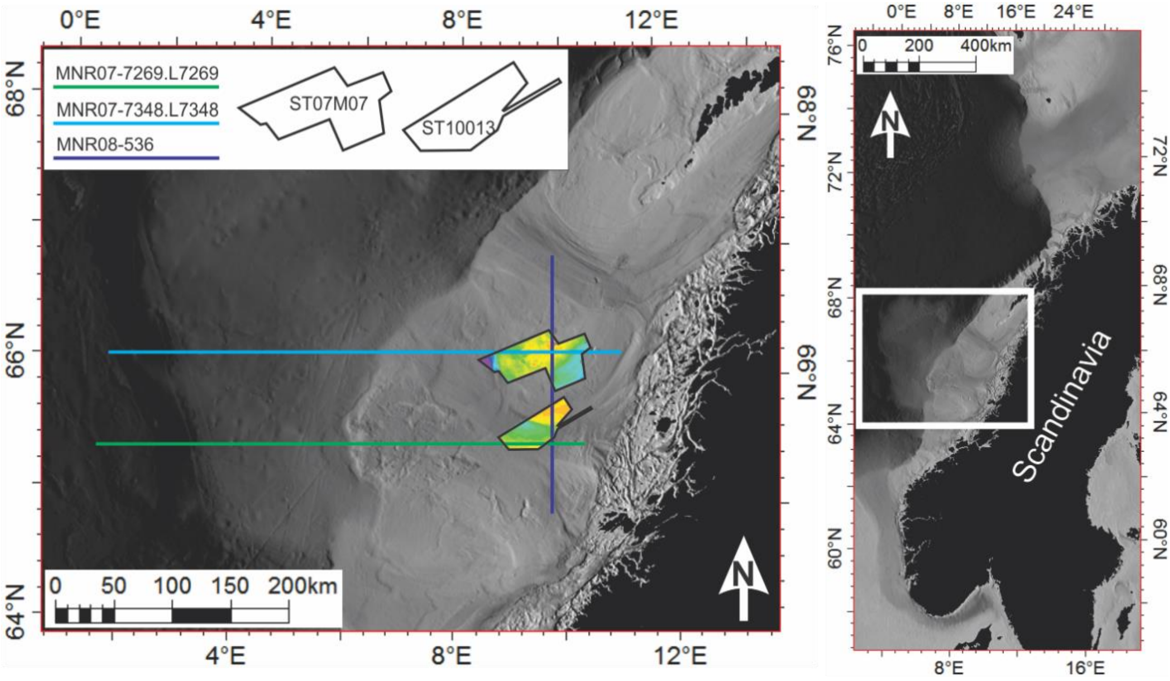


Figure 4.1.1 Bathymetry map of the mid-Norwegian margin indicating the location of the MNR07-7269.L7269, MNR07-7348.L7348 and MNR07-536 2D-lines as well as the ST07M07 and ST10013 3D-seismic surveys.

The ST07M07 survey located on Trænabanken has been correlated to the stratigraphy of the 2D-line GMNR-94-106 by Ottesen et al. (2009) as this line stretches trough the 3D-survey. The stratigraphy is displayed in Fig. 4.1.2 using the MNR07-7348.L7348 2D-line to demonstrate the different sequences on a larger regional scale. All the sediment sequences of the Naust Formation are represented in the survey, although the S sequence is barely seen and is therefore not consistent enough to be interpreted in the 3D-survey.

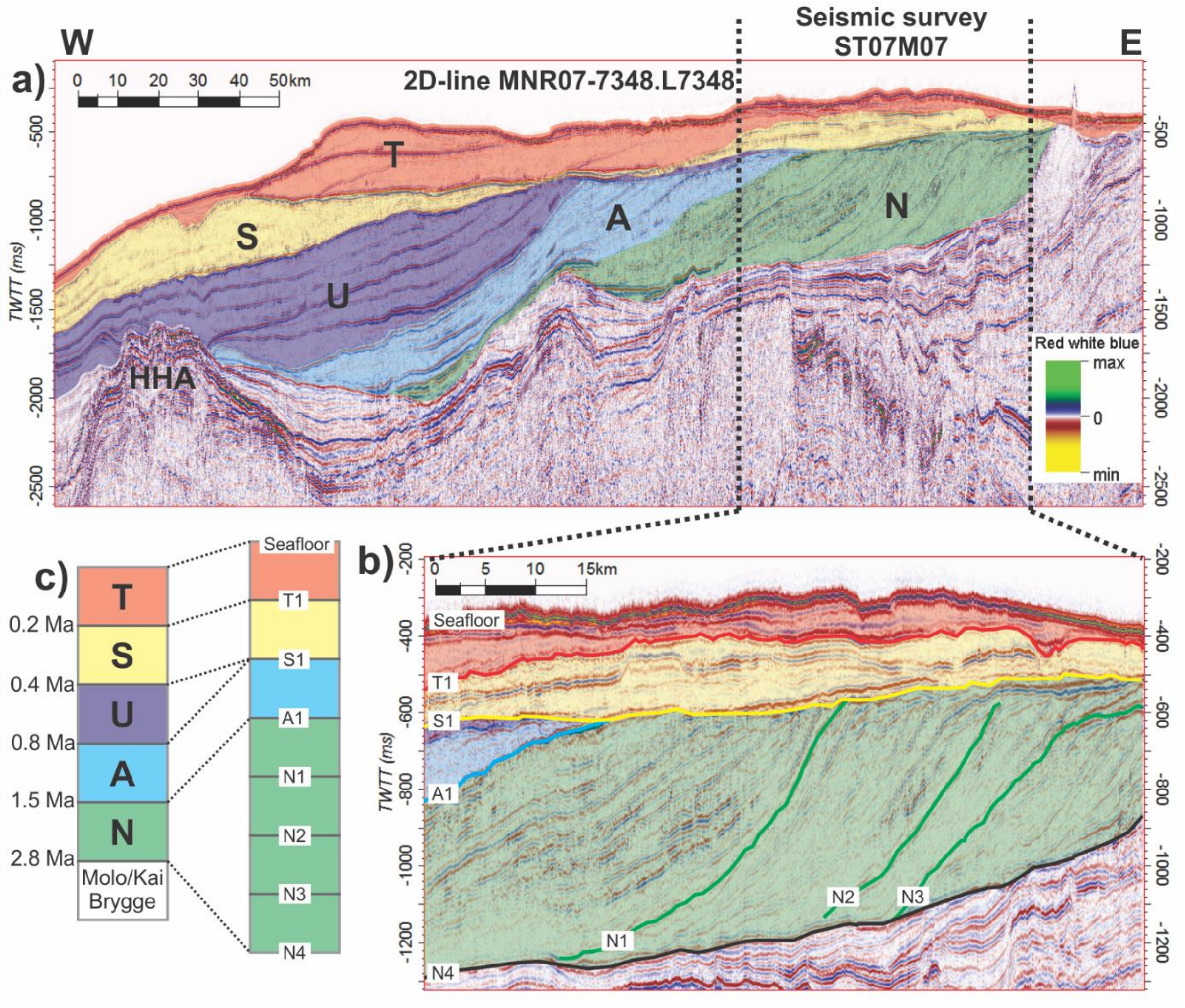


Figure 4.1.2 a) Seismic section of the MNR07-7348.L7348 2D-line displaying the sedimentary sequences of the Naust Formation. HHA: Helland Hansen Arch. b) Seismic section of arbitrary line displaying the sedimentary sequences and interpreted reflections (Seafloor, T1, S1, A1 and N1-N4) within the ST07M07 3D-survey. c) Age estimate of the different sedimentary sequences and interpreted reflections based on the age model of Rise et al. (2010). Location indicated in Fig. 4.1.1.

The ST10013 survey is located in Sklinnadjupet where no direct examples of the stratigraphy demonstrated in literature could be found. Therefore, the stratigraphy of the survey has been interpreted using the GMNR-94-106 2D-line by Ottesen et al. (2009) located on Trænabanken and the GMNR-94–105 2D-line by Ottesen et al. (2012) located north of Haltenbanken, combined with interpretations from Rise et al. (2006); Eidvin et al. (2014). Using several crossing MNR 2D-lines as well as the seismic signatures of the reflectors, an estimate of the stratigraphy was established. This is just an estimate as it is an especially difficult area affected by erosion as well as tectonic processes, cutting and deforming the reflectors making them hard to recognize. There are also no core samples or well logs available from this area. The estimated stratigraphy is displayed in Fig. 4.1.3 using the MNR07-7269.L7269 2D-line to demonstrate the different sequences on a larger scale. Only the N, S and T sequences of the Naust Formation are located within the ST10013 survey.

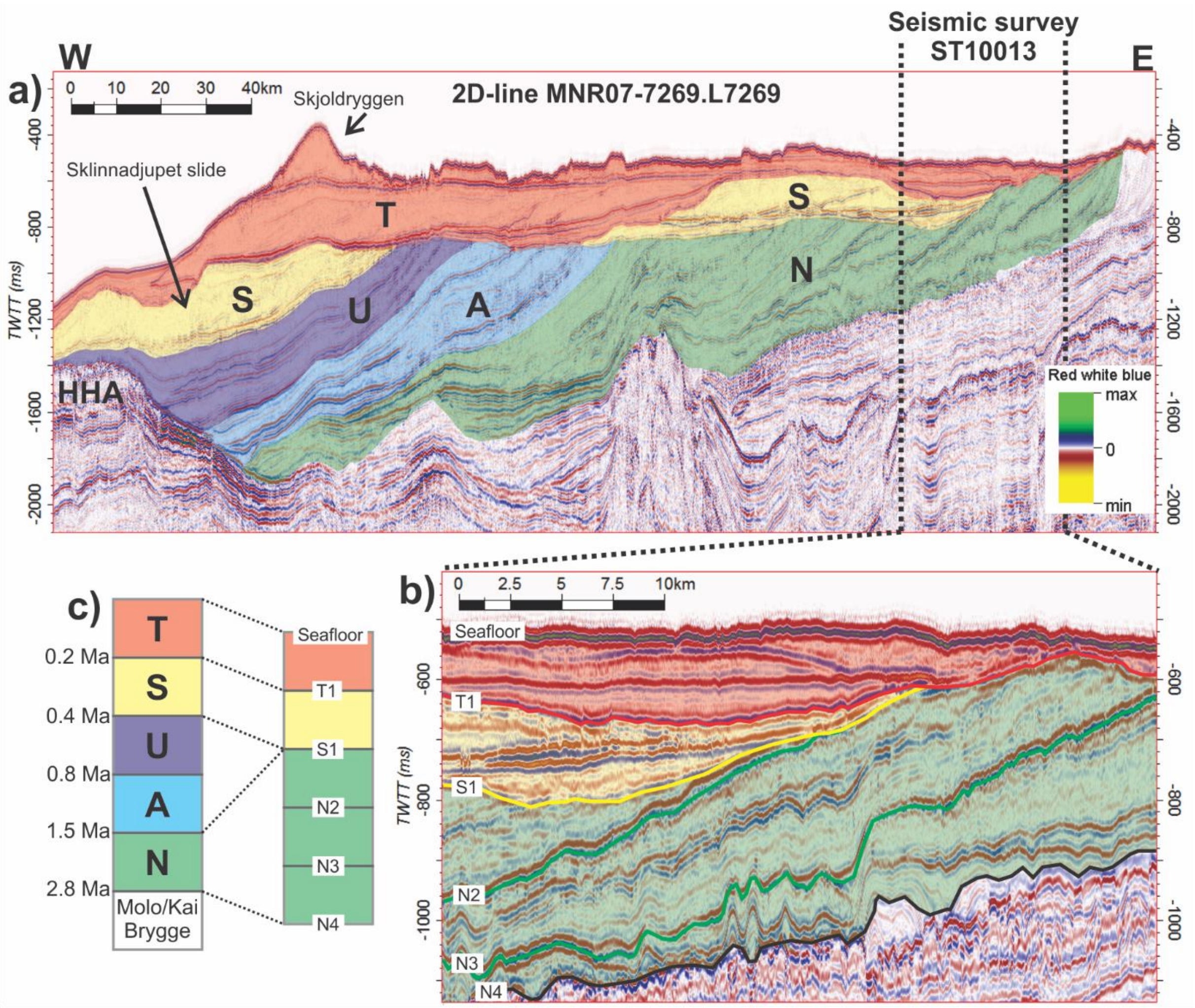


Figure 4.1.3 a) Seismic section of the MNR07-7269.L7269 2D-line showing the sedimentary sequences of the Naust Formation. HHA: Helland Hansen Arch. b) Seismic section of arbitrary line indicating the sedimentary sequences and interpreted reflections (Seafloor, T1, S1, and N2-N4) within the ST10013 3D-survey. c) Age estimate of the sedimentary sequences and interpreted reflections within the study area based on the age model of Rise et al. (2010). Location indicated in Fig. 4.1.1.

The two different 3D-surveys have then been correlated with one another using 2D-lines from the MNR surveys stretching between them. This gives a good perspective of how the sequences develop within the study area as displayed in Fig. 4.1.4.

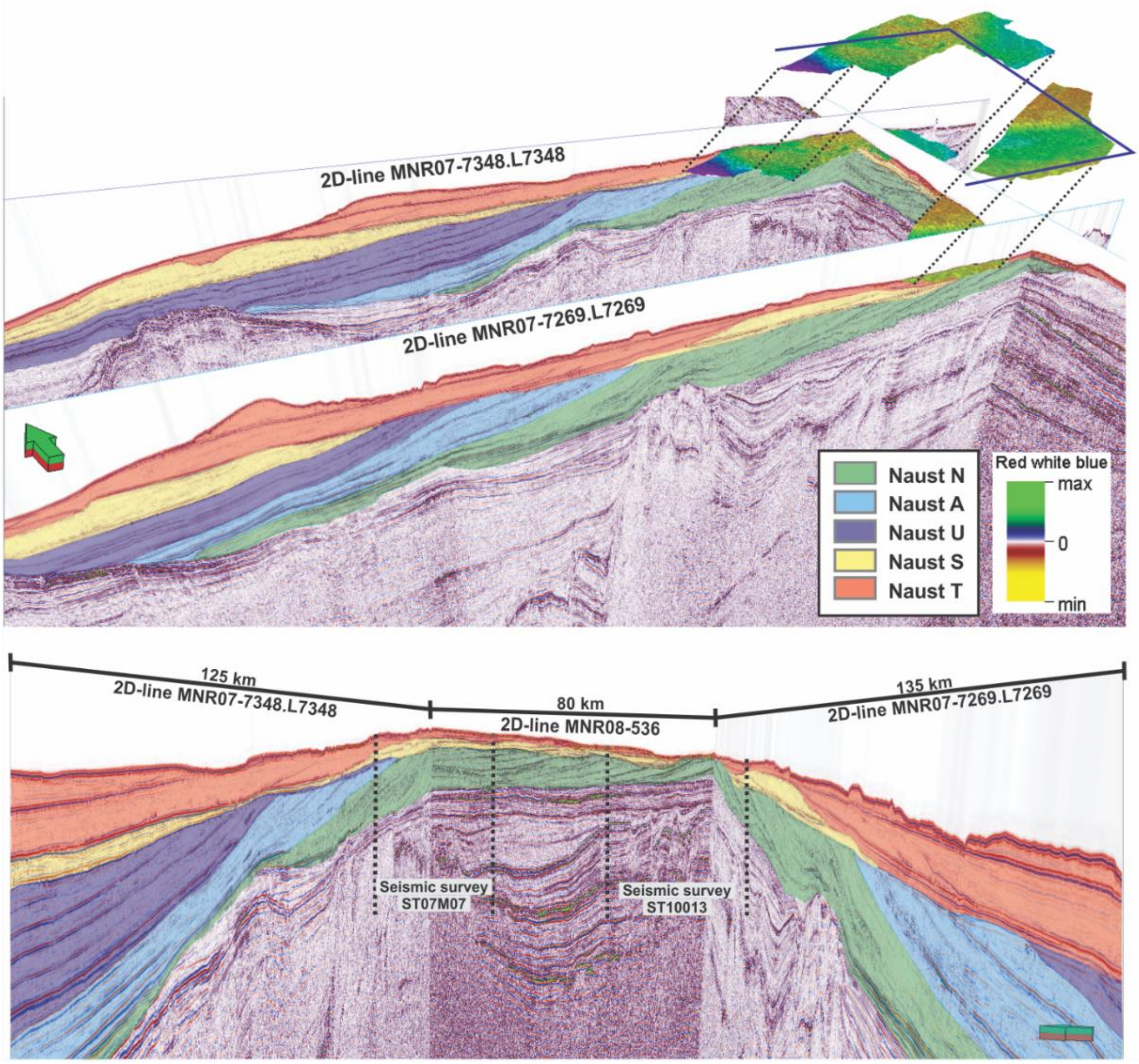


Figure 4.1.4 3D-view of the MNR07-7269.L7269, MNR07-7348.L7348 and MNR07-536 2D-lines displaying the propagation of the different sediment sequences within the Naust Formation from the study area toward the continental shelf break. Location is shown in Fig. 4.1.1.

The seismic stratigraphy of the Naust Formation within the study area is dominated by two main reflection configurations. The lowermost consists of prograding clinoform wedges while the uppermost consists of sheet-like sequences with sub-parallel layers (Fig. 4.1.4).

4.1.1 Reflection N4 (Base Naust N)

N4 is defined by prograding clinoform layers down-lapping on to the reflection making it the base of the prograding wedges. The reflection is sub-horizontal, dipping towards the west. This is interpreted to be an unconformity indicating the change in depositional environment between the Naust Formation and the underlying Molo/Kai- and Brygge Formation, and the N4 reflection is correlated to the base of Naust N. In the ST07M07 survey the reflection has medium to strong amplitudes with a relatively good continuity (Fig. 4.1.2). In the ST10013 survey the eastward reflection resemble the one in ST07M07, but towards the west the reflection develop a slightly stronger amplitude while the continuity decreases (Fig. 4.1.3). This change in continuity is interpreted to be the result of polygonal faulting of the Brygge Formation (Eidvin et al., 2014).

4.1.2 Reflection N1-N3 (Intra Naust N)

The N1-N3 reflections are interpreted to represent internal layers of the N sequence of the Naust Formation (Fig. 4.1.2 and 4.1.3). The sequence consists of prograding clinoform layers with sigmoidal to tangential oblique reflection configuration. The layers are dipping towards the west where they are increasingly affected by the underlying reflection, which they are on-lapping onto. In the ST10013 survey the reflections assumes a wavy configuration interpreted to be a result of the underlying polygonal faults of the Brygge Formation (Fig. 4.1.3). In the ST07M07 survey the layers decrease in dip towards the west. Within the N sequence several reflection with strong amplitudes and good continuity embrace packages of low amplitudes and poor continuity.

4.1.3 Reflection A1 (Base Naust A)

The A1 reflection is only located in the NW corner of the ST07M07 survey (Fig. 4.1.4) and is interpreted to represent the base of the Naust A sequence. The reflection configuration is similar to that of the N sequence consisting of prograding clinoform layers, but with a decrease in the angle of dip.

4.1.4 Reflection S1 (Base Naust S/upper regional unconformity)

The prograding clinoform layers which makes up Naust N is truncated by the S1 reflection. This unconformity is interpreted to be the base of Naust S, which represents the upper regional unconformity (URU). Above the URU the reflection configuration alternate to a sub-parallel sheet-like structure within the S sequence of the Naust Formation. This structure appear to transcend into clinoforms as they continue out of the study area and over the continental slope. The sheets in ST07M07 appear to be aggradational towards the west, while the layers in ST10013 display an on-lapping reflection termination towards the prograding clinoform in the east. The S1 reflection has a generally good continuity and strong amplitudes with exception of some few places. The reflection continuous throughout the entire ST07M07 survey, the reflection appears to terminate towards the east in the ST10013 survey (Fig. 4.1.2 and 4.1.3).

4.1.5 Reflection T1 (Base Naust T)

The T1 reflection in the ST10013 survey truncates S1 as well as the underlying prograding clinoforms coming up towards the east (making it the URU in a small area of the survey). This have been correlated with the base of Naust T, which marks the beginning of the youngest sediment sequence within the Naust Formation. The reflection configuration is similar to that of the S sequence, displaying a sheet-like structure which appear to be aggradational towards the west with some indications of on-lapping towards the east. The T1 reflection in the ST10013 survey has good continuity and strong amplitudes while the reflection in ST07M07 varies as the reflection is less continuous and display weaker amplitudes at some locations (Fig. 4.1.2 and 4.1.3).

4.1.6 Age estimate

The age estimate is based on the age model of Rise et al. (2010), although it is important to remember that the age and development of the Naust Formation may have varied along the margin. The age estimates of the different sequences are also poorly constrained due to lack of core material which can be dated. These cores also contain few index fossils, which may have been postponed to extensive reworking. Therefore the age of the sequences should only be regarded as provisional (Ottesen et al., 2009).

The T1 reflection, which represents the base of Naust T, has been given an age of 0.2 Ma. The S1 reflection, which is correlated to the base of Naust S, has been dated to 0.4 Ma (Rise et al., 2010). A1 is correlated with the base of the A sequence with an age estimate of 1.5 Ma. The N1-N3 reflections are interpreted to be internal layers of Naust N, which gives them an age estimate of between 1.5 and 2.8 Ma. The N4 reflection has been given an age estimate of 2.8 Ma as it is correlated with the base of Naust N (Rise et al., 2010).

4.2 Seafloor geomorphology

The geomorphology of the mid-Norwegian continental shelf is characterized by shallow banks separated by deeper troughs orientated sub-parallel to the Norwegian coast. Within these first-order geomorphological features, several smaller features can also be observed. These features will be described and interpreted for the study area, which consists of the ST07M07 survey located on inner Trænabanken and the ST10013 survey located in the inner part of Sklinnadjupet (Fig. 4.2.1). The water depth has been calculated using an assumed water velocity of 1480 m/s.

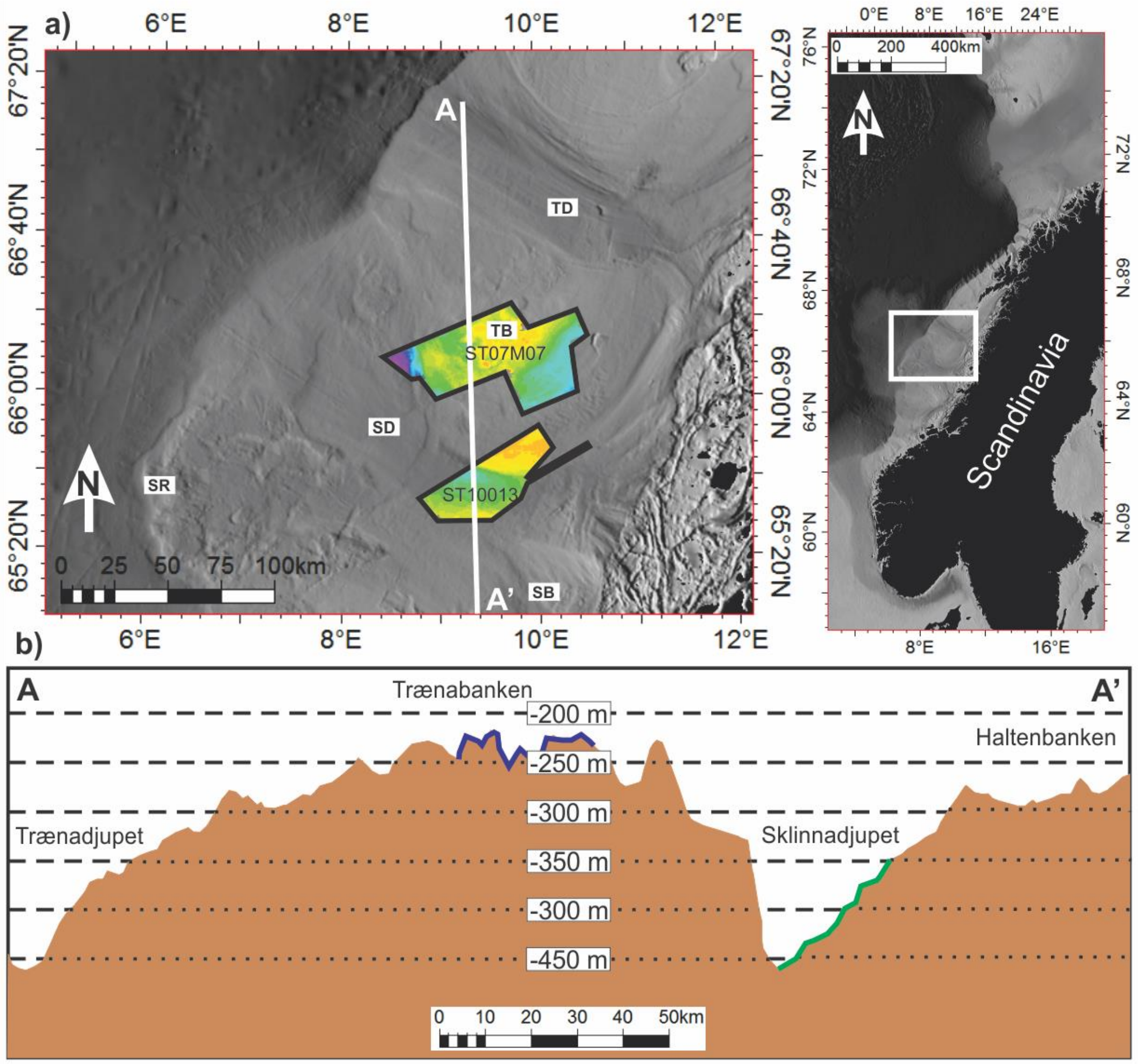


Figure 4.2.1 a) Bathymetry map of the mid-Norwegian continental shelf indicating the 3D-seismic survey ST07M07 located on Trænabanken and the 3D-seismic survey ST10013 located in Sklinnadjupet. TD: Trænadjupet; TB: Trænabanken; SR: Skjoldryggen; SD: Sklinnadjupet; SB: Sklinnabanken. White line indicates location of b). b) Cross section of the mid-Norwegian continental shelf showing the water depth (large stippled lines) along the seafloor. Colored lines indicate the location of ST07M07 (purple) and ST10013 (green).

4.2.1 ST10013 Seafloor geomorphology

The ST10013 seafloor surface (Fig. 4.2.2) has been divided into 3 areas based on geomorphology. The trough (Fig. 4.2.3) which constitutes the inner part of Sklinnadjupet is located in the middle of the survey. This cross-shelf trough separate the northern part of Sklinnabanken (Fig. 4.2.8) and the southern part of Trænabanken (Fig. 4.2.11).

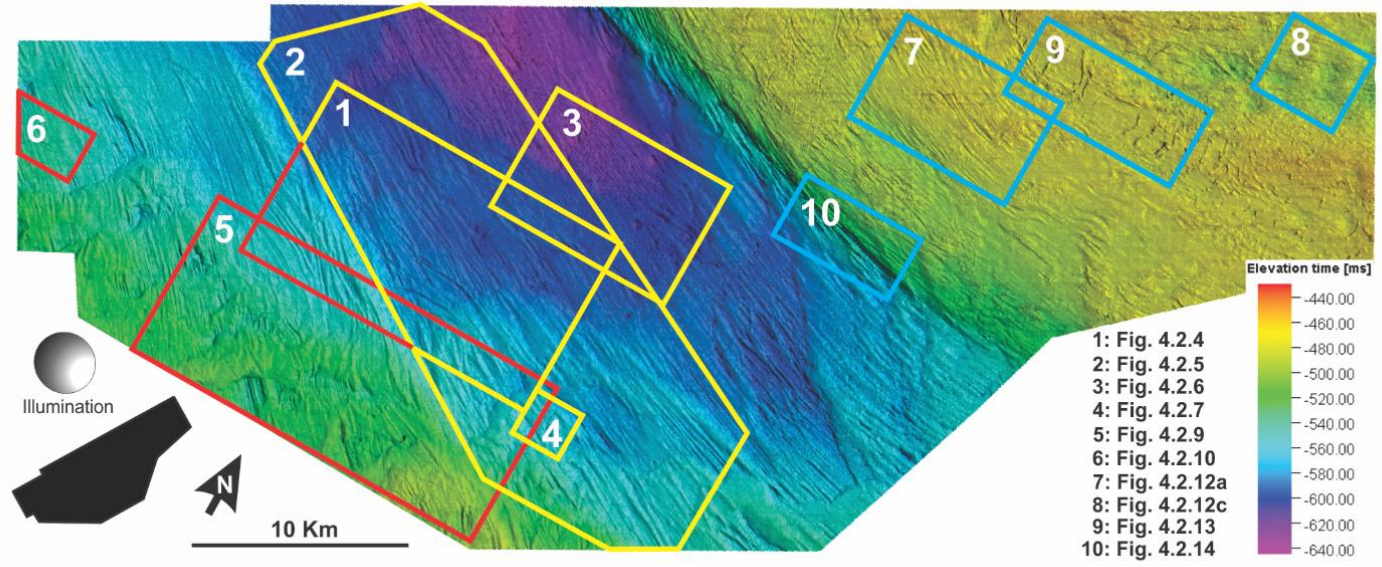


Figure 4.2.2 Seafloor surface of the ST10013 3D-survey located in the inner part of Sklinnadjupet (Fig. 4.2.1). Yellow (trough), red (Sklinnabanken) and blue (Trænabanken) frames outlines location of zoom-in figures.

4.2.1.1 Trough

In the ST10013 survey, a distinct trough can be observed with an E-SE to W-NW orientation (Fig. 4.2.3). The trough stretches throughout the survey and has a width between 20 and 23 km. The trough lies at a water depth between approximately 390-480 m and is deepest to the NW where the depth reaches up to 130 m deeper than the adjacent banks. The geomorphology varies within the trough, going from hummocky in the east to smoother towards the west. The trough is interpreted as a first-order geomorphological feature created by erosion by fast-flowing ice streams moving from the mainland towards the continental shelf edge (Vorren, 2003) as the trough can be followed across the shelf and it is over-deepened. Several smaller geomorphological features are located within the trough, where most of these appear to be of glacial origin as will be further documented below.

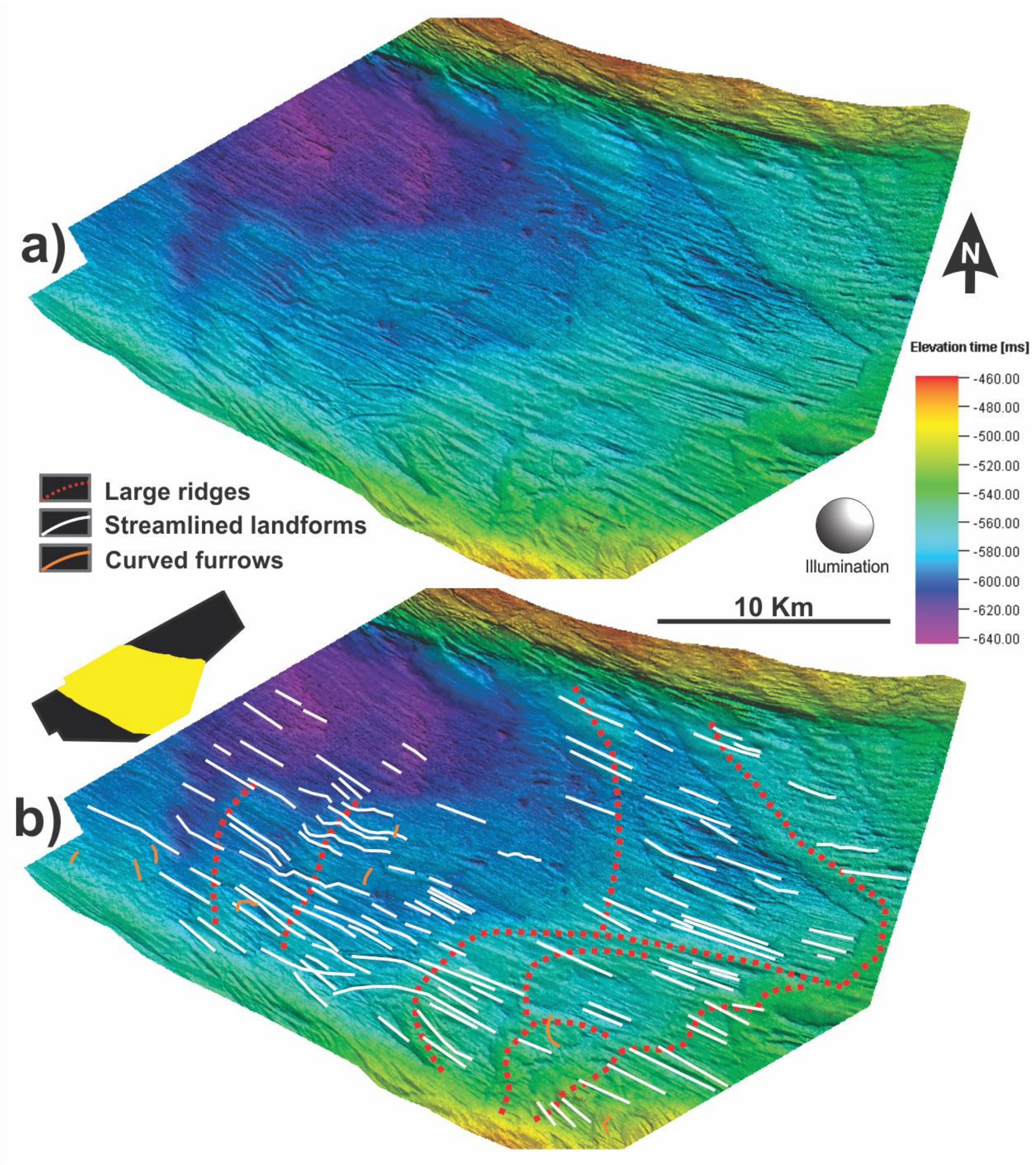


Figure 4.2.3 a) Seafloor of the cross-shelf trough on the ST10013 survey. b) Indication of different geomorphological features within the trough including large ridges, streamlined landforms and curved furrows.

Streamlined landforms:

A large number of parallel, large-scale linear furrows can be observed on the seafloor within the trough (Fig. 4.2.3 and 4.2.4). They have a mean direction trending from the E-SE towards the W-NW. They are generally linear but some slightly curved furrows have also been observed. They are generally U- or V-shaped, the depth has been measured up to 6 m, and the width can be up to 300 m. The continuity of the lineations are poor but the length has been measured up to 8,5 km. Parallel to these furrows elongated ridges can be seen, especially in the landward part of the trough. The length can be measured up to right above 5 km. They have a relatively blunt stoss side with a narrowing lee side. The height is hard to distinguish as the ridges are located alongside the linear furrows, but has been measured to reach approximately 3 m where the highest point is located on the blunt side. The elongated ridges are widest on the blunt side where the width reaches up to 600 m.

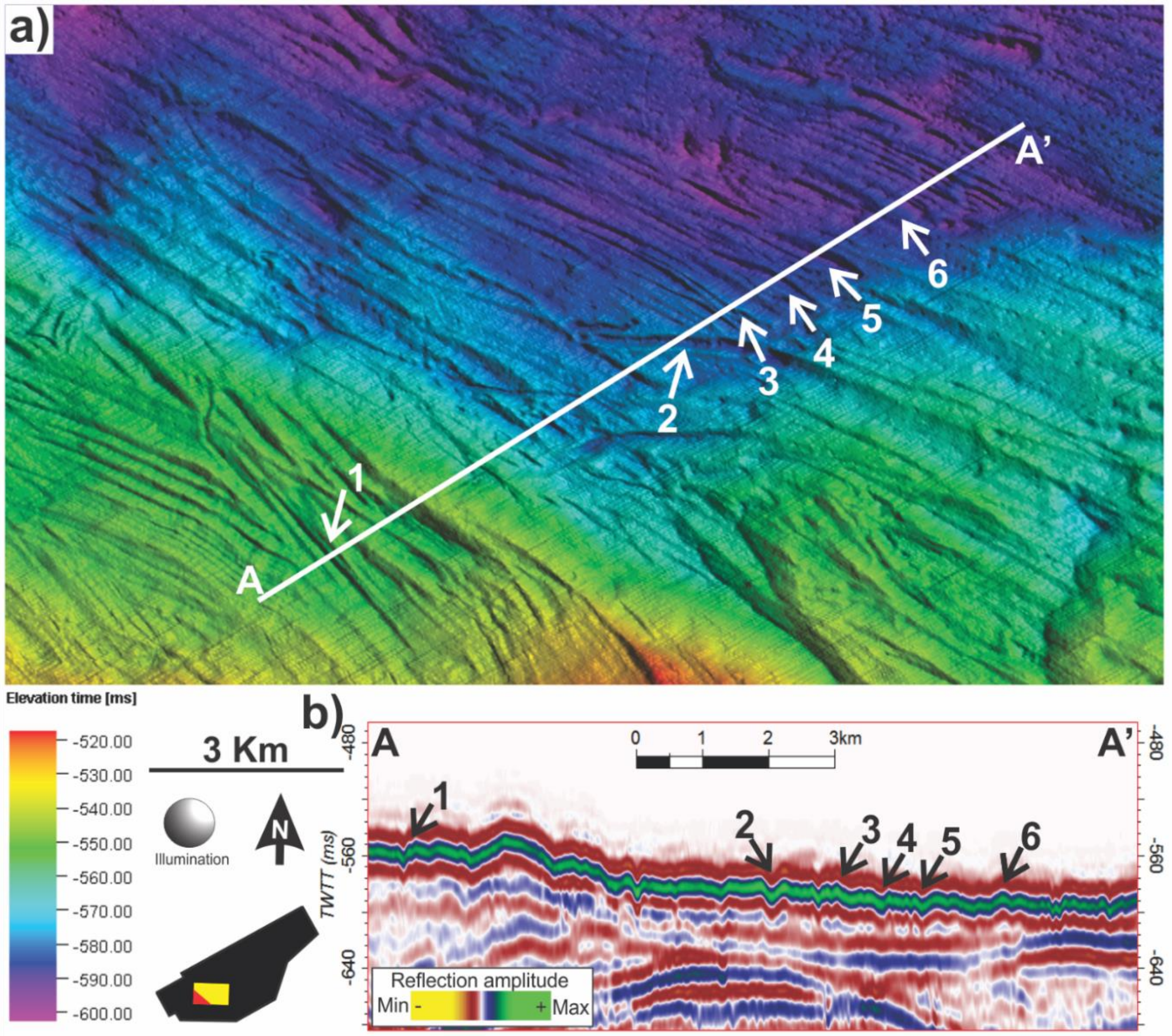


Figure 4.2.4 a) Seafloor with streamlined landforms on the bank (1) and in the trough (2-6) interpreted as MSGL and flutes. b) Seismic section of arbitrary line indicated by white line. The location is displayed in Fig. 4.2.2.

Interpretation:

The parallel, large-scale linear furrows shape and geomorphology resembles that of mega-scale glacial lineations (MSGL) described by Ottesen et al. (2005a) among others, which are formed by sub-glacial sediment deformation caused by fast-flowing ice streams. Troughs like the one in the study area are known to have acted as highways for such ice streams making it a likely place to find MSGL. The geometry and geomorphology of the ridges are interpreted to represent flutes created by glacial erosion and deposition as described by Munro-Stasiuk et al. (2013). MSGL and flutes have also been located in other cross-shelf troughs in close regional proximity and similar settings as the study area by Ottesen et al. (2005a); Rydningen et al. (2013). MSGL have also been described on the seafloor in the Barents Sea by Andreassen et al. (2008). The streamlined landforms are parallel to the trough indicating the direction of the paleo-ice stream.

Large ridges:

Several large ridges with a main trending direction SW-NE can be observed in the trough (Fig. 4.2.3 and 4.2.5). The sharpest ridges with the strongest relief are located in the landward direction towards the east and as the trough gets deeper towards the west the ridges almost disappear. The width of the ridges to the reaches up to right above 4000 m while the length is approximately 8 km. The spacing between them is measured to right above 2000 m and the height up to 18 m. The ridges with a stronger relief to the east have a distinct lobe shape with a length varying from 4500 m to 10 km. The lobes merges, making it hard to see where one starts and another ends, but they have been measured to range between 2500-4000 m. The height is measured up to 10 m. There appear to be both symmetrical and asymmetrical ridges and they are all overprinted by MSGL and flutes.

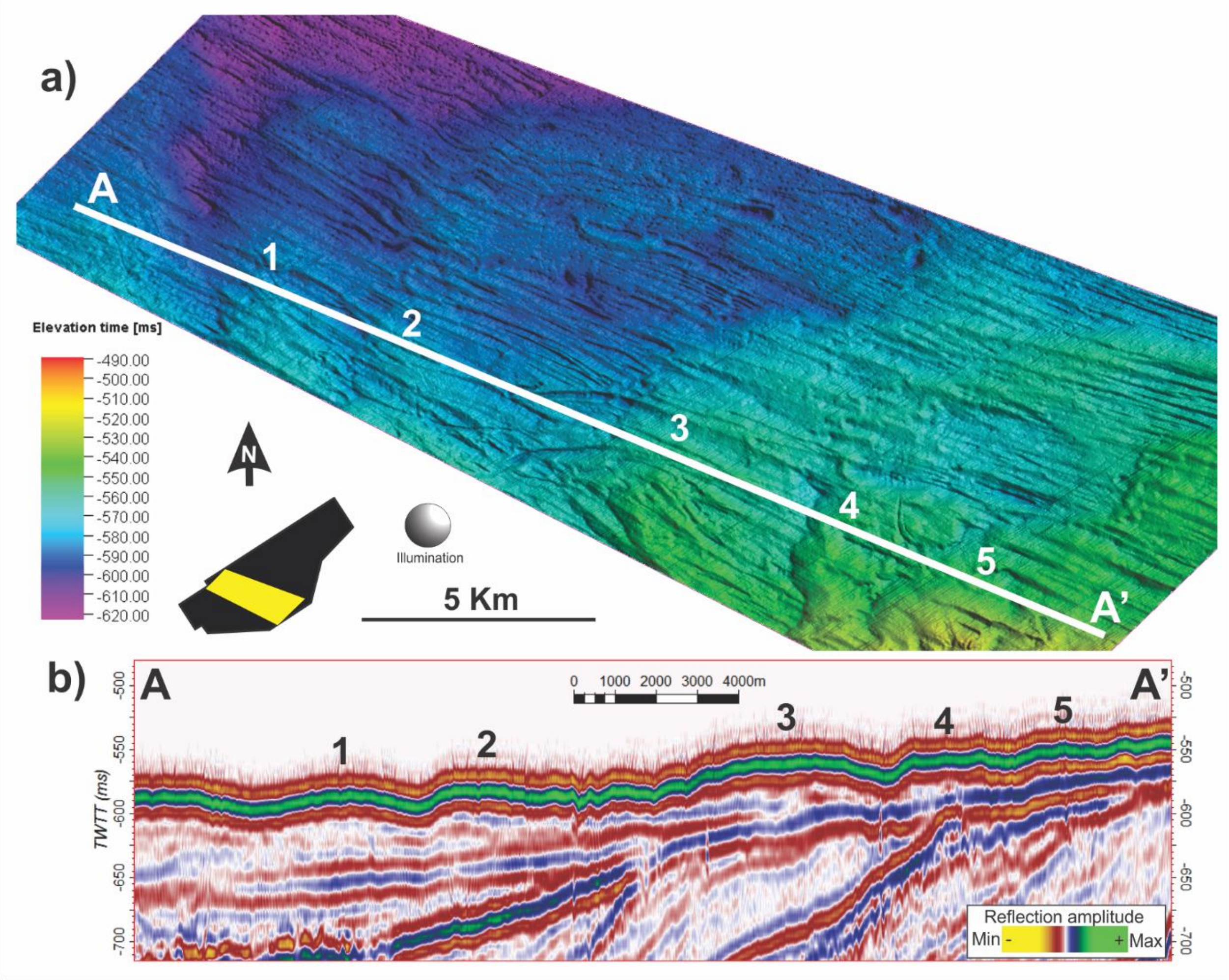


Figure 4.2.5 a) Seafloor with large ridges interpreted as moraines. b) Seismic section of arbitrary line indicated by white line with numbers indicate the crest of the large ridges. The location is displayed in Fig. 4.2.2.

Interpretation:

The large ridges that are located in the trough and have an orientation perpendicular to the large-scale linear furrows. This indicates that the ridges would have been parallel to the moving ice front during the last glacial period. This, combined with the geometry of the ridges indicates that they are moraines deposited in front of the glacier, probably during several small readvances during the deglaciation. Because the ridges appear to merge, where the landward build onto the ridges further out on the shelf, it is likely that the ridges are gradually older towards the continental shelf break. The location of the ridges also appear to take place where the trough is slightly narrower. Pinning points like this are known to be natural places for ice-contact fans and morainal banks to form (Laberg et al., 2007a). Similar moraines have been described by Rydningen et al. (2013) in the northern parts of the mid-Norwegian continental margin.

Circular depressions:

Within the trough, a high concentration of small circular depressions can be observed on the seabed surface (Fig. 4.2.6). The diameter varies up to approximately 100 m and the depth is up to 5 m. They are distributed across the trough but the highest concentration with up to 50 pockmarks per km^2 can be found along the northern side and in the deepest areas of the trough. They have a parabolic shape and some of the depressions appear to line up in the linear furrows described above. Some of the depressions are larger than the rest, and display a more oval shape. They are up to 7.5 m deep and have a diameter up to 600 m (Fig. 4.2.6).

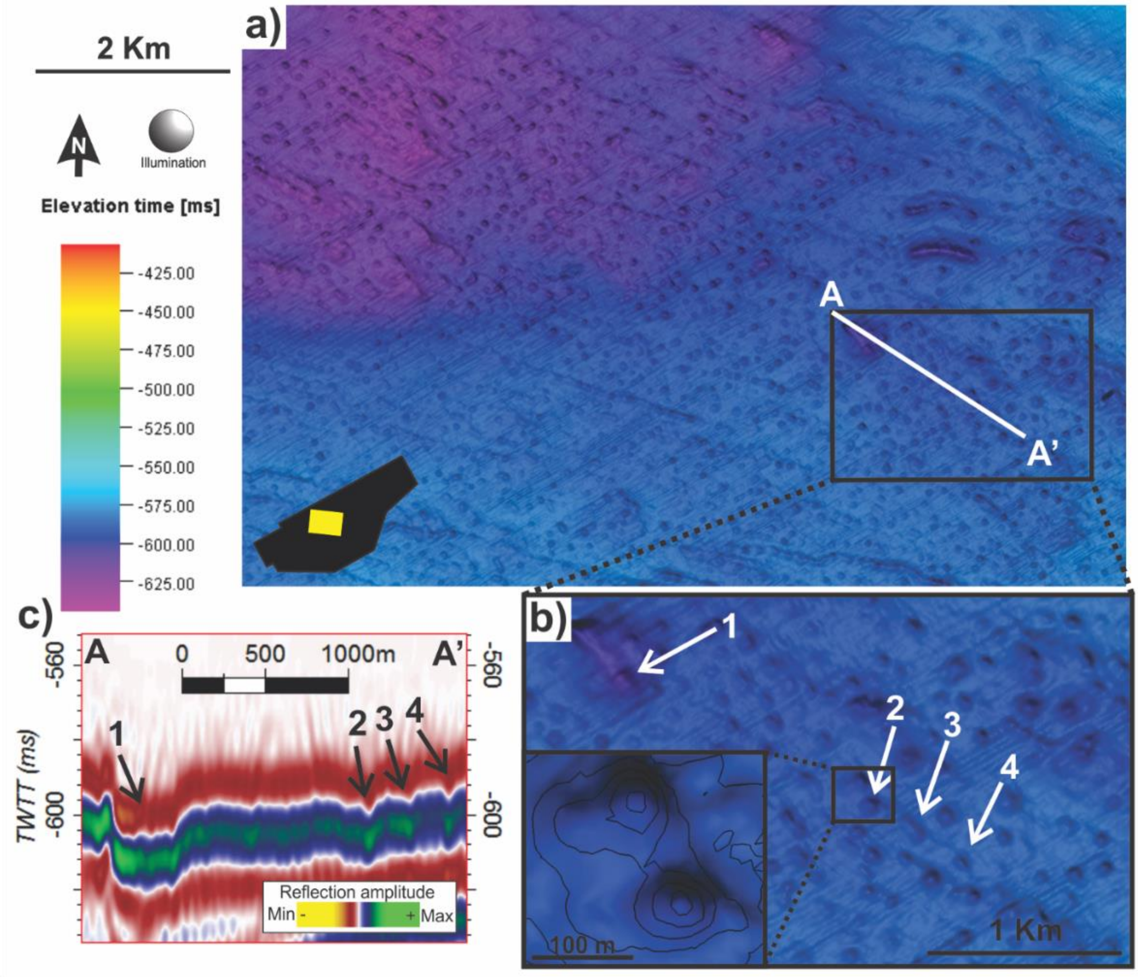


Figure 4.2.6 a) Seafloor with circular depressions interpreted to be pockmarks and iceberg pits. The black box indicates location of b), white line indicates location of c). b) Zoom-in of seabed showing a possible iceberg pit and pockmarks. Figure in the lower left corner show close-up of two of the pockmarks. c) Seismic section of arbitrary line. Arrows indicating iceberg pit (1) and pockmarks (2-4). Location indicated in Fig. 4.2.2.

Interpretation:

The small circular depressions located in the trough are interpreted to be small pockmarks. Løseth et al. (2009) describes pockmarks as shallow seafloor depressions that may appear as circular features up to tens of meters deep. The pockmarks are generally formed in fine-grained, soft sediments on the seafloor by fluids or gas escaping into the water column. Pockmarks are often located above hydrocarbon indicators or areas with signs of fluid migration (Hovland & Judd, 1988). It is also a possibility that the depressions are a result of grounding icebergs. Nevertheless, the fact that the depressions only occur in the deeper part of the survey as well as the sheer number of depressions makes this hypotheses unlikely. However, some bigger depressions that have a circular to elongated shape are more likely the result of this process. Small pockmarks like these have also been observed in Trænadjupet by Ottesen et al. (2005b) and in the Barents Sea by Chand et al. (2009).

There seems to be some connection between the furrows and depressions as they line up. This might be explained by the possible differential sealing of the till within the furrows. The thinner till layer might result in easier fluid migration compared to the thicker till surrounding the furrows. There have also been described numerous minor faults and fissures in the zone stressed by the formation of the furrows in other areas by Hovland and Judd (1988). This may locally increase permeability, which is utilized by fluid seeking the easiest migration pathway. There is also a possibility that the concentration of pockmarks within the furrows are simply caused by infilling of soft sediments where pockmarks easily can develop (Hovland & Judd, 1988; Forwick et al., 2009). This would mean that the fluid migration to the surface has been active after the creation of the furrows. This might also be the case on a larger scale, explaining why the pockmarks are concentrated in the trough. The trough may act as a sediment trap for both sediments transported out from the fjords at the coast and sediments transported across the shelf by ocean currents. Pockmarks are known to develop in fine sediments, making the trough an ideal place. This has been described by Chand et al. (2009) in the Barents Sea. There are no distinct signs of fluid migration directly beneath the pockmarks. However, small vertical discontinuities have been located throughout the 3D-survey (described later)

Elongated curved furrows:

Chaotically orientated elongated and curved furrows with a main direction going from NE-SW are randomly located on the seabed surface (Fig. 4.2.3 and 4.2.7). They are generally U- or V-shaped in cross sections and have a depth up to 3 m with some displaying elevated flanks. The furrows can be followed up to 2 km and have a width up to 150 m. The chaotic pattern results in furrows crossing and overprinting the linear furrows.

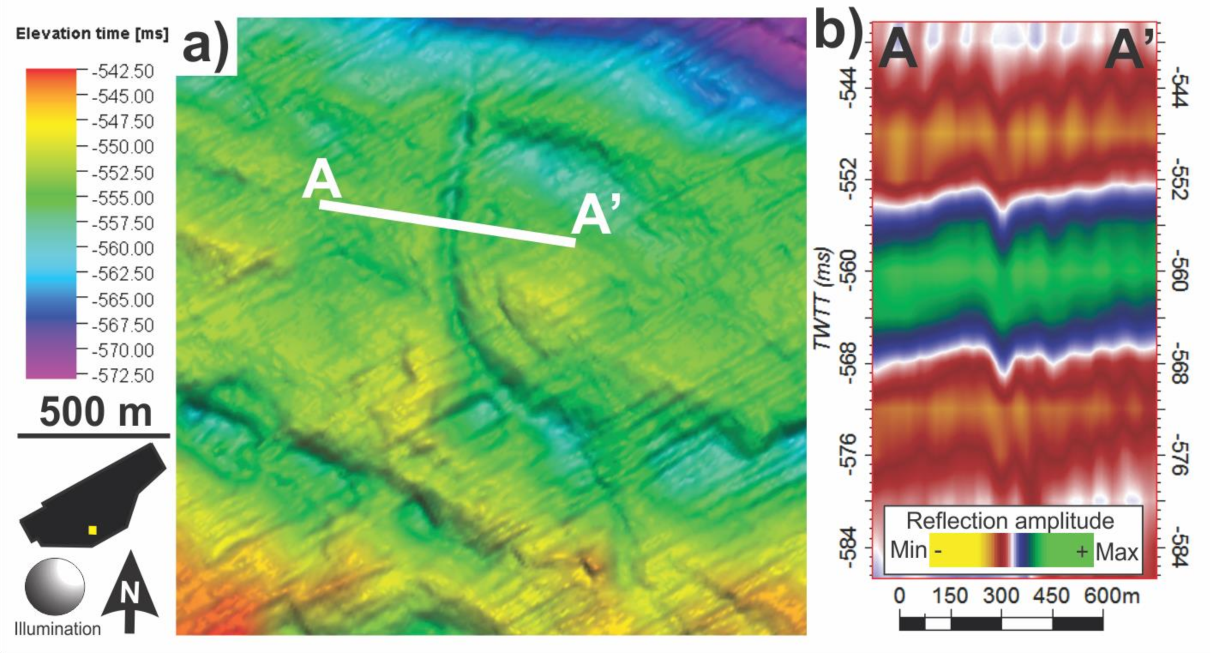


Figure 4.2.7 a) Seafloor with elongated curved furrow interpreted to be iceberg plough-marks. White line indicating location of b). b) Seismic section of arbitrary line. Location indicated in Fig. 4.2.2.

