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The role of grounding-line sediment supply in ice-sheet advances and growth on continental shelves: an example from the mid-Norwegian sector of the Fennoscandian ice sheet during the Saalian and Weichselian

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Abstract

We discuss the consequence of sediment accumulation at the grounding line of glaciers advancing across continental shelves. Sediment transfer through a deformable till bed and deposition at the grounding line act to decrease the water depth and adds support to the termini. Both are mechanisms that act to lower the calving rate and hence reduce mass losses during an advance of a grounded glacier. We use the geological record of the Saalian and Weichselian advances of the Fennoscandian ice sheet across the mid-Norwegian continental shelf to elucidate the consequence of this process. Based on seismic investigations and published maps, we infer that the development of a morainal bank fed and sustained through the advance(s) by means of a deformable bed was indeed important. This allowed the ice sheet to advance across a wide seaward dipping shelf, depositing thick diamicton (in places of more than 200 m thick) and a terminal morainal bank complex. We relate the reasons for this depositional mode, i.e. shelf and shelf edge accumulation rather than deposition of glacial debris flows on the continental slope, to slow and fast glacier flow regimes.

1. Introduction

During the inception stages of the past mid-latitude ice sheets snow accumulated, and glaciers formed, allowing ice to disperse from highland areas. For example, the Fennoscandian ice sheet was mountain centred during the early Weichselian (Kleman et al., 1997). Recent studies from the Barents and Kara Sea region have shown that the coasts of northern Russia and western Siberia have repeatedly been inundated by ice sheets centred over the continental shelf areas to the north (Svendsen et al., 1999; Houmark-Nielsen et al., in press; Mangerud et al., 2001). Thus, from an 'inception' point of view, it is also important to elucidate the mechanisms which allow glaciers to form and expand on continental shelves.

When advancing glaciers reach a body of water, calving becomes increasingly more important in influencing the mass balance. As ablation through calving is much more effective than surface melting, it may be the most dominant mode of mass loss for glaciers terminating in water (cf. Jacobs et al., 1992). Although no universal calving law has been established (cf. Hughes, 1992; van der Veen, 1996), many investigations have shown a relation between calving rate and water depth at the glacier terminus (Brown et al., 1982; Pelto and Warren, 1991; Warren, 1992; Warren et al., 1995). Consequently, a relationship between water depth and calving rate is also often incorporated into numerical ice-sheet models (cf. Dowdeswell and Siegert, 1999).

The resulting water depth at the advancing ice-sheet terminus is determined by the pre-existing bathymetry, glacio iso- and eustatic sea-level changes, and gravitational attraction. The amount of sediment released by the glacier at the grounding line will also eventually affect the water depth (Powell, 1991; Powell and Alley, 1997). In this paper, we concentrate on the mechanisms of sediment supply at the grounding line and its relation to the fluctuations of glaciers on continental shelves. We use the Fennoscandian ice-sheet advances on the mid-Norwegian continental shelf (Figs. 1 and 2) during the Saalian and Weichselian as an example. The discussion is based on our own reflection seismic data from the outer continental shelf and upper slope areas (Fig. 3),

