Flow switching and large-scale deposition by ice streams draining former ice sheets

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ABSTRACT

Fast-flowing ice streams are responsible for the bulk of mass transfer through large ice sheets. We use extensive three-dimensional seismic data from the western Norwegian margin to explain how a several-hundred-kilometer-long ice stream has undergone major switching in flow direction from one glaciation to the next. The direction of ice flow is inferred from the pattern of buildup of thousands of cubic kilometers of glacier-derived debris and observations of large-scale streamlined landforms on former subglacial beds. We demonstrate that ice streams can undergo major changes in flow direction through modification of their large-scale topographic setting. Whereas ice-stream switching in modern ice sheets has been regarded mainly as a reflection of internal changes in ice-sheet dynamics, switching over successive 100 k.y. glacial cycles may in this case be a response to the effects of continuing sediment deposition and the large-scale development of ice-influenced continental margins.

Keywords: ice streams, Norwegian margin, three-dimensional seismic data, glacial lineations, glacial bedforms.

INTRODUCTION

Fast-flowing ice streams and outlet glaciers currently drain more than half of the mass from the Antarctic and Greenland ice sheets (e.g., Bentley, 1987; Thomas, 2004). Some temporal and spatial variability has been observed in the flow of modern West Antarctic ice streams (e.g., Retzlaff and Bentley, 1993; Jacobel et al., 1996; Conway et al., 2002), but major shifts in the location of ice streams flowing in deep channels have not been observed. We use an extensive three-dimensional seismic data set from the Norwegian margin to demonstrate and explain how an ice stream, >400 km long and draining an interior basin of >100,000 km^2, has undergone major switching in flow direction. We show that the ice stream flowed southwestward down a major depression during repeated glacial episodes, depositing a large accumulation of sediment eroded from beneath the parent ice sheet on the continental margin of mid-Norway. The direction and fast flow of ice are inferred from the pattern of buildup of glacier-derived debris and the observation of streamlined landforms on former subglacial beds. However, a change in orientation of these streamlined landforms indicates that the flow direction of the lowermost half of the ice stream switched dramatically by 90° between the penultimate (Saalian) and most recent (Weichselian) glacial periods, as the accumulation of sediments deposited during previous glacials progressively obstructed southwestward flow. The ice stream eroded a new 150-m-deep trough in underlying sediments, built a new depositional center ~100 km north of its previous terminus region, and became more than 100 km shorter. This demonstrates that ice streams can undergo major changes in flow direction as a result of long-term modification of their large-scale topographic setting over a number of glacial cycles, with considerable implications for the sedimentary architecture of the continental margin involved. Switching is linked to the long-term pattern of glacial erosion, transport, and deposition of several thousands of cubic kilometers of debris over a number of cycles of ice-sheet growth and decay since the first buildup of ice on Scandinavia ~2.5 m.y. ago (Jansen and Sjøholm, 1991).

ICE STREAMS: BACKGROUND

Ice streams are fast-flowing (10^2–10^3 m yr^{-1}) curvilinear elements within ice sheets that have sharp velocity gradients to slower-flowing (10 m yr^{-1}) ice beyond their crevassed margins (Bentley, 1987). They are usually tens of kilometers wide, as long as hundreds of kilometers, and ~500–2500 m thick. Fast motion is related to the deformation of their soft sedimentary beds, which, in contrast with slower-flowing ice, are at the melting point and probably water saturated. A component of basal sliding over the sediment surface may also be involved (Engelhardt and Kamb, 1998). Ice streams are important both glaciologically and geologically, because their rapid flow is responsible for the bulk of ice and sediment delivery to the margins of present and past ice sheets (e.g., Dowdeswell and Siegert, 1999; Pollard and DeConto, 2003). The successful reconstruction of past ice sheets requires that the locations and dimensions of former ice streams can be identified in the geological record and in numerical models of paleo–ice-sheet dynamics. In addition, knowledge of the nature and rate of sediment delivery to high-latitude glacier-influenced continental margins is also fundamental to understanding their evolution and sedimentary architecture.