Interpretation:

The chaotic orientation of the elongated curved furrows as well as the geomorphology of the features are interpreted to represent iceberg plough-marks. Plough-marks are the result of glacimarine environments where keels of calved icebergs erode the soft sediments on the seafloor. The icebergs are driven by wind- and ocean currents resulting in the chaotic pattern (Andreassen et al., 2008). Andreassen et al. (2008) found that plough-marks were common features on banks and water depths of under 450 m. The study area has been relatively unaffected by these features. This is probably because the water depth is too high, reaching almost 500 m at some places in the trough. Thus, only the very large icebergs were able to reach the ocean floor. The main direction of the furrows can be related to the ocean currents flowing along the Norwegian coast. They line up as the ocean currents would be the main influence of the transportation of floating icebergs. The curved furrows overprinting the linear furrows indicates that the latter is the oldest features of the two. This is likely as the icebergs would have originated from the calving glacier as it withdrawals from the continental shelf. Similar features have been described by Dowdeswell et al. (2007) on the mid-Norwegian continental shelf and by Andreassen et al. (2008) in the Barents Sea.

4.2.1.2 Sklinnabanken

To the south of the cross-shelf trough the survey stretches up on Sklinnabanken which is mainly dominated by two geomorphological features, large ridges and streamlined landforms (Fig. 4.2.8). The water depth had been calculated to between approximately 340-420 m.

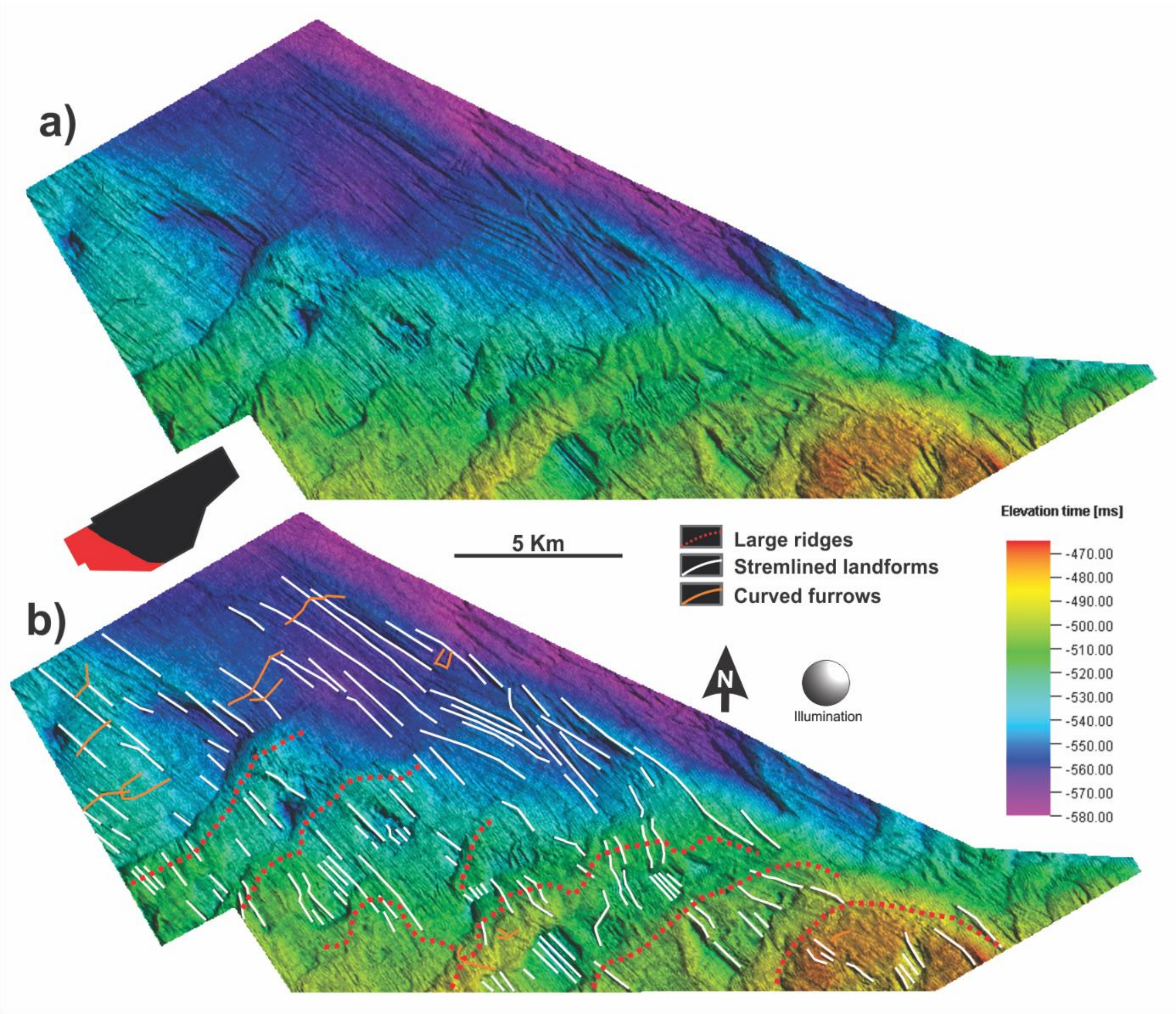


Figure 4.2.8 Seafloor of the northern part of Sklinnabanken to the south of the trough on the ST10013 survey. b) Indication of geomorphological features on the bank including large ridges, streamlined landforms and curved furrows.

Streamlined landforms:

A large number of parallel large-scale linear furrows have been observed on the northern part of Sklinnabanken (Fig. 4.2.4 and 4.2.8). They have their main orientation trending E-SE towards W-NW. However, on the middle of the bank edge the direction may vary leading to crossing furrows. The longest of the furrows have been measured to 6 km and are located in the north where the seabed is smoothest. They furrows are generally linear but some appear to be slightly curved. They are generally U- or V- in cross sections and the depth has been measured up to 7 m while the width can be up to 200 m. Parallel to the furrows elongated ridges have been observed. The length can be measured up to 3 km. They have a relatively blunt stoss side with a narrowing lee side. The height is hard to distinguish, as the ridges are located alongside the linear furrows, but has been measured to reach approximately 5 m where the highest point is located on the blunt side. The width reaches up to right above 400 m on the blunt side.

Interpretation:

The streamlined landforms are similar to the streamlined features described earlier and interpreted in the cross-shelf trough. These features are therefore also interpreted to be MSGL and flutes.

Large ridges:

Several large ridges trending in a SW-NE direction have been observed on the southern flank (Fig. 4.2.8 and 4.2.9). The width of the ridges varies from 1000-4000 m while the length is hard to measure, as they appear to continue out of the study area. The spacing between them varies from being merged at some places to a distance of up to 2000 m. The seabed in between the ridges display imprints of the streamlined landforms described above that comes to an abrupt stop at the beginning of the ridges. The ridges are up to 25 m high and the ridges themselves are also covered with some streamlined landforms. The sharpest ridges with the strongest relief are located to the east and gets progressively less distinct towards the west. The ridges appear to be asymmetric with a steeper angle on the landward side.

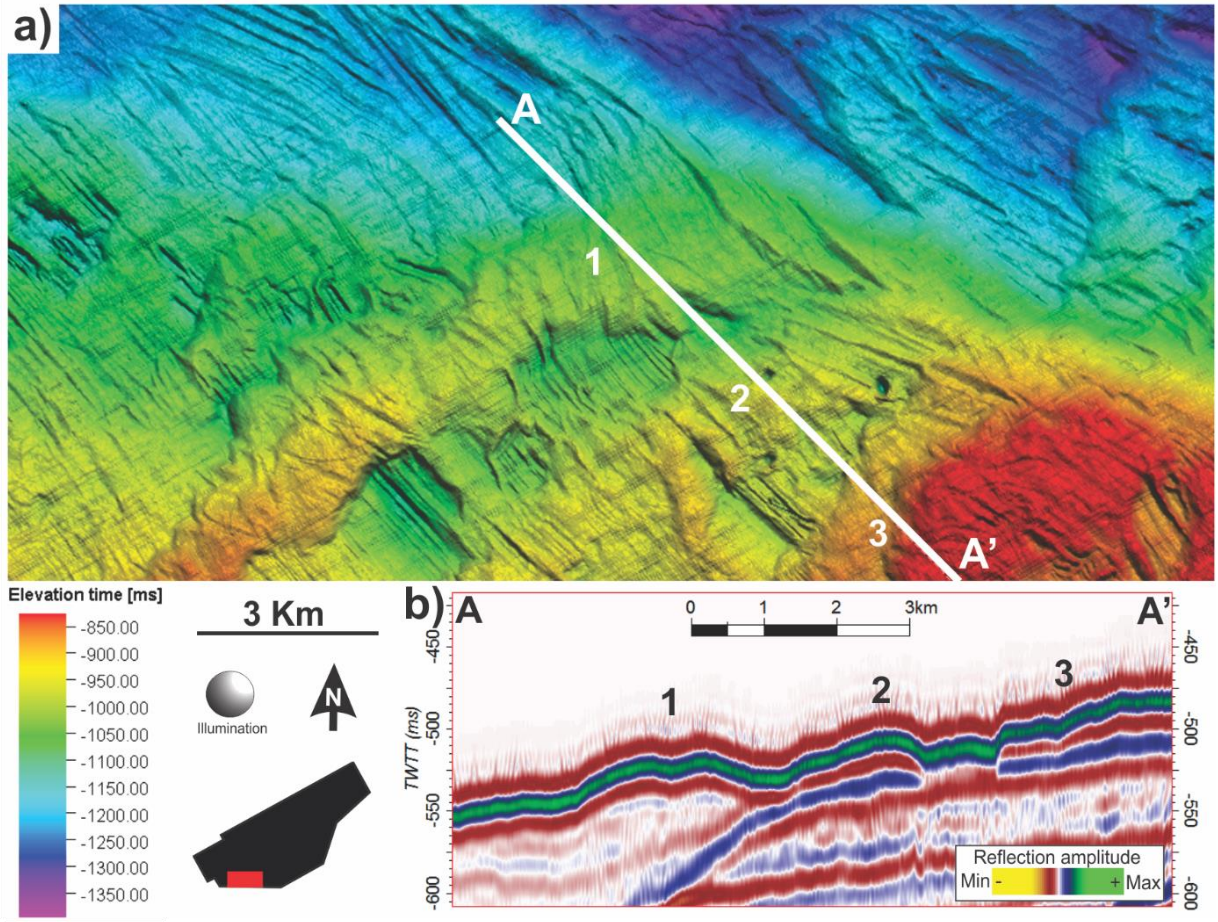


Figure 4.2.9 a) Seafloor with large ridges interpreted to be moraines. White line indicating location of b). b) Seismic section of arbitrary line. White numbers indicating the crest of large ridges interpreted as moraines. Location indicated in Fig. 4.2.2.

Interpretation:

The geomorphology of the ridges show close similarities to the large ridges found in the trough. Therefore, they are also interpreted as moraines deposited at the front of the glacier during small readvances, although it might not have been the same readvances as the glacier have different momentum in the trough than on the bank. The furrows that are located between the moraines have been interpreted to be part of the original surface that has been buried by the moraines. This implies that some of the streamlined landforms are older than the moraines while the streamlined landforms imprinted on top of the moraines are younger.

Elongated curved furrows:

Chaotic orientated elongated curved furrows with a main direction going from NE-SW are randomly located at the seafloor (Fig. 4.2.8 and 4.2.10). They are U- or V-shaped in cross sections and have a depth up to 4 m with some displaying elevated flanks. The furrows can be followed up to 3 km and have a width up to 150 m. The chaotic pattern results in furrows crossing and overprinting other furrows.

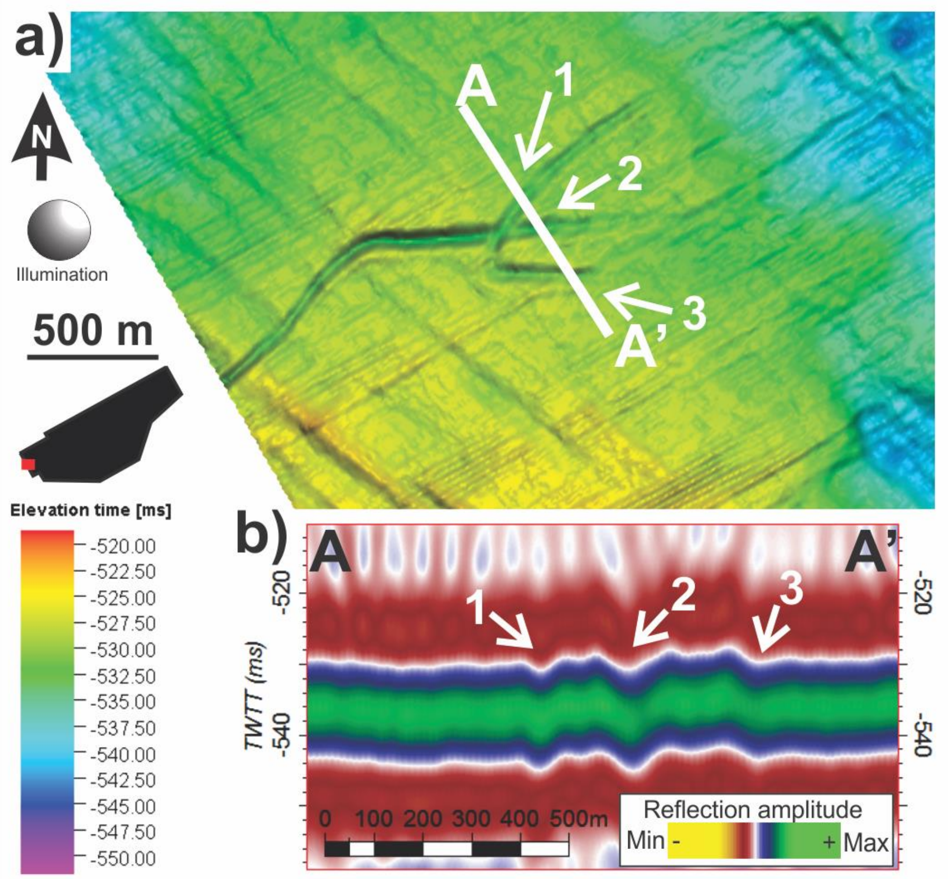


Figure 4.2.10 a) Seafloor with elongated curved furrows interpreted to be iceberg plough-marks. White line indicating location of b). b) Seismic section of arbitrary line. White arrows indicating iceberg plough-marks. Location indicated in Fig. 4.2.2.

Interpretation:

The elongated curved furrows are similar to the ones described and interpreted earlier in the trough. These features are therefore interpreted to be iceberg plough-marks. The fact that they are longer and more numerous than in the trough may be explained by the decrease in water depth on the flanks. Resulting in more icebergs reaching the seafloor.

4.2.1.3 Northern flank

Two geomorphological features, streamlined landforms and small ridges (Fig. 4.2.11), mainly dominate the northern part of the survey that stretches up onto Trænabanken. The water depth has been calculated to be approximately 330-370 m.

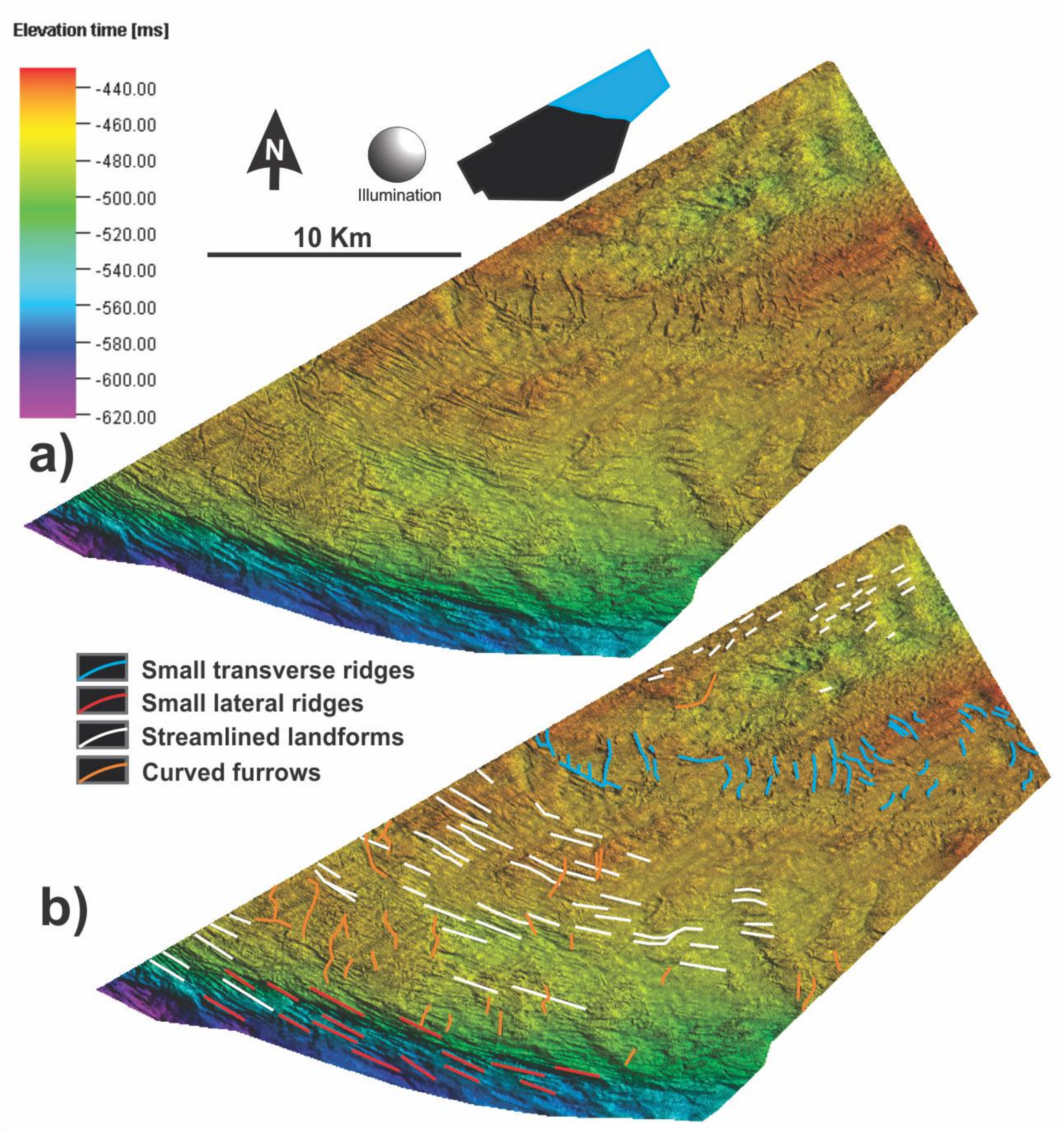


Figure 4.2.11 a) Seafloor of the southern part of Trænabanken to the north of the trough on the ST10013 survey. b) Indication of geomorphological features on the bank including small ridges, streamlined landforms and curved furrows.

Streamlined landforms:

Several parallel, large-scale linear furrows have been observed on parts of the flank with close proximity to the trough (Fig. 4.2.11 and 4.2.12a). They have a mean direction trending from the NE towards the SW. They are U- or V-shaped in cross sections and are generally linear. The depth has been measured up to 3 m, the width up to 150 m and the length up to 3 km. Parallel to the furrows some elongated ridges have been observed. The length has been measured up to 1500 m. They have a relatively blunt stoss side with a narrowing lee side. The height has been measured to reach up to approximately 3 m and the width reaches up to 200 m. In the NE corner of the survey there are signs of lineations with a NE-SW trend, but artefacts with the same orientation make them harder to interpret. The elongated ridges can however still be seen relatively clearly, stretching from NE-SW (Fig. 4.11 and 4.12c).

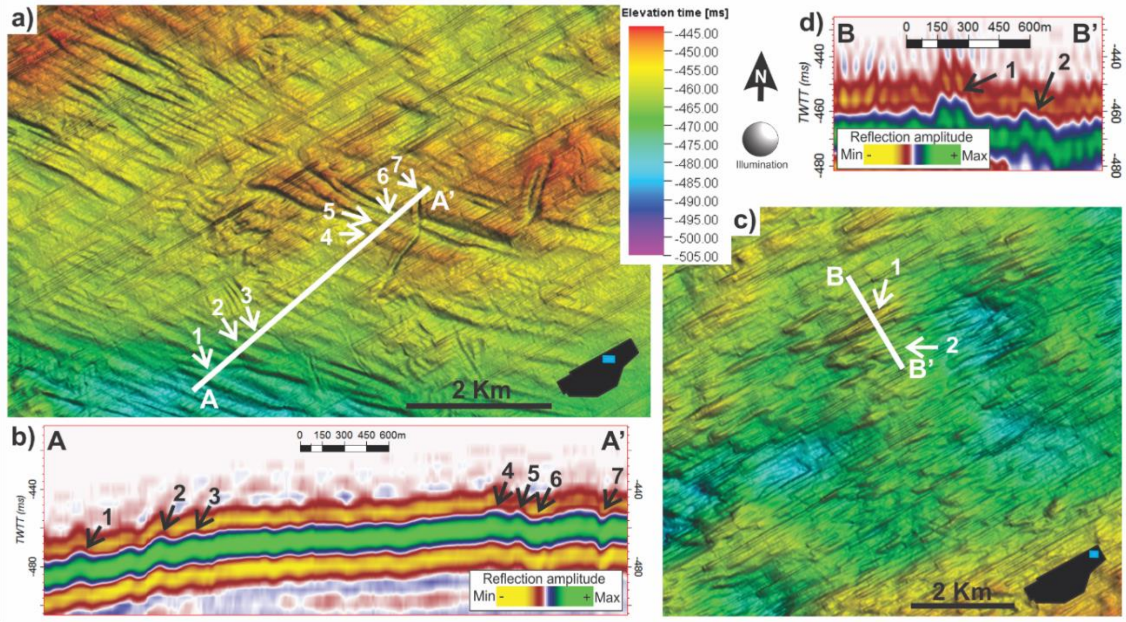


Figure 4.2.12 a) Seafloor with streamlined landforms interpreted as MSGL and flutes (1-6) as well as an elongated curved furrow (7) interpreted to be an iceberg plough-mark. White line indicating location of b). b) Seismic section of arbitrary line. c) Seafloor surface with streamlined landforms interpreted to be flutes. White line indicating location of d). d) Seismic section of arbitrary line. Arrows indicating examples of MSGL, flutes and iceberg plough-mark. Location indicated in Fig. 4.2.2.

Interpretation:

The streamlined landforms are similar to the streamlined features described and interpreted in the trough. The linear furrows are therefore interpreted to be MSGL and the ridges to represent flutes. The MSGL on the flanks of the trough indicates that the ice were moving relatively fast also in close proximity to the trough. In the NE corner of the survey the MSGL and flutes appear to have a different orientation with a NE-SW trend, which means that the ice was probably flowing in a different direction at some time in this location.

Small transverse ridges:

Several small transverse ridges have been observed on Trænabanken (Fig. 4.2.11 and 4.2.13a). They are orientated between two main directions, where on the eastern side of the flank the trend is NW-SE before gradually trending N-S towards the west. The two different trends make some of the ridges almost appear perpendicular to each other. The width of the ridges varies from 40-200 m while the length and continuity can be very inconsistent varying from right above 100 m up to over 2000 m. The ridges in general have a slightly curved to linear shape and some of them are asymmetrical. They are up to 8 m high with a sharp relief. There is no consistent spacing between the ridges with a length varying from under 100 m up to 3000 m.

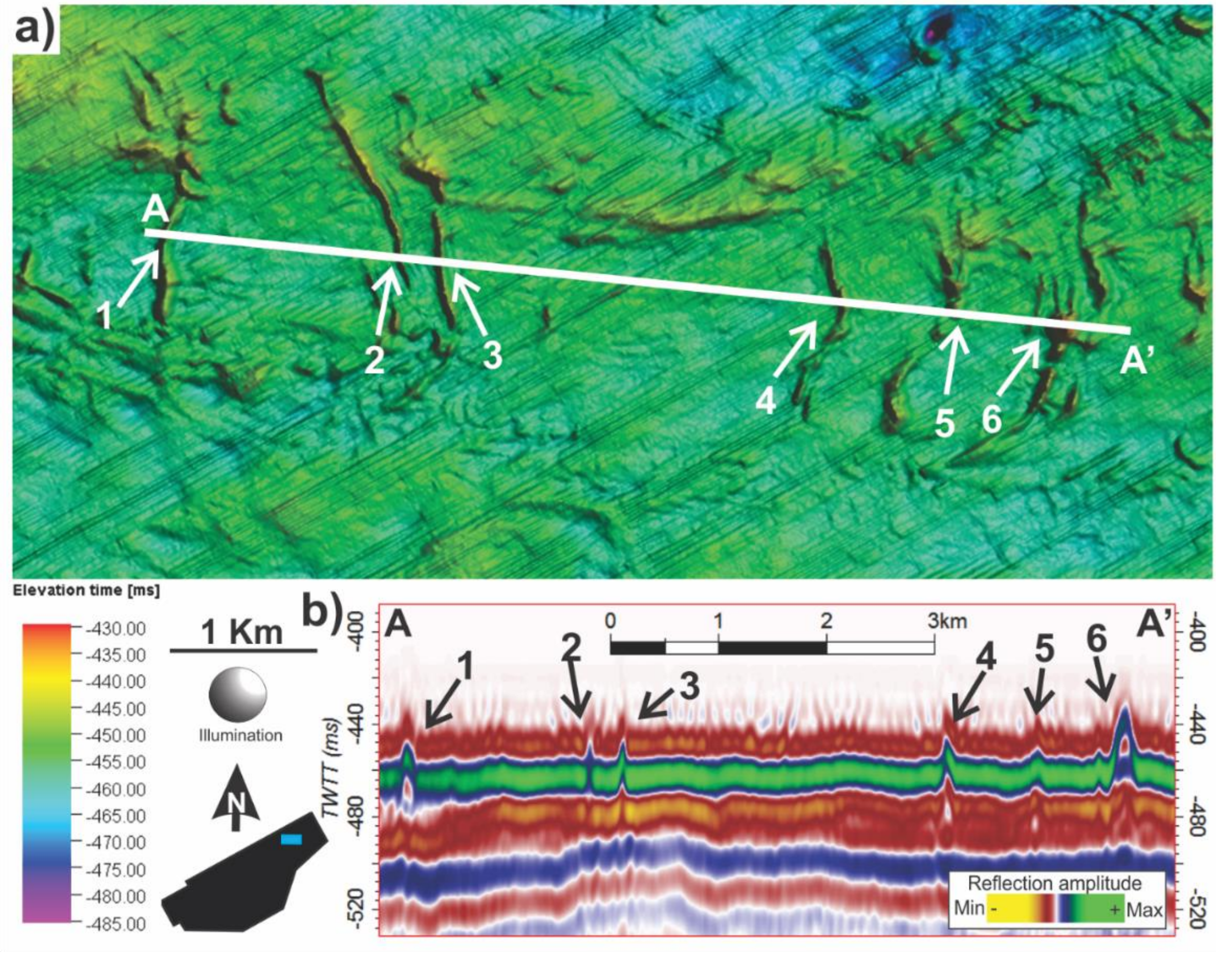


Figure 4.2.13 a) Seafloor surface with ridges interpreted to represent small moraines. The white line indicating location of b). b) Seismic section of arbitrary line. White arrows indicating small transverse ridges interpreted to be small marginal moraines. Location of figure is indicated in Fig. 4.2.2.

Interpretation:

The small transverse ridges on the north flank are located between the streamlined landforms which are parallel to the trough and the streamlined landforms that appear to have a NE-SW trend. They are interpreted as small marginal moraines deposited under the deglaciation of the flank during minor superimposed standstills or readvances, or possibly De Geer moraines reflecting annual recession (Rydningen et al., 2013). The change in orientation of the moraines appear to be the result of the two different directions of ice flow. Similar moraines have been observed by Ottesen et al. (2005a); Dowdeswell et al. (2007); Rydningen et al. (2013) along the mid-Norwegian continental shelf as well as by Solheim et al. (1990) in the Barents Sea.

Elongated curved furrows:

Chaotic orientated elongated curved furrows with a main direction going from NE-SW have been located at relatively random places on the seabed surface on Trænabanken (Fig. 4.2.11 and 4.2.12a). The only pattern observed is that the concentration appear higher in close proximity to the trough while they are almost absent further in on the bank. They are generally U- or V-shaped and have a depth up to 7 m with some displaying elevated sides. The furrows can be followed up to 3 km and have a width up to 200 m. The chaotic pattern results in furrows crossing and overprinting other furrows.

Interpretation:

The elongated curved furrows are similar to the curved furrows described and interpreted earlier in the cross-shelf trough. These features are therefore interpreted to be iceberg plough-marks. The fact that they are longer and more numerous than in the trough can be explained by the decrease in water depth on the bank, resulting in more icebergs reaching the seafloor. This can be seen by the plough-marks starting at the edge of the flank (Fig. 4.2.11) where icebergs that floated freely in the trough suddenly reaches the seafloor at the bank.

Lateral elongated ridges:

Along the transition between the bank and the trough, several lateral and elongated ridges are displayed on the seabed with an orientation from E-SE to W-NW (Fig. 4.2.11 and 4.2.14). They have a length of up to 3 km and have a symmetric shape with a width of up to 300 m. They have a relatively sharp relief, with a height reaching just above 20 m.

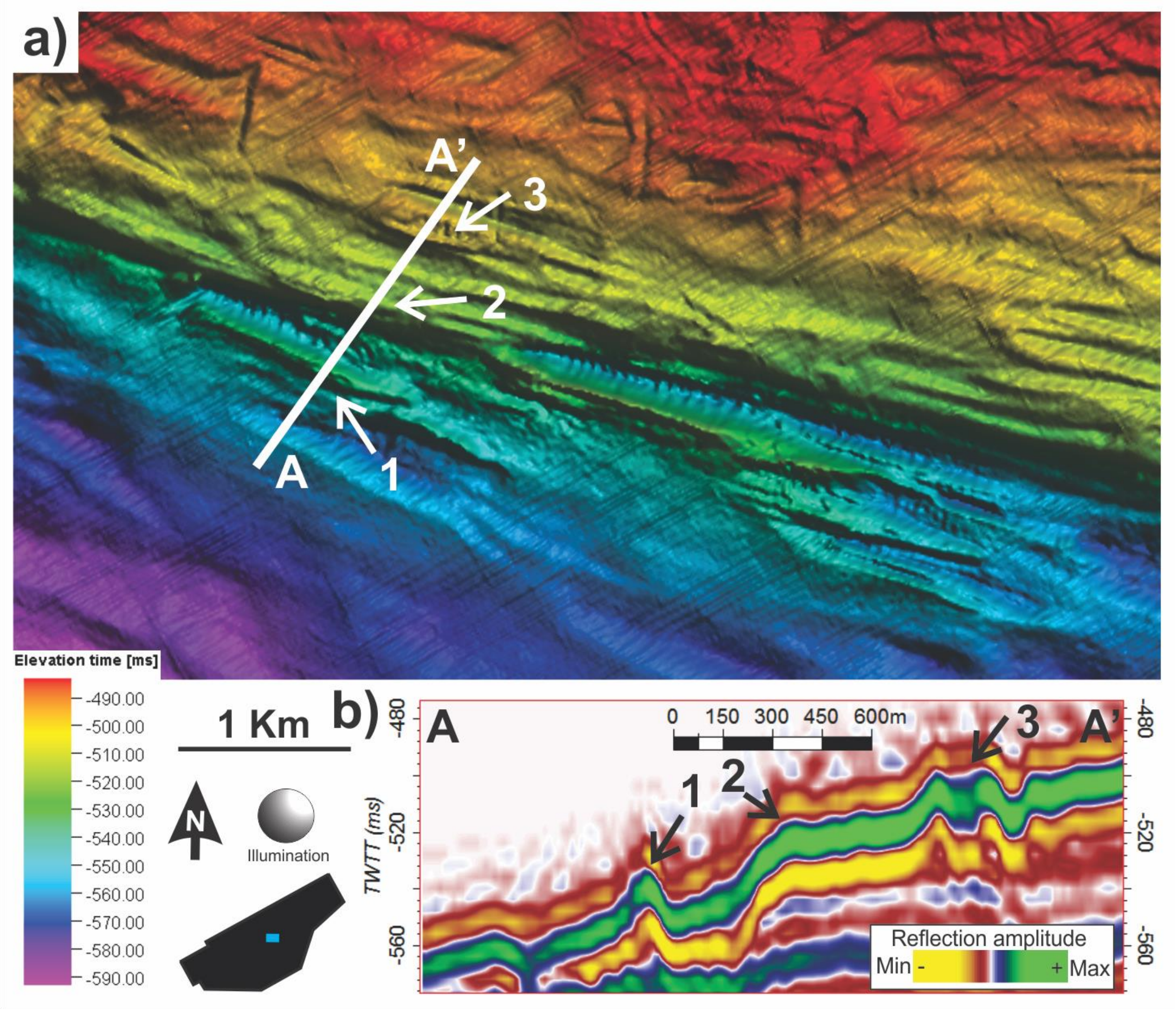


Figure 4.2.14 a) Seafloor with lateral elongated ridges interpreted to be lateral shear zone moraines. White line indicating location of b). b) Seismic section of arbitrary line. Arrows indicates examples of lateral shear zone moraines. Location indicated in Fig. 4.2.2.

Interpretation:

Based on their location and the geomorphology of the ridges, they are interpreted to represent lateral shear zone moraines (LSZM). LSZM are described by Rydningen et al. (2013) as lateral moraines formed in the lateral transition between fast moving ice streams in the trough and slow moving ice on the flanks. The shear stress of this transition zone would result in basal cracking of the glacier, where eroded sediments could accumulate (Rydningen et al., 2013). The placement of the ridges in the transition between the trough and the north flank as well as the orientation which is parallel to the trough supports this interpretation. Another possibility is that the ridges simply are more prominent flutes, which are surrounded by MSGL as described earlier.

4.2.2 ST07M07 Seafloor geomorphology

The ST07M07 seafloor surface of inner Trænabanken (Fig. 4.2.15) has been divided into 3 different areas on the count of location and geomorphology. The top of Trænabanken which is located in the middle of the survey (Fig. 4.2.16), a deeper part of the Trænabanken to the SE of the survey (Fig. 4.2.21) and a small part reaching down into the Sklinnadjupet trough in the western part of the survey (Fig. 4.2.26).

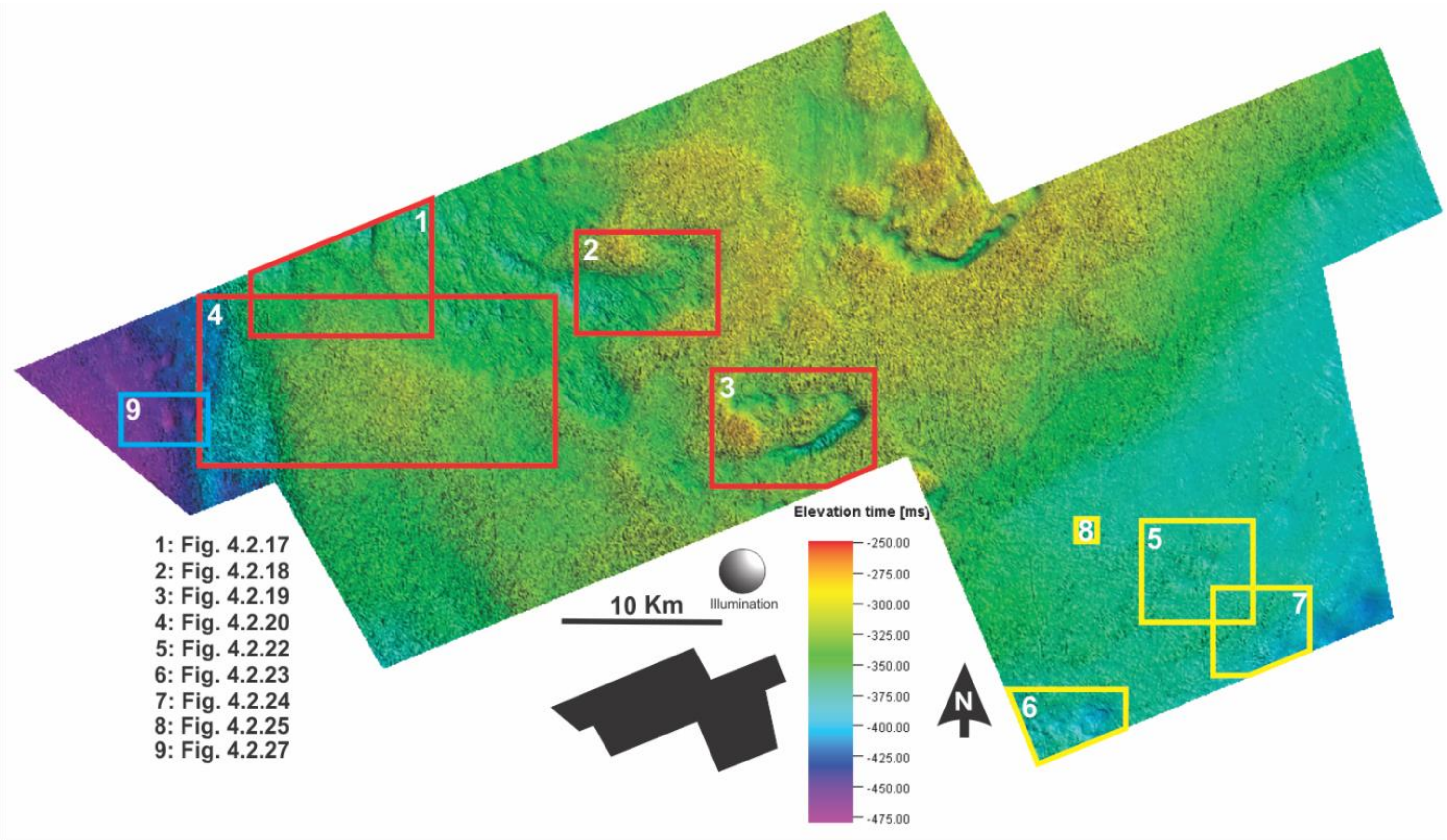


Figure 4.2.15 Seafloor from the ST07M07 3D-survey at the inner part of Trænabanken (Fig.4.2.1). Red (Shallow bank), yellow (deep bank) and blue (Sklinnadjupet trough) frames outlines location of zoom-in figures.

4.2.2.1 Shallow bank

The shallow part of Trænabanken is located at a depth between approximately 210-270 m. The area is mainly dominated by on-lapping sediments, which are covered in elongated curved furrows. Some places the morphology display large depressions and ridges (Fig. 4.2.16).

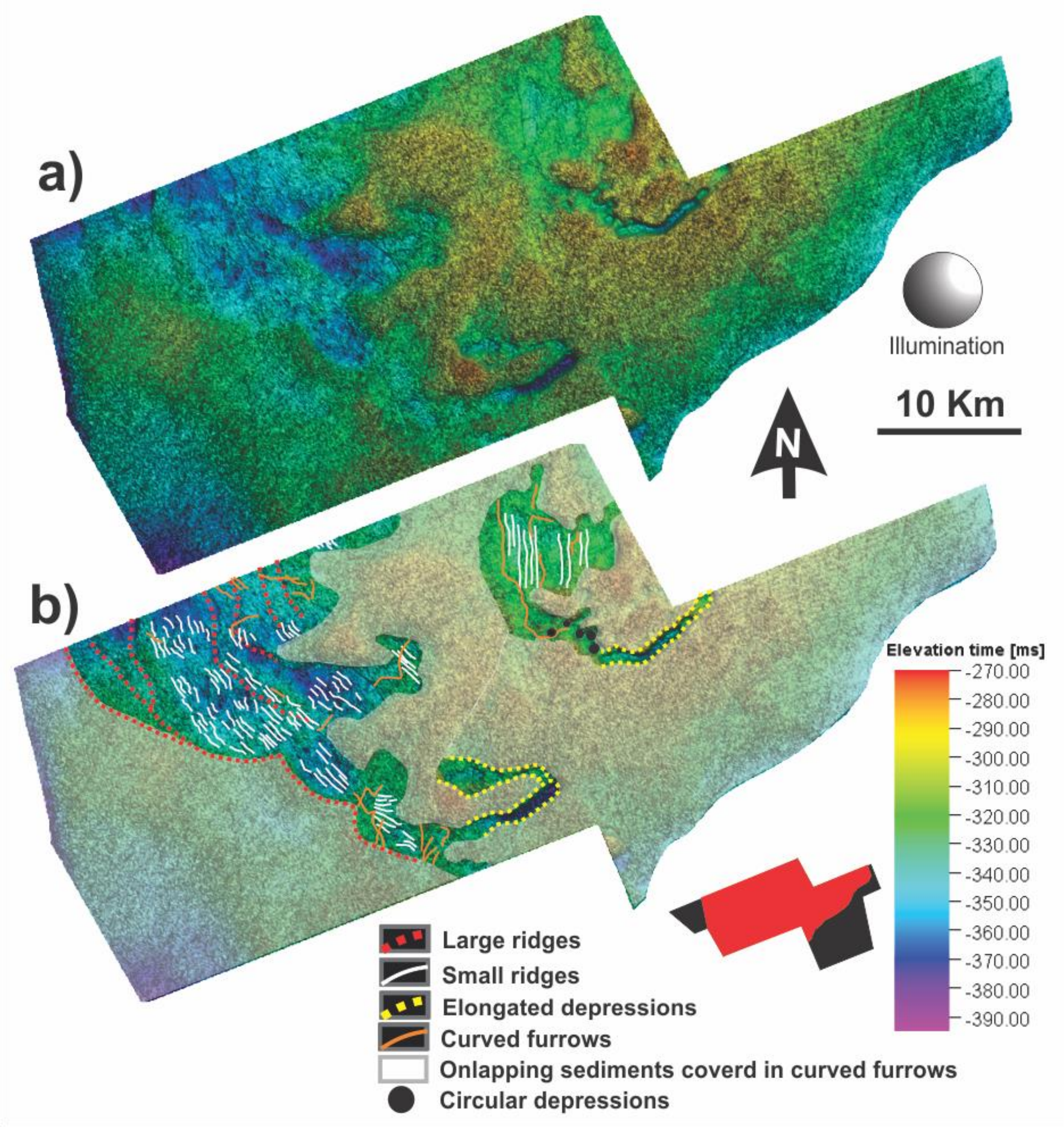


Figure 4.2.16 a) Seafloor surface display of the shallow part of Trænabanken in the ST07M07 survey. b) Indication of different geomorphological features on the bank including ridges, depressions and furrows.

Large ridges:

Several large and parallel ridges are located on the shallow part of the bank (Fig. 4.2.16 and 4.2.17). They are slightly curved and have a main orientation from NW-SE. The width of the ridges varies from 1000-2500 m while the length is hard to measure as they appear to continue out of the survey areas towards the north. The spacing between them varies from being merged at some areas to a distance of up to 2000 m. The ridges are up to 20 m high and are generally covered by small curved furrows. The ridges with the sharpest relief are located to the west in close proximity to the trough and gets progressively less distinct towards the east.

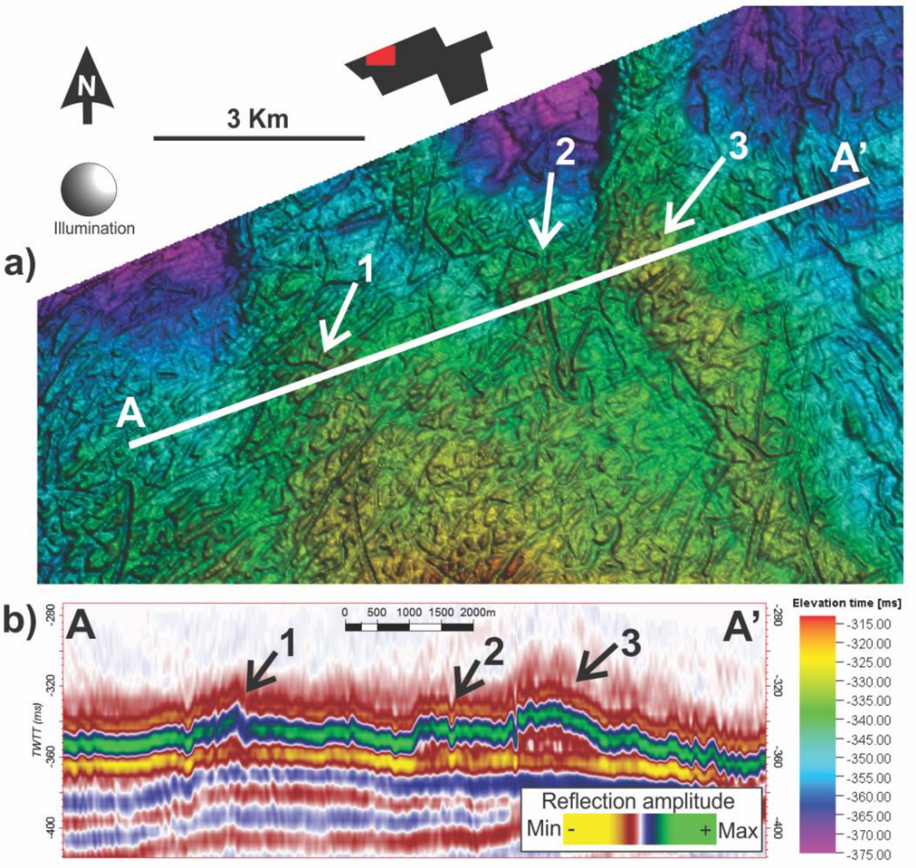


Figure 4.2.17 a) Seafloor surface showing large ridges interpreted to be moraines covered in elongated furrows interpreted to be iceberg plough-marks. White line indicating the location of b). b) Seismic section of arbitrary line. Arrows indicating the crest of the moraines. Location indicated in Fig. 4.2.15.

Interpretation:

The geomorphology of the large ridges show close similarities to the large ridges found in the ST10013 survey. Therefore, they are also interpreted as moraines deposited at the front of the ice sheet. One of the ridges are clearly truncating two of the other ridges, indicating that it was deposited during a glacial advance. This also indicates that the ridges are progressively younger toward the east.

Small ridges:

In the deeper part of the shallow bank area, mainly in the NE and NW area, several small transverse ridges are located (Fig. 4.2.16 and 4.2.18). They appear on the relatively flat areas between the large ridges, which they are relatively parallel to and with an orientation varying from NV-SE to S-N. The distance between the ridges varies from under 100 m up to right above 400 m while the length varies from approximately 500 m up to right above 6 km. The height of the ridges reaches up to 6 m and the width up to 200 m. The shape differ from linear to slightly meandering and some of the ridges are truncated by elongated curved furrows.

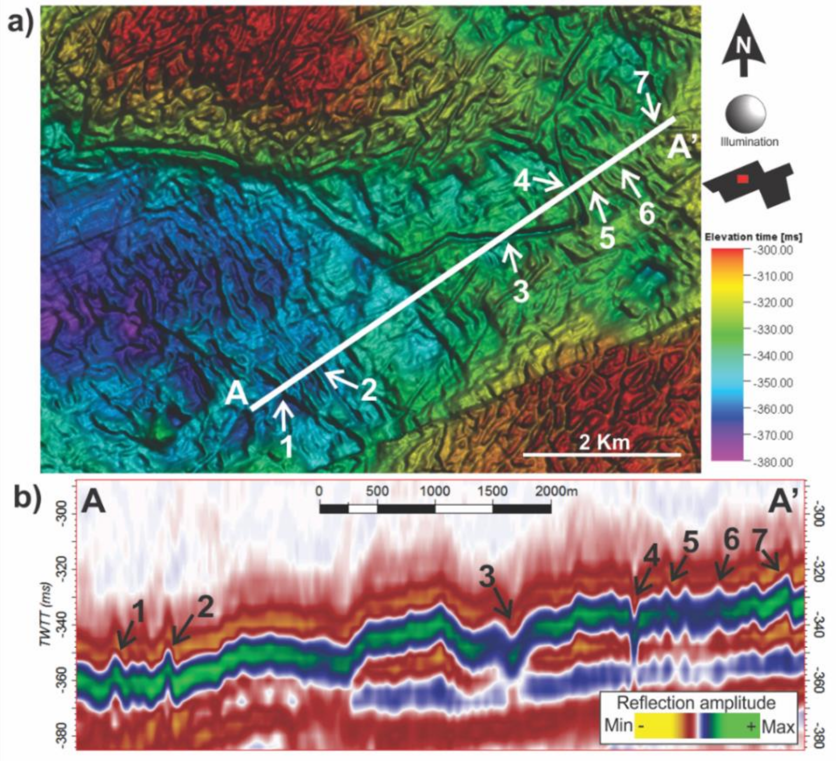


Figure 4.2.18 a) Seafloor with small ridges (arrows 1-2 and 5-7) interpreted to be small marginal moraines and elongated curved furrows (arrows 3-4) interpreted to be iceberg plough-marks. White line indicating location of b). b) Seismic section of arbitrary line. Location indicated in Fig. 4.2.15.

Interpretation:

These small ridges resemble the small ridges found in the ST10013 survey. Therefore, they are interpreted as small marginal moraines deposited under the deglaciation of the flank during minor superimposed standstills or readvances, possibly De Geer moraines reflecting annual recession. Rydningen et al. (2013) has described such features along the continental margin off Troms. The fact that the small ridges are relatively parallel to the larger moraines indicates that they have been deposited parallel to the glacial front. The ridges must be older than the elongated curved furrows as the furrows truncates them.

Elongated depressions:

Three elongated depressions can be seen on the shallow bank (Fig. 4.2.16), where two are located to the South (Fig. 4.2.19) and the third is located towards the NE. They are relatively linear but the one to the NE eventually takes on a meandering shape. They all have an orientation going from approximately E-NE to W-SW. They appear to gradually get deeper towards the W-SW, with some over-deepening at some areas, which here are referred to as plungepools. The over-deepening areas divides the depression into several discrete segments which starts with a steep drop into a plungepool before it runs for several hundred meters before the next plungepool. This gives the main depression a downslope gradient interrupted by short reverse gradients. This is more distinct in two of the depressions. The length has been measured to 7,5 km for the two linear depressions and up to 13 km for the meandering depression (Fig. 4.2.16). The width is up to right above 1000 m in the straight parts and up to 1500 m in the meandering parts. The depressions can be right above 40 m deep and on the surface within them several transverse ridges are located. The geomorphology of these ridges resembles the ridges described above both in shape and orientation. Several circular depressions are located within the meandering bends part of the NE depression.

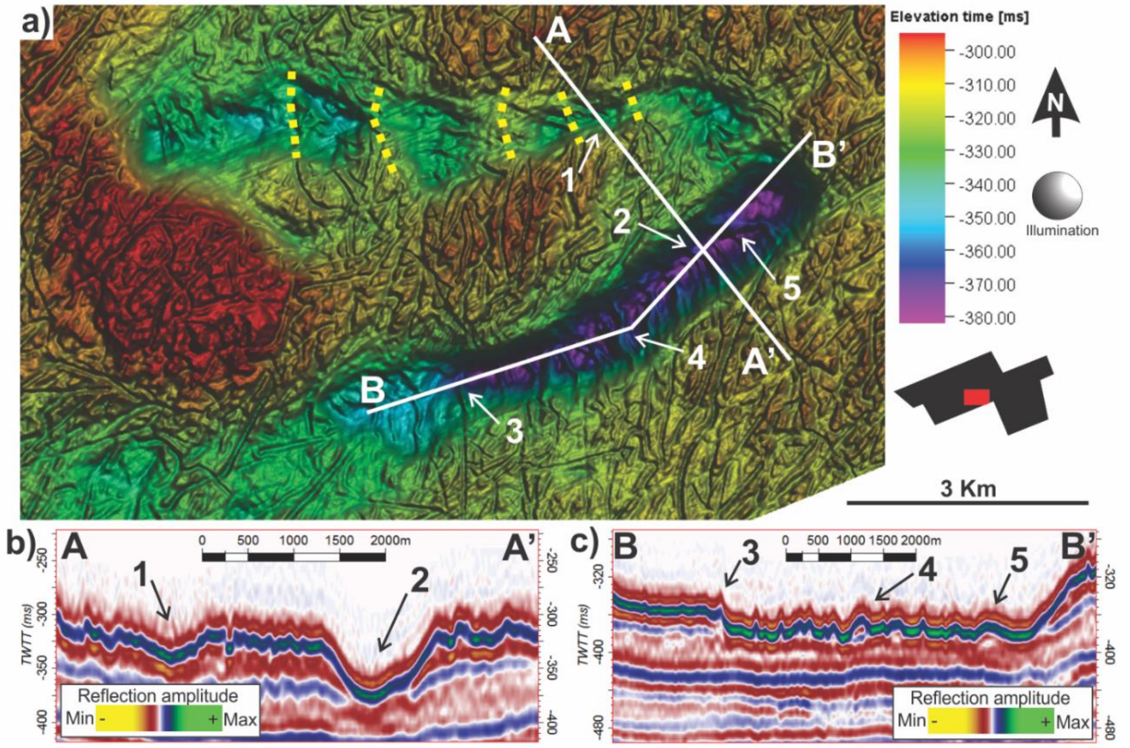


Figure 4.2.19 a) Seafloor showing elongated depressions (arrows 1-2) interpreted to be subglacial meltwater channels and small ridges (arrows 3-5) interpreted as small moraines. Yellow stippled lines indicate areas of separation between the different segments of the depression. White lines indicating location of b) and c) displaying seismic section of arbitrary lines. Location indicated in Fig. 4.2.15.

Interpretation:

The elongated depressions are interpreted to represent part of a subglacial meltwater channels. Mattingsdal (2008) described similar features in the Nordkappbanken area. Sugden et al. (1991) description of subglacial meltwater channels in Antarctica also have similar features with a gradually downslope gradient interrupted by plungepools as well as circular depressions which are interpreted to be potholes. Potholes are common in sharp bends, which explains why they mainly appears in the meandering part of the channel. The ridges within the depressions are probably older than the channels themselves. This is because it is not likely that the channels would be so distinct if the processes making the ridges affected them. One possibility is that the ridges are more durable against erosion than the adjacent sediments. This could be the case if the ridges are moraines buried by fine-grained glacimarine deposits, as the moraines consist of more rigid till.