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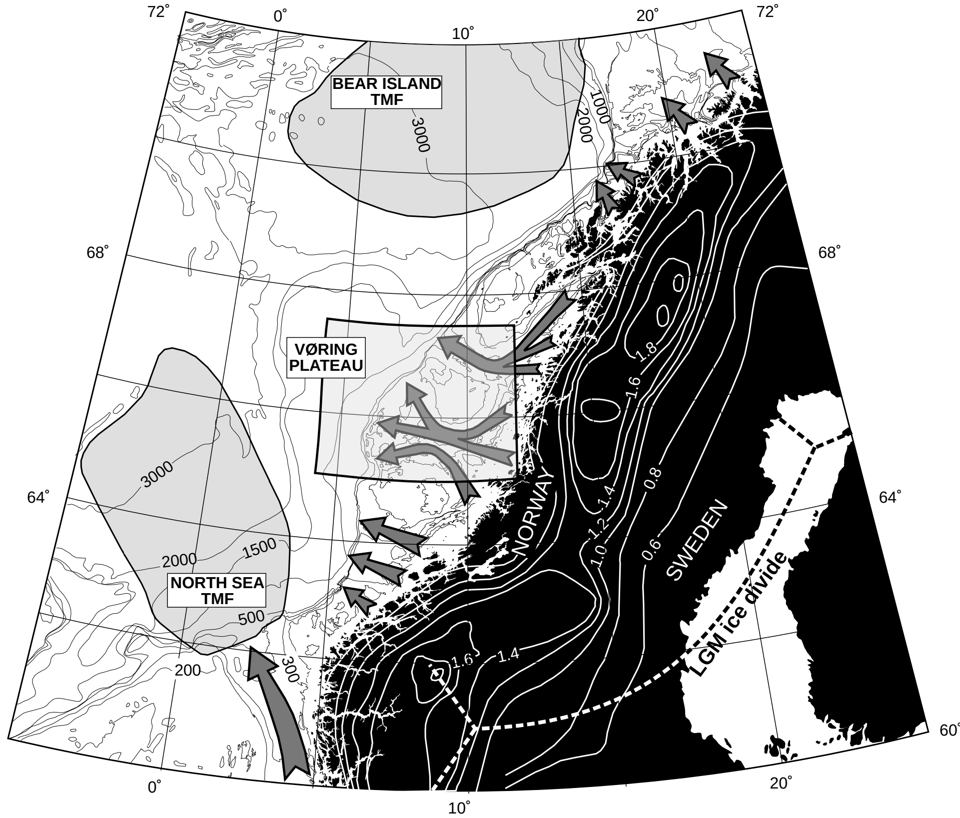

Fig. 1. Overview of the Norwegian Sea and mainland Norway and Sweden, showing trough mouth fans (TMF) after Vorren et al. (1998). The study area is marked by the shaded box. The bathymetric contours are shown in 100 m intervals down to 500 m depth, 500 m interval between 500 and 2000 m depth, and below 2000 m the interval is 1000 m. The land contours are enveloping curves in km. The ice divide of the Fennoscandian ice sheet during the last glacial maximum is adapted from Kleman et al. (1997). The simplified ice-flow pattern (arrows) on the continental shelf is modified from Ottesen et al. (2001).

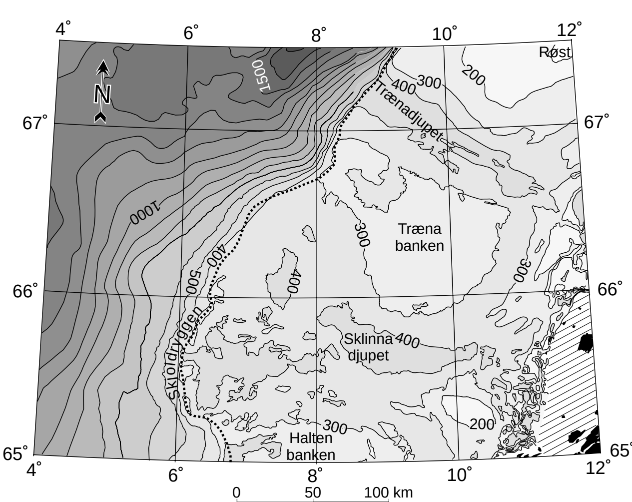

Fig. 2. Bathymetry of the study area (100 m contour interval). The bathymetry of the shelf mimics the surface topography of the Upper (Weichselian) till. The shelf break is marked by the dotted line. The hachured area denotes a region of complex bathymetry along the coast.

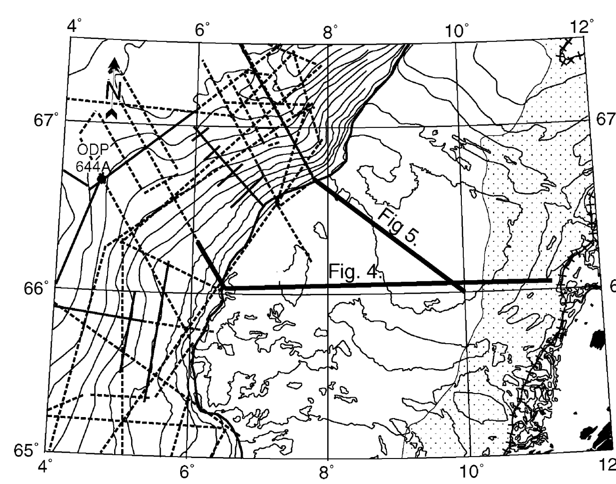

Fig. 3. Map showing location of seismic lines. Broken lines denotes mini sleeve gun data acquired by the Seabed Project, and the solid lines represent mini sleeve gun and sparker data acquired by the University of Tromsø. The boundary between the crystalline basement to the east and Jurassic to Miocene sedimentary rocks sub-/outcropping on the inner shelf (shaded area) is shown by the hachured line. Seaward of these is the Late Plio-Pleistocene prograding wedge subcropping. The shelf break is marked by the heavy solid curve.

and thickness and sub-surface maps of till units on the shelf by King et al. (1987).

