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Title	Glacigenic and glacimarine sedimentation from shelf to trough settings in the NW Barents Sea
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Abstract

A PARASOUND (3.5 kHz) sub-bottom echosounder profile acquired across the Spitsbergenbanken between Kveithola and Storfjorden troughs, NW Barents Sea, documents the lateral variation of sedimentary processes from shelf areas to troughs during the post Last Glacial Maximum (LGM) sea-level rise. In particular, while the Spitsbergenbanken and the southern margin of the Storfjorden trough are characterized by superficial glacial till and eventual post-glacial deposits reworked to a certain extent by iceberg keels, the Kveithola trough documents extensive glacimarine and bottom current sedimentation above the glacial till, only partially affected by ice movement. This evidence suggests that both the Spitsbergenbanken and the southern margin of the Storfjorden trough were mostly sediment bypass areas during the post glacial phase, whereas the Kveithola trough was a comparatively protected area in which relatively weak currents allowed the accumulation of fine-grained deposits. These findings highlight a marked lateral sedimentary variability due to local physiography and hydrodynamics in areas that were covered by thick ice sheets during the LGM, which must be taken into account to produce models that describe post-glacial depositional processes.

Keywords	Barents Sea; Spitsbergenbanken; Kveithola trough; Storfjorden trough; glacimarine sedimentation; sub-bottom profiles
Taxonomy	Ice Sheets, Seismic Stratigraphy

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Submission Files Included in this PDF

File Name [File Type]

Revision notes.doc [Response to Reviewers]

Zecchin & Rebesco Rev_1_marked.docx [Revised Manuscript with Changes Marked]

Highlights.docx [Highlights]

Zecchin & Rebesco Rev_1.docx [Manuscript File]

Zecchin & Rebesco Fig 01.tif [Figure]

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Dear Editor,

I am the first author of the manuscript entitled: "Glacigenic and glacimarine sedimentation from shelf to trough settings in the NW Barents Sea", submitted to Marine Geology for the GLAMAR (Glaciated Margins) Special Issue.

The manuscript has been revised following the recommendations of the reviewers. In particular, I would like to bring to your attention our response to the following points:

Response to comments by the Editor

I would like you to address the issue of novelty that the reviewers raise (i) how does this add significantly to the data published in Zecchin et al 2016; (ii) the conclusion (that there is thin sediment over inter-trough banks, and thicker sediment in troughs) is rather well known already, and so the paper needs a much clearer explanation of how this is new. The reviewers also note that there is rather little data (one profile) underpinning this paper. Given the issue of novelty this may be a fatal problem with thw paper ?

R. Although the different sedimentation pattern between troughs and banks is generically known, this is usually recognized by comparing unconnected studies performed either on banks or within troughs. Studies that directly show how the post-glacial sedimentation varies along a transect, such as the present one, are rare, and this is now more clearly remarked at the beginning of the Discussion (page 9). Another example is the recently published paper by Lantzsch et al. (2017), which shows in detail this variability but in a much more limited area (just in one trough and its immediately adjacent southern margin).

Regarding, the data availability, there is another profile intersecting that we have used. However, it is redundant with respect to the illustrated profile, and its irregular, zigzag path does not help for our purpose. However, with respect to our initial submission we now added information about three cores that are published with different levels of detail in three distinct previous studies (Fig. 7) and report datings. These cores are all aligned on the profile we describe, one from each of the different settings crossed by the profile (the two troughs and the intervening bank). The novel direct correlation of these cores along a single profile allows us to compare the sedimentation in the different settings.

This comparison performed in our revision conducted to another outcome that in part contrasts with the conclusions by Lantzsch et al. (2017). It highlights a diachronism in the onset of sedimentation of glacimarine and bottom current deposits between troughs and banks (see the Discussion, page 10, and Fig. 8). We believe that only for this, the paper would merit to be published. Moreover, the comparison between units and ages available from the literature has allowed to ascertain that in the

Kveithola trough Unit 3 is not found and is replaced by Unit 4 (Fig. 2). This led to some modifications in the description of Units 3 and 4.

Response to comments by Reviewer 1

Although this works is clearly supported by previous papers published by the authors, as well as, other authors in the study area, the analysis of only one sub-bottom profile is always risky. Discussion and conclusions are a rehash of conclusions that other authors have been pointing at least from 1993 (e.g. Andersen et al., 1996; Bjarnadóttir et al., 2013; Elverhøi et al., 1993; Mangerud et al., 1998; Rebesco et al., 2016). New insights are poor and need to be clearly improved. Open questions are the base for a new projects and works, but seem that is the only new in this work.

R. OK, we improved the discussion also by citing the references suggested by the reviewer and we now significantly augmented the new insights as detailsed in the previous comment to the Editor.

Specific comments:

Line 13: Also line 29 and all the manuscript, check for consistency (e.g. sub-bottom).

R. OK, we chacked the consistency.

Lines 34-37: The sentence seems to point that the highest deposition is in the troughs, while it occurs on the fan (e.g. Dowdeswell et al., 1999, Laberg et al., 2012). Please, re-write the sentence.

R. OK, we rephrased.

Lines 45-49: Are you pointing out that your work can not appreciate this variability? I guess you mean: "so far concentrated on Kveithola and Storfjorden troughs, and (not 'or') Spitsbergenbanken".

R. OK, we rephrased.

Line 69: Not only one ice sheet covered the Barents Sea continuously from Pliocene to Present. Delete "An".

R. OK. Done.

Line 84: Methods. Too details on how PARASOUND works. Explain just the important details of acquisition and you could refer to: Hanebuth et al., 2013 (CORIBAR – Ice Dynamics and Meltwater Deposits: Coring in the Kveithola Trough, NW Barents Sea. Cruise MSM30) for more details. Also, the bathymetry has no details about the acquisition while in the cruise reports explain the three different acquisition systems that have been used. Which is the final resolution of the joined reprocessed bathymetry?

R. OK, thanks for the suggstion. The part dealing with the PARASOUND profiles has been now simplified, whereas the requested details on the bathymetry were added.

Line 104: change online to real-time.

R. OK, this part was removed.

Line 128: The thickness is extracted from a core or from TWTT to depth conversion. If it's the last option, please point out the velocity used. The same applies for further unit thicknesses.

R. OK. The information for the conversion was added in the Methods (line 97).

Line 163: Maybe better to change 'to' to 'towards'.

R. OK. Done.

Discussion and conclusions: As has been pointed above, this section has to be deeply improved. i.e. lines 233-235: when approximately the sea level was high enough? e.g. (Elverhøi et al.,1995; Andersen et al., 1996; Mangerud et al., 1998).

R. As remarked above the Discussion was significantly improved. However, we have not enough data to precisely estimate when the sea level was high enough to lead to the disappearance of the grounded ice on the Spitsbergenbanken.

Figure 2 shows the location of cores. Although the authors do not use in this work, they should be labeled and, maybe refer to previous works that have used these cores.

R. OK. Done. And in fact we now make a novel use of the cores (see details in the Response to comments by the Editor).

Response to comments by Reviewer 2

This is an interesting study that will be of broad interest to scientists working on high-latitude continental margins, ice sheet change, sedimentary processes and ice sheet modelling. The authors use subbottom profiler data to assess lateral sedimentary variability and the influence of local physiography and hydrodynamics on this. The study highlights some interesting observations and is well written. I recommend accepting the manuscript with minor revisions detailed below.

I included here two main comments about the manuscript, with specific comments detailed below.

1) Consider adding a summary figure or table detailing and showing examples of each of the acoustic units and characteristics. It is difficult to distinguish differences in acoustic unit characteristics on the figures. Alternatively separate panels could be added to each of the figures showing 'zoom in' of acoustic unit.

R. OK, thanks for the suggestion. We now added a new figure (Fig. 6), reporting units, acoustic facies and their interpretation.

2) It seems that a large part of the interpretation in this study is based on previous work by Zecchin et al. (2016) using acoustic and core data. The section integrating existing core data with new acoustic data should be extended to show how this interpretation was extended.

R. OK, agreed, and in fact we now added core data from further studies (see the new Fig. 7) that are aligned on the profile (see details in the Response to comments by the Editor).

Specific comments

Abstract:

L13. Consider adding total length in km of acoustic profile analysed.

R. We attempted, but found this difficult. However, the length may be estimated based on Fig 1B.

L18. Change 'iceber' to 'iceberg'

R. OK. Done.

Text:

L41. Remove 'to define'

R. OK. Done.

L42. Add 'to be defined' at end of sentence.

R. OK. Done.

L44. Add 'in order to' after 'considered'

R. OK. Done.

L47. Change ‘was’ to ‘has’

R. OK. Done.

L52. Change ‘to compare’ to ‘the’; add ‘to be compared’ after ‘erosional processes’.

R. OK. Done.

L54. Change ‘dinamics’ to ‘dynamics’

R. OK. Done.

L72. Change ‘E-W’ to ‘East – West’

R. OK. Done.

L85. Add total length in km of acoustic profile analysed.

R. See point L13.

L109. Is the multibeam bathymetric data new data? Has this been previously described in the area of interest?

R. OK. This part was expanded.

L114. The multibeam data is not described anywhere yet is detailed in the methods section. Consider adding a short paragraph on this.

R. OK. This part was expanded.

L117. Is profile ‘20130725’ the whole profile in Fig 1? This should be mentioned in the methods section.

R. OK. Done (line 91).

L112 (and throughout the results sections). ‘Segment A’ (and B, C and D herein) where is this? This has not been labelled on Figure 1. This should be added.

R. OK. Done.

L127. ‘the base of this higher amplitude zone’ – can you show a zoom in or inset figure of this? This is not clear from the current figure.

R. OK. We now added the new Fig. 6, reporting units, acoustic facies and their interpretation.

L161. Again, consider adding inset figure to show this.

R. Ok. See above point about new Fig. 6.

L167. Can you elaborate on how core data supports this? Consider adding few sentences to integrate core results. You show some cores of the figures but this is left out of the discussion.

R. OK. Further core data were added, and this led to modifications in the Results and Discussion (see previous reply to the comment to Fig. 2 and details in the Response to comments by the Editor).

L198. What core data? Extend this.

R. OK. See previous point.

L203. Change 'to document' to 'documentation of the'

R. This part was modified.

L204. Are there any previous dates available from cores?

R. Yes, see also our new Fig. 7 and the modifications in the Results and discussion.

L218. Change 'affect' to 'affected'

R. OK. Done.

L238. How does this relate to local physiography?

R. This was intended as a general statement, which only highlights that also physiography (e.g., banks and troughs) affects the sedimentation pattern. We hence not modified the text.

L239. Change 'hydrodinamic' to 'hydrodynamic'

R. OK. Done.

L242. What are the other local factors? Can this section be extended?

R. This was intended as a general statement. In any case, the phrase was modified.

Figures:

Figure 1. What is the thin black line parallel to the parasound line (below the text ‘Storfjorden’ and above the text ‘Fig.4’. Can this be removed?

