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Evidence of an ice-dammed lake outburst in the North Sea during the last deglaciation

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Abstract :

Recent reconstructions suggest that the British-Irish and Fennoscandian ice sheets coalesced and covered the central and northern North Sea from ca. 26 cal. ka BP and until ca. 19 cal. ka BP. At ca. 19 cal. ka BP the Norwegian Channel Ice Stream started to retreat and the ice sheets broke apart at ca. 18.7 cal. ka BP. This led to a drainage of an ice-dammed lake in the southern North Sea northwards via the Norwegian Channel into the SE Nordic Seas. In this paper we combine information from high resolution TOPAS profiles, bathymetric records and shallow borings to study the ice-dammed lake outburst, a common deglaciation process but which rarely has been evidenced in such a detail from the marine realm. A 12 m deep and 3 km wide incision at the northeastern part of the Dogger Bank is suggested to represent the point where the ice-dammed lake breached. The glacial lake outburst flood, which had an estimated peak discharge of 9.8 x 10(4)-2.9 x 10(5) m(3)/s and lasted for about 5-15 months, flowed between the withdrawing British-Irish and Fennoscandian ice sheets following the crest of the Ling Bank northwards. Along this path, about 300 km downstream of the break-through point, an up to 10 m thick sediment package with a prograding-aggrading sedimentation pattern, typical for ice-dammed lake outburst deposits, has been deposited. This sediment package was deposited in a high-energy environment, immediately following extensive erosion of the underlying till unit of Last Glacial Maximum age. An oxygen isotope anomaly and an associated ultra-rapidly deposited meltwater plume on the Norwegian continental margin, dated to ca. 18.7 cal. ka BP, also witness this lake outburst. The ice-dammed lake outburst flood occurred when evidence suggest a sea level at least 110 m lower than at present in the region. As the sea level rose, following the melting of the Last Glacial Maximum ice sheet, the Ling Bank Delta developed on top the outburst deposits. The delta, indicating a sea level close to 80 m below present, has an extent of 80 km and up to 12 m deep fluvial channels are associated with the topset beds. This fluvial environment may have lasted until the end of the Younger Dryas time period when the Ling Bank was submerged and attained its present water depth.

Highlights

► An ice-dammed lake existed in the southern North Sea during the Last Glacial Maximum. ► The ice-dammed lake outbursts at 18.7 cal. ka BP. ► The lake outburst had an estimated peak discharge of 9.8×10^4–2.9×10^5 m^3/s. ► The drainage lasted for about 5–15 months.

Keywords : North Sea, Ice-dammed lake, Glacial lake outburst flood, Last Glacial Maximum, Deglaciation, Delta

1. Introduction

Ice-dammed lakes develop supraglacially, subglacially or ice-marginally and their formation and length of existence are strongly dependent on the dynamics of the ice sheet and the character of the neighboring environment (Carriwick and Tweed, 2013). Well-studied examples of paleo ice-dammed lakes are Lake Agassiz (Laurentide Ice Sheet) which existed for a time period of 4000 years during the last deglaciation, the late Wisconsin Glacier Lake Missoula (Coredellian Ice Sheet), and the Younger Dryas Baltic Ice Lake (Scandinavian Ice Sheet) (e.g., Jensen et al., 1997; Teller et al., 2004; Alho et al., 2010). Such ice-dammed lakes can cover considerable areas and contain huge volumes of water. The 9700 km^2 Glacier Lake Missoula held a water volume of 2600 km^3, whereas the Baltic Ice Lake was nearly four times lager in area and 10 times larger in volume (Teller et al., 2002; Jakobsson et al., 2007). On the other hand, Lake Agassiz covered a total area of 841,000 km^2 and contained a water volume of 163,000 km^3 when it merged with Lake Ojibway about 8200 years ago (Teller et al., 2002).

We note that the largest lake on Earth today, the Caspian Sea, covers 371,000 km ^{2} and has a volume of 78,200 km^3 (Rodionov, 2012).

Ice-dammed lakes can be drained, often periodically, and such glacial lake outburst floods (GLOFs) commonly represent abrupt discharges of large volumes of water. It has been estimated that the prominent 8.2 cal. ka BP drainage of Lake Agassiz was ongoing for 6 months, with an average flux of 5 Sv, and involved a total water volume of 10^{14} m^3 (Clarke et al., 2004). GLOFs are reported from onshore areas as canyons and giant gravel bars, whereas in the marine domain such sudden release of dense fresh water can give rise to prominent meltwater peaks in sediment cores (e.g., Alley and Ágústsdóttir, 2005; Høgaas and Longva, 2016).

It is of importance to have knowledge on GLOFs, and their associated processes, as they give information on deglaciation character and as they may have a strong impact on climate and ocean circulation (Carriwick and Tweed, 2013). Notably, the around 1000 year-long Younger Dryas event has been suggested to be related to the 9500 km^3 Herman Drainage Stage of Lake Agassiz (Broecker et al., 1989; Teller et al., 2002). Smaller ice-dammed lakes are at present located on e.g. Iceland, in Scandinavia and in the Central European Alps and it is suggested that the number of such lakes will increase in the years to come due to the inferred warming climate (Carriwick and Tweed, 2016). Thus, outburst floods may increase in frequency and become an increasing threat to infrastructure and buildings.

In this study we will investigate the drainage route of a paleo-GLOF from an ice-dammed lake predicted by many authors (e.g., Hijma et al., 2012; Sejrup et al., 2016) to have existed during the Last Glacial Maximum (LGM) in the southern North Sea (Fig. 1), and which we here name the Late Weichselian North Sea Lake. In this effort we will integrate high resolution acoustic data and information from already analyzed shallow borings, and **(1)** identify outburst processes using seismic facies analyses, **(2)** evaluate seabed features and their possible relationship with the GLOF, **(3)** study sediment character of identified seismic facies and seismic units, and **(4)** discuss a chronological framework for the identified processes. Finally, we will put the ice-dammed lake outburst in context of the late glacial-Holocene paleo-environmental history of the North Sea region.

2. Background

The epicontinental North Sea is characterized by water depths of <150 m except for in the Norwegian Channel, a prominent seabed depression along the south and west coast of Norway that reaches a maximum water depth of 700 m in the Skagerrak (Figs. 1-3). In general, the water depth in the North Sea shows a gradually increase from south to north. South of Dogger Bank the water depth does not exceed 60 m. North of Dogger Bank the North Sea is characterized by an embayment. This embayment reaches a maximum water depth of 150 m in the Fladen Basin and is bounded to the east by the Ling Bank (Figs. 2 and 3). Several larger-sized rivers, including the Rhine, Elbe, Weser and Ems, are at present entering the southern North Sea (Fig. 1). The effect these rivers had on shaping the seabed morphology during glacial low sea level stands is easily visible in the bathymetric data (Fig. 3a).

It has been suggested that the northern and central North Sea have been partly or fully ice covered several times during the Late Quaternary Northern Hemisphere Glaciations (Sejrup et al., 2005; Graham et al., 2011; Lee et al., 2012), and that the British-Irish (BIIS) and Fennoscandian (FIS) ice sheets coalesced in this region for the last time during the LGM (Clark et al., 2012; Sejrup et al., 2016). Evidence of these ice advances are imprinted in the sediment stratigraphy as moraine packages, and as networks of buried and exposed tunnel valleys (Sejrup et al., 1987; Sejrup et al., 1995; Stewart and Longergan, 2011). The last glacial-deglaciation cycle of the North Sea region is partly evidenced in the present day seabed, which shows a complex pattern of ice marginal features, lateral shear zone moraines and glacial lineations (Fig. 3) (Bradwell et al., 2008; Sejrup et al., 2016).

During maximum glacial stages global eustatic sea level was around 120 m lower than today (e.g., Lambeck et al., 2014), and parts of the North Sea were located above sea level for some time after the withdrawal of the LGM ice sheet. Especially, the Dogger and Ling banks (Figs. 1 and 2) must have been sub-aerially exposed for a considerable time span, and these now "lost lands" have attracted strong interest as they in post-glacial time may have been sites for early settlements (e.g., Coles, 2000; Hammer et al., 2015).

It has been suggested that an ice-dammed lake has occupied the region south of Dogger Bank during various glacial stages, including Marine Isotope Stage (MIS) 12, MIS 6 and MIS 2 (e.g., Hijma et al., 2012; Murton and Murton, 2012). The Late Weichselian North Sea Lake outburst was by Sejrup et al. (2016) suggested to follow an ice free corridor that existed between the BIIS and FIS as these ice sheets started to unzip, flowing into the Norwegian Channel through the proposed Ling Bank Drainage Channel (Fig. 1). Also a light spike in oxygen-isotopes in planktonic foraminifera, possibly reflecting large input of freshwater to the ocean, is identified close to 18.7 cal. ka BP in cores from the SE Nordic Seas margin (Lekens et al., 2005), and which probably reflect the Late Weichselian North Sea Lake drainage event (Sejrup et al., 2016). The ice-dammed lake has, based on maximum North Sea ice margins and bathymetric variations in the area, been estimated to be 3900 km^3 (Bigg et al., 2012). Thus, the Late Weichselian North Sea Lake is comparable to the proposed Late Wisconsion Glacier Lake Missoula in North America (Teller et al., 2002).

3. Data and methods

The data base used in this study includes TOPAS high resolution seismic profiles, bathymetric data and shallow borings (Figs. 2 and 3).

The seismic profiles, which have been collected during several University of Bergen cruises onboard R/V G.O. Sars between 2006 and 2014, define a broad grid within the study area (Fig. 2). During data acquisition, a TOPAS PS18 system from Kongsberg AS was used, giving seismic profiles with a vertical resolution of around 30 cm and a maximum penetration of ca. 100 m. The seismic profiles analyzed for this study have an overall good quality and were interpreted using the Petrel 2013 software from Schlumberger AS. We base the seismic interpretation on seismic facies character and changes in this throughout the study area.

An isopach map, in millisecond(two-way travel time) [ms(twt)], showing thickness and distribution of the sediments deposited in the Norwegian Channel between the last deglaciation (19-17.5 cal. ka BP) and the end of the Younger Dryas (11.6 cal. ka BP) has been generated. In addition to the TOPAS seismic profiles presented in this study, this map is also based on numerous other TOPAS lines collected in the Norwegian Channel (see Fig. 1a in Sejrup et al., 2016). For conversion of sediment thickness and sediment depth in ms(twt) to depth in meter, a velocity in the sediments of 1500 m/s has been applied.

The bathymetric database used in this study, Olex, has been made available by Olex AS (www.olex.no). In Olex, individual data sets, acquired by fishing and research vessels, have been merged into a single database with a horizontal resolution of 5x5 m. The vertical resolution of the database is <1 m, and positioning errors are commonly less than 10 m. The Olex database has good coverage in the northern part of the North Sea, whereas regions with more scattered data coverage are identified in the central part and particularly in the southern part of the North Sea (Figs. 2 and 3). The analyses of the bathymetric data was done both in the Olex system, where the bathymetry can be viewed as 2D contours, 2D shaded relief, 3D views or as 2D profiles, and on exported .tiff files which were georeferenced and interpreted in the ArcGIS 10.3 software from Esri.