The existence of morainal banks (Powell, 1984) or moraine shoals have previously been shown to be important for allowing tidewater glaciers to advance into deep fjords (Clapperton et al., 1989; Powell, 1991; Warren, 1992). With this in mind, the possibility that tidewater margins of past ice sheets deposited sediments and built their own 'road bank' which effectively decreases the water depth at the grounding line with up to hundreds of metres clearly deserves attention (cf. Alley et al., 1989; Powell and Alley, 1997). This also has important implications for numerical ice-sheet modelling experiments trying to reproduce the advance or growth of ice sheets on continental shelves, as the interplay between sediment delivery and water depth at the grounding-line influences the calving rate. Also, if discrepancies in model output and geological ground truth are encountered, this mechanism can possibly explain some of the inconsistencies.

2. Physiographic setting

The mid-Norwegian continental shelf (65–67°N) is characterised by bank areas at 200–300 m water depth and transverse glacial troughs at 300–500 m water depth (Figs. 1 and 2). The boundary between crystalline and sedimentary rocks is situated just off the outer islands of the Norwegian coast (Fig. 3). On the innermost part of the shelf, Jurassic to Oligocene and Miocene sedimentary strata sub- and/or outcrop (Bugge et al., 1984). The largest part of the continental shelf is, however, underlain by a large late Plio-Pleistocene prograding wedge. During its deposition, the shelf break migrated some 100 km seaward (Henriksen and Vorren, 1996).

During the past ca. 340 ka, the outer shelf is inferred to have subsided at a rate of ca. 1.2 m/ka, while the inner shelf seems to have been relatively stable or experiencing a very modest uplift (Dahlgren and Vorren, submitted). Although the exact origin of this subsidence is unknown, sediment loading in response to the deposition of the late Plio-Pleistocene wedge is probably one important reason. The inferred differential subsidence has acted to tilt the strata and the upper regional unconformity (URU) seaward. The last major phase of reshaping of the URU is dated to marine isotope stage 10, ca. 340 ka BP (Dahlgren, 2000; Dahlgren and Vorren, submitted).

3. Methods and data

The seismic sources used were 30 and 40 cubic inch sleeve guns and a nine-electrode sparker. The data were recorded by single channel streamers and were stored digitally as well as analogue. The data have a resolution of better than 10 m. For the interpretation of the seismic data we used paper copies of the seismic records. For conversion of seismic velocity to depth/thickness, we applied a value of the seismic velocity in the sediments of 1500 m/s to be able to correlate to King et al.'s (1987) results. Although this value likely underestimates the true velocity (and thickness) by up to 25%, it probably varies laterally and with depth. Thus, we have also used this value.

4. The sedimentary record

4.1. Chronology

We have correlated the Vøring Plateau and continental slope seismic stratigraphy (cf. McNeill et al., 1998) to the stratigraphy on the shelf as presented by King et al. (1987) (Fig. 4; Dahlgren et al., submitted). The Upper, Middle and Lower tills on the shelf (King et al., 1987) are mainly composed of gravity flows released at the grounding line according to King (1993). Thus they represent flow–till complexes according to the INQUA terminology (King, 1993). However, they might also include other glacigenic diamicton types. We use 'till' here in a stratigraphical sense in order not to complicate the original stratigraphic nomenclature for the area. We have further correlated the seismic stratigraphy to ODP hole 644A on the Vøring Plateau (Fig. 3) and are thus able to constrain the ages of both the Upper till (Late Weichselian, Marine Isotope Stage 2) and the Middle till (Saalian, Marine Isotope Stage 6). The Lower till is bracketed between deposits of Marine Isotope Stage 6 and 10 ages, and is inferred to be of Marine Isotope Stage 8 age (Dahlgren, 2000).