R. This cannot be removed.

Segment labels A-D needs to be added to Figure 1.

R. OK. Done.

Figure 2. What is the core number / reference? This is not discussed in the text so consider leaving out or add discussion.

R. OK. Done. We now added this and expanded the discussion.

References:

Missing references:

- Rasmussen & Thomsen (2015)

R. We do not refer to the paper of 2015, but to that of 2014, which is included in the reference list.

- Rebesco et al (2014) should be 2014a and 2014b in text and reference list.

R. OK. Done.

On the behalf of all authors,

Yours sincerely,

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Glacigenic and glacimarine sedimentation from shelf to trough settings in the NW Barents Sea

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ABSTRACT

A PARASOUND (3.5 kHz) sub-bottom echosounder profile acquired across the Spitsbergenbanken between Kveithola and Storfjorden troughs, NW Barents Sea, documents the lateral variation of sedimentary processes from shelf areas to troughs during the post Last Glacial Maximum (LGM) sea-level rise. In particular, while the Spitsbergenbanken and the southern margin of the Storfjorden trough are characterized by superficial glacial till and eventual post-glacial deposits reworked to a certain extent by iceberg keels, the Kveithola trough documents extensive glacimarine and bottom current sedimentation above the glacial till, only partially affected by ice movement. This evidence suggests that both the Spitsbergenbanken and the southern margin of the Storfjorden trough were mostly sediment bypass areas during the post glacial phase, whereas the Kveithola trough was a comparatively protected area in which relatively weak currents allowed the accumulation of fine-grained deposits. These findings highlight a marked lateral sedimentary variability due to local physiography and hydrodynamics in areas that were covered by thick ice sheets during the LGM, which must be taken into account to produce models that describe post-glacial depositional processes.

Keywords: Barents Sea; Spitsbergenbanken; Kveithola trough; Storfjorden trough; glacimarine sedimentation; sub-bottom profiles.

1. Introduction

High-latitude margins, which are covered by thick ice caps and ice streams during full-glacial conditions, have a typical physiography consisting of deep ice-carved troughs reaching the shelf margin separated by shallower banks (Canals et al., 2003; Batchelor and Dowdeswell, 2015). The glacigenic sedimentation is mostly concentrated within the troughs and at their seaward ends, and encompasses subglacial, terminal, lateral and recessional moraines, grounding zone wedges composed of glacial till and forming transverse ridges, and trough mouth fans composed of glacigenic debris flow-deposits (e.g., Ó Cofaigh et al., 2003; Rebesco et al., 2011; Bjarnadóttir et al., 2013; Andreassen et al., 2014). These deposits are typically draped by glacimarine and hemipelagic sediments. In contrast, glacigenic and glacimarine sediments are relatively thin on shelf banks separating the troughs (Elverhøi et al., 1993; Andersen et al., 1996; Mangerud et al., 1998; Batchelor and Dowdeswell, 2015; Bjarnadóttir et al., 2014). This general depositional framework has allowed a sequence stratigraphic model for high-latitude shelves to be defined (Zecchin et al., 2015).

The complex physiography of high-latitude margins, therefore, determines strong lateral variability of depositional processes along both depositional dip and strike, which must be considered in order to reconstruct glacial and deglacial histories. However, shelf studies are usually concentrated either on troughs or bank areas, and therefore this variability commonly cannot be appreciated by a direct comparison. In the case of this study area for example, the work has so far concentrated on Kveithola (e.g. Rebesco et al., 2011, 2016; Bjarnadóttir et al., 2013; Lantzsch et al., 2017) and Storfjorden (e.g., Pedrosa et al., 2011) troughs or on Spitsbergenbanken (Zecchin et al., 2016).

The present study is aimed at documenting the lateral variation of sedimentary processes between the Spitsbergenbanken and the Kveithola and Storfjorden troughs, in the NW Barents Sea (Fig. 1A,B). This allows the sedimentary and erosional processes, and ice overprint between topographic highs and lows, to be directly compared along a single sub-bottom profile. The present results need to be taken into account to construct general models of glacigenic and glacimarine sedimentation, as well as of ice dynamics, in high-latitude margins (Colleoni et al., 2016; Petrini et al., 2017).

2. Geological setting

The study area is located in the NW Barents Sea, between Kveithola and Storfjorden troughs (Fig. 1A,B). A rifting phase between Greenland and Spitsbergen, leading to the opening of the Fram

Strait, started during the Oligocene, and a narrow oceanic corridor developed during early Miocene (Engen et al., 2008). The Barents Sea, which covers one of the widest continental shelves in the world, is dissected by glacially-carved troughs (e.g. the Bear Island Trough, the Storfjorden and Kveithola Troughs; Andreassen et al., 2004, 2014; Winsborrow et al., 2010; Pedrosa et al., 2011; Rebesco et al., 2011; Fig. 1B) that are associated with wide trough mouth fans at the continental slope (e.g., Rebesco et al., 2014a).

A Plio-Pleistocene progradational phase favored by tectonic uplift and high sediment supply, initially related to fluvial discharge and to subglacial sediment discharge later on, led to the seaward expansion of the shelf margin by up to 150 km and to the formation of the topographic troughs (Forsberg et al., 1999; Dahlgren et al., 2005). Ice sheets covered the northern part of the Barents Sea since the late Pliocene, progressively expanding to the south (Vorren and Laberg, 1997; Knies et al., 2009). The Spitsbergenbanken was covered by a marine-based ice dome during the LGM, whereas paleo-ice streams flowed in the Storfjorden and Kveithola troughs (Lucchi et al., 2013). East-West trending mega-scale glacial lineations, recording ice stream movement, developed inside the Kveithola Trough during LGM, and got in parts overprinted by grounding-zone wedges during the early deglaciation (Rebesco et al., 2011; Bjarnadóttir et al., 2013). Since Early Pleistocene, contourite drifts started to develop on the Svalbard margin under the action of Norwegian Sea Deep Water episodically ventilated by relatively dense and turbid shelf water from the Barents Sea (Rebesco et al., 2013). Such contourite drifts on the continental rise grow in geographical coincidence with the mouths of the major glacial troughs on the continental shelf and experience an interaction of processes during glacial-interglacial periods, reflecting size variations of the ice sheets and water masses dynamics (Villa et al., 2003; Grützner et al., 2003; Giorgetti et al., 2003; Amblas et al., 2006; Rebesco et al., 2007). The huge sediment supply due to an exceptionally large output of glacial meltwater led to the accumulation of relatively thick plumite sequences (*sensu* Hesse et al., 1997) on the Svalbard margin and on the Storfjorden and Kveithola Trough mouth fans during the subsequent later deglaciation phase (Fohrmann et al., 1998; Rasmussen et al., 2007; Jessen et al., 2010; Lucchi et al., 2013; Rasmussen and Thomsen, 2014; Llopart et al., 2015).

3. Methods

The acoustic profile used in this study (profile 20130725, Fig. 1B) was acquired using a PARASOUND DS III-P70 system (Atlas Hydrographic) during research cruise MSM30 CORIBAR with the German RV MARIA S. MERIAN in July/August 2013 (Hanebuth et al., 2013, 2014). The PARASOUND system generates two parametric frequencies (approx. 4 kHz and 40 kHz, respectively). The parametric frequency and 70 kW transmission power allows sub-bottom penetration up to 200 m (depending on the sediment composition) with a vertical resolution of about 40 cm. The conversion from TWT to depth (Figs. 2-5) is based on a velocity of 1500 m/s. Multibeam bathymetric data shown in Fig. 1 were acquired during three different cruises with different vessels: SVAIS (Camerlenghi et al., 2007), EGLACOM (Zgur et al., 2008) and CORIBAR (Hanebuth et al., 2013). The three datasets have been jointly reprocessed at OGS by importing all data in CarisHips&Sips, removing refraction problems, applying tide corrections and rejecting spurious data using a surface filter based on 2D editing in Subset Editor. The data were then imported in Global Mapper UTM 33 WGS84 (20m grid) and superimposed onto IBCAO data (Jakobsson et al., 2012) with a vertical exaggeration of 2.7 and Light Direction Attitude 35°, Azimuth -30°.

PARASOUND and Multibeam data were successively displayed with the Kingdom Suite software (IHS Inc., Englewood, CO) for interpretation.

4. Results

4.1. Acoustic units

Four acoustic units (Unit 1 to Unit 4 from the base to the top) were defined from the PARASOUND profile 20130725 based on acoustic facies appearance and bounding internal surfaces (Figs. 2-5).

Acoustic units and facies are summarized in Fig. 6.

4.1.1. Unit 1

Unit 1 is the lowermost acoustic unit and is recognizable in all segments of the studied profile (Figs. 2-5). It is opaque and its base is not visible. Some variably inclined reflections are present in places toward the upper part of the unit, especially in segment A of the profile (Fig. 2), and they tend to merge with the irregular upper boundary. While in segment A and in the southern part of segment B of the studied profile Unit 1 is overlain by Units 2-4 and locally crops out (Figs. 2 and 3), in the northern part of segment B and in segments C and D, i.e. on the Spitsbergenbanken and toward the Storfjorden trough, the upper part of the unit is irregular, in places chaotic and shows higher amplitude (Figs. 3-5). The base of this higher-amplitude zone is very irregular, in places incised and commonly fuzzy and poorly defined (Figs. 3-5). This zone reaches a maximum thickness of ca. 15 m. Within the Kveithola trough, Unit 1 forms convex-up bodies 5 to 10 km wide and up to 50 m high with respect to the adjacent depressions (Fig. 2).

4.1.2. Unit 2

Unit 2 is found only in segment A and in the southern part of segment B of the studied acoustic profile (Figs. 2 and 3). It is up to ca. 17 m thick and overlies Unit 1. Unit 2 is semitransparent and structureless on the topographic highs, between the northern part of segment A and the southern part of segment B, where exhibits an extremely irregular upper boundary marked by numerous incisions (Figs. 2 and 3). In segment A, these deposits rapidly grade downdip, toward the adjacent Kveithola trough, into laminated, transparent to semitransparent deposits characterized by low- to high-amplitude reflections, which drape the irregular top of Unit 1 (Fig. 2). Laminated deposits characterized by medium- to high-amplitude irregularly undulating reflections are found also in local shallower depressions separating the topographic highs, such as in the northernmost part of segment A (Fig. 2). The laminated facies never exhibits an incised upper boundary (Fig. 2). Unit 2 is locally exposed at the seafloor in areas where Units 3 and 4 are absent (Figs. 2 and 3).

4.1.3. Unit 3

Unit 3 is up to ca. 7.5 m thick and is found only in the northern part of segment A and in the southern part of segment B of the studied acoustic profile (Figs. 2 and 3). It fills the irregular incisions found at the top of Unit 2 on the topographic highs, or drapes the laminated part of Unit 2 in the minor depressions (Figs. 2 and 3). Unit 3 is well laminated and consists of high- to medium-amplitude reflections (Figs. 2 and 3). In the Kveithola trough it cannot be discriminated, and it is possibly replaced by the lower part of Unit 4 (Fig. 2). Unit 3 is absent also on the highest parts of the topographic highs, where Unit 1 and/or Unit 2 are exposed at the seafloor (Figs. 2 and 3).