We have also utilized information from three previously analyzed shallow borings in the study area, B2001 (1.72°E-58.39°N), LH-BH3/4 (2.26°E-58.79°N) and 3/6-1 (4.89°E-56.58°N) (Fig. 2). B2001 was drilled in 110 m water depth and penetrated to a depth of 119.3 m below the seabed, and information on the upper 20 m on grain-size, shear strength and chronology have previously been published by Sejrup et al. (1987) and Sejrup et al. (1994). Boring 3/6-1 was raised from a water depth of 64 m at the southern part of the Ling Bank (Fig. 2), and penetrates 37 m into the sediments. The upper 12 m of this boring has been sub-divided into five units based on grain size and various geotechnical parameters (Hammer et al., 2015). LN-BH3/4 is located in a water depth of 109 m at the northern tip of the Ling Bank, and information on grain size and shear strength are available from this borehole (Reinardy et al., 2017). In addition to these study area specific borings we have also used published information from sediment cores located elsewhere in the North Sea and on the Norwegian continental margin (Figs. 2 and 3).

4. Results

4.1 Bathymetry and seabed character

In the southernmost North Sea maximum water depths of 50 m is reached in an elongated bathymetric depression bounded by the coastlines of Denmark, Germany, the Netherlands and UK in east, west and south and the Dogger Bank to the north (Fig. 2). A ridge, standing up to 10 m above the surrounding seabed, interrupts the otherwise rather flat sea floor of the depression (Fig. 2 and 3). Two prominent seabed incisions, Inc-I and Inc-II (Fig. 3), are observed at the western and eastern edges of the bathymetric depression. Inc-I has an east-west trend, is up to 30 km wide and reaches a maximum water depth of 83 m, whereas Inc-II has a maximum water depth of 56 m and a width of around 10-15 km.

The SW-NE trending Dogger Bank (Fig. 2) is a prominent elevated area located at the boundary between the southern and central North Sea. The bank has a length of nearly 300 km in the E-W direction and is up to 100 km wide. The shallowest part of the Dogger Bank is located to the southwest, where the seafloor is situated only 11 m below the present day sea level. Towards the northeast the Dogger Bank is both narrowing and deepening, and at its northwestern tip, where the Dogger Bank is incised by Inc-II (Fig. 3), the water depth is around 40 m. The northern boundary of the Dogger Bank is characterized by an $<0.2^{\circ}$ slope, along where the water depth is increasing from 40-50 m to approximately 60-80 m.

Northeast of the Dogger Bank is the Ling Bank located (Figs. 1 and 3). Along the crest of this bank the water depth is only 65 m, shallowing to 45 m across Store Fiskebank (Great Fisher Bank) (Figs. 2 and 3). Store Fiskebank resembles a typical moraine ridge shape, with a northern flank that is much steeper than the southern. The Ling Bank is approximate 200 km wide nearby Dogger Bank, narrowing to only around 40 km at its northern tip where a rather abrupt deepening in the water depth to 110-120 m, across a 0.03° slope, is observed (Fig. 3b). The slope of the Ling Bank towards the Norwegian Channel is as steep as 0.6°, whereas the western slope is gentler. East and west of the Ling Bank the water depth is around 80-90 m and the seabed is expressing a glacial landscape, where tunnel valleys, inclined ledges and ice marginal features have been identified (Sejrup et al., 2016). In the northern North Sea the seabed is dominated by a fresh glacial landscape (Bradwell et al., 2008; Sejrup et al., 2016), except for in the Fladen and Viking Bank basins areas (Fig. 3) where a relatively flat and smooth seabed in water depths of 150 m and 110 m is observed.

4.2 Seismic facies and sediment character

Two seismic facies are dominating in the study area; acoustically transparent and acoustically well laminated. The acoustically transparent seismic facies has been shown to represent till, as documented both by sediment core-seismic profile correlation in this study and by previous work in the region on similar data (e.g,. Sejrup et al., 2015). The acoustically well laminated seismic pattern, comprising medium to high amplitude continuous and parallel reflectors are, based on a comparison to studies by Graham et al. (2010) and Sejrup et al. (2015), suggested to represent glacimarine deposits.

4.2.1 Area north of Ling Bank

The region north of the Ling Bank comprises two prominent accumulation areas of postglacial sediments, the Fladen Basin and the not previously studied Viking Bank Basin (Fig. 2). The Fladen Basin contains an up to 25 m thick unit of acoustically well laminated glacimarine sediments which are interfingered by several glacigenic debris flows (Sejrup et al., 2015). The Viking Bank Basin covers an area of around 3500 km^2, and contains an up to 35 m thick sediment package that drapes one or several acoustically transparent till units (Fig. 4). Several deep incisions, both exposed at the seabed and buried, are observed, and we infer these features to represent tunnel valleys. Tunnel valleys are commonly identified in the North Sea (e.g., Huuse and Lykke-Andersen et al., 2000). The acoustic data also show that the Viking Bank Basin is an area of shallow gas (Fig. 4), locally reducing the seismic penetration. The sediment package deposited in the Viking Bank Basin is characterized by an acoustically well laminated seismic facies, inferred to represent glacimarine sediments. However, in the uppermost 15-20 ms(twt) (ca. 12-15 m) of the deposited sequence a wavier and more contorted seismic pattern is identified. Furthermore, numerous point source reflectors are identified in this part of the sediment column, most likely representing more coarse-grained sediments.

At the northern tip of the Ling Bank, prominent changes in the seismic facies make us divide the sediment succession in this region into four sub-units, LBI (oldest) - LBIV (Figs. 5

and 6a). Sub-unit LBI comprises continuous, parallel medium to high amplitude reflectors and seems to represent classic glacimarine sediments deposited above a till unit. This till unit is, locally, defining the base of the Fladen and Ling Bank sediment basins, and can also easily be followed into the Norwegian Channel.

LBII reaches a maximum thickness of about 10 m, and is characterized by medium to high amplitude continuous reflections that define a prograding-aggrading seismic pattern (Fig. 6a). This seismic facies cover an area of ca. 3400 km^2 (Fig. 3a), and can be followed for a distance of up to 40 km. At the base of sub-unit LBII several mounds, up to 5 m in height and 2 km in diameter, are observed (Fig. 6b). Commonly, sub-unit LBII is overlying sub-unit LBI. We note, however, that LBII, locally, downlap the mapped till unit (Fig. 6a). In this downlapping region the surface of the till unit is extremely flat.

Sub-unit LBIII has been deposited stratigraphically above LBII, and is characterized by an acoustically contorted seismic facies where point-source reflectors are frequently identified (Fig. 5). Towards the Norwegian Channel this sediment package increases in thickness and incisions, up to 500 m in width and 5 ms(twt) (ca. 3.5 m) deep, are observed. These incisions are commonly observed at two levels in the sediment package. The uppermost identified sub-unit, LBIV, has an acoustically transparent to acoustically weakly layered character.

Shallow borings B2001 and LH-BH3/4 (Fig. 2) penetrate sub-units LBII-LBIV, and reveal that the observed changes in acoustic facies are mirroring lithology variations in the deposited sediment package (Fig. 7). Mapping of LBI-LBIV equivalent sediments in the Norwegian Channel shows that these deposits reach a maximum thickness of 160 ms(twt) (ca. 120 m) in the Skagerrak region (Fig. 8). In the central part of the Norwegian Channel the sediment thickness is much less, reaching a maximum of 70 ms(twt) (ca. 50 m) in a depocentre along the western edge of the Norwegian Channel. The outermost part of the

Norwegian Channel is characterized by sediment thicknesses of less than 20 ms(twt) (ca. 15 m).

4.2.2. Ling Bank

Along the Ling Bank stacks of acoustically transparent units, which we suggest to represent till units, dominate the sub-seabed sediment succession (Fig. 9). Several major incisions, assumed to partly represent tunnel valleys, have eroded into these units. Still, these incisions have remnants of their presumed original sediment infill, represented by an acoustically well-laminated seismic facies, and which we infer to represent glacimarine deposits (Fig. 9). However, mostly such possible infills have been removed and replaced by till packages.

At the northernmost part of the Ling Bank, in present water depths of 65-70 m, a unit composed of northward dipping clinoforms is identified (Figs. 3 and 10). The clinoforms are most likely representing topset, forset and possibly bottomset beds of a delta, which we name the Ling Bank Delta. The delta is about 80 km in length, up to 10 m thick and shows a well-defined pinch-out at its southern boundary. The TOPAS seismic profiles show indications of several incisions in the topset beds (Fig. 10). At the northern tip of the Ling Bank, the delta front seems to downlap the upper surface of sub-unit BFII, and the boundary between the downlapping clinoforms and sub-unit BFII are identified as a zone of high amplitude patches (Fig. 6a).

Along the crest of the Ling Bank, near the present day seabed, three incisions are identified (Figs. 3, 9a and 9b). These incisions have eroded 10-20 ms(twt) (7-15 m) into the sub-seabed sediment succession and can be traced for up to 6 km in the available seismic profiles. A draping or prograding infill style characterizes these features.

At the southern part of the Ling Bank, at the boundary towards the Dogger Bank, the present day current system in the region have caused sand waves and sand dunes to develop, prohibiting seismic penetration with the TOPAS system (Fig. 11a). The TOPAS seismic profiles, however, reveal a 20 ms(twt) (ca. 15 m) deep cut in the sediment succession at the location where a prominent bathymetric depression is observed (Inc-II in Fig. 3c). In this region we also observe erosion of the surrounding sediment packages (Fig. 11a). Southeast of Store Fiskebank, in an area where glacial imprints in the seabed are not observed, we identify erosion of the surface of the uppermost identified till unit (Figs. 3 and 11b). Furthermore, the sub-bottom data show that a less than 10 ms(twt) (ca. 7 m) thick sediment package, displaying the same prograding pattern as sub-unit LBII further north, has been deposited in this region. Boring 3/6-1 (Hammer et al., 2015) indicates that this sediment package is dominated by sand.

5. Discussion

5.1 Acoustic evidence of a lake outburst flood, its transport route and its dimensions

The studied bathymetric and seismic data give several indications about both the existence of a GLOF in the North Sea and the transport route it followed after the collapse of the lake-supporting ice-barrier. A strong evidence is the identified seismic sub-unit LBII, mapped at the northern tip of the Ling Bank (Figs. 3, 5 and 6a). The observed northward prograding direction of this unit (Fig. 6a) suggests that LBII has had a southerly source, which is in line with the existence of an ice-dammed lake south of Dogger Bank (Fig. 1). The prograding-aggrading character of this unit also typically resembles the depositional nature of lake-outburst deposits, as are reported from field studies of terrestrial GLOFs (Russell et al., 2001; Smith, 2006; Carling et al., 2013).

Seismic sub-unit LBII is in the study area, furthermore, overlying a seismically homogenous unit which, based on seismic characteristics and information from cores in the region (Fig. 7), has been identified as till or glacially overridden sediments representing the last glacial phase in the area. The boundary of the till towards LBII is characterized by a very flat and smooth surface when comparing it with regions where LBI is deposited on top of this unit (Fig. 5). This relationship between LBII deposits and the flat surface make us infer that sub-unit LBII during deposition had a strong erosion capacity, and reshaped the upper boundary of the till to a smooth and slightly westward dipping surface in an approximately 2200 km^2 large area (Figs. 3a and 5). This inferred high-sedimentation rate environment is also supported by the seismic signature observed near the bottom of LBII. Here, smaller-sized mounds are observed, and which, when comparing to land-based field data from GLOFs in NW Germany (Fig. 16 in Meinsen et al., 2011), may represent convoluted bedding formed during high energy deposition. We note that erosional boundaries between GLOF deposits and underlying strata are frequently reported from land-based studies (e.g., Hanson and Calgue, 2016). Alho et al. (2010) have also, from a paleohydraulic drainage reconstruction of Glacier Lake Missoula, shown that the shear stress affecting the bed during a GLOF is high and capable of eroding the substrata. Thus, the combined observation of erosion, its location, at the till-LBII boundary, and the character of BFII suggests that this unit is related to a lake outburst flood. Similar indications of outburst sediments and erosion are observed at the southern part of the Ling Bank (Figs. 3 and 11b).