On-lapping sediments:

On-lapping sediments comprising a high concentration of elongated curved furrows dominates the shallow bank (Fig. 4.2.16 and 4.2.20). This area is relatively flat and lies at shallower water depth than the rest of the bank. The positive relief is displayed in the seismic sections where it is possible to see the sediments lapping on to the underlying surface (Fig. 4.2.20b). The thickness of the sediments varies from approximately 25-60 m. As well as being totally covered in elongated curved furrows, the sediments appear to be affected by the three elongated depressions and circular depressions described above.

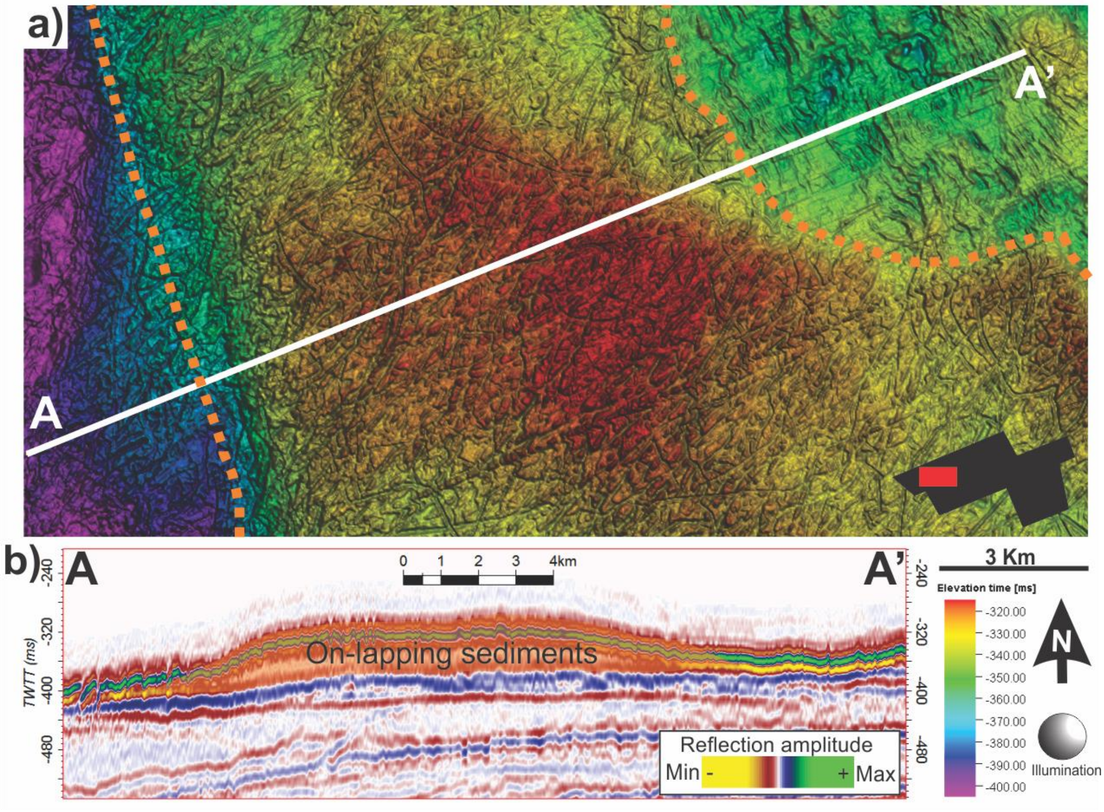


Figure 4.2.20 a) Seafloor showing on-lapping sediments interpreted to be glacimarine deposits covered in elongated curved furrows interpreted to be iceberg plough-marks (area between orange stippled lines). White line indicating location of b). b) Seismic section of arbitrary line with shaded area indicating the glacimarine deposits. Location indicated in Fig. 4.2.15.

Interpretation:

The on-lapping sediment layer is interpreted to represent glacimarine deposits. The deposition probably took place in front of the glacier where the sediments where distributed from subglacial meltwater channels. This meltwater flows from the front of the ice sheet as either a jet or a plume, and as the velocity decreases the buoyancy result in a plume of sediment-laden meltwater. These plumes carry large amounts of fine-grained sediments in suspension which can be transported and deposited several tens of kilometers from the glacial front (Powell, 1990). The uneven distribution of the sediments may be a result of the distribution of the meltwater channels as well as the effect of ocean currents. The sediments distribution also appears to have been affected by erosion as described above.

Another possibility is that the sediments are contourites deposited by ocean currents, but the shallow water depth of the bank makes this unlikely as they tend to erode in shallow areas and deposit in deeper areas e.g. troughs and slide scars (Laberg et al., 2001; Vorren, 2003). The meltwater channels described above which have eroded down into the sediments also supports a glacimarine environment.

Elongated curved furrows:

Chaotically orientated elongated curved furrows with their main direction going from NE-SW are located in high concentrations on the on-lapping sediments described above (Fig. 4.2.20) as well as in smaller concentrations in between (Fig. 4.2.16 and 4.2.18). They are generally U- or V-shaped in cross sections and have a depth up to 4 m where some display elevated flanks. The furrows can be followed up to 12 km and have a width up to 150 m. The chaotic pattern results in furrows crossing and overprinting other features.

Interpretation:

The chaotic orientation of the elongated curved furrows as well as the geomorphology of the features are similar to the ones described on the ST10013 seabed surface and are therefore interpreted to represent iceberg plough-marks. The concentration is much higher than in the ST10013 survey, which can be explained by the difference in water depth. The shallower water depth result in more icebergs reaching the seafloor. This also explains why the shallower on-lapping sediments described above are more affected. The fine-grained sediments in this area may also be easier to deform by ploughing.

4.2.2.2 Deep bank

The deeper part of Trænabanken is located at a depth between approximately 270-310 m. The on-lapping sediments do not cover this area. It display a smoother surface, but some depressions and ridges can be seen as well as larger furrows (Fig. 4.2.21).

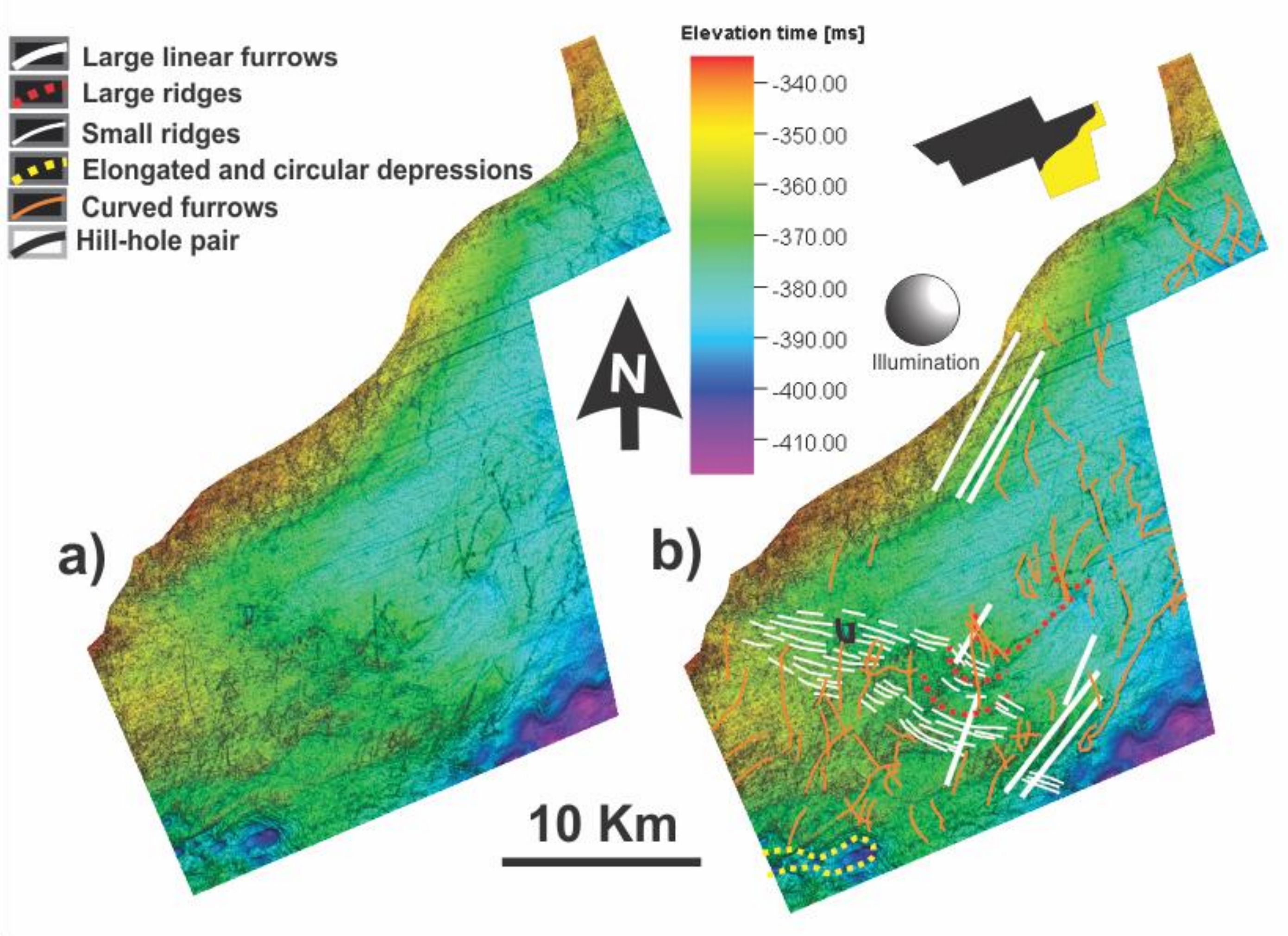


Figure 4.2.21 a) Seafloor surface displaying the deeper part of Trænabanken in the ST07M07 survey. b) Interpretation of geomorphological features on the bank including ridges, furrows and depressions.

Large ridges:

Three parallel and lobe-shaped ridges are located on the deeper part of the bank (Fig. 4.2.21 and 4.2.22). They are orientated from E-NE to W-SW with a spacing of approximately 400-700 m. The width of the ridges varies from 1000-2000 m while the length varies from 2 km up to almost 4 km. The ridges are almost up to 20 m high and are generally covered in small curved furrows and some small ridges.

Interpretation:

The large ridges bear resemblance to the large ridges on the shallow part of Trænabanken. They are therefore interpreted to be moraines deposited at the front of the glacier. They have a slightly different orientation, which means that the ice flow was slightly different around the edges of the bank than on the top.

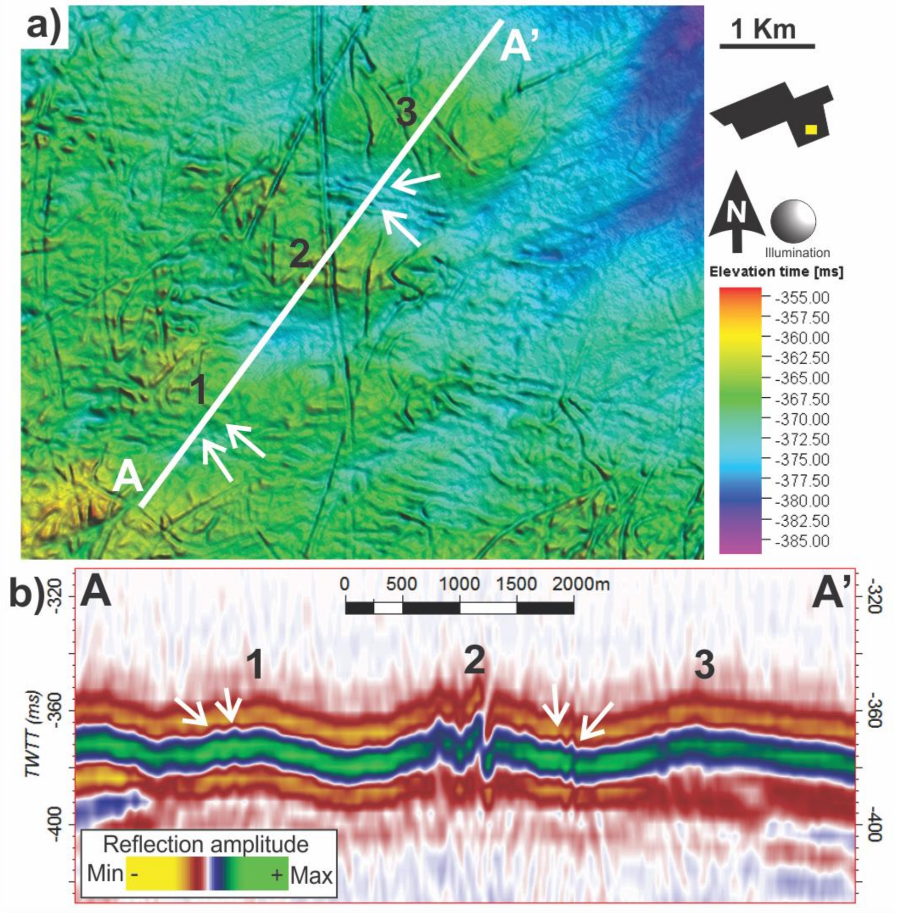


Figure 4.2.22 a) Seafloor showing large ridges interpreted as large moraines (numbers 1-3) and small ridges interpreted as small moraines (arrows). White line indicating location of b). b) Seismic section of arbitrary line. Location indicated in Fig. 4.2.15.

Small transverse ridges:

On the deeper parts of the bank, a large number of parallel small transverse ridges have been observed (Fig. 4.2.21 and 4.2.22). The ridges are parallel to the larger ridges described above with an orientation from E-NE to W-SW. The distance between the ridges can vary from under 100 m up to right above 400 m while the length vary from right above 100 m up to almost 4 km. The height of the ridges have been measured up to 5 m and the width up to 200 m. The ridges are relatively linear but some appear slightly curved, elongated curved furrows also truncate some of the ridges.

Interpretation:

The small ridges bear resemblance to the small ridges at the shallow part of the bank, as they both are parallel to the adjacent large ridges, therefore they have been interpreted to represent small marginal moraines as described earlier and by Ottesen et al. (2005a) along the mid-Norwegian continental shelf.

Elongated and circular depressions:

In the south corner of the deeper bank an elongated depression trending from approximately E-NE to W-SW is located with an overall downslope gradient (Fig. 4.2.21 and 4.2.23). The length is measured to 5,5 km but the depression appears to continue out of the survey. The width varies from 600-1000 m. Within and adjacent to the depression several smaller circular and oval depressions have been located. They generally have a parabolic shape with a diameter that varies from 200-1300 m, and have a depth of up to approximately 22 m. In the seismic section, signs of vertical discontinuities and amplitude anomalies are located directly underneath the depressions (Fig. 4.2.23c).

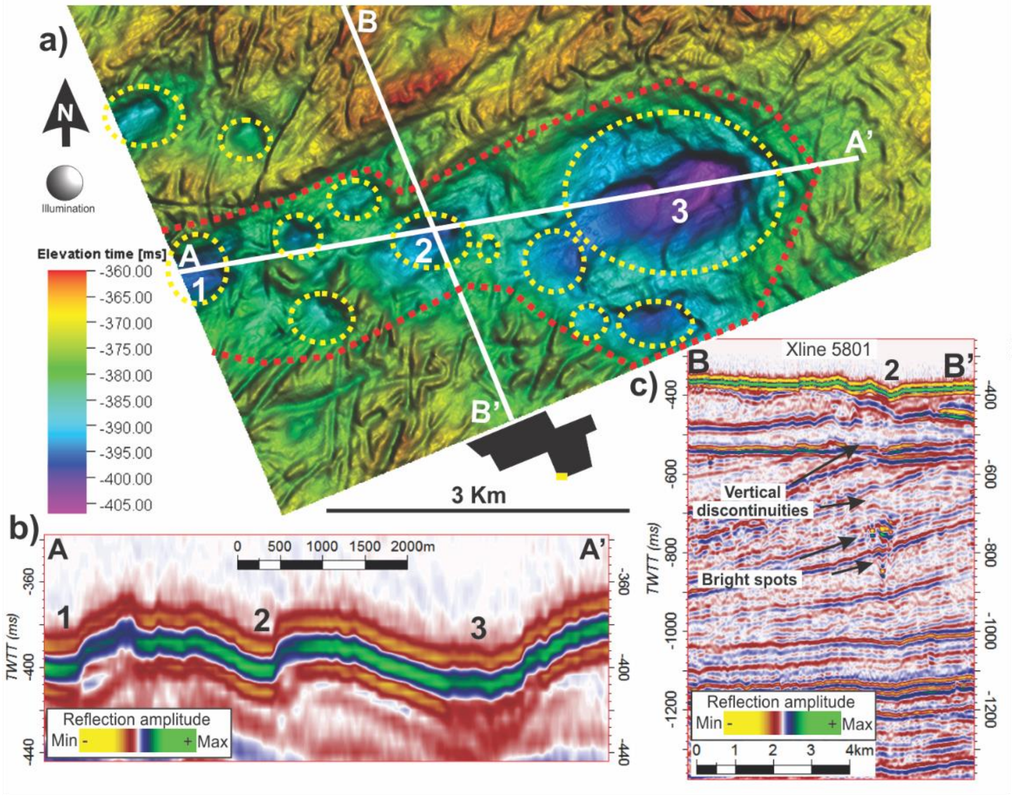


Figure 4.2.23 a) Seafloor showing circular depressions (yellow stippled lines) interpreted to be pockmarks. Red stippled line indicates elongated depression possibly representing a subglacial meltwater channel. White lines indicating location of b) and c). b) Seismic arbitrary line of pockmarks. c) Seismic section of crossline 5801 showing vertical discontinuities and bright spots in the subsurface underlying the depressions. Numbers indicating center of the pockmarks displayed in the seismic sections. Location indicated in Fig. 4.2.15.

Interpretation:

The large circular depressions are interpreted to be pockmarks in conformity with interpretation of similar features by Hovland and Judd (1988); Hovland et al. (2002); Løseth et al. (2009). The larges pockmarks are more than 10 times larger than the pockmarks described on the ST10013 survey seabed, but they are formed by the same processes. Another possibility is that the seafloor is affected by the shape of underling deposits instead of fluid migration, or a combination of the two processes. Since the depressions more or less lines up in on larger elongated depression it is also possible that the depressions are a result of erosion by a subglacial meltwater channel, where the separate circular depressions represent plungepools as discussed earlier. There is also a possibility that the depressions were formed by glacigenic erosion creating several hill-hole pairs (discussed later). It is hard du make a definite conclusion as the features are located in the corner of the survey, making it hard to get an understanding of the extent and surroundings. However, the seismic section, which display vertical discontinuities together with seismic anomalies interpreted to be bright spots, may indicate fluid migration from the subsurface. This combined with the geomorphology of the depressions may favor the pockmark hypothesis. Similar pockmarks have also been described in the Nyegga area by Hovland et al. (2005).

Large elongated linear furrows:

Several parallel to sub-parallel large-scale elongated linear furrows have been observed on the seafloor surface on the deeper part of the bank (Fig. 4.2.21 and 4.2.24). They have a main orientation from NE towards SW and have a linear to slightly curved shape. They are U- or V-shaped and the depth has been measured up to 6 m with some displaying elevated flanks. The width is measured up to 150 m and the length up to 12 km. The curved elongated furrows truncates the elongated linear furrows.

Interpretation:

The large elongated linear furrows, which are perpendicular to the large ridges, are interpreted to be MSGL. They bear close resemblance to some of the MSGL that were described and discussed on the ST10013 survey seabed.

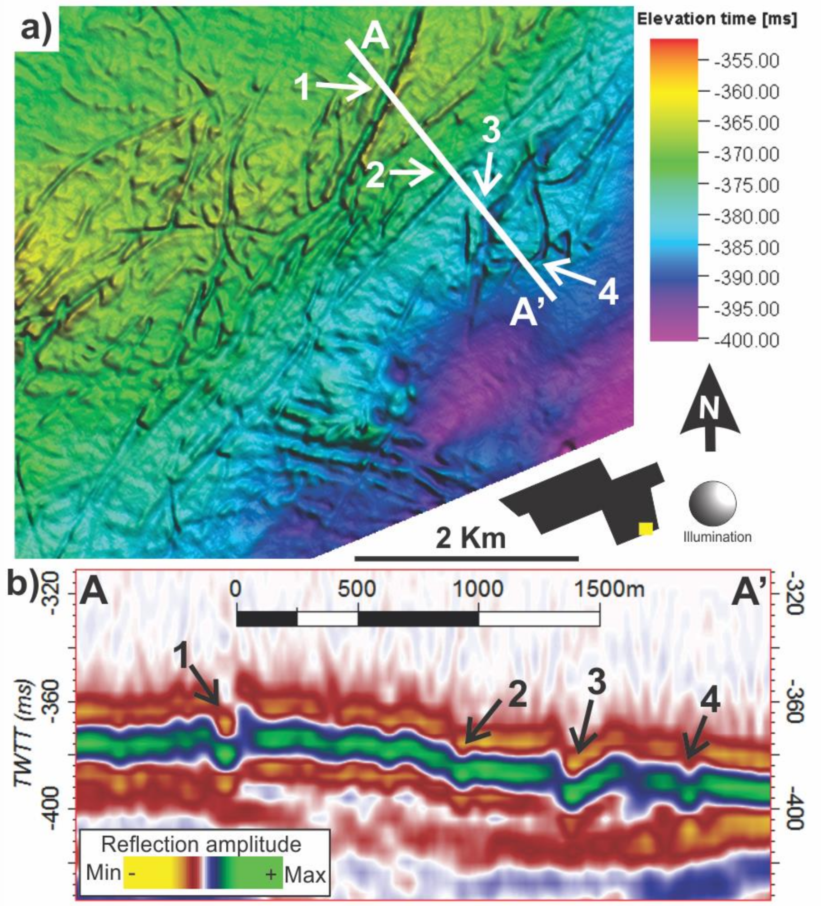


Figure 4.2.24 a) Seafloor with white arrows indicating large elongated linear furrows (1-2) interpreted as MSGL and elongated curved furrows (3-4) interpreted to be iceberg plough-marks. White line indicating location of b) seismic section of arbitrary line. Location indicated in Fig. 4.2.15.

Elongated curved furrows:

Elongated curved furrows with a chaotic pattern and main orientation from S-SW to N-NE have been located at what appears random places around the deeper part of the bank (Fig. 4.2.21 and 4.2.22). They are generally U- or V-shaped in cross sections and have a depth up to 7 m with some displaying elevated levees on the sides. The furrows can be followed up to 11 km and have a width up to 150 m. The chaotic pattern results in furrows crossing and overprinting the linear furrows.

Interpretation:

The chaotic elongated curved furrows are similar to the curved furrows described in the cross-shelf trough of the ST10013 survey. They are therefore interpreted to be plough-marks imprinted by icebergs on the seabed.

Hill and elongated depression

A small slightly elongated depression has been located adjacent to a small hilltop on the NW part of the deeper bank (Fig. 4.2.21 and 4.2.25). The pair have an orientation going from the north where the depression begin toward the south where it ends as the hilltop. This makes it semi-parallel to the MSGL described above. The depression has a depth of almost 8 m and the hilltop has a height of right above 20 m. The length of the depression is approximately 650 m while the length of the hilltop is 250 m. The width of both are measured to 380 m.

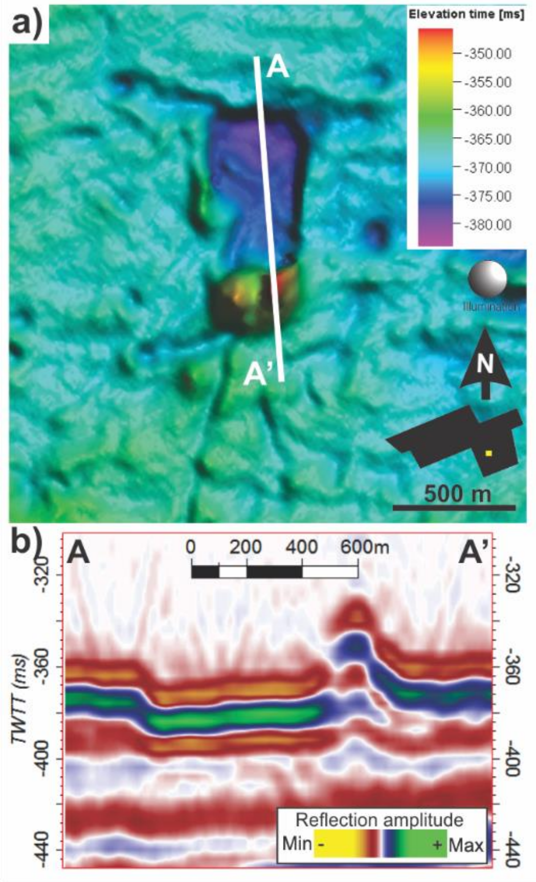


Figure 4.2.25 a) Seafloor surface displaying a depression and hill to interpreted to be a hill-hole pair. White line indicating location of b) seismic section of arbitrary line. Location indicated in Fig. 4.2.15.

Interpretation:

The depression and hill top is interpreted as a single feature because of the close proximity. Together they bear close resemblance to a small hill-hole pair as described by Bluemle and Clayton (1984). The hill-hole pair is a result of both erosion and deposition by the glacier as all the material from the depression is transported to the end on the downstream side and deposited as a hill top. The volume of the depression and hilltop is approximately the same supporting the interpretation. The feature is also relatively parallel with the direction of the paleo-ice flow indicated by the MSGL. Hill-hole pairs have been documented along the Norwegian coast by Ottesen et al. (2005a) and Hogan et al. (2010) in the Svalbard area.

4.2.2.3 Trough

The area that reaches down into Sklinnadjupet is located at a depth between approximately 270-340 m. The seafloor in this area gets progressively smother with depth where several large depressions are located (Fig. 4.2.26).

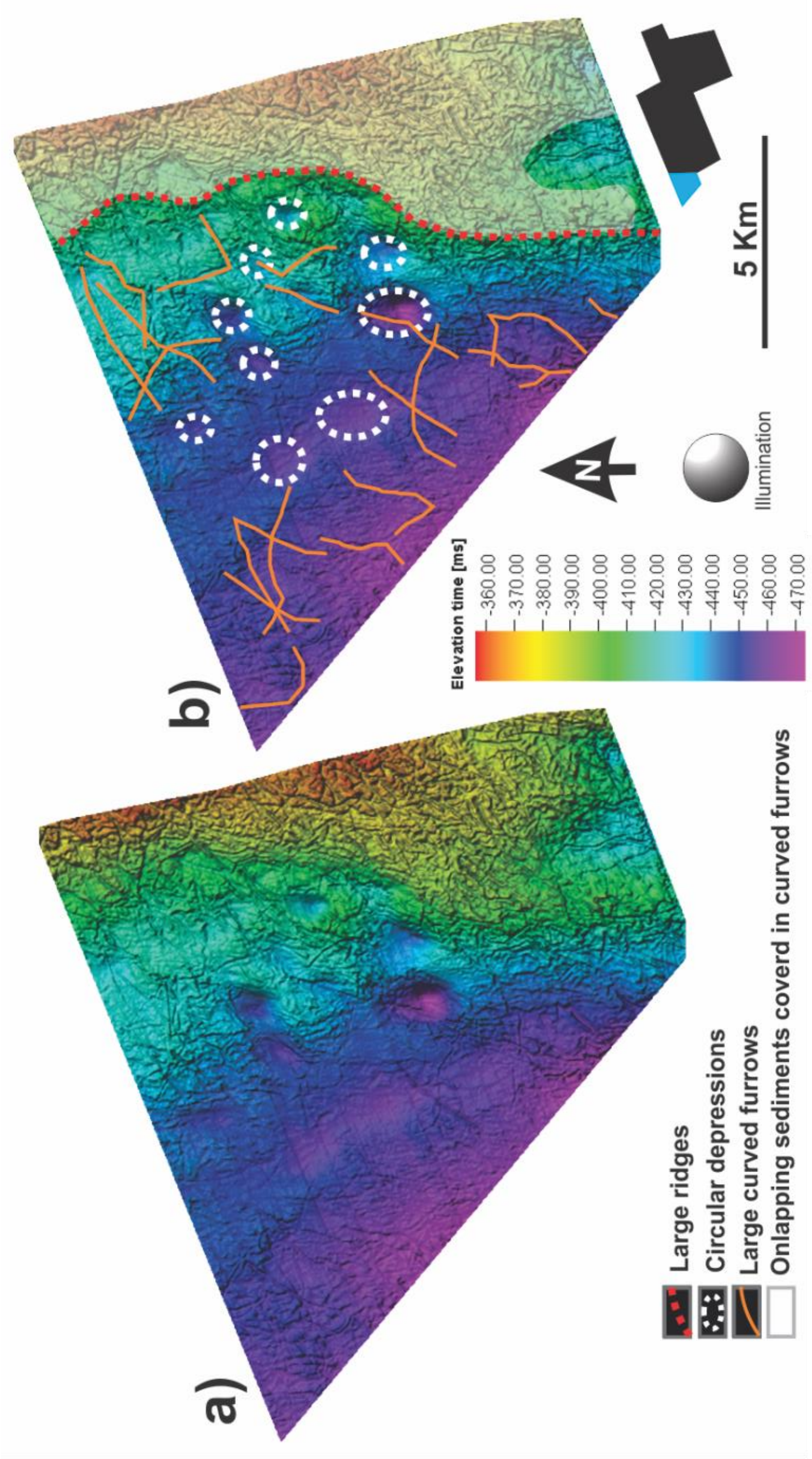


Figure 4.2.26 a) Seabed surface displaying the part of the ST07M07 survey reaching down into Sklinnadjupet. b) Display of geomorphological features on the seabed surface including circular depressions and the most district curved furrows.

Large circular depressions:

Several large circular to semi-circular depressions are located along the edge of Sklinnadjupet (Fig. 4.2.26 and 4.2.27). The diameter varies from 400 m up to 1300 m and the depth reaches up to almost 20 m. They have a parabolic shape and some are imprinted by elongated curved furrows. In the seismic section, signs of vertical discontinuities have been located in the strata underneath the depressions (Fig. 4.2.27c).

Interpretation:

The large circular depressions have the same geomorphology as the circular depressions discussed earlier. In addition, here, some signs of vertical discontinuities and small bright spots have been located, which may indicate fluid migration from the subsurface (Fig. 4.2.27c). Therefore, these features are also interpreted as pockmarks. The edge of Sklinnadjupet may also be a natural place for fine grained, soft sediments to build up as the trough may act as a sediment trap for sediments transported by ocean currents.

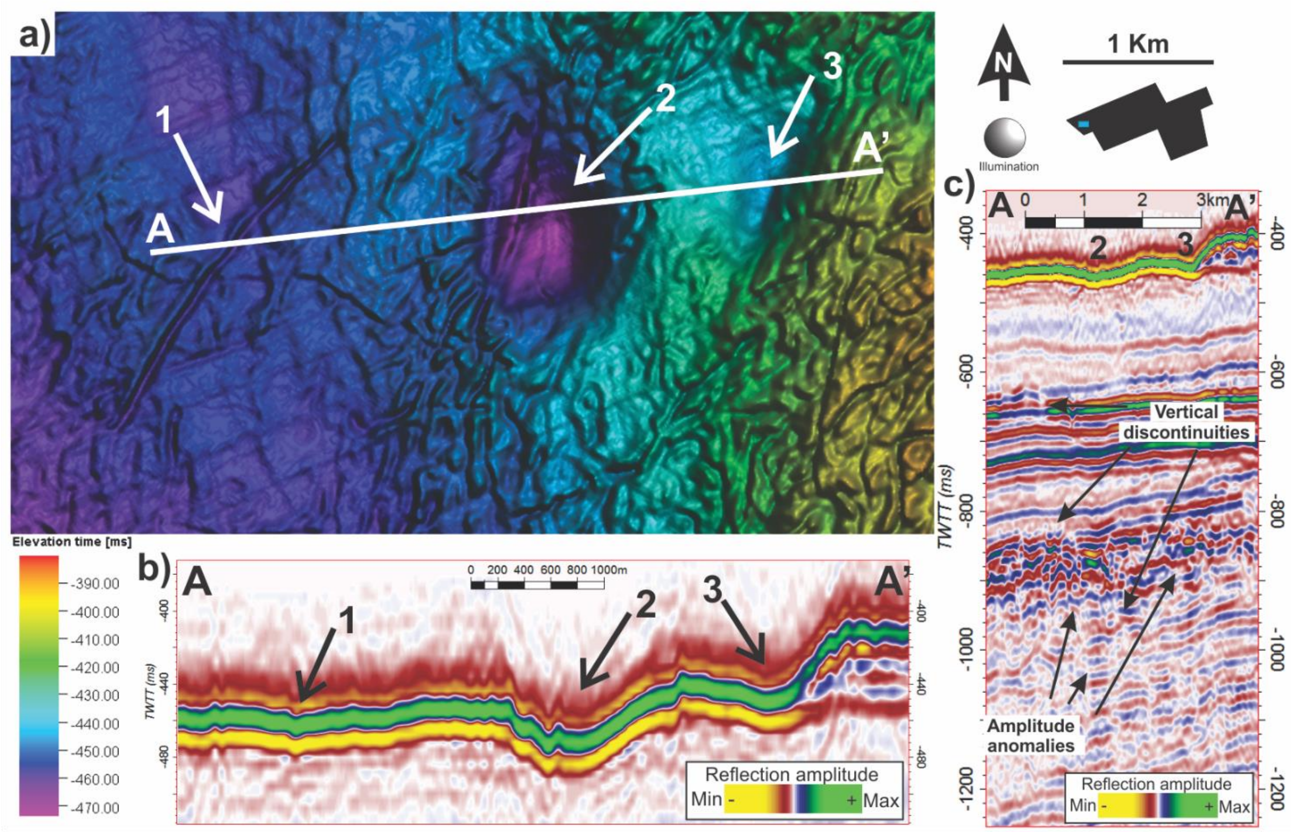


Figure 4.2.27 a) Seafloor surface showing elongated curved furrow (arrow 1) interpreted to be an iceberg plough-mark and circular depressions (arrow 2-3) interpreted to be pockmarks. White line indicates location of b) seismic section of arbitrary line. c) Extension of same arbitrary line showing signs of fluid migration in the subsurface directly beneath the pockmarks. Location is indicated in Fig. 4.2.15.

Elongated curved furrows:

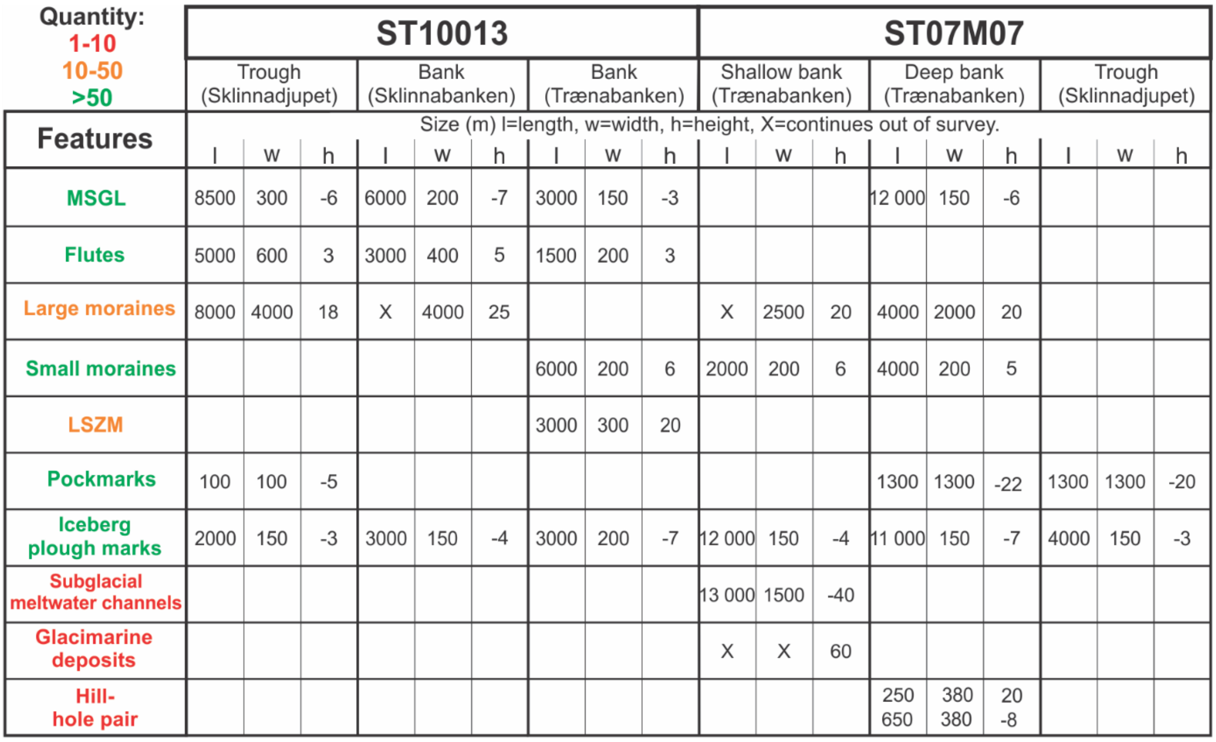
Elongated curved furrows randomly orientated, but with a main direction from S-SW to N-NE cover the entire side stretching down into Sklinnadjupet (Fig. 4.2.26 and 4.2.27). They are generally U- or V-shaped and may display elevated flanks. They have poor continuity, as there are many crossing furrows, making them hard to measure. The most distinct of the furrows are indicated in Fig. 4.2.27 and can be measured to a length of up to 4 km. They have a width of up to 150 m and a depth up to 3 m.

Interpretation:

The chaotic elongated curved furrows show resemblance to the curved furrows described earlier. They are therefore interpreted to be iceberg plough-marks. The concentration of the furrows decreases with depth supporting this hypothesis.

4.2.3 Summary

All the different geomorphological features that have been interpreted on the seafloor have been summarized with their largest dimensions in Table 1. This is to give a perspective of where the different features are located and to make it easier to compare the size of similar features. MSGL and flutes dominate the ST10013 survey, which are less predominant within the ST07M07 survey. The size of the large and small moraines appear to coincide between the two surveys supporting that they have been deposited by similar processes. Iceberg plough-marks are the only feature that can be found in all areas, but the length and concentration decreases significantly with depth. Pockmarks are located at three different areas where two have almost identical measurements and quantity while the last area has pockmarks that are under 1:10 of the size, but with a much higher concentration. The glacimarine deposits and subglacial meltwater channels, which can be linked together, are only found in the shallowest area of the bank.



Quantity: 1-10 10-50 >50	ST10013									ST07M07								
	Trough (Sklinnadjupet)			Bank (Sklinnabanken)			Bank (Trænabanken)			Shallow bank (Trænabanken)			Deep bank (Trænabanken)			Trough (Sklinnadjupet)		
Features	Size (m) l=length, w=width, h=height, X=continues out of survey.																	
	l	w	h	l	w	h	l	w	h	l	w	h	l	w	h	l	w	h
MSGL	8500	300	-6	6000	200	-7	3000	150	-3				12 000	150	-6			
Flutes	5000	600	3	3000	400	5	1500	200	3									
Large moraines	8000	4000	18	X	4000	25				X	2500	20	4000	2000	20			
Small moraines							6000	200	6	2000	200	6	4000	200	5			
LSZM							3000	300	20									
Pockmarks	100	100	-5										1300	1300	-22	1300	1300	-20
Iceberg plough marks	2000	150	-3	3000	150	-4	3000	200	-7	12 000	150	-4	11 000	150	-7	4000	150	-3
Subglacial meltwater channels										13 000	1500	-40						
Glacimarine deposits										X	X	60						
Hill-hole pair													250 650	380 380	20 -8			

Table 1 Summary of all the geomorphological features interpreted on the seafloor in the study area. The dimensions are based on the largest and most distinct features of their kind. Colors indicate the quantity of the features on the two surfaces combined. MSGL: mega-scale glacial lineations; LSZM: lateral shear zone moraines.

4.3 Geomorphological features on buried surfaces

Six of the surfaces identified and named T1 of unit Naust T, S1 of unit Naust S, A1 of unit Naust A and N1-N3 of unit Naust N (Fig. 4.1.2 and 4.1.3) display several different geomorphological features. These features will be described and interpreted in their stratigraphic order, starting with T1 which is the youngest, ending with the oldest paleo-surface N3. The depth of the surfaces are given in milliseconds two way travel time (TWTT). The thickness of the features have been calculated using an assumed velocity of 1800 m/s in sequences above S1 while the sequences below S1 have been given an assumed velocity of 2100 m/s based on Storvoll et al. (2006); Rise et al. (2010). Some areas of the surfaces that were impossible to interpret because of a weak or discontinuous reflection configurations have been left out (marked on the figures). This may be caused by both stratigraphic and sediment properties as well as seismic noise.

4.3.1 Base Naust T (T1)

Base Naust T reflection represent the start of Naust T, which according to Rise et al. (2010) was deposited during the two last glacial cycles, the Saalian and Weichselian glaciations. The paleo-surfaces have been interpreted from both the ST10013- and ST07M07-survey (Fig. 4.3.1 and 4.3.6).

4.3.1.1 Base Naust T – ST10013

The T1 surface in the ST10013 survey display several geomorphological features, including depressions, ridges and furrows (Fig. 4.3.2). The most dominating features on the surface are two large paleo-troughs with an E-SE to W-NW trend, which coincides towards the west. The chaotic reflection pattern between the paleo-troughs, possibly a result of glacial reworking, makes the surface very irregular and impossible to interpret in this area. This is also the case where clinoforms from the underlying sequences have been truncated.

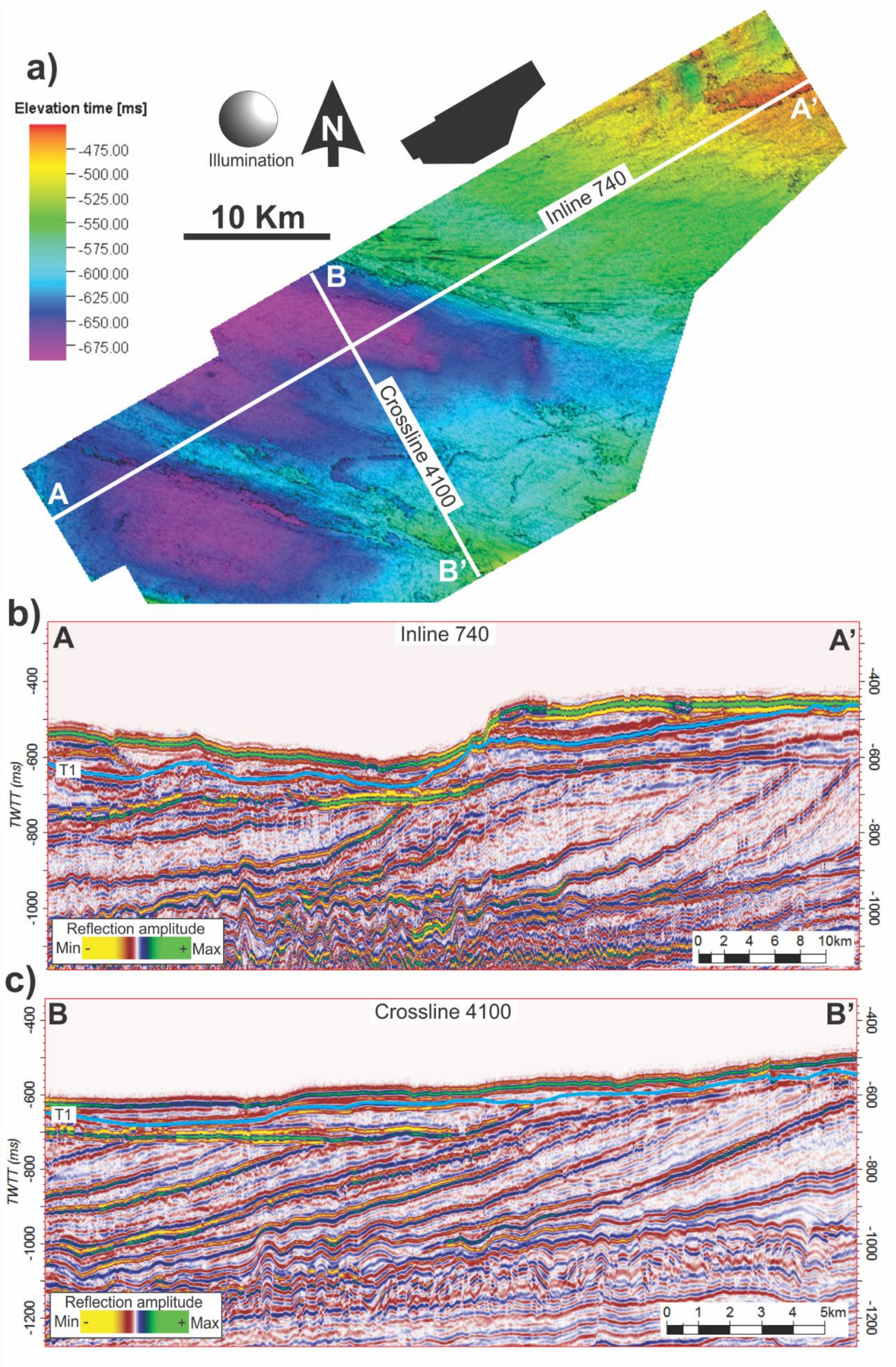


Figure 4.3.1 a) T1 surface in the ST10013 3D-survey with white lines indicating location of inline 740 and crossline 4100. b) Seismic section of inline 740 with light blue line indicating the T1 surface. c) Seismic section of crossline 4100 with light blue line indicating the T1 surface.

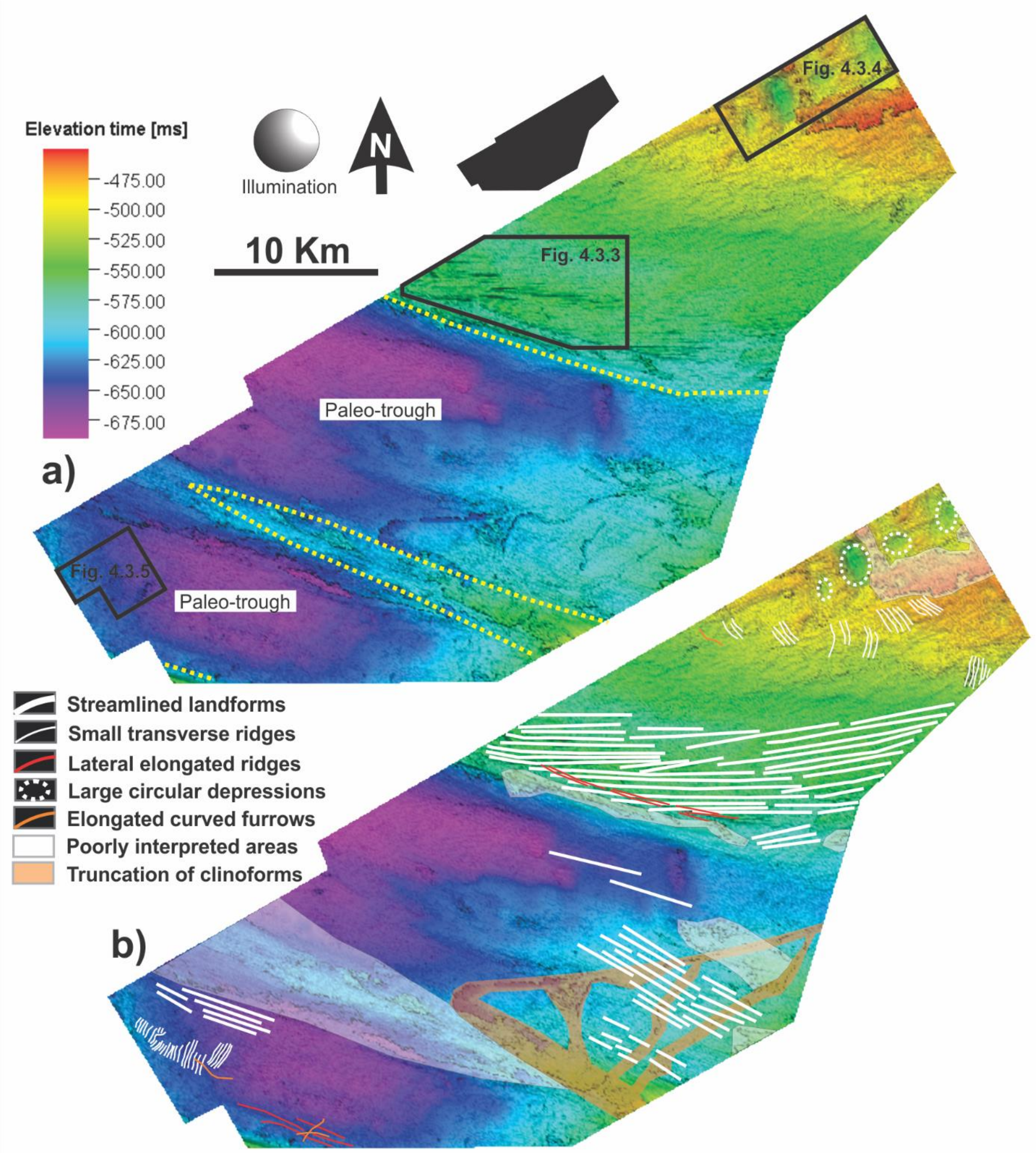


Figure 4.3.2 a) Overview of the T1 surface of the ST10013 3D-survey with two paleo-troughs outlined by the yellow stippled line. Frames outlines figure 4.3.3-4.3.5. b) T1 surface with display of interpreted features such as depressions, ridges and furrows. The shaded areas indicate problematic sections (white) or areas where the surface truncates underlying clinoforms (orange).

Streamlined landforms

The T1 surface display a large number of parallel, large-scale furrows and elongated ridges (Fig. 4.3.2). They are located within the paleo-troughs trending from E-SE towards the W-NW. There is also a large number of the large-scale furrow on the flank of the paleo-trough towards the north with a main east-west trend. These furrows appear to terminate against the transitional slope leading into the trough (Fig. 4.3.3). The furrows are relatively linear and have a U- or V-shape in cross sections. In the paleo-troughs where the furrows are adjacent to the elongated ridges the continuity is relatively poor and their length reaches up to 6 km. On the flank, the furrows are more continuous and reaches up to as much as 15 km in length. The width and depth of the furrows are measured to approximately 150 m and 7 m. This gives the furrows an elongation ratio of up to 40:1 and 100:1. The ridges that are located alongside the linear furrows in the paleo-troughs have a relatively blunt stoss side, with a narrowing lee side. They reach a length of up to 3 km, and the width and height reach approximately 300 m and 5 m.

Interpretation:

The streamlined landforms located on the T1 surface has the same geomorphology as the streamlined landforms which were described on the seafloor. Therefore, the large furrows are interpreted to be MSGL and the elongated ridges are interpreted to represent flutes, eroded and deposited by fast-flowing ice streams. Such features have been described on paleo-surfaces by Stokes and Clark (1999); Andreassen et al. (2004) among others. The streamlined landforms and the paleo-troughs generally shear the same orientation, indicating the direction of ice flow. The only exception is the lineations to the north, which comes in at an angle to the main trend. These lineations are interpreted to represent an ice flow, which came in from the north, gradually coinciding with the flow within the trough.

Lateral elongated ridged

Along the transition between the paleo-troughs and the flanks, several lateral elongated ridges have been observed (Fig. 4.3.2 and 4.3.3). They are located on the outer edges of both paleo-troughs with an orientation from E-SE to W-NW, making them parallel to the troughs. They have a symmetric shape and the length is measured up to 2.5 km. The width and height of the ridges reaches up to approximately 150 m and 8 m.

Interpretation:

The lateral elongated ridges have the same geomorphology as the lateral ridges described on the seafloor. They are also located at the transition between the troughs and the adjacent flanks. Therefore, they are interpreted to represent lateral shear zone moraines formed by cracks in the base of the glacier. There is also a strong possibility that the ridges may represent features similar to the streamlined landforms described above, only with slightly different dimensions. Lateral shear zone moraines have been described on the seafloor of northern mid-Norwegian continental shelf by Rydningen et al. (2013).