4.1.4. Unit 4

Unit 4 is up to ca. 25 m thick and is found only in segment A and in the southern part of segment B of the studied acoustic profile (Figs. 2 and 3). In the depressions on the southern flank of the Spitsbergenbanken, Unit 4 drapes the upper boundary of Unit 3, or unconformably overlies the tops of Units 1 or 2 where Unit 3 is absent (Figs. 2 and 3). In the Kveithola trough, the unit drapes the top of Unit 2 (Fig. 2). Unit 4 is laminated and can be distinguished from the underlying Units 2 and 3 by its average lower amplitude which makes its appearance more transparent (Figs. 2 and 3). The boundary between Units 2/3 and Unit 4 is usually well recognizable due to the contrast in amplitude of the reflections (Figs. 2 and 3). Unit 4 is present only in topographic depressions; in the Kveithola trough, it shows characteristics lateral pinch-outs and disappear towards the south (Fig. 2).

4.2. Interpretation of acoustic data

Units 1-4 correspond to the homonymous units described by Zecchin et al. (2016) on the southern margin of the Spitsbergenbanken on the basis of both acoustic and core data. The overlap between two intervals in segments A and B of the studied acoustic profile (Figs. 2 and 3), and those illustrated by Zecchin et al. (2016), enable us to extend laterally the recognized acoustic units in the whole study area.

Following Zecchin et al. (2016), Unit 1 is interpreted as subglacial till related to grounded ice (e.g., Batchelor et al., 2011; Rebesco et al., 2011; 2014b; Ó Cofaigh et al., 2005). This interpretation is also consistent with that provided by Lantzsch et al. (2017) in the Kveithola trough. The convex-up bodies found in the Kveithola trough (Fig. 2) are interpreted as grounding-zone wedges accumulated during stillstand in grounding-zone position (e.g., Rebesco et al., 2011). The local reflections within Unit 1 probably represent interfaces between depositional stages (Ó Cofaigh et al., 2005; Rebesco et al., 2011; Bjarnadóttir et al., 2013; Hanebuth et al., 2014).

The appearance of the irregular higher-amplitude zone found in the uppermost part of Unit 1 suggests intense reworking, most probably by iceberg keels, of the top of the glacial till and/or of younger glacimarine deposits (e.g., Zecchin et al., 2016). Some major depressions in the southern margin of the Storfjorden trough might correspond to mega-scale glacial lineations, recording ice stream movement (e.g., Pedrosa et al., 2011; Lucchi et al., 2015). This interval is called 'reworked zone' in Figs. 2-5.

Unit 2 is interpreted as a glacimarine deposit, inferred to have accumulated from the vertical settlement of muddy and sandy sediment during the onset of the deglaciation, originating from hyperpycnal flows (Zecchin et al., 2016). Glacimarine deposits, tentatively correlated with those that form Unit 2, or both Units 2 and 3 (see below), and overlain by hemipelagites (here correlated with Unit 4), are locally preserved also in some depressions of the Storfjorden trough, close to the northern end of the studied acoustic profile (Llopart, 2016; core GeoB17610-2 in Fig. 7).

The extremely irregular upper boundary of Unit 2 on the topographic highs (Figs. 2 and 3) was interpreted by Zecchin et al. (2016) as the result of ploughmarks produced by iceberg-keel scouring (e.g., Dowdeswell et al., 1993; Barnes, 1997; MacLean, 1997; Solheim, 1997; López-Martínez et al., 2011; Robinson and Dowdeswell, 2011). This scouring by iceberg keels probably led to the dismembering of the laminated deposits of Unit 2 and to a formation of ploughmarks on the topographic highs. In contrast, iceberg keels were probably not deep enough to affect the sediment accumulated inside the topographic depressions.

On the basis of core GeoB17623-2 (Fig. 7), Zecchin et al. (2016) interpreted Unit 3 as a glacimarine deposit accumulated from suspension clouds, which were related to ice melting carrying muddy sediment (e.g., Hesse et al., 1997; Lucchi et al., 2013; 2015). The presence of layers produced by fall-out of ice-rafted debris (IRD) may explain the higher amplitude of the internal reflections in Unit 3 (Zecchin et al., 2016).

Unit 4 is inferred to have deposited from bottom currents (Zecchin et al., 2016). This is confirmed by core GeoB17623-2 (Zecchin et al., 2016; Fig. 7) and by previous studies performed in the Kveithola trough, which interpreted the laminated deposits overlying glacimarine ones and showing lateral pinch-outs as being part of a sediment drift (Bjarnadóttir et al., 2013; Rebesco et al., 2016; Lantzsch et al., 2017) (see core GeoB17607-5 in Fig. 7).

5. Discussion and conclusions

The studied acoustic profile provides the rare opportunity to observe how the post-LGM sedimentation varies between a shelf bank and the adjacent troughs, specifically from the Spitsbergenbanken to the Kveithola and Storfjorden troughs. This variation is usually difficult to appreciate in individual studies performed in significantly smaller areas.

Unit 1 probably records ice movement during the LGM and the early phase of ice retreat, which were characterized by the formation of moraines, mega-scale glacial lineations and grounding zone wedges (e.g., Rebesco et al., 2011; Bjarnadóttir et al., 2013, 2014) (Fig. 8A). The most striking feature of the studied transect is the occurrence of laminated glacimarine and bottom current deposits only on the southern margin of the Spitsbergenbanken and in the Kveithola trough (Fig. 8B-E). Following Zecchin et al. (2016) and Lantzsch et al. (2017), these deposits accumulated during specific phases related to both ice melting and glacio-eustatic sea-level rise. In particular, Unit 2 is inferred to have accumulated after a phase of sea-level rise accompanied by ice lifting (Zecchin et al., 2016), which favored the flow of meltwater beneath the ice and the accumulation of glacimarine deposits south of the Spitsbergenbanken (Fig. 8B). This phase was probably at least in part concomitant with the known brief episode of glacio-eustatic sea-level rise called meltwater pulse 1A (14.6 to 13.5 cal ka BP; Bard et al., 1990; Deschamps et al., 2012). However, glacimarine sedimentation above the subglacial till initiated earlier, at ca. 16 cal ka BP, in the Kveithola trough (Lantzsch et al., 2017), probably due to a greater accommodation available in that location after the ice started to melt. The following phase was characterized by ice break up and subsequent production of icebergs, which disturbed the previously accumulated sediments and formed the ploughmarks that affected Unit 2 (Zecchin et al., 2016) (Fig. 8C). With the progress of the deglaciation, sediment supply from suspension clouds led to the accumulation of Unit 3, which filled the irregularities of the seabed on the southern flank of the Spitsbergenbanken (Fig. 8D). Finally, the accumulation of the bottom current deposits of Unit 4 persisted in iceberg-free conditions (Fig. 8E).

Datings of core samples have revealed that Unit 4 started to accumulate at ca. 13.5 cal ka BP in the Kveithola trough (Lantzsch et al., 2017), and at ca. 9 cal ka BP just south of the Spitsbergenbanken (Zecchin et al., 2016; see core GeoB17623-2 in Fig. 7). This observation highlights a significant diachronism in the timing of sedimentation of post-glacial units between throughs and minor depressions on the banks. The possible persistence of partially grounded ice shelf (e.g., Yokoyama et al., 2016) on the Spitsbergenbanken, leading to accumulation from suspension plumes related to ice melting in protected locations away from the Kveithola trough, might explain the delayed sedimentation of bottom current deposits. This diachronism implies that the accumulation of Unit 3 on the southern flank of the Spitsbergenbanken was coeval with that of the lower part of Unit 4 in the Kveithola trough (Fig. 8D).

Some hypothesis can be made regarding the lack of Units 2-4 on the Spitsbergenbanken and in the southern margin of the Storfjorden trough, although up to 3 m of glacimarine and hemipegic sediments may locally drape the subglacial till in the latter (Llopart, 2016; core 17610 in Fig. 7). A deeper reworking by iceberg keels might have removed or strongly disturbed previously accumulated glacimarine deposits, which would have been replaced by a reworked zone (Fig. 8B,C). Afterwards, relatively strong currents north of the Spitsbergenbanken may have prevented the accumulation of very thick laminated glacimarine and bottom current deposits, which instead accumulated in the smaller, more protected Kveithola trough (Fig. 8D,E). The Spitsbergenbanken and the southern margin of the Storfjorden trough, therefore, would be mostly sediment bypass areas. The possible persistence of grounded ice on the Spitsbergenbanken, until the sea level approximated that of the present day (Fig. 8C,D), may conceivably explain the lacking recognition of glacimarine sediments in that location.

The variable sedimentary response between the Kveithola and the Storfjorden troughs identified in this work points to a marked variability of ice dynamics, hydrodynamics and sediment dispersal patterns in the study area, at least in part related to local physiography. However, more research is needed to better document the variability of hydrodynamic conditions between the two considered troughs. The present case history shows that care must be taken in applying standard depositional models of glacimarine sedimentation during deglaciation phases, as strong lateral variability even in adjacent areas is commonly found, especially between troughs and morphological highs.

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FIGURE CAPTIONS

Fig. 1. (A) Location map with the study area (red box) in the NW Barents Sea (bathymetry from IBCAO, Jakobsson et al., 2012). (B) Shaded relief map of the study area, showing the Kveithola Trough, the southern part of the Storfjorden trough and the SW margin of the Spitsbergenbanken. The studied PARASOUND sub-bottom echosounder profile is highlighted.

Fig. 2. PARASOUND profile 20130725, segment A (see Fig. 1B for location). Four acoustic units (Units 1-4) are identified (see the line drawing below). Where exposed, the top of Unit 1 is locally reworked (reworked zone). Note on the right the interval considered by Zecchin et al. (2016).

Fig. 3. PARASOUND profile 20130725, segment B (see Fig. 1B for location). Four acoustic units (Units 1-4) are identified (see the line drawing below). The top of Unit 1 is reworked in the northern part of the profile (reworked zone). Note on the left the interval considered by Zecchin et al. (2016).

Fig. 4. PARASOUND profile 20130725, segment C (see Fig. 1B for location). One acoustic unit (Units 1) is identified (see the line drawing below), the top of which is reworked (reworked zone).

Fig. 5. PARASOUND profile 20130725, segment D (see Fig. 1B for location). One acoustic unit (Units 1) is identified (see the line drawing below), the top of which is reworked (reworked zone).

Fig. 6. Acoustic units (Unit 1 to Unit 4 from the base to the top), defined from the PARASOUND profile based on acoustic facies appearance. See text for details of the interpretation.

Fig. 7. Sedimentary facies and inferred corresponding acoustic units (see Figs. 2-5) in the cores considered in this study (see Fig. 1B for location). Where available, calibrated radiocarbon ages are

indicated in red on the left. Cores GeoB17607-5, GeoB17623-2 and GeoB17610-2 are modified respectively from Lantzsch et al. (2017), Zecchin et al. (2016) and Llopart (2016).