SEISMIC EVIDENCE FOR LARGE-SCALE DEPOSITION ON THE MID-NORWEGIAN MARGIN

On the mid-Norwegian margin (Fig. 1A), seismic surveys have allowed detailed mapping of the three-dimensional form of the Naust Formation, which comprises a series of sedimentary units as thick as 2 km that make up the past 3 m.y. of predominately glacier-derived deposition (e.g., Dahlgren et al., 2002; Rise et al., 2005). Seismic reflectors within the formation that are often associated with past

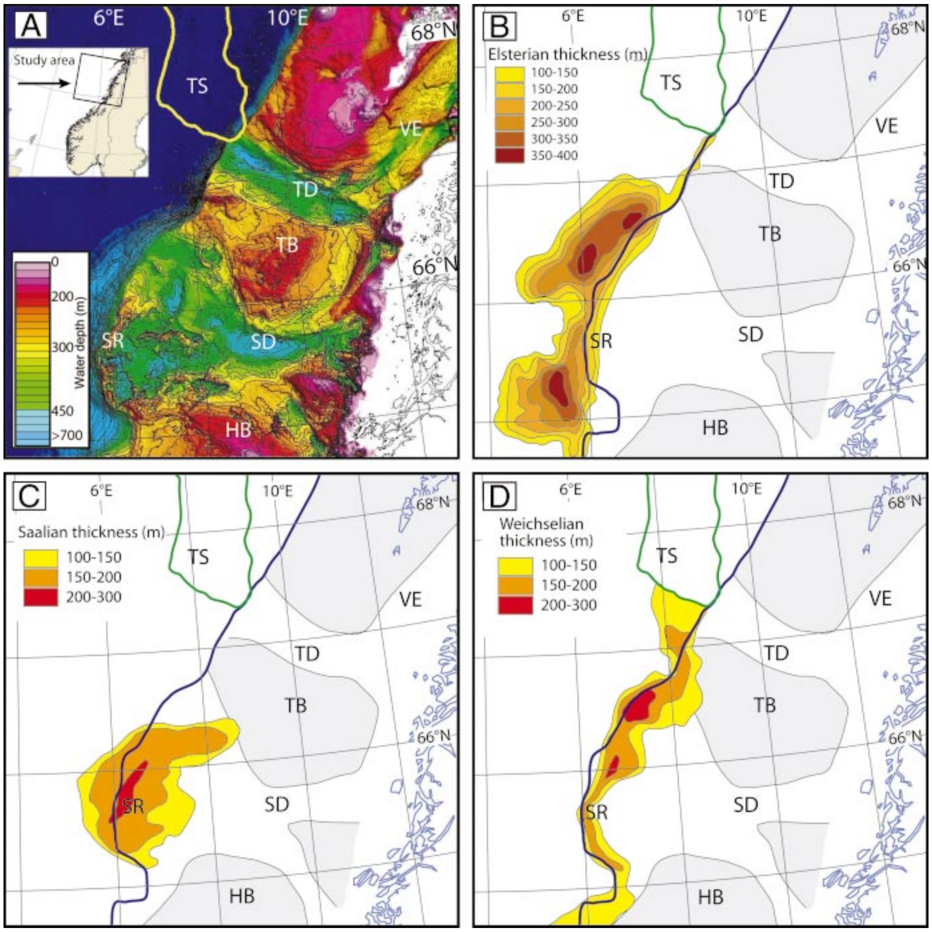

Figure 1. A: Bathymetric map of mid-Norwegian shelf. Study area is ~63,000 km^2. Isopach maps show sediment thickness for major glacial depositional centers along mid-Norwegian margin for Elsterian (B), Saalian (C), and Weichselian (D) glacial periods. Sediment thicknesses >100 m are plotted assuming sound velocity of 2000 m s^{-1}. Shelf edge at ~500 m water depth is shown in blue. Shaded areas in B–D are shallow banks. HB—Haltenbanken, SD—Sklinnadjupet, SR—Skjoldryggen, TB—Traenabanken, TD—Traenadjupet, TS—Traenadjupet Slide, VE—Vestfjorden.

ice-sheet erosion allow the thickness and volume of a number of units to be mapped. Maps have been constructed of sediment thickness along the mid-Norwegian margin between 65° and 67.5°N for each of the past 3 100-k.y.-long glacial cycles, known as the Elsterian, Saalian, and Weichselian (Figs. 1B–1D).