We note that there is a distance of about 300 km from the assumed Late Weichselian North Sea Lake (Fig. 1) and the sediments in LBII, but large travel distances seem to be common for GLOFs. During the Glacier Lake Missoula drainage, outburst flood features covered distances of up to 700 km (Hansson et al., 2012). Two borings, B2001 and LN-BH3/4, penetrate the assumed GLOF deposits at the tip of the Ling Bank (Figs. 2, 5 - 7), documenting that 40-60%

of the outburst sediments consist of sand and coarser material, indicating high energy environments. The borings further indicate that the GLOF deposits represent an upward-coarsening sequence. However, the relative low core recovery, and also the distance between borings and seismic profiles (up to 5 km) should call for some caution. Boring 3/6-1 (Figs. 2 and 3) (Hammer et al., 2015), suggest a similar composition of the possible outburst sediments on the southern Ling Bank, noting that this assumption is based on only one sediment sample from these deposits.

Our bathymetric data give further evidence for the pathway of the outburst. At the NE part of the Dogger Bank the water depth is reaching a maximum of 56 m, and the seafloor is thus lying about 15 m deeper than the surrounding areas (Inc-II in Fig. 3c). We infer that this seabed depression represents the transport pathway that developed when the ice-barrier broke, causing the GLOF to flow northwards. The seabed morphology (Fig. 3a) also suggests that this region of the North Sea has been a lake-outburst point, showing the same characteristic features as found in a DTM (Digital Terrain Model) from the Lower Rhine Embayment where a moraine ridge has been dissected by a Middle Pleistocene glacial lake outburst flood (Lang and Winsemann, 2013). It should, however, be noted that the TOPAS seismic profiles reveal that large regions in the southern North Sea is draped by post-glacial deposition of cover sand and sand waves, thereby concealing some of the drainage features in bathymetric maps. Across the observed bathymetric incision (Inc-II in Fig. 3) our sub-bottom data also reveal an infilled 15 m deep and 3000 m wide depression with associated erosional surfaces at its flanks (Fig. 11a). This adds supporting evidence that this region at the NE part of the Dogger Bank represents the out-burst point of the ice dammed lake.

Thus, based on observations in the available acoustic data we infer that the Late Weichselian North Sea Lake had a catastrophic drainage and formed a prominent seabed/sub seabed incision at the NE part of the Dogger Bank (Figs. 3c and 11b). The outburst flood followed the Ling Bank east of Store Fiskebank (Fig. 3a) northwards before depositing unit LBII (Fig. 6a) at the northernmost tip of the Ling Bank. By utilizing equation $Q = V \times 0.5(A_1 + A_2) \times H$, where Q is peak discharge (m^3/s), V is velocity (m/s), A_1 and A_2 is minimum and maximum width (m) of the outburst channel and H is the pass height (m), a first estimate of the flood discharge can be calculated in a similar way as has been demonstrated by Meinsen et al. (2011) for a Saalian glacial outburst flood in NW Germany.

A pass height of 6 m and channel widths of 555 m (channel bottom), 1500 m and 3000 m (channel top) were utilized to calculated discharge for two depth intervals (0-6 m and 6-12 m) of the assumed break-out channel (Fig. 11a). We used 5 and 15 m/s, which is suggested to be characteristic velocities for GLOFs (Baker, 2009), as a minimum and maximum velocity. Thus, a peak discharge in the range of 9.8×10^4 m^3/s - 2.9×10^5 m^3/s is estimated for the Late Weichselian North Sea Lake, suggesting that this outburst is a “major” jökulhlaup (see Meinsen et al. (2011) and references herein for classification system of jökulhlaup). The estimated discharge of the Late Weichselian North Sea Lake is similar to that of Glacier Lake Nedre Glomsjø in southeast Norway (Høgaas and Longva, 2016), but ten times less than the calculated discharge of the Glacier Lake Missoula (Alho et al., 2010).

If utilizing the estimated lake volume of 3900 km^3 (Bigg et al., 2012) it took between 5 and 15 months to drain the Late Weichselian North Sea Lake.

5.2 Late Glacial – Holocene paleo-environmental history

It has been suggested that between ca. 26 and ca. 19 cal. ka BP the central and northern North Sea was covered by the BIIS and FIS, with a southern ice margin at the Dogger Bank and the northern at the present day shelf edge (Figs. 1, 12 and 13) (Sejrup et al., 2016, Becker et al., this issue). During this time period the Late Weichselian North Sea Lake is possibly draining southwards, through the English Channel (Toucanne et al., 2010).

In the Norwegian Channel the Norwegian Channel Ice Stream (NCIS) was operating, transporting huge amounts of sediments to the North Sea Fan (Figs. 1 and 13) (Sejrup et al., 2003; Nygård et al., 2005; Nygård et al., 2007; Hjelstuen et al., 2012). These sediments were transported downslope as glacigenic debris flows (GDFs), considered to represent signature deposits for shelf edge located ice streams (King et al., 1996). At ca. 19 cal. ka BP the last pulse of GDF activity is recorded at the North Sea Fan (King et al., 1998; Nygård et al., 2007), and the NCIS started to retreat into the Norwegian Channel. Soon after NCIS had left its position at the shelf edge, an up to 20 m thick fine-grained unit had been deposited along the Norwegian margin (e.g., Hjelstuen et al., 2004) (Figs. 1, 12 and 13). Age constrains from several IMAGES cores along the Norwegian margin (Fig. 1) reveal that this unit was deposited nearly instantaneously, at ca. 18.7 cal. ka BP (Lekens et al., 2005; Becker et al., this issue). It was earlier assumed that this unit, interpreted to be a meltwater plume, was related to the withdrawal and rapid melting of the NCIS (Sejrup et al., 2003; Hjelstuen et al., 2004; Lekens et al., 2005). We now suggest, however, that this meltwater flux is closely related to the sudden drainage of the Late Weichselian North Sea Lake. Seismic correlation of the till unit identified at the northern tip of the Ling Bank (Figs. 5 and 6) to shallow borings in the Fladen Basin (Fig. 2) suggests that it is related to the LGM. The observed deep erosion of this unit and the undisturbed outburst sediments superimposed (Figs. 5 and 6a) also evidence that the GLOF must have occurred in relation to the last deglaciation of the central and northern North Sea.

Thus, we follow the reconstruction of Sejrup et al. (2016) suggesting that there was a corridor between the BIIS and FIS at ca. 18.7 cal. ka BP, allowing for transportation of GLOF sediments and freshwater to the SE Nordic Seas (Fig. 13). As the GLOF entered the Norwegian Channel, through the proposed Ling Bank Drainage Channel, it flowed along the western edge of the retreating NCIS. The ice stream was at this time located about 200 km inside the Norwegian Channel, close to the location of boring 8903 (Figs. 3 and 13). The observation of a grounding zone wedge in this region (Sejrup et al., 2016; Morén et al., in review) indicates that the NCIS stood still at this location for a period before it continued to retreat.

If taking sea level into account, using the eustatic sea level curve of Lambeck et al. (2014), it seems that the Late Weichselian North Sea Lake related GLOF sediments were deposited above sea level (Fig. 12). However, it should be noted that the North Sea have been influenced by a combined effect of glasioisostatic uplift and subsidence during the latest part of the Quaternary (Sejrup et al., 1987; Sejrup et al., 1998), making it challenging to envisage the exact sea level in the North Sea at a given time. Eustatic sea level curves should thus only be considered as a first approximation when evaluating paleo-environments in the North Sea.

After a time period of up to 15 months, which is based on estimated peak discharge and lake volume in the present study, the Late Weichselian North Sea Lake was drained. Notably, Lekens et al. (2005) counted 854 laminae, deposited in a rhythmic pattern, in the assumed meltwater plume deposits on the southern Vøring Plateau (Figs. 1 and 13). If assuming the rhythmic lamina pattern to represent tidal influence on an ice-dammed lake outburst, the drainage of the Late Weichselian North Sea Lake is close to have taken 15 months (854 laminae represents 900 tidal cycles, or about 450 days). Thus, this supports the findings in this work. Following this assumed short-lived outburst event the NCIS continued its retreat though the Norwegian Channel, and by 17.6 cal. ka BP the NCIS had withdrawn to a position in the innermost Skagerrak (Morén et al., in review). Larger parts of the central and northern North Sea are now suggested to be ice free, with an ice cap over the British and the Shetland islands extending into the Fladen Basin region (Clark et al., 2012; Becker et al., this issue).

After the glacial ice-dammed lake outburst event a fluvial depositional environment developed in the study area, as evidenced by the build-up of the Ling Bank Delta at the northern part of the Ling Bank (Figs. 3, 10, 12 and 13). We interpret the observed incisions at a shallow depth beneath the present day seabed (Fig. 9) to be channels in a meandering river system, transporting sediments to the steadily growing delta. The characteristic sediment infill pattern of these incisions (Fig. 9b) also supports their association with a river system (e.g., Toonen et al., 2012). The assumed GLOF break-through point, at the NE part of the Dogger Bank (Fig. 11a), was also presumably used by rivers after the drainage of the Late Weichselian North Sea Lake.

Borings B2001 and LN-BH3/4 (Figs. 3 and 7) also evidence the changes in depositional environments after the Late Weichselian North Sea Lake outburst event. Sediments with a sand content of up to 80% are now deposited, suggested to reflect the input of fluvial-dominated sediments. Based on inspection of seismic facies character, where we infer that coarse grained sediments are reflected in the seismic data as point source reflectors, it seems that such sediments were deposited in a wide area north of the Ling Bank including the Viking Bank Basin (Figs. 3 and 4). The thick sediment depocentre at the western edge of the Norwegian Channel (Fig. 8) also seems mostly to be build up by fluvial deposits feed through the Ling Bank delta system. This assumption is based on analyze results from boring 8903 (Fig. 2) (Sejrup et al., 1994) and interpretation of the acoustic data, which indicate that sediments related to the GLOF and the withdrawal of the NCIS only are represented as a thin, uniform sediment package in this region.

After the break-up and withdrawal of the BIIS and FIS from the main study area, the FIS margin was located along the coast of Norway until the start of the Allerød time period, at ca. 14 cal. ka BP. Then the ice sheet continued to withdraw onshore with a short-lived terrestrial readvance during the Younger Dryas (e.g., Mangerud et al., 2011). Throughout this time period the sea level was rising, but with observed still stands at around 15 cal. ka BP, 13.5 cal. ka BP (Allerød) and 12 cal. ka BP (Younger Dryas) (Fig. 12). We note that the ca. 1000 year-long halt in the sea level rise at around 15 cal. ka BP seems to coincide with the level of identified high-amplitude patches at the Ling Bank Delta front (Figs. 6a and 12), suggesting that these features may be related to a shoreline and an associated beach zone.