Fig. 8. Interpreted depositional history between the Kveithola and Storfjorden troughs based on the studied acoustic profile (see Fig. 1B for location; please notice that the orientation of the profile is progressively changing by about 180°). (A) The early phase of ice retreat that followed the Last Glacial Maximum was characterized by the accumulation of moraines and grounding zone wedges composing Unit 1. (B) After an episode of sea-level rise accompanied by ice lifting, which favored the flow of meltwater beneath the ice, glacimarine deposits composing Unit 2 accumulated south of the Spitsbergenbanken and possibly toward the Storfjorden trough. Unit 2 probably started to accumulate earlier in the Kveithola trough with respect to the southern margin of the Spitsbergenbanken (see text). (C) Icebergs produced by ice break up formed the ploughmarks that affect Unit 2 south of the Spitsbergenbanken and a reworked zone to the north. (D) Sediment supply from suspension clouds led to the accumulation of Unit 3 in the depressions of the southern flank of the Spitsbergenbanken, filling the irregularities of the seabed, whereas bottom current deposits (Unit 4) already started to accumulate in the Kveithola trough. Relatively strong currents may have prevented the accumulation of laminated glacimarine deposits in the northern part of the study area. (E) Later, the accumulation of the bottom current deposits of Unit 4 initiated also in the depressions of the southern flank of the Spitsbergenbanken, probably in iceberg-free conditions.

The lateral variation of sedimentary processes between banks and troughs is documented

Local physiography affected ice dynamics, hydrodynamics and sediment dispersal patterns

A diachronism in the timing of sedimentation between troughs and banks was recognized

Glacigenic and glacimarine sedimentation from shelf to trough settings in the NW Barents Sea

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ABSTRACT

A PARASOUND (3.5 kHz) sub-bottom echosounder profile acquired across the Spitsbergenbanken between Kveithola and Storfjorden troughs, NW Barents Sea, documents the lateral variation of sedimentary processes from shelf areas to troughs during the post Last Glacial Maximum (LGM) sea-level rise. In particular, while the Spitsbergenbanken and the southern margin of the Storfjorden trough are characterized by superficial glacial till and eventual post-glacial deposits reworked to a certain extent by iceberg keels, the Kveithola trough documents extensive glacimarine and bottom current sedimentation above the glacial till, only partially affected by ice movement. This evidence suggests that both the Spitsbergenbanken and the southern margin of the Storfjorden trough were mostly sediment bypass areas during the post glacial phase, whereas the Kveithola trough was a comparatively protected area in which relatively weak currents allowed the accumulation of fine-grained deposits. These findings highlight a marked lateral sedimentary variability due to local physiography and hydrodynamics in areas that were covered by thick ice sheets during the LGM, which must be taken into account to produce models that describe post-glacial depositional processes.

Keywords: Barents Sea; Spitsbergenbanken; Kveithola trough; Storfjorden trough; glacimarine sedimentation; sub-bottom profiles.

1. Introduction

High-latitude margins, which are covered by thick ice caps and ice streams during full-glacial conditions, have a typical physiography consisting of deep ice-carved troughs reaching the shelf margin separated by shallower banks (Canals et al., 2003; Batchelor and Dowdeswell, 2015). The glacigenic sedimentation is mostly concentrated within the troughs and at their seaward ends, and encompasses subglacial, terminal, lateral and recessional moraines, grounding zone wedges composed of glacial till and forming transverse ridges, and trough mouth fans composed of glacigenic debris flow-deposits (e.g., Ó Cofaigh et al., 2003; Rebesco et al., 2011; Bjarnadóttir et al., 2013; Andreassen et al., 2014). These deposits are typically draped by glacimarine and hemipelagic sediments. In contrast, glacigenic and glacimarine sediments are relatively thin on shelf banks separating the troughs (Elverhøi et al., 1993; Andersen et al., 1996; Mangerud et al., 1998; Batchelor and Dowdeswell, 2015; Bjarnadóttir et al., 2014). This general depositional framework has allowed a sequence stratigraphic model for high-latitude shelves to be defined (Zecchin et al., 2015).

The complex physiography of high-latitude margins, therefore, determines strong lateral variability of depositional processes along both depositional dip and strike, which must be considered in order to reconstruct glacial and deglacial histories. However, shelf studies are usually concentrated either on troughs or bank areas, and therefore this variability commonly cannot be appreciated by a direct comparison. In the case of this study area for example, the work has so far concentrated on Kveithola (e.g. Rebesco et al., 2011, 2016; Bjarnadóttir et al., 2013; Lantzsch et al., 2017) and Storfjorden (e.g., Pedrosa et al., 2011) troughs or on Spitsbergenbanken (Zecchin et al., 2016).

The present study is aimed at documenting the lateral variation of sedimentary processes between the Spitsbergenbanken and the Kveithola and Storfjorden troughs, in the NW Barents Sea (Fig. 1A,B). This allows the sedimentary and erosional processes, and ice overprint between topographic highs and lows, to be directly compared along a single sub-bottom profile. The present results need to be taken into account to construct general models of glacigenic and glacimarine sedimentation, as well as of ice dynamics, in high-latitude margins (Colleoni et al., 2016; Petrini et al., 2017).

2. Geological setting

The study area is located in the NW Barents Sea, between Kveithola and Storfjorden troughs (Fig. 1A,B). A rifting phase between Greenland and Spitsbergen, leading to the opening of the Fram

Strait, started during the Oligocene, and a narrow oceanic corridor developed during early Miocene (Engen et al., 2008). The Barents Sea, which covers one of the widest continental shelves in the world, is dissected by glacially-carved troughs (e.g. the Bear Island Trough, the Storfjorden and Kveithola Troughs; Andreassen et al., 2004, 2014; Winsborrow et al., 2010; Pedrosa et al., 2011; Rebesco et al., 2011; Fig. 1B) that are associated with wide trough mouth fans at the continental slope (e.g., Rebesco et al., 2014a).

A Plio-Pleistocene progradational phase favored by tectonic uplift and high sediment supply, initially related to fluvial discharge and to subglacial sediment discharge later on, led to the seaward expansion of the shelf margin by up to 150 km and to the formation of the topographic troughs (Forsberg et al., 1999; Dahlgren et al., 2005). Ice sheets covered the northern part of the Barents Sea since the late Pliocene, progressively expanding to the south (Vorren and Laberg, 1997; Knies et al., 2009). The Spitsbergenbanken was covered by a marine-based ice dome during the LGM, whereas paleo-ice streams flowed in the Storfjorden and Kveithola troughs (Lucchi et al., 2013). East-West trending mega-scale glacial lineations, recording ice stream movement, developed inside the Kveithola Trough during LGM, and got in parts overprinted by grounding-zone wedges during the early deglaciation (Rebesco et al., 2011; Bjarnadóttir et al., 2013). Since Early Pleistocene, contourite drifts started to develop on the Svalbard margin under the action of Norwegian Sea Deep Water episodically ventilated by relatively dense and turbid shelf water from the Barents Sea (Rebesco et al., 2013). Such contourite drifts on the continental rise grow in geographical coincidence with the mouths of the major glacial troughs on the continental shelf and experience an interaction of processes during glacial-interglacial periods, reflecting size variations of the ice sheets and water masses dynamics (Villa et al., 2003; Grützner et al., 2003; Giorgetti et al., 2003; Amblas et al., 2006; Rebesco et al., 2007). The huge sediment supply due to an exceptionally large output of glacial meltwater led to the accumulation of relatively thick plumite sequences (*sensu* Hesse et al., 1997) on the Svalbard margin and on the Storfjorden and Kveithola Trough mouth fans during the subsequent later deglaciation phase (Fohrmann et al., 1998; Rasmussen et al., 2007; Jessen et al., 2010; Lucchi et al., 2013; Rasmussen and Thomsen, 2014; Llopart et al., 2015).

3. Methods

The acoustic profile used in this study (profile 20130725, Fig. 1B) was acquired using a PARASOUND DS III-P70 system (Atlas Hydrographic) during research cruise MSM30 CORIBAR with the German RV MARIA S. MERIAN in July/August 2013 (Hanebuth et al., 2013, 2014). The PARASOUND system generates two parametric frequencies (approx. 4 kHz and 40 kHz, respectively). The parametric frequency and 70 kW transmission power allows sub-bottom penetration up to 200 m (depending on the sediment composition) with a vertical resolution of about 40 cm. The conversion from TWT to depth (Figs. 2-5) is based on a velocity of 1500 m/s.

Multibeam bathymetric data shown in Fig. 1 were acquired during three different cruises with different vessels: SVAIS (Camerlenghi et al., 2007), EGLACOM (Zgur et al., 2008) and CORIBAR (Hanebuth et al., 2013). The three datasets have been jointly reprocessed at OGS by importing all data in CarisHips&Sips, removing refraction problems, applying tide corrections and rejecting spurious data using a surface filter based on 2D editing in Subset Editor. The data were then imported in Global Mapper UTM 33 WGS84 (20m grid) and superimposed onto IBCAO data (Jakobsson et al., 2012) with a vertical exaggeration of 2.7 and Light Direction Attitude 35°, Azimuth -30°.

PARASOUND and Multibeam data were successively displayed with the Kingdom Suite software (IHS Inc., Englewood, CO) for interpretation.

4. Results

4.1. Acoustic units

Four acoustic units (Unit 1 to Unit 4 from the base to the top) were defined from the PARASOUND profile 20130725 based on acoustic facies appearance and bounding internal surfaces (Figs. 2-5).

Acoustic units and facies are summarized in Fig. 6.

4.1.1. Unit 1

Unit 1 is the lowermost acoustic unit and is recognizable in all segments of the studied profile (Figs. 2-5). It is opaque and its base is not visible. Some variably inclined reflections are present in places toward the upper part of the unit, especially in segment A of the profile (Fig. 2), and they tend to merge with the irregular upper boundary. While in segment A and in the southern part of segment B of the studied profile Unit 1 is overlain by Units 2-4 and locally crops out (Figs. 2 and 3), in the northern part of segment B and in segments C and D, i.e. on the Spitsbergenbanken and toward the Storfjorden trough, the upper part of the unit is irregular, in places chaotic and shows higher amplitude (Figs. 3-5). The base of this higher-amplitude zone is very irregular, in places incised and commonly fuzzy and poorly defined (Figs. 3-5). This zone reaches a maximum thickness of ca. 15 m. Within the Kveithola trough, Unit 1 forms convex-up bodies 5 to 10 km wide and up to 50 m high with respect to the adjacent depressions (Fig. 2).