During the Elsterian and Saalian glaciations (~300 k.y.–135 k.y. ago) sedimentation on the mid-Norwegian margin was centered on the Skjoldryggen area between 65° and 66.5°N (Figs. 1B–1C), beyond the major cross-shelf trough of Sklinnadjupet. As much as 350 m of sediments were deposited, causing the building out of the continental shelf edge into deep water (Figs. 1B–1C). Thick sequences of glacial sediments were also deposited in the Traenabanken area during the Elsterian and Saalian glaciations. By contrast, ~100 km north of Skjoldryggen and Sklinnadjupet, offshore of what is now the cross-shelf trough of Traenadjupet (67°N), little sediment was delivered over these two glacial cycles (Figs. 1B–1C). During the last 100 k.y. of the Weichselian glacial cycle, however, sedimentation increased greatly beyond Traenadjupet to build a new depositional center, part of which was removed by more recent slides (Fig. 1D). The large-scale pattern of sediment delivery to the mid-Norwegian margin has therefore undergone a major shift during the Weichselian as compared with the two preceding glacial periods. In addition, the analysis of seismic data from the continental shelf around Traenadjupet also shows that a series of older reflectors has been truncated by a surface that forms the base of the Weichselian sedimentary unit (Fig. 2). Thus, the ~150 m overdeepened cross-shelf trough of Traenadjupet is a relatively recent morphological feature of the margin, which has developed mainly during the past ~100 k.y.

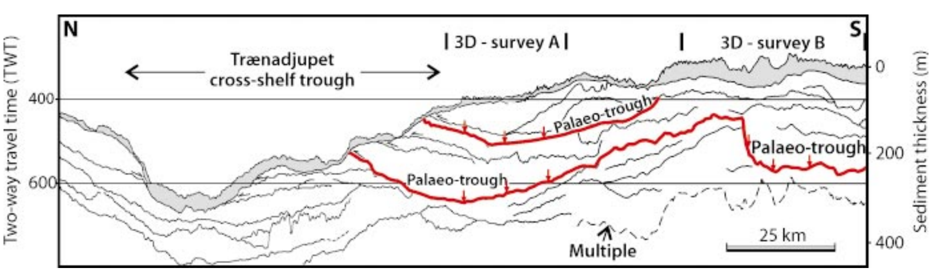

Figure 2. Seismic stratigraphy of upper ~0.5 m.y. of Naust Formation deposited on mid-Norwegian shelf. Sediment thickness is calculated using sound velocity of 2000 m s^{-1}. Seismic line (IKU B81–208) is located as N-S in Figure 3. Note erosion of underlying units by recent ice-stream flow in Traenadjupet and older ice-stream channels within sediments of Traenabanken to south (red lines labeled paleo-trough). Red arrows indicate presence of streamlined bedforms on buried paleotrough surfaces. Three-dimensional survey is NLGS-95 and survey B is NNE-2000.