4.2. Morphology

The surface topography of the Upper till which is mimicked by the present-day bathymetry (Fig. 2) displays a large terminal morainal bank/grounding-line wedge complex, Skjoldryggen (Andersen, 1979), along the shelf edge off the Sklinnadjupet Trough. A less developed morainal bank/grounding-line wedge can be observed at a similar location on the surface of the Middle till (Fig. 6B). In contrast, areas both directly to the north of the large morainal bank complex and off Trænadjupet to the north, are marked by troughs intersecting the shelf break (Fig. 2).

4.3. Sedimentology/environment

The large-scale architecture on the outer part of Sklinnadjupet is characterised by thick aggrading and prograding till and glacigenic debris flow deposits

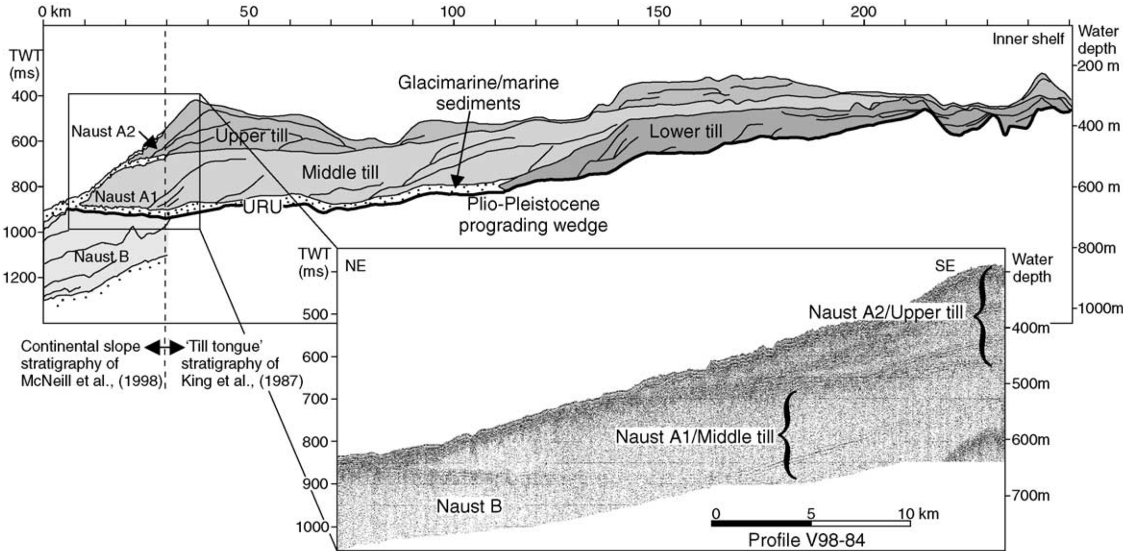

Fig. 4. Interpreted seismic profile, comprising an interpreted sleeve gun profile from the upper slope (McNeill et al., 1998), and an interpreted sparker profile on the shelf (King et al., 1987; Profile B81-114). The inset illustrates a sparker profile with the seismostratigraphic units on the continental slope of McNeill et al. (1998) and Dahlgren and Vorren (submitted) and the corresponding till units of King et al. (1987). Note the overall seaward dipping surfaces of the URU and the middle till which are inferred to be due to outer shelf subsidence, for location of the profile see Fig. 3.