The fluvial-dominated environment within the central North Sea, including a period with an active delta system on the Ling Bank, may have lasted for almost 7000 years until the Ling Bank submerged at the end of the Younger Dryas time period (Fig. 12).

6. Conclusions

Based on high resolution acoustic records and information from shallow borings we have mapped the pathway and processes related to a glacial lake outburst flood in the North Sea. The main findings are:

- The existence of a Late Weichselian North Sea Lake outburst is evidenced from:
    - An incision, about 12 m deep and 3000 m wide, at the NE part of the Dogger Bank. This incision is located in a water depth of about 56 m and is thought to represent the break-through point of the ice-dammed lake.
    - A prograding-aggrading unit (BFII) deposited at the northern tip of the Ling Bank which resembles typical characteristics of GLOF deposits. A similar depositional pattern is also observed on the southernmost part of the Ling Bank.
    - Erosional surfaces in glacial sediments are associated with the identified prograding-aggrading sediment sequences. Such surfaces are commonly associated with GLOFs.
- Dates from the North Sea and the continental slope suggest that the outburst took place at ca. 18.7 cal. ka BP. The flood followed the Ling Bank northwards for about 300 km before depositing an up to 10 m thick prograding-aggrading unit (BFII) at the northern tip of the Ling Bank. A meltwater plume and an associated meltwater spike, observed in

sediment cores and acoustic data from the Norwegian continental margin, are suggested to represent the far-field evidence of the GLOF.

- A first approximation in estimating GLOF peak discharge resulted in values between 9.8×10^4 and 2.9×10^4 m^3/s, indicating that the Late Weichselian North Sea Lake outburst is a "major" jökulhlaup. Thus, the discharge of the Late Weichselian North Sea Lake appears to be about 10 times smaller than that estimated for Glacier Lake Missoula.
- The Late Weichselian North Sea Lake is estimated to have drained in 5-15 months.
- The Late Weichselian North Sea Lake GLOF event was followed by a fluvial-dominated environment, where the Ling Bank Delta built up at the northern part of the Ling Bank during a rising sea level. A meandering river system seems to have existed in association with this delta. This fluvial environment may have existed as long as 7000 years, until the end of the Younger Dryas time period when the Ling Bank got submerged.

Acknowledgements

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Figure caption

Figure 1. a) Overview map of North Sea and Norwegian continental margin. Outlines of meltwater plume deposits on the south Vøring Plateau (from Hjelstuen et al., 2004), Late Weichselian North Sea Lake, Dogger Bank, Ling Bank, Ling Bank Drainage Channel (from Sejrup et al. [2016]), North Sea Fan (from Nygård et al. [2005]), Storegga Slide (from Haflidason et al. [2004]) and LGM ice extend (based on Sejrup et al. [2005]) are shown. Location of major rivers entering the southern North Sea and sediment cores mentioned in this study are also indicated. SS: Storegga Slide; NSF: North Sea Fan; LBDC: Ling Bank Drainage Channel; DB: Dogger Bank; LB: Ling Bank; LGM: Last Glacial Maximum.

Figure 2. North Sea bathymetric map based on the Olex bathymetric database (www.olex.no). Location of shallow borings, sediment cores and TOPAS seismic profiles applied or mentioned in this study are shown (For full TOPAS seismic database see Fig. 1a in Sejrup et al. [2016]). DB: Dogger Bank; SF: Store Fiskebank (Great Fisher Bank); LB: Ling Bank; FB: Fladen Basin; VBB: Viking Bank Basin; VB: Viking Bank; NC: Norwegian Channel; RE: River Elbe; RW: River Weser; REm: River Ems.

Figure 3. a) 3D bathymetric view, based on the Olex bathymetric database, of southern and central North Sea. Location of Ling Bank Delta, channels and ice-dammed lake outburst sediments are indicated. DB: Dogger Bank; SF: Store Fiskebank (Great Fisher Bank); LB: Ling Bank; FB: Fladen Basin; VBB: Viking Bank Basin; VB: Viking Bank; NC: Norwegian Channel; TV: Tunnel valley; Inc: Incision; IL: Inclined ledge (from Sejrup et al. [2016]); IFP: Ice front position (based on Sejrup et al. [2016]); RE: River Elbe; RW: River Weser; REm:

River Ems. **b)** and **c)** Bathymetric profiles across the Dogger and Ling banks. For location see Fig. 3a. The profiles are generated from the Olex bathymetric database.

Figure 4. TOPAS profile across Viking Bank Basin. Profile location in Fig. 3a. G: Gas; GM: Glacimarine sediments; F: Fluvial-dominated sediments; TV: Tunnel valley.

Figure 5. TOPAS seismic profile across the northern tip of Ling Bank showing typical seismic facies characters in this area. Profile location in Fig. 3a. LBI-LBIV and T: Identified seismic units.

Figure 6. **(a)** TOPAS seismic profile, location in Fig. 3a, showing assumed lake outburst deposits (LBII) north of Ling Bank. Note also the delta front pinch out. LBI-LBIV and T: Identified seismic units. **(b)** Zoom-in on ice dammed lake-outburst deposits. Arrows point at observed mounds at the base of sub-unit LBII. Figure location in Fig. 6a.

Figure 7. Lithology, grain size and shear strength of LGM moraine and post-LGM sediments (from Sejrup et al. (1994) [B2001] and Reinardy et al. (2017) [LN-BH3/4]). (*) Age information from Sejrup et al. (2016). Correlation to seismic units identified in this study (T and LBII-IV) is indicated. Please note the long correlation distance of 5 km between B2001 and the seismic profile (Fig. 5), which results in the upper and lower boundaries of seismic units only being inferred. Si: Silt; C: Clay; S: Sand; G: Gravel; GM: Glacimarine; F: Fluvial; M: Marine.

Figure 8. Isopach map in ms(twt) of sediments deposited in the Norwegian Channel between ca. 19 cal. ka BP (end LGM) and ca. 11.6 cal. ka BP (start of the Holocene). Black dot shows

location of boring 8903. LB: Ling Bank, VBB: Viking Bank Basin, VB: Viking Bank, FB: Fladen Basin, LBDC: Ling Bank Drainage Channel.

Figure 9. (a) TOPAS seismic example showing typical seismic stratigraphy, including tunnel valleys, possible river channels, glacimarine sediments (GM) and till units, across the Ling Bank. Profile location in Fig. 3a. **(b)** TOPAS seismic example highlighting sediment infill in an assumed river channel observed at the crest of the Ling Bank. Profile location in Fig. 3a.

Figure 10. TOPAS seismic profile from the northern part of the Ling Bank, showing the presumed Ling Bank Delta with bottomset, forset and topset beds. Profile location in Fig. 3a.

Figure 11. (a) Sub-seabed incision observed at the Inc-II bathymetric low at the northeastern part of Dogger Bank. Location of TOPAS seismic profile in Fig. 3a. **(b)** Seismic facies character northwest of Store Fiskebank. Location of TOPAS seismic profile in Fig. 3a.

Figure 12. Post-glacial sea level curve, from Lambeck et al. (2014). Main glacial events, post-glacial processes, and depth to significant surfaces observed in the seismic profiles are indicated. Numbers (i) - (ii) - (iii) refer to time slices shown in Figure 13. Note change in horizontal scale. NC: Norwegian Channel; NCIS: Norwegian Channel Ice Stream; BIIS: British-Irish Ice Sheet; FIS: Fennoscandian Ice Sheet; LGM; Last Glacial Maximum.

Figure 13. Conceptual models for selected time slices of the Late glacial-Holocene paleo-environmental development of the North Sea. **(i) LGM**. Confluence of the British-Irish (BIIS) and Fennoscandian (FIS) ice sheets in the North Sea and formation of the Late Weichselian North Sea ice-dammed lake (LWNSL) south of Dogger Bank (DB). Location of boring 8903

(red dot) and drainage direction of LWNSL are indicated (open black arrow). LB: Ling Bank; NCIS: Norwegian Channel Ice Stream; GDF: Glacigenic Debris Flow. **(ii) 18.7 cal. ka BP**. Initiation of Late Weichselian North Sea Lake (LWNSL) outburst, deposition of outburst sediments (LBII) at the northern tip of Ling Bank and meltwater flux along the Norwegian margin. Ling Bank Drainage Channel indicated with a red arrow. GZW: Grounding Zone Wedge; NCIS: Norwegian Channel Ice Stream; FIS: Fennoscandian Ice Sheet; BIIS: British-Irish Ice Sheet. **(iii) 13 cal. ka BP**. Build-up of Ling Bank Delta, meandering rivers across Ling Bank and development of fluvial depocentre in the Norwegian Channel. Indicated shoreline is drawn approximately along present day 80 m water depth contour.

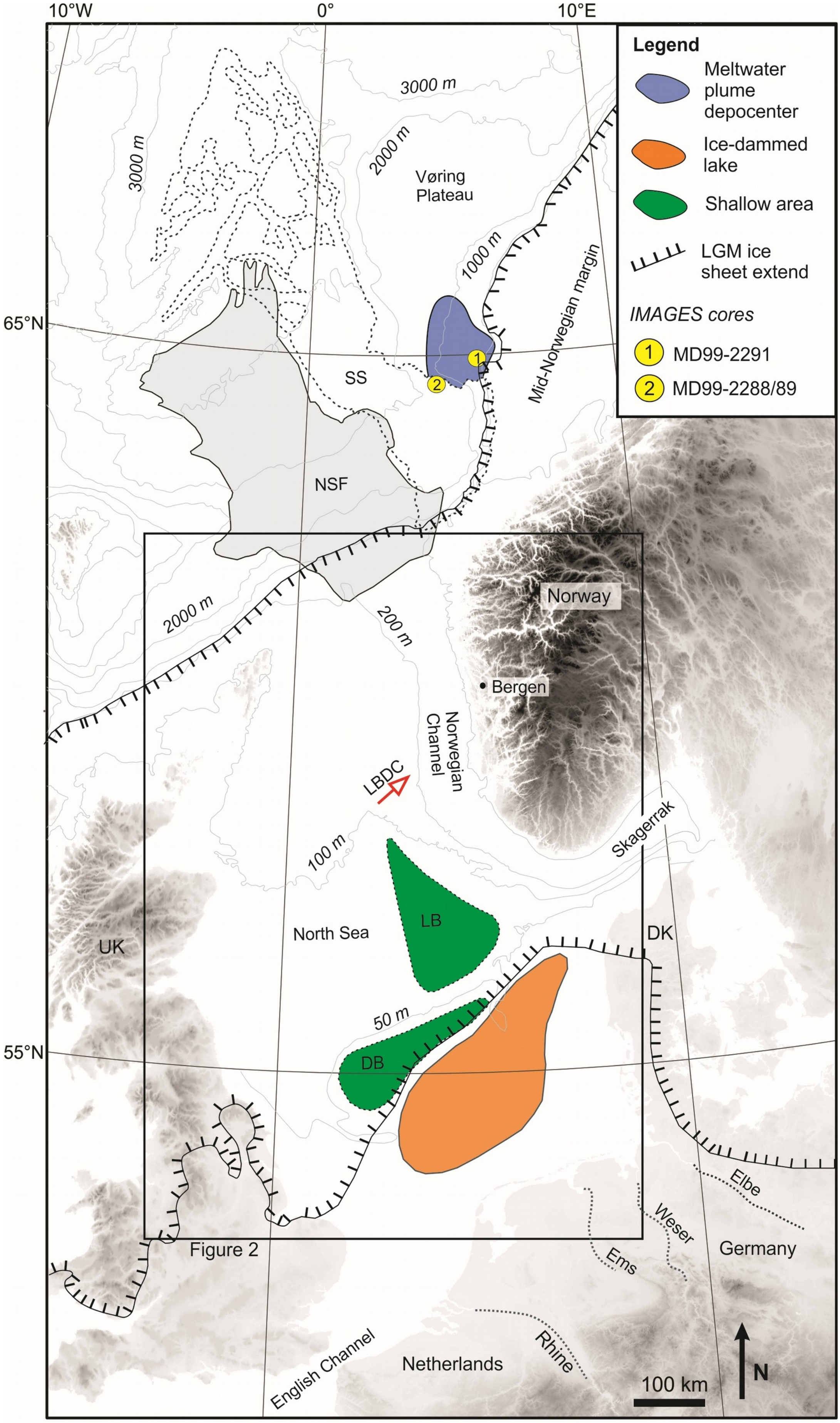


Figure 1. Hjelstuen et al.