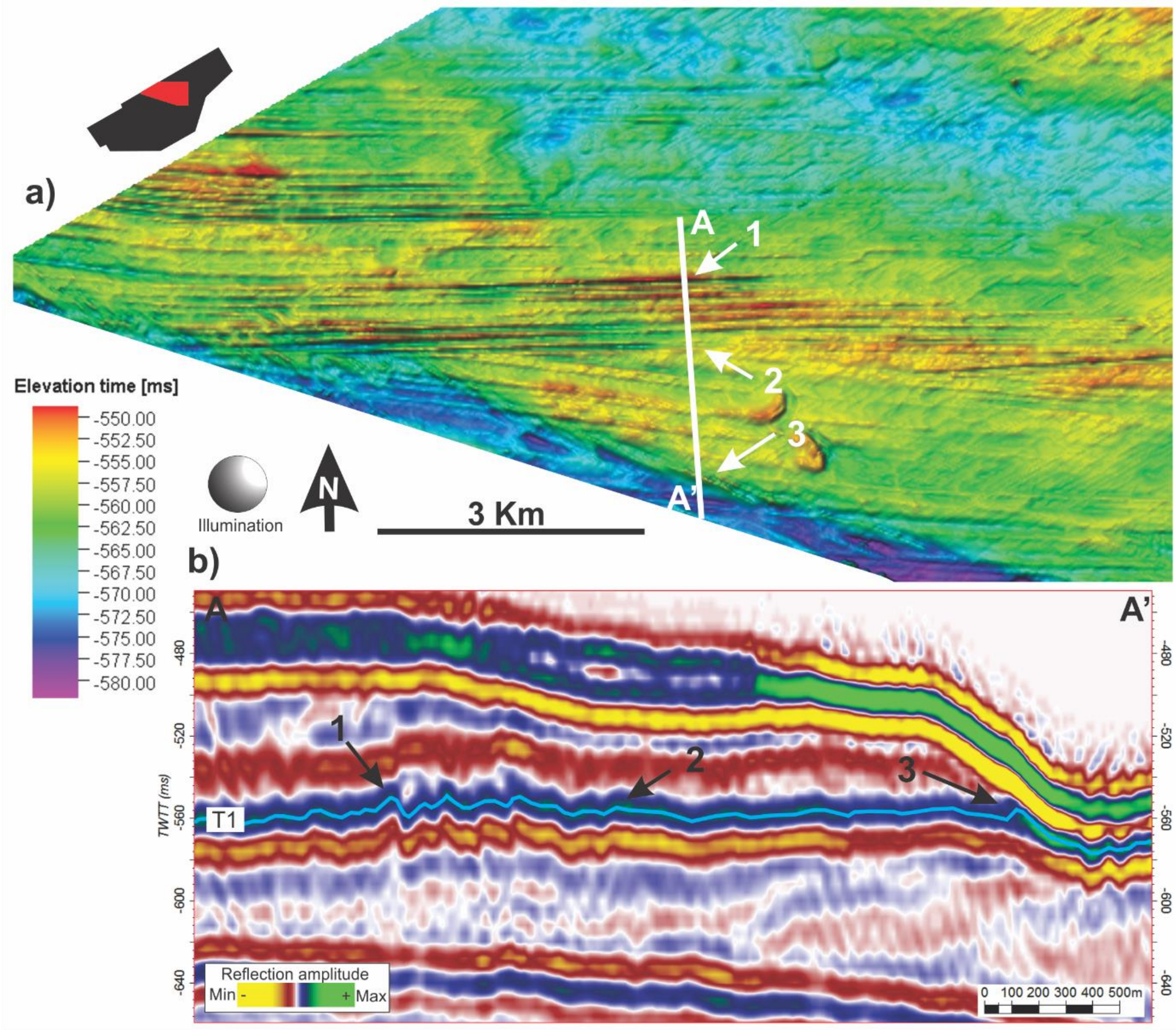


Figure 4.3.3 a) Furrows and ridges on the T1 surface interpreted to be MSGL and LMZS. White line indicates location of b). b) Seismic section of arbitrary line with arrows (1-2) displaying MSGL and arrow (3) displaying LMZS on the T1 surface (light blue line). Location of figure is indicated in Fig. 4.3.2a.

Circular depressions

On the NE corner of the T1 surface four large circular to sub-circular depressions are located (Fig. 4.3.2 and 4.3.4). These depressions have a parabolic shape with a diameter of 500-2500 m. The depth measures up to approximately 30 m and in seismic sections signs of vertical discontinuities and amplitude anomalies are located in the underlying strata (Fig. 4.3.4b). Also smaller circular depressions with a diameter and depth up to 200 m and 9 m are scattered around the entire T1 surface (Fig. 4.3.4a).

Interpretation:

The circular depressions on the T1 surface are interpreted to be glacial erosion features as the show close similarities to the features described by Rafaelsen et al. (2002) in the Barents Sea. They are probably formed by subglacial erosion and may also have been modified by meltwater (Rafaelsen et al., 2002). There is also a possibility that the circular depressions are large paleo-pockmarks as the ones described on the ST07M07 seafloor. In seismic sections seismic anomalies interpreted to represent bright spots as well as vertical discontinuities are located directly underneath the features. This may indicates fluid flow in the underlying strata (Andreassen, 2009; Løseth et al., 2009). The small circular depressions in the area are interpreted as paleo-pockmarks, which also suggest fluid flow reaching this surface.

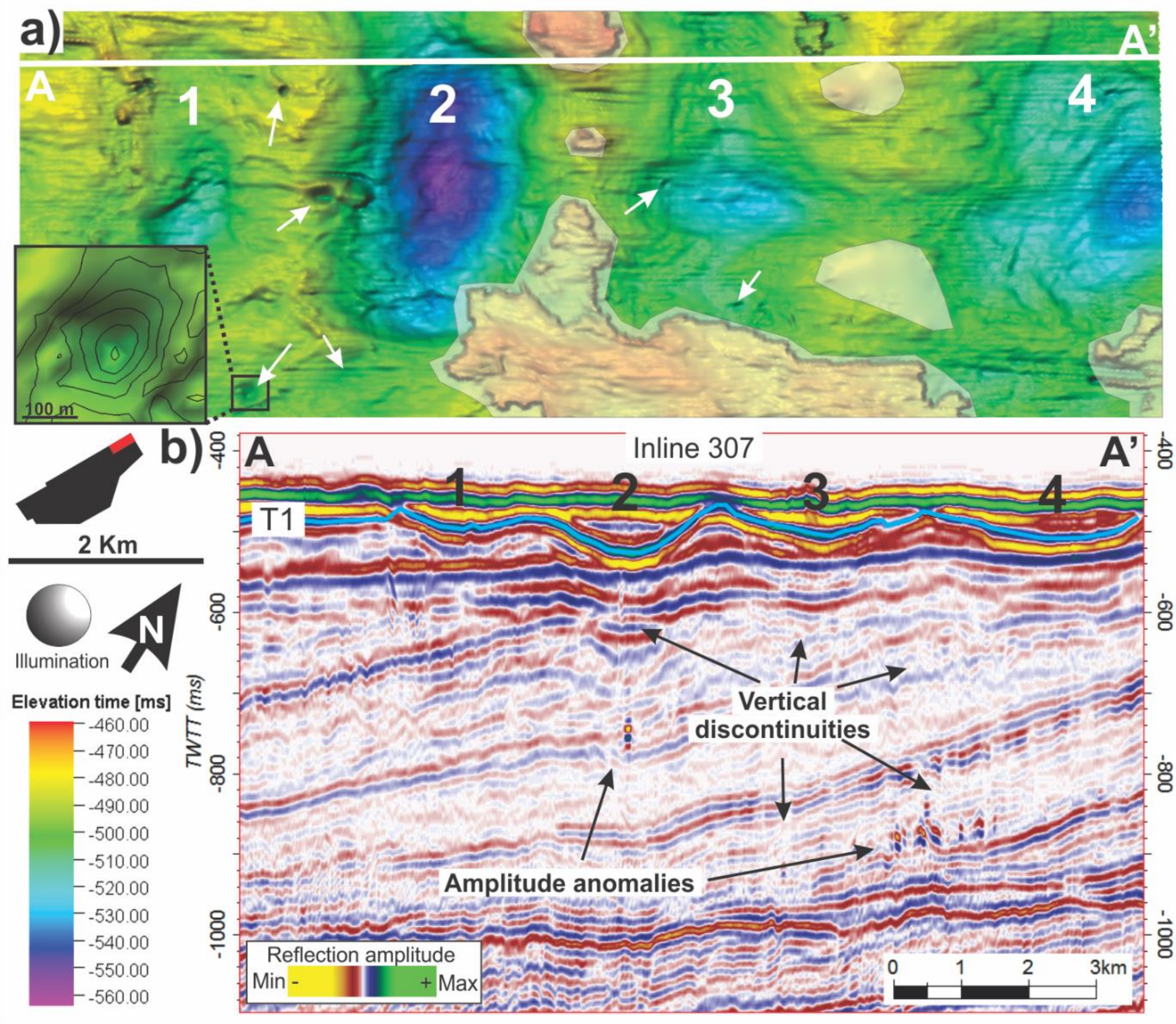


Figure 4.3.4 a) T1 surface showing large (numbers 1-4) and small (arrows) circular depressions interpreted to be subglacial erosional features and paleo-pockmarks. Frame in the lower left corner display zoom-in of paleo-pockmark. White line indicates location of b). b) Seismic section of inline 307 displaying subglacial erosional features (numbers 1-4) on the T1 surface (light blue line) with indicators of fluid migration in the underlying strata. Location of figure is indicated in Fig. 4.3.2a.

Small transverse ridges

On the T1 surface two areas, one to the NE and one to the SW, have concentrated fields of parallel, small transverse ridges (Fig. 4.3.2 and 4.3.5). In the area to the SW the main direction of the ridges are from the N-NE to S-SW while the NE area has a main orientation from NW to SE, with the exception of one field which has the same orientation as the area to the SW. The ridges are up to 2 km in length and the shape is linear to slightly curved. The width of the ridges are up to approximately 120 m while the distance between them are less than 100 m. The height is measured up to right above 5 m and they appear to be relatively symmetrical.

Interpretation:

The small transverse ridges are interpreted to be small marginal moraines or De Geer moraines as described earlier. This is because they share the same geomorphological features as the small transverse ridges found on the seafloor in the study area. They are also orientated perpendicular to the features indicating the direction of ice flow (e.g. MSGL), supporting the possibility of the ridges being deposited parallel to the front of the ice. Some of these features may also be the result of acquisition noise, as they have a relatively similar orientation as the sampling direction. Possible noise can also be seen in the overlaying strata in Fig. 4.3.5b.

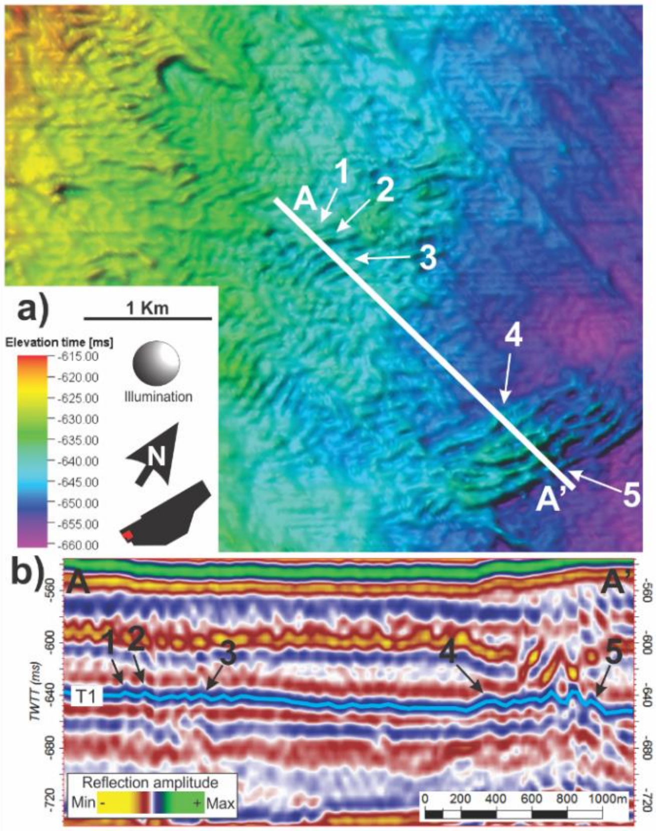


Figure 4.3.5 a) Small ridges interpreted to represent small marginal moraines or De Geer moraines on the T1 surface. White line indicates location of b). b) Seismic section of arbitrary line with moraines on the T1 surface (light blue line) where arrows indicate the crest. Location of figure is displayed in Fig. 4.3.2a.

Elongated curved furrows

A few elongated curved furrows appear to be randomly distributed on the T1 surface (Fig. 4.3.2). A general direction of orientation is not possible to establish as there are just a few of them and they are orientated differently. The length of the furrows stretches to 2 km, while the width and depth reaches 150 m and 5 m. They appear to have a V- or U-shape in cross sections.

Interpretation:

The elongated curved furrows shear the same chaotic geomorphology as the curved furrows described on the seafloor. Therefore, they are interpreted as iceberg plough-marks as described earlier on the seafloor and by Andreassen et al. (2008) in the Barents Sea.

4.3.1.2 Base Naust T – ST07M07

The T1 surface in the ST07M07 survey display several geomorphological features, including depressions, hills, ridges and furrows (Fig. 4.3.7). There appear to be a distinct connection between the hills and large depressions as they are located in direct proximity to each other. There are also three elongated depressions which represent artefacts of the subglacial meltwater channels on the seafloor (Fig. 4.3.7). As they are not real features they will not be described and interpreted.

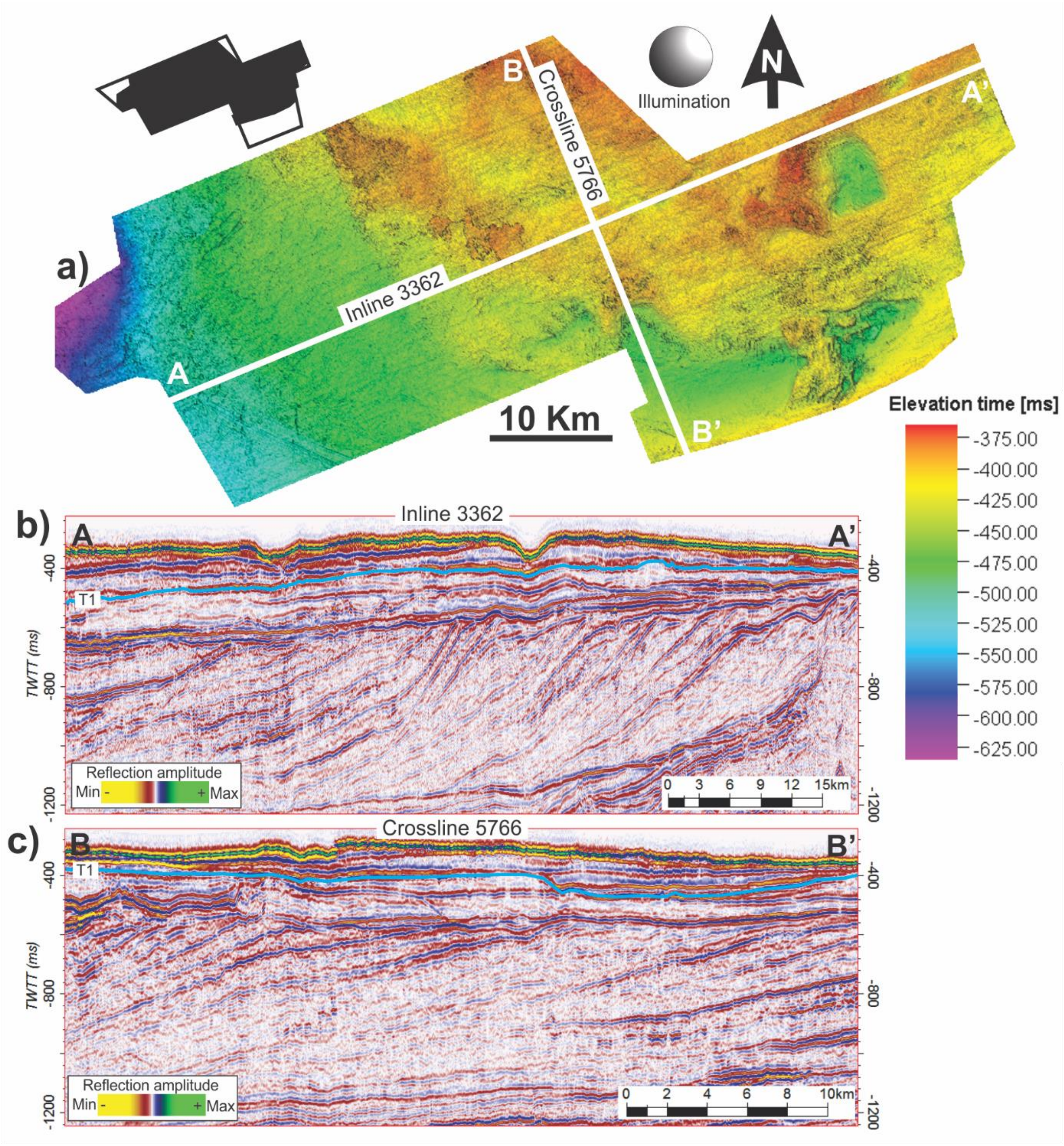


Figure 4.3.6 a) T1 surface in the ST07M07 3D-survey with white lines indicating location of inline 3362 and crossline 5766. b) Seismic section of inline 3362 with light blue line indicating the T1 surface. c) Seismic section of crossline 5766 with light blue line indicating the T1 surface. Black polygon indicates the location of the T1 surface of the ST07M07 survey.

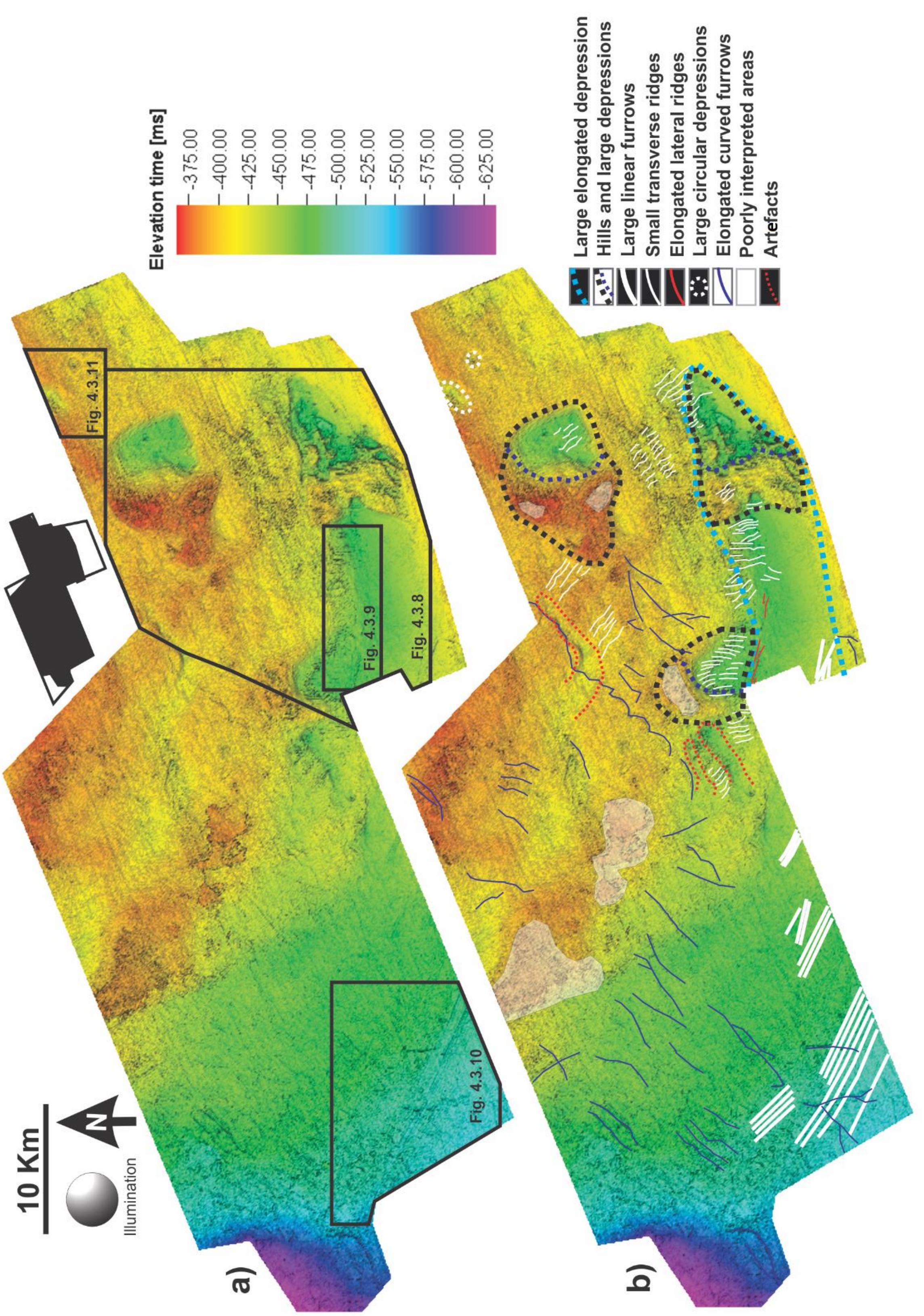


Figure 4.3.7 a) Overview of the T1 surface of the ST07M07 3D-survey with frames outlining the location of figure 4.3.9-4.3.11. b) T1 surface with display of interpreted features such as depressions, hills, ridges and furrows. Shaded areas indicate problematic areas related to discontinues reflectors. Black polygon indicates the location of the surface within the ST07M07 3D-survey.

Hills and large depressions

At three different places on the east side of the T1 surface large depressions with direct proximity to hills are located (Fig.4.3.7 and 4.3.8). Each of the features have been given a number to separate them (1-3 in Fig. 4.3.8). Two of the depressions (1-2) both have the hills located to the west of them, while one depression (3) has the hill located towards the NW. All the hills display weak reflection amplitudes and continuity in seismic sections.

The first depression (1 in Fig. 4.3.8) is sub-circular with a diameter of almost 6 km and a depth of approximately 60 m. Small ridges are located within the depression (described later). The hill located directly beside it is lobe-shaped with a width and length of 8 km and 6 km. The height is right above 55 m and the top of the hill appear to be truncated in the seismic sections. The volume of the depression and hill can roughly be calculated to be 1.7 km^3 and 1.65 km^3.

The second depression (2 in Fig. 4.3.8) has no clear shape except being slightly elongated, getting wider and deeper towards the west. It also appear to be part of a bigger elongated depression (described later). The length is measured to 8 km and the width varies from 1-7 km. The depression reaches a depth of up to 60 m in the deepest places. The surface display a hummocky landscape with ridges and smaller depressions. The adjacent hill also display a hummocky surface with ridges. It has a width and length of 7 km and 6 km while the height is approximately 55 m. Because of the unclear boundaries and hummocky surface it is difficult to measure the volume of both the depression and the adjacent hill.

The third depression and hill (3 in Fig. 4.3.8), which has a slightly different orientation, is sub-circular and lobe-shaped. The depression has a diameter of approximately 4.5 km and a depth of up to 40 m. Several small transverse ridges are displayed within the depression and lateral elongated ridged marks the transition from the depression to another large elongated depression on the side (described later). The associated hill is lobe-shaped with a width of up to 5 km and length of up to almost 3 km. The height is measured to right above 20 m but also here the top appears to be truncated in the seismic sections. The volume of the depression and hill is roughly calculated to be 0.6 km^3 and 0.3 km^3.

Interpretation:

The large depressions and hills occur to be connected considering the close proximity and shape, and therefore they are interpreted as one feature. They are interpreted to be hill-hole pairs as they show resemblance to the smaller depression and hill described earlier on the seafloor and display close similarities to the hill-hole pairs described on the mid-Norwegian margin by Ottesen et al. (2005a) and in North-Dakota by Bluemle and Clayton (1984)

The different orientation of the third hill-hole pair (3) from the two others (1 and 2) can be explained by the change in ice-flow direction. The third hill-hole pair is located further to the west where the ice-flow appears to bend around the shallowest parts of the surface, gradually getting an NW-SE orientation.

The volume of the first hill and depression appear to correspond relatively close which supports the hill-hole pair interpretation. The second was hard to measure because of the uneven geomorphology, which could be a result of the placement within a larger depression. The volume of the third depression is twice the volume of the adjacent hill. This could also be a result of the placement where it merges with the bigger elongated depression, making the boundaries unclear. In the seismic section the apex of the hill is clearly truncated, which may imply that the top has been prone to erosion, removing some of the sediments. Sediment may also have been transported out of the study area.

In seismic sections, all the hills display the same transparent seismic signature with weak amplitudes and discontinues reflections (Fig. 4.3.8). This is common in sediments with high clast content and is often a problem in glacigenic sediments, but may also be caused by diamictic or disturbed sediments (Lysa & Vorren, 1997). This could explain the seismic signature of the hills as they should comprises of glacigenic redistributed sediments.

Large elongated depression

A large elongated depression in the shape of a small trough is located on the SE section of the T1 surface (Fig. 4.3.7 and 4.3.8). It is orientated with an N-NE to S-SW trend but appear to bend towards the west in the S-SW direction. The start of the second depression described earlier coincides with the start of the elongated depression in the N-NE, and the hill fills the entire width. The elongated depressions continuous out of the survey in the S-SW but it appears to terminate, as there is no sign of it reentering the survey and continuing towards the west. The length would then be measured to approximately 25 km. The width and depth reaches up to 7 km and 6 m. Small ridges are located within and along the side of the depression.

Interpretation:

The depression is over-deepened which suggests that it is a result of glacial erosion. It is located among features interpreted to be hill-hole pairs, and therefore this large feature is also interpreted to represent the depression of a larger hill-hole pair where the hill has been transported out of the study area. The orientation of the hole suggests an ice-flow moving parallel to the mid-Norwegian coast on inner Trænabanken before bending around the bank and following Sklinnadjupet seaward. This coincide with the large linear furrows interpreted to be MSGL (described later).

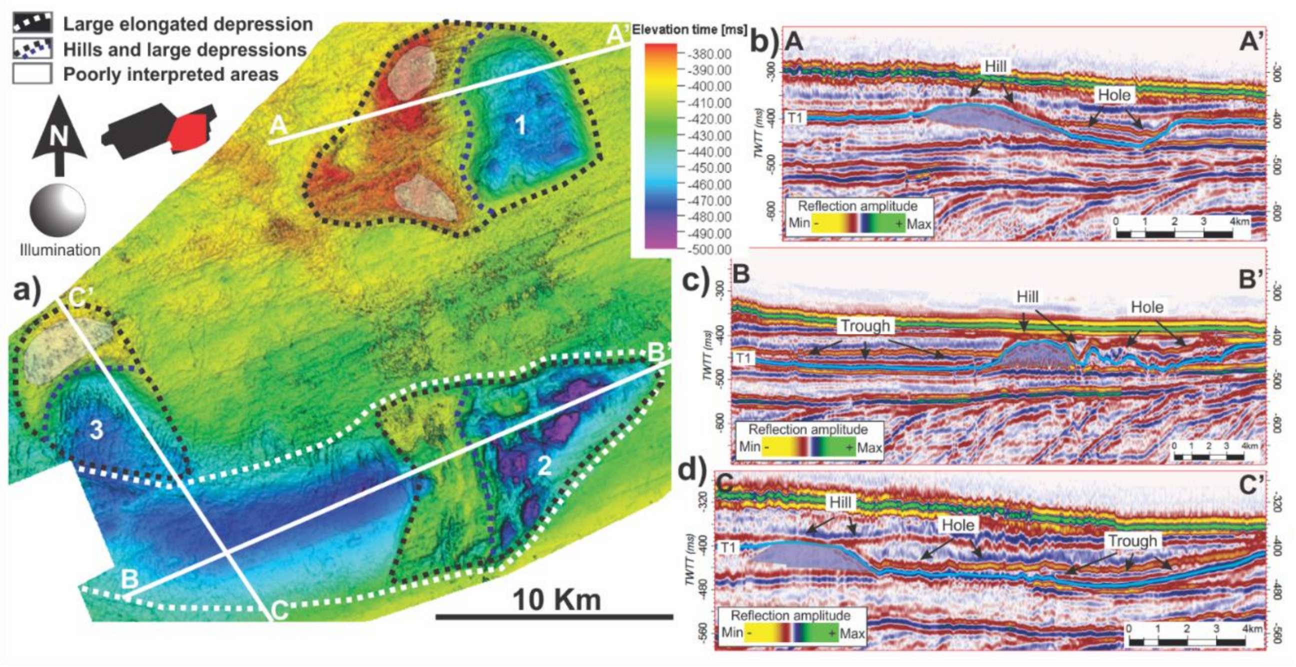


Figure 4.3.8 a) T1 surface displaying large depressions and hills interpreted to be hill-hole pairs. The hill-hole pairs have been marked with numbers (1-3) and the transition between the hill and the depression is indicated by stippled purple lines. Shaded areas display discontinuities on the apex of the hills. White lines indicate location of b), c) and d). c) Seismic section of hill-hole pair (1). c) Seismic section along the depression in the shape of a small trough and of hill-hole pair (2). d) Seismic section across the depression in shape of a small trough and hill-hole pair (3). T1 surface indicated by light blue line. Shaded areas indicate seismic signature of weak amplitudes and discontinuous reflectors. Location of figure is indicated in Fig. 4.3.7a.

Small transverse ridges

In the eastern part of the T1 surface several parallel, small transverse ridges are located (Fig. 4.3.7 and 4.3.9). The ridges are linear to slightly curved with a main orientation from S-SE to N-NW. The length reaches up to 3 km, while the width and height reaches approximately 200 m and 12 m. The ridges appear to be relatively symmetrical.

Interpretation:

The small transverse ridges display similar characteristics as the small transverse ridges described earlier on the seafloor and by Rydningen et al. (2013) on the seafloor of the northern mid-Norwegian continental shelf. They are therefore interpreted to be small marginal moraines or De Geer moraines. Some of the ridges are concentrated around the edges of the depressions described above. Therefore, it is also possible that they are the result of sediments being pushed up in cracks developed in the base of the ice as the ice may move at different velocities within and outside the depressions.

Elongated lateral ridges

On the edge of the large elongated depression described above, where the transition to what has been interpreted to be a hill-hole pair is located, elongated lateral ridges are displayed on the T1 surface (Fig. 4.3.7 and 4.3.9). They appear to have a symmetric shape with a length that is measured to right above 4 km. The width and height of the lateral ridges reaches up to 150 m and 14 m.

Interpretation:

The lateral elongated ridges are similar to the lateral ridges described earlier on the seabed and in adjacent areas by Rydningen et al. (2013). As they have the same geomorphology and are located at the boundary of a trough, they are interpreted as lateral shear zone moraines formed in basal glacial cracks. It is also possible that the ridges represent streamlined landforms as described earlier.

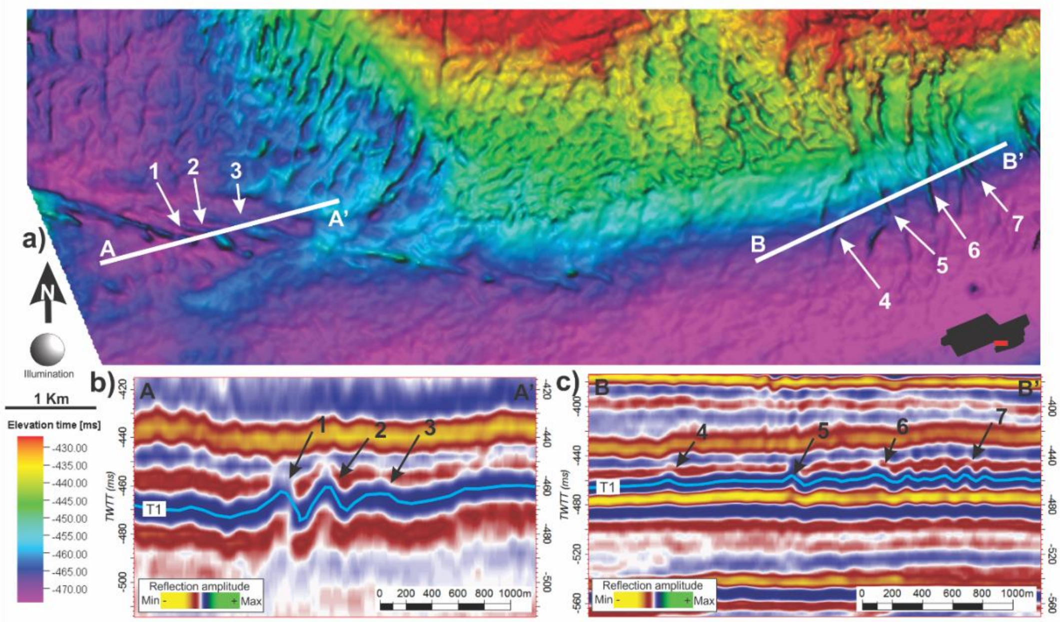


Figure 4.3.9 a) Lateral (arrow 1-3) and transverse (arrow 4-7) ridges interpreted to be moraines and lateral shear zone moraines along the edge of the depression shaped as a small trough on the T1 surface. White lines indicate location of b) and c). b) Seismic section of arbitrary line displaying lateral shear zone moraines on the T1 surface (light blue line). c) Seismic section of arbitrary line indicating small moraines on the T1 surface (light blue line). Location is indicated in Fig. 4.3.7a.

Large linear furrows

In the SE corner of the T1 surface several parallel, large-scale linear furrows stretches into the study area (Fig. 4.3.7 and 4.3.10). They have a main orientation from SE toward NW with a U- or V-shape in cross sections. The length is measured up to 15 km before they disappear out of the survey. The width is measured up to 200 m and the depth to approximately 10 m. The elongation ratios varies from 40:1 up to 75:1.

Interpretation:

The large linear furrows are interpreted to represent MSGL as they have similar features as the MSGL described earlier. There orientation indicate the direction of ice-flow which is supported by the orientation of the trough and hill-hole pairs described earlier. Similar MSGL have also been described on buried surfaces in the Barents Sea by Andreassen et al. (2007b) which have a elongation ratios between 33:1 and 85:1.

Elongated curved furrows

The entire western part of the T1 surface is covered in a large amount of elongated curved furrows (Fig. 4.3.7 and 4.3.10). They are chaotically orientated but have a main direction going from the SW towards the NE. The length varies, where the largest is measured up to 18 km. They are generally U- or V-shape, the width reaches up to 300 m and the depth up to 9 m. The furrows are truncating other geomorphological features as well as other elongated curved furrows.

Interpretation:

The elongated curved furrows show close similarities to the elongated curved furrows described on the seafloor as well as by Dowdeswell et al. (2007) in the Norwegian Sea and by Andreassen et al. (2007b) in the Barents Sea. Therefore, they are interpreted to represent iceberg plough-marks.

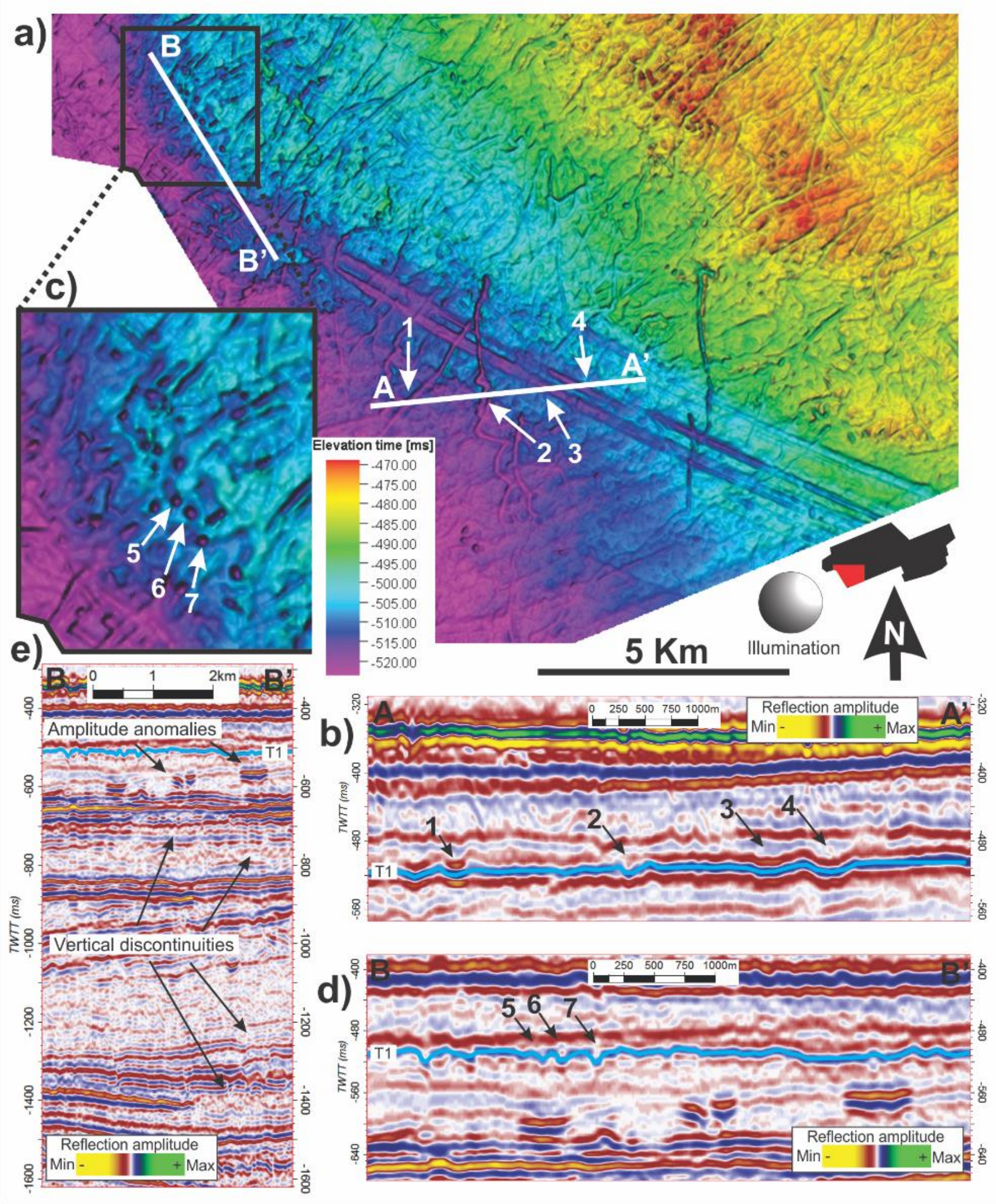


Figure 4.3.10 a) T1 surface displaying geomorphological features as small circular depressions and ridges interpreted to be small pockmarks, iceberg plough-marks (1-2) and MSGL (3-4). Black frame indicates location of c) and white lines indicate location of b), d) and e). b) Seismic section of arbitrary line displaying iceberg plough-marks (1-2) and MSGL (3-4) on the T1 surface (light blue line). c) Zoom-in of area with relatively high concentration of small pockmarks (5-7). d) Seismic section of arbitrary line displaying small pockmarks (5-7) on the T1 surface (light blue line). e) Seismic section of arbitrary line showing vertical discontinuities and amplitude anomalies interpreted be bright spots in the layers underlying the pockmarks on the T1 surface (light blue line). Location is indicated in Fig. 4.3.7a.

<u>Circular depressions</u>

Two large circular to sub-circular depressions have been located in the NE corner of the T1 surface (Fig. 4.3.7 and 4.3.11). The largest is semi-circular, has a diameter between 1-2 km and a depth of 55 m. The depressions have a parabolic shape. The smaller depression has a diameter of 750 m and a depth of 16 m. Scattered around the rest of the surface, small circular depressions with a diameter up to 150 m and a depth of up to 9 m. These depressions are especially concentrated towards the deeper western parts of the surface (Fig. 4.3.10c). In the subsurface underneath the depressions, seismic anomalies and vertical discontinuities are observed in seismic sections (Fig. 4.310e and 4.3.11b).

Interpretation:

The small circular depressions are interpreted to be paleo-pockmarks as they have similar geomorphology as the pockmarks described on the T1 surface in the ST10013 survey as well as the seafloor. The large semi-circular depression might possibility be a the result of subglacial erosion as described earlier and by Rafaelsen et al. (2002) in the Barents Sea. However, it is also possible that the depression is a large paleo-pockmark as vertical discontinuities may indicate fluid flow in the underlying strata. The smaller pockmarks surrounding the large circular depression also suggests that fluid migration has taken place in the area (Fig. 4.2.11).

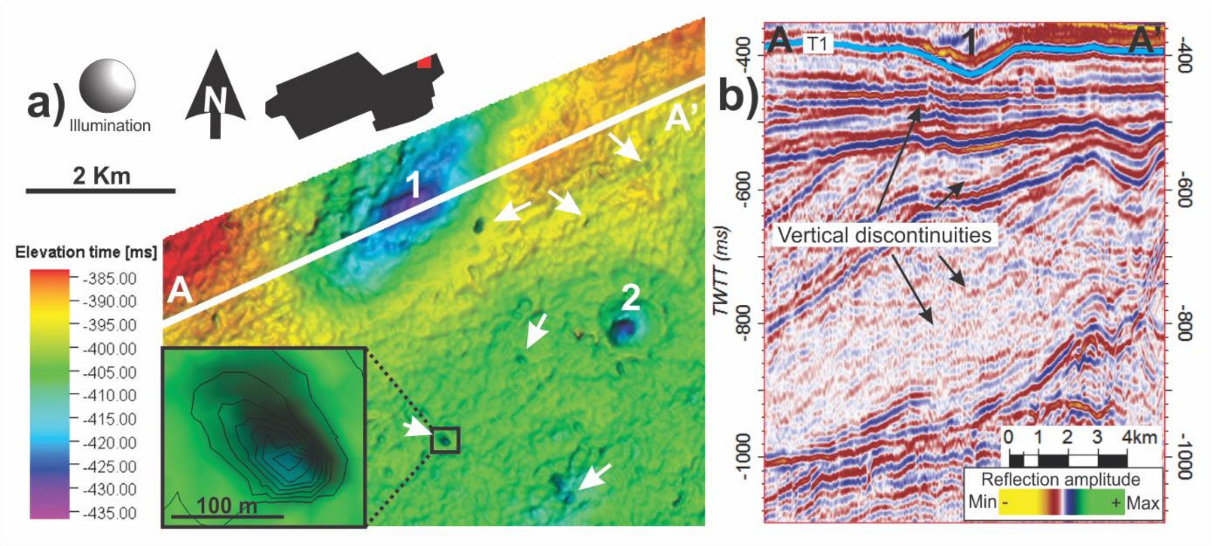


Figure 4.3.11 a) Display of large (number 1-2) and small (arrows) circular depressions on the T1 surface interpreted to be subglacial erosional features and paleo-pockmarks. Frame in the lower left corner display zoom-in of a small paleo-pockmark. White line indicates location of b). b) Seismic section of arbitrary line with what has been interpreted a subglacial erosional (1) on the T1 surface (light blue line). The seismic section shows possible signs of fluid migration in the form of small vertical discontinuities directly beneath the pockmark. Location of figure is shown in Fig. 4.3.7a.

4.3.2 Base Naust S (S1) (URU)

The base of Naust S separate the flat lying sheets of glacigenic sediments from the underlying prograding clinoforms, and is interpreted to represent the upper regional unconformity (URU) in the study area. This surface indicates the beginning of the S sequence located between T1 and S1, which was deposited during the Elsterian glaciation. The S1 surface has been described and interpreted from both seismic surveys (Fig. 4.3.12 and 4.3.15).

4.3.2.1 Base Naust S – ST10013

The S1 reflection in the ST10013 seismic survey is also on this surface dominated by two large paleo-trough. On this surface, the northernmost of the troughs that is located in the inner parts of Sklinnadjupet has a different orientation with a NE-SW direction. In addition, here the reflection pattern between the troughs is slightly chaotic. Smaller geomorphological features on the surface include lobes, ridges and furrows (Fig. 4.3.13). The areas of the surface that truncates prograding clinoforms from below have been marked as the reflection is inconsistent in these areas. There also appears to be a change in topography on the surface, which mimics the outline of the cross-shelf trough on the seafloor. This is interpreted to be an artefact as the seismic survey is displayed in two way travel time (Fig. 4.3.14).

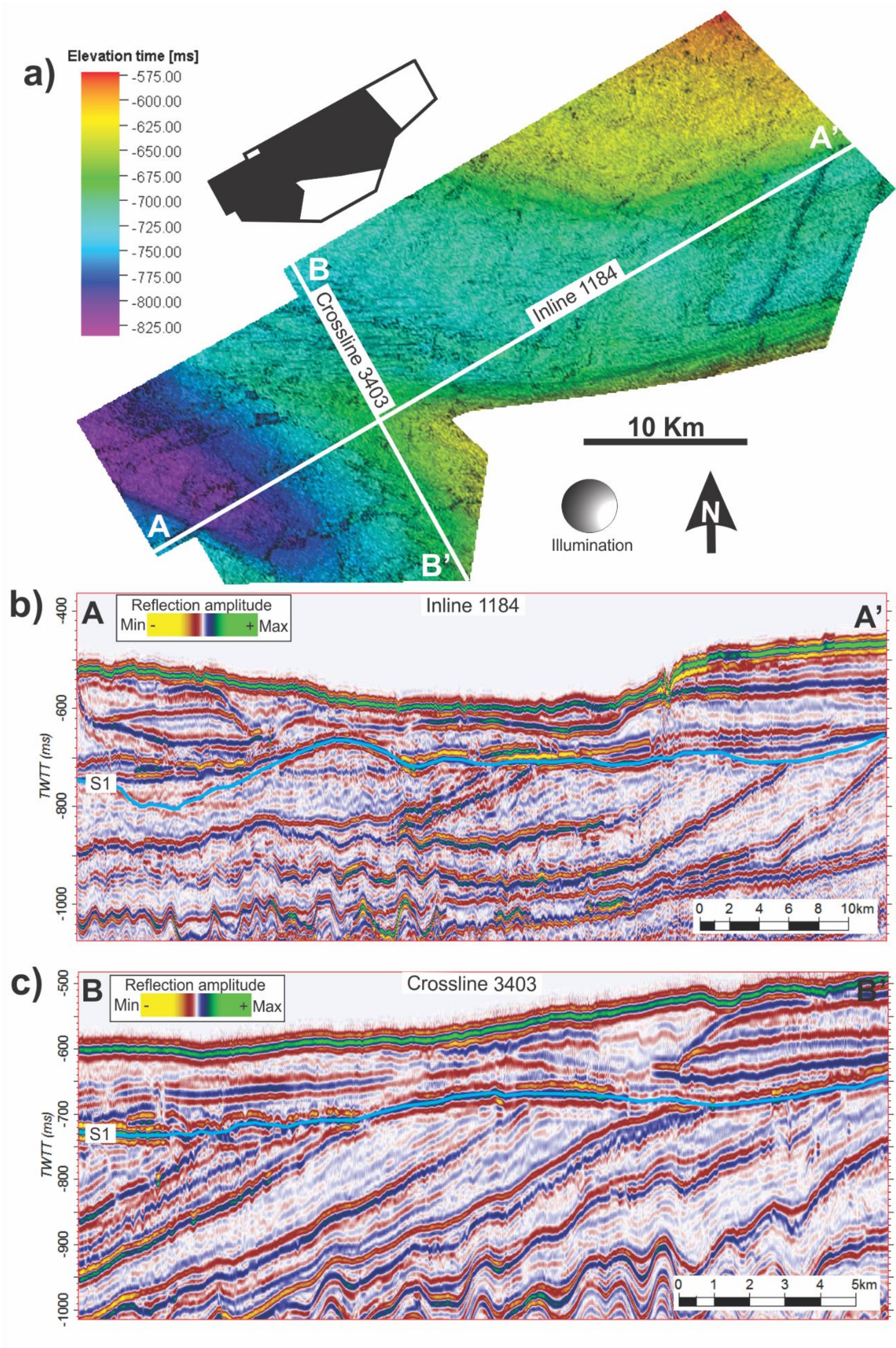


Figure 4.3.12 a) S1 surface in the ST10013 3D-survey where white lines indicate location of inline 1184 and crossline 3403. b) Seismic section of inline 1184 where the light blue line indicate the S1 surface. c) Seismic section of crossline 3403 with light blue line indicating the S1 surface. The location of the S1 surface in the ST10013 survey is indicated by the black polygon.

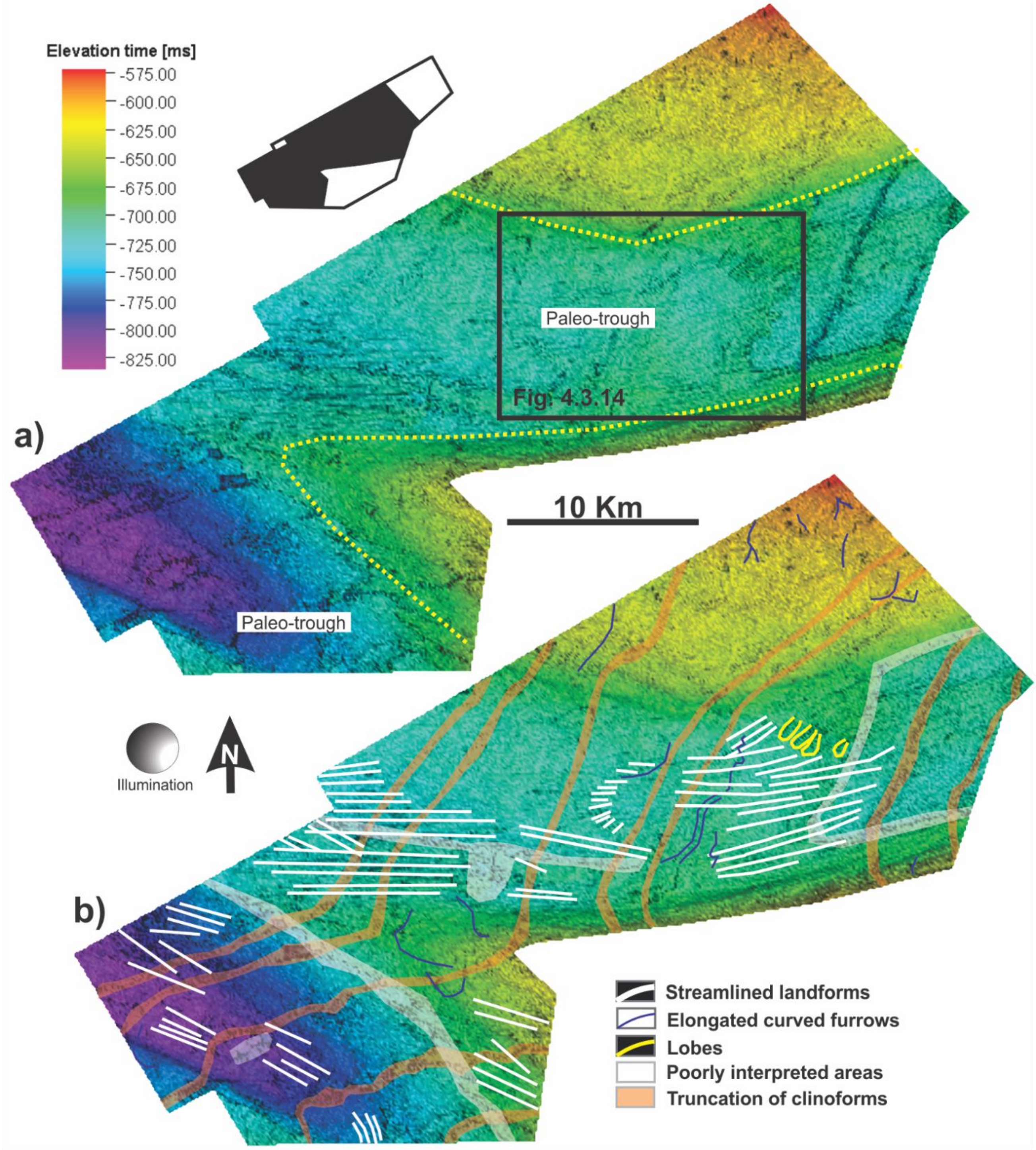


Figure 4.3.13 a) The S1 surface of the ST10013 3D-survey with two paleo-troughs coinciding, outlined by the yellow stippled line. The black frame outlines figure 4.3.14. b) S1 surface with display of interpreted features such as furrows and lobes. Shaded areas indicate poorly interpreted sections (white) or truncation of underlying clinoforms (orange). Black polygon indicate the location of the surface within the survey.

Streamlined landforms

The streamlined landforms consists of parallel, elongated ridges and large-scale furrows (Fig. 4.3.13 and 4.3.14). They are distributed within the two paleo-troughs with two main directions orientated form E-SE towards the W-NW (southern trough) and from east to west (northern trough). The ridges are up to 4 km long and 300 m wide, which gives them a length:width ration of 14:1. The height has been measured up to 5 m. The large-scale furrows are linear with a U- or V-shape and have a length of up to 16 km. The width and depth reaches up to 200 m and 5 m while the elongation ratio is up to 80:1.

Interpretation:

The ridges and furrows have been interpreted as flutes and MSGL made by fast-flowing ice streams within the paleo-troughs. They show close similarities to the streamlined landforms described earlier on the seafloor and by Dowdeswell et al. (2007).

Lobes

Four lobes are located along what appears to be a small change in topography within one of the troughs on the S1 surface (Fig. 4.3.13 and 4.3.14). The lobes stretches for up to 1000 m where the change in topography constitutes about 20 m. Although the change in topography may not represent a real feature as the change show close similarities to the outer edge of the trough on the seafloor. The width and height reaches approximately up to 350 m and 10 m. The lobes have an orientation form NE-SW.

Interpretation:

There is no clear reason for the creation of the lobes on the S1 surface but the surface in general has an uneven morphology, especially within the paleo-trough (Fig.4.3.14). Features like these lobes may represent relics from glacial erosion, which would take place in the paleo-trough. However, the origin of these features are relatively uncertain might as well be the result of seismic noise or poor interpretation of the chaotic seismic.

Elongated curved furrows

Several elongated curved furrows are located mainly on the banks on the S1 surface (Fig. 4.3.13 and 4.3.14). They are U- or V-shape and have a chaotic pattern with a main orientation from north to south. The length reaches up to 6 km while the width and depth are measured up to approximately 150 m and 5 m. The furrows appear to truncate other geomorphological features on the surface.

Interpretation:

The elongated curved furrows display the same geomorphology as the curved furrows described on the seabed as well as features described by Dowdeswell et al. (2007) on the mid-Norwegian continental shelf and on paleo-surfaces in the Barents Sea described by Andreassen et al. (2007b). Therefore, they are interpreted as iceberg plough-marks imprinted in the paleo-shelf by floating icebergs.

Small circular depressions

Serval small circular depressions are located on the S1 surface of the ST10013 survey. They are distributed on the whole surface with high concentrations in areas where some of the clinoforms are truncated (Fig. 4.3.14). They have a general diameter of approximately 100 m but some reached up to 200 m. They have a parabolic shape and the depth reaches approximately 12 m.

Interpretation:

The small circular depressions are interpreted as small pockmarks as they display the same morphology as the small circular depressions described earlier within the trough of the seafloor. Similar small pockmarks with a size range of up to 100 m have been described in the Barents Sea by Chand et al. (2009). The high concentration around the truncated clinoforms may be a result of fluids following the stratigraphic layers up to the URU. However, it is also possible that these circular depressions simply are the result of the poorly interpreted surface along the truncated clinoforms.