4.1.2. Unit 2

Unit 2 is found only in segment A and in the southern part of segment B of the studied acoustic profile (Figs. 2 and 3). It is up to ca. 17 m thick and overlies Unit 1. Unit 2 is semitransparent and structureless on the topographic highs, between the northern part of segment A and the southern part of segment B, where exhibits an extremely irregular upper boundary marked by numerous incisions (Figs. 2 and 3). In segment A, these deposits rapidly grade downdip, toward the adjacent Kveithola trough, into laminated, transparent to semitransparent deposits characterized by low- to high-amplitude reflections, which drape the irregular top of Unit 1 (Fig. 2). Laminated deposits characterized by medium- to high-amplitude irregularly undulating reflections are found also in local shallower depressions separating the topographic highs, such as in the northernmost part of segment A (Fig. 2). The laminated facies never exhibits an incised upper boundary (Fig. 2). Unit 2 is locally exposed at the seafloor in areas where Units 3 and 4 are absent (Figs. 2 and 3).

4.1.3. Unit 3

Unit 3 is up to ca. 7.5 m thick and is found only in the northern part of segment A and in the southern part of segment B of the studied acoustic profile (Figs. 2 and 3). It fills the irregular incisions found at the top of Unit 2 on the topographic highs, or drapes the laminated part of Unit 2 in the minor depressions (Figs. 2 and 3). Unit 3 is well laminated and consists of high- to medium-amplitude reflections (Figs. 2 and 3). In the Kveithola trough it cannot be discriminated, and it is possibly replaced by the lower part of Unit 4 (Fig. 2). Unit 3 is absent also on the highest parts of the topographic highs, where Unit 1 and/or Unit 2 are exposed at the seafloor (Figs. 2 and 3).

4.1.4. Unit 4

Unit 4 is up to ca. 25 m thick and is found only in segment A and in the southern part of segment B of the studied acoustic profile (Figs. 2 and 3). In the depressions on the southern flank of the Spitsbergenbanken, Unit 4 drapes the upper boundary of Unit 3, or unconformably overlies the tops of Units 1 or 2 where Unit 3 is absent (Figs. 2 and 3). In the Kveithola trough, the unit drapes the top of Unit 2 (Fig. 2). Unit 4 is laminated and can be distinguished from the underlying Units 2 and 3 by its average lower amplitude which makes its appearance more transparent (Figs. 2 and 3). The boundary between Units 2/3 and Unit 4 is usually well recognizable due to the contrast in amplitude of the reflections (Figs. 2 and 3). Unit 4 is present only in topographic depressions; in the Kveithola trough, it shows characteristics lateral pinch-outs and disappear towards the south (Fig. 2).

4.2. Interpretation of acoustic data

Units 1-4 correspond to the homonymous units described by Zecchin et al. (2016) on the southern margin of the Spitsbergenbanken on the basis of both acoustic and core data. The overlap between two intervals in segments A and B of the studied acoustic profile (Figs. 2 and 3), and those illustrated by Zecchin et al. (2016), enable us to extend laterally the recognized acoustic units in the whole study area.

Following Zecchin et al. (2016), Unit 1 is interpreted as subglacial till related to grounded ice (e.g., Batchelor et al., 2011; Rebesco et al., 2011; 2014b; Ó Cofaigh et al., 2005). This interpretation is also consistent with that provided by Lantzsch et al. (2017) in the Kveithola trough. The convex-up bodies found in the Kveithola trough (Fig. 2) are interpreted as grounding-zone wedges accumulated during stillstand in grounding-zone position (e.g., Rebesco et al., 2011). The local reflections within Unit 1 probably represent interfaces between depositional stages (Ó Cofaigh et al., 2005; Rebesco et al., 2011; Bjarnadóttir et al., 2013; Hanebuth et al., 2014).

The appearance of the irregular higher-amplitude zone found in the uppermost part of Unit 1 suggests intense reworking, most probably by iceberg keels, of the top of the glacial till and/or of younger glacimarine deposits (e.g., Zecchin et al., 2016). Some major depressions in the southern margin of the Storfjorden trough might correspond to mega-scale glacial lineations, recording ice stream movement (e.g., Pedrosa et al., 2011; Lucchi et al., 2015). This interval is called 'reworked zone' in Figs. 2-5.

Unit 2 is interpreted as a glacimarine deposit, inferred to have accumulated from the vertical settlement of muddy and sandy sediment during the onset of the deglaciation, originating from hyperpycnal flows (Zecchin et al., 2016). Glacimarine deposits, tentatively correlated with those that form Unit 2, or both Units 2 and 3 (see below), and overlain by hemipelagites (here correlated with Unit 4), are locally preserved also in some depressions of the Storfjorden trough, close to the northern end of the studied acoustic profile (Llopart, 2016; core GeoB17610-2 in Fig. 7).

The extremely irregular upper boundary of Unit 2 on the topographic highs (Figs. 2 and 3) was interpreted by Zecchin et al. (2016) as the result of ploughmarks produced by iceberg-keel scouring (e.g., Dowdeswell et al., 1993; Barnes, 1997; MacLean, 1997; Solheim, 1997; López-Martínez et al., 2011; Robinson and Dowdeswell, 2011). This scouring by iceberg keels probably led to the dismembering of the laminated deposits of Unit 2 and to a formation of ploughmarks on the topographic highs. In contrast, iceberg keels were probably not deep enough to affect the sediment accumulated inside the topographic depressions.

On the basis of core GeoB17623-2 (Fig. 7), Zecchin et al. (2016) interpreted Unit 3 as a glacimarine deposit accumulated from suspension clouds, which were related to ice melting carrying muddy sediment (e.g., Hesse et al., 1997; Lucchi et al., 2013; 2015). The presence of layers produced by fall-out of ice-rafted debris (IRD) may explain the higher amplitude of the internal reflections in Unit 3 (Zecchin et al., 2016).

Unit 4 is inferred to have deposited from bottom currents (Zecchin et al., 2016). This is confirmed by core GeoB17623-2 (Zecchin et al., 2016; Fig. 7) and by previous studies performed in the Kveithola trough, which interpreted the laminated deposits overlying glacimarine ones and showing lateral pinch-outs as being part of a sediment drift (Bjarnadóttir et al., 2013; Rebesco et al., 2016; Lantzsch et al., 2017) (see core GeoB17607-5 in Fig. 7).

5. Discussion and conclusions

The studied acoustic profile provides the rare opportunity to observe how the post-LGM sedimentation varies between a shelf bank and the adjacent troughs, specifically from the Spitsbergenbanken to the Kveithola and Storfjorden troughs. This variation is usually difficult to appreciate in individual studies performed in significantly smaller areas.

Unit 1 probably records ice movement during the LGM and the early phase of ice retreat, which were characterized by the formation of moraines, mega-scale glacial lineations and grounding zone wedges (e.g., Rebesco et al., 2011; Bjarnadóttir et al., 2013, 2014) (Fig. 8A). The most striking feature of the studied transect is the occurrence of laminated glacimarine and bottom current deposits only on the southern margin of the Spitsbergenbanken and in the Kveithola trough (Fig. 8B-E). Following Zecchin et al. (2016) and Lantzsch et al. (2017), these deposits accumulated during specific phases related to both ice melting and glacio-eustatic sea-level rise. In particular, Unit 2 is inferred to have accumulated after a phase of sea-level rise accompanied by ice lifting (Zecchin et al., 2016), which favored the flow of meltwater beneath the ice and the accumulation of glacimarine deposits south of the Spitsbergenbanken (Fig. 8B). This phase was probably at least in part concomitant with the known brief episode of glacio-eustatic sea-level rise called meltwater pulse 1A (14.6 to 13.5 cal ka BP; Bard et al., 1990; Deschamps et al., 2012). However, glacimarine sedimentation above the subglacial till initiated earlier, at ca. 16 cal ka BP, in the Kveithola trough (Lantzsch et al., 2017), probably due to a greater accommodation available in that location after the ice started to melt. The following phase was characterized by ice break up and subsequent production of icebergs, which disturbed the previously accumulated sediments and formed the ploughmarks that affected Unit 2 (Zecchin et al., 2016) (Fig. 8C). With the progress of the deglaciation, sediment supply from suspension clouds led to the accumulation of Unit 3, which filled the irregularities of the seabed on the southern flank of the Spitsbergenbanken (Fig. 8D). Finally, the accumulation of the bottom current deposits of Unit 4 persisted in iceberg-free conditions (Fig. 8E).

Datings of core samples have revealed that Unit 4 started to accumulate at ca. 13.5 cal ka BP in the Kveithola trough (Lantzsch et al., 2017), and at ca. 9 cal ka BP just south of the Spitsbergenbanken (Zecchin et al., 2016; see core GeoB17623-2 in Fig. 7). This observation highlights a significant diachronism in the timing of sedimentation of post-glacial units between throughs and minor depressions on the banks. The possible persistence of partially grounded ice shelf (e.g., Yokoyama et al., 2016) on the Spitsbergenbanken, leading to accumulation from suspension plumes related to ice melting in protected locations away from the Kveithola trough, might explain the delayed sedimentation of bottom current deposits. This diachronism implies that the accumulation of Unit 3 on the southern flank of the Spitsbergenbanken was coeval with that of the lower part of Unit 4 in the Kveithola trough (Fig. 8D).

Some hypothesis can be made regarding the lack of Units 2-4 on the Spitsbergenbanken and in the southern margin of the Storfjorden trough, although up to 3 m of glacimarine and hemipegic sediments may locally drape the subglacial till in the latter (Llopart, 2016; core 17610 in Fig. 7). A deeper reworking by iceberg keels might have removed or strongly disturbed previously accumulated glacimarine deposits, which would have been replaced by a reworked zone (Fig. 8B,C). Afterwards, relatively strong currents north of the Spitsbergenbanken may have prevented the accumulation of very thick laminated glacimarine and bottom current deposits, which instead accumulated in the smaller, more protected Kveithola trough (Fig. 8D,E). The Spitsbergenbanken and the southern margin of the Storfjorden trough, therefore, would be mostly sediment bypass areas. The possible persistence of grounded ice on the Spitsbergenbanken, until the sea level approximated that of the present day (Fig. 8C,D), may conceivably explain the lacking recognition of glacimarine sediments in that location.

The variable sedimentary response between the Kveithola and the Storfjorden troughs identified in this work points to a marked variability of ice dynamics, hydrodynamics and sediment dispersal patterns in the study area, at least in part related to local physiography. However, more research is needed to better document the variability of hydrodynamic conditions between the two considered troughs. The present case history shows that care must be taken in applying standard depositional models of glacimarine sedimentation during deglaciation phases, as strong lateral variability even in adjacent areas is commonly found, especially between troughs and morphological highs.

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FIGURE CAPTIONS

Fig. 1. (A) Location map with the study area (red box) in the NW Barents Sea (bathymetry from IBCAO, Jakobsson et al., 2012). (B) Shaded relief map of the study area, showing the Kveithola Trough, the southern part of the Storfjorden trough and the SW margin of the Spitsbergenbanken. The studied PARASOUND sub-bottom echosounder profile is highlighted.