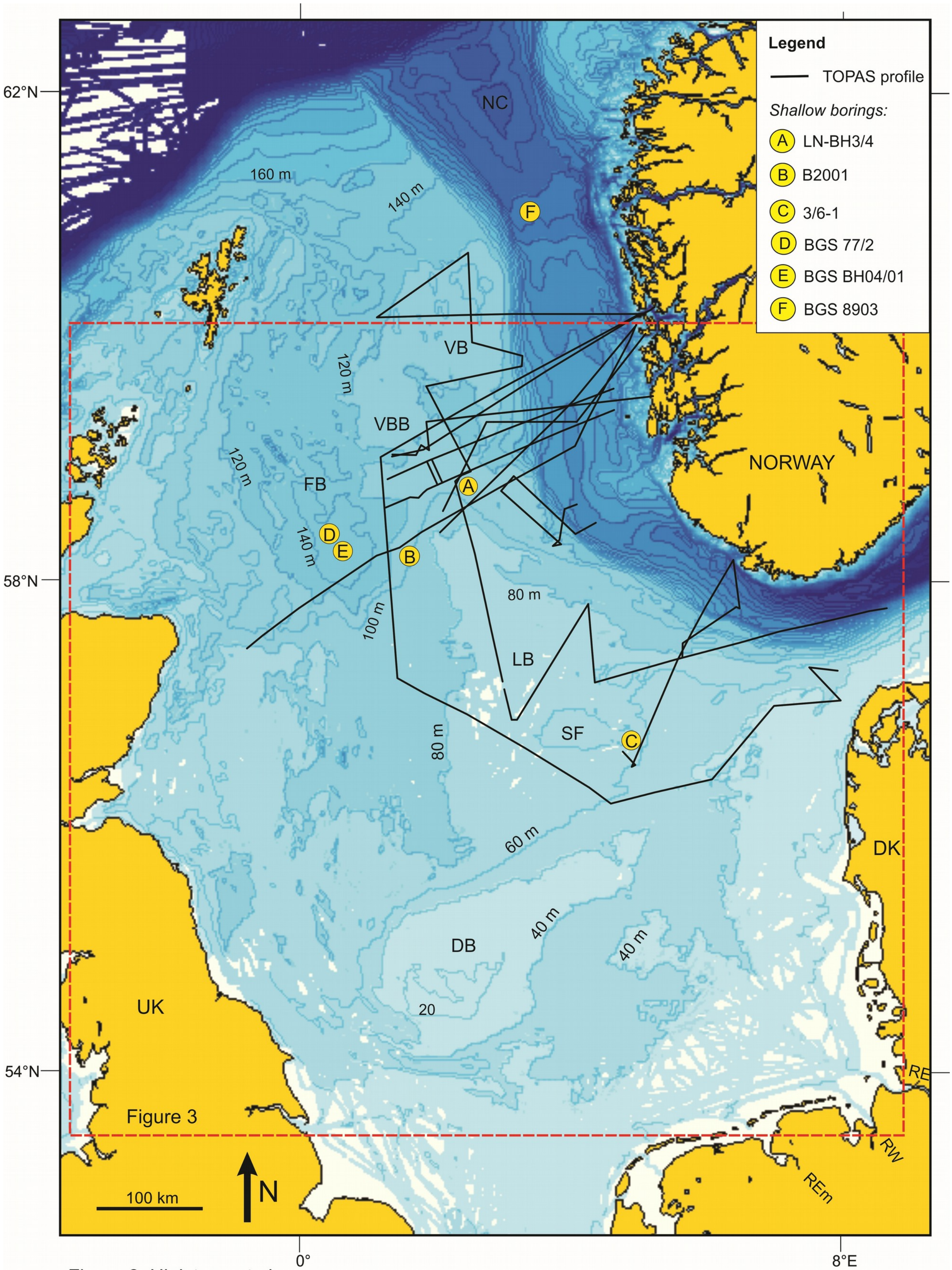


Figure 2. Hjelstuen et al.

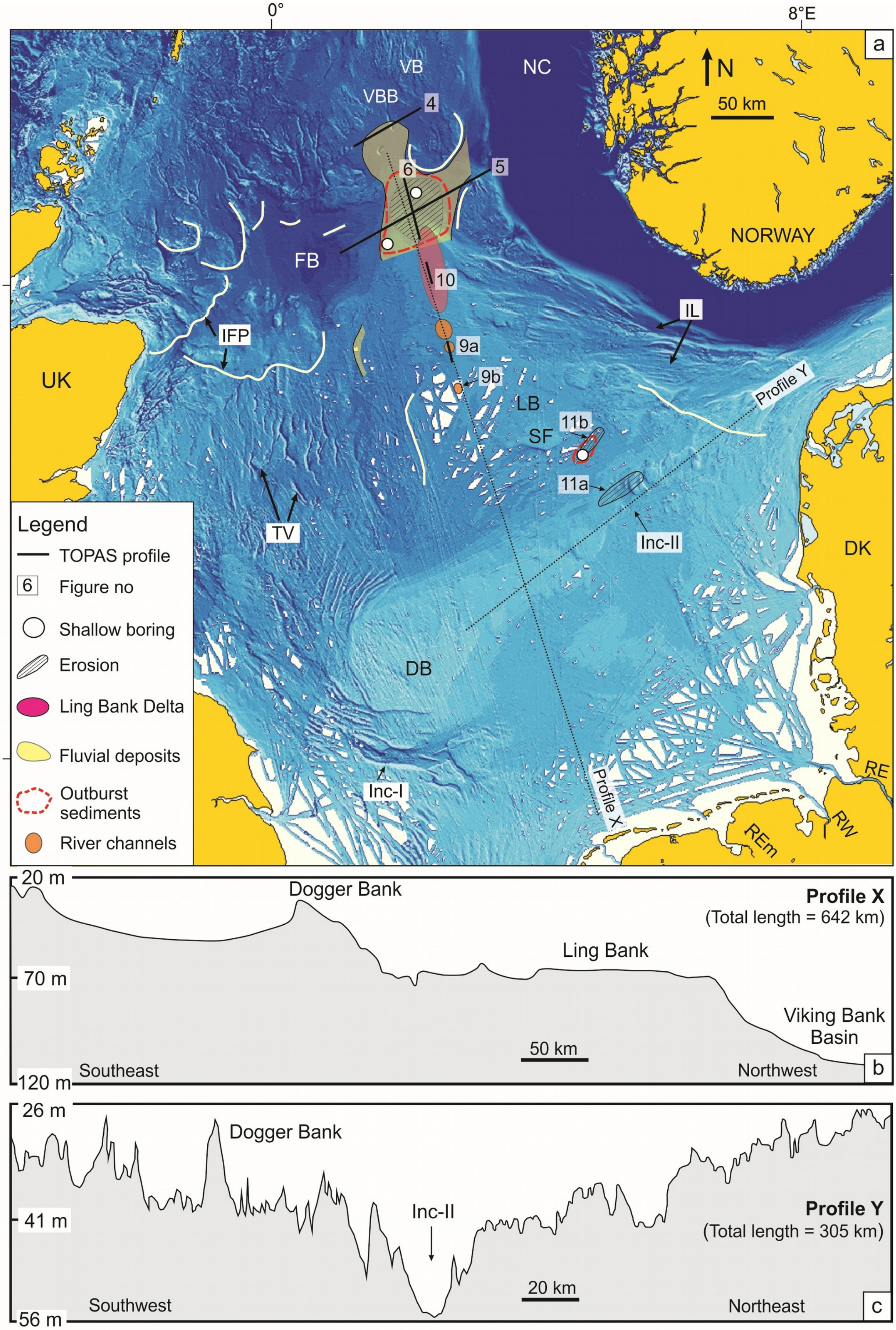


Figure 3. Hjelstuen et al.

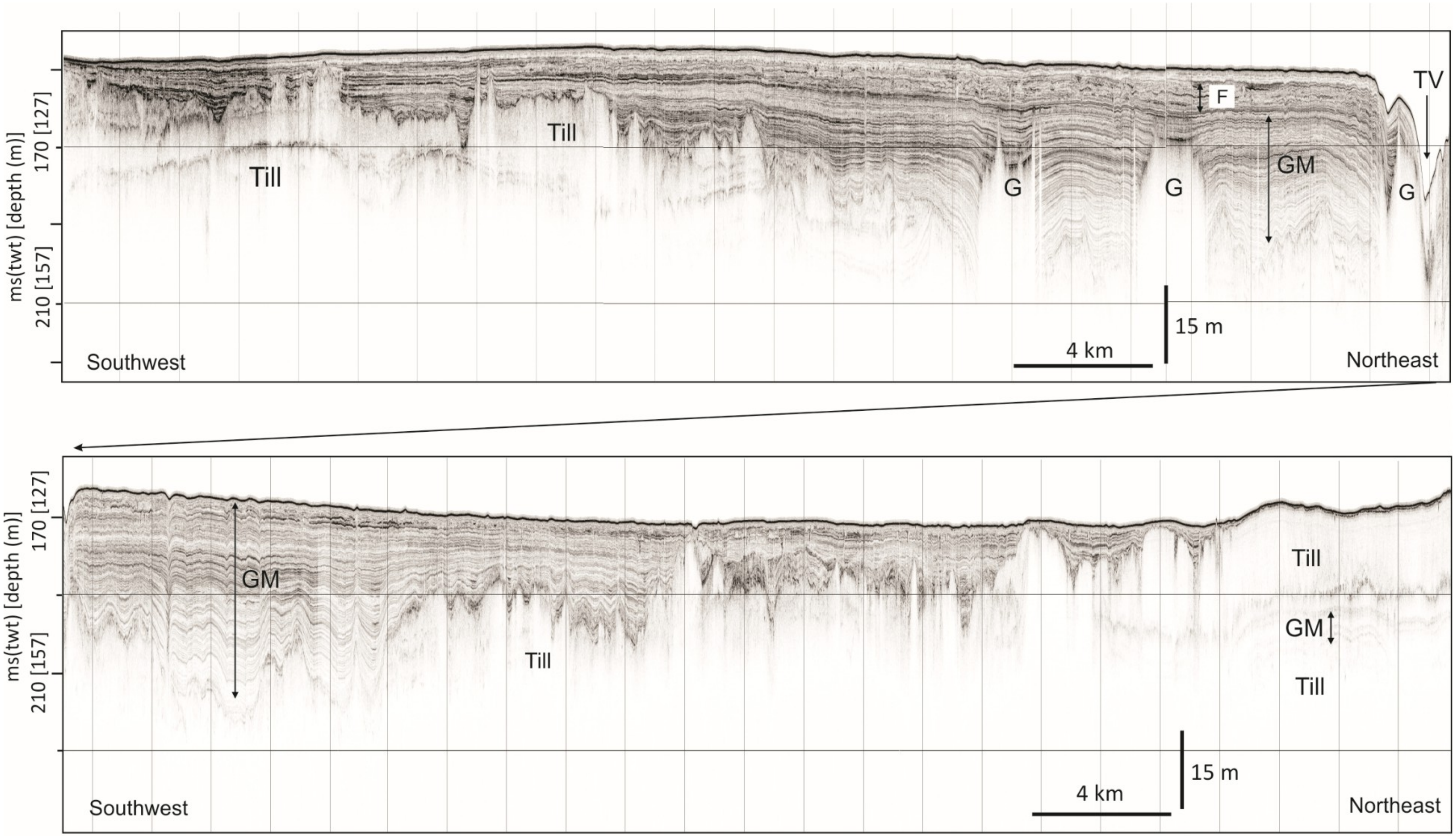


Figure 4. Hjelstuen et al.