PALEO–ICE STREAMS: FLOW DIRECTION AND SEDIMENT DELIVERY

Ice sheets have been the major source of sediment delivery to the entire Norwegian margin over the past ~2.5 m.y., since glaciers first formed on the Scandinavian mountains and extended outward to reach the coast and adjacent continental shelf (Jansen and Sjøholm, 1991). In addition, thick fast-moving ice streams, set within cold-based slower-flowing ice, provide the major source of icebergs, meltwater, and debris to the margin (e.g., Dowdeswell et al., 1996; Dowdeswell and Siegert, 1999; Siegert and Dowdeswell, 2002). These ice streams extended to the shelf edge during cold full-glacial conditions. The locations of past ice streams can be inferred from the presence of large-scale streamlined bedforms, known as megascale lineations, in continental shelf sediments. The lineations are formed at the base of fast-flowing ice streams by deformation processes affecting the upper few meters of sediment, which are often water saturated (Kamb, 2001; Clark et al., 2003; Dowdeswell et al., 2004). Individual lineations are as much as 15 m high and hundreds of meters wide. They are usually spaced hundreds of meters apart and are orientated in the direction of ice flow (Ó Cofaigh et al., 2002). Sets of lineations are well preserved and characteristic of modern cross-shelf troughs in both polar regions, where ice was present as recently as 10–15 k.y. ago (Shipp et al., 1999; Ó Cofaigh et al., 2002; Ottesen et al., 2005a, 2005b). They have been used to define the distribution of ice streams along the entire 2500-km-long western margin of the Scandinavian-Svalbard ice sheet at the last glacial maximum ~18 k.y. ago (Ottesen et al., 2005a).

We have used megascale glacial lineations (Clark, 1993) to define the locations and directions of ice-stream flow on the mid-Norwegian shelf over the past 300 k.y. Seismic reflectors, representing former glacier beds now buried hundreds of meters below the modern seafloor, have been identified and mapped (Figs. 3A–3B). These reflectors reveal detailed patterns of streamlined bedforms, identical in form to those from the latest Weichselian glaciation (Figs. 3C–3D). The changing pattern of ice flow inferred from the orientations of these sets of bedforms is shown in Figure 3E. During the Elsterian and Saalian glacial periods ice flowed southwest from the deep trough of Vestfjorden, across what is now Traenabanken, and into the Skjoldryggen area (Figs. 3A–3B). However, the present seafloor of Traenadjupet and Vestfjorden shows lineations extending down Vestfjorden and then turning almost 90° into Traenadjupet, where they extend ~100 km to the shelf edge (Ottesen et al., 2005a, 2005b) (Figs. 3C–3D). A major switch in ice-stream flow direction has therefore taken place (Fig. 3E).

The change in ice flow direction after the Saalian glaciation is supported by the growth of a major depositional center of at least 1500 km^3 at the mouth of Traenadjupet during the Weichselian period (Fig. 1D). The depocenter is composed mainly of stacked glacigenic debris flows, but ~900 km^3 has been removed by the 4-k.y.-old Traenadjupet Slide (Fig. 1D) (Henriksen and Vorren, 1996; Laberg et al., 2002) and an unknown but probably much smaller volume from the older Nyk Slide (Fig. 3E) (Lindberg et al., 2004). Rapid delivery of sediments from fast-flowing ice is required in order to build a depocenter of these dimensions (Dowdeswell and Siegert, 1999). In addition, seismic data show that these glacier-derived deposits are underlain by acoustically layered fine-grained sediments deposited over the Elsterian and Saalian periods (Dahlgren et al., 2002; Bryn et al., 2005). This material is interpreted as a contourite, deposited by northward-flowing ocean currents in the absence of large-scale sediment delivery from glaciers to the slope beyond the present Traenadjupet. The switch in flow direction is further supported through evidence of deep erosion by the Weichselian ice stream, which truncated earlier seismic reflectors and units at the flanks and base of Traenadjupet (Fig. 2). We