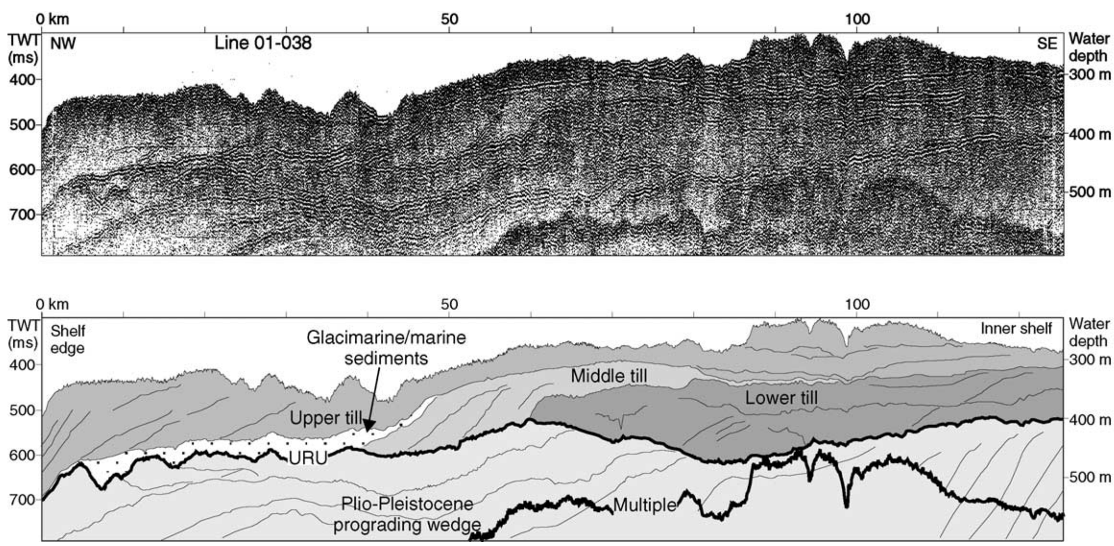

Fig. 5. Interpreted sleeve gun profile displaying internal progradation pattern within the till units on the outer shelf. The progradational pattern within the till units on the mid-Norwegian continental shelf is interpreted to reflect sediment supply to the grounding-line through a deformable bed (cf. Boulton, 1990; King, 1993; Boulton et al., 1996). For location of the profile see Fig. 3.

(Figs. 4–6; King, 1993; Dahlgren and Vorren, submitted; Dahlgren et al., submitted). In contrast, the Trænadjupet Trough (Fig. 2) only has a relatively thin layer of the Upper till overlying bedrock (King et al., 1987). Input of glacigenic debris flows to the continental slope region off Trænadjupet is evident during both Marine Isotope Stages 2 and 6 (Fig. 6).

Both the Upper and Middle tills are characterised by internally prograding clinoforms. Prograding units which extend beyond the shelf edge can be followed down the continental slope (Figs. 4 and 6) where they appear as acoustically transparent and structureless glacigenic debris flows (Dahlgren et al., submitted).

5. Discussion

Important factors at play during ice-sheet advances across continental shelves are the relative sea level, and the ability to deposit and further advance across morainal banks or grounding-line wedges (Powell and Alley, 1997), or grounding-zone wedges (Anderson,

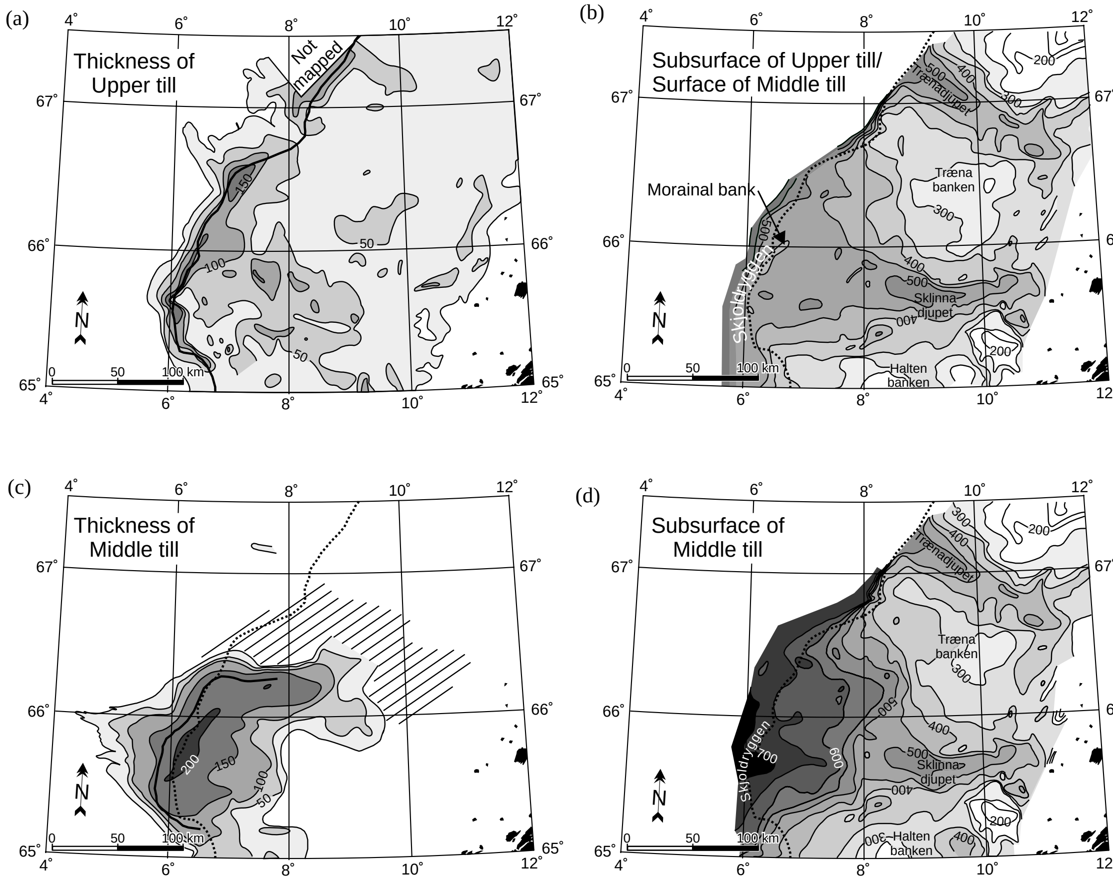

Fig. 6. Maps showing the thickness and subsurface in m, of the Upper till (A and B) and the Middle till (C and D), respectively. The subsurface maps are modified from King et al. (1987). The thickness maps are based on our data on the continental slope and outermost shelf, for the remainder of the shelf data was adopted from King et al. (1987). The maximum ice extent is shown by the heavy solid lines, and dotted lines mark the present shelf break. The hachured region in C represents an area where our data conflicts to that of King et al. (1987) who included the distal glaciomarine (our interpretation cf. Fig. 5B) sediments in the thickness map.

1999). Accumulation of morainal banks/grounding-line/zone wedges is a function of sediment supply and the relief on the shelf. Can enough sediment be supplied in order to fill the relief (accommodation space) on the shelf such that the glacier can advance to the shelf break? As we will see, this depends both on the variables related to the sediment supply and the magnitude of the glaciation, as well as the various factors which control the accommodation space. A conceptual model of the glacier advances onto and across the mid-Norwegian continental shelf is shown in Fig. 7. A theoretical account of the erosional and depositional patterns beneath ice sheets applicable to the situations shown in Fig. 7 is found in Boulton (1990, 1996).

In theory, shelf areas characterised by relatively deep water pose a crucial obstacle to advancing glaciers due to calving. Thus, processes allowing the glacier to provide its own 'road bank' are in many cases inferred to be a prerequisite for the glacier to advance (Fig. 7C). It is possible and in many instances likely, that this mechanism is at work as glaciers start to advance and fill in transverse troughs, to deposit a morainal bank/grounding-line wedge at the shelf break (Fig. 7D1). However, the deposited sediments may be eroded if the ice flux either is sustained or increased, causing the sediments to be dumped over the shelf edge (Fig. 7D2).

The creation and renewal of accommodation space between each glacial advance on the (outer) mid-Norwegian shelf is mainly a function of the relatively high subsidence rate. The implication being that the advancing glacier has to deposit a thick sediment package in order to compensate for the subsidence, which during the time span from the previous glacial–interglacial cycle would amount to 100–150 m, assuming a subsidence rate of 1.2 m/ka (Dahlgren et al., submitted) and a period between full glacial maxima of 100–120 ka.

The contrasting morphology at the shelf break, terminal-morainal bank (Fig. 7D1) versus an open trough-mouth (Fig. 7D2) we infer to reflect relatively slow versus fast glacier flow. Alternatively, the open trough-mouth and dumping of sediments over the shelf break could reflect sustained ice flow while the sector characterised by the morainal bank had stagnated.

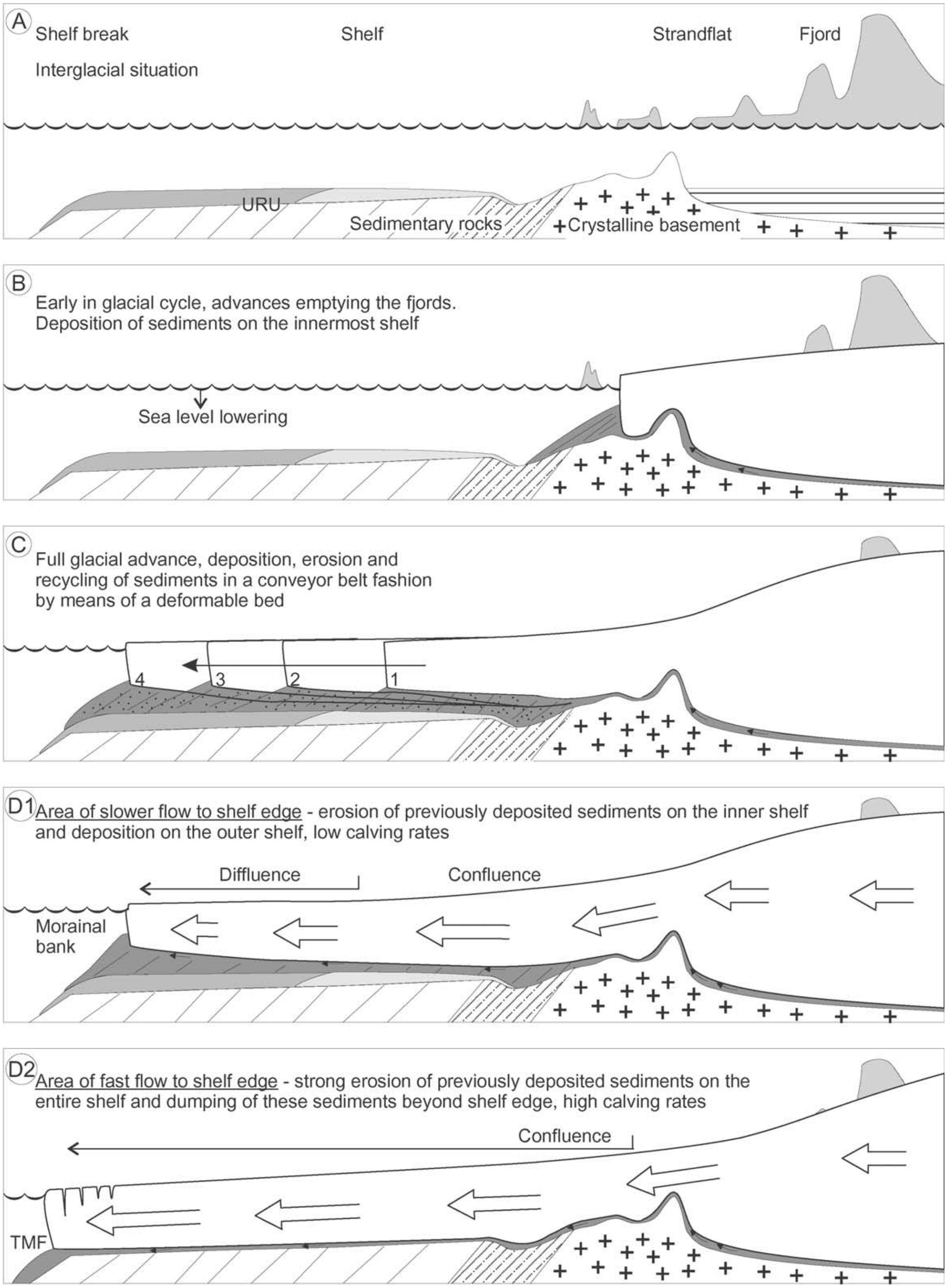

Fig. 7. A conceptual model of the glacier advances across the mid-Norwegian continental shelf. (A–C) depicts the progressive advance of the continental ice sheet. (D1) displays a situation of diffluent ice flow implying more sluggish flow on the outermost shelf. (D2) shows a situation of fast ice flow in a transverse glacial trough reaching the shelf break. In this instance all the previously deposited sediments were eroded and dumped over the shelf break, creating a trough mouth fan. If, however, the subsidence of the shelf is high and/or the erosive power of the ice is low, some sediments may be preserved.

However, Ottesen et al. (2001) showed that the sea floor morphology in Trænadjupet is characterised by large-scale lineations, and inferred that Trænadjupet was the drainage route for an ice stream during the last glacial. Thus, we favour the interpretation that the open trough-mouths indeed reflect areas of fast glacier flow at the shelf break.

Inferred slow ice flow at the outer southern Sklinnadjupet, where the large Skjoldryggen terminal morainal bank complex is situated (Figs. 2 and 5), is supported by the diffluent pattern at the mouth of the Sklinnadjupet Trough (Figs. 2 and 8; Ottesen et al., 2001). Further supporting evidence of sluggish ice flow at the outer southern Sklinnadjupet was presented by Sættem et al. (1996). They explained the extensive consolidation and fissility of the till in this particular area in terms of partly frozen bed conditions at the end of the last glacial advance. The terminal morainal bank (Fig. 8) off the southern sector of Sklinnadjupet Trough reflects the theoretical configuration of an ice stream terminating on the shelf without significant calving (Boulton, 1990, Fig. 12a).

On the other hand, the northern sector off the Sklinnadjupet Trough and the Trænadjupet Trough both mimic the geological record of marine terminating paleo-ice streams (e.g. Boulton, 1990, Fig. 12b; Stokes and Clark, 2001, Fig. 7c). The greater preservation of previously deposited sediments in the outer northern sector off Sklinnadjupet compared to the outer scoured Trænadjupet Trough (Fig. 6) can be explained as a combination of higher ice flux and a higher degree of confluence in the latter (Fig. 8). It can also be explained in terms of a higher subsidence off the Sklinnadjupet Trough (see morphology of the lower surface of Middle till, Fig. 6D.) which would enhance the preservation potential of the sediments as the glacier would have to deposit sediments to compensate for the greater accommodation space.

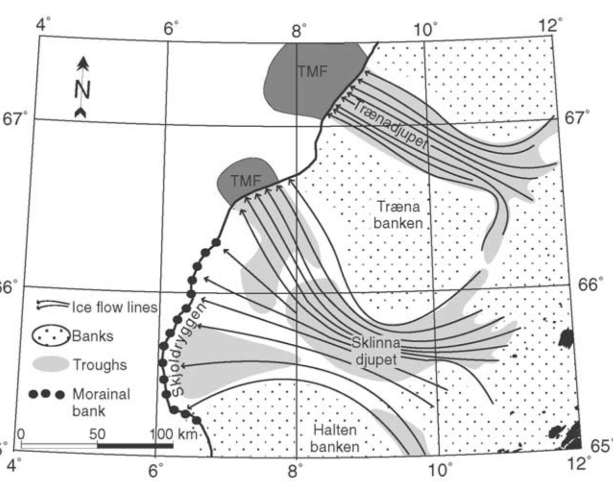

Fig. 8. Schematic ice flow pattern for the last phase of the Late Weichselian glacier advance based on the present day morphology of the shelf (troughs and banks). The occurrences of trough mouth deposition are marked with TMF.

The inferred low calving losses for the southern sector in front of the Sklinnadjupet Trough is due to the terminal morainal bank acting to lower the water depth at the calving front and adding support to the terminus. The added support at the terminus would increase the restraining forces acting on the glacier margin (Fischer and Powell, 1998), and hence limit the calving that is due to the development of crevasses related to tensile strain.

As the role of grounding line sediment supply probably was important along many portions of past ice-sheet margins as they advanced or grew on continental shelves, the process should be considered integrated in future numerical ice-sheet models. Ice sheet models portraying the sediment delivery and flux at the terminus already exist, cf. Dowdeswell and Siegert (1999). The feedback mechanism of decreased water depth at the terminus (lowering the calving), however, remains to be integrated.

6. Conclusions

Based on studies of seismic data and published maps of till thickness and surface topography we conclude that:

- Contrasting sediment accumulation on the shelf and along the shelf break is related to glacier flow regime. Diffluent flow produces morainal banks/grounding-line wedges and confluent flow produces open trough mouths, and debris lobes on the upper slope.
- Sediments deposited at the diffluent grounding line in front of southern Sklinnadjupet effectively reduced the water depth of up to more than 200 m, which acted to reduce losses through calving. Morainal banks/grounding-line wedges were deposited here.
- In northern Sklinnadjupet and Trænadjupet confluent flow caused ice flow to have high velocity and the deposition of trough mouth fans on the continental slope. But this does not preclude that morainal banks/grounding-line wedges were deposited on the shelf during the advance.
- High subsidence in outer Sklinnadjupet explains the greater preservation of sediments in northern Sklinnadjupet as opposed to Trænadjupet, which is eroded into bedrock.
- These mechanisms of sedimentation inferred to have been active during glacier advances across the shelf are important with regard to numerical ice-sheet models attempting to mimic the growth of the marine portions of past ice sheets. This is especially true for continental shelves characterised by large water depths and rapid subsidence.

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