Fig. 2. PARASOUND profile 20130725, segment A (see Fig. 1B for location). Four acoustic units (Units 1-4) are identified (see the line drawing below). Where exposed, the top of Unit 1 is locally reworked (reworked zone). Note on the right the interval considered by Zecchin et al. (2016).

Fig. 3. PARASOUND profile 20130725, segment B (see Fig. 1B for location). Four acoustic units (Units 1-4) are identified (see the line drawing below). The top of Unit 1 is reworked in the northern part of the profile (reworked zone). Note on the left the interval considered by Zecchin et al. (2016).

Fig. 4. PARASOUND profile 20130725, segment C (see Fig. 1B for location). One acoustic unit (Units 1) is identified (see the line drawing below), the top of which is reworked (reworked zone).

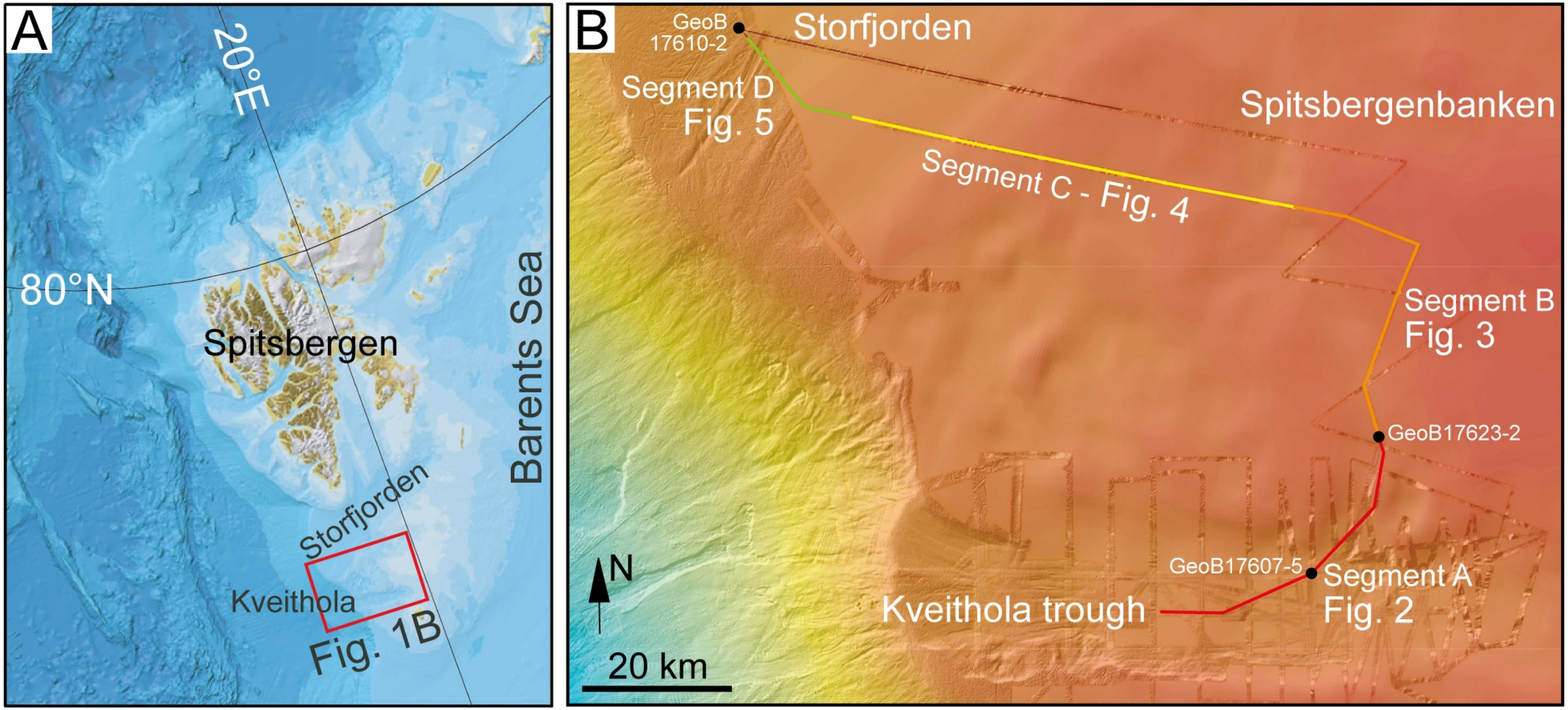
Fig. 5. PARASOUND profile 20130725, segment D (see Fig. 1B for location). One acoustic unit (Units 1) is identified (see the line drawing below), the top of which is reworked (reworked zone).

Fig. 6. Acoustic units (Unit 1 to Unit 4 from the base to the top), defined from the PARASOUND profile based on acoustic facies appearance. See text for details of the interpretation.

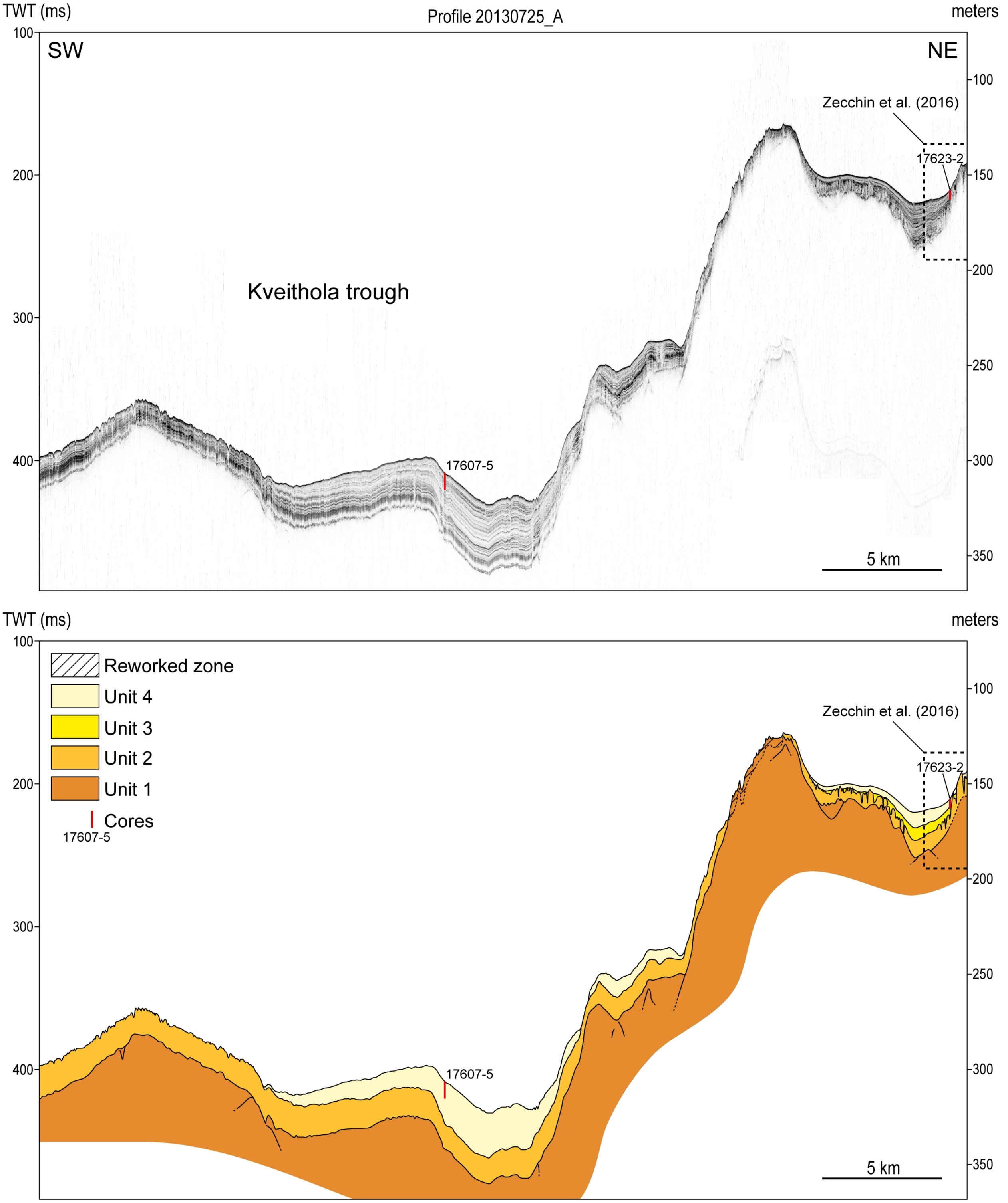
Fig. 7. Sedimentary facies and inferred corresponding acoustic units (see Figs. 2-5) in the cores considered in this study (see Fig. 1B for location). Where available, calibrated radiocarbon ages are

indicated in red on the left. Cores GeoB17607-5, GeoB17623-2 and GeoB17610-2 are modified respectively from Lantzsch et al. (2017), Zecchin et al. (2016) and Llopart (2016).

