BOREAS An international journal of Quaternary research

Complex past ice flow from Norway to the North Sea Plateau during the Quaternary: evidence from Marstein Trough and earlier reconstructions using 3D seismic data sets

DAG OTTESEN, JAMES D. KIRKHAM, JULIAN A. DOWDESWELL, HARALD BRUNSTAD AND MORTEN HALVORSEN

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Ottesen, D., Kirkham, J. D., Dowdeswell, J. A., Brunstad, H. & Halvorsen, M. 2025 (July): Complex past ice flow from Norway to the North Sea Plateau during the Quaternary: evidence from Marstein Trough and earlier reconstructions using 3D seismic data sets. *Boreas*, Vol. 54, pp. 351–369. https://doi.org/10.1111/bor.70007. ISSN 0300-9483.

Based on a regional 3D seismic data set and a small high-resolution 3D seismic data set (~40 km^2) we have mapped a buried glacially eroded trough on the North Sea Plateau, west of the Norwegian Channel (latitude 59°N, longitude 3°E). The trough, which we informally name Marstein Trough, is 60 km long, 30 km wide, 120 m deep, and trends NE–SW. Marstein Trough contains an extensive pattern of glacial lineations at its base, which follow the trough axis, and is infilled by two seismic units interpreted as tills. From its stratigraphical position, we infer that the trough was eroded by an ice stream that flowed from western Norway and crossed the Norwegian Channel in a southwesterly direction, probably during the penultimate, Saalian glaciation. Marstein Trough, and its diagnostic landforms, provide detailed evidence of complex, switching ice flow across the North Sea during the Quaternary. Westward ice flow from Norway took place during early Scandinavian Ice-Sheet build-up prior to the activation of the Norwegian Channel Ice Stream. In contrast, ice-flow patterns during full-glacial conditions caused ice flow to reorientate to a S–N direction when the Norwegian Channel Ice Stream with a huge catchment that included the Baltic was established. Our results highlight the complex patterns of ice flow experienced over this region of the North Sea, with implications for reconstructions of Quaternary history, modern renewable energy infrastructure installation, and glacial processes during the build-up phase of ice sheets.

Dag Ottesen, Geological Survey of Norway, Leiv Erikssonsvei 39, 7040 Trondheim, Norway; James D. Kirkham, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK; Julian A. Dowdeswell (corresponding author: jd16@cam.ac.uk), Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK; Harald Brunstad and Morten Halvorsen, AkerBP, Oksenøyveien 10, 1366 Lysaker, Norway; *received 11th September 2024, accepted 11th March 2025.*

The entire Norwegian continental shelf, along with much of the North Sea, has been covered by ice sheets during several glacial periods of the Quaternary (e.g. Svendsen *et al.* 2004; Hughes *et al.* 2015; Batchelor *et al.* 2019; Clark *et al.* 2022). The regional stratigraphy, together with the morphology of buried surfaces preserved in North Sea sediments, is a product of glacial processes during Quaternary glaciations, as well as open-marine processes in interglacial periods. However, the detailed glacial history and complexity of past ice flow over the North Sea remains poorly understood (Rise *et al.* 2004; Clark *et al.* 2012, 2022) despite being one of the most extensively investigated formerly glaciated margins in the world. Geophysical surveys, originally conducted for hydrocarbon exploration and more recently for wind-farm siting, provide large volumes of 2D and 3D seismic data containing a wealth of information about shallow continental-shelf stratigraphy and the sea-floor morphology of the North Sea Basin.

In this study, we investigate the shallow stratigraphy of the greater Johan Sverdrup area of the North Sea Plateau west of the Norwegian Channel (Fig. 1). Using a combination of regional 3D seismic data, one high-resolution 3D (HR3D) seismic cube, high-resolution 2D seismic profiles and geotechnical boreholes, we identify and map a large glacially eroded trough buried beneath up to 60 m of sediment. The detailed stratigraphy of the trough and associated glacial sediments is described and interpreted, together with the morphology of buried surfaces linked to its erosion. From these observations, the direction and nature of past ice flow are inferred and compared with reconstructions from earlier and later glaciations to demonstrate the complexity of past ice-sheet flow in this region of the North Sea.

Geological background

North Sea Basin: configuration and glacial influence

The North Sea (500 000 km^2) is divided into the North Sea Plateau (425 000 km^2) and the Norwegian Channel (75 000 km^2). The North Sea Plateau has modern water depths ranging from less than 50 m in the south to more than 150 m in the north, whereas the Norwegian Channel, offshore of southern Norway and east of the North Sea Plateau, is deeper at between 200 and 700 m. The North Sea Basin has been continuously subsiding through the Cenozoic and contains up to 3000 m of sediment (Japsen 1998; Michelsen *et al.* 1998; Lamb *et al.* 2017; Ottesen *et al.* 2018). At the start of the Quaternary, the North Sea Basin was a 1200 km long and 100–200 km wide S–N-trending basin situated between the Netherlands to the south and its outlet into the Norwegian Sea between Norway and Shetland at about 62°N

DOI 10.1111/bor.70007

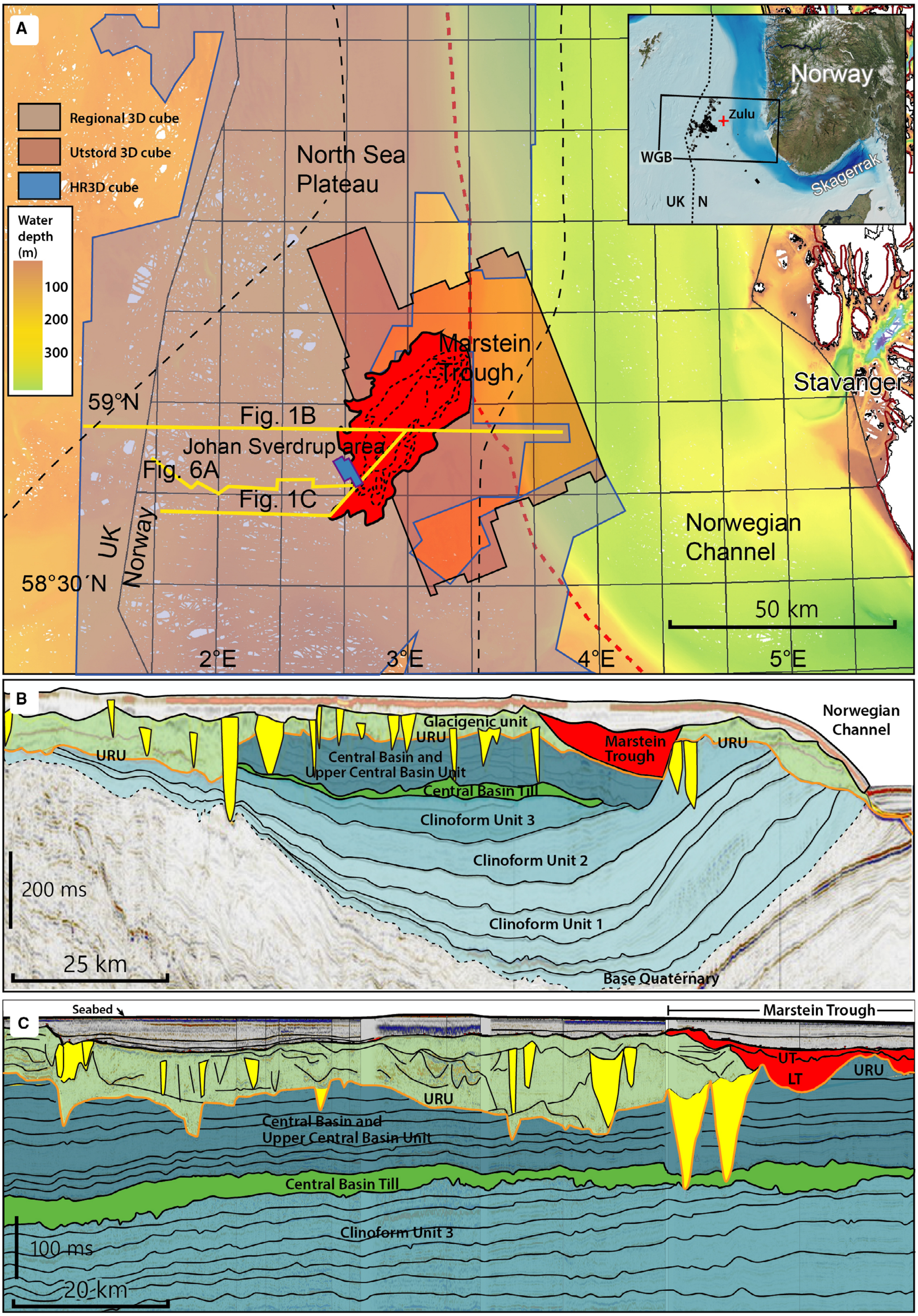
A
Regional 3D cube
Utstord 3D cube
HR3D cube
Water depth (m)
100
200
300
North Sea Plateau
Norway
Zulu
WGB
UK
N
Skagerrak
Marstein Trough
59°N
Fig. 1B
Johan Sverdrup area
Fig. 6A
Fig. 1C
UK
Norway
58°30´N
2°E
3°E
4°E
5°E
Stavanger
Norwegian Channel
50 km
B
Glacigenic unit
URU
Central Basin and Upper Central Basin Unit
Central Basin Till
Marstein Trough
Norwegian Channel
Clinoform Unit 3
Clinoform Unit 2
Clinoform Unit 1
Base Quaternary
200 ms
25 km
C
Seabed
Marstein Trough
UT
LT
URU
Central Basin and Upper Central Basin Unit
Central Basin Till
Clinoform Unit 3
100 ms
20 km

Fig. 1. A. Overview map of the North Sea Plateau and the Norwegian Channel showing the location of the TGS regional-scale 3D seismic data set (transparent blue), the Utstord cube (transparent red), and the HR3D seismic cube (opaque blue). The mapped erosional trough, termed informally as Marstein Trough, is marked in red with 20-ms contours. Inset map displays the study area (black rectangle in the North Sea west of Norway). Red stippled line shows the western margin of the Norwegian Channel. Black stippled lines mark the 500-ms contours of the Quaternary North Sea Basin showing the shape of the infilled basin. WGB = Witch Ground Basin; Zulu = Zulu Well. B. Interpreted regional seismic line with Quaternary seismic stratigraphy shown. Marstein Trough is shaded in red. The orange line is the upper regional unconformity (URU), and yellow polygons are tunnel valleys. Data owner, TGS. C. Interpreted high-resolution seismic line across the study area showing mid/late Quaternary sediments in the region of the trough. UT = Upper Till; LT = Lower Till.