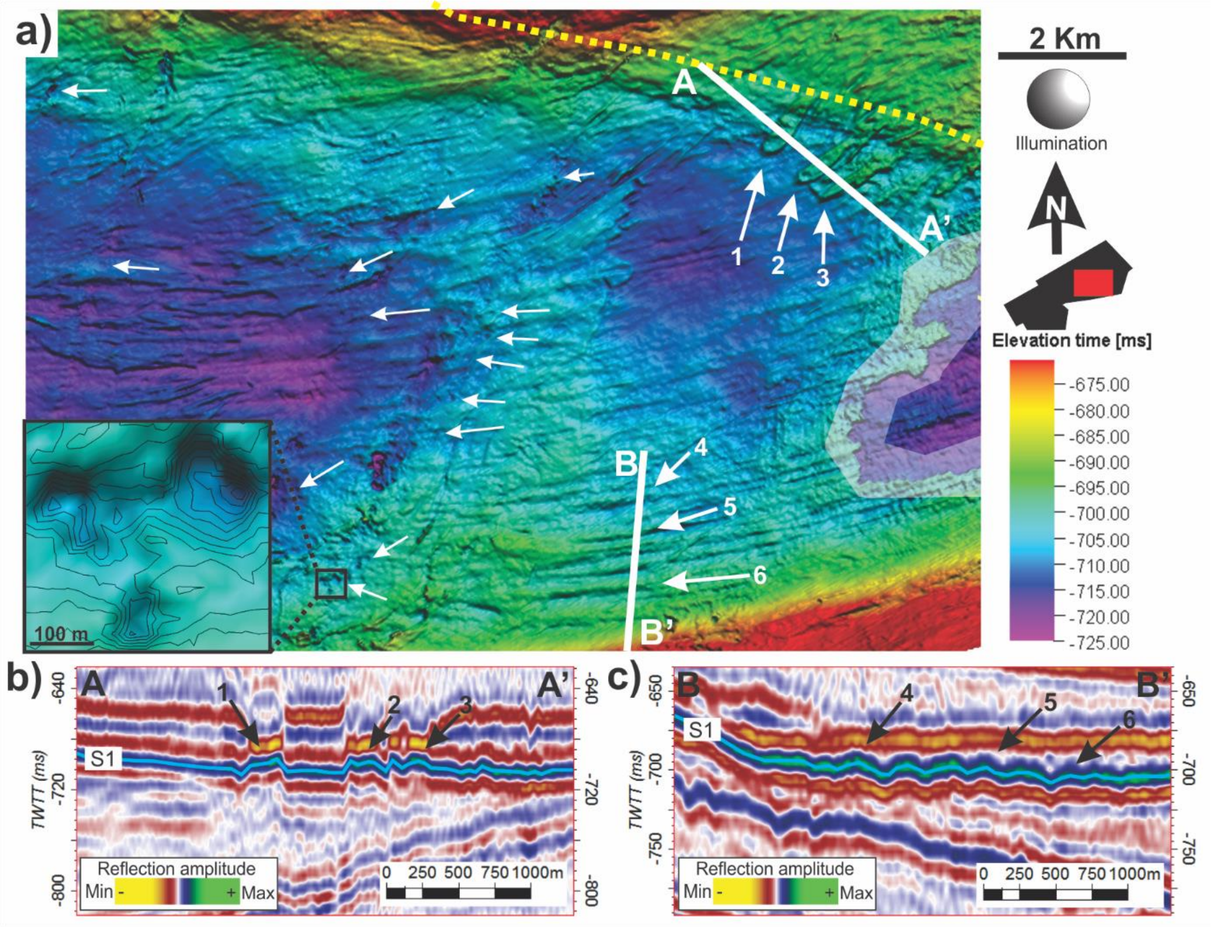


Figure 4.3.14 a) Display of different morphological features on the S1 surface. Arrows (1-3) indicating lobes interpreted to e relics of glacial erosion. Arrows (4-6) indicating elongated ridges between linear furrows interpreted to be flutes and MSGL. Small arrows indicating circular depressions concentrated along truncated clinoforms interpreted to be paleo-pockmarks, which also can be seen in the zoom-in frame. Shaded area represents poorly interpreted sections. Yellow stippled line indicate artefact from the cross-shelf trough on the seafloor. White lines show location of b) and c). b) Seismic section of arbitrary line displaying lobes on the S1 surface. c) Seismic section of arbitrary line displaying parallel ridges and furrows. S1 surface is indicated by light blue line in seismic sections. Location of figure is displayed in Fig. 4.3.13.

4.3.2.2 Base Naust S – ST07M07

The S1 surface in the ST07M07 survey is mainly dominated by streamlined landforms. The surface also display circular depressions and large grooves (Fig. 4.3.16). Also here the surface truncates prograding clinoforms resulting in inconsistent areas.

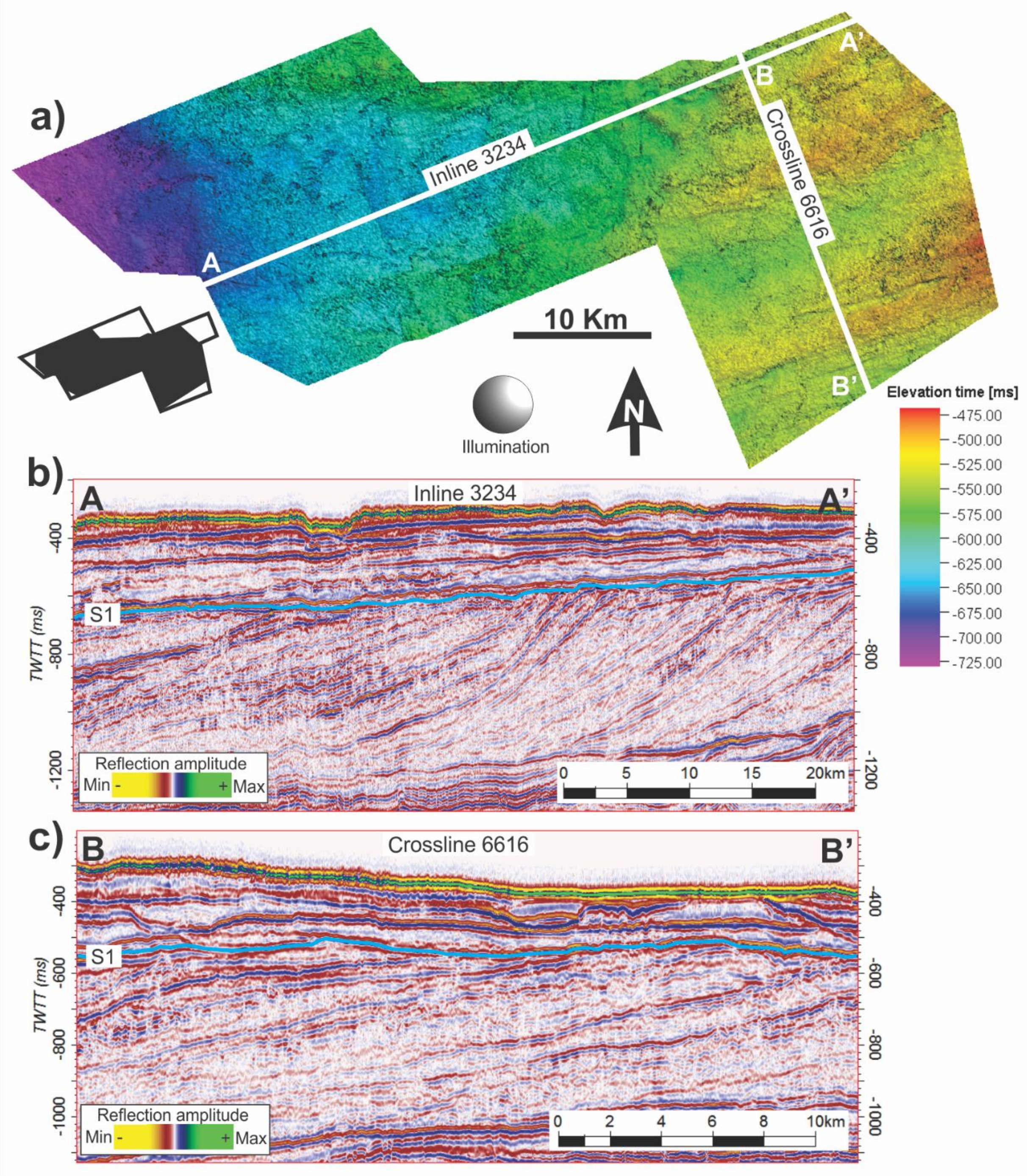


Figure 4.3.15 a) S1 surface in the ST07M07 3D-survey where white lines indicate location of inline 3234 and crossline 6616. b) Seismic section of inline 3234 where the light blue line indicate the S1 surface. c) Seismic section of crossline 6616 where the light blue line represents the S1 surface. Black polygon show location of the S1 surface.

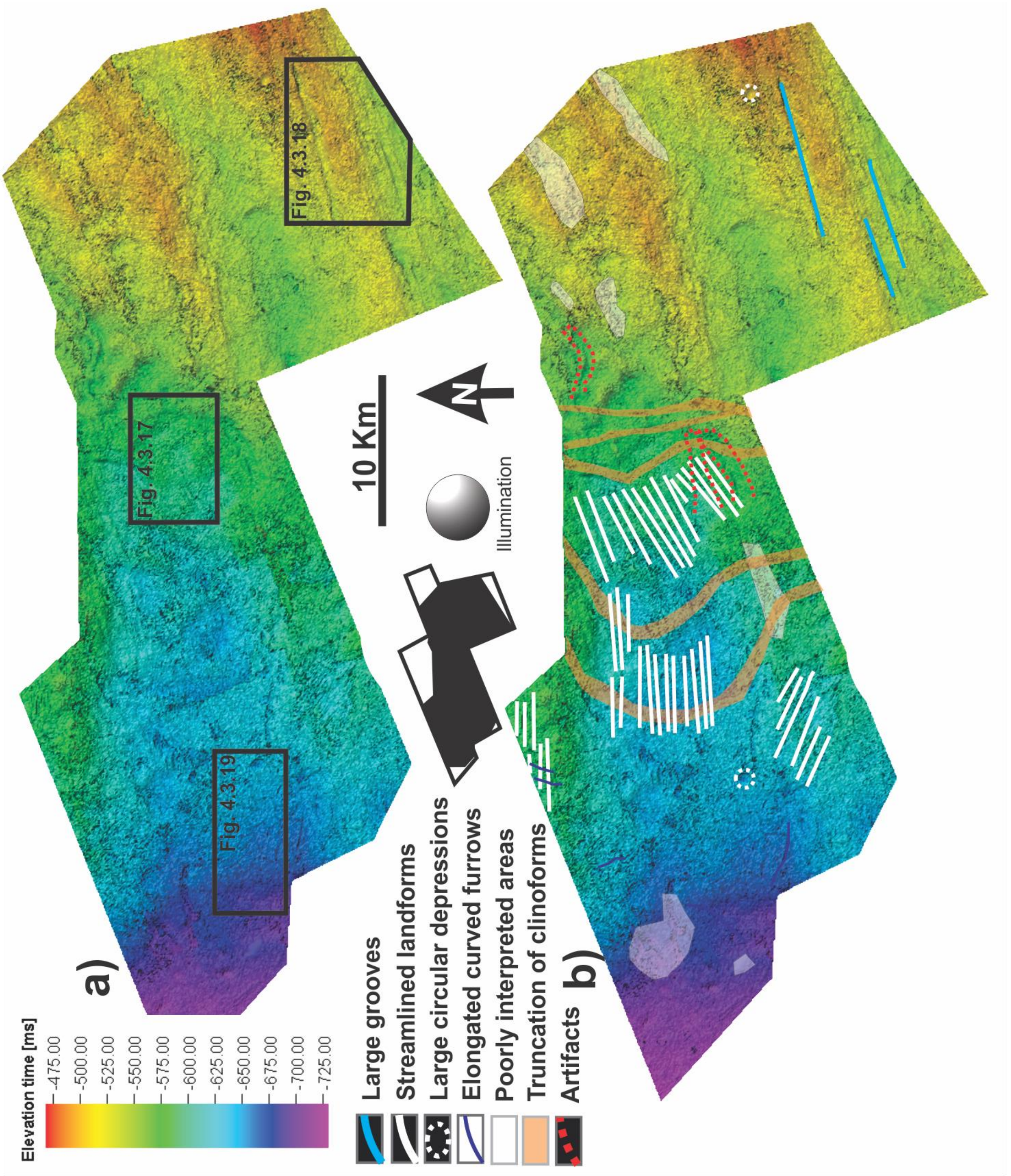


Figure 4.3.16 a) Overview of the S1 surface in the ST07M07 3D-survey. The black frames outlines figure 4.3.17-4.3.19. b) The S1 surface with display of interpreted features such as furrows, ridges and grooves. Shaded sections indicate poorly interpreted areas (white) or truncation of underlying clinoforms (orange). Black polygon indicates location of the S1 surface in the ST07M07 survey.

Streamlined landforms

Streamlined landforms which consists of parallel, large-scale furrows and elongated ridges are located in the middle of the S1 surface in the ST07M07 survey (Fig. 4.3.16 and 4.3.17). They have a main orientation going from east to west, with the exception of the ridges and furrows in the SE corner which are orientated SE-NW. The lineations are up to 6 km in length, 200 m in width and 5 m in depth. This gives them a length:width ration of 30:1. They are linear with a U- or V-shape in cross sections. The elongated ridges which are parallel to the furrows are up to 8 m high and 150 m wide. The length can be measured to approximately 2.5 km and the length:width ratio is 17:1.

Interpretation:

The streamlined landforms are interpreted as MSGL and flutes, as they show close similarity to the streamlined landforms described on the seafloor of the study area and in adjacent areas by Rydningen et al. (2013). There is also a possibility that the streamlined landforms are affected by seismic noise or consists of artefacts, as the direction is almost parallel to the acquisition direction of the survey.

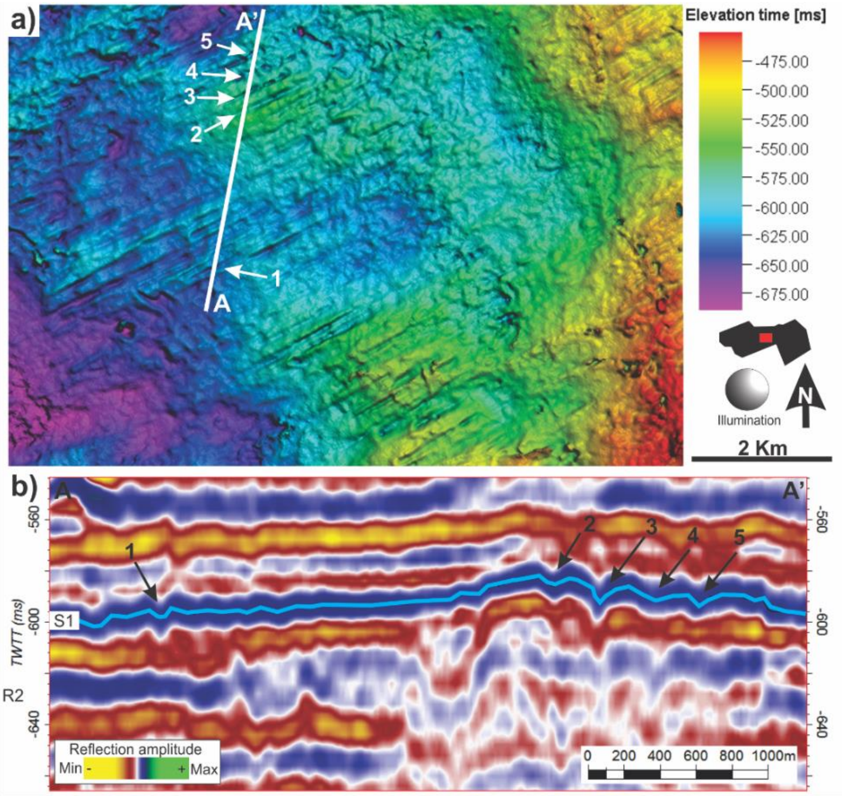


Figure 4.3.17 a) Display of streamlined landforms on the S1 surface consisting of linear furrows (white arrows) interpreted to represent MSGL, in between parallel elongated ridges interpreted to be flutes. White line indicated location of b). b) Seismic section of arbitrary line displaying streamlined landforms on the S1 surface (light blue line). Location of figure is indicated in Fig. 4.3.16.

Large grooves

Three large grooves are located in the NE corner of the S1 surface (Fig. 4.3.16 and 4.3.18). The groves have an orientation going from the E-NE towards the W-SW, where the grooves gradually becomes wider and less pronounced. They are linear in shape and the length is measured up to 14 km. The width and depth have been measured to 200 m and 22 m at the starting point. The depth then decreases as the width increases, reaching a width of just above 800 m before disappearing. The grooves are also over-deepened in some areas.

Interpretation:

The grooves are interpreted to represent erosional features from created by glaciers, as the features are over-deepened and parallel to the MSGL described above and the paleo-ice flow described by Dowdeswell et al. (2006). They show some similarities to depressions described by Rafaelsen et al. (2002) in the Barents Sea, and although the grooves are narrower and longer they are also interpreted to have been formed by erosion from a warm-based ice sheet.

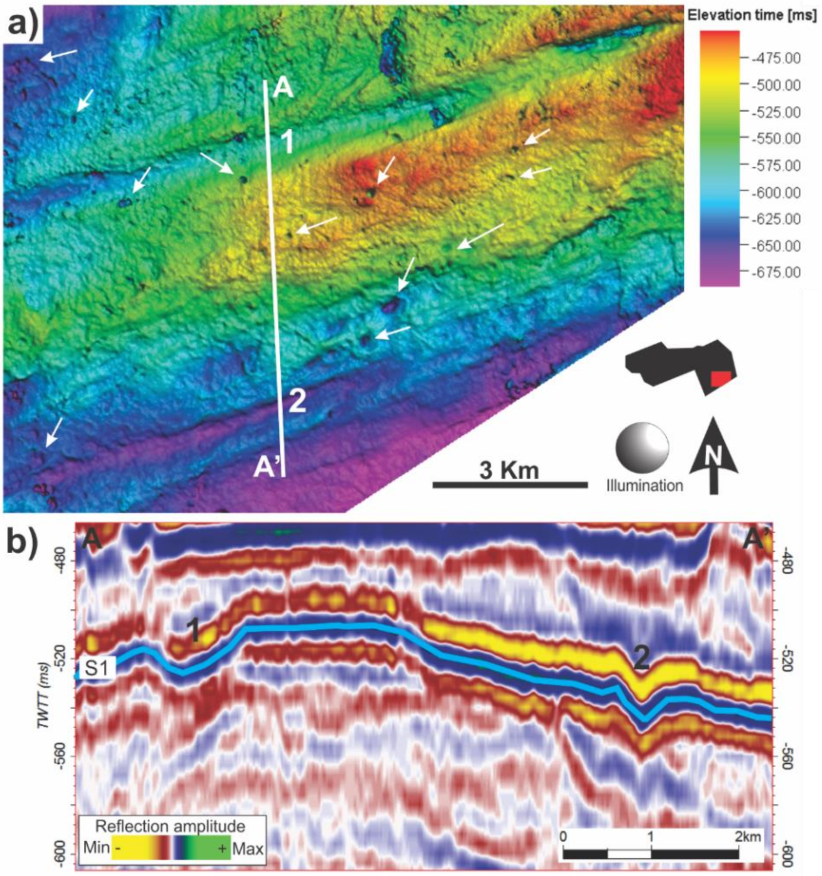


Figure 4.3.18 a) Display of groves (numbers) and small circular depressions (arrows) interpreted to represent erosional features and small paleo-pockmarks on the S1 surface. White line shows location of b). b) Seismic section of arbitrary line with groves indicated by numbers on the S1 surface (light blue line). Location of figure is indicated in Fig. 4.3.16.

Circular depressions

Circular depressions with varying size are located relatively random on the S1 surface (Fig. 4.3.16, 4.3.18 and 4.3.19). Most of the depressions only have a diameter reaching up to a few hundred meters, while a few larger depressions have been measured up to 1200 m. The largest depressions are up to 15 m deep while the smaller depression only reaches a few meter. The smaller circular depression appear in high concentrations where clinoforms from the underlying strata is truncated. In seismic sections, small vertical discontinuities are located directly beneath some of the circular depressions (Fig. 4.3.19b).

Interpretation:

The geomorphology of the depressions display similar features to those that have been interpreted as the small and large pockmarks on the seafloor. They are located above areas that display vertical discontinuities, which might indicate fluid migration in the underlying sediments. The high concentration of depressions around the truncating clinoforms may indicate that the fluid flow follows stratigraphic layers of increased permeability. Similar pockmarks have been described by Chand et al. (2009) on the seafloor of the Barents Sea.

Elongated curved furrows

Some few elongated curved furrows are located on the S1 surface in the ST07M07 survey (Fig. 4.3.16 and 4.3.19). They are U- or V-shaped and display a chaotic pattern with a general orientation from south to north. The length reaches up to 6 km while the width and depth are approximately 300 m and 8 m.

Interpretation:

The elongated curved furrows have similar features as the curved furrows documented by Dowdeswell et al. (2007) and are therefore interpreted to be plough-marks from drifting icebergs as described on the seafloor in chapter 4.2.

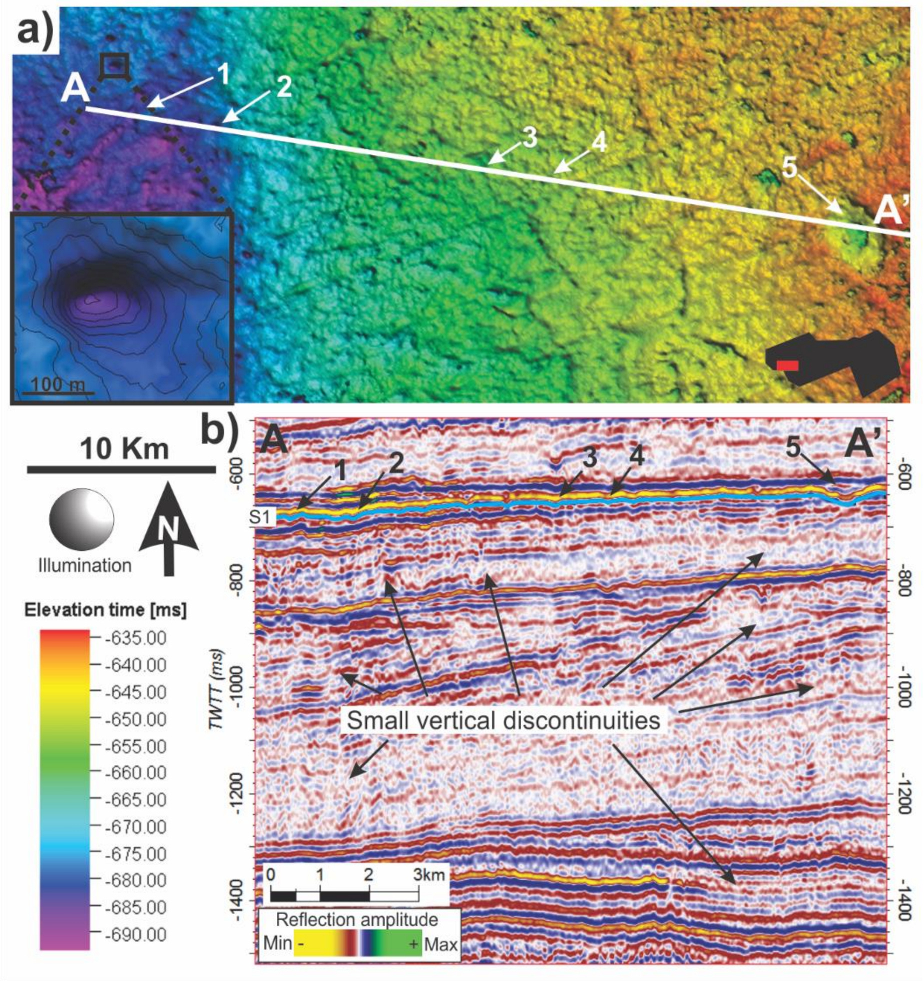


Figure 4.3.19 Display of the S1 surface with white arrows indicating elongated curved furrows (1) and various circular depressions (2-5) interpreted to be iceberg plough-marks and paleo-pockmarks (zoom-in). White line indicates location of b). b) Display of seismic section showing signs of vertical discontinuities in the subsurface underneath paleo-pockmarks (arrow 2-5) on the S1 surface (light blue line). Location of figure is shown in Fig. 4.3.16.

4.3.3 Base Naust A (A1)

The A1 reflection is interpreted to represent the base of the A sequence in the Naust Formation. This sediment sequence is only represented in the NW corner of the ST07M07 survey and is confined between A1 and S1 as well as the base of the U sequence, which barely stretches into the ST07M07 survey (Fig. 4.3.20). The sequence consists of low gradient prograding clinoforms dipping towards the west and continuing out of the study area. The A1 surface is dominated by to geomorphological features consisting of streamlined landforms and curved furrows. There is also a large depression stretching across the surface from SE towards NW, which is interpreted to be a cross-shelf paleo-trough (Fig. 4.3.21).

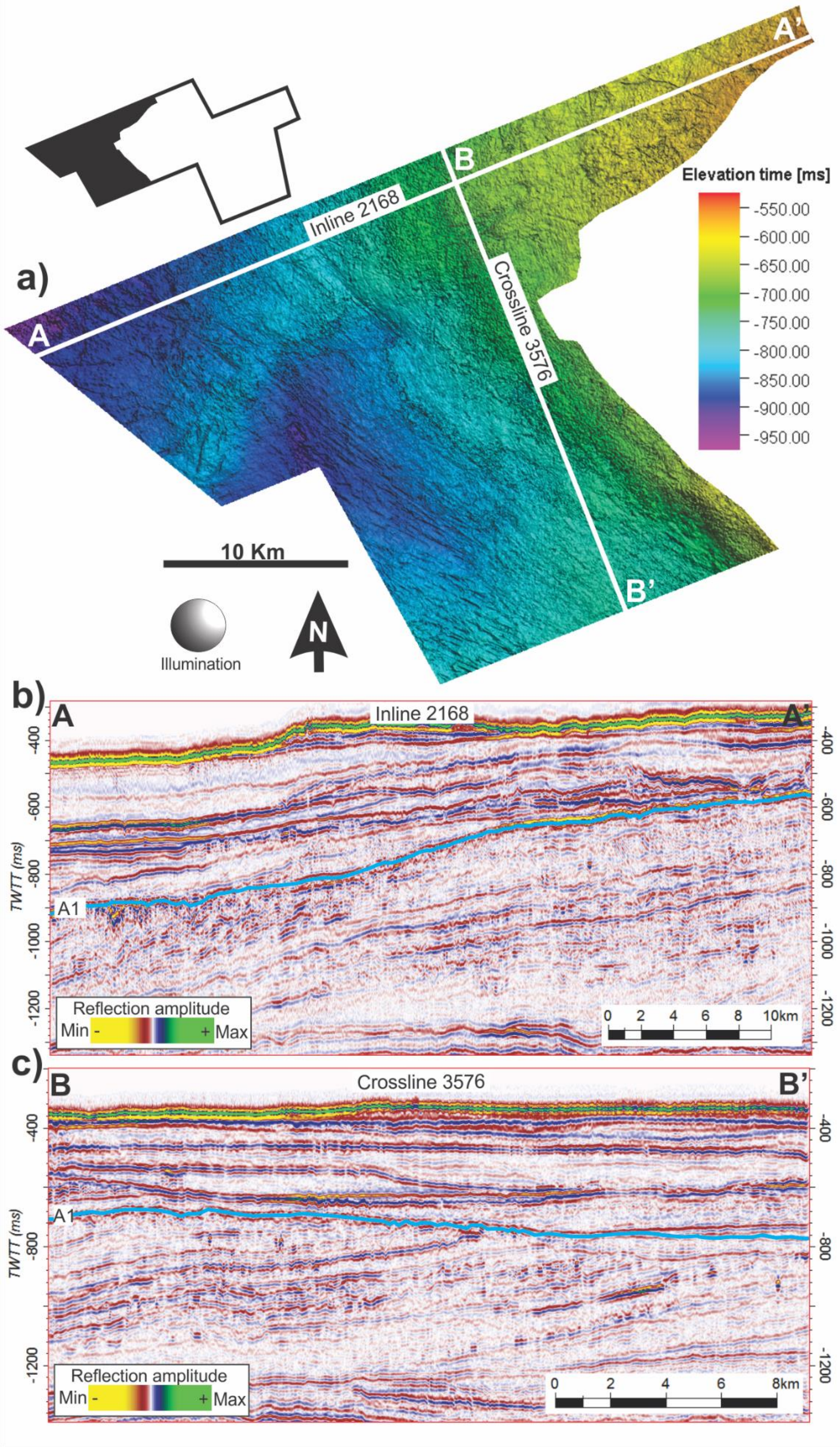


Figure 4.3.20 a) A1 surface from the ST07M07 3D-survey where white lines display location of inline 2168 and crossline 3576. b) Seismic section of inline 2168. c) Seismic section of crossline 3576. The light blue line show location of the A1 surface in the strata. Location indicated by black polygon.

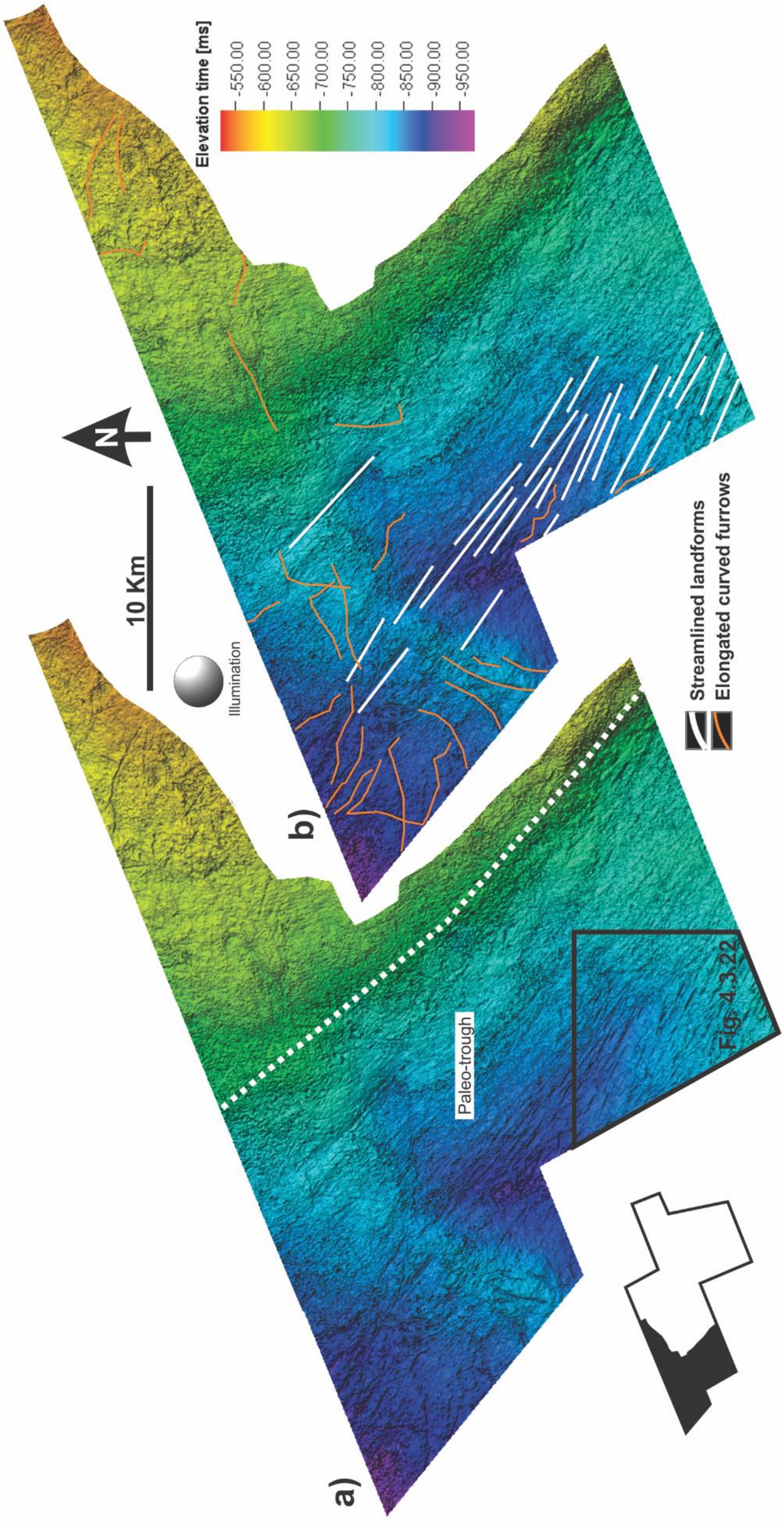


Figure 4.3.21 a) Overview of the A1 surface in the ST07M07 3D-survey. Black frame outlines figure 4.3.22. White line indicates boundary of paleo-trough. b) The A1 surface showing interpreted features such as furrows and ridges. Black polygon indicates the location of the A1 surface in the ST07M07 seismic survey.

Streamlined landforms

Streamlined landforms are displayed in the lower part of the A1 surface located on the southwestern side (Fig. 4.3.21 and 4.3.22). They are orientated from the SE towards the NW and consists of parallel, large-scale linear furrows and elongated ridges. The furrows have a length of up to 11 km while the length and depth have been measured up to 300 m and 10 m. The elongated ridges have a height up to 15 m while the length and width reaches up to 5 km and 400 m. The ridges are relatively blunt on the stoss side with a narrowing lee side.

Interpretation:

The streamlined landforms are interpreted as MSGL and flutes formed by fast-flowing ice streams moving from the SE towards the NW, as they show close similarities to streamlined landforms described on earlier surfaces. They are only located within what is interpreted as a paleo-trough, which act as “highways” for fast-flowing ice streams.

Elongated curved furrows

Chaotic, elongated curved furrows are located on the A1 surface (Fig. 4.3.21). The highest concentration appears in the shallowest parts of the surface, although the furrows in the deeper parts are more distinct. The furrows are mainly orientated from SW-NE with the exception of the deepest part in the eastern corner of the surface where the orientation is W-E. The furrows reaches a length of up to 8 km and a width of up to 250 m. They have a V- or U-shape in cross sections witch reaches a depth of 8 m.

Interpretation:

The curved furrows have been interpreted as plough-marks formed by drifting icebergs reaching the seabed as described earlier. The high concentration in the shallower parts is probably a result of more icebergs being able to reach the seafloor. The deeper furrows are probably more distinct as the icebergs that generated them had to be massive in size.

Small circular depressions

Small circular depressions are scattered around the A1 surface (Fig. 4.3.22). The diameter reaches just above 200 m with a depth of only a few meters. They have a parabolic shape and appear to line up within the furrows (describe earlier) at some places.

Interpretation:

The circular depressions are interpreted to represent small paleo-pockmarks as described on earlier surfaces, as the show close similarities to these features. They line up within the furrows as this might possibly be an easier migration pathway for fluids as described for the small pockmarks on the seafloor.

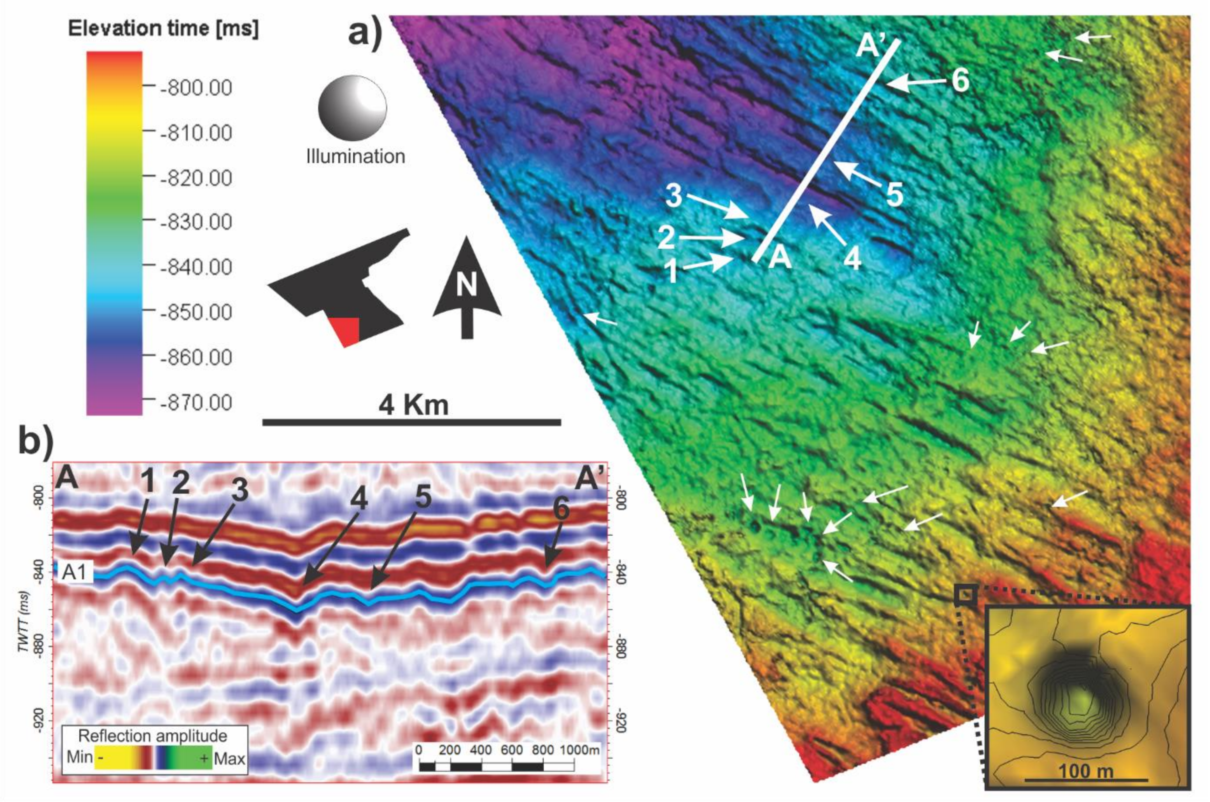


Figure 4.3.22 a) Display of streamlined landforms interpreted to represent flutes (1-3) and MSGL (4-5) as well as small circular depressions interpreted to be small paleo-pockmarks (small arrows). The white line indicates location of b). b) Seismic section of arbitrary line where flutes (1-3) and MSGL (4-6) are indicated on the A1 surface (light blue line). Location of figure is displayed in Fig. 4.3.21.

4.3.4 Intra Naust N-1 (N1)

The N1 reflection is interpreted to represent an internal paleo-seafloor surface of the N sequence of the Naust Formation. The surface can only be located in the ST07M07 3D-survey as it is located to far west to reach into the ST10013 survey. The reflection configuration of the Naust N sequence in this area is complex sigmoidal/oblique down-lapping onto the base of the Naust Formation. This is interpreted to represent part of the paleo-shelf and paleo-slope, although the paleo-shelf is only present in some areas as it has been subject to erosion. The general angle (1-2°) of the slope is dipping towards the west (Fig. 4.3.23). The N1 surface display morphological features as mounds, ridges and depressions (Fig. 4.3.24).

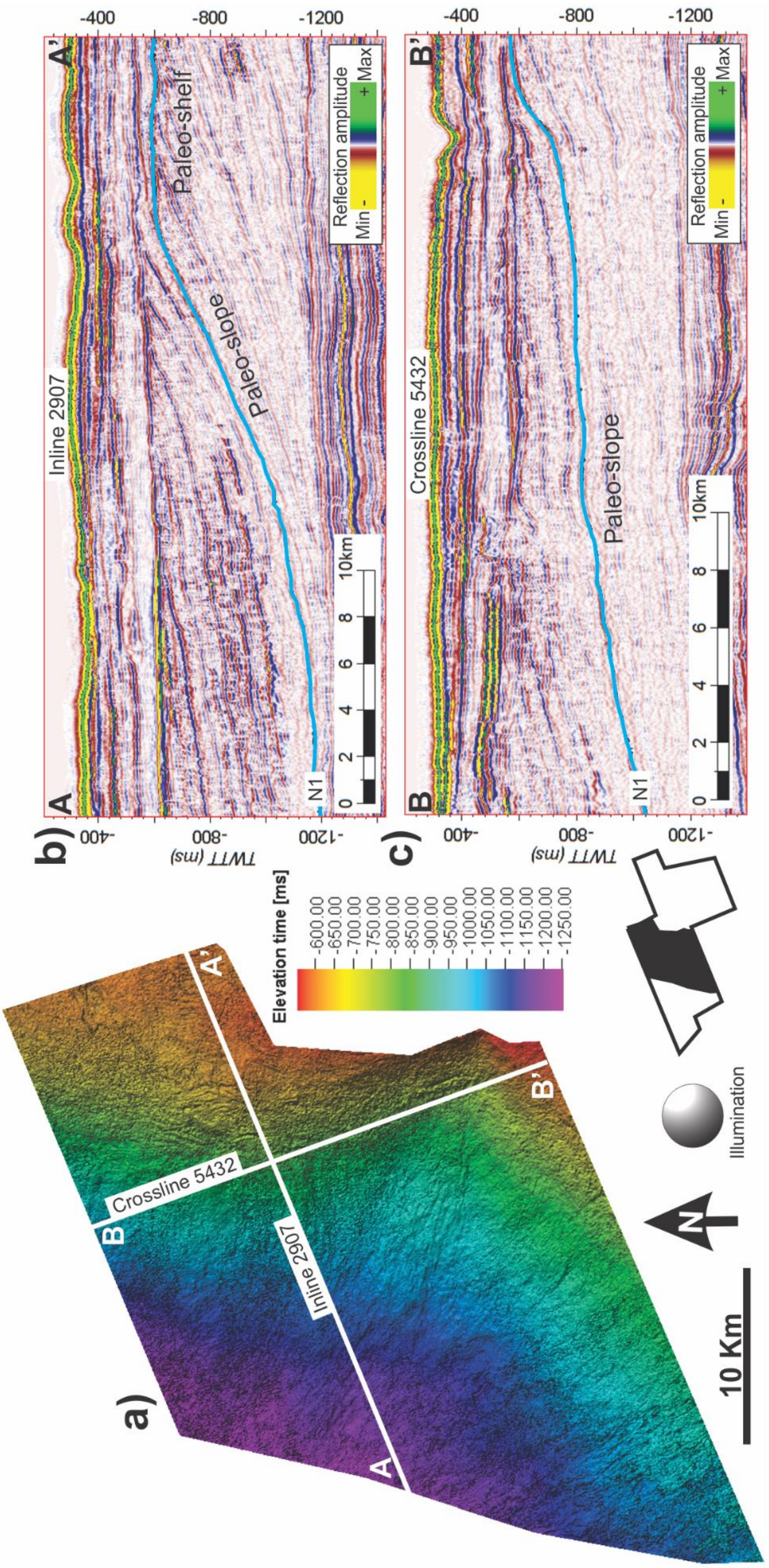


Figure 4.3.23 a) Display of the N1 surface in the ST07M07 survey interpreted to represent an internal layer within the N sequence of the Naust Formation. White lines indicate location of inline 2907 and crossline 5432. b) Seismic section of inline 2907 where the N1 reflection is indicated by the light blue line. c) Seismic section of crossline 5432 where N1 is indicated by the light blue line. Location of the N1 surface in the ST07M07 3D-survey is indicated by black polygon.

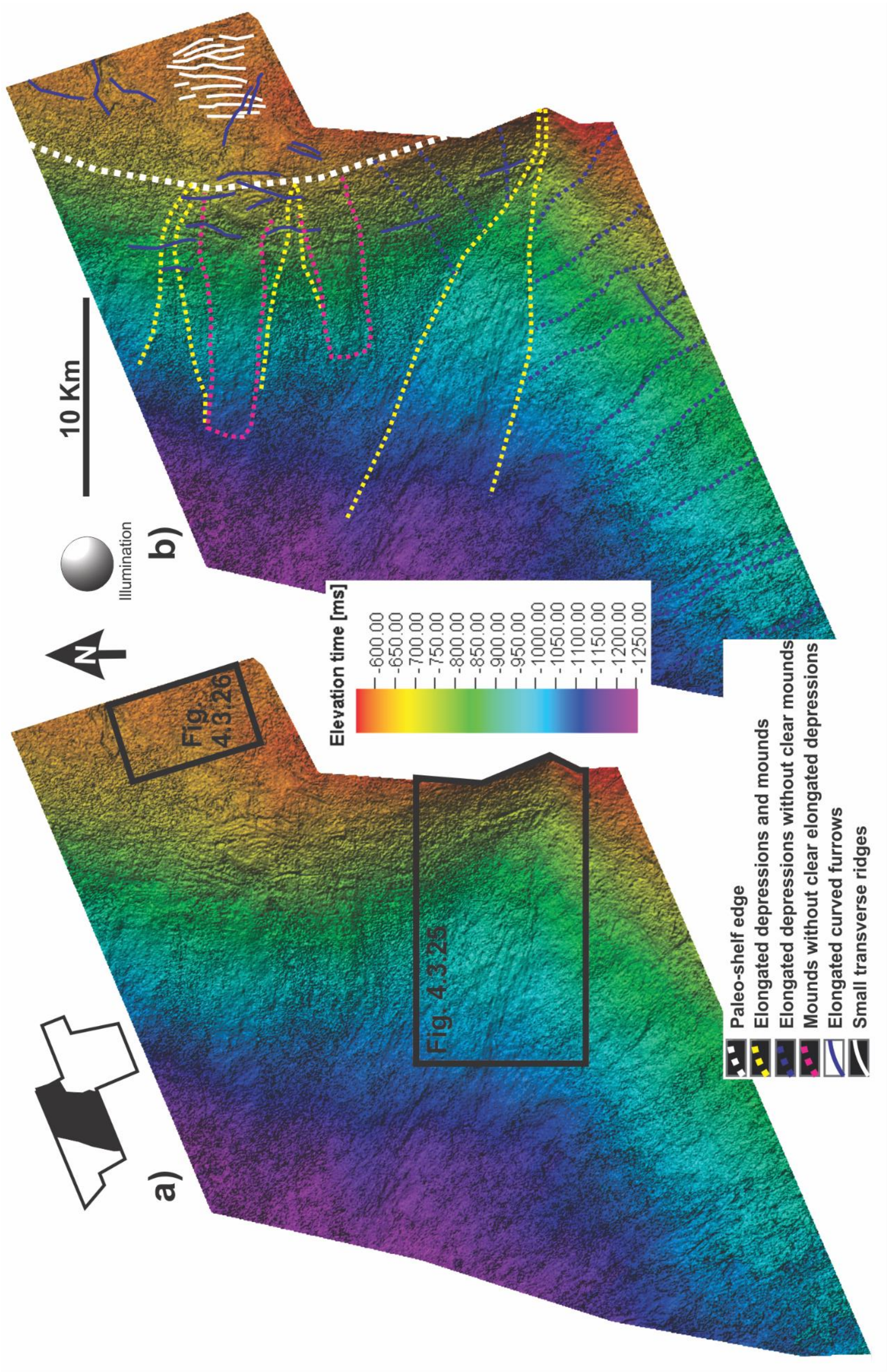


Figure 4.3.24 a) Display of the N1 surface with black frames indicating location of Fig. 4.3.25 and 4.3.26. b) N1 surface with indication of morphological features including the paleo-shelf edge, depressions, ridges and mounds. Black polygon indicate location of surface in the ST07M07 survey.

Elongated depressions and mounds

Along the paleo-slope section of the N1 surface, several downslope orientated, elongated depressions are located. Some of these depressions end in fan-shaped mounds where the angle of the paleo-slope decreases. There are also two fan-shaped mounds, which appears to start directly of the paleo-shelf edge without any elongated depression (Fig. 4.3.24 and 4.3.26). While some of these mounds truncate the elongated depressions, some elongated depressions continue across the mounds.

The elongated depressions starts at the paleo-shelf edge and can be followed up to 10 km down-slope. They may be slightly sinuous and generally obtain a U-shape in cross sections (Fig. 4.3.26b). The width and depth reaches up to 200 m and 10 m. Some of the depressions appear to have elevated ridges along the flanks.

The fan-shaped mounds differ in size and tend to merge as they propagate downslope. The general width and length reaches up to 4 km and 10 km, while the height is calculated to approximately 22 m at the highest point. One of the mounds is significantly larger than the rest, with a length reaching up to 16 km as well as a width and height up to 5 km and 21 m respectively. This larger mound is located within a recess in the paleo-slope (Fig. 4.3.26) and display strong amplitudes (Fig. 4.3.25). The two mounds that starts at the paleo-shelf edge also have strong amplitudes (Fig. 4.3.25). They are also at their widest at the start of the paleo-slope, getting narrower as they propagate downslope, which is the opposite of the other mounds.

Interpretation:

The elongated depressions and mounds are interpreted to represent channels and submarine fans. The channels work as sediment transportation routes from the paleo-shelf, down the paleo-slope where submarine fans are deposited as the slope gradient decreases.

The channels bears resemblance to submarine rills described by Nittrouer et al. (2007). Submarine rills are narrow gullies which can be found along low-gradient open-slope areas. They can range from narrow furrows 5-10 m wide and 1-2 m deep, to larger depressions up to 50-300 m wide and 10-40 m deep. The gullies are erosional features which develop as a result of turbidity currents moving down the continental slope. The elevated ridges are interpreted as levees deposited by turbidity overflow (Nittrouer et al., 2007). As the depressions start at the paleo-shelf edge, the turbidity currents are likely a result of sediment-laden subglacial meltwater emitted from the glacial front or simply water emitted from rivers. Another possibility is that the turbidity currents started as smaller sediment failures on the uppermost part of the continental slope (Ó Cofaigh et al., 2003). Similar features have also been described along the Norwegian continental slope by Laberg et al. (2010); Gales et al. (2013).

The submarine fans are interpreted as sediment depocenters comprising turbidites from turbidity currents as described above. In general submarine fans are dominated by mass-flow deposits, mainly turbidity current, processes (Nichols, 2009). They are located downslope where the decrease in flow velocity would result in sediment deposition. Similar sediment lobes have also been described from the end of gullies by Ó Cofaigh et al. (2003) along the Norwegian and Greenland margin as well as Antarctica. The large size of one of the lobes can be explained by the location within the retracted area of the paleo-slope, as this leads to several gullies transporting sediments to the lobe. Some lobes also display submarine fan channels imprinted on the surface (Nichols, 2009). The geometry and the location of the two mounds starting at the paleo-shelf edge separate these from the rest of the mounds. They may therefore represent debris flow deposits, which have been transported as subglacial sediments before being re-deposited downslope as described by Ó Cofaigh et al. (2003). The strong amplitudes may represent a different lithology or fluid content.

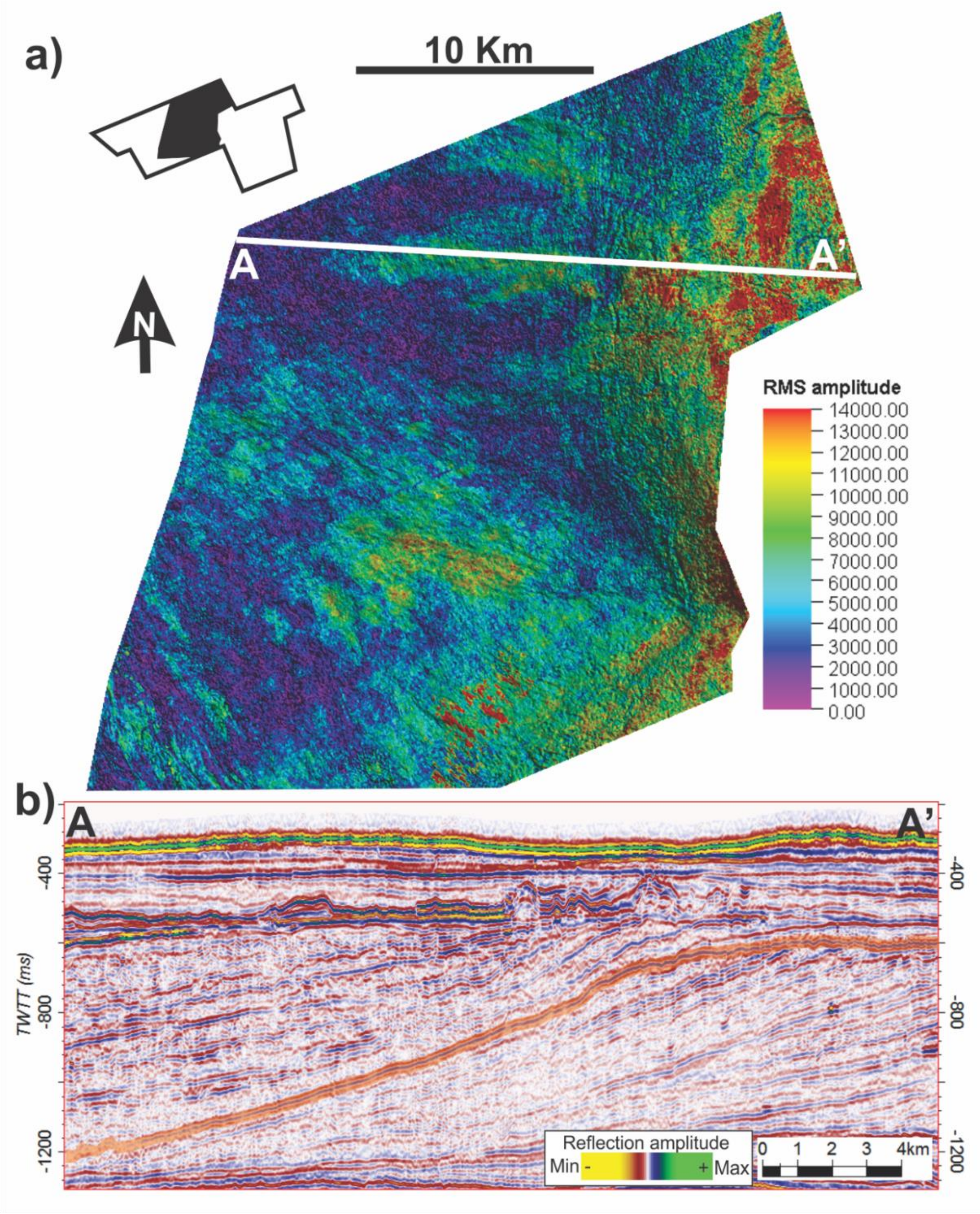


Figure 4.3.25 a) RMS amplitude map of a 30 ms window from 10 ms above to 20 ms below the N1 surface showing strong amplitudes in fan deposits. White line indicated location of b). b) Seismic section of arbitrary line showing the location of the RMS window (shaded area). Location in the ST07M07 survey is indicated by the black polygon.