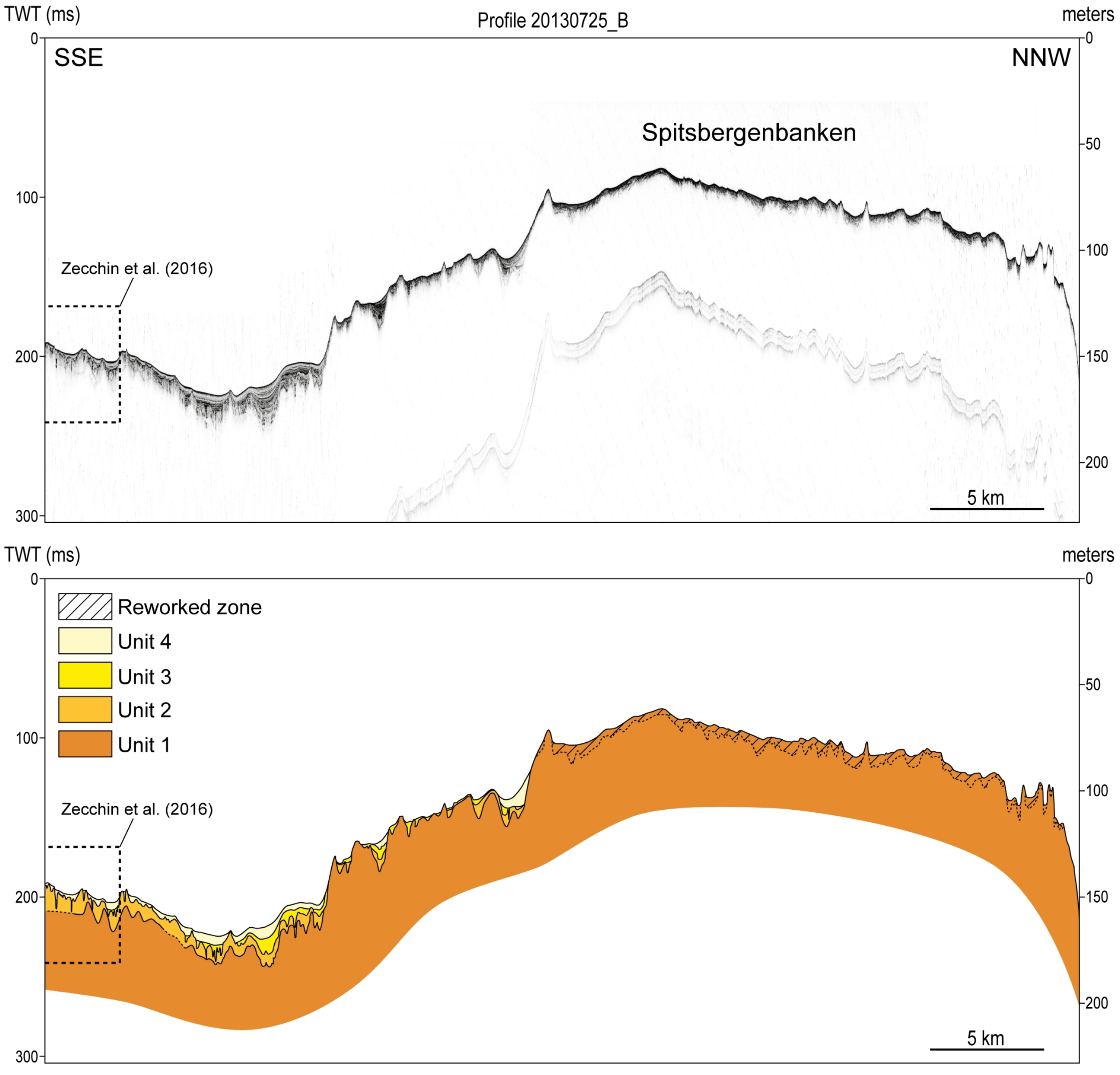
Fig. 8. Interpreted depositional history between the Kveithola and Storfjorden troughs based on the studied acoustic profile (see Fig. 1B for location; please notice that the orientation of the profile is progressively changing by about 180°). (A) The early phase of ice retreat that followed the Last Glacial Maximum was characterized by the accumulation of moraines and grounding zone wedges composing Unit 1. (B) After an episode of sea-level rise accompanied by ice lifting, which favored the flow of meltwater beneath the ice, glacimarine deposits composing Unit 2 accumulated south of the Spitsbergenbanken and possibly toward the Storfjorden trough. Unit 2 probably started to accumulate earlier in the Kveithola trough with respect to the southern margin of the Spitsbergenbanken (see text). (C) Icebergs produced by ice break up formed the ploughmarks that affect Unit 2 south of the Spitsbergenbanken and a reworked zone to the north. (D) Sediment supply from suspension clouds led to the accumulation of Unit 3 in the depressions of the southern flank of the Spitsbergenbanken, filling the irregularities of the seabed, whereas bottom current deposits (Unit 4) already started to accumulate in the Kveithola trough. Relatively strong currents may have prevented the accumulation of laminated glacimarine deposits in the northern part of the study area. (E) Later, the accumulation of the bottom current deposits of Unit 4 initiated also in the depressions of the southern flank of the Spitsbergenbanken, probably in iceberg-free conditions.

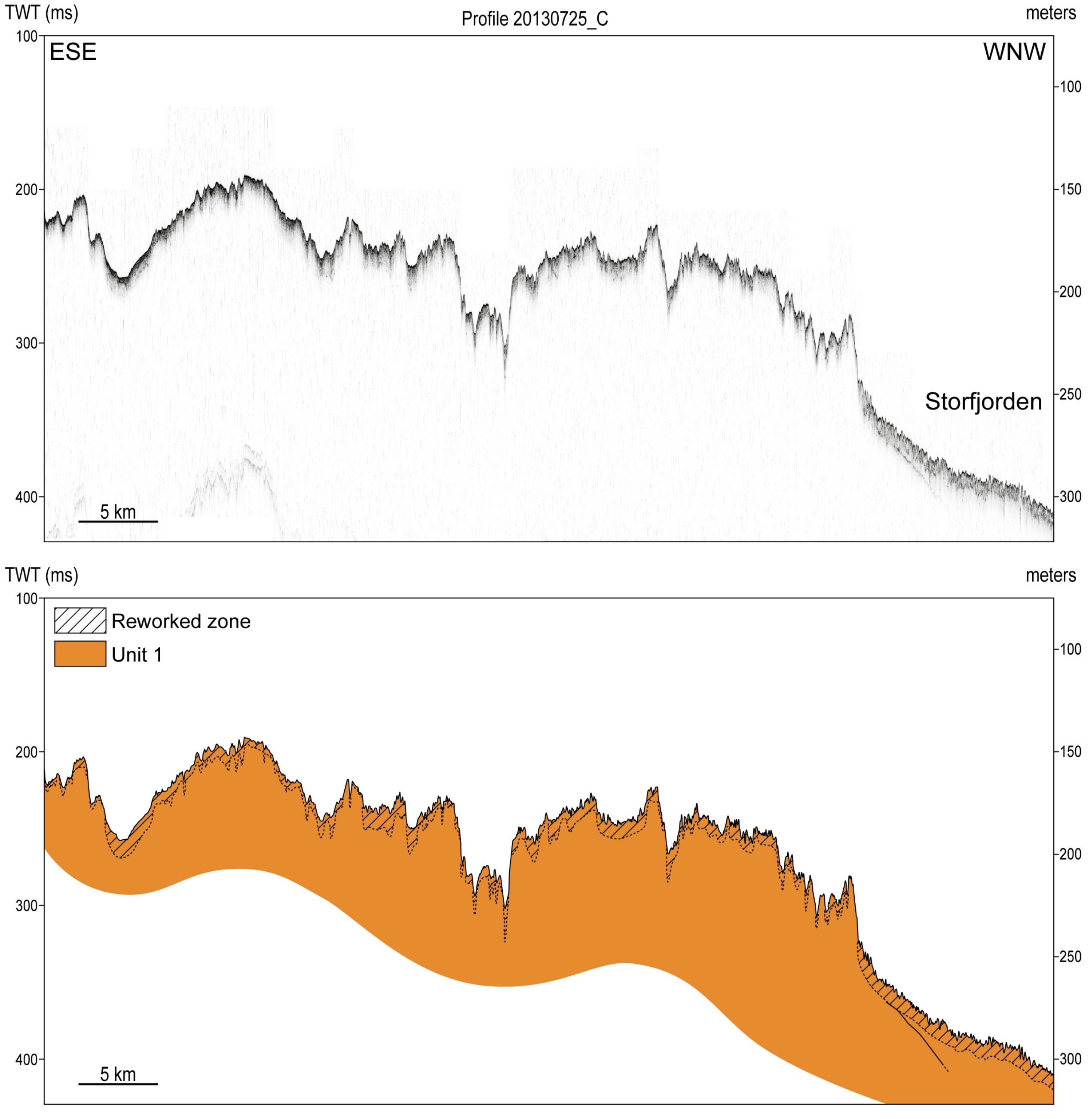


A
20°E
80°N
Spitsbergen
Barents Sea
Storfjorden
Kveithola
Fig. 1B
B
GeoB
17610-2
Storfjorden
Segment D
Fig. 5
Spitsbergenbanken
Segment C - Fig. 4
Segment B
Fig. 3
GeoB17623-2
GeoB17607-5
Segment A
Fig. 2
Kveithola trough
N
20 km

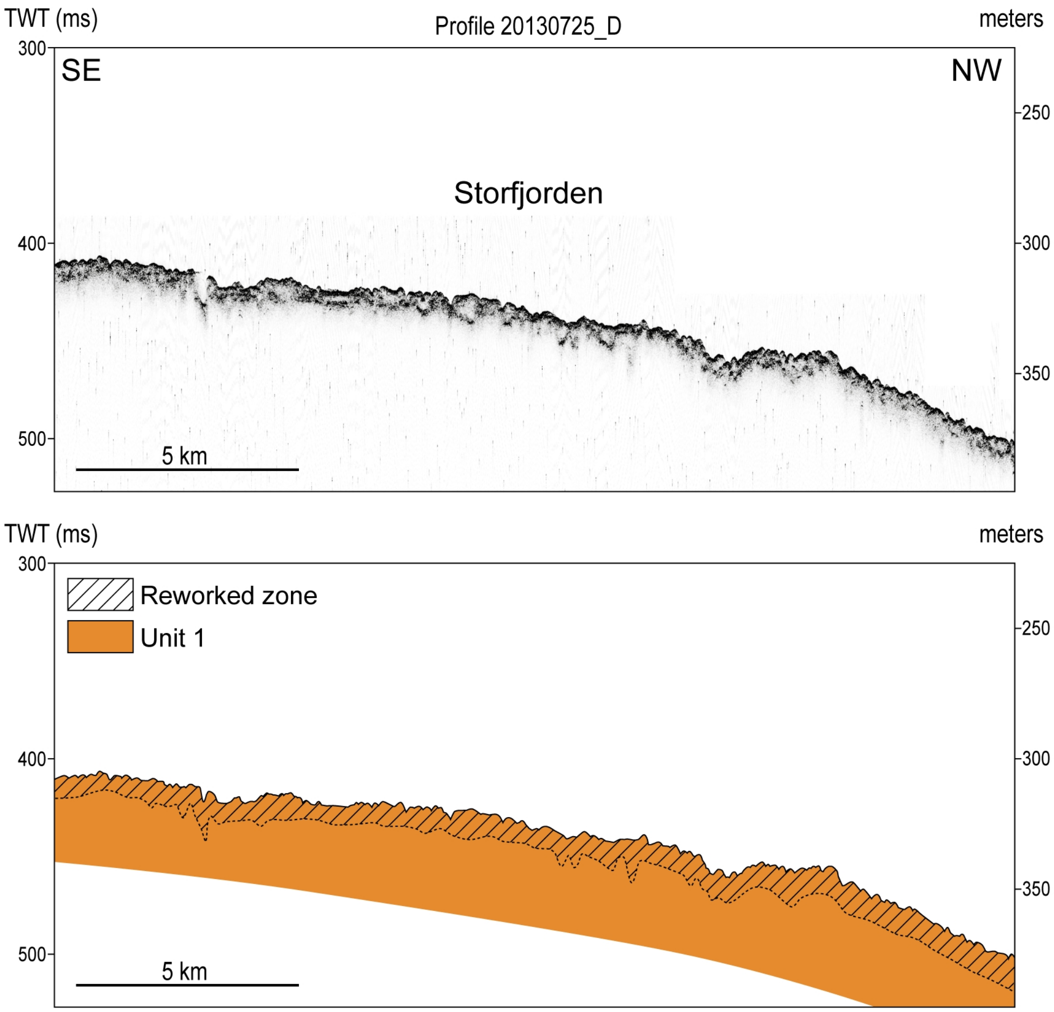


TWT (ms)
Profile 20130725_A
meters
SW
NE
Zecchin et al. (2016)
17623-2
Kveithola trough
17607-5
5 km
100
200
300
400
100
150
200
250
300
350
Reworked zone
Unit 4
Unit 3
Unit 2
Unit 1
Cores