(Ottesen *et al*. 2014, 2018; Lamb *et al*. 2017; Rea *et al*. 2018). The central and southern portions of the North Sea Basin (52–59°N) have been filled by a variety of fluvial, marine, and glacial sediments deposited during the last 3 Ma (e.g. Cameron *et al*. 1992; Overeem *et al*. 2001; Kuhlmann & Wong 2008; Ottesen *et al*. 2014, 2018; Thöle *et al*. 2014; Bendixen *et al*. 2017; Coughlan *et al*. 2018; Winsemann *et al*. 2020; Fig. 1B), whilst the northern North Sea Basin (north of 59°N) has been infilled mainly with glacial sediments, primarily in the form of glacigenic debrisflows (e.g. Ottesen *et al*. 2014, 2018; Batchelor *et al*. 2017; Løseth *et al*. 2020).

In the early Quaternary, an ice sheet advanced into the central parts of the North Sea Basin and deposited a till unit more than 100 m thick (Ottesen *et al*. 2018; Rea *et al*. 2018). Above this, a crenulate surface with glacial lineations was formed (Rose *et al*. 2016). Rea *et al*. (2018) mapped several surfaces with glacial lineations and dated these to between 1.9 and 0.9 Ma ago. These authors claimed that the ice advanced from both the UK and the Scandinavian sides of the North Sea. Ottesen *et al*. (2018) mapped this ice advance and interpreted it to come solely from Scandinavia, around 1.2 Ma ago. After this ice advance, the basin was infilled with sediments around 1.0 Ma ago. Sometime after that, the Norwegian Channel began to form. During the Early Quaternary, the North Sea Basin was a few hundred metres deep and was occasionally influenced by icebergs that calved from the margins of the surrounding ice sheets (Dowdeswell & Ottesen 2013; Ottesen *et al*. 2024). Most of these icebergs probably originated from the western margin of Norway. The icebergs drifted into the now largely filled North Sea Basin and ploughed the sea floor in Early Quaternary time between 2.5 and 1.8 Ma ago (Kuhlmann & Wong 2008; Knutz 2010; Dowdeswell & Ottesen 2013; Lamb *et al*. 2017; Rea *et al*. 2018; Fig. 1).

The contemporary trough of the Norwegian Channel is up to 100 km wide and 700 m deep (it is deepest in the Skagerrak; Fig. 1A) and has been eroded by the recurring flow of the Norwegian Channel Ice Stream (NCIS) during several of the last glaciations (e.g. Sejrup *et al*. 2003; Ottesen *et al*. 2005, 2016; Hjelstuen *et al*. 2012). Underlying structural controls have influenced the overall form of the channel as its eastern boundary generally follows the transition zone between crystalline and sedimentary bedrock along the modern Norwegian coastline (Sigmond 2002).

The NCIS played an important role in regulating the mass balance of the southwestern part of the Scandinavian Ice Sheet (e.g. Sejrup *et al*. 2003; Nygård *et al*. 2007; Hjelstuen *et al*. 2012). The age of inception of the Norwegian Channel is uncertain. Sejrup *et al*. (1995) dated a till at the base of the Channel to 1.1 Ma ago based on amino acid-, magneto- and bio-stratigraphy, and proposed that this was the first time an ice sheet had entered the shelf areas beyond the Norwegian coast. Løseth *et al*. (2022) conducted a seismo-stratigraphical study linking flat-lying layered sediments in the lower part of the Norwegian Channel to the stratigraphy of the North Sea Fan (Nygård *et al*. 2005), suggesting that the Channel may be much younger – perhaps even as young as 350 ka.

The NCIS was very active during the last three glaciations and was fed from a drainage basin that included much of the southern part of the Scandinavian Ice Sheet (Nygård *et al*. 2005; Ottesen *et al*. 2005; Hjelstuen *et al*. 2012). During the Late Weichselian glaciation the ice stream reached the shelf edge only around the Last Glacial Maximum (LGM), transporting large volumes of ice and sediment to the shelf edge (Nygård *et al*. 2005; Hjelstuen *et al*. 2012). Up to 400 m of sediment was deposited on the North Sea Fan between 23 and 19 cal. ka BP (e.g. Nygård *et al*. 2007; Bellwald *et al*. 2020). The Scandinavian and the British–Irish ice sheets coalesced during the LGM and also during the Saalian and Elsterian glaciations (Bradwell *et al*. 2008; Graham *et al*. 2010, 2011; Clark *et al*. 2012, 2022; Sejrup *et al*. 2016; Ottesen *et al*. 2020). However, the configuration and behaviour of the ice sheets in the central North Sea are complex, poorly understood, and have been debated for many years (Bradwell *et al*. 2008; Clark *et al*. 2012; Merritt *et al*. 2016; Ottesen *et al*. 2020).

Quaternary stratigraphy of the North Sea Basin

The North Sea Basin has been infilled by a mixture of glacial, fluvial, marine, and lacustrine sediments during the Quaternary. The depositional history of the central and southern North Sea basins is very different from the northern basin, and our study area is located in the transition zone between the two (Fig. 1). The northern North Sea Basin was infilled mainly by glacigenic debrisflows from the east (Løseth *et al*. 2022), whereas the southern and central North Sea Basin was infilled by a huge fluvio-deltaic system that filled in the basin from both the south and the east (Overeem *et al*. 2001; Lamb *et al*. 2017; Ottesen *et al*. 2018). An Upper

Regional Unconformity (URU) exists in the study area, and the stratigraphy beneath and above this surface is described below.

Quaternary stratigraphy below the URU. – In the central and southern North Sea basins, Ottesen *et al.* (2014, 2018) mapped three early Quaternary clinoform units (Unit 1, Unit 2 and Unit 3; Fig. 1B). The units are interpreted to be deltaic sediments infilling the basin from the east and south. The uppermost part of Unit 3 comprises a till with a crenulate surface (Rose *et al.* 2016; Fig. 1B, C). Above the till, Ottesen *et al.* (2018) defined and mapped a Central Basin Unit and an Upper Central Basin Unit that filled the North Sea Basin with sediment (Fig. 1B, C). All of these units have an early to early/mid Quaternary age and were deposited before the Norwegian Channel started to be eroded. Above these units, an URU is found. No tunnel valleys – subglacially eroded channels incised by meltwater flowing beneath a grounded ice sheet (Kehew *et al.* 2012) – are present in the sediments below the URU (defined as the depth at which the tops of valley flanks occur), although the bases of some tunnel valleys cut deeply into these sediments from the units above the URU (e.g. Fig. 1B).

In contrast to the southern basin, the northern North Sea Basin was infilled mainly by glacigenic debrisflows sourced from the east from 2.6 Ma onwards (Ottesen *et al.* 2014, 2018; Batchelor *et al.* 2017; Løseth *et al.* 2020). The layers prograde towards the west and are interbedded with sediments from a fluvio-deltaic system deposited along the eastern margin of the East Shetland Platform.

Upper Regional Unconformity (URU) and overlying stratigraphy. – In the North Sea, the URU normally represents an erosional surface cut by glacial erosion beneath an active ice sheet. In some places, however, it can represent a hiatus between two different depositional systems. The surface appears to be a composite unconformity, with different ages depending on the area in which it is observed. For example, on the North Sea Plateau west of the Norwegian Channel, the URU probably dates from the Elsterian glaciation (Ottesen *et al.* 2014). By contrast, in the Skagerrak area of the Norwegian Channel itself, the URU has been assigned a Late Weichselian age of only about 20 cal. ka BP due to extensive glacial erosion by the NCIS during the LGM (Rise *et al.* 2008).

The stratigraphy above the URU comprises a variety of units, including flat-lying layered sediments (both marine and lacustrine), tills, moraines, glaciotectonized complexes and tunnel valleys (see below). Several glacial erosional surfaces are mapped in the area, producing a very complex stratigraphy. An intricate pattern of tunnel valleys in the area adds further complexity (Ottesen *et al.* 2020; Kirkham *et al.* 2024). All of the tunnel valleys found within the region of the glacial trough described in this study are located stratigraphically below the base of the trough.

Study area

The greater Johan Sverdrup area of the North Sea is found on the relatively flat North Sea Plateau (58°30′N to 59°30′N, 2°E to 3°30′E) west of the Norwegian Channel in modern water depths between 100 and 140 m (Fig. 1). The area is located over the axial parts of the Quaternary North Sea Basin where the thickest Quaternary deposits occur (Fig. 1B; Ottesen *et al.* 2018). The modern sea floor represents a wide elevated region between the Norwegian Channel to the east and the Witch Ground Basin (up to 150 m water depth) in the UK sector to the west (Fig. 1A). The shallow regional stratigraphy comprises flat-lying layers of till or bedded sediments, cut through by a complex pattern of tunnel valleys, with the deepest eroding into sediments down to more than 500 ms two-way travel time (TWT) (Lamb *et al.* 2017; Ottesen *et al.* 2020; Kirkham *et al.* 2024).

Using several types of 2D and 3D seismic data, we mapped a pronounced URU 100–200 m beneath the sea floor. The URU separates units that generally have a glacial character from the slightly dipping layered sediments below (Fig. 1C). The glacial trough, Marstein Trough, which we discuss below is located east of the Johan Sverdrup hydrocarbon field. The base of the trough represents the URU in this part of the North Sea.

Material and methods

High-resolution 2D site survey data

A number of site-survey investigations within a 50-km (E–W) by 60-km (N–S) area, located between 2° to 3°E and 58°30′ to 59°N, were utilized in our study (inset map in Fig. 1A). The smallest surveys contain only a few seismic lines and the largest hold several hundred. The surveys are most often shot in a regular E–W/N–S or a SW–NE/SE–NW grid with a typical line spacing of 250 or 500 m, and 100 m in some limited areas. Most of the lines are registered down to 2500 ms TWT, and some down to 1000 ms TWT, which covers the depths of interest to us (the uppermost ~ 500 ms TWT).