Small transverse ridges

Small transverse ridges are located on the NE corner on the part of the N1 surface interpreted to represent the paleo-shelf (Fig. 4.3.24 and 4.3.27). The ridges are orientated from north to south and have a length of up to 3 km. The width and depth reaches up to 200 m and 13 m respectively. The rides appear relatively symmetrical and have a spacing from 400 m to the point where they merge. The ridges are relatively linear and elongated curved furrows truncate some of the ridges.

Interpretation:

The small transverse ridges show morphological similarities to the small ridges described on the seabed, therefore they are interpreted to be small moraines. This is support by the location as they are only located on the paleo-shelf where grounded ice is possible. These moraines have also been documented by Halvorsen (2012). However, the ridges may simply be the result of seismic noise as they are not as distinct as the ridges on the younger surfaces. Dowdeswell et al. (2007) and Rydningen et al. (2013) have also described small moraines like these on buried surfaces and the present seafloor of the mid-Norwegian margin.

Elongated curved furrows

Several elongated curved furrows are located on the N1 surface (Fig. 4.3.24 and 4.3.27). They are concentrated along what has been interpreted to represent the paleo-shelf break and have a main orientation from south to north. They have a V- or U-shape in cross sections and a length of up to 4 km. The width reaches up to 200 m and the depth has been measured up to 8 m.

Interpretation:

The furrows are interpreted as iceberg plough-marks imprinted on the seabed by icebergs. Similar plough-marks have been described by Andreassen et al. (2007b) from the Barents Sea. The plough-marks are generally orientated parallel to the paleo-shelf edge, and are interpreted to represent the main direction of the paleo-currents along the mid-Norwegian continental.

Circular depressions

Small circular depressions are located on the paleo-shelf (Fig. 4.3.27) and along the paleo-slope (Fig. 4.3.26) on the N1 surface. They have a parabolic shape and a diameter of up to 150 m. The depth has been measured up to 12 m.

Interpretation:

The small circular depressions are very similar to the circular depressions described in the trough on the seafloor and are therefore interpreted to represent paleo-pockmarks. Present pockmarks with similar geomorphology have also been described by Chand et al. (2009) in the Barents Sea.

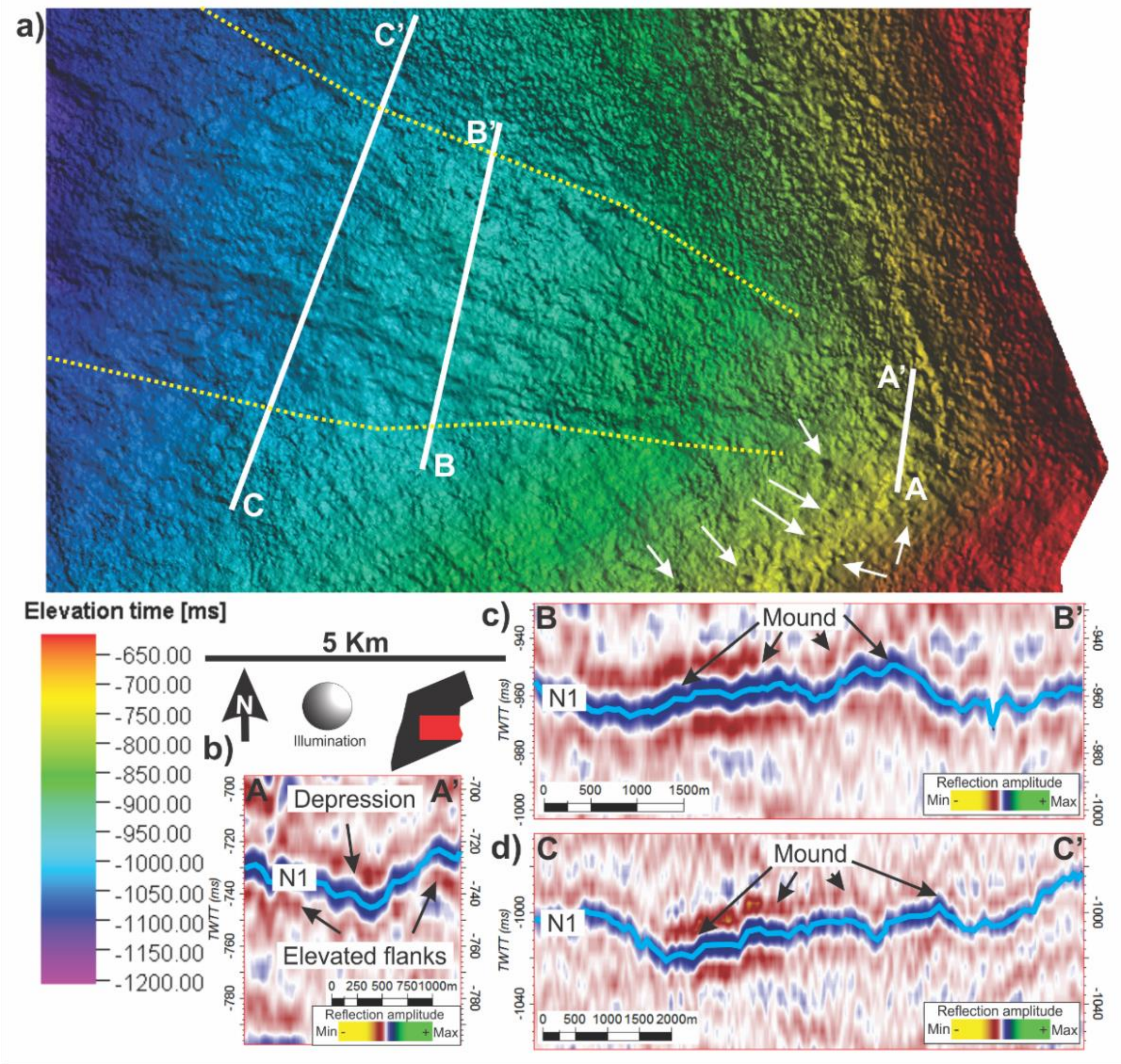


Figure 4.3.26 a) N1 surface displaying elongated depressions and mound interpreted to represent gullies and a submarine fan along the paleo-slope. Small white arrows indicate circular depressions interpreted to be paleo-pockmarks. White lines indicated location of b), c) and d). b) Seismic section of arbitrary line showing gullies with adjacent levees. c) Seismic section of arbitrary line showing cross section of submarine fan. d) Seismic arbitrary line indicating a lobe on the N1 surface. The light blue line indicates the location of the N1 surface in the cross sections. Location of figure is indicated in Fig. 4.3.24.

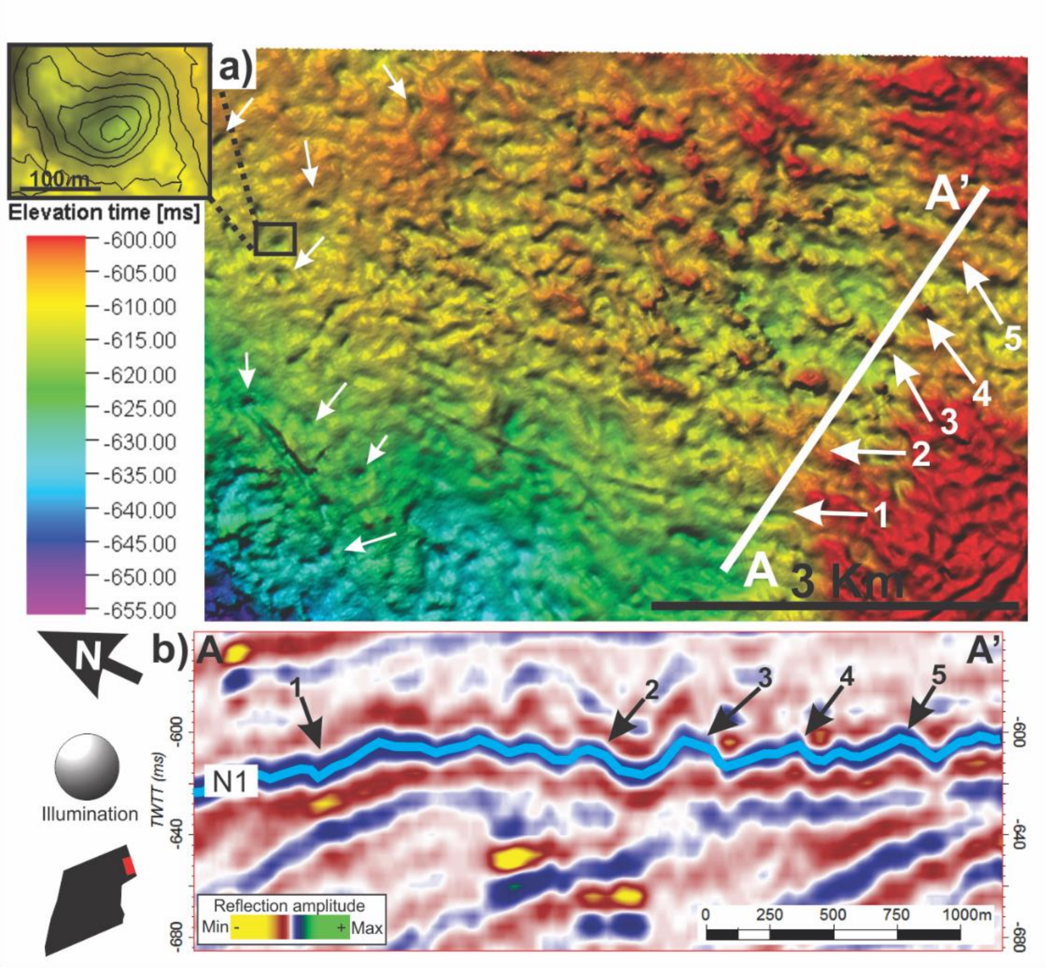


Figure 4.3.27 a) N1 surface displaying several different geomorphological features. Large white arrows indicated elongated curved furrow (1) interpreted to be an iceberg plough-mark and ridges (2-5) interpreted to represent small moraines. The small white arrows and zoom-in indicate circular depressions interpreted to be paleo-pockmarks. White lines indicate location of b). b) Seismic section of arbitrary line displaying iceberg plough-mark (1) and small moraines (2-5) on the N1 surface (light blue line). Location of the figure is indicated in Fig. 4.3.24.

4.3.5 Intra Naust N-2 (N2)

The N2 reflection is interpreted to represent an internal paleo-surface of the N sequence of the Naust Formation. The reflection configuration in this interval is tangential oblique, down-lapping onto the base of the Naust Formation. This is interpreted to represent the paleo-slope dipping westwards with an angle of approximately 1-2°. N2 Surfaces from the ST10013 and ST07M07 surveys are displayed relative to one another in Fig. 4.3.28, showing the extent of the paleo-slope. The surfaces include features such as mounds and depressions (Fig. 4.3.29 and 4.3.31). Where the surface is on-lapping onto the base of the Naust Formation, areas that have been poorly interpreted occur because of weak amplitudes and poor continuity. In the NE corner of the ST10013 survey, the reflections acquire a wavy shape, which is reflected on the N2 surface (Fig. 4.3.29). This is interpreted to be the result of underlying polygonal faults of the Brygge Formation.

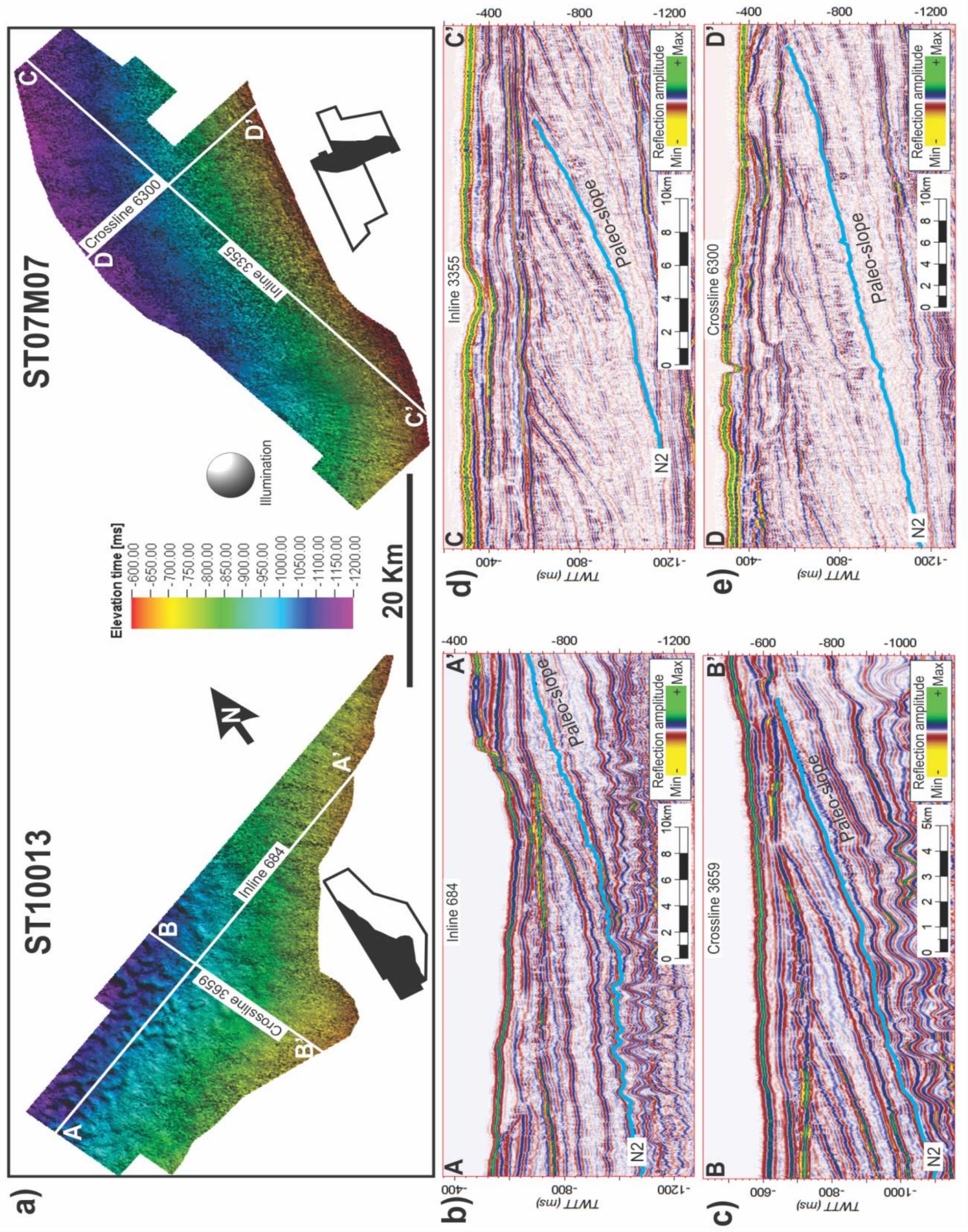


Figure 4.3.28 a) Display of the N2 surface on the ST10013 and ST07M07 surveys shown relative to one another. White lines indicate position of b), c), d) and e). b) Seismic section of inline 684 from the ST10013. c) Seismic section of crossline 3659 from the ST10013 survey. D) Seismic section of inline 3355 of the ST07M07 survey. e) Seismic section of the 6300 crossline from the ST07M07 survey. Light blue line indicates location of the N2 surfaces. The black polygons indicate the location of the N2 surfaces within the seismic surveys.

4.3.5.1 ST10013 (N2)

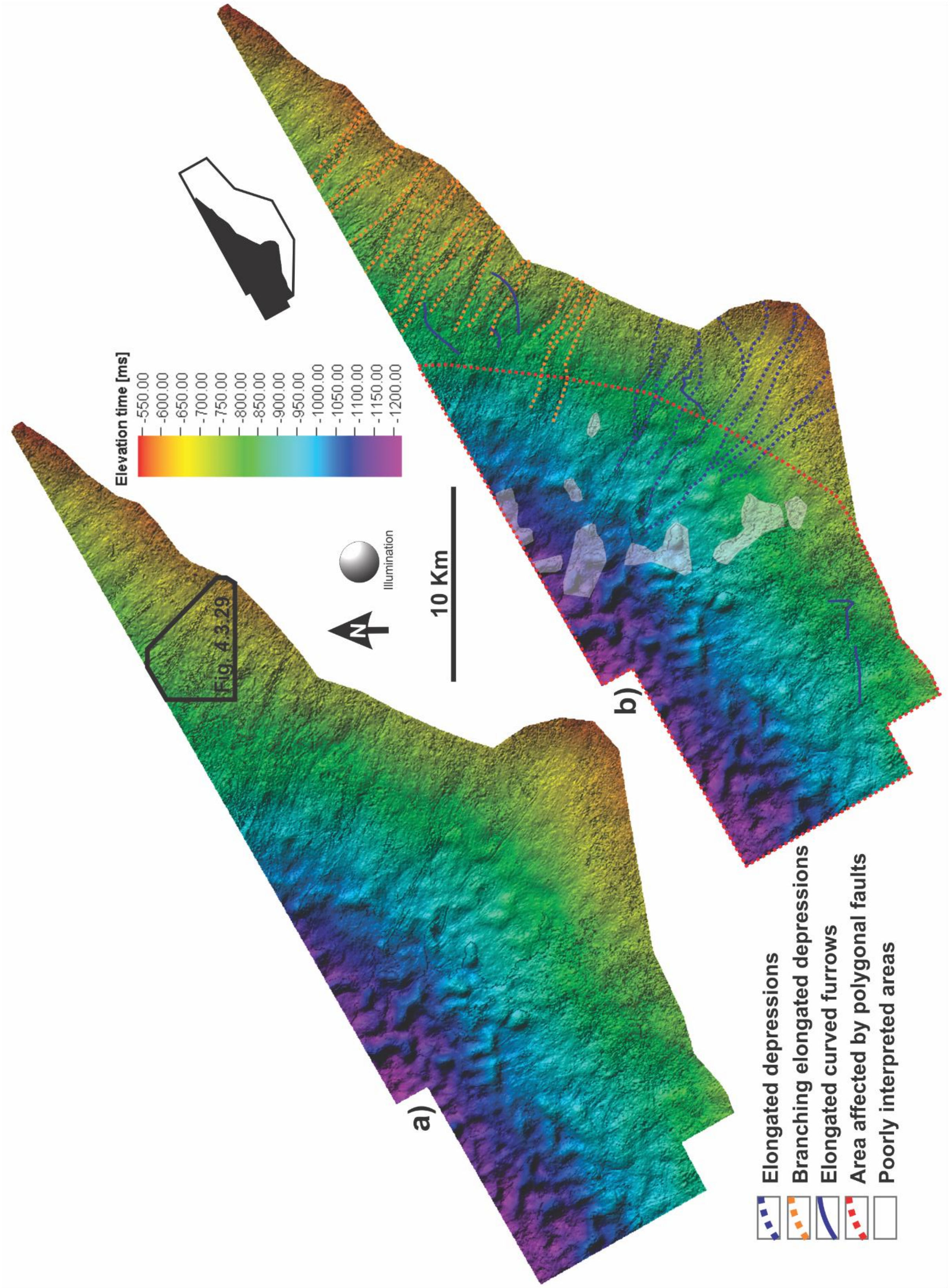


Figure 4.3.29 a) N2 Surface of the ST10013 survey interpreted to represent the paleo-slope on-lapping onto polygonal faults. The black frame indicates location of Fig. 4.3.29. b) Indication of geomorphological features on the N2 surface consisting of elongated depressions, mounds and furrows along the paleo-slope. Shaded sections indicate areas that have been poorly interpreted. The black polygon show location of the surface within the ST10013 survey.

Elongated depressions

Along the N2 paleo-slope of the ST10013 survey several elongated depressions extends downwards (Fig. 4.3.29). The elongated depressions appear slightly curved and the depressions to the NE side of the surface, where the slope angle appears steepest, branch out downslope. The length of the depression reaches up to 15 km while the width is approximately 150 m. The depth of the depressions is measured up to 9 m and the sides appear to be elevated. The RMS amplitude map from the NE of the area show that the depressions mostly display weak amplitudes while the elevated flanks, which have positive relief, display strong amplitudes. Downslope the weak amplitude depressions appears to develop into fan-shapes with strong amplitudes (Fig. 4.3.30)

Interpretation:

The elongated depressions are interpreted as gullies with levees, which transport sediments across the paleo-slope. The steepest channels branch out, which might be a result of higher transport velocity down the slope. The depositional model of Nichols (2009) suggests that the higher velocity may lead to poorly channelized gravel-rich systems to braided sand-rich channels. While the low gradient channels appear slightly curved and are more confined as a result of a relatively low sediment flow velocity. However, the model does not consider the influence of glacial processes and may therefore not be accurate for these deposits (Nichols, 2009). The strong amplitudes in the cross sections represent a soft event, meaning that the acoustic impedance decreases, creating bright spots. Bright spots may be an indication of gas, as the acoustic velocity will drastically decrease in gas-bearing sediments (Andreassen, 2009). The variation in amplitude is possibly caused by the channel infill consisting of a different lithology than the surrounding strata while the areas with positive relief may be gas bearing. Gas-bearing channels and fans have been described in the Barents Sea by Andreassen et al. (2007a).

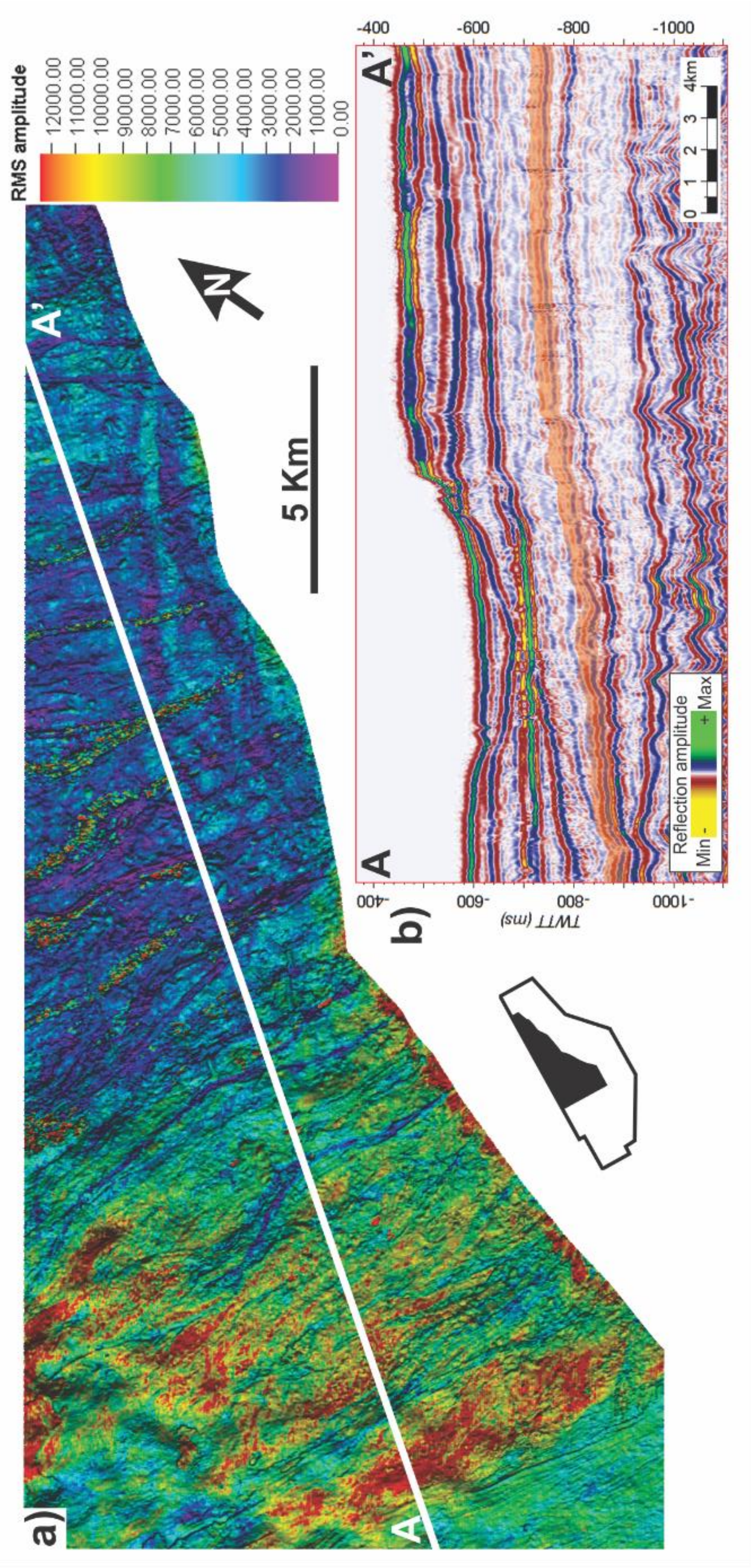


Figure 4.3.30 +30 - -10 a) RMS amplitude map of a 40 ms window from 30 ms above to 10 ms below parts of the N2 surface of the ST10013 survey. The map displays serval gullies consisting of mainly weak amplitudes as well as strong amplitude levees and fans. White line indicates location of b). b) Seismic section of arbitrary line showing the RMS interval window that is indicated by the shaded area. Location of figure in indicated by the black polygon.

Circular depressions

Circular depressions are located along the N2 surface with the highest concentration located along the top of the paleo-slope (Fig. 4.3.31). They have a parabolic shape, with a depth and diameter of up to 200 m and 8 m.

Interpretation:

The circular depressions are similar to the small circular depressions interpreted in the trough on the seafloor as small paleo-pockmarks. Similar pockmarks have been located on the modern seabed of the mid-Norwegian margin by Ottesen et al. (2005b).

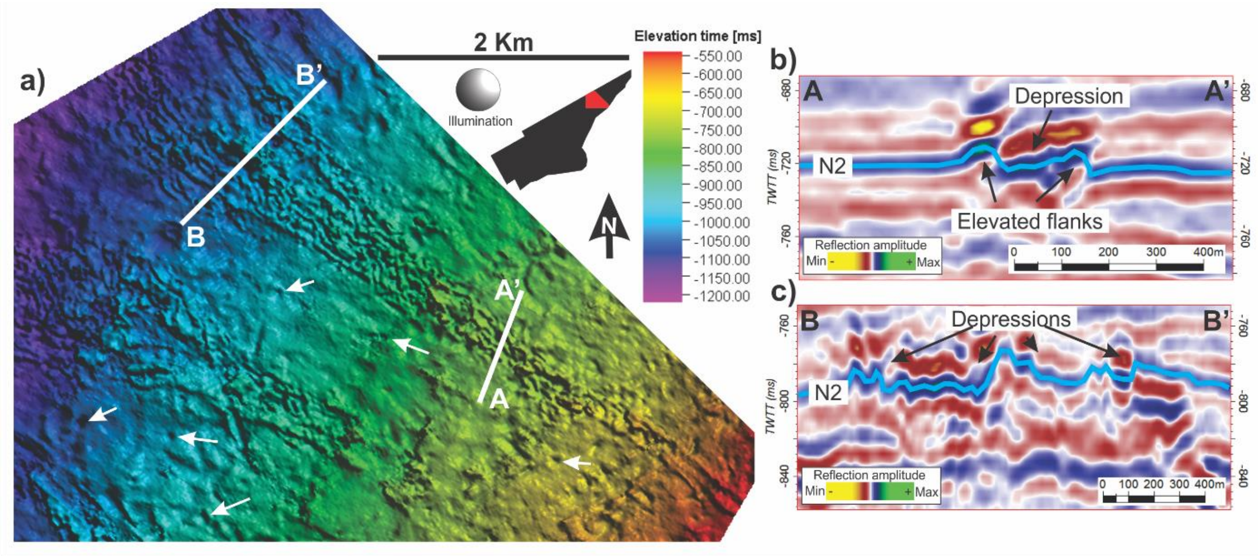


Figure 4.3.31 a) Elongated depressions branching out on the N2 surface interpreted to be paleo-channels stretching down the paleo-slope. Small white arrows indicate small circular depressions interpreted to represent small pockmarks. White lines show location of b) and c). b) Seismic section of arbitrary line showing channel with adjacent levees on the N2 surface (light blue line). c) Seismic section of arbitrary line displaying several channels as they branch out downslope on the N2 surface (light blue line). Location of the figure is indicated in Fig. 4.3.29.

4.3.5.2 ST07M07 (N2)

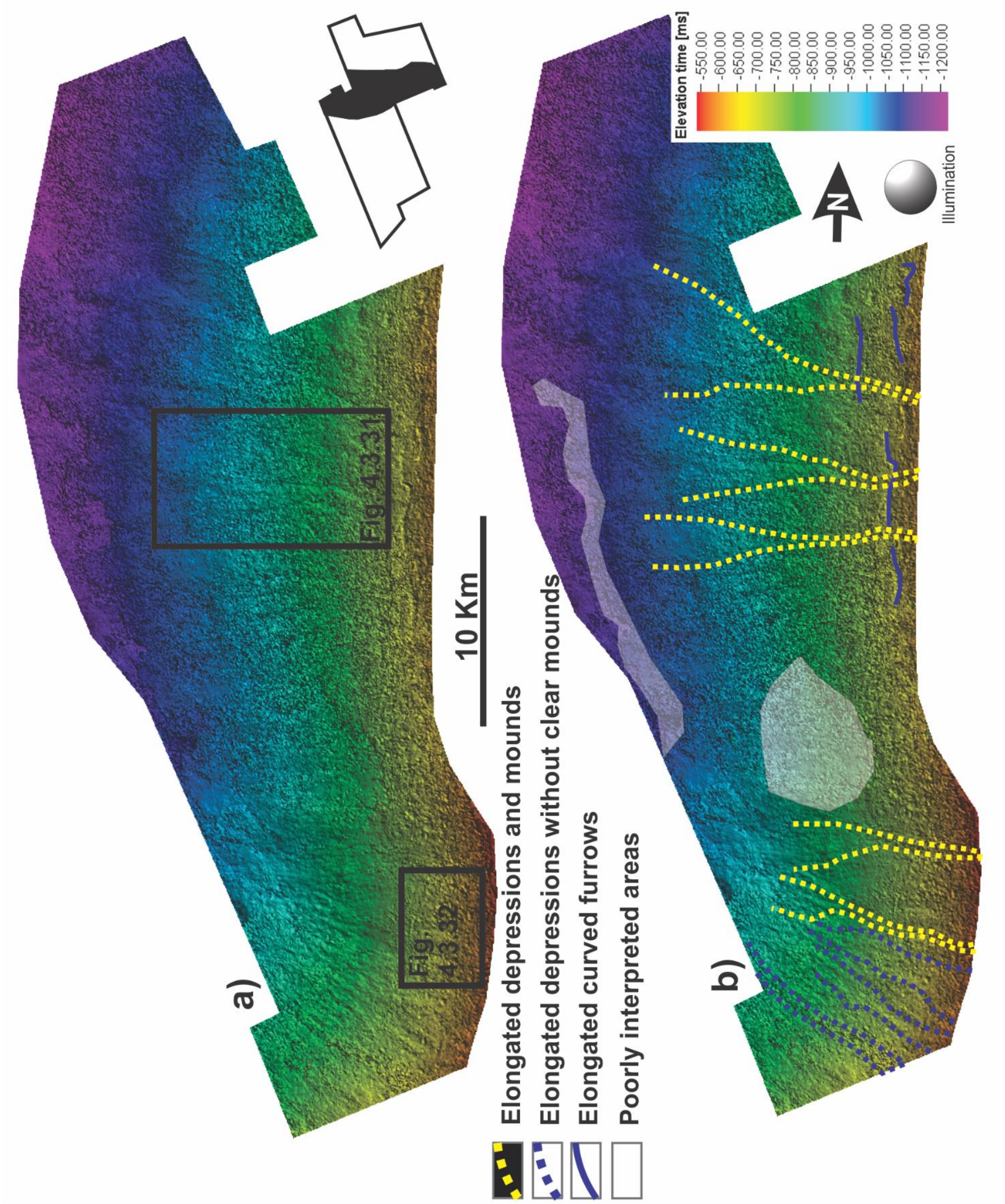


Figure 4.3.32 a) Display of the N2 surface in the ST07M07 3D-survey interpreted to represent the paleo-slope. Black frames indicating Fig. 4.3.31 and 4.3.32. b) Indication of different features on the N2 surface including furrows, elongated depressions and mounds. Shaded areas indicate poorly interpreted sections of the surface. Location within the ST07M07 seismic survey is indicated by the black polygon.

Elongated depressions and mounds

Along the paleo-slope of the N2 surface in the ST07M07 survey, elongated depressions starches downwards. The depressions lead down to fan-shaped mounds located at the base of the slope (Fig. 4.3.32).

The elongated depressions are slightly sinuous and the length reaches up to 9 km. The width and depth reaches up to 200 m and 6 m respectively. The depressions appear U-shaped in cross sections with elevated, side-parallel ridges (Fig. 4.3.33 and 4.3.34).

The mounds are fan-shaped and merge as they propagate down the slope. The length reaches up to 8 km, while the width and depth is approximately 5 km and 25 m. Some elongated depressions appears to continue over the mounds (Fig. 4.3.33).

Interpretation:

The elongated depressions and mound along the paleo-slope show close similarities to the depressions and mounds described on the N1 surface. Therefore, they are interpreted to be gullies and submarine fans, where the gullies have eroded across the fans at some places.

Elongated curved furrows

Elongated curved furrows preferentially with a north-south orientation are located parallel to the paleo-shelf edge on the N2 surface (Fig. 4.3.32). In seismic sections, they show a V- or U-shaped with a length up to 4 km. The width and depth reaches up to 250 m and 8 m.

Interpretation:

The elongated curved furrows are similar to the curved furrows described on several of the younger paleo-surfaces of the Naust Formation (see above) and by Dowdeswell et al. (2007), and are therefore interpreted to be iceberg plough-marks.

Circular depressions

Circular depressions with a diameter up to 400 m are located on the N2 surface (Fig. 4.3.34). They have a parabolic shape and the concentration is highest along the top of the paleo-slope. The depth of the depressions reaches up to 8 m.

Interpretation:

The circular depressions resemble the circular depressions that have been described on several of the earlier surfaces as well as by Chand et al. (2009) and Forwick et al. (2009) in the Barents Sea and of along the Svalbard margin. Therefore, the depressions are interpreted as paleo-pockmarks formed as a result of fluid migration.

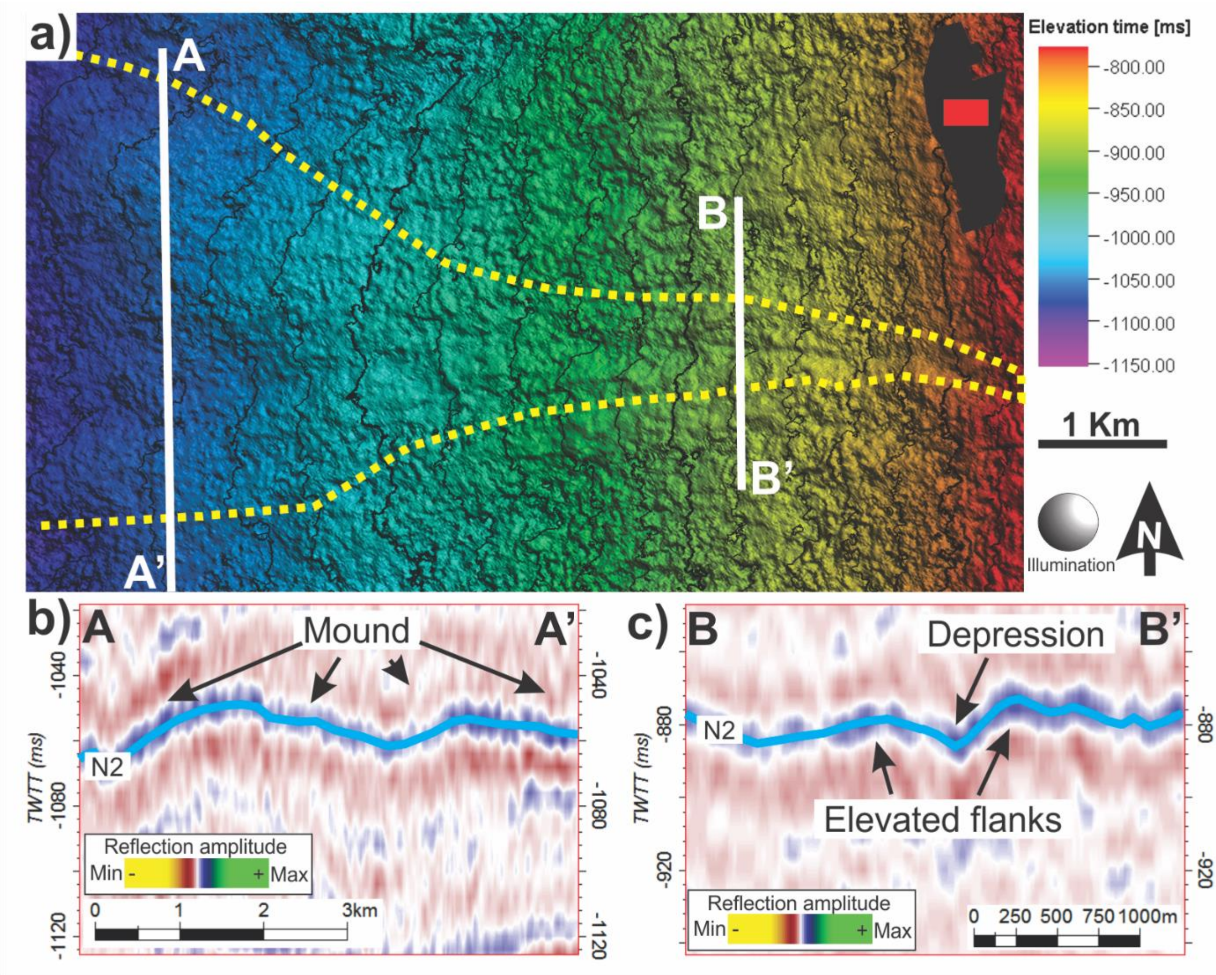


Figure 4.3.33 a) Elongated depression propagating into a mound (yellow stippled line) on the N2 surface interpreted to be a gully and submarine fan. White lines show the location of b) and c). b) Seismic section of arbitrary line showing a submarine fan deposited on the N2 surface (light blue line). c) Seismic arbitrary line indicating levees beside the gully on the N2 surface (light blue line). Location indicated in Fig. 4.3.32.

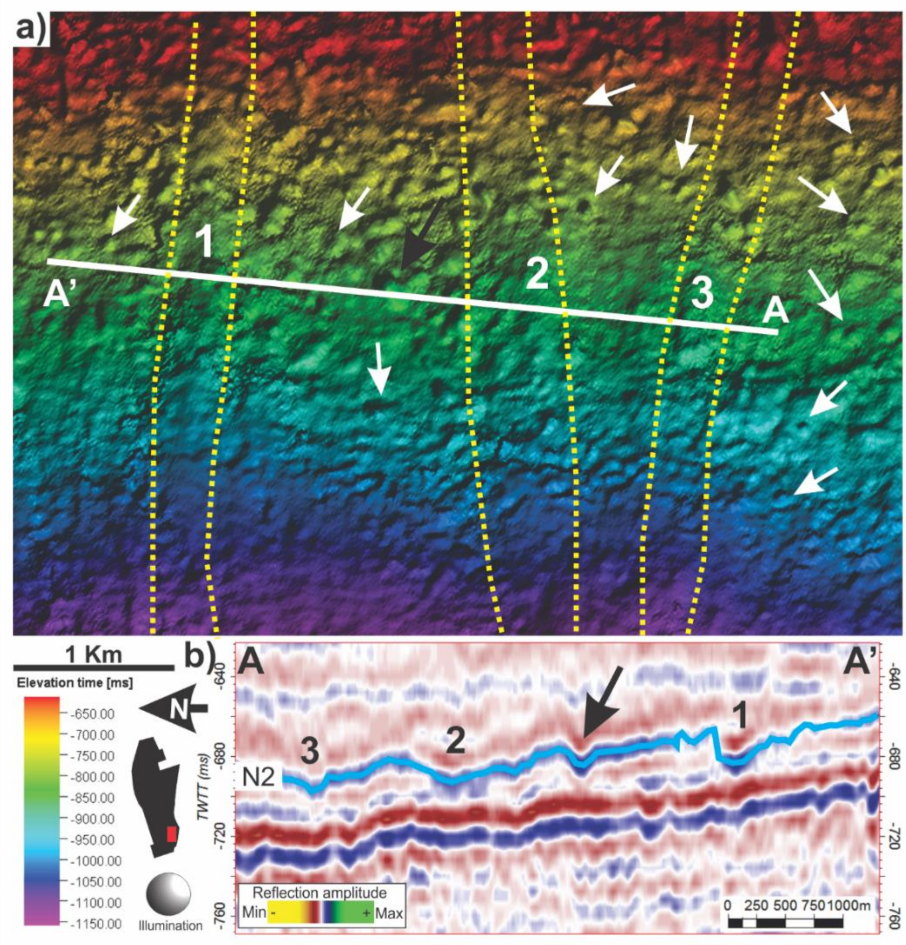


Figure 4.3.34 a) N2 surface displaying elongated depressions (1-3) and circular depressions (arrows) interpreted to be gullies and paleo-pockmarks. White line indicates location of b). b) Seismic arbitrary line showing cross section of elongated depressions (1-3) and one of many circular depressions (arrow) on the N2 surface (light blue line). Location is indicated in Fig. 4.3.32.

4.3.6 Intra Naust N-3 (N3)

The N3 reflection is interpreted to represent an internal surface displaying the paleo-slope and paleo-shelf of the N sequence of the Naust Formation. The reflection configuration in this part of Naust unit N is tangential oblique in the ST10013 survey while in the ST07M07 a complex sigmoidal/oblique pattern is displayed. The reflection is down-lapping onto the base of the Naust Formation with a dip (~1-2°) generally towards the west. The N3 surfaces from the ST10013 and ST07M07 surveys are displayed relative to one another in Fig. 4.3.35, showing the extent of the paleo-shelf and paleo-slope in the area. Discontinuous areas occur on the N3 surfaces where the reflection is down-lapping onto the underlying layers. In the NE corner of the ST10013 survey, the reflections acquire a wavy shape as a result of underlying polygonal faults from the Brygge Formation. Geomorphological features displayed on the surface include elongated depressions, mounds and furrows (Fig. 4.3.36 and 4.3.38).

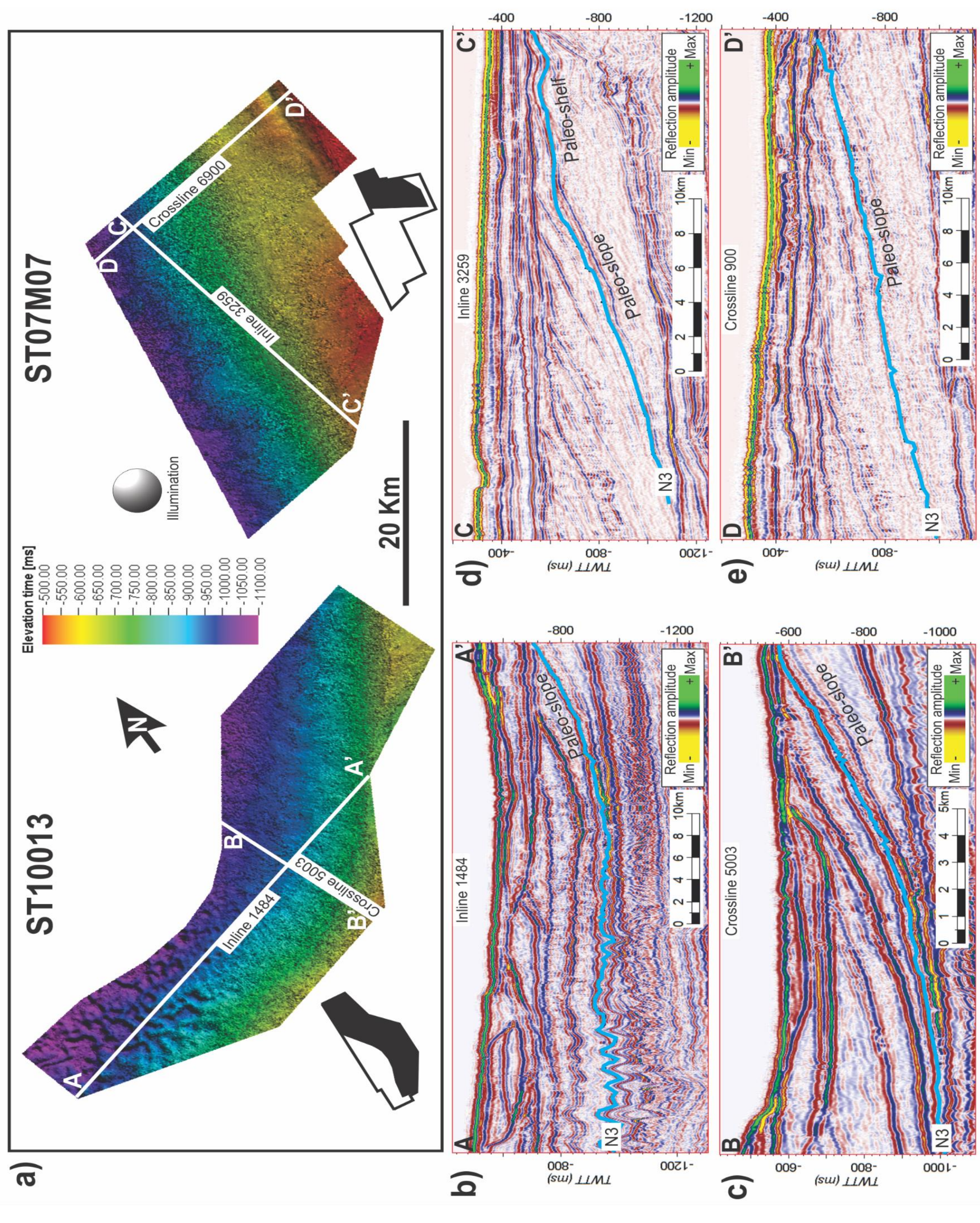


Figure 4.3.35 a) Display of the N3 surface on the ST10013 and ST07M07 surveys relative to one another. White lines indicate position of b), c), d) and e). b) Seismic section of inline 1484 from the ST10013. c) Seismic section of crossline 5003 from the ST10013 survey. D) Seismic section of inline 3259 of the ST07M07 survey. e) Seismic section of the 900 crossline from the ST07M07 survey. Light blue line indicates the N3 surfaces in the sections. Location within the 3D-surveys are indicated by black polygons.

4.3.6.1 ST10013 (N3)

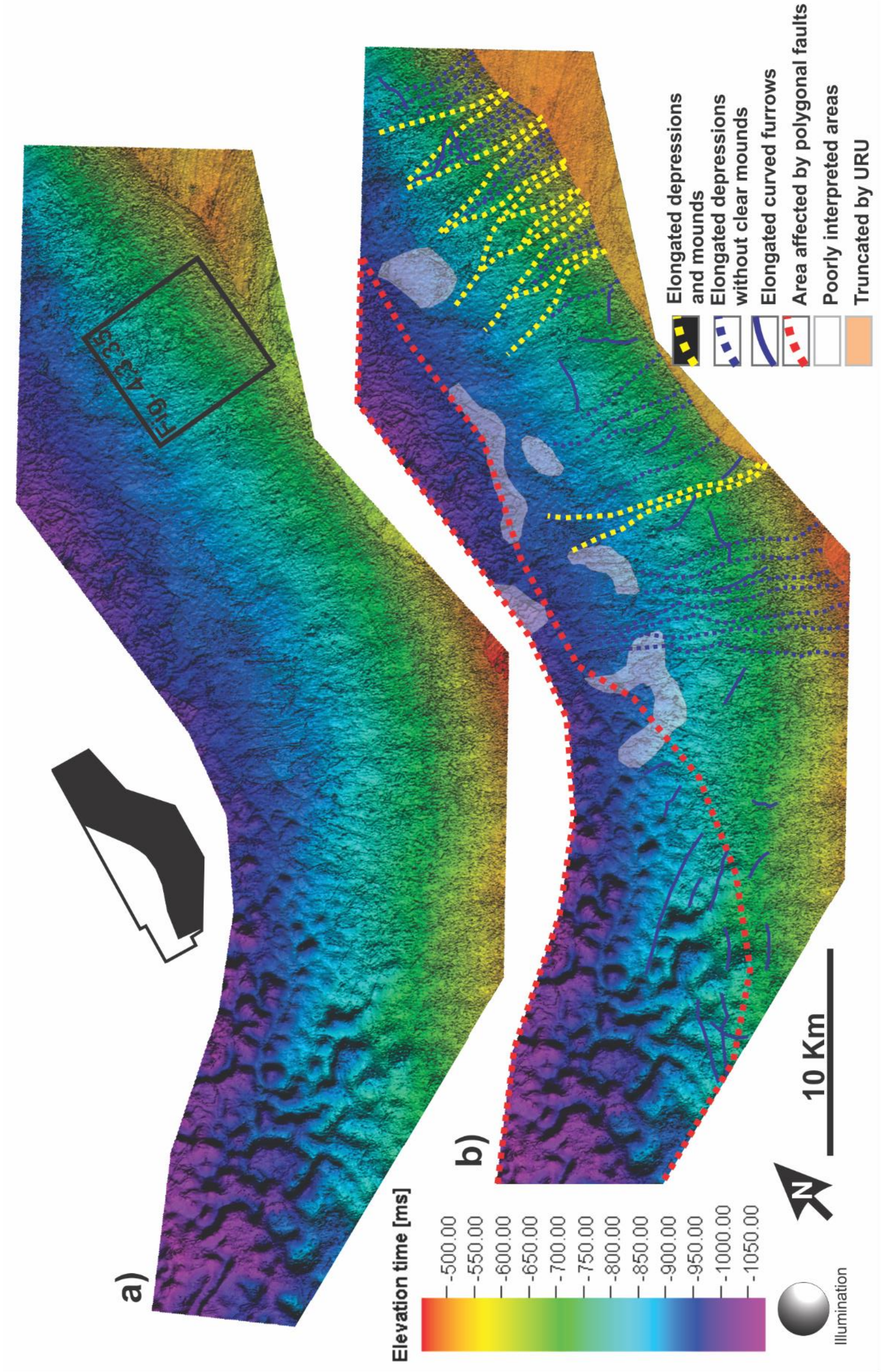


Figure 4.3.36 a) The N3 surface from the ST10013 survey displaying the paleo-slope on-lapping onto polygonal faults in the NE corner. Black frame indicates the location of Fig. 4.3.35. b) N3 surface where geomorphological features are indicated including furrows, elongated depressions and mounds. Shaded areas indicated there the surface is truncated by the URU (orange) and poorly interpreted areas (white). Black polygon display location of the surface in the ST10013 3D-survey.

Elongated depressions and mounds

Elongated depressions are located along what has been interpreted as the paleo slope of the N3 surface. The largest concentration of the depressions is located in the NE corner of the surface where the slope angle appear to be steepest. Some of the elongated depressions appear to develop into fan-shaped mounds at the bottom of the slope where the slope angle decreases (Fig. 4.3.36).

The elongated depressions are slightly curved and have a V- or U-shape in cross sections (Fig. 4.3.38b). They have a length of up to 14 km and a width of approximately 200 m. The depth is measured up to 9 m and the sides display signs of elevation.

The fan-shaped mounds have a length of up to 6 km and merge as they get wider downslope. At the widest they measure up to 4 km and the height reaches approximately 25 m.

The RMS amplitude map show that the depressions and fan-shaped mounds mainly consist of weak amplitudes. Only a few strong amplitude areas can be seen in what appears to be highpoints of a fan-shaped mound (Fig. 4.3.37).

Interpretation:

The elongated depressions and mounds on the N3 surface of the ST10013 survey are interpreted to be submarine gullies and fans as they are similar to the features described on the N2 surface. They also show close resemblance to features described on the modern continental slope of Greenland and Norway by Ó Cofaigh et al. (2003) and Gales et al. (2013), respectively.

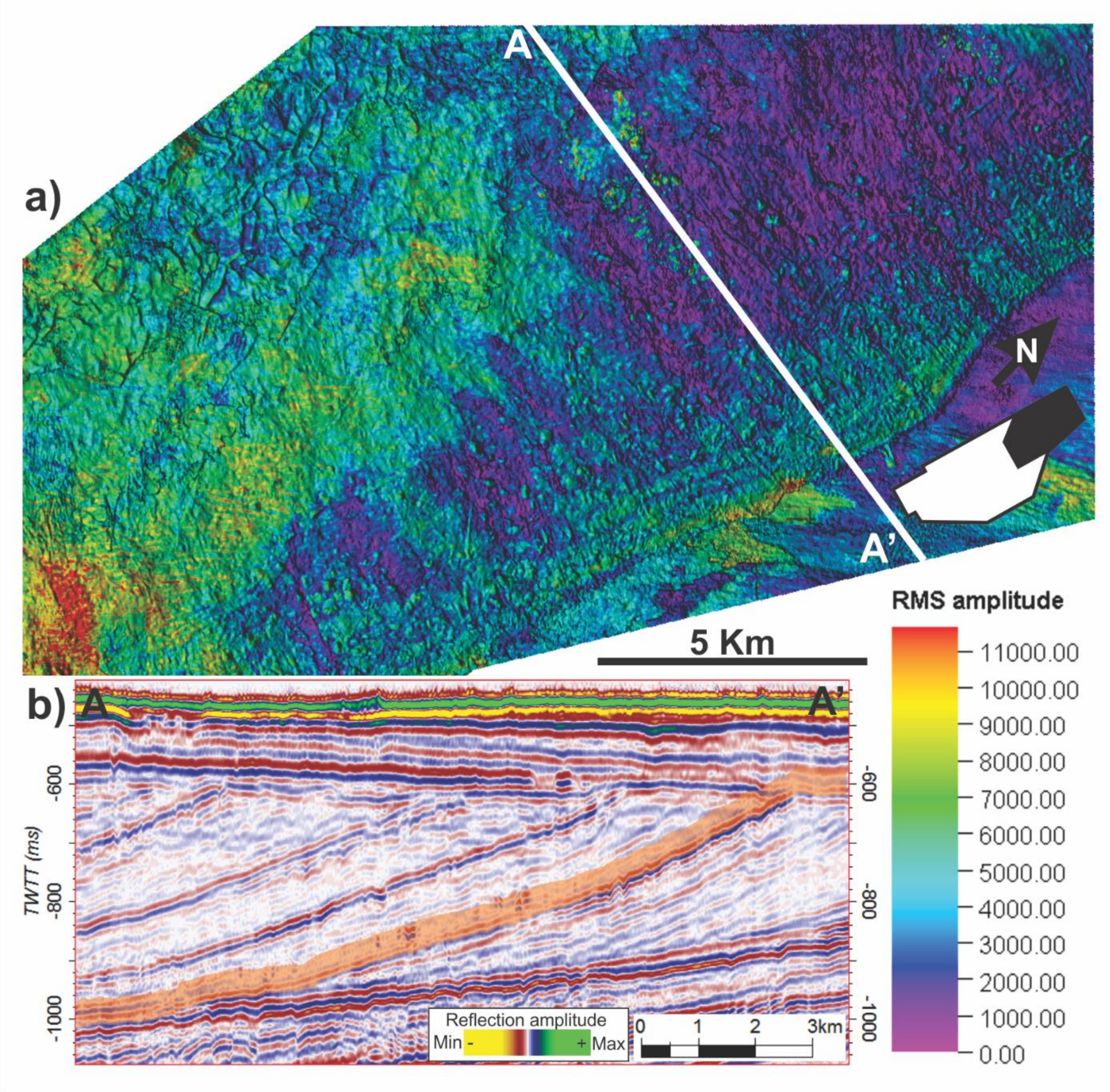


Figure 4.3.37 a) RMS amplitude map from the N3 surface to 45 ms above displaying weak amplitudes that has been interpreted as gullies and submarine fans. White line shows the location of b) Polygons shows the location of the figure. b) Seismic arbitrary line showing the 45 ms window of the RMS map (shaded area).