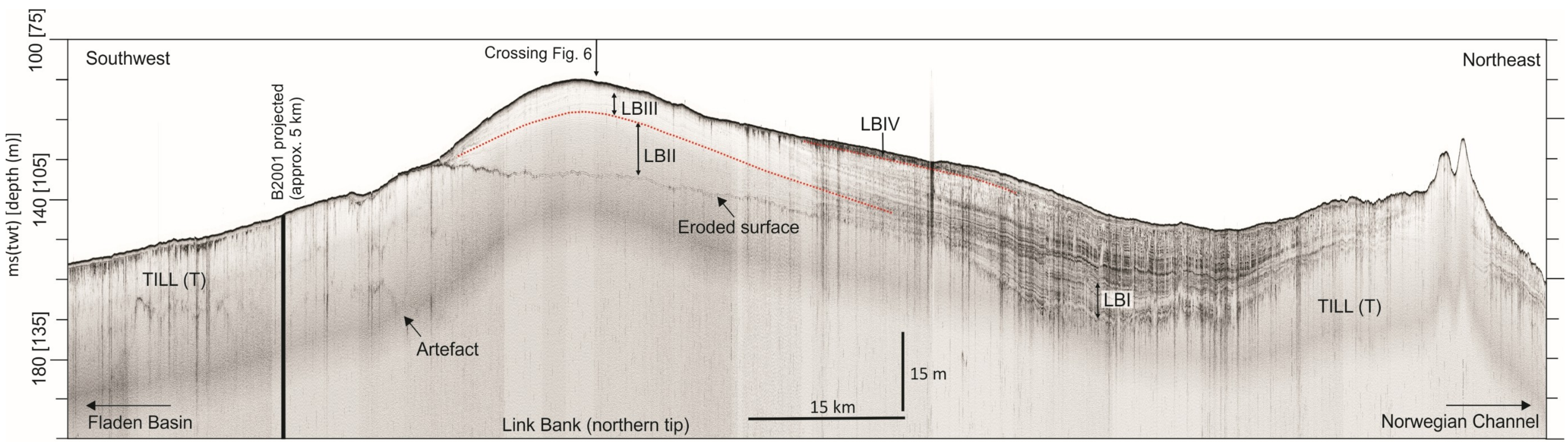


Figure 5. Hjelstuen et al.

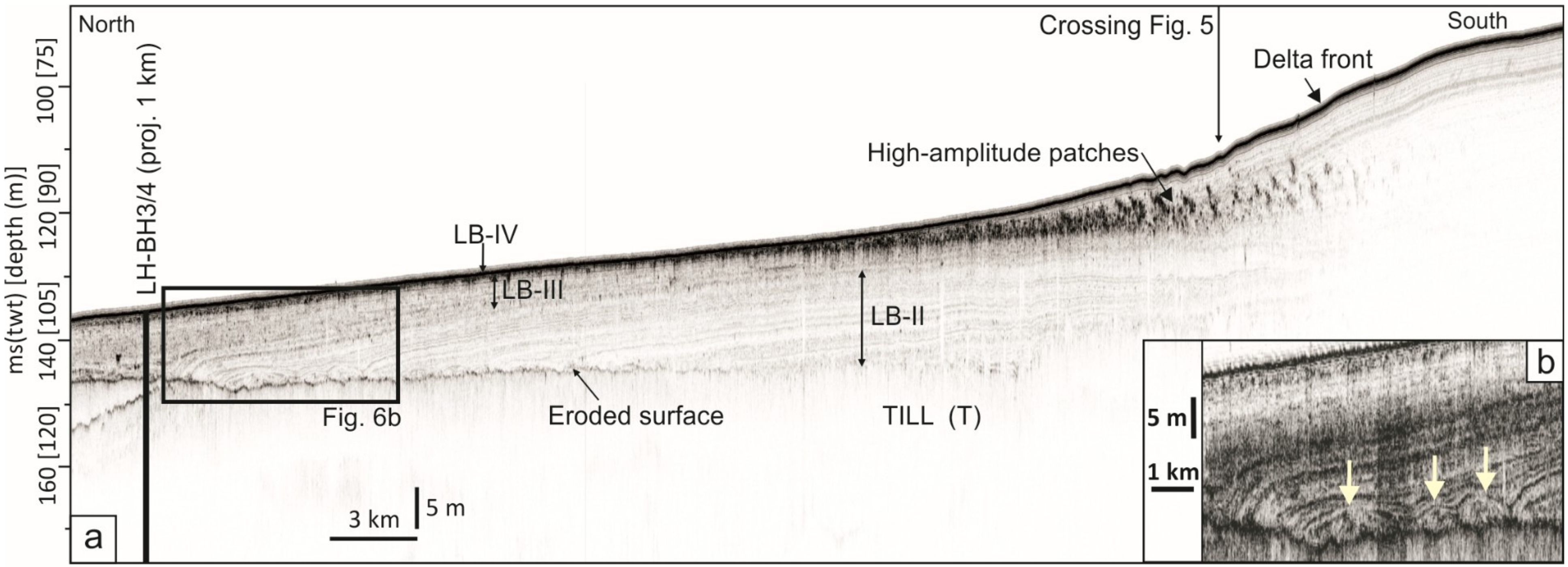
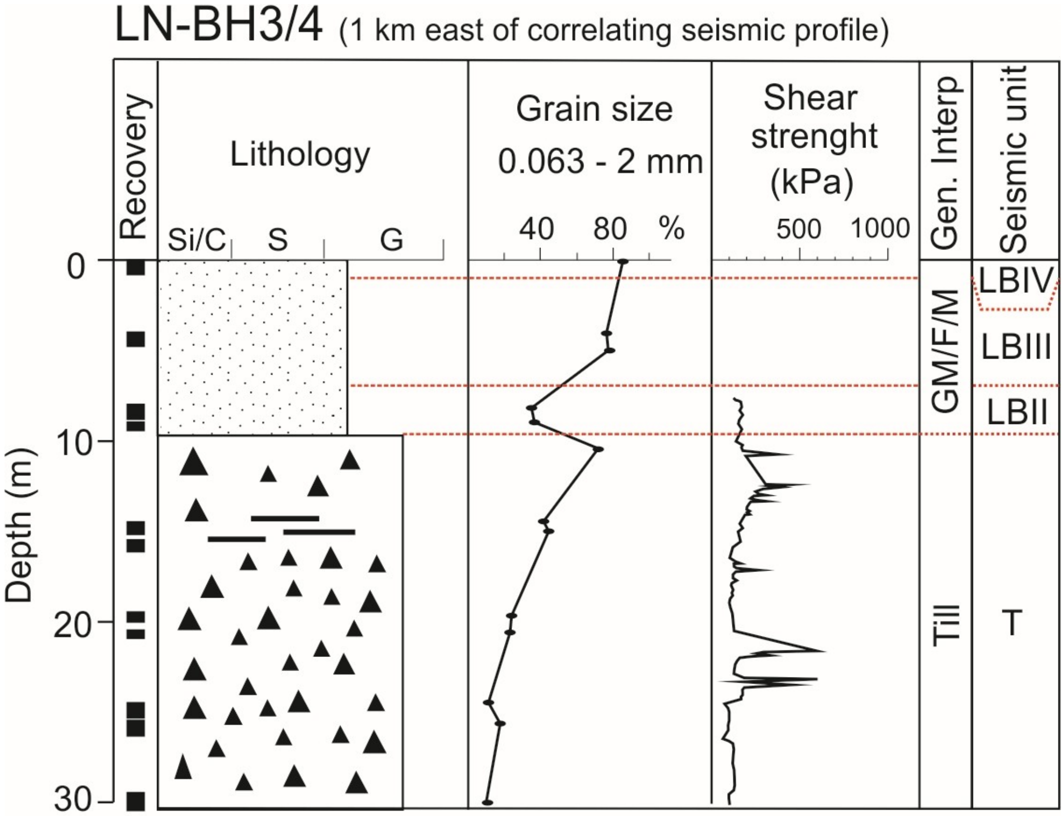


Figure 6. Hjelstuen et al.



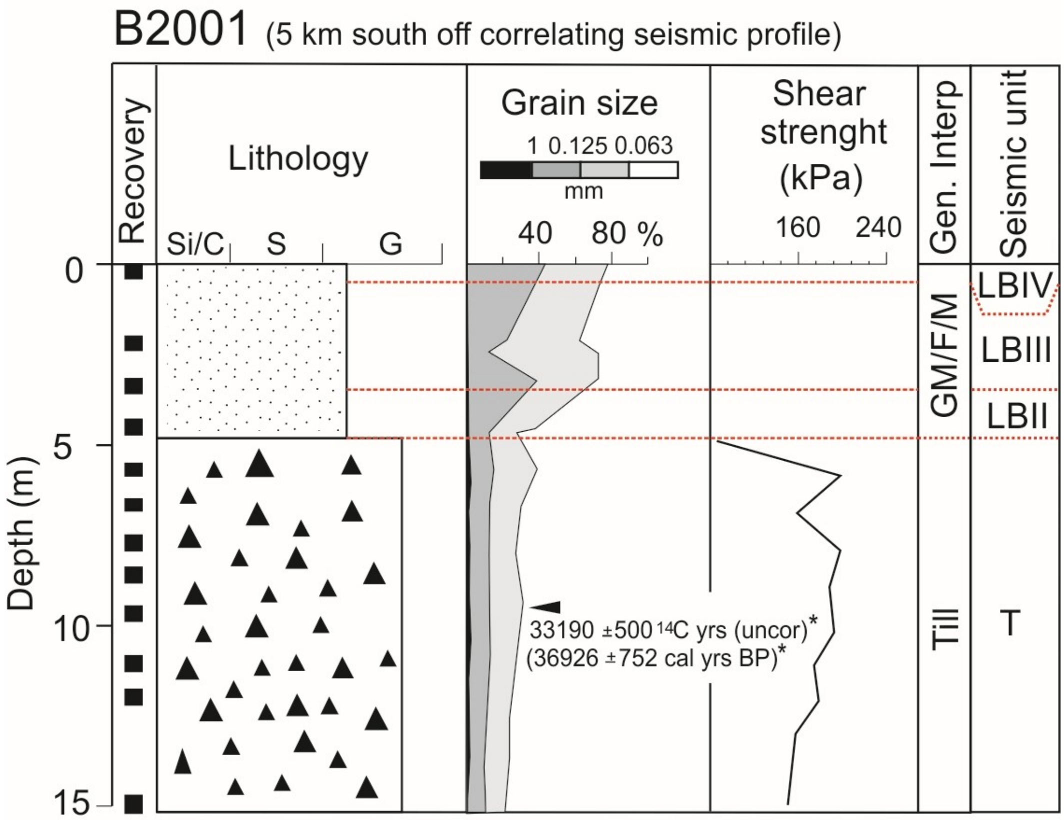


Figure 7. Hjelstuen et al.