Only the southwestern part of the glacial trough mapped in this study is covered by site-survey data (Fig. 1). An exception is one small area of 7 × 8 km^2 in the central part of the trough around the Zulu hydrocarbon discovery (59°N, 3°E; Fig. 1A). This site survey comprises a regular grid of high-resolution seismic lines (line spacing 500 m) and a few regional tie-lines.

3D seismic data

The high-resolution 2D site survey data are contextualized by many individual 3D surveys that have been merged into a 67 000 km^2 regional scale 3D seismic data set produced by the marine geophysical company TGS (formerly PGS; Petroleum Geo-Services). We focus here on an area that lies between 58°30′N and 59°30′N (Fig. 1A). The area includes most of the Norwegian side of the North Sea Plateau west of the Norwegian Channel and a small part of the British sector (Fig. 1). The seismic bin size is 25 × 25 m and the vertical sampling is 4 ms (~3 m).

A second 3D seismic cube (named Utstord, 5000 km^2 in area) partially overlaps with the regional 3D-merge and extends to the east into the Norwegian Channel (Fig. 1A). It covers the easternmost part of the trough and the transition into the Norwegian Channel. The line spacing for the Utstord cube is 25 m and we have access to the uppermost 800 ms. The vertical sampling is 4 ms.

In addition to the high-resolution 2D and conventional 3D seismic data, one HR3D seismic data set covering an area of 41 km^2 is present within the study area (Figs 1A, 2A). The data set consists of a time-migrated 3D stack with a 1-ms sample rate, a 6.25 × 6.25 m bin size and a vertical resolution of ~4 m, given the 100–125 Hz dominant frequency of the seismic-reflection data (Kallweit & Wood 1982). The detection limit for depth changes along individual reflectors is ~0.5 m (Kirkham *et al*. 2021, 2022).

Geotechnical boreholes

We have access to several geotechnical boreholes in the Johan Sverdrup area that are located in and around the glacial trough. The depth of the boreholes varies between 53 and 99 m, penetrating the entire shallow stratigraphy above the URU, and some penetrate slightly into the laminated layers beneath (Central Basin Unit or Upper Central Basin Unit of Ottesen *et al*. 2018). In this study, we focus on borehole JS2001, which is located within the glacial trough (Fig. 2) and, at 78 m deep, samples all of the major sedimentary units that fill and overlay the trough. A number of physical, mechanical, and geotechnical parameters have been measured in the core sediments, and we present both the resistance from cone penetration tests (CPTs) and undrained shear strength (Fig. 5). Both parameters are a measure of the load that the sediments have been exposed to (either by sediments or by ice) and can thus give an indication of the soil type sampled.

A well was drilled in the Zulu prospect in 2015. This well is located in the centre of the glacial trough (Figs 1A, 2). During the site survey investigations, five CPTs were taken inside a 3 × 3 km area around the planned well location. The deepest of these CPTs reached 15 m into the sediments and covers only the upper part of the 'Uppermost Unit' (Fig. 3).

Results: a glacial trough on the North Sea Plateau

Here we present geophysical evidence for a large erosional trough west of the Norwegian Channel on the North Sea Plateau, now buried beneath up to 60 m (70 ms) of overlying sediments (Fig. 1). For ease of reference throughout this paper, we informally name this buried trough as Marstein Trough after a lighthouse southwest of Bergen. For the regional understanding and the stratigraphical context of Marstein Trough, which are the focus of this study, we mapped several seismic surfaces regionally. These comprise the URU, two older glacial erosional surfaces that cut into older sediments, and some tunnel valleys that cross the study area (Figs 1B, C, 2A).

URU and overlying regional stratigraphy

The URU surface is generally easy to distinguish in seismic profiles because it comprises a strong seismic reflector, but it can be rather time consuming to map since the form of the surface shows large variations over short distances; this is especially true where dissected by tunnel valleys. We mapped the URU surface on the available site-survey lines (inset in Fig. 1A, C) and used a regional 3D seismic cube in areas where site-survey seismic data are missing. The URU is generally a glacial eroded surface (Fig. 2) but can also represent a hiatus between different glacial systems, for example when ice flow changes direction or where sediment supply is cut off from one direction.

The general upper Quaternary stratigraphy of the study area is shown in Fig. 1B, C. The URU (orange line) is used to identify the base of the mapped trough where it exists (to the right in the profile; red polygon). Farther west, the URU represents a deeper surface both stratigraphically and in two-way travel time, where the ice sheet has eroded deeper into the Central Basin Unit and the Upper Central Basin Unit of the North Sea stratigraphy (Fig. 1C). The URU reflector is normally present at depths between 100–200 m below the sea floor, but where tunnel valleys cut through the sediments it can reach depths of up to 400 m beneath the seabed. In the profile shown in Fig. 1C, a glacial erosion surface is developed on top of two tunnel valleys. Above the two units that infill the trough, a well-developed but rather flat glacial erosion surface is mapped. This surface continues beyond the trough as a clearly defined, slightly undulating, seismic reflection towards the west. Above the glacial erosion surface, flat-lying slightly laminated sediments are present, probably overridden by an ice sheet of Saalian and/or Weichselian age. Several of these layers contain iceberg ploughmarks as seen in the HR3D cube (Fig. 3A).

A buried glacial trough – Marstein Trough

On the North Sea Plateau, west of the western margin of the Norwegian Channel (~59°N, 3°E), we identified and mapped a glacially eroded trough, the Marstein Trough, from 3D seismic data (Figs 1, 2). The trough has been

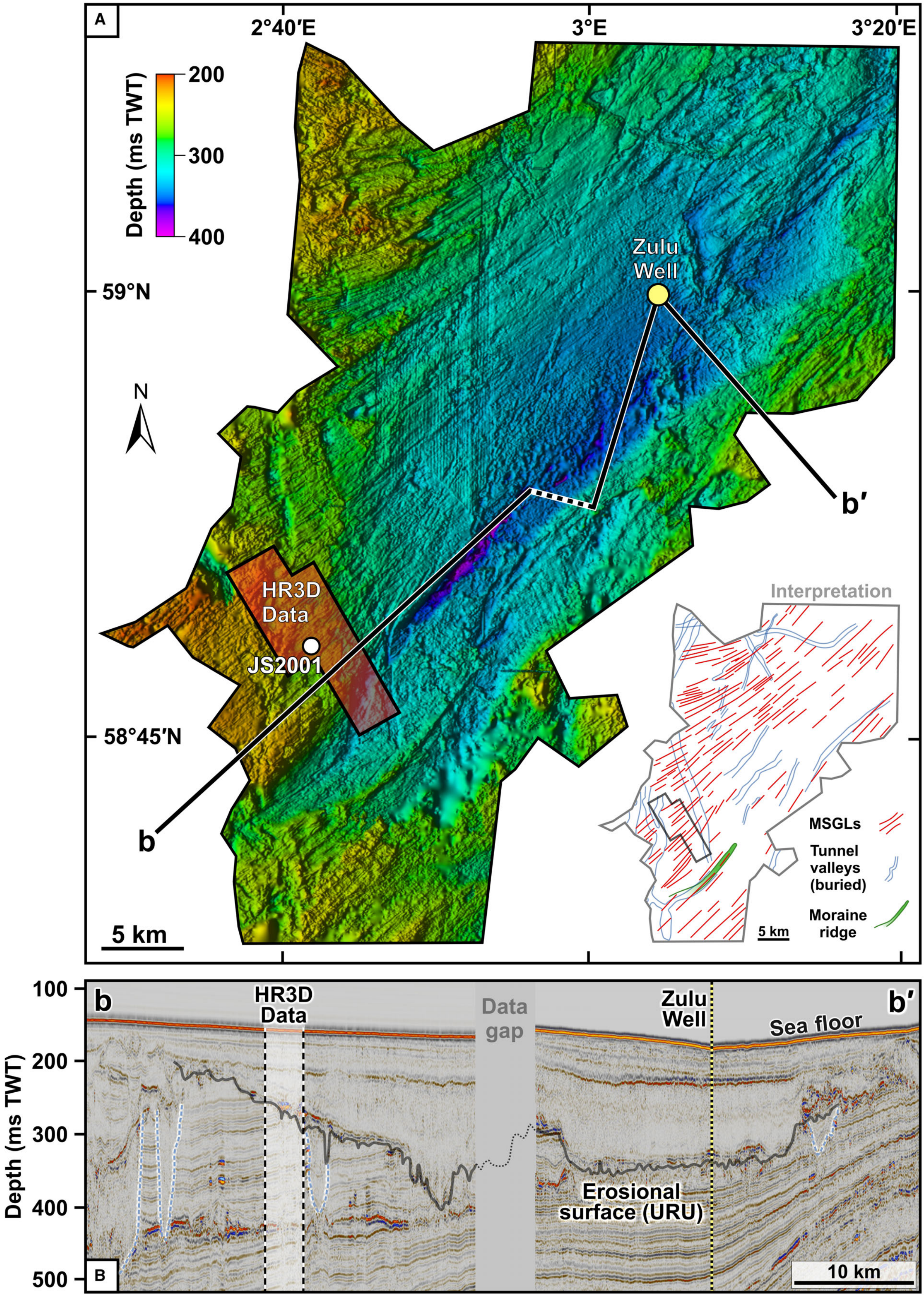
A
2°40′E
3°E
3°20′E
Depth (ms TWT)
200
300
400
Zulu Well
59°N
N
b′
HR3D Data
JS2001
58°45′N
b
5 km
Interpretation
MSGLs
Tunnel valleys (buried)
Moraine ridge
5 km
100
200
300
400
500
Depth (ms TWT)
b
HR3D Data
Data gap
Zulu Well
b′
Sea floor
Erosional surface (URU)
10 km
B

Fig. 2. A. The Marstein Trough erosion surface derived from 3D seismic data. The colour scale shows depth in ms TWT. The locations of the HR3D seismic cube and geotechnical borehole JS2001 and the Zulu Well are shown. The seismic line displayed in B is shown as a black line. Inset map shows lineations, interpreted as MSGLs, buried tunnel valleys that underlie the trough, and the curved ridge (interpreted as a moraine) on the Marstein Trough erosional surface. Data owner, TGS. B. Composite high-resolution seismic tie-line showing the erosional surface and general stratigraphy of the infilled trough. Tunnel valleys that underlie the trough are marked as blue stippled lines.

infilled subsequently by sediments and has no surface expression on the modern sea floor of the North Sea. The buried NE to SW-trending trough is 60 km long, up to 30 km wide, and 150 ms (~120 m) deep, covering an area of ~1500 km^2 (Figs 1A, 2). It is slightly asymmetrical with a steeper side towards the SE. The trough reaches a maximum depth of 400 ms in its centre and narrows towards both the NE and SW, shallowing to ~300 ms in the NE and ~250 ms in the SW. On seismic profiles, the trough represents a glacial erosional unconformity, eroded into layered and slightly dipping early to middle Quaternary sediments (the Central Basin Unit and Upper Central Basin Unit of Ottesen *et al*. 2018; Figs 1C, 2B). Towards the sides of the trough, the erosional surface flattens out and it can be difficult to define the lateral extent of the trough accurately (Figs 1C, 2).

The dimensions of Marstein Trough are very similar to a number of other glacially eroded cross-shelf troughs that have been investigated using multibeam bathymetric data sets of the modern sea floor on formerly glaciated continental shelves (e.g. Bellec *et al*. 2016; Canals *et al*. 2016; Ryan *et al*. 2016). For example, Malangsdjupet on the north Norwegian shelf is a clear modern analogue for Marstein Trough as it has very similar dimensions at about 50 km long and 12–30 km wide. In Malangsdjupet, only a few metres of postglacial sediment cover well-preserved sea-floor features, which show the imprint of a fast-flowing LGM ice stream, including a variety of subglacially produced landforms (Bellec *et al*. 2016).

Landforms in Marstein Trough

The buried surface of the trough was mapped using 3D seismic data (Figs 2A, 3). Several distinctive morphological features have been identified and are described and interpreted below.

Curvilinear ridges and depressions – MSGLs. – The erosional surface mapped from the regional 3D seismic cube has a well-developed pattern of slightly curving linear features in the form of elongate ridges and depressions (Figs 2A, 3C). The ridges have heights of a few metres and are spaced roughly parallel to one another at distances of ~300 m, although ridges as small as 0.5 m high and spaced less than 100 m apart can be resolved in the HR3D seismic data (Fig. 3). The lineations generally follow the main trend of the basin (SW–NE). Towards the west, however, they widen in a fan-shaped pattern that is particularly clear in the northwestern corner of the data set (Fig. 2A; inset map).

We interpret these lineations as mega-scale glacial lineations (MSGLs), formed by soft sediment deformation beneath a fast-flowing ice stream (e.g. Clark 1993; Ó Cofaigh *et al*. 2007; Lang *et al*. 2018). MSGLs are common on glaciated and formerly glaciated continental shelves (e.g. Shipp *et al*. 1999; Spagnolo *et al*. 2014; Dowdeswell *et al*. 2016). On the Norwegian shelf, MSGLs have been observed in cross-shelf troughs such as the Norwegian Channel and the Bear Island Trough (Sejrup *et al*. 2003; Andreassen *et al*. 2004, 2014). On the mid-Norwegian shelf, MSGLs are present in all cross-shelf troughs (Ottesen *et al*. 2005, 2022).

Importantly, MSGLs have also been observed actually forming in soft deformable sediments beneath active modern Antarctic ice streams (King *et al*. 2009). Their presence has been widely interpreted to indicate the operation of fast-flowing ice streams that typically drain large ice-sheet catchments (e.g. Ottesen *et al*. 2005; Spagnolo *et al*. 2014). As such, it is likely that a similar fast-flowing ice stream eroded the Marstein Trough.

Curved ridge – possible lateral or medial moraine. – In the southwestern part of the trough, a 15 km long, 1 km wide, and up to 40 m high slightly curving ridge is present. The ridge is oriented in the same direction as the main trough (NE–SW; Fig. 2A). It widens and increases in height towards the SW end of the trough. A tunnel valley, up to 90 ms deep (~80 m) and up to 1 km wide, is located beneath the ridge along 8 km of its length.

We interpret the ridge as a subglacially formed moraine. The ridge has similar dimensions to about 70 lateral shear-margin moraines up to 3.5 km wide and 60 m thick, reported from the sides of a number of Quaternary ice streams by Batchelor and Dowdeswell (2016). The moraines maintain a relatively constant width, thickness and cross-sectional shape along their length and are interpreted as ice-stream lateral shear-moraines formed subglacially in the shear zone between ice streams and slower-flowing regions of an ice sheet. In Marstein Trough, however, the distribution of MSGLs suggests that fast ice flow persisted on either side of the ridge (Fig. 2A; inset map). We infer, therefore, that the ridge was formed subglacially, potentially as a result of differing water pressure and hence deformation rate in the sediments of the tunnel valley that underlies it (Batchelor & Dowdeswell 2016; Kirkham *et al*. 2021, 2024).

Sediments in and above the trough

Marstein Trough is infilled by two units of semi-transparent sediments, which we refer to as the Lower

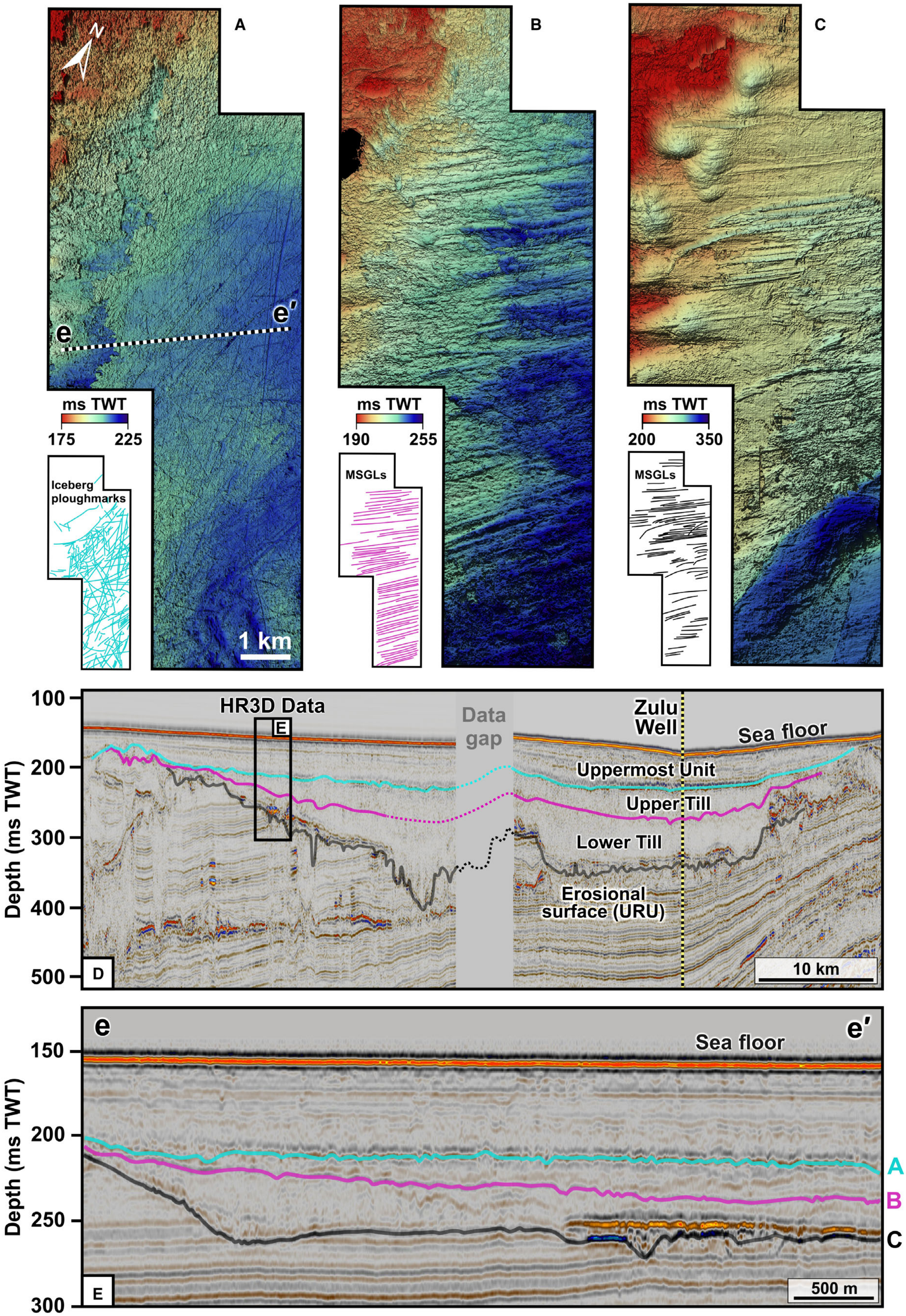
A
e
e′
ms TWT
175
225
Iceberg ploughmarks
1 km
B
ms TWT
190
255
MSGLs
C
ms TWT
200
350
MSGLs
100
200
300
400
500
Depth (ms TWT)
HR3D Data
E
Data gap
Zulu Well
Sea floor
Uppermost Unit
Upper Till
Lower Till
Erosional surface (URU)
D
10 km
e
e′
Sea floor
150
200
250
300
Depth (ms TWT)
A
B
C
E
500 m

Fig. 3. High-resolution morphology of three buried surfaces in the HR3D seismic cube (located in Figs 1A, 2A). A. Base of the Uppermost Unit exhibiting chaotic surface depressions that are interpreted as ploughmarks formed by the keels of drifting icebergs. B. Base of the Upper Till layer characterized by curvilinear ridges and depressions that are interpreted as mega-scale glacial lineations (MSGLs). C. Base of Marstein Trough (and Lower Till layer) – representing the upper regional unconformity (URU) in this part of the North Sea – with lineations interpreted as subglacially formed MSGLs. D. Composite seismic profile (LN13303-02001, LN14303-02001, LN14303-04001) showing the three imaged surfaces. The irregular unit between 400–450 ms depth is a different till deposited in the central North Sea representing the first ice advance into this part of the North Sea about 1.2 million years ago (Ottesen *et al.* 2024). E. HR3D seismic profile across the HR3D cube, displaying the extent of the surfaces mapped in A–C.

and Upper Till based on the arguments outlined below (Figs 3D, 4). Together, these two units have a total thickness of 160 ms (~140 m) with the thickest sediments following the trough axis (Fig. 4D). Above the infilled trough, a further unit with a much more regional distribution is present; we term this the Uppermost Unit (Fig. 3D). The surface of the Uppermost Unit represents the modern sea floor in the area. The Uppermost Unit is up to 70 ms thick and fills in the basin, giving the modern sea floor a gently sloping form (Fig. 3D). This unit has a more layered character than the two till units beneath, although the layering seems to have been deformed and partly broken by folding.

To provide regional stratigraphical context, we interpreted some seismic horizons beyond Marstein Trough itself (Fig. 6A); this also yields a better understanding of the genesis of the different seismic units. Figure 6B shows that the ‘Uppermost Unit’ can be separated into three subunits. The lowest part comprises layered sediments, up to 25 ms thick. Above the layered sediments sits a transparent unit with few internal reflections that is interpreted as a till because of its seismic character (Dowdeswell & Ottesen 2016). The final subunit of the Uppermost Unit comprises a layered drape that gives the seabed a flat appearance.

The central till layer of the Uppermost Unit is characterized by a strong seismic reflection that is visible across a large regional extent. When traced further west from the region of Marstein Trough, the reflection deepens slightly but remains an internal reflector within the ‘Uppermost Unit’ that tops the trough. In the Marstein Trough area it is difficult to classify the unit as a till based on seismic character in this location alone; however, farther west the unit exhibits seismic properties that are consistent with a till layer (e.g. Dowdeswell & Ottesen 2016). This implies that the ‘Uppermost Unit’ has been overridden by ice after its deposition.

In Borehole JS2001 (Fig. 2A), the upper 28 m comprises a clayey, sandy silt that sometimes contains shell fragments (Fig. 5). The silt is characterized by typically low to medium undrained shear strength values of 25–140 kPa but reaches peaks of >200 kPa when beds of sand are encountered. Below this silt (from 28 to 50 m) are two units of moderate to high strength clay with undrained shear strength values between ~95–195 kPa (Fig. 5D). Elsewhere, five CPTs sampled down to 10–15 m in the Zulu Well site survey core indicate that the upper part of the ‘Uppermost Unit’ is a silty clay with low to medium strength. We interpret the Uppermost Unit to comprise sediments that may have initially formed as layered deposits in water but were later overridden by ice and slightly deformed. Multiple layers of iceberg ploughmarks are observed in the HR3D seismic data from the base of the unit through to just below the sea floor (Fig. 3A), suggesting that these sediments were deposited in an environment that had both a marine and a glacial influence during deposition and subsequent reworking.

Situated at depths between 50 and 67 m, the Upper Till rests directly beneath the Uppermost Unit and is composed of sandy clay that contains traces of angular gravel. The Upper Till has a maximum thickness of 90 ms (~70 m) and thins towards the margins of the trough. It has a transparent character in seismic-reflection data, with few internal structures, and is characterized by high to extremely high undrained shear strength values between 200–400 kPa (Fig. 5D). At ~40 km long and 15 km wide, the top surface of the Upper Till mirrors the subdued form of the underlying trough (Fig. 4C). Its surface also shows irregular chaotic depressions (Fig. 3A); these features are characteristic of past ploughing of the sea floor by icebergs (e.g. Woodworth-Lynas *et al.* 1991; Dowdeswell *et al.* 1993; Dowdeswell & Ottesen 2013).

The Lower Till rests beneath the Upper Till and has a similar transparent character with few internal reflections. It is up to 100 ms (~80 m) thick and thins towards the flanks of the trough. The unit is comprised of slightly sandy clay and is characterized by high undrained shear strength values typically between 200–250 kPa (Fig. 5D). When mapped in 3D, the upper surface of this unit forms a major depression with a NE–SW trend that mirrors that of the main trough (Fig. 4B) and, importantly, displays surface lineations similar to the MSGLs on the trough floor below (Fig. 3B, C). This indicates that ice was active when the sediments were deposited and implies that the unit is likely to be a till.

We interpret both of these units, the Lower and Upper Till, to be tills deposited by the ice sheet that eroded Marstein Trough. This interpretation is based on the distribution and geotechnical character of sediments that have filled in the erosional depressions, the surface morphology of the units, which resemble a muted yet still elongate NE to SW-trending trough that contains MSGLs, and the glacial landforms present on top of the Lower and Upper Till (Fig. 3B, C).

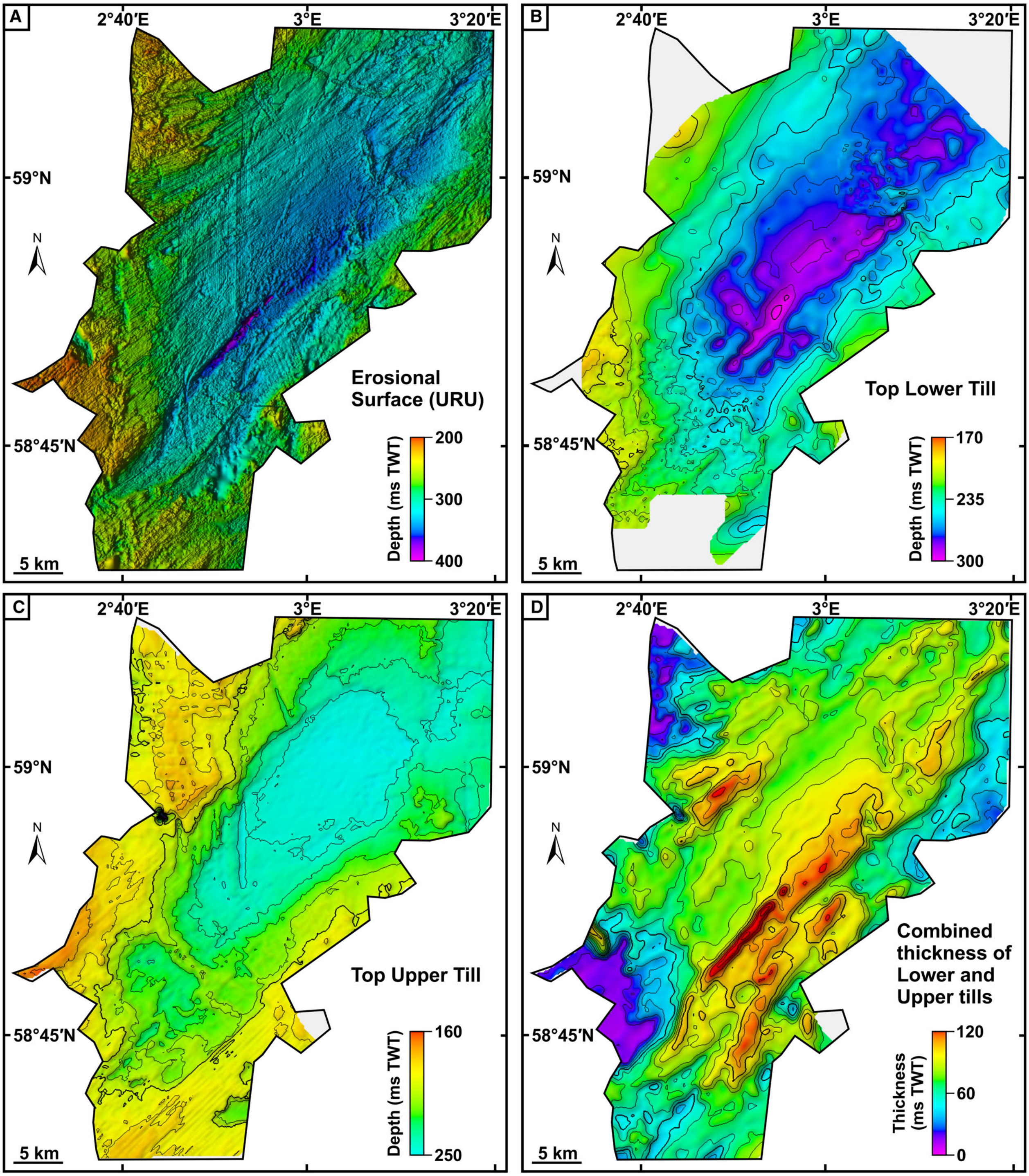

Fig. 4. Palaeo-surfaces and sediment thickness in Marstein Trough derived from 3D seismic data. A. Depth to the trough erosion surface, defining the form of Marstein Trough. B. Depth to the top of the Lower Till. C. Depth to the top of the Upper Till. D. Combined thickness of the Lower and Upper tills, which fill the trough.

Discussion

Ice-flow direction within Marstein Trough

The broad-scale form of the 120-m-deep Marstein Trough, including the well-developed pattern of glacial lineations that follow the basin axis (Fig. 2A; inset map), clearly indicates that this is a glacially eroded feature. The central North Sea has experienced a complex history of ice flow throughout the Quaternary, with ice often flowing into the central basin from the Scandina-

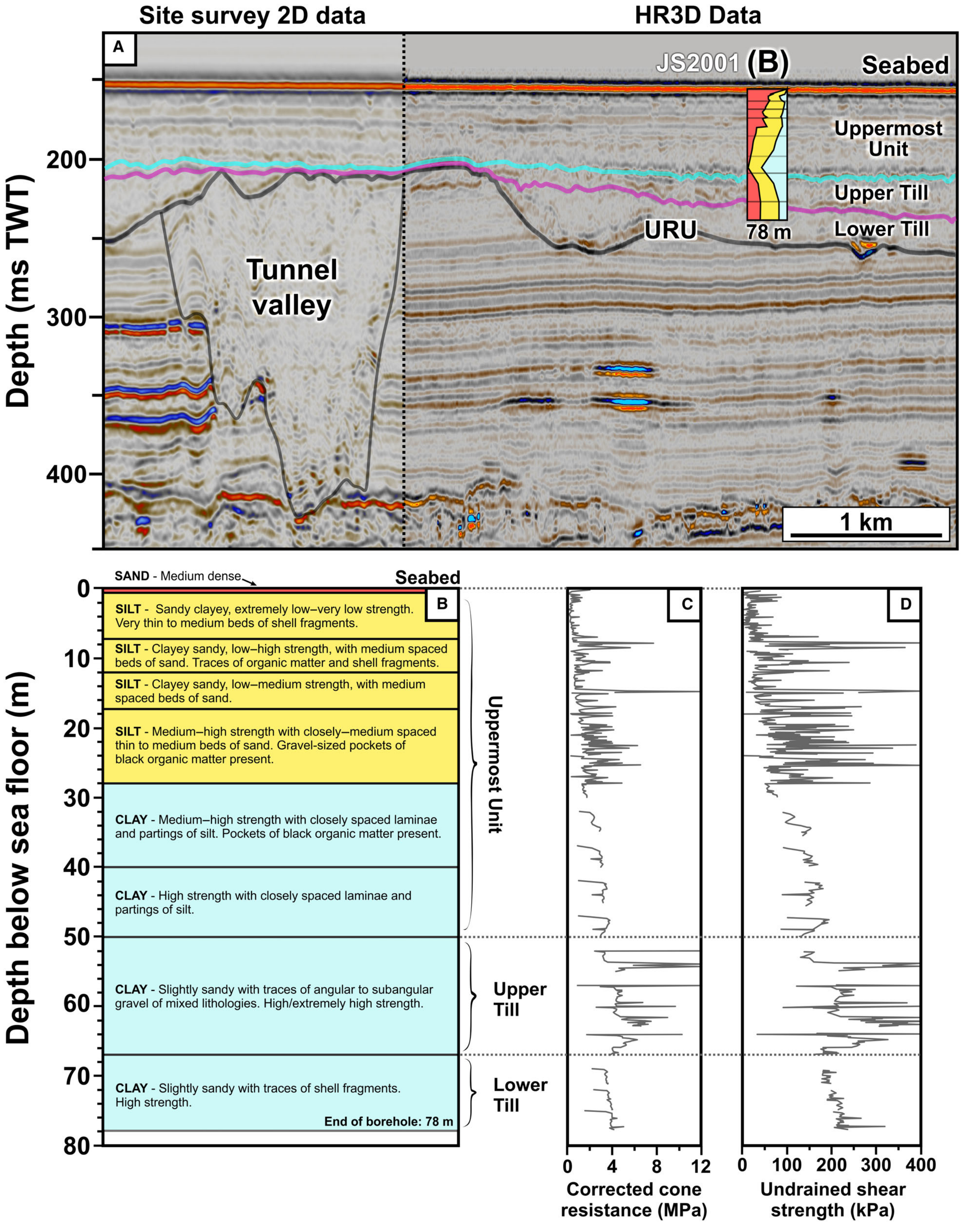

Fig. 5. Geotechnical borehole JS2001. A. Seismic profile with location of borehole JS2001 shown. Colours within the borehole represent the distribution of grain sizes with depth (red = sand; yellow = silt; blue = clay). B. Lithological description of borehole JS2001. C. Corrected cone resistance (MPa). D. Undrained shear strength (kPa).

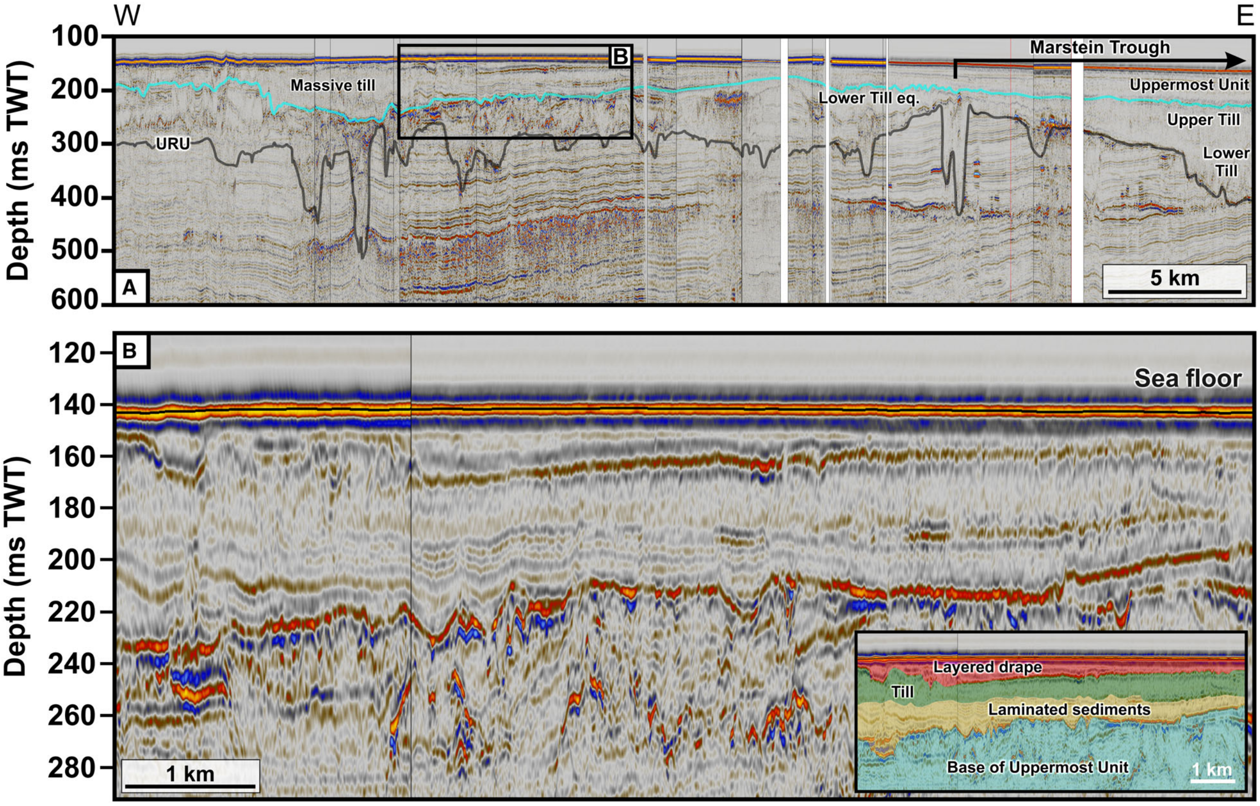

Fig. 6. A. Regional composite seismic profile across parts of the Marstein Trough and the shelf areas west of the trough (for location see Fig. 1A). B. Stratigraphy and interpretation (inset) of the Uppermost Unit. The Uppermost Unit is composed of three subunits: (1) at the base laminated sediments that are disrupted along parts of the line; (2) a middle, semi-transparent unit with irregular internal reflections interpreted to be a till; (3) a top unit of layered sediments.

vian, western European, and British landmasses (e.g. Graham *et al.* 2007; Dove *et al.* 2017; Roberts *et al.* 2018; Batchelor *et al.* 2019; Ottesen *et al.* 2024).

The consistent NE–SW axial trend of Marstein Trough implies that the feature was most likely carved out by ice either flowing in a southwesterly direction from Norway or in a northeasterly direction from Britain. Given that the distance from the trough to the Norwegian coast (~150 km) is significantly shorter than the distance to the British coast (~350 km), the simplest explanation is that the ice that eroded the trough originated from Norway. This interpretation is supported by the fact that the westernmost part of the trough widens slightly, with its MSGLs fanning outwards (Fig. 2A; inset map), suggesting that the flow pattern of the palaeo-ice stream widened towards the west in a fan-shaped pattern. Similar fanning patterns of MSGLs have been observed at the termination of other ice streams, for example the Bear Island Trough and Storfjordrenna in the Barents Sea (Ottesen *et al.* 2005; Pedrosa *et al.* 2011), in the Melville Bugt Trough on the western Greenland continental shelf (Newton *et al.* 2020), and in Malangsdjupet cross-shelf trough in northern Norway (Ottesen *et al.* 2008; Bellec *et al.* 2016).

Furthermore, the HR3D seismic cube demonstrates that the erosional surface shallows towards the west, with MSGLs terminating in a series of bowl-like depressions at the margin of a filled tunnel valley (Fig. 3C). This geomorphological transition potentially indicates a nearby shift to a very different ice-flow regime, or complex interactions of the ice with the tunnel valley infill material compared to the surrounding substrate (Kirkham *et al.* 2024). Taken together, the trough location, orientation, and characteristics of the MSGLs within the trough suggest that ice flowed through the trough in a southwesterly direction before potentially terminating a little further to the west of our HR3D seismic data coverage.

Age of Marstein Trough

The stratigraphical context of Marstein Trough places its excavation after the initial formation of the deep S–N trending Norwegian Channel to the east (Fig. 1B; Sejrup *et al.* 2003; Ottesen *et al.* 2016). This is because Marstein Trough is incised into a buried ledge that runs along the western side of the modern-day boundary of the Norwegian Channel that probably corresponds to one of the first (oldest) stages of its erosion, most likely during the Elsterian glaciation (Nygård *et al*. 2005; Løseth *et al*. 2022). The lateral extent of Marstein Trough also shows that it is younger than the complex glacial stratigraphy farther west, where at least two deeper glacial erosional unconformities, several generations of tunnel valleys, and glaciotectonic complexes are present (Figs 1C, 6A); these features also likely relate to the extensive Elsterian glaciation (Sejrup *et al*. 1987; Wingfield 1990; Gatliff *et al*. 1994), implying that Marstein Trough was formed in a more recent glaciation than the Elsterian.

The base of Marstein Trough is buried by three overlying units – two of them contained within the trough itself (Fig. 3D). The two tills present within the trough (Lower and Upper Till) – including the glacial features on top of these units – were probably deposited in close temporal proximity to the erosion of the trough (Figs 2B, 3D, 4). Above these two units rests the Uppermost Unit, which in certain areas can be subdivided into three subunits. This unit is widely distributed across large areas of the North Sea Plateau (Figs 1B, C, 6A). The thickness and very wide distribution of the Uppermost Unit suggest that it was not deposited during the last, Weichselian, glaciation. Rather, it is more probable that this unit was deposited during the penultimate and much larger Saalian glaciation and was subsequently overridden by one or several Weichselian ice advances. From the regional seismic profile (Fig. 6) we can clearly see that a large part of the 'Uppermost Unit' has the character of a till. This unit is up to 30 ms thick (25 m), which is greater than the thicknesses of most Weichselian sediments reported elsewhere on the North Sea Plateau (Graham *et al*. 2007). The stratigraphical context of Marstein Trough therefore places its erosion between the Elsterian and Weichselian glaciations. Consequently, we suggest that the ice-sheet advance that excavated the trough most likely occurred during the Saalian glaciation, although more detailed chronostratigraphical evidence than available presently would be required to confirm or refute this hypothesis.

Given the contrast between the consistent NE–SW axial trend of Marstein Trough and the dominant S–N direction orientation of ice flow along the Norwegian Channel, we propose that Marstein Trough was excavated during an early growth phase of the Scandinavian Ice Sheet, likely during the Saalian glaciation. The trough was probably carved out by an ice sheet that crossed the topographic deep of the Norwegian Channel when the ice-sheet catchment was largely sourced from terrestrial Norway (Fig. 7D). Under this initial growth phase, the ice sheet would have expanded in a radial ice-flow pattern from southern Norway across into the marine areas of the Norwegian Channel and the North Sea Plateau (Longva & Thorsnes 1997). Upon the culmination of full-glacial conditions (when the ice sheet had grown substantially larger and had an ice divide spanning across Sweden and the Baltic Sea areas), Scandinavian ice merged with ice draining out from the Baltic to form a much larger catchment, reorganizing the dominant direction of ice flow northwards through the partially formed Norwegian Channel (Fig. 7D). In this setting, the NCIS would have needed the support of a passive ice dome on the North Sea Plateau to facilitate flow along the Norwegian coast to the shelf break outside western Norway.

Complex past ice flow from the Scandinavian Ice Sheet

The form of Marstein Trough, including the glacial lineations on its floor, combined with other reconstructions of earlier as well as more recent ice flow in this region, allows us to reconstruct a much more detailed ice-flow pattern than was available previously (Fig. 7). Ottesen *et al*. (2018) and Løseth *et al*. (2020) reported extensive glaciations from 2.6 Ma in the northern North Sea between western Norway and Shetland at about 59 and 62°N (Fig. 7A). During this time, an ice sheet covering large parts of Norway and possibly also Sweden reached the coastal zone and crossed the narrow shelf to the shelf break west of Norway all the way from Stavanger to Lofoten (59–67°N; Ottesen *et al*. 2010, 2018; Montelli *et al*. 2017; Løseth *et al*. 2020). The northern North Sea Basin was filled by glacigenic debrisflow deposits from the east, demonstrating that ice sheets from Norway entered the sea and crossed the shelf to the shelf break, which at that time was located west of western Norway. At the same time, fluvial sediments were deposited in the basin from the Shetland Platform to the west, forming a large delta along the eastern platform margin. Coeval with this, a large fluvial system filled in the central and southern North Sea Basin mainly from the east and south (Fig. 7A).

Around 1.2 Ma, a SW–NE-trending basin, named the Central Basin by Ottesen *et al*. (2018), was developed. An ice sheet advanced into this basin and deposited a till (Central Basin Till) that is more than 100 m thick in some areas (Rea *et al*. 2018; Figs 1B, C, 7B). A crenulate surface was developed on the top of this till with glacial lineations trending mostly SW–NE (Buckley 2016; Rose *et al*. 2016). Rea *et al*. (2018) suggested that the Central Basin Till was deposited by ice that advanced multiple times from both eastern and western sides of the central North Sea, whereas Ottesen *et al*. (2024) argued on the basis of high-resolution 3D seismic data that grounded ice extended across the central North Sea only once, from western Norway, during the early Quaternary to deposit this till. The ice advance represented by the Central Basin Till unit is stratigraphically much deeper and thus much older than the ice advance responsible for carving out Marstein Trough (Fig. 1B, C). However, the ice-flow direction is very similar to that which we infer to have eroded Marstein Trough (Figs 7B, D, 8A).

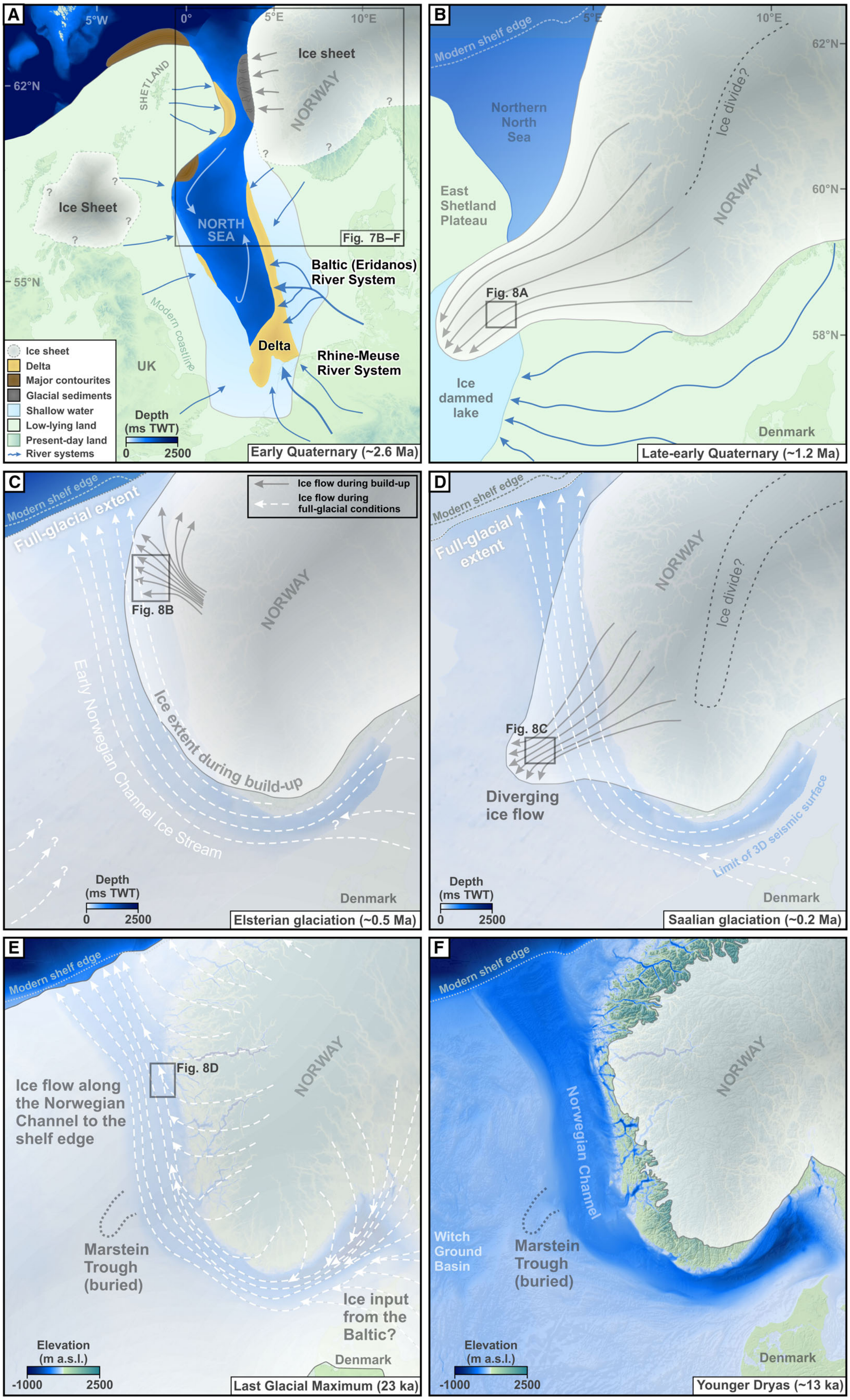
A
5°W
0°
5°E
10°E
62°N
55°N
Ice sheet
NORWAY
SHETLAND
Ice Sheet
NORTH SEA
Fig. 7B–F
Baltic (Eridanos) River System
Delta
Rhine-Meuse River System
Modern coastline
UK
Ice sheet
Delta
Major contourites
Glacial sediments
Shallow water
Low-lying land
Present-day land
River systems
Depth (ms TWT)
0 2500
Early Quaternary (~2.6 Ma)
B
Modern shelf edge
5°E
10°E
62°N
60°N
58°N
Northern North Sea
Ice divide?
NORWAY
East Shetland Plateau
Fig. 8A
Ice dammed lake
Denmark
Late-early Quaternary (~1.2 Ma)
C
Modern shelf edge
Full-glacial extent
Ice flow during build-up
Ice flow during full-glacial conditions
Fig. 8B
NORWAY
Early Norwegian Channel Ice Stream
Ice extent during build-up
Depth (ms TWT)
0 2500
Denmark
Elsterian glaciation (~0.5 Ma)
D
Modern shelf edge
Full-glacial extent
NORWAY
Ice divide?
Fig. 8C
Diverging ice flow
Limit of 3D seismic surface
Depth (ms TWT)
0 2500
Denmark
Saalian glaciation (~0.2 Ma)
E
Modern shelf edge
Fig. 8D
NORWAY
Ice flow along the Norwegian Channel to the shelf edge
Marstein Trough (buried)
Ice input from the Baltic?
Elevation (m a.s.l.)
-1000 2500
Denmark
Last Glacial Maximum (23 ka)
F
Modern shelf edge
NORWAY
Norwegian Channel
Witch Ground Basin
Marstein Trough (buried)
Elevation (m a.s.l.)
-1000 2500
Denmark
Younger Dryas (~13 ka)

Fig. 7. Ice flow from the Scandinavian Ice Sheet into the North Sea during the Quaternary. A. Early Quaternary ice flow from the Scandinavian and UK landmasses at ~2.6 Ma (Ottesen *et al.* 2018). Inset box shows the locations of B–F. Depth of the North Sea Basin at 2.6 Ma in TWT is from Ottesen *et al.* (2018). B. Ice flow from Scandinavia into the central North Sea in a southwesterly direction around ~1.2 Ma (Ottesen *et al.* 2024). C. Ice flow from Scandinavia at two periods during the Elsterian glaciation: limited extent and northwesterly ice flow during build-up; and the full-glacial extent in which ice from Scandinavia conjoined with ice from the UK landmass to bridge the North Sea and reach the continental shelf edge (Rise *et al.* 2016). D. Saalian southwesterly ice advance from Scandinavia to erode Marstein Trough (this study). E. Late Weichselian LGM ice flow from a major part of southern Scandinavia draining northwards through the Norwegian Channel (Ottesen *et al.* 2005). The isostatically corrected bathymetry of the North Sea at 23 ka is from Bradley *et al.* (2023). F. Scandinavian ice extent during the Younger Dryas (~13 ka; Mangerud *et al.* 2023). Modern topography from GEBCO (https://www.gebco.net).

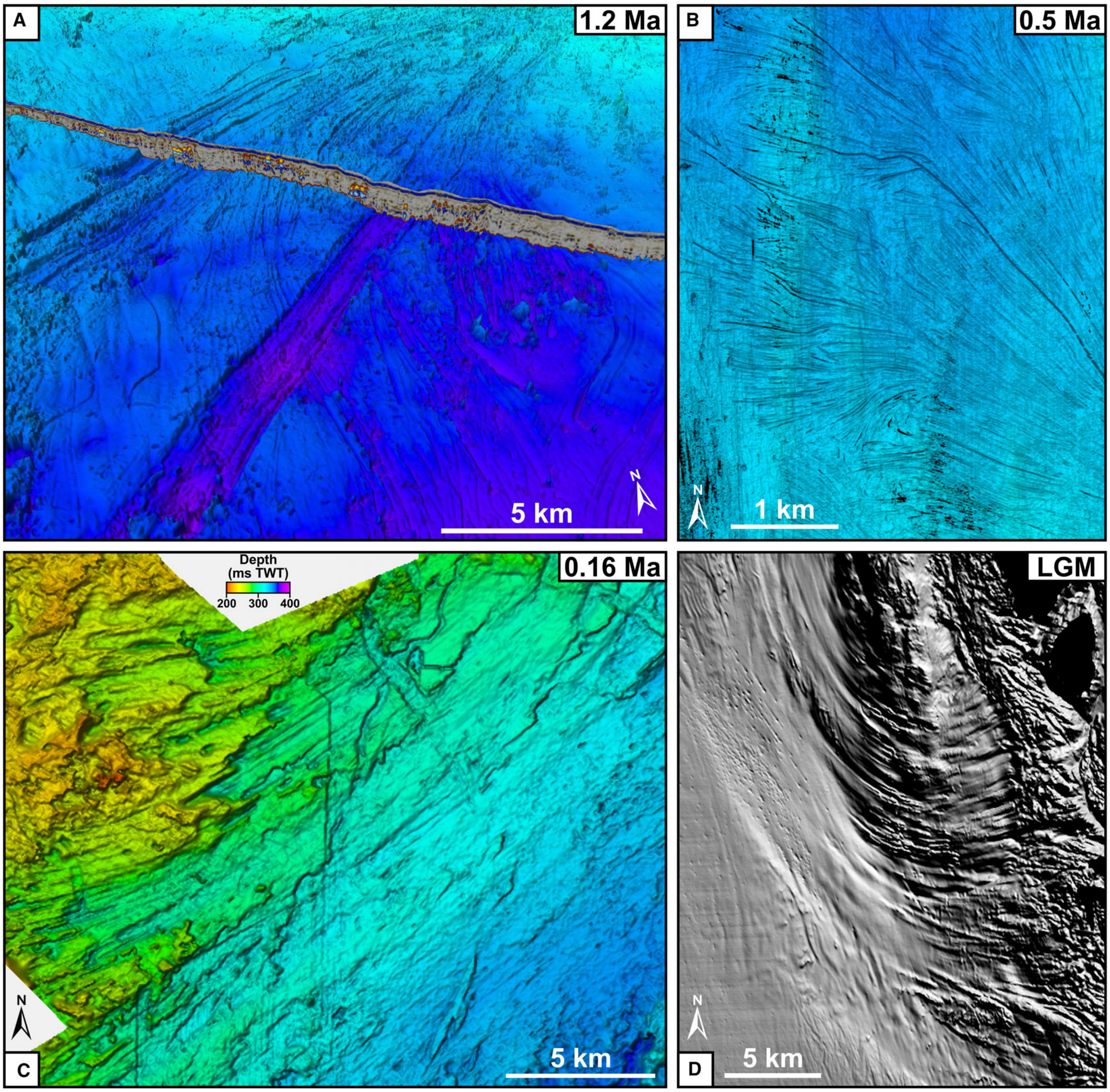

Fig. 8. Examples of mega-scale glacial lineations (MSGLs) from different parts and depths of the North Sea (locations shown in Fig. 7). A. Southwesterly oriented MSGLs from two buried surfaces from the Central North Sea with an approximate age of 1.2 Ma (adapted from Ottesen *et al.* 2024). The depth of the surface ranges between 800–1000 ms TWT. Note how one set of MSGLs has eroded into the uppermost layer. B. Fan-shaped pattern of MSGLs in the outer part of the Norwegian Channel, northwest of Sognefjorden, showing ice flow in a northwesterly direction (Rise *et al.* 2004). The ice-flow pattern probably derives from the Elsterian glaciation at ~500 ka in an early phase of the development of the Norwegian Channel. Surface depth is between 600–630 ms TWT. C. MSGLs from the Marstein Trough flowing southwest and broadening out into a fan-shaped pattern (this study). D. Bathymetric map showing MSGLs in the transition zone from crystalline to sedimentary bedrock outside western Norway where the ice from the fjords of western Norway was assimilated into the main trunk of the Norwegian Channel Ice Stream and deflected towards the north (Ottesen *et al.* 2016). Water depth ranges between 0 and 400 m.

When the ice-flow directions of the Scandinavian Ice Sheet are compared for the five past time periods shown in Fig. 7, it is clear that ice flow in the Norwegian sector of the North Sea has a varied and complex history (Fig. 8). At times of ice-sheet growth before the formation of the Norwegian Channel, ice-flow directions were westwards from Norway onto the North Sea Plateau (Fig. 7B, D; e.g. Løseth *et al*. 2020; Ottesen *et al*. 2024). Once the Norwegian Channel was formed, this topographic deep tended to direct ice flow towards the north, particularly during full-glacial conditions when the NCIS with a huge catchment that included the Baltic was established (Fig. 7E; e.g. Rise *et al*. 2004; Nygård *et al*. 2007; Hjelstuen *et al*. 2012).

However, the MSGLs formed on buried surfaces at about 0.5 Ma and in Marstein Trough show additional complexity in flow directions (Figs 7C, D, 8B, C). Rise *et al*. (2004, 2016) mapped a very complex pattern of superimposed MSGLs that suggested ice flowed first across and then northward through the Norwegian Channel (Fig. 7C). Our work from a subsequent glaciation (probably of Saalian age) showing the orientation of both Marstein Trough, and the MSGLs within it, indicates that ice flowed across the Norwegian Channel and onto the North Sea Plateau. We suggest that this direction of ice flow took place early in the Scandinavian Ice Sheet build-up, before the addition of ice from the Baltic Sea during full-glacial conditions caused flow to reorientate to a S–N direction as an ice stream developed within the deep Norwegian Channel (Fig. 7D). Such ice-stream flow switching between ice-sheet growth stages and full-glacial conditions within a single glacial period has been reported previously in locations such as the western Svalbard margin (Dowdeswell & Elverhøi 2002).

Conclusions

We have mapped a buried glacially eroded trough on the North Sea Plateau west of Stavanger and the Norwegian Channel (59°N, 3°E; Figs 1, 2). The trough is 60 km long, 30 km wide and 120 m deep. It trends NE–SW and has an extensive pattern of glacial lineations at its base that follow the trough axis. The trough is infilled by two seismic units interpreted as tills and is also overlain by a unit of flat-lying sediments that contains at least one till subunit. From its stratigraphical position, we infer that the trough was carved out by an ice stream sourced from western Norway, crossing the Norwegian Channel in a southwestern direction during the penultimate, Saalian glaciation. Marstein Trough, and the diagnostic landforms it contains (Fig. 3), provides detailed evidence of complex, switching ice flow across the North Sea during the Quaternary (Fig. 7). Westward ice flow from Norway took place early in the Scandinavian Ice Sheet build-up and prior to the full establishment of the NCIS. In contrast, during full-glacial conditions, ice derived from both Scandinavia and the Baltic Sea caused flow reorientation to a S–N direction as full-glacial ice streams developed within the deep Norwegian Channel (Fig. 7D).

Although the observations made in this paper allow us to reconstruct a much more detailed ice-flow pattern than was available previously for the North Sea, the history of the Scandinavian Ice Sheet is clearly highly complex and much remains to be understood. There are few constraints on exactly where the Saalian ice advance that eroded Marstein Trough terminated, and how and where it interacted with ice flow coming from the British sector (e.g. Reinardy *et al*. 2025). Further back in time, although the maximum positions of the last three glaciations are relatively well known, the internal dynamics of the ice sheets during growth and decay are poorly understood. Greater coverage and use of high-quality 3D seismic data may reveal some details of ice-flow behaviour from previous glaciations, coupled with deep borehole constraints and better chronostratigraphy.

Acknowledgements. – We thank AkerBP ASA, Equinor Energy AS, Gardline Limited, Lundin Energy Norway AS, Petoro AS, TGS, TotalEnergies EP Norge AS for access and permission to publish images extracted from the 2D, 3D and HR3D seismic data and geotechnical information. The interpretations made in this paper are the views of the authors and not necessarily those of the licence owners. JDK was supported by the Natural Environment Research Council (grant NE/L002507/1). We thank Ed Self and Ken Games for their invaluable support in gaining access to the HR3D seismic and geotechnical data. We thank Schlumberger for a Petrel academic license for DO. A draft of this manuscript was written