Elongated curved furrows

Elongated curved furrows are imprinted along what is interpreted as the paleo-slope of the N3 surface (Fig. 4.3.36). They are generally parallel to the slope, resulting in a change in direction as the slope curves from SW-NE towards an N-S orientation. The furrows are V- or U-shaped and have a length up to 9 km. They have a width and depth of up to 150 m and 8 m.

Interpretation:

The elongated curved furrows are interpreted to represent iceberg plough-marks as they have similar features as the curved furrows described on several of the earlier surfaces and from the Barents Sea by Andreassen et al. (2007b).

Circular depressions

Relatively small circular depressions are mainly located along the top of the paleo-slope on the N3 surface (Fig. 4.3.38). They have a parabolic shape with a diameter varying from 70 to 350 m and a depth of up to 10 m.

Interpretation:

The circular depressions are interpreted as paleo-pockmarks as they show close similarities to the small circular depressions described on earlier surfaces. Similar pockmarks have also been described in the Barents Sea and of the coast of Svalbard by Chand et al. (2009) and Forwick et al. (2009).

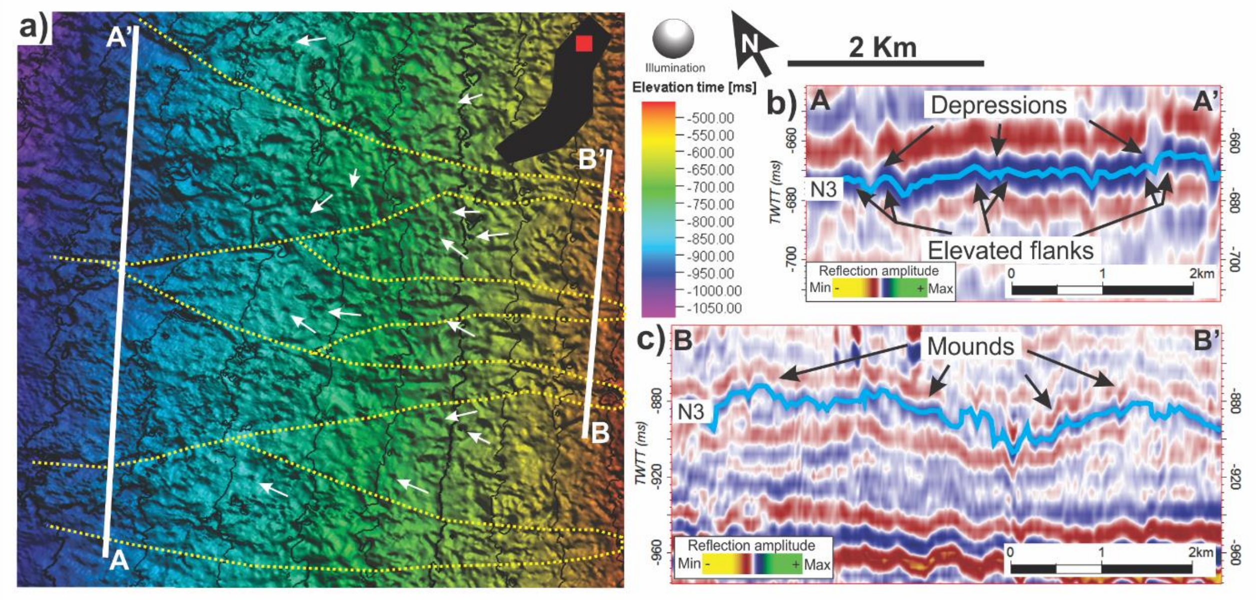


Figure 4.3.38 a) Display of what have been interpreted as several submarine rills and fans (yellow stippled lines) along the paleo-slope on the N3 surface. Small arrows indicated what have been interpreted as paleo-pockmarks. White lines indicate the location of b) and c). b) Seismic section showing several rills along the N3 surface (light blue line) with levees on the sides. c) Seismic section of arbitrary line showing the cross section of submarine fans on the N3 surface (light blue line). Location of figure is indicated in Fig. 4.3.36.

4.3.6.2 ST07M07 (N3)

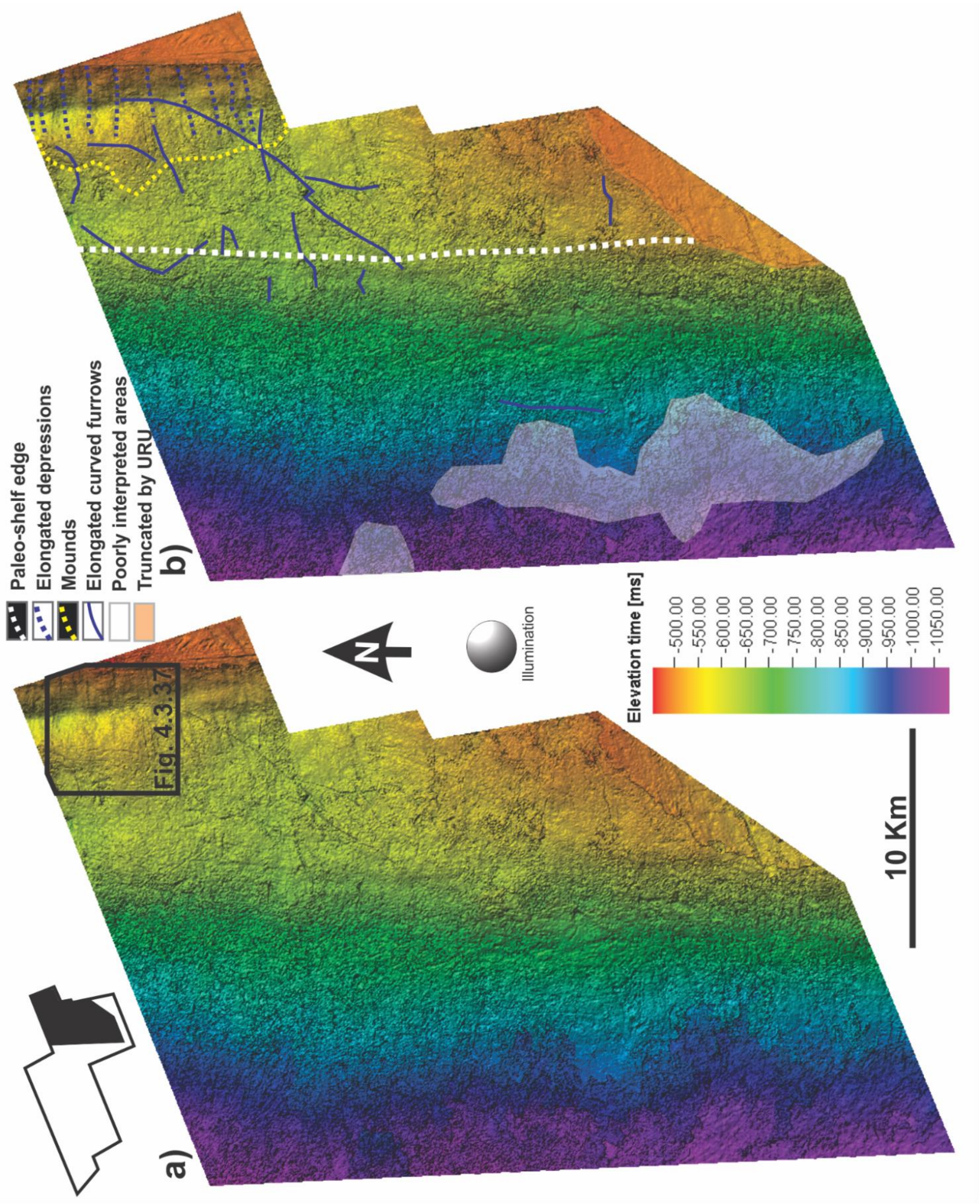


Figure 4.3.39 a) The N3 surface within the ST07M07 3D-survey interpreted to represent the paleo-shelf and paleo-slope. b) The N3 surface, where the paleo-shelf edge, elongated curved furrows, elongated depressions and mounds have been indicated. Shaded sections indicate poorly interpreted areas where the surface is on-lapping onto the underlying reflector. Black polygon display location of surface within the ST07M07 survey.

Elongated depressions and mounds

Elongated depressions are located in the NE corner on the N3 surface of the ST07M07 survey. They are located on the paleo-shelf along a sudden change in slope. The depressions end at mounds where the shelf flattens (Fig. 4.3.39).

The elongated depressions are U- or V-shaped in seismic sections and reaches a length of 5 km. The width and depth reaches up to 200 m and 10 m, respectively (Fig. 4.3.40).

The mounds merge and almost appear as on large feature. They have a distinct relief with a height reaching up to 30 m. The length and width reaches approximately 4 km and 2 km (Fig. 4.3.40).

Interpretation:

The elongated depressions and mounds are interpreted as gullies and sediment fans. They show some similarities as the elongated depressions and mounds described earlier, but the gullies are shorter and the mounds are more distinct. This may be because they are located on the paleo-shelf along a smaller change in slope. The small change in slope is interpreted to be caused by the underlying Molo Formation, which has substantially steeper layering than the Naust Formation (Fig. 4.3.40b). The sediment fans are more distinct as they are deposited on the paleo-shelf which is relatively flat.

Elongated curved furrows

The N3 surface of the ST07M07 survey has several elongated curved furrows, which are mainly located on the paleo-shelf (Fig. 4.3.39 and 4.3.40). They have two main directions where one is orientated north to west witch is parallel to the paleo-slope, and one from west toward east moving inward on the paleo-shelf. They are V- or U-shaped in cross sections with a length measured to be up to 15 km. The width and depth reaches up to 150 m and 6 m.

Interpretation:

The elongated curved furrows are interpreted to represent iceberg plough-marks as described on the seafloor. The orientations are interpreted to be the result of paleo-currents traveling along the paleo-slope, where the consecration gets higher on the paleo-shelf as smaller icebergs reaches the seafloor.

Circular depressions

Small circular depressions are spread around the N3 surface. They have a parabolic shape, with a diameter and depth of up to 200 m and 10 m (Fig. 4.3.40).

Interpretation:

The small circular depressions on the N3 surface have been interpreted to represent paleo-pockmarks. They show close similarities to the pockmarks that have been described on earlier surfaces as well as pockmarks described by Chand et al. (2009) among others.

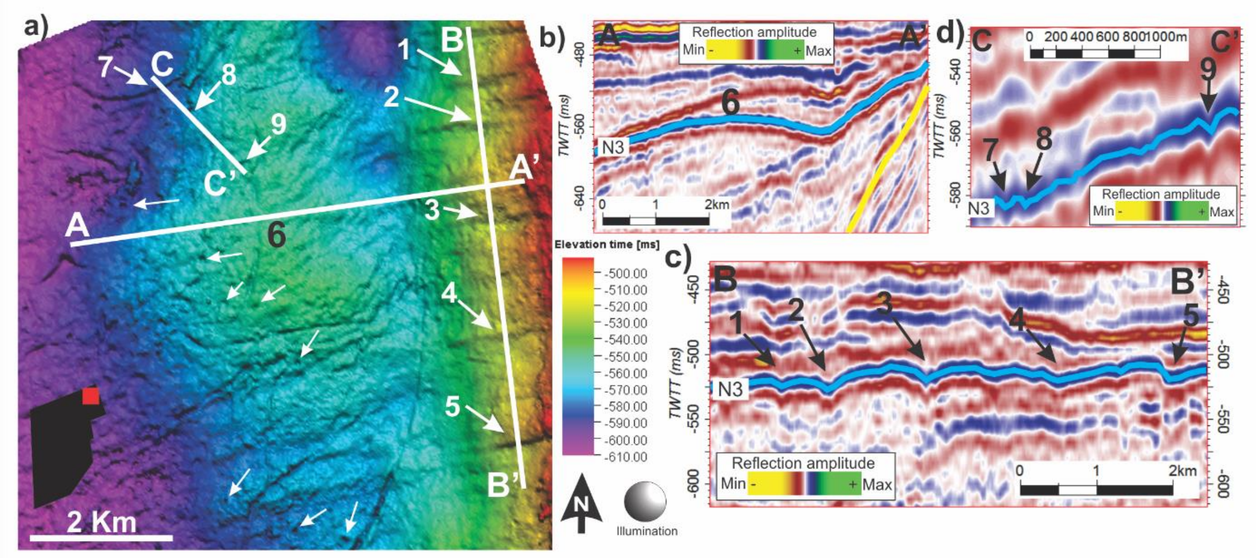


Figure 4.3.40 a) Depressions and mounds on the paleo-shelf of the N3 surface interpreted to represent gullies (1-5) and sediment fans (6) as well as iceberg plough-marks (7) and paleo-pockmarks (8-9 and small white arrows),. White lines indicated the location of b), c) and d). b) Seismic section of arbitrary line displaying the change in angle on the paleo-shelf and what have been interpreted as sediment fans (6). The ligth blue line showe the location of the N3 surface. The yellow line indicated the boundary between the Naust- and Molo Formation. c) Seismic section of arbitrary line showing what have been interpreted as gullies (1-5) along the N3 surface (ligth blue line). d) Seismic section of arbitrary line dispaliyng iceberg plough-mark (7) and paleo-pockmarks (8-9). The N3 surface is indicated by light blue line. Location cis showen in Fig. 4.3.39.

4.3.7 Summary

The buried surfaces display a number of geomorphological features. The base of Naust units A, S and T in the study area have been interpreted to represent the part of paleo-shelf. This is because they are dominated by features such as cross-shelf troughs, MSGL, flutes as well as glacitectonic features and moraines. These features indicate the presence of grounded and fast-flowing ice on the studied part of the paleo-shelf. The Intra N surfaces have been interpreted to mainly represent part of the paleo-slope and as they have been affected by different processes. Gullies and submarine-fans dominate the oldest part of Naust N, before debris flows deposits appear to become more present in the younger part of Naust N. Smaller remains of the paleo-shelf have also been identified, where small morainal ridges parallel to the paleo-shelf edge appear to be present. Paleo iceberg plough-marks and paleo pockmarks have been identified on all the buried surfaces.

4.4 Seismic anomalies and their origin

4.4.1 Reflection discontinuities

There are several areas with vertical discontinuities within the two 3D-seismic surveys ST10013 and ST07M07. They consist of zones affected by acoustic wipe-out which stretches across the stratigraphic layers (Fig. 4.4.1 and 4.4.2). The horizontal and vertical extent of these zones varies but are generally circular to semi-circular in shape when observed in time slices and pipe shaped in seismic sections (Fig 4.4.1a). They can be identified as areas of distorted seismic signals with weak amplitudes and low continuity. Some of these zones of acoustic wipe-out terminate in areas of strong amplitude anomalies. Within some of the zones upward bending occurs, there are also signs of pull-down effect.

In the ST10013 3D-survey, several large vertical discontinuities are located towards the NW (Fig. 4.4.1b). They are located in the strata under the Naust Formation, and appear to terminate at the base of Naust. The vertical extent is unclear, as the pipes get less distinct with depth. However, they can be followed up to 1300 ms (TWTT) down, reaching well beyond the polygonal faults of the Brygge Formation. They have a diameter of up to almost 500 m and show signs of pull-up. Some of the pipes lead into overlaying vertical zones of acoustic masking within wavy layers of the Naust Formation and some display strong amplitudes along the sides.

In the ST07M07 3D-survey, the large vertical zones of discontinuities are located within the Naust Formation (Fig. 4.4.2b). They appear to originate above the polygonal faults of the underlying Brygge Formation, as well as where the Nordland Ridge is located. They have a vertical extent between 300-700 ms (TWTT) and a width of 300-400 m. The zones terminate at different stratigraphic levels, where some end at strong amplitude anomalies interpreted to be bright spots. Signs of pull-down effect have also been located within some of the discontinuities.

Within the Naust Formation in both surveys, smaller zones of vertical discontinuity have been located throughout the seismic data (Fig. 4.4.1c and 4.4.2b). These zones only have a vertical extent of up to approximately 300 ms (TWTT) and a width that varies from less than 100 m to about 350 m.

Interpretation:

The large vertical zones of discontinuity have been interpreted as focused fluid flow moving through the strata, which is often referred to as pipes (Løseth et al., 2009; Løseth et al., 2011). Similar features have been observed above polygonal faults further out on the mid-Norwegian shelf by Berndt et al. (2003); Hustoft et al. (2007); Chand et al. (2011) and by Andreassen et al. (2007a) in the Barents Sea. There is also a possibility that some these pipes are the result of acoustic masking by the strong amplitude anomalies located above. The smaller vertical discontinuities may represent smaller pipes. Such features have been described by Løseth et al. (2009) which suggests that the dimming of these amplitudes are related to gas traveling through low permeable sediments. However, such discontinuities may also be the result of seismic noise in the 3D-surveys.

Vertical reflection discontinuities may also represent faults crossing the stratigraphic layers. No such faults have been identified within the Naust Formation. However, fault zones consisting of the widespread polygonal faults of the underlying Brygge Formation are located across almost the entire study area (Fig. 1.1.5d and 1.1.6d). Larger deep-seated faults have also been located (Fig. 4.4.1a and 4.4.2a).

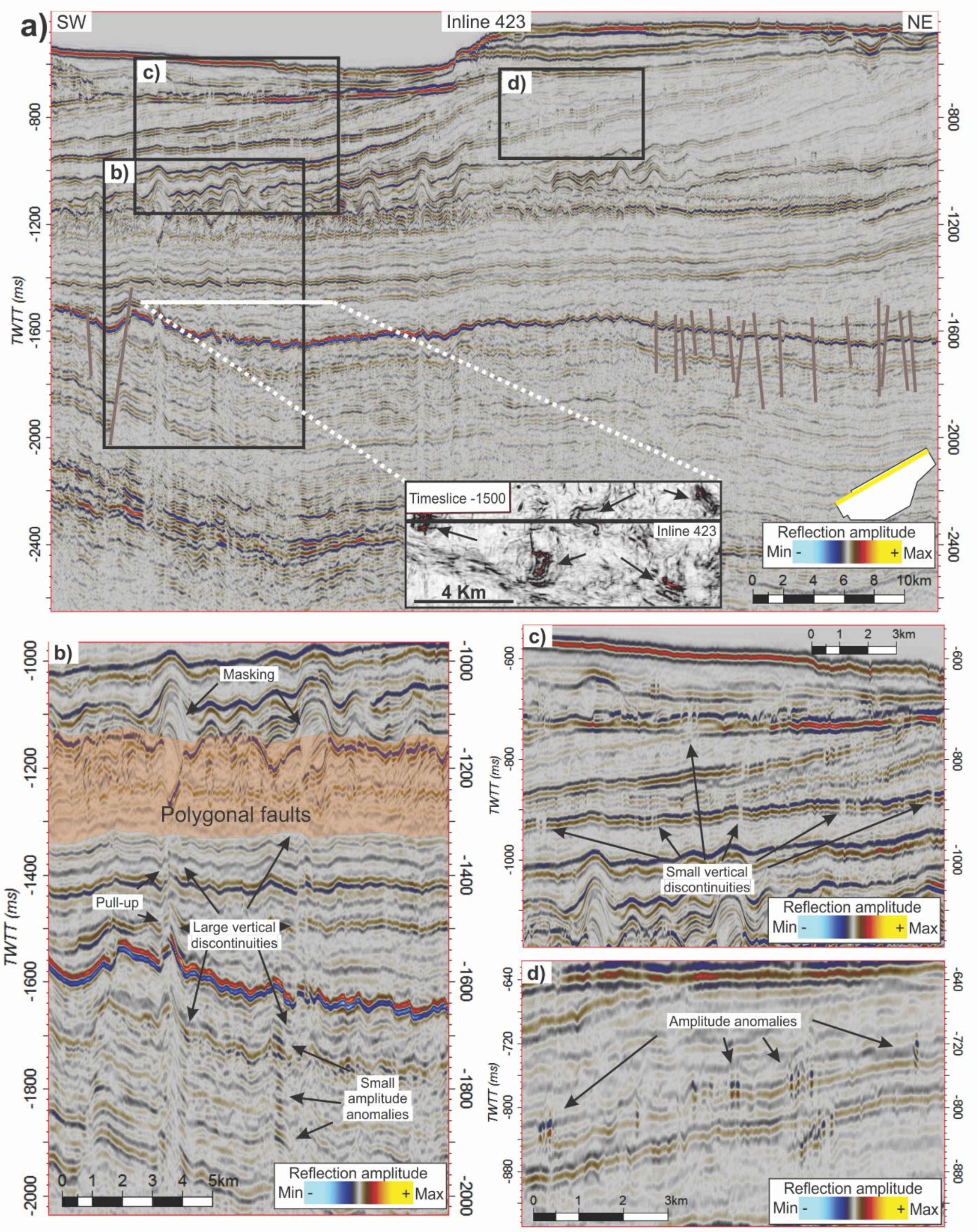


Figure 4.4.1 a) Seismic section of inline 423 from the ST10013 3D-seismic survey showing several seismic features displayed in figure b), c) and d) (black frames). The white line indicate the location of timeslice -1500 generated from a variance cube, which show several pipe structures (black arrows). Brown lines indicate deep-seated faults. The location of the seismic section is shown by the yellow line in the white polygon. b) Zoom-in of large vertical discontinuities interpreted to be pipes that terminate above the polygonal faults of the Brygge Formation. c) Zoom-in of small vertical discontinuities. d) Zoom-in of amplitude anomalies interpreted as bright spots that fallow stratigraphic layers of the Naust Formation.

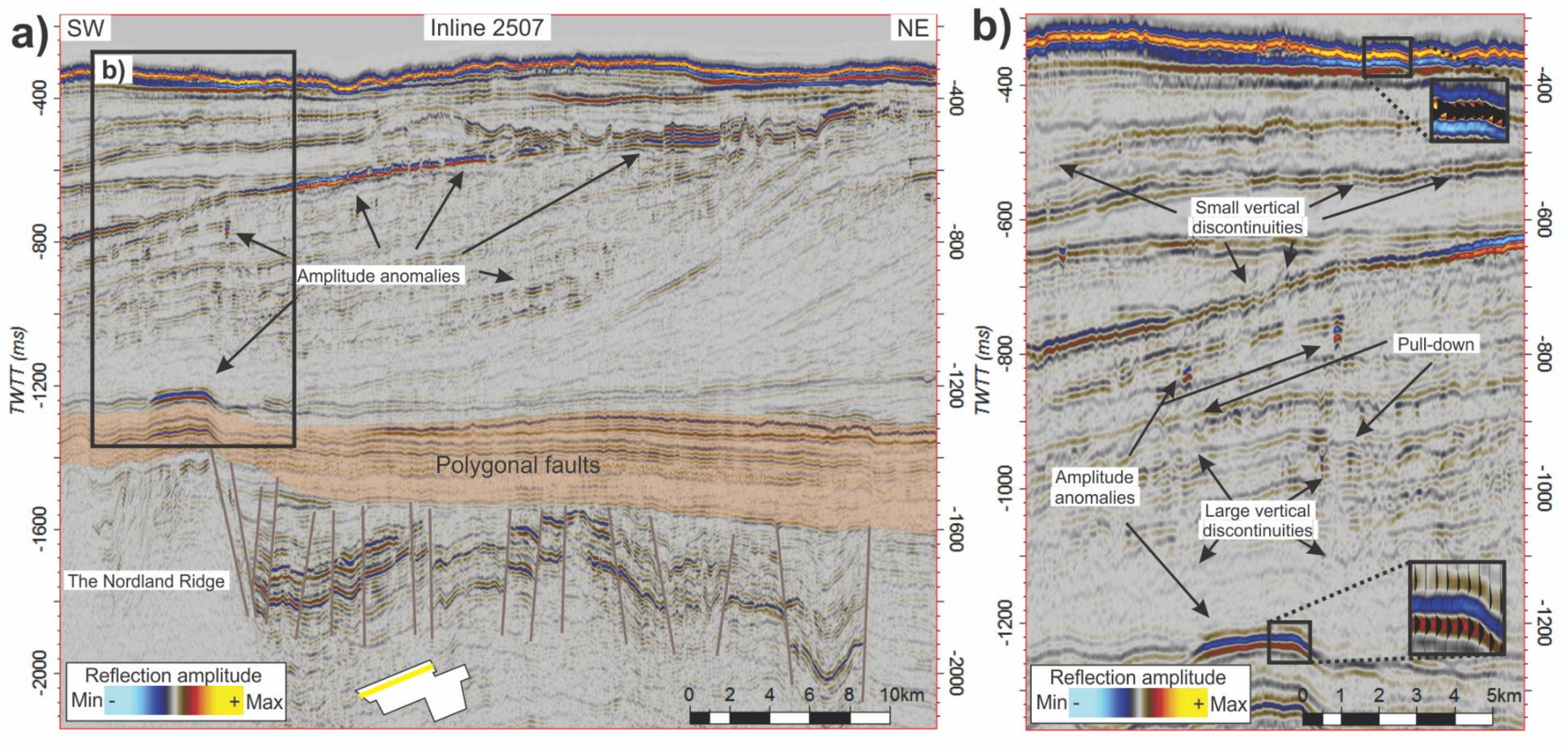


Figure 4.4.2 a) Seismic section of the 2507 inline of the ST07M07 survey which show seismic features such as amplitude anomalies and geomorphological features such as polygonal faults (shaded area) and deep-seated faults (brown lines). Black frame indicates the location of figure b). Location of the figure is shown on the white polygon. b) Zoom-in of area with a large amplitude anomaly above the Nordland Ridge. The black frames show wiggle display where the anomaly has a phase reversal relative to the seafloor. The section also display pipe structures with pull-down as well as small vertical discontinuities.

4.4.2 Distribution of bright spots

Bright spots are anomalously high amplitudes, which occur as the result of a negative change in acoustic impedance. This may occur when the seismic wave encounters gas-filed pore space, because of the decrease in velocity and density of gas-bearing sediments compared to water-bearing sediments (Andreassen, 2009). However, it is important to remember that this change may also be related to lithological differences. Bright spots can be identified by comparing the seismic response to the seafloor, as the seafloor interface (fluid to solid interface) is always represented as a positive change in acoustic impedance. Several bright spots can be located within both the ST10013 and the ST07M07 3D-surveys.

In the ST10013 survey, the bright spots appear to mainly be located within some of the geomorphological features with positive relief described on the paleo-surfaces in chapter 4.3. This can be seen on the RMS amplitude map displayed in Fig. 4.3.30 and 4.3.37, where the bright spots appear to be concentrated along levees and sediment-fans. These features, which display bright spots, are often located along the same lithological boundaries (Fig. 4.4.1d).

In the ST07M07 survey, bright spots have been located at several places. Two large bright sports are located in approximately the same geographical area on the western side of the survey, but in different stratigraphic sections. The deepest is located within an anticlinal structure at the upper border of the polygonal faults of the Brygge Formation. It is also placed above the edge of the Nordland Ridge where deep-seated faults penetrates up towards the amplitude anomaly (Fig. 4.4.2). Two of the pipes described above appear to originate along the flanks of this anomaly. There are also several large bright spot located further up in the strata, at the base of Naust A and along the URU (Fig. 4.4.2). The most distinct is the bright spot further up from the bright spot at the base of Naust N, which is located where the URU truncates the base of Naust A (Fig. 4.4.2).

Also in the ST07M07 survey some of the geomorphological features with positive relief on paleo-surfaces display stronger amplitudes than the surrounding lithology. An increase in bright spots have been located along what have been interpreted as glacigenic debris flows within the younger part of the Naust N sequence (Fig. 4.3.25 and 4.4.3). These debris flows lead down to, and intertwine with large bright spots located just outside the western side of the study area. These anomalies are displayed in the MNR05 7352 2D-line shown in Fig. 4.4.4. They have been interpreted by Ottesen et al. (2012) as gas-bearing contourites, which also suggest the presence of intertwining debris flows.

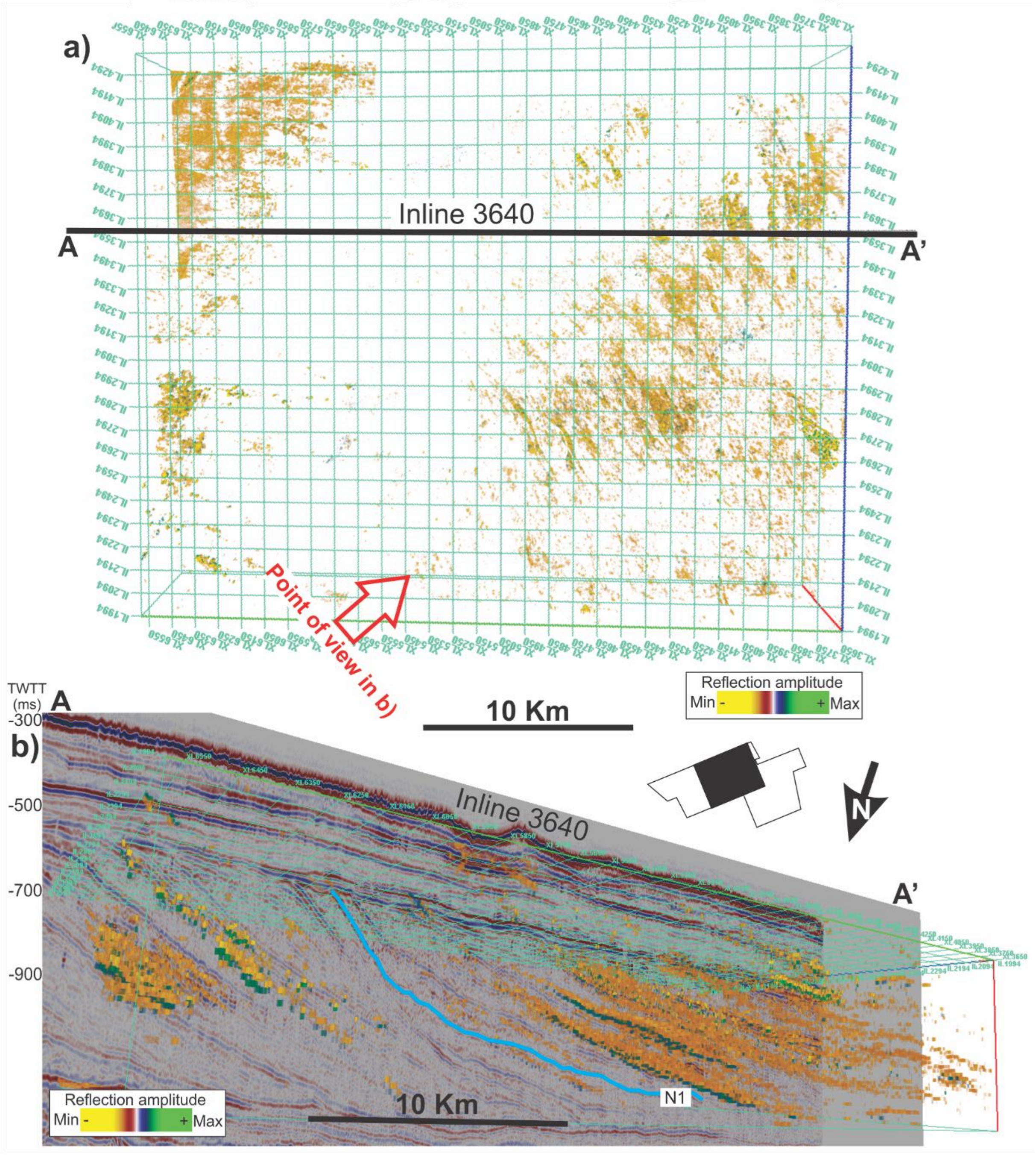


Figure 4.4.3 a) Display of 3D-cube within the ST07M07 survey where the weak amplitudes are transparent. The red arrow indicates the point of view in figure b). Seismic section of the 3640 inline displayed together with the strong amplitudes from the 3D-cube from figure a). The strong amplitudes likely represent gas-bearing debris flows within the youngest part of the Naust N sequence. The light blue line indicate the location of the N1 surface. View point is set from the north.

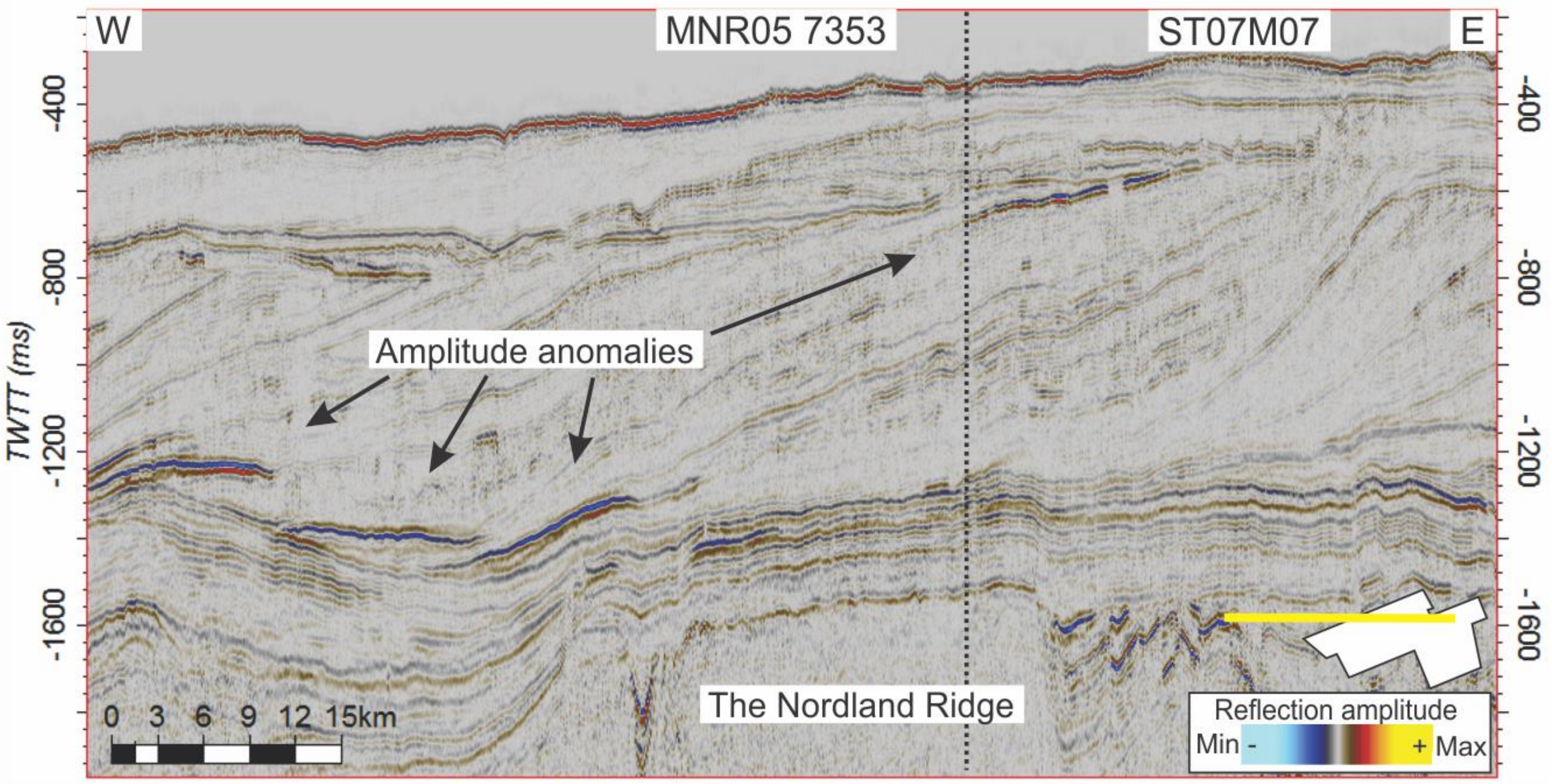


Figure 4.4.4 Seismic section of the MNR05 7353 2D-line, which stretches through the ST07M07 3D-seismic survey. The section display bright spots interpreted to represent gas-bearing contourites located just outside the study area as well as a bright spot under the URU. The white polygon and the yellow line show the location of the 2D-line in relation to the 3D-survey.

4.4.3 Distribution of pockmarks

Paleo-pockmarks have been identified on all the interpreted surfaces described in chapter 4. The pockmarks are generally formed in fine-grained, soft sediments on the seafloor by fluids escaping into the water column and often located above hydrocarbon indicators or areas with signs of fluid migration (Hovland & Judd, 1988). Therefore, variance cubes were generated to get a better understanding of the distribution of the pockmarks throughout the two 3D-surveys (Fig. 4.4.5 and 4.4.6). It becomes clear that the pockmarks have a higher concentration along belts that follow some of the prograding wedges, which display strong amplitudes within the Naust Formation. Some of these belts of paleo-pockmarks appear to lead up to strong amplitude anomalies located at the URU, especially in the younger Naust N deposits of the ST07M07 survey (Fig. 4.4.6a). The generation of the pockmarks also appear to begin along the base of the Naust Formation, which is located above the polygonal faults of the Brygge Formation (Fig. 4.4.5 and 4.4.6). There is no clear distributional pattern throughout the flat lying sheets of the S and T sequences. However, on the seafloor of Sklinnadjupet, the pockmarks can only be found within the cross-shelf trough where they appear in large quantities.

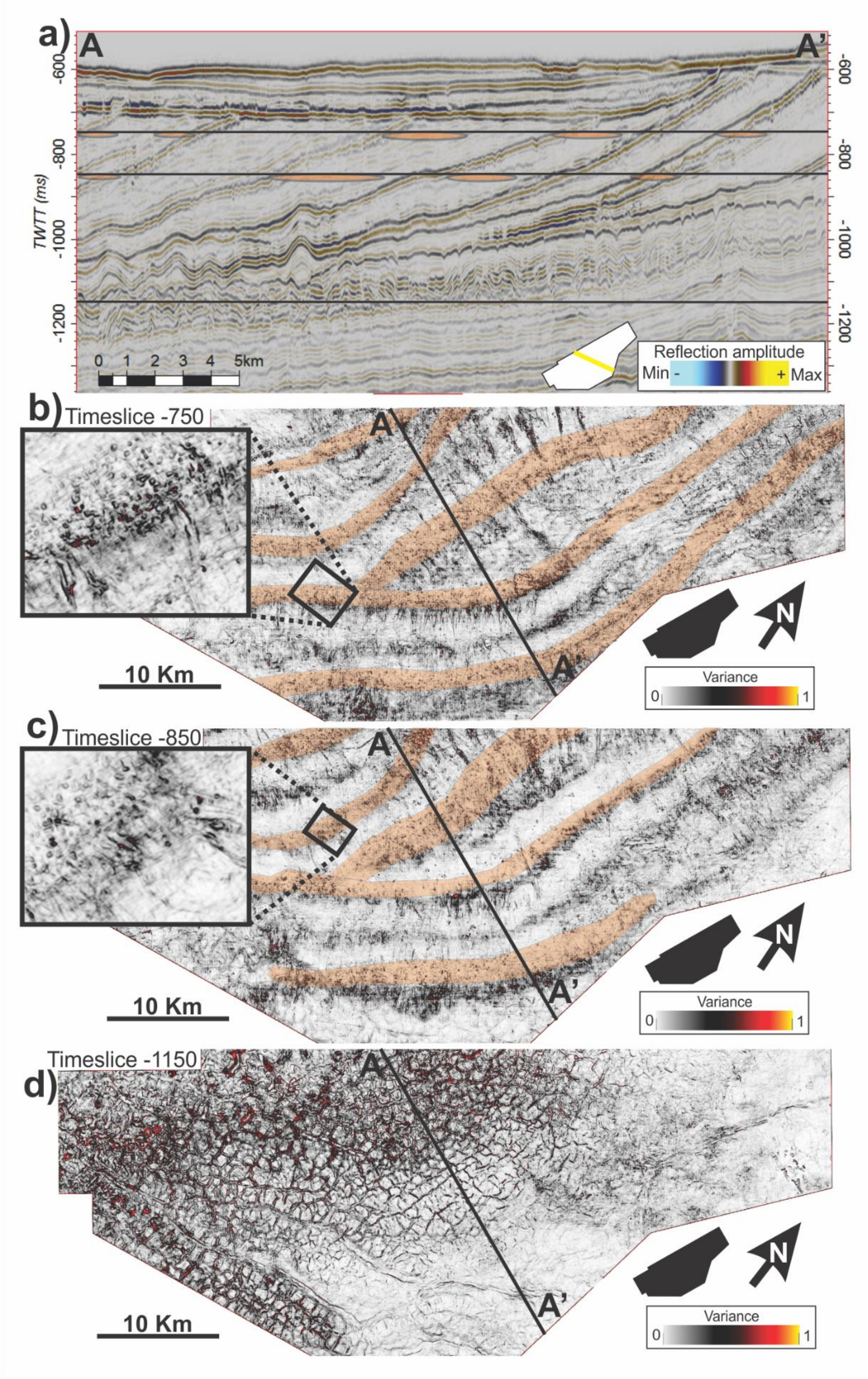


Figure 4.4.5 a) Seismic arbitrary line from the ST10013 survey showing the distribution of pockmarks (orange areas) along the internal stratigraphic boundaries of the Naust N sequence. The black lines indicate the location of b). c) and d). b) Timeslice with zoom-in at -750 ms (TWTT) generated from variance cube of the ST10013 survey displaying the main distribution of pockmarks (shaded area). c) Timeslice with zoom-in, located at a depth of -850 ms (TWTT) showing the general distribution of pockmarks (shaded area). d) Timeslice rom -1150 ms (TWTT) which show the polygonal faults of the Brygge Formation.

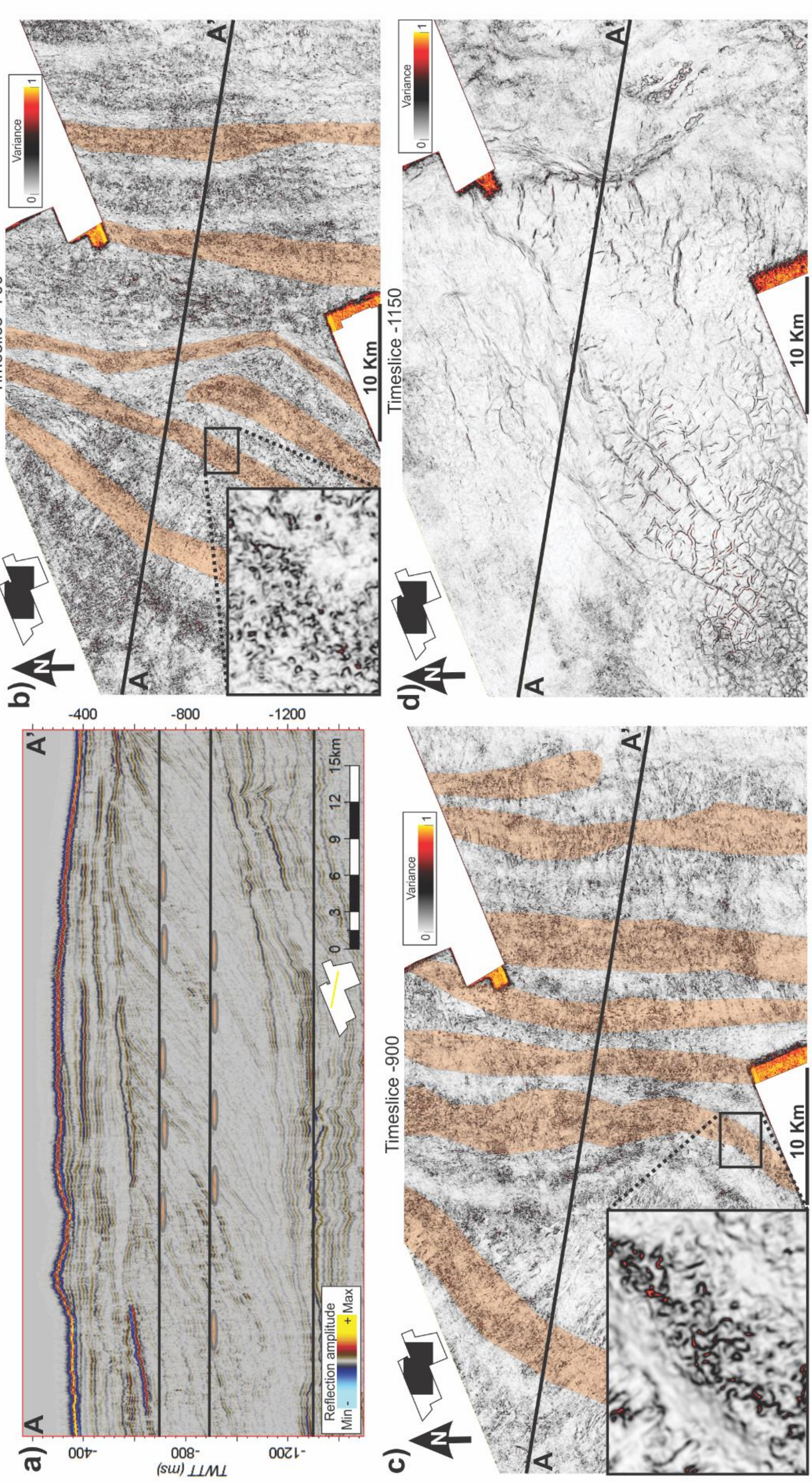


Figure 4.4.6 a) Seismic section of arbitrary line within the ST07M07 survey where the distribution of pockmarks along the -700 and -900 timeslices have been indicated in orange shading. The black lines indicate the location of b), c) and d). b) Timeslice with zoom-in generated from variance cube of the ST07M07 survey. The timeslice in located at a depth of -700 ms (TWTT) and show the main distribution of pockmarks (shaded areas). c) Timeslice with zoom-in from -900 ms (TWTT) showing the main distribution of pockmarks. d) Timeslice from -1150 MS (TWTT) showing polygonal faults of the Brygge Formation.

5. Discussion

In this chapter, the results will be discussed in two sections. First, the stratigraphy and origin of the interpreted surfaces T1, S1, A1 and N1-3 as well as the seafloor will be discussed in relations to the glacial history of the mid-Norwegian continental shelf. The discussion will follow the development of the depositional environment over the last 2.8 Ma, starting with the oldest surface. Then indications of fluid migration in the area will be addressed and related to the depositional environment as well as the glacial history. Pockmarks will be discussed in context with the fluid migration in the study area and will therefore not be included with the other geomorphological features on the interpreted surfaces.

5.1 Development of the Late Cenozoic mid-Norwegian continental margin

5.1.1 Stratigraphy

In chapter 4.1 it was established that the Naust Formation in the study area consists of prograding clinoforms and aggradational sheet-like layers, which transforms into clinoforms further out on the shelf. The clinoforms are confined by the base of Naust (N4 reflection) and differ in shape from sigmoidal to oblique. Similar deposits have been described along the Norwegian continental margin by Dahlgren et al. (2005); Sejrup et al. (2005); Rise et al. (2010) which concluded that these sequences mainly consists of glacigenic sediments. This has been supported by samples form well loges as well as the seismic signature of the sequences (Dahlgren et al., 2005; Stoker et al., 2005; Ottesen et al., 2012; Eidvin et al., 2014). Dahlgren et al. (2005) has presented a model for the development of such prograding clinoforms (Fig. 5.1.1). The model discusses the geometry of the wedges in relationship to the geometry and subsidence of the margin.

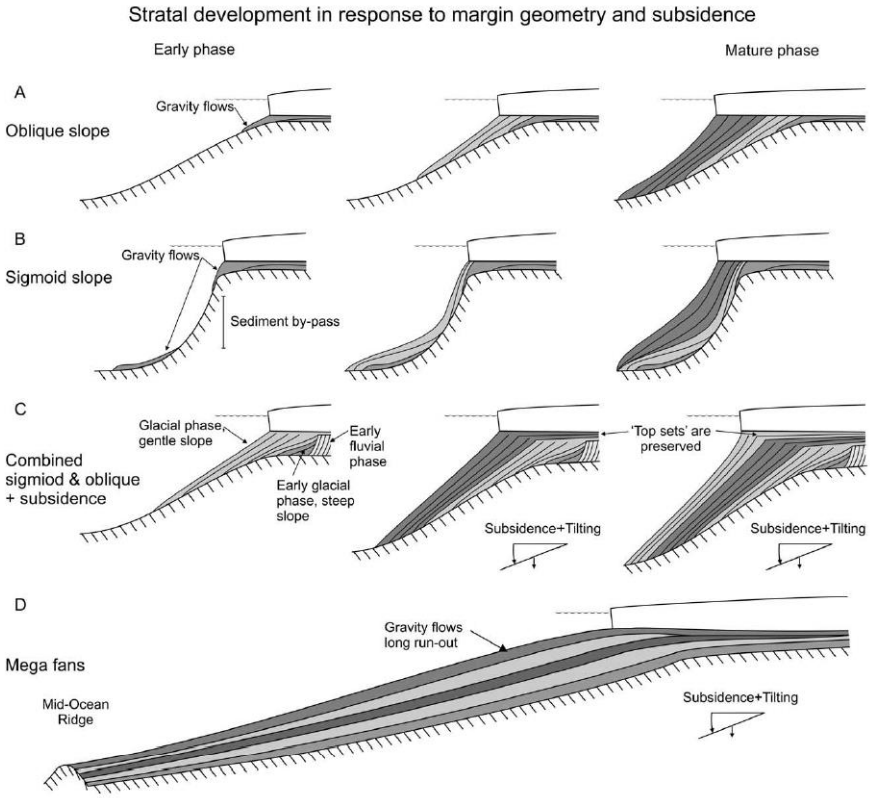


Figure 5.1.1 Conceptual model from Dahlgren et al. (2005) showing the influence of the margin geometry and subsidence on the progradation and stratal stacking pattern of the prograding wedges.

If the reflection configuration of the Naust Formation along Trænabanken and Sklinnadjupet is compared with the model from Dahlgren et al. (2005), the C configuration of Fig. 5.1.1 show similar features and geometry. The inner parts of the Naust Formation, which is located above the deltaic Molo Formation, display a steep slope from the early glacial phase. As the glacigenic wedges started to increase in size, the slope angle decreased. This phase can be compared with the N, A and U sequences of the Naust Formation which lies under the URU, where the topsets are poorly preserved. Although, small unconformities located under the URU may be a result of smaller episodes of subsidence, these units have probably been mainly affected by the sediment supply to the margin (Dahlgren et al., 2005). The rapid increase of glacial sediments deposited on the margin then resulted in subsidence and tilting. This combined with erosion of the shelf lead to a combination of aggregation and progradation where the topsets are preserved. The S and T sequence of the Naust Formation in the study area, which is located above URU, represents such preserved topsets (Dahlgren et al., 2005).

Using 2D-lines (Fig. 4.1.3) the progradation of the paleo-shelf edge towards the west over time can be estimated for the Naust Formation in the study area. However, as the N, A and U units have been affected by erosion, especially in the Sklinnadjupet area, these distances may not always represent the distance to the paleo-shelf edge. They may represent the distance to the highest point of the paleo-slope that have not been removed by glacial erosion. During Naust N time (2.8-1.5 Ma) the paleo-shelf extended right above 60 km beyond the top of the Molo Formation in the Trænabanken area and almost 100 km in the Sklinnadjupet area. In Naust A time (1.5-0.8 Ma) the extensive progradation continued, building out the paleo-shelf edge by approximately 55 km in the Trænabanken area and 40 km in the Sklinnadjupet area. During Naust U time (0.8-0.04 Ma), the shelf only prograded right under 40 km in Trænabanken and 15 km in Sklinnadjupet. Then the URU marks a change in depositional pattern where aggregation in addition to progradation takes place during Naust S (0.4-0.2 Ma) and T (0.2-Ma) time as described above and by Dahlgren et al. (2005). This resulted in more flat laying sheet deposits, which built out an additional 25 km during the last three glacial periods. This total build out of around 180 km lead to the widest section of the mid-Norwegian continental shelf, which can be seen today, ending at Skjoldryggen where the slope extends down onto the Vøring Plateau (Fig. 5.1.2).