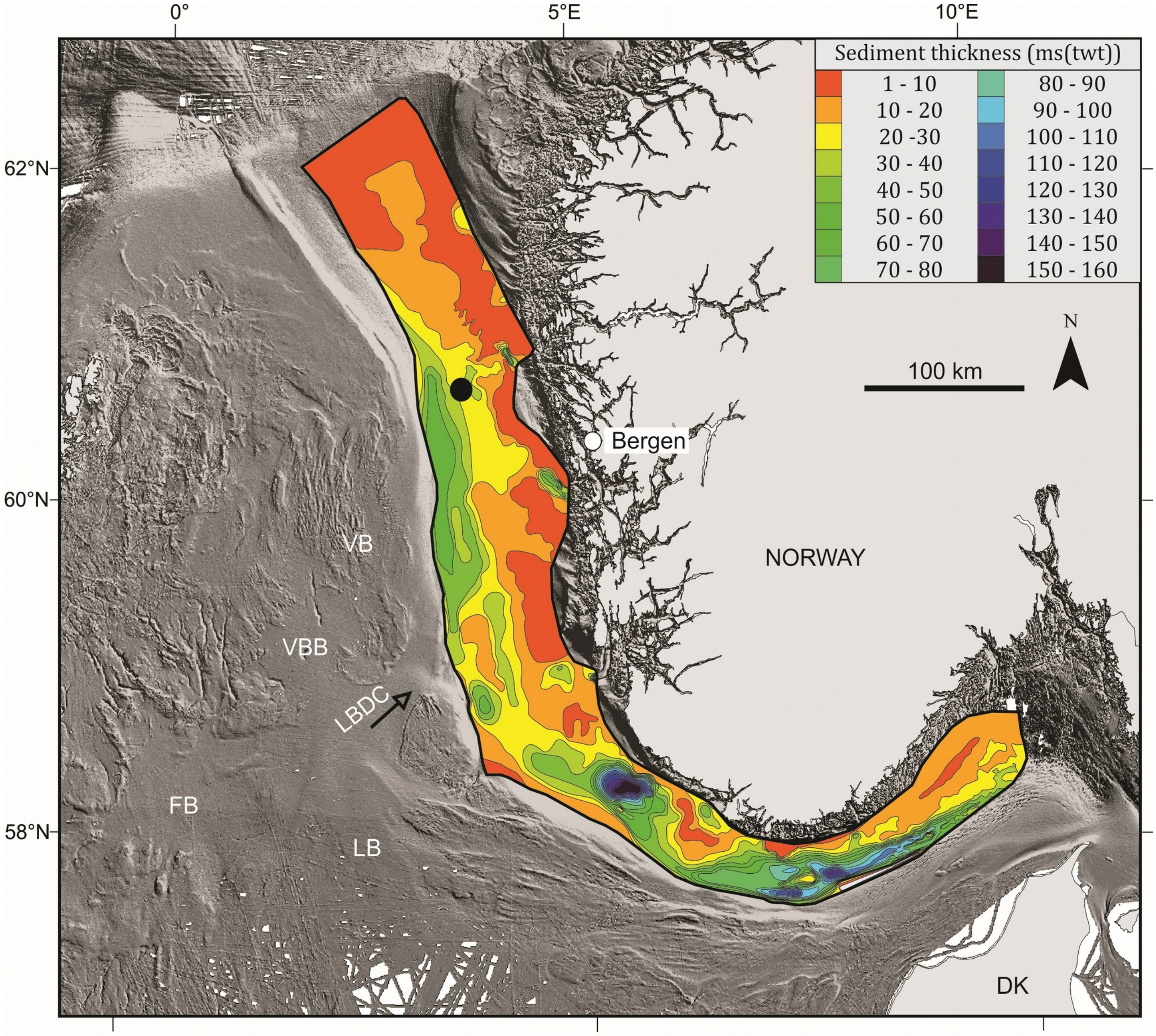


Figure 8. Hjelstuen et al

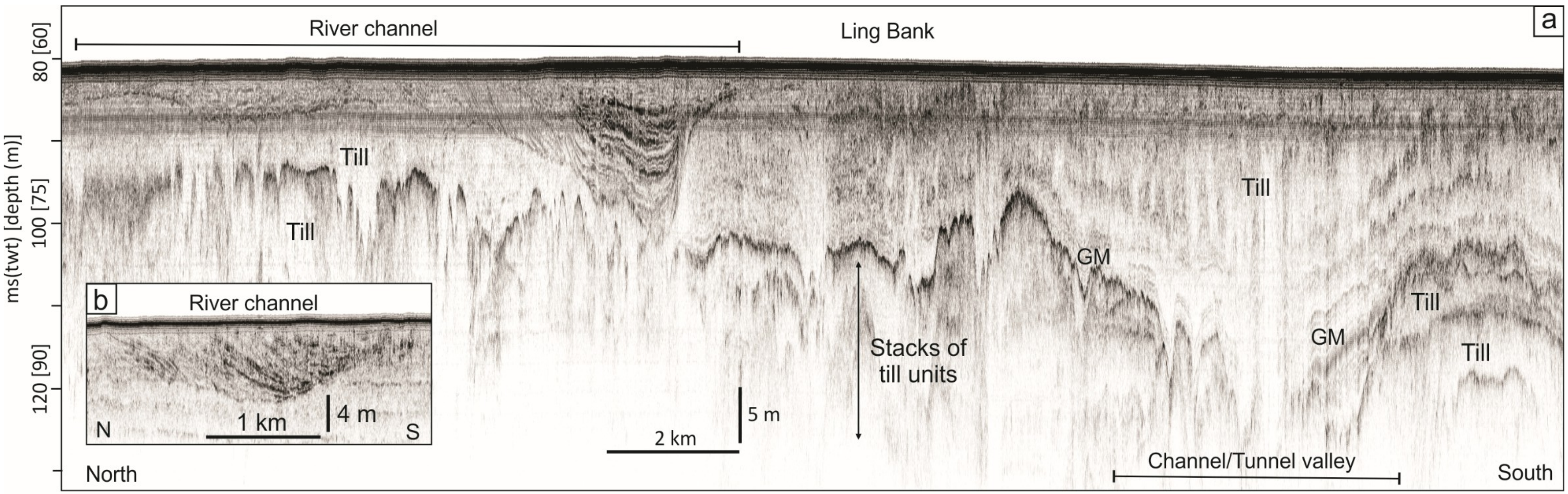


Figure 9. Hjelstuen et al.

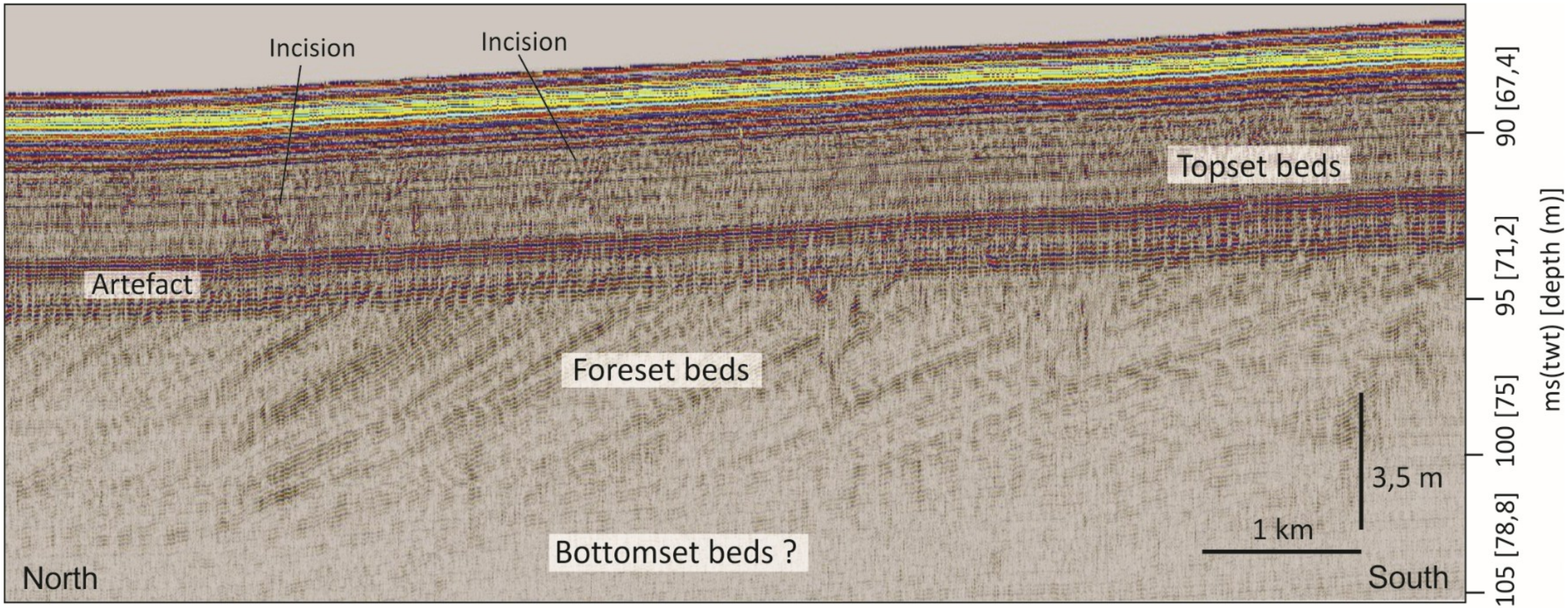


Figure 10. Hjelstuen et al.

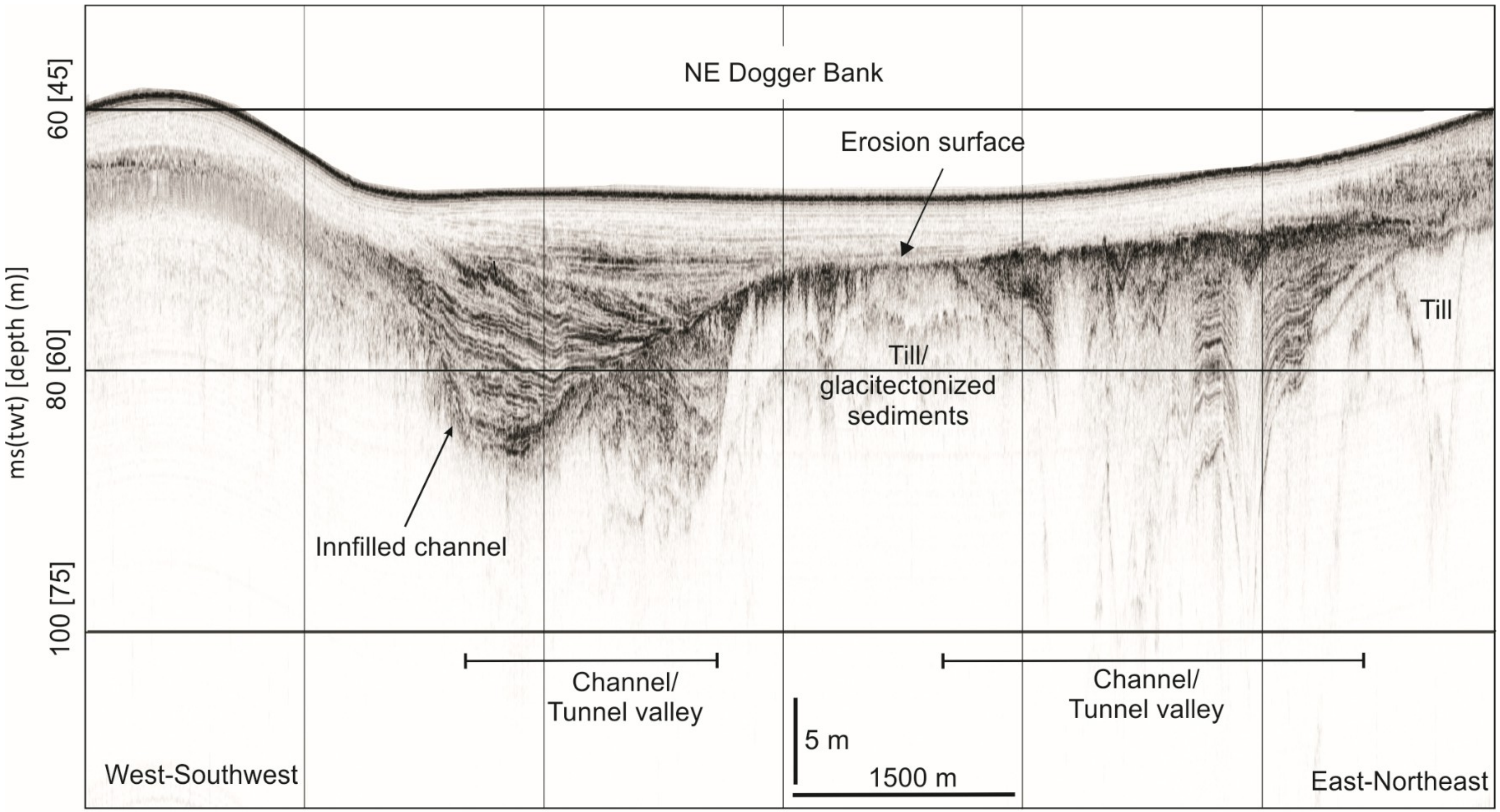


Figure 11a. Hjelstuen et al.

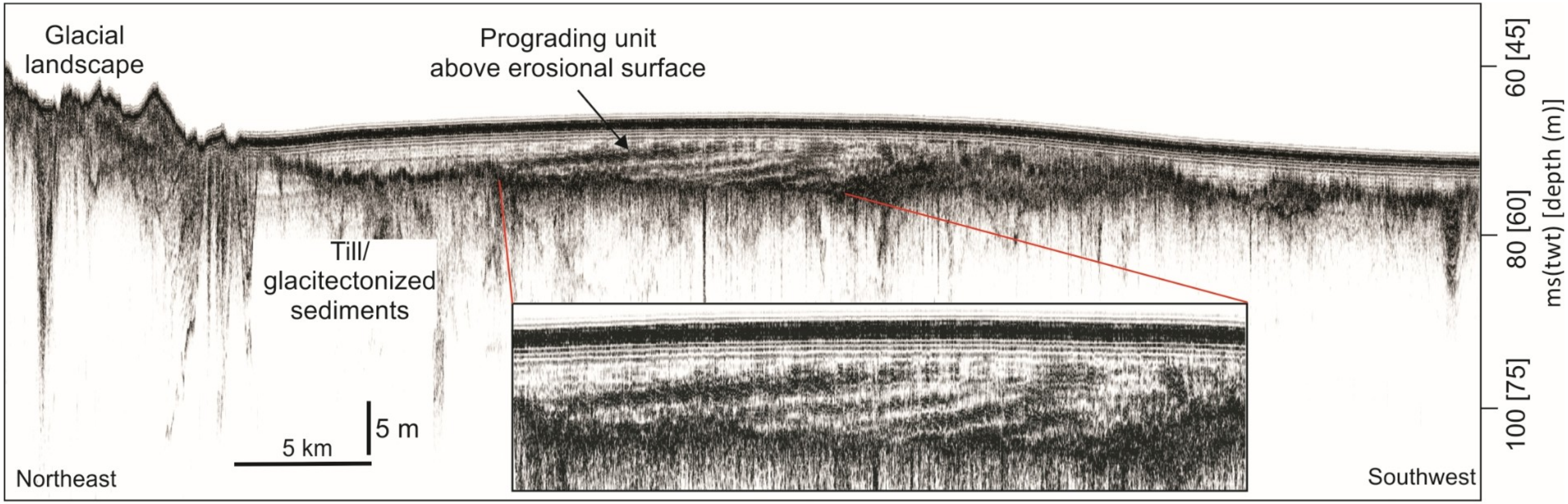


Figure 11b. Hjelstuen et al.

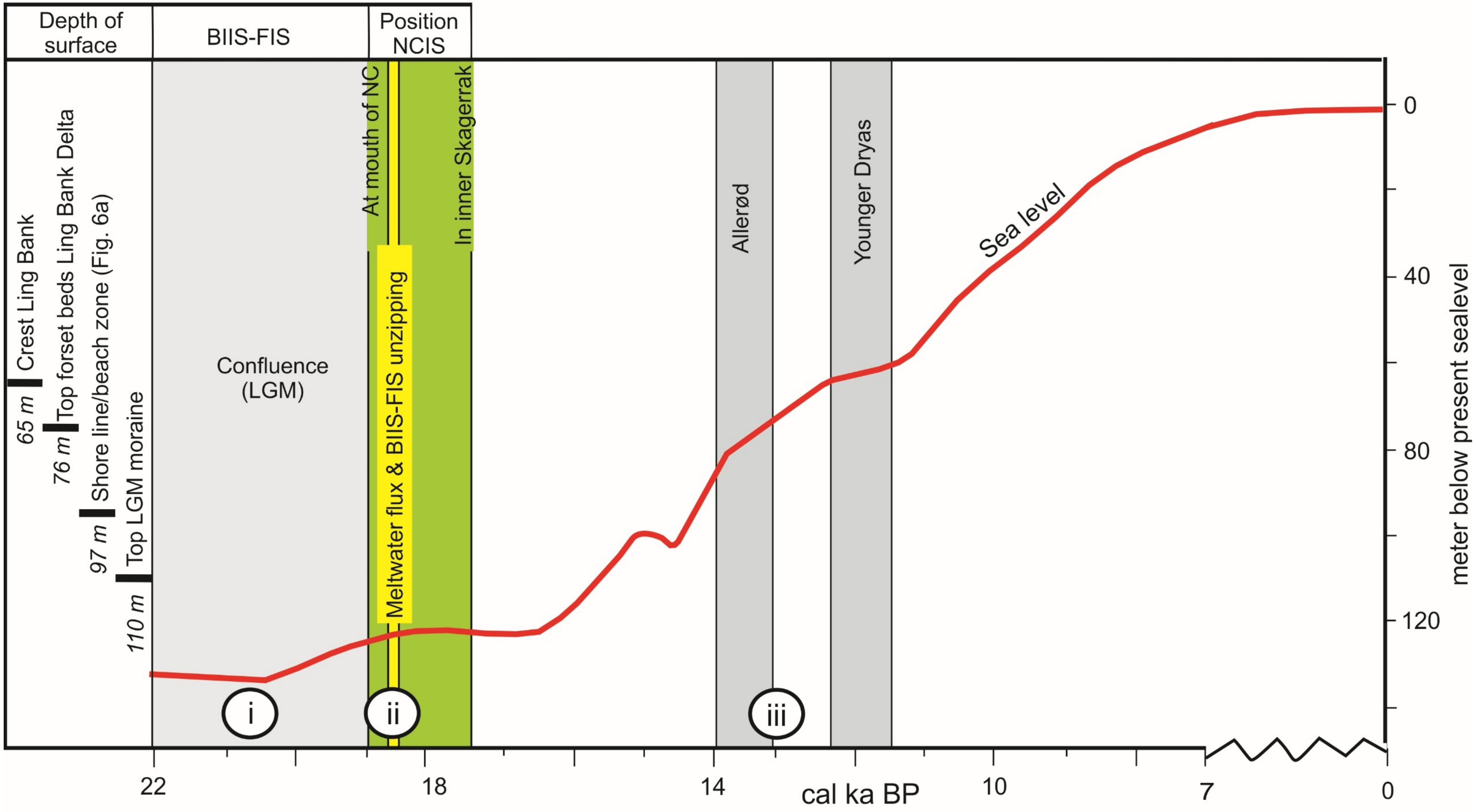


Figure 12. Hjelstuen et al.

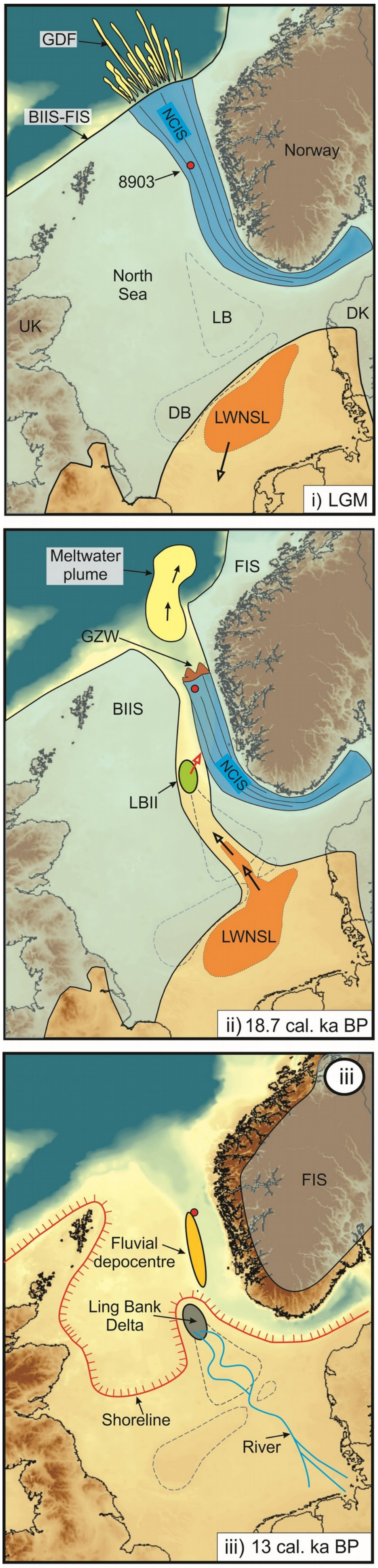


Figure 13. Hjelstuen et al.