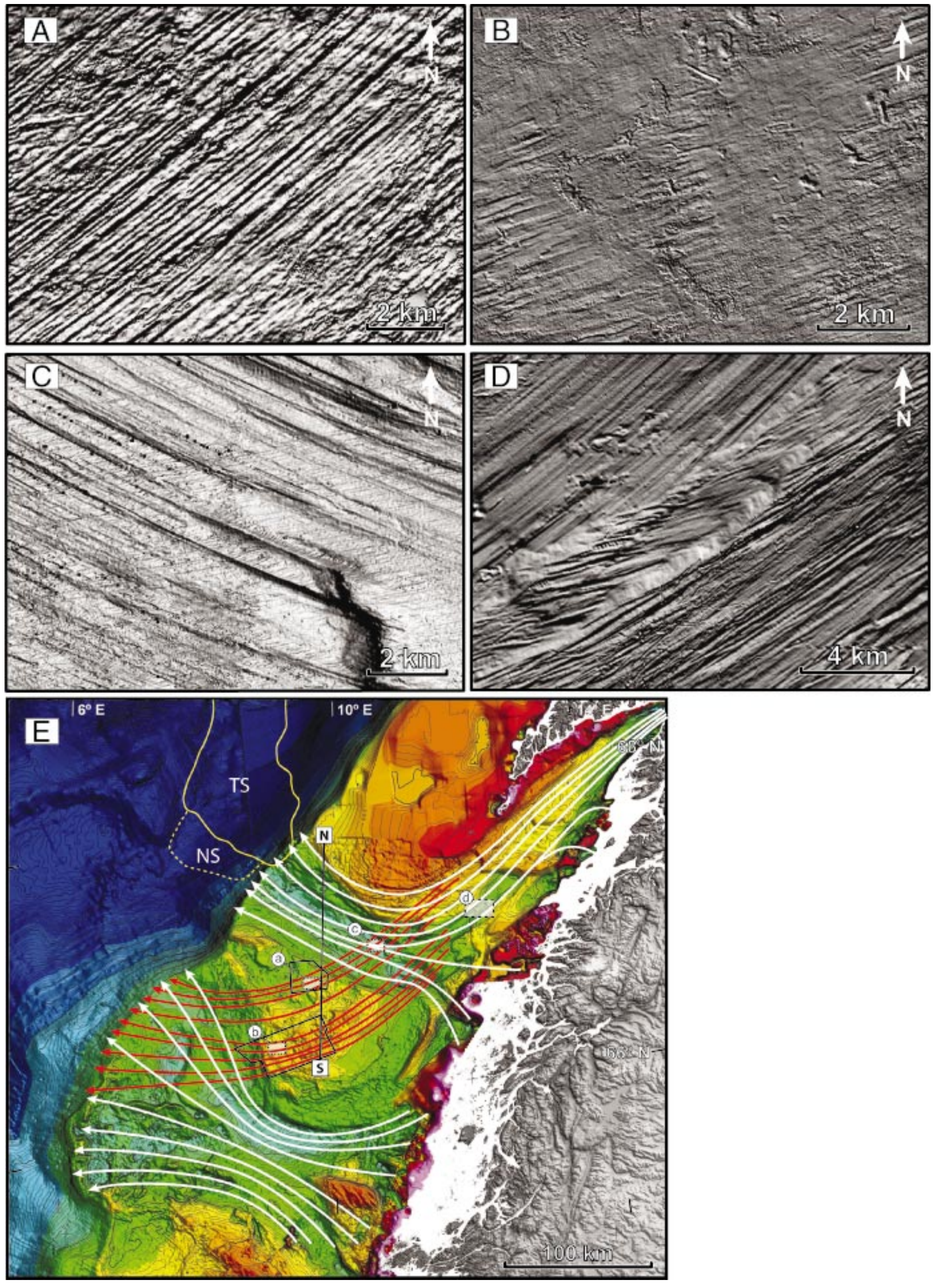

Figure 3. Streamlined sedimentary bedforms produced beneath paleo–ice streams on mid-Norwegian continental shelf. A: Buried surface ~100 m deep within upper Naust Formation (three-dimensional [3D] seismic block NLGS-95). B: ~200 m deep within upper Naust Formation (3D seismic block NNE-2000). C: Late Weichselian sediments at modern seafloor of Traenadjupet (3D seismic block ST-9404). D: Seafloor of Vestfjorden (EM1002 swath bathymetry). E: Map of changing ice-stream flow directions inferred from orientation of streamlined bedforms on mid-Norwegian shelf (located in Fig. 1A). Red lines are Elsterian–Saalian and white lines are Weichselian ice-stream flow directions, respectively. TS—Traenadjupet Slide, NS—Nyk Slide. Locations of surfaces in A–D are shown in E (labeled a–d), together with seismic line from Figure 2 (labeled N-S). Black boxes locate two 3D seismic blocks.

calculate that the ice stream, ~100 km long, 50 km wide, and having an erosive depth of 0.15 km, evacuated at least 750 km^3 of sediment from this cross-shelf trough.