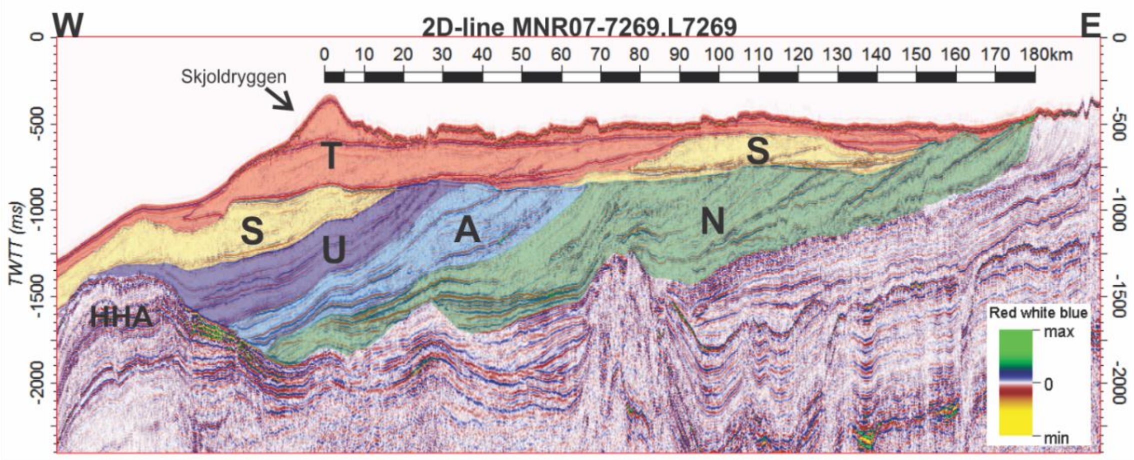


Figure 5.1.2 Seismic section of the MNR07-7269.L7269 2D-line showing the Naust Formation stretching 180 km out to the mid-Norwegian shelf edge. Location of the 2D-line is displayed in Fig. 4.1.1.

5.1.2 Intra Naust N3-N1

The N sequence (2.8 Ma-1.5 Ma) of the Naust Formation is the thickest and most dominating unit in the study area. N3-N1, which have been described and interpreted in chapter 4.3.4, represent internal paleo-surfaces of this sequence. These surfaces distinguish themselves from the other surfaces in the study, as they represent mainly the paleo-slope where different processes and geomorphological features dominate. The topset, which represent the paleo-shelf, is only preserved in small areas on some of the surfaces. Features that have been identified on the surfaces include iceberg plough-marks, gullies/rills, submarine/depositional fans, paleo-pockmarks and possibly debris flows as well as small moraines.

Iceberg plough-marks

Iceberg plough-marks have been identified on all the intra N surfaces, which is an indication of a glacimarine environment, where free icebergs were drifting in the Norwegian Sea already in early Naust N time. These icebergs have most likely originated from calving glaciers, meaning that ice front must have reached sea level during this time (Fig. 5.1.3). This is supported by several studies, which discusses the sudden increase of ice rafted debris. The ice rafted debris flux can be used as a decisive proxy to reconstruct the glacial history. The increase, which has been interpreted to represent the glacial ice reaching the Norwegian coastline, has been dated to 2.74 Ma (Jansen et al., 2000; Dahlgren et al., 2005; Knies et al., 2014). The 6610/7-2 well, which is located on Trænabanken in close proximity to the study area has been described by Eidvin et al. (1998) and Ottesen et al. (2009). The cores from the lower parts of the Naust Formation reviled clasts interpreted to be ice rafted debris. The clast consisted mainly of crystalline rocks originated from the Norwegian mainland. However, it is also possible that the ice rafted debris originated from other sources as this form of deposition also is controlled by ocean currents and water temperature as well as the prevailing wind direction. Therefore, the icebergs may have originated from the Greenland Ice Sheet or been derived from drifting sea ice (Mangerud et al., 2011).

The iceberg plough-marks on the intra N surfaces are chaotically distributed although they appear to follow the paleo-slopes and have a general orientation from south to north. The orientation provide an insight in the direction of paleo-currents during Naust time. This correlate well with the direction of the Norwegian Atlantic Current, which has been suggested to establish during Mid Miocene (Laberg et al., 2005b). Some of the iceberg plough-marks alternate from the general orientation and appear to trend east to west. This might be a result of alternating currents, driven by meltwater and katabatic winds moving away from the glacial front (Vorren et al., 1990).

The iceberg plough-marks generally truncates other geomorphological features on the surfaces, which indicates that they are the last features to form. The calving might be caused by the withdrawal of the ice front during the deglaciations. There is also a possibility that the ice sheet extended into deep open water as suggested by Mangerud et al. (2011). This suggests that the Scandinavian Ice Sheet extent was limited by the water depth, and not climatic conditions, during early Naust time (Mangerud et al., 2011). There are some geomorphological features that might be an indication of former grounded ice on the paleo-shelf within the Naust N sequence (discussed below). Unfortunately, later glacial erosion has limited the preservation of such possible features.

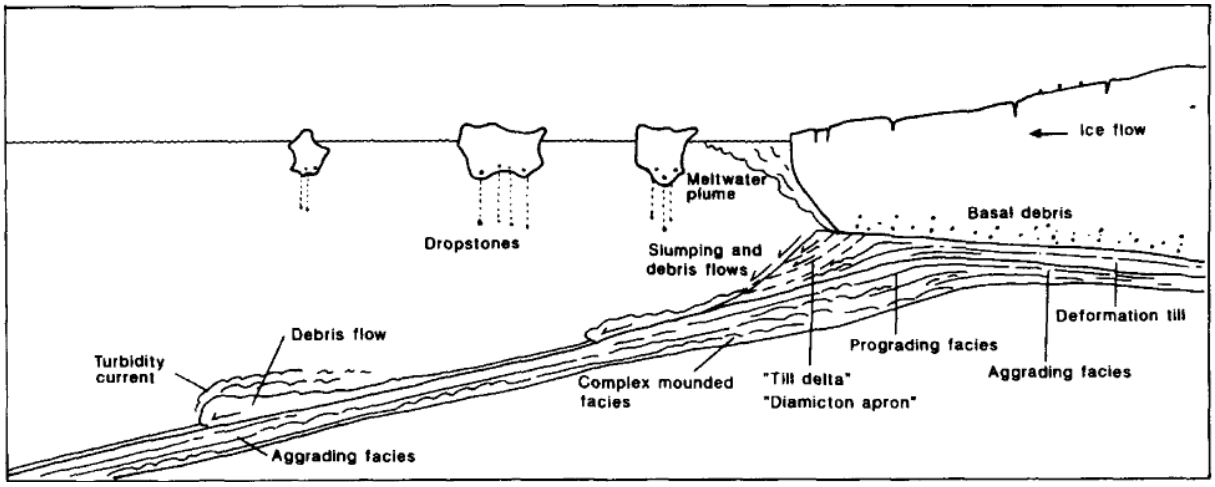


Figure 5.1.3 Ice sheet depositional model of the mid-Norwegian continental shelf during the deposition of the Naust Formation (Henriksen & Vorren, 1996). Sediments are eroded from the continent and inner shelf, transported mainly subglacially, and deposited at or near the shelf edge. Sediments are remobilized down the slope by mass movements and part of the slope is eroded by turbidity currents. Sediment laden-meltwater may lead to meltwater plumes and calving of the ice front results in ice rafted debris.

Gullies and fans

Gullies have been identified on all the interpreted surfaces of the N sequence. They appear to be erosional features with elevated levees, formed by gravitational driven flows, most likely a result of turbidity currents. These turbidity currents are turbulent flows, which are driven by the higher density compared to the ambient water. Such flows can travel at extremely low angles (<1°) which correlates well with the mid-Norwegian continental slope of approximately 1-2 degrees (Nichols, 2009). The turbidity currents can be a result of the transformation of mass movements down the slope, dens sediment-laden water emitted subglacially, rivers reaching the slope or a combination of these (Fig. 5.1.3) (Ó Cofaigh et al., 2003; Laberg et al., 2007b; Gales et al., 2013).

Rise et al. (2005) and Ottesen et al. (2009) discussed that it is unlikely that rives contributed substantially to the massive progradation of the Naust Formation as it mainly consist of clay/silt, and only some layers of sand. However, in early Naust time when the continental shelf was still relatively narrow in comparison to the present day shelf it is possible that fluvial processes contributed. The N3 surface display gullies on the paleo-shelf as the Naust Formation is influenced by the steeper underlying, deltaic Molo Formation. Therefore, it is not inconceivable that rivers could reach this level of the shelf, and the NDP project attributed the initial build out of the Naust Formation to fluviomarine and downslope processes (Ottesen et al., 2009). The gullies appear to have developed from the paleo-shelf edge with no clear signs of mass movements above. It is however possible that such features have been removed by erosion on paleo-surfaces where the upperpart of the slope is missing. The gullies that start at the paleo-shelf edge may also indicate that the glacial front was located on or in close proximity to the edge. This would make it possible for subglacial meltwater to be transported down the paleo-slope (Gales et al., 2013).

Processes like these have been discussed by Laberg et al. (2010) that suggested an glacimarine environment with warm glaciers emitting sediment-laden underflow of meltwater. This resulted in turbidity currents forming channels in the Barents Sea during the Late Pliocene-Early Pleistocene, which correlates to Naust N time. Gales et al. (2013) has done quantitative analyses classifying over 1450 gullies from the Norwegian and Antarctic margins. They suggest that the large quantities of glacigenic sediments transported to the shelf edge during glacial periods would infill the shelf edge depressions resulting in new gullies forming with each new glacial cycle. This would explain the low incisions of the paleo-gullies found within the Naust N sequence. Similar features and processes have also been discussed by Ó Cofaigh et al. (2003) along the Arctic and Antarctic margins.

The gullies develop into submarine fans/turbidities as the slope angle decreases and lower transport velocity leads to the sediments falling out of suspension (Nichols, 2009). On the N1 surface there are also two fan-shaped sediment accumulations that start at the paleo-shelf edge, which might represent debris flows. This could be a result of subglacial transport of sediment directly to the shelf edge where the sediments are remobilized downslope (Fig. 5.1.3). This is on the same surface as glacial moraines have been located on the outer shelf (discussed below), supporting the presence of grounded ice in the area. This surface may therefore represent a change in depositional environment on the paleo-shelf edge during Naust N time. The change resulted in the younger surfaces being dominated by glacigenic debris flow processes instead of the fluvial/fluviomarine processes which dominated the Molo Formation, and most likely the beginning of the Naust N unit. This is supported by Fig. 4.4.3, where anomalies interpreted to be debris flows drastically increase after the deposition of the N1 surface. These debris flows have also been described by Ottesen et al. (2012). Debris flows and submarine fans have also been described on paleo-surfaces by Andreassen et al. (2007a) in the Barents Sea as well as by Ó Cofaigh et al. (2003) on the present day seafloor in the Arctic and Antarctic.

Small moraines

Small moraines have been located on the N1 surface paleo-shelf. These moraines are probably a result of small annually readvances of the ice sheet and is the earliest documented evidence of grounded ice located in the study area. These moraines have also been documented by Halvorsen (2012). Early studies of the Naust Formation by Henrich and Baumann (1994); Hjelstuen et al. (1999) among others suggested a moderate glacial environment with moderate small ice caps on the surrounding land masses during Naust N time. This has later been disputed and Rise et al. (2005) argued that the extensive progradation in the Trænabanken area was formed during numerous ice sheet advances to the paleo-shelf edge. If the ridges on the N1 surface are small moraines similar to those described by Dowdeswell et al. (2007) on younger paleo-surfaces in the same area, this would strongly support the suggestion that grounded ice had a major impact on deposition of the prograding wedges, even relatively early in Naust N time. The debris flows discussed above also support a glacigenic environment on the paleo-shelf edge from the middle of Naust N time.

5.1.3 Base Naust A (A1)

The base of the Naust A sequence (~1.5 Ma) is only represented in a small part of the study area as it mainly propagate further out on the mid-Norwegian continental shelf. Although most of the A sequence consist of prograding wedges, the surface in the study area is part of the paleo-shelf as it represent the inner part of the unit. Geomorphological features that have been located on the surface consist of iceberg plough-marks, paleo-pockmarks, flutes and MSGL as well as parts of a large cross-shelf paleo-trough.

Paleo-trough, flutes and MSGL

The over-deepened, cross-shelf paleo-trough and the glacial lineations are the first direct indicators of fast-flowing ice streams within the study area. The orientation from SE towards NW within the ST07M07 survey indicate the drainage pattern the ice was following during early Naust A time, over what now is considered the Trænabanken area (Fig. 5.1.5a). However, as the surface is so confined and only one side of the cross-shelf trough has been interpreted, it is hard to determine the exact ice flow pattern during this time. Evidence for grounded ice sheets in the form of glacial lineations have also been documented by Ottesen et al. (2009) in the transition zone between Naust N and A. This indicate that the grounded ice reached out on the paleo-shelf and that erosion/transportation by fast-flowing ice streams towards the paleo-shelf edge was an important process during the build out of the Naust A sequence. Dowdeswell et al. (2006) has also documented cross-shelf paleo-troughs and MSGL in the exact same area as this study. However, this was in younger sediments located further up the strata, estimated to be less than ~0.5 Ma.

Iceberg plough-marks

The iceberg plough-marks indicate that the ice sheet reached the coast and was calving during Naust A time. This is supported by the MSGL and the cross-shelf trough, which are clear indicators of ice streams erosion in the area. The plough-marks have the same two orientations as the surfaces from the N unit. One orientation is from SW-NE, while the other orientation which is mainly located within the paleo-trough is from east to west. Also her the plough-marks orientations are interpreted to represent the ocean current moving icebergs towards the NE, as well as meltwater currents and katabatic winds transporting the icebergs away from the glacial front, towards the west. The higher concentration of the W-E orientated plough-marks within the trough support this, as the paleo-troughs likely would be the first locations where the glacial ice retreats. This would create an ice-free bay where the main current would flow towards the east. Vorren et al. (1990) suggest that this process controlled iceberg drift directions in the Barents Sea during Naust time.

5.1.4 Base Naust S (S1)

The base of Naust S (~0.4 Ma) represent the URU for most of the study area, as it indicate a change in depositional environment and truncates the underlying prograding clinoform. The surfaces within the 3D-surveys represent the paleo-shelf where geomorphological features such as paleo-pockmarks, iceberg plough-marks, flutes and MSGL have been identified. Two large cross-shelf paleo-troughs that merge towards the west are also located within the ST10013 3D-survey. The URU itself is a clear indicator that the ice sheet was present on the paleo-shelf during base Naust S time, eroding large quantities of sediment. It marks a change in depositional geometry from progradational to aggradational within the study area (Fig. 5.1.3). The S sequence has been correlated to the Elsterian glaciation (marine isotope stage 10-8) which Rise et al. (2006) described as a very thick and erosive ice sheet, transporting eroded sediment from the paleo-shelf, depositing it on the paleo-shelf edge and paleo-slope.

Paleo-troughs, flutes and MSGL

The paleo-troughs indicate two drainage pathways for fast-flowing ice streams trough the study area. The ice streams have advanced from two different directions, one from the NE and the other from the SE, merging into one stream after what is now considered to be the Sklinnabanken area. This combined with the flutes and MSGL in the area is a good indication of the paleo-ice flow, which appears to originate from Vestfjorden in the NE before gradually getting a more eastward orientation towards the south. At the same time, ice was also draining to the same area form the SE resulting in a large depocenter where Sklinnadjupet descent down to the Vøring Plateau today (Skjoldryggen area) (Fig.5.1.5b). It was in this area the Sklinnadjupet slide was triggered during Naust S time. This has been interpreted to be a result of the high deposition rate to the area during the Elsterian glaciation, leading to large excess pore pressure in the sediments (Rise et al., 2006). The findings of this study also correlates well with the suggestions of Dowdeswell et al. (2006) which have found MSGL with the same orientation. These lineations were found on a paleo-surface, which originated from the same time and area, also concluding with a drainage pattern from Vestfjorden.

Iceberg plough-marks

The iceberg plough-marks in the area generally have a south to north orientation on the S1 surface. Here as on the previous surfaces the direction is interpreted as an indicator of paleo-ocean currents. The direction is also here correlated to the Norwegian Atlantic Current moving along the Norwegian margin (Bryn et al., 2005; Laberg et al., 2005b). As the plough-marks truncate other geomorphological features such as MSGL they have probably originated from calving icebergs drifting from the retreating glaciers.

5.1.5 Base Naust T (T1)

The base of Naust T (~0.2 Ma) represents the start of Naust T time, consisting of the Saalian and Weichselian glaciations (marine isotope stage 6 and 2), which were the two last glacial cycles on the mid-Norwegian continental shelf (Dahlgren et al., 2002b; Rise et al., 2005; Rise et al., 2010). On the interpreted surfaces, large erosional features have been located along with iceberg plough-marks, pockmarks, small moraines, lateral shear zone moraines, flutes and MSGL. Also on the base of Naust T, two large cross-shelf paleo-trough appears to merge within the ST11013 3D-survey.

Paleo-troughs, flutes and MSGL

The cross-shelf paleo-troughs that indicate the drainage pattern of the fast-flowing ice streams of the time have changed direction from the underlying S1 surface. The two troughs have become more parallel with an E-SE to W-NW orientation perpendicular to the coastline. This change indicates that the ice flow within Sklinnadjupet was mainly dominated by ice from the east during Naust T time, while the influence of the southwards flow from Vestfjorden had decreased (Fig. 5.3.4c). This has also been discussed by Dowdeswell et al. (2006) who suggested a major shift in the large-scale glacial patterns between the Saalian and Weichselian glaciations. This was a result of thick sediments sequences being deposited on the shelf during the Elsterian and Saalian glaciation, building up what is now known as Trænabanken. When the Weichselian glaciation started, the easiest pathway for the Vestfjorden ice flow to take was no longer over the Trænabanken area, leading to the development of Trænadjupet. However, there is also a possibility that the change in ice flow was a result of internal changes in ice sheet dynamics (Dowdeswell et al., 2006). The change in the paleo-troughs as well as the direction of the MSGL and flutes in the study area support this change in ice-flow during Naust T time. However, there are no direct signs of fast-flowing ice streams going directly over Trænabanken on the T1 surface, only glacitectonic features and moraines (discussed below).

Glacitectonic features

Glacitectonic features such as hill-hole pairs are located on the shallowest part of the T1 surface of the study area. They indicate an ice-flow from the north, which gradually appears to bend towards the west. The area is interpreted to represent the early stages of Trænabanken, which was built up during the Elsterian and Saalian glaciation (Dowdeswell et al., 2006). The buildup resulted in the stagnation of the ice-flow on Trænabanken during Naust T time and Ottesen et al. (2005b) suggested a passive ice dome with an ice divide trending NW–SE across the middle of Trænabanken during the last glaciation. As the ice streams stagnate, the base may freeze to the underlying sediments, resulting in the glacitectonic activity observed on the bank (Nielsen et al., 2005; Ottesen et al., 2005a). Ottesen et al. (2005a) discussed that the slow moving ice may be a result of a deglacial situation where thinning of the ice lead to the decrease in flow velocity and therefore basal freezing. It is also distinguished that the orientation of such features can be a good indication of former ice flows. If this were the case in the study area, the hill-hole pairs would correlate well with the deglaciation of the Saalian, both in time (Naust T time) and direction (ice-flow towards the SW).

Moraines

There are two different type of moraines located on the T1 surfaces, small moraines and lateral shear zone moraines. The small moraines are orientated transverse to the ice-flow direction indicated by the glacial lineations and glacitectonic features discussed above. These features resembles De Geer moraines and the spacing between them likely represent standstills or small charges of the ice front, possibly affected by seasonal changes during deglaciation as discussed based on studies of other parts of the Norwegian continental shelf (Solheim et al., 1990; Rydningen et al., 2013). The lateral shear zone moraines are located along depth changes on the surfaces indicating where fast-flowing ice streams borders to more stagnant ice. The moraines are therefore a good indication, both of the movement of the former glacial front, as well as the borders of ice streams with higher velocity within the study area.

Iceberg plough-marks

The iceberg plough-marks have a main orientation from SW towards NE. This is a good indication of the paleo-ocean currents moving almost parallel to the Norwegian continental margin. The plough-marks are probably relatively young features, as they truncate older features, created by icebergs calving during the deglaciation.

5.1.6 Seafloor

Most of the features on the seafloor represent the last glaciation on the mid-Norwegian continental shelf. Among the geomorphological features identified are MSGL, flutes, moraines, pockmarks and iceberg plough-marks as well as subglacial meltwater channels in glacimarine deposits. Most of these features are a result of the Weichselian glaciation.

Trough, MSGL and flutes

The cross-shelf trough, which is located within parts of Sklinnadjupet, has an E-SE to W-NW orientation indicating the main ice-flow direction from the mainland within the study area during the last glacial period. This correlates well with the findings of Ottesen et al. (2002); Dahlgren et al. (2002b); Dowdeswell et al. (2006), which concluded that fast-flowing ice streams flowed through Sklinnadjupet to the shelf edge located at Skjoldryggen. This is further supported by the MSGL and flutes which also suggest fast-flowing ice streams moving in the same direction. However, there are also MSGL with an NE to SW trend located at the inner parts of Trænabanken. These lineations indicate that there have also been fast-flowing ice moving E-SE parallel to the coast. This ice stream appears to have merged with the Sklinnadjupet ice flow as it flowed around the eastside of Trænabanken. The age and origin of this ice flow is however unclear. One possibility is that the ice may be related to late readvance of the Vestfjorden ice stream during the deglaciation. Although there is no clear evidence that the ice-flow reached this far south during this period, it has become evident that the Fennoscandian Ice Sheet was much more dynamic during the early deglaciation than previously assumed (Laberg et al., 2007a).

Moraines

Three different types of moraines have been identified on the seafloor in the study area, large frontal moraines, small De Geer moraines and lateral shear zone moraines. The large frontal moraines in the ST10013 survey have a SW-NE trend, stretching across the trough and onto one of the flanks. Some of them are lobe-shaped indicating that they were deposited along ice-lobes of the glacial front. As buried plough-marks can be seen emerging from underneath the moraines they are interpreted to have been deposited during readvances under the deglaciation. In the ST07M07 survey, the large frontal moraines located on Trænabanken have an NW-SE trend implying that they have been influenced by another ice streams than the one overlaying Sklinnadjupet. They are believed to have been created by ice flowing from the NE where the Vestfjorden ice-stream descended to Trænadjupet. This correlates well with the MSGL located on the inner part of Trænabanken. However, the stationary ice that is believed to have been located over Trænabanken during the Weichselian glaciation would probably retreat in a later face than the fast-flowing ice streams. It is therefore possible that the moraines have been created by the front of this slow moving ice. Another possibility is that the moraines have been deposited after the ice-cap on Trænabanken withdrew, during readvances of the Vestfjorden ice-stream under the deglaciation. As some of the moraines truncate each other, at least some of them must have been deposited during glacial readvances.

The De Geer moraines on Trænabanken are located between the larger moraines and share the same orientation. They are therefore interpreted to relate from the same period, formed as a result of small readvances, possibly controlled by seasonal changes, during the glacial retreat. The De Geer moraines in the ST10013 survey have a NW-SE trend before gradually trending N-S towards the west. This is interpreted to be the result of the moraines gradually being more affected by the Sklinnadjupet ice-stream, which correlates well with the change in MSGL in the study area.

The lateral shear zone moraines on the seafloor is located along the edges of the cross-shelf trough. This confirms that the ice moves faster within the trough then the adjacent flanks.

Subglacial meltwater channels in glacimarine deposits and plough-marks

The glacimarine sediments on top of Trænabanken have probably been deposited in front of the ice sheet, during the glacial retreat from the area during the Weichselian. The sediments were deposited from suspension fallout derived from meltwater plumes (Fig. 5.1.3). The deposition from such meltwater plumes have been documented for the same deglacial period in the Storegga area and Vøring Plateau where the deposition is shown to have terminated at approximately 15 ka (Dahlgren & Vorren, 2003; Dahlgren et al., 2005; Hjelstuen et al., 2005). The subglacial meltwater channels, which only eroded into the glacimarine sediments, are believed to have been formed during the same period. The bottom of these channels display ridges that have been interpreted to be De Geer moraines from the underlying surface. They have probably been preserved as they consist of a more resistant and compacted glacial till. Ottesen et al. (2002) discusses that there have been identified several such channels in the North Sea, while only a few have been located on the mid-Norwegian continental shelf. It is suggested that this may relate to the deeper waters of the Norwegian Sea, which might explain why such channels only have been located on the shallower Trænabank within the study area. However, the geomorphology of the shallow parts of Trænabanken suggests that there has been a clear abundance of meltwater in the area.

The iceberg plough-marks on the seafloor clearly affects the glacimarine deposits more than the surrounding area. This is probably the result of the located on the shallowest parts of the study area, where icebergs easily could reach the seafloor. The glacimarine sediments also consist of a fine-grained lithology, which could be imprinted easier than glacial till. The plough-marks indicate an ocean current towards the N-NE, which correlates well with the Norwegian Atlantic Current following the Norwegian margin (Laberg et al., 2005b).

5.1.7 Summary

The Naust Formation was deposited above the deltaic Molo Formation (Fig. 5.1.4a). Already during early Naust N time there have been identified iceberg plough-marks indicating that the ice sheet probably reached the Norwegian coast. However, it is important to remember that these icebergs may have had a different origin (Fig. 5.1.4b). Later during Naust N time, what may be small moraines have been located on the paleo-shelf edge. If this is the case, the ice sheet expanded all the way out to the shelf edge relatively early in Naust N time. This is supported by the sudden increase in glacigenic debris flows, indicating a change in depositional environment along the shelf edge (Fig. 5.1.4b). During Naust A time, a cross-shelf paleo-trough and MSGL have been identified. This suggests that fast-flowing ice was draining to the paleo-shelf edge through the study area (Fig. 5.1.4c). Because of limited amount of data from this period in the study area, it is difficult to make any accurate assumptions of the ice flow direction (Fig.5.1.5a). As Naust S time initiated a change in depositional geometry took place, from progradational to aggradational. This has been related to high subsidence which probably was caused by the rapidly increasing sediment load, and during the last 350 ka it has been estimated that the outer Norwegian continental shelf has subsided at a rate of up to ca. 1.2 m/ka (Dahlgren et al., 2002a, 2002b). There have been identified geomorphological features indicating fast-flowing ice, flowing to the paleo-shelf edge (Fig. 5.1.4d). This ice-flow appears to originate from Vestfjorden, crossing Trænabanken before reaching the paleo-shelf edge at the Skjoldryggen area (Fig. 5.1.5b). During early Naust T time, fast-flowing ice reached the shelf edge again during the Saalian and Weichselian glaciations (Fig. 5.1.4e). However, as Trænabanken was established the fast-flowing ice streams encountered more resistance over this area and the drainage pattern began to change (Fig. 5.1.5c). Ice-streams from the east now increasingly influenced Sklinnadjupet, while the Vestfjorden ice-stream excavated Trænadjupet, resulting in the drainage pattern that can be observed on the seafloor today (Fig. 5.1.5d).

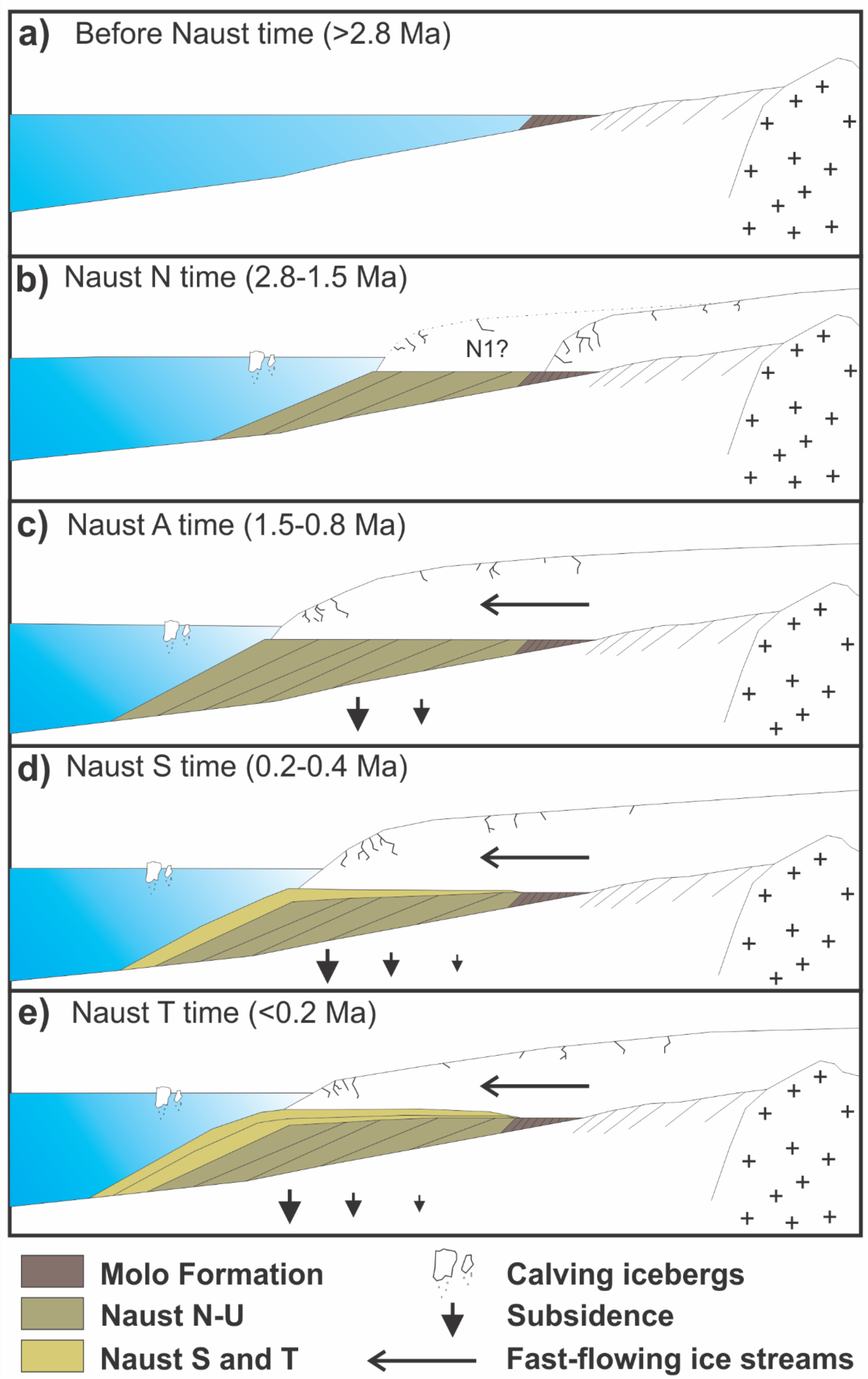


Figure 5.1.4 Simplified model of the glacial history during a) before Naust time, b) Naust N time, c) Naust A time, d) Naust S time and e) Naust T time in the study area derived from geomorphological features on the interpreted surfaces. As Naust U is more or less absent within the study area it has not been included in the model. Short description of the stages can be found in the summery chapter above (5.1.7).

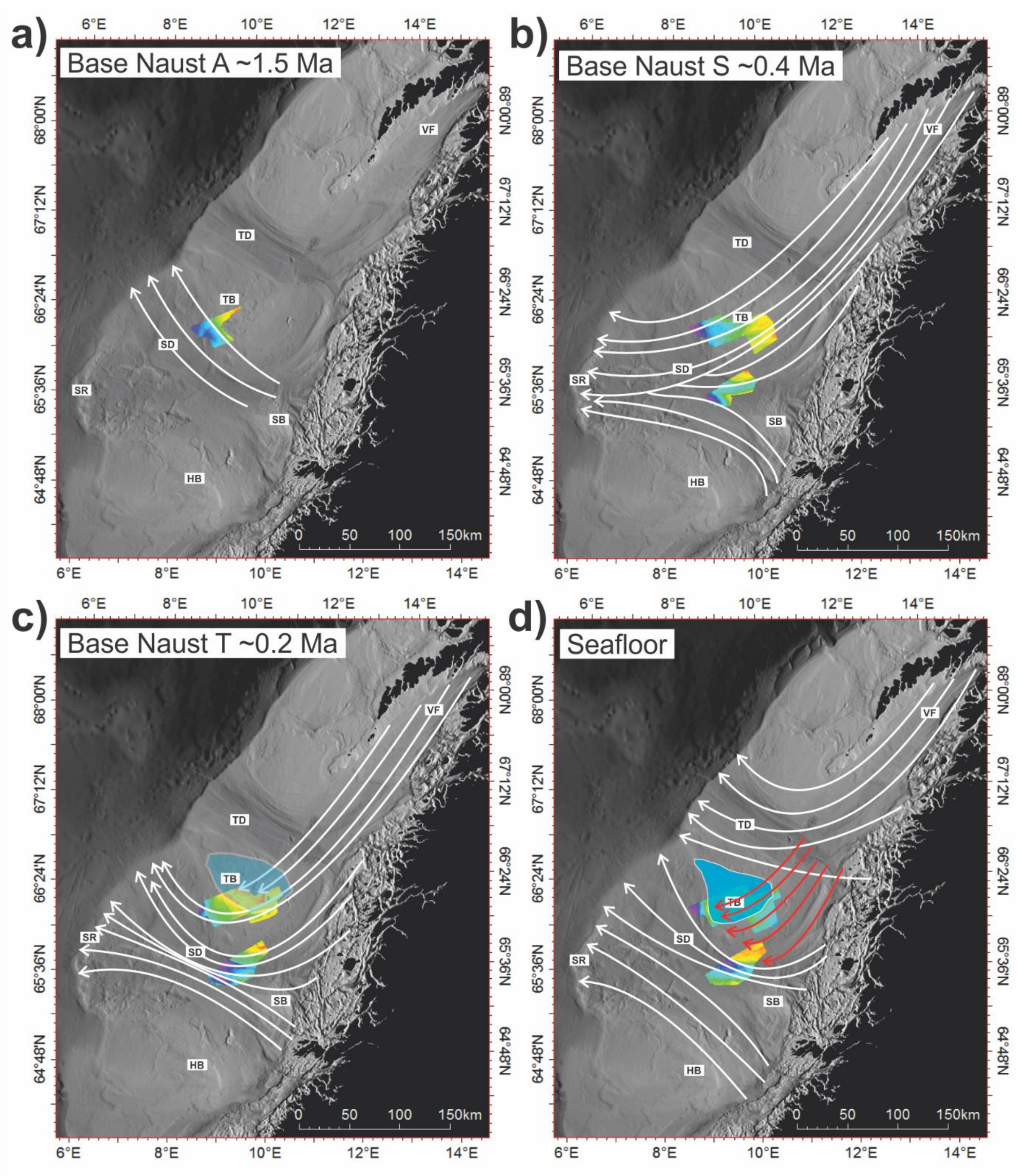


Figure 5.1.5 Simplified model of the evolution of fast-flowing ice streams on the mid-Norwegian shelf derived from geomorphological features on a) the base of Naust A (colored area), b) the base of Naust S (colored area), c) the base of Naust T (colored area) and d) the seafloor (colored area). The model is displayed on the present day seafloor. White arrows indicated the dominant direction of fast-flowing ice streams. Red arrows indicated second direction of fast-flowing ice, most likely at a different glacial stage. Shaded blue area show possible location of stagnated ice starting to develop during Naust T time. VF: Vestfjorden; TD: Trænadjupet; TB: Trænabanken; SR: Skjoldryggen; SD: Sklinnadjupet; SB: Sklinnabanken; HB: Haltenbanken.

5.2 Seismic anomalies and their origin

The distribution of pockmarks and seismic anomalies described in the results give an indication of potential fluid migration pathways within the study area. In this chapter, how the fluid flow move throughout the strata as well as the possible source of these fluids will be discussed.

5.2.1 Fluid migration within the Naust Formation

Several indicators of fluid flow have been located and described within the Naust Formation in chapter 4.4. However, one indicator alone is not necessarily evidence of fluid flow as there are geological situations that may produce the same effects. Therefore, several of these indicators together makes it more likely that fluid flow is responsible (Andreassen, 2009).

The few large pipes that have been identified within the Naust Formation are located in the western part of the ST07M07 survey. This is where the bright spot directly above the southern edge of the Nordland Ridge is located. As this area deviate from the rest of the study area, both in fluid flow and bright spots, it is reasonable to assume a different fluid source. This is therefore interpreted to relate to the deep-seated faults of the Nordland Ridge. As fluids ascended from the deep, they are interpreted to have been sealed at the anticlinal structure located at the boundary between the Naust and Brygge Formation, resulting in a large bright spot (Fig. 5.2.1). The overlaying pipes are located on the flank of this bright spot, indicating that the fluid migration continued up into the strata of the Naust Formation. The pull-down of some of the pipes may indicate active fluid expulsion and gas within the column. The bright spots located at the termination of the pipes further indicate the presence of gas (Fig. 4.4.2). However, the largest drop in P-wave velocity occurs at gas concentrations of as little as 4% of the sediment pore space (Andreassen et al., 2007a), meaning that the volume of gas not necessarily is too large. The bright spots may also be caused by lithological differences, which again may lead to acoustic masking of the underlying strata.

The large bright spots in the area where the base of Naust A is truncated by URU, is interpreted as a second trap for the migrating fluids from the Nordland Ridge. It is also possible that the fluids have migrated along the prograding wedges consisting of debris flows from the west, which is where the large anomalies at the base of Naust are located outside the 3D-survey (Fig. 4.4.4). Ottesen et al. (2012) interpreted these anomalies as gas-bearing contourites where the seal was relatively uncertain, which makes it possible that gas have migrated further up. Some of the other bright spots located along the URU can be correlated to the concentration of paleo-pockmarks along the prograding wedges of the undelaying N sequence. Especially along the younger Naust N deposits where there is an increase in bright spots (Fig 4.4.3). This may be cause by the lithological differences within the Naust N sequence, as the younger deposits appear to be dominated by debris flows. These debris flows probably have better permeability than the more fine-grained deposits from early Naust N time and therefore they are more suitable for fluid flow. These bright spots are located under the URU where the overlaying sheets of glacial till probably represent a decrease in permeability from the prograding wedges, and therefore act as a cap rock. Similar scenarios have been described by Ottesen et al. (2012) on the mid-Norwegian shelf, where gas-bearing glacifluval sands are sealed by layers of flat lying tills and fine grained, marine/glacimarine sediments along the URU of the Norwegian Channel. However, as the bright spot is located where the URU truncates a prograding reflection, the anomalies may also be a result of constructive interference. The maximum constructive interference would occur at the tuning thickness, which has been calculated to be approximately 15 m or less than 10 ms. This makes it unlikely that this would be the single cause of the anomalies. Small vertical discontinuities appear to continue upwards from this area (Fig. 4.4.2b). They can be correlated to the large pockmarks on the western part of the seafloor in the ST07M07 survey, which also is located above the Nordland Ridge area. This might also be an indication of greater fluid flow within this specific area, reaching all the way to the seabed (Fig. 5.2.2).

The rest of the Naust Formation in the study area include no clear migration pathways. However, smaller vertical discontinuities appear to be randomly distributed within the surveys. There are also seismic anomalies located within what have been identified as debris flows, sediment-fans, channels and levees. This has been interpreted as an indication of diffuse flow of fluids that is not observable in the seismic data unless it is gathered in pockets surrounded by sediments of lower permeability such as the geomorphological features listed above. As the pore pressure increases within the pockets, it will eventually exceed the strength of the trap. This will lead to episodically expulsion of fluids, resulting in the small vertical discontinuities. This correlates well with the description of vertical discontinuities by Løseth et al. (2009) which suggest that such discontinuities indicate forced gas flow in low permeable sediments. This may be made possible by the gas bobbles reducing the grain to grain contacts or by gas deforming the surrounding sediments (Løseth et al., 2009). Similar diffuse flows as a result of polygonal faults within the Kai Formation have been describe by Berndt et al. (2003) on the outer mid-Norwegian continental shelf. Therefore, it is probable that the fluid flow from the polygonal faults of the Brygge Formation also could result in similar processes. These anomalies may also be seismic noise, but as they correspond directly to the geomorphological features this is unlikely (Fig. 4.3.30).

The distribution of paleo-pockmarks and seismic anomalies indicate that the upward fluid migration not always flow vertically, but follow some of the sub-horizontal prograding wedges of the lower Naust Formation. This suggests that some of the layers have higher permeability as the fluids always will follow the path of least resistance. This has been described on the outer mid-Norwegian continental shelf by Chand et al. (2011), which stated that the layered architecture of the Naust Formation allowed the fluid flow to follow the topographic gradient, depending on the properties of the sediments. This has also been described by Andreassen et al. (2007a) in the glacial deposits of the Barents Sea. If the permeable layers with high paleo-pockmark concentrations are followed upward through the strata, some of these layers can be correlated to bright spots along the URU. This further supports that fluids may fallow the stratigraphic layers before being trapped along the sheets of glacigenic deposits above the URU.

The pockmarks on the seafloor of the study area indicate that the fluid migration has been active after the last glaciation. They might possibly also be active seeps, as they have not been buried. This, along with the paleo-pockmarks distribution of all the stratigraphic levels within the Naust Formation of the study area, suggest a relatively stable fluid flow during the deposition of the glacial sediments. This correlates with Berndt et al. (2003) which concluded that long-term, and still ongoing, fluid flow from polygonal faults is a general pattern along the mid-Norwegian continental shelf.

5.2.2 Fluid source

The study area display indications that the fluids originated in deposits older than the Naust Formation. One potential source of the fluids are the widespread Brygge Formation, where the polygonal faults may act as conduits of increased permeability for the fluids. Pipes consisting of fractured sediments along with deep-seated faults may also serve as conduits for fluids originating from the deep.

The Brygge Formation lies directly underneath the Naust Formation and several signs of fluid migration appear to originate at this boundary. The formation of polygonal faults are still poorly understood, but the faulting of the fine-grained hemipelagic oozes of the Brygge Formation are probably related to the sudden loading by the thick glacial deposits of the Naust Formation. During Naust time, the sediment load of the Brygge Formation gradually increased, resulting in compaction. This would lead to dewatering, forcing as much as 60% of the fluid volume out of the sediments (Berndt et al., 2003; Hustoft et al., 2007). It is therefore likely that the Naust Formation has been affected by the fluid flow from the underlying Brygge Formation. This process has been suggested to also have taken place further out on the mid-Norwegian continental shelf by Berndt et al. (2003) and Hustoft et al. (2007). There the polygonal faulting mainly affected the underlying Kai Formation. They concluded that the polygonal faults were the main source of fluids in the area. However, the Brygge Formation is not as massive in the study area as the Kai Formation is on the outer shelf. It also consist of a different lithology, which mean that the fluid expulsion might not be the same.

There are also seismic features that suggest fluid flow within deep-seated faults from older deposits. The pipes in the ST10013 survey stretches far below the Brygge Formation, but the direct source of the fluids are however unclear. It is also possible that the pipes are pseudo-velocity structures as they display pull-up. This may be a result of the wavy layering located above or high velocity sediments within the pipes. However, small bright spots have been identified along the vertical extent of the pipes, which strengthens the possibility of gas migration from the deep. The large bright spot in the ST07M07 survey, which is located above the edge of the Nordland Ridge, is most likely a result of fluids from a deeper source. Faults may act as fluid migration pathways, as numerous interconnected fractures could be gas fluid conduits. The fluids are probably not detectable within the fault zones, but strong amplitudes may appear as they migrate into adjacent layers of permeable sediments (Andreassen, 2009). These fluids may therefore follow the lager faults along the Nordland Ridge, which correlates well with some of the amplitude anomalies (Fig. 5.2.1).

In the shallow layers, there is also a possibility that the fluids have a bacterial origin. Bacterial methane formation is derived from microbial degradation of organic matter. However, this only takes place in shallow sediments such as organic-rich layers deposited during the last glacial stage (Hovland et al., 1993). Therefore, it is not likely that this has affected the lower parts of the Naust Formation in recent time.

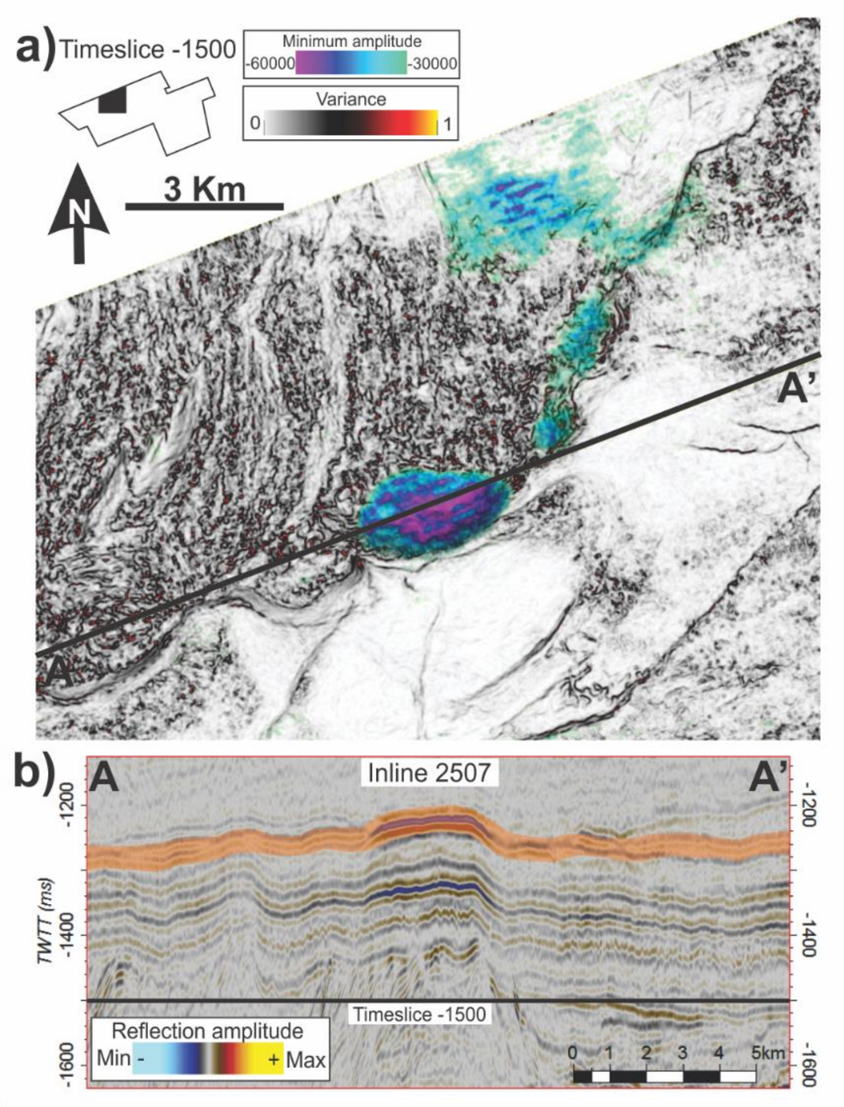


Figure 5.2.1 a) Combination of timeslice (-1500 ms TWTT) from variance cube generated from the ST07M07 survey and a minimum amplitude map where the low values have been made transparent. The map show the alignment of a large bright spot with the edge of the Nordland Ridge. Black line indicate location of b). b) Seismic section of the 2507 inline that show the location of the timeslice (black line) and the 40 ms window from which the minimum amplitude map has been generated (shaded area).

5.2.3 Conceptual fluid flow model

Based on the observations made in the study area, a conceptual fluid flow model was created. This model gives an image of how fluids travel through the strata and interacts with the geomorphology. It shows how the study area probably is affected by both fluids from the Brygge Formation, as well as fluids traveling through deep-seated faults. The fluids within the Naust Formation flow vertically within pipes or through fractures created by overpressure and as the fluids encounter permeable layers it can flow freely along the stratigraphic boundaries. Diffuse flow may not be observable in the seismic data, except from fluid accumulations within pockets, debris flows, sediment-fans, etc. (Fig. 5.2.2).

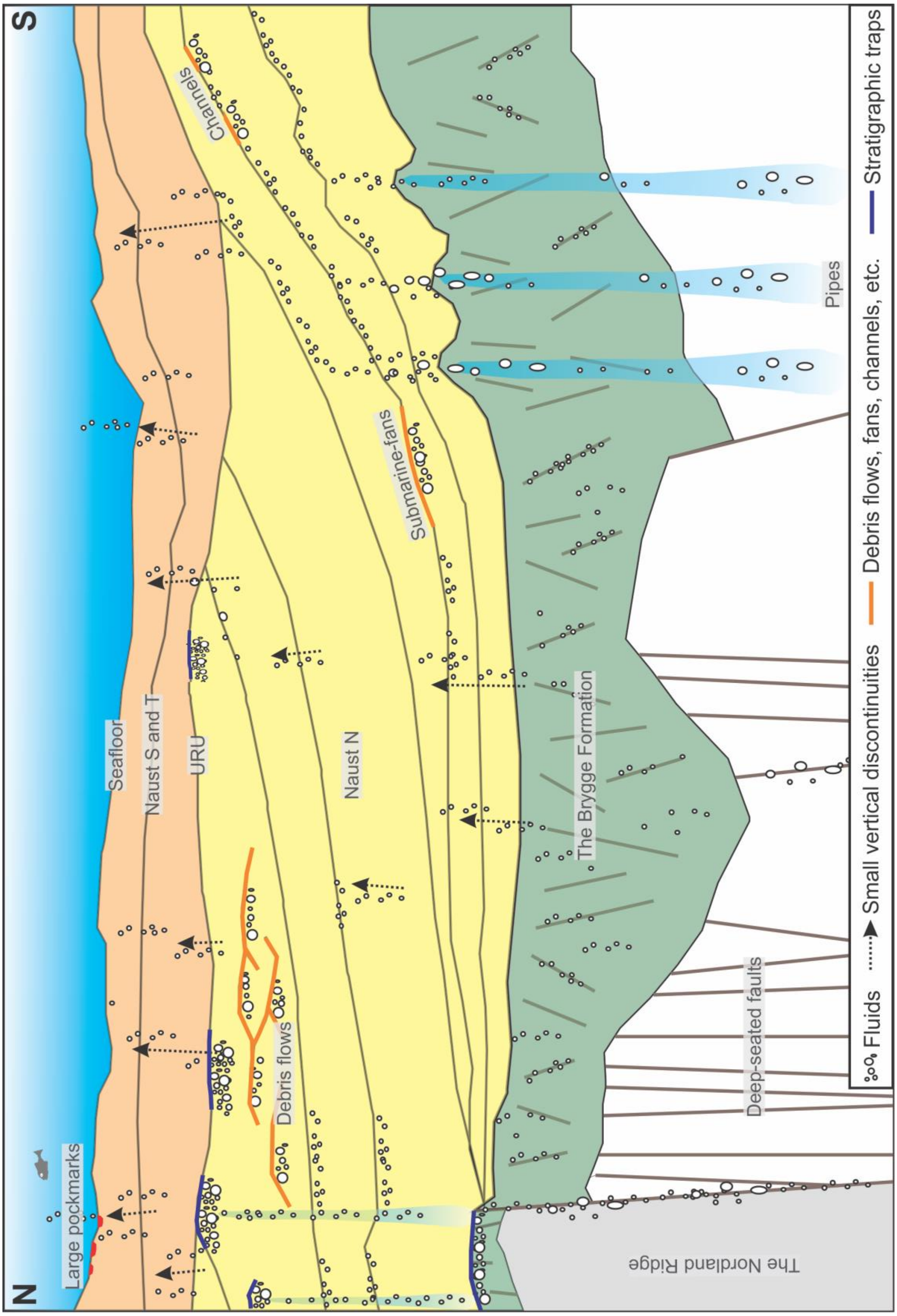


Figure 5.2.2 Conceptual fluid flow model showing how fluids might behave within the Naust Formation on the inner part of the mid-Norwegian continental shelf.

6 Conclusion

Using 3D-seismic data from Trænabanken and Sklinnadjupet along with regional 2D-lines, the deposition of the Naust Formation has been studied. The overall aim was to increase our understanding of the development in this part of the Naust Formation and from this, the glacial history along the mid-Norwegian continental margin. A second objective has been to describe and discuss if and how fluid migration has occurred. The findings of this study can be summed up in the following points:

- During the last 2.8 Ma glacial processes have been the main influence on the mid-Norwegian continental shelf, resulting in the up to 1000 m thick and 180 km wide Naust Formation. The reflection configuration displayed in seismic sections show a change in depositional geometry after the URU (base Naust S) from progradational to aggradational as well as progradational, due to subsidence and erosion generating accommodation space.

- Iceberg plough-marks have been identified within the study area from early Naust N time indicating the possibility that the ice front reached the Norwegian coast from this time onwards. However, it is also possible that the icebergs originated from other areas (e.g. the Greenland Ice Sheet).

- Morainal ridges suggest that the ice front reached the paleo-shelf edge in the study area during the middle of Naust N time. This is supported by a profound increase in deposition of debris flows on the paleo-slopes, which suggest that the depositional environment may have changed to become glacially dominated earlier than previously assumed.

- Paleo-troughs, MSGL and flutes have been identified all the way back to the base of Naust A (~1.5 Ma). This suggest that fast-flowing ice streams have played an important role in the outbuilding of the Naust Formation, and indicate the direction of the ice flow.

- During Naust A time (1.5-0.8 Ma) the main ice flow in the study area appears to have originated from the east. During Naust S time (0.4-0.2 Ma) the Elsterian glaciation resulted in the development of the URU in the study area with the ice flowing from Vestfjorden, all the way to the Skjoldryggen area. During Naust T time (<0.2 Ma) the direction of ice flow appeared to change between the Saalian and Weichselian glaciation. This was probably the result of the buildup of Trænabanken, changing the flow of the Vestfjorden ice stream to throughout Trænadjupet. Sklinnadjupet now became mostly affected by ice from the east, while Trænabanken was cowered by ice that is more stagnant.

- The relatively rapid deposition of the thick Naust Formation lead to polygonal faulting of the underlying Brygge Formation, which probably lead to dewatering and fluid flow. This may be the main source of fluid flow within the study area along with fluids flowing through deep-seated faults from a deeper source, in areas such as the Nordland Ridge.

- Vertical discontinuities indicating fluid flow within pipes or through fractures created by overpressure have been identified, while paleo-pockmarks and bright spots concentrated along specific stratigraphic layers suggest that as the fluids encountered permeable layers the flow could freely follow along the stratigraphic boundaries.

- Paleo-pockmarks have been found on all the interpreted surfaces, indicating that the fluid flow has been relatively constant through the deposition of the Naust Formation. The pockmarks identified on the seafloor suggest that the fluid flow has been active after the last glaciation, and might possibly be active seeps.

7 References

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