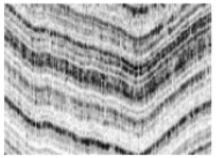
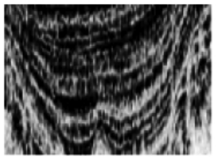
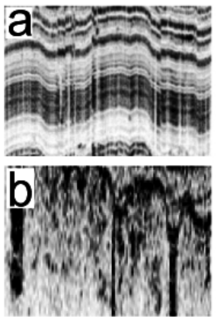
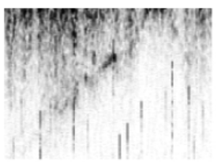

TWT (ms)
Profile 20130725_B
meters
SSE
NNW
Spitsbergenbanken
Zecchin et al. (2016)
5 km
0
100
200
300
0
50
100
150
200
TWT (ms)
meters
Reworked zone
Unit 4
Unit 3
Unit 2
Unit 1
Zecchin et al. (2016)
5 km
0
100
200
300
0
50
100
150
200

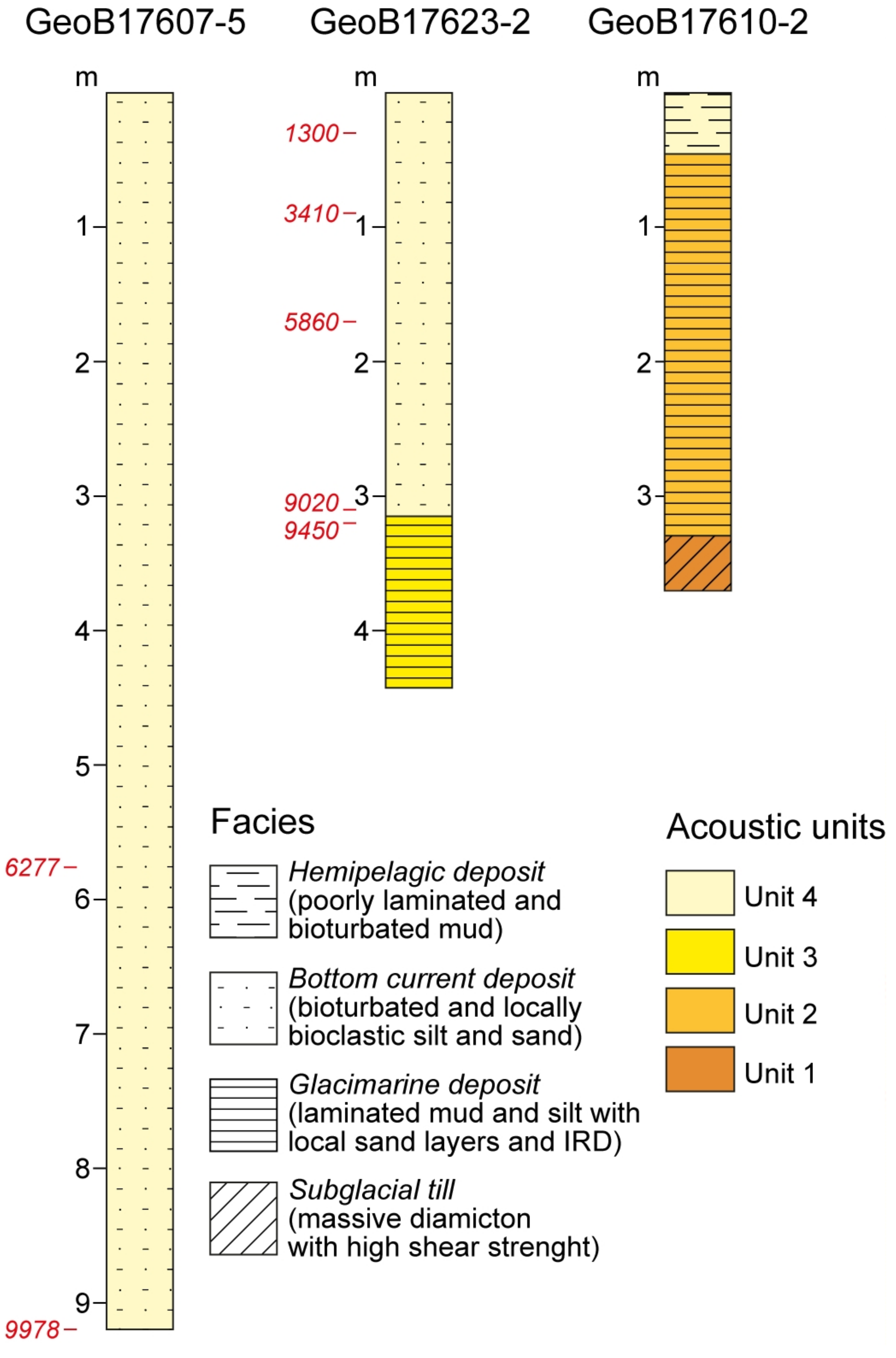


TWT (ms)
Profile 20130725_C
meters
ESE
WNW
Storfjorden
5 km
100
200
300
400
100
150
200
250
300
Reworked zone
Unit 1

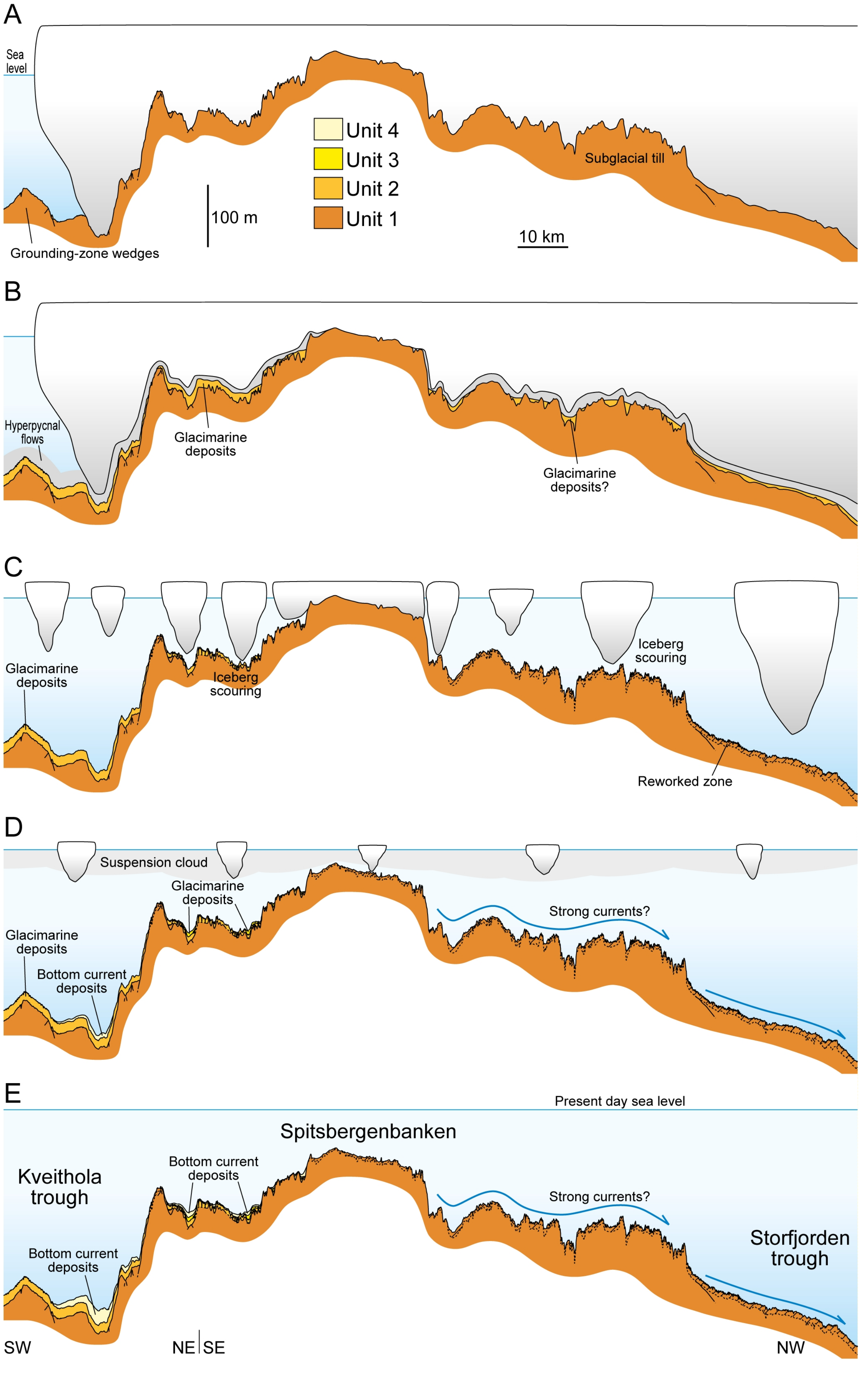


Profile 20130725_D
TWT (ms)
meters
300
400
500
250
300
350
SE
NW
Storfjorden
5 km
TWT (ms)
meters
300
400
500
250
300
350
Reworked zone
Unit 1
5 km

Units	*Acoustic facies*		*Interpretation*
Unit 4		Laminated, low-amplitude and transparent. Lateral pinch-outs in the troughs	Bottom current deposit
Unit 3		Laminated, high- to medium-amplitude reflections, levelling the irregularities at the boundary between Units 2 and 3 on the topographic highs	Glacimarine deposit
Unit 2		Low- to high-amplitude undulating reflections (a) inside the depressions; semitransparent and structureless, with irregular upper boundary (b) on the topographic highs	Glacimarine deposit that underwent scouring by iceberg keels on the topographic highs
Unit 1		Opaque in its lower part, inclined reflections and/or irregular/chaotic appearance toward the top	Subglacial till



GeoB17607-5
GeoB17623-2
GeoB17610-2
m
m
m
1300
3410
5860
9020
9450
6277
9978
1
2
3
4
5
6
7
8
9
Facies
Hemipelagic deposit (poorly laminated and bioturbated mud)
Bottom current deposit (bioturbated and locally bioclastic silt and sand)
Glacimarine deposit (laminated mud and silt with local sand layers and IRD)
Subglacial till (massive diamicton with high shear strenght)
Acoustic units
Unit 4
Unit 3
Unit 2
Unit 1


A
Sea level
Unit 4
Unit 3
Unit 2
Unit 1
100 m
10 km
Subglacial till
Grounding-zone wedges
B
Hyperpycnal flows
Glacimarine deposits
Glacimarine deposits?
C
Glacimarine deposits
Iceberg scouring
Iceberg scouring
Reworked zone
D
Suspension cloud
Glacimarine deposits
Glacimarine deposits
Bottom current deposits
Strong currents?
E
Present day sea level
Spitsbergenbanken
Kveithola trough
Bottom current deposits
Bottom current deposits
Strong currents?
Storfjorden trough
SW
NE
SE
NW