LARGE-SCALE ICE-STREAM SWITCHING

This evidence demonstrates large-scale switching of ice-stream flow within a major ice sheet from one glaciation to the next. The change in flow direction may have taken place because of continuing buildup of glacier-derived sediments on the mid-Norwegian continental shelf and the filling of the available accommodation space. When Weichselian ice began to flow down Vestfjorden, its easiest path to the shelf edge was no longer across Traenabanken, supplying ice and debris to the

Skjoldryggen area to the southwest. Instead, a new trough was excavated through sediments to produce the 150-m-deep depression now known as Traenadjupet (Figs. 2 and 3E). A large-scale geological consequence of this radical shift in ice-stream location was the development of a major new depositional center on the continental margin near 67°N (Fig. 1D). However, we cannot rule out the possibility that large-scale switching was a response to glaciological changes in, for example, the dimensions of the inland ice-sheet drainage basin or the thermal structure of the ice-sheet base. Ice-stream switching in modern ice sheets has previously been regarded mainly as a reflection of such internal changes in ice-sheet dynamics. We show that switching over longer periods may also be influenced by the effects of continuing sediment deposition and the large-scale topographic development of high-latitude continental margins.

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REFERENCES CITED

Bentley, C.R., 1987, Antarctic ice streams: A review: Journal of Geophysical Research, v. 92, p. 8843–8858.

Bryn, P., Berg, K., Stoker, M.S., Haflidason, H., and Solheim, A., 2005, Contourites and their relevance for mass wasting along the Mid-Norwegian Margin: Marine and Petroleum Geology, v. 22, p. 85–96, doi: 10.1016/j.marpetgeo.2004.10.012.

Clark, C.D., 1993, Mega-scale glacial lineations and cross-cutting ice-flow landforms: Earth Surface Processes and Landforms, v. 18, p. 1–19.

Clark, C.D., Tulaczyk, S.M., Stokes, C.R., and Canals, M., 2003, A groove-ploughing theory for the production of mega scale glacial lineations, and implications for ice stream mechanics: Journal of Glaciology, v. 49, p. 240–256.

Conway, H., Catania, G., Raymond, C., Scambos, T., Engelhardt, H., and Gades, A., 2002, Switch of flow direction in an Antarctic ice stream: Nature, v. 419, p. 465–467, doi: 10.1038/nature01081.

Dahlgren, K.I.T., Vorren, T.O., and Laberg, J.S., 2002, Late Quaternary glacial development of the mid-Norwegian margin–65 to 68°N: Marine and Petroleum Geology, v. 19, p. 1089–1113, doi: 10.1016/S0264-8172(03)00004-7.

Dowdeswell, J.A., and Siegert, M.J., 1999, Ice-sheet numerical modeling and marine geophysical measurements of glacier-derived sedimentation on the Eurasian Arctic continental margins: Geological Society of America Bulletin, v. 111, p. 1080–1097, doi: 10.1130/0016-7606(1999)111<1080:ISNMAM>2.3.CO;2.

Dowdeswell, J.A., Kenyon, N.H., Elverhøi, A., Laberg, J.S., Hollender, F.-J., Mienert, J., and Siegert, M.J., 1996, Large-scale sedimentation on the glacier-influenced Polar North Atlantic margins: Long-range side-scan sonar evidence: Geophysical Research Letters, v. 23, p. 3535–3538, doi: 10.1029/96GL03484.

Dowdeswell, J.A., Ó Cofaigh, C., and Pudsey, C.J., 2004, Thickness and extent of the subglacial till layer beneath an Antarctic paleo-ice stream: Geology, v. 32, p. 13–16.

Engelhardt, H., and Kamb, B., 1998, Basal sliding of Ice Stream B: West Antarctica: Journal of Glaciology, v. 44, p. 223–230.

Henriksen, S., and Vorren, T.O., 1996, Late Cenozoic sedimentation and uplift history on the mid-Norwegian continental shelf: Global and Planetary Change, v. 12, p. 171–199, doi: 10.1016/0921-8181(95)00019-4.

Jacobel, R.W., Scambos, T.A., Raymond, C.F., and Gades, A.M., 1996, Changes in the configuration of ice stream flow from the West Antarctic ice sheet: Journal of Geophysical Research, v. 101, p. 5499–5504, doi: 10.1029/95JB03735.

Jansen, E., and Sjøholm, J., 1991, Reconstruction of glaciation over the past 6 Myr from ice-borne deposits in the Norwegian Sea: Nature, v. 349, p. 600–603, doi: 10.1038/349600a0.

Kamb, B., 2001, Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion, *in* Alley, R.B., and Bindschadler, R.A., eds., The West Antarctic Ice Sheet: Behavior and environment: American Geophysical Union Antarctic Research Series, v. 77, p. 157–199.

Laberg, J.S., Vorren, T.O., Mienert, J., Evans, D., Lindberg, B., Ottesen, D., Kenyon, N.H., and Henriksen, S., 2002, Late Quaternary palaeoenvironment and chronology in the Traenadjupet Slide area offshore Norway: Marine Geology, v. 188, p. 35–60, doi: 10.1016/S0025-3227(02)00274-8.

Lindberg, B., Laberg, J.S., and Vorren, T.O., 2004, The Nyk Slide—Morphology, progression, and age of a partly buried submarine slide offshore northern Norway: Marine Geology, v. 213, p. 277–289, doi: 10.1016/j.margeo.2004.10.010.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A., and Morris, P., 2002, Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf: Geophysical Research Letters, v. 29, doi: 10.1029/2001.GL014488.

Ottesen, D., Dowdeswell, J.A., and Rise, L., 2005a, Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: The 2,500-km-long Norwegian-Svalbard margin (57° to 80°N): Geological Society of America Bulletin, v. 117, p. 1033–1050, doi: 10.1130/B25577.1.

Ottesen, D., Rise, L., Knies, J., Olsen, L., and Henriksen, S., 2005b, The Vestfjorden-Traenadjupet palaeo-ice stream drainage system, mid-Norwegian continental shelf: Marine Geology, v. 218, p. 175–189, doi: 10.1016/j.margeo.2005.03.001.

Pollard, D., and DeConto, R.M., 2003, Antarctic ice and sediment flux in the Oligocene simulated by a climate-ice sheet-sediment model: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 198, p. 53–67, doi: 10.1016/S0031-0182(03)00394-8.

Retzlaff, R., and Bentley, C.R., 1993, Timing of stagnation of Ice Stream C, West Antarctica, from short-pulse radar studies of buried surface crevasses: Journal of Glaciology, v. 39, p. 553–561.

Rise, L., Ottesen, D., Berg, K., and Lundin, E., 2005, Large-scale development of the mid-Norwegian margin during the last 3 million years: Marine and Petroleum Geology, v. 22, p. 33–44, doi: 10.1016/j.marpetgeo.2004.10.010.

Shipp, S., Anderson, J., and Domack, E., 1999, Late Pleistocene–Holocene retreat of the West Antarctic Ice Sheet system in the Ross Sea: Part 1—Geophysical results: Geological Society of America Bulletin, v. 111, p. 1486–1516, doi: 10.1130/0016-7606(1999)111<1486:LPHROT>2.3.CO;2.

Siegert, M.J., and Dowdeswell, J.A., 2002, Late Weichselian iceberg, meltwater and sediment production from the Eurasian Ice Sheet: Results from numerical ice-sheet modelling: Marine Geology, v. 188, p. 109–127, doi: 10.1016/S0025-3227(02)00277-3.

Thomas, R.H., 2004, Greenland: recent mass balance observations, *in* Bamber, J.L., and Payne, A.J., eds., Mass balance of the cryosphere: Cambridge, Cambridge University Press, p. 393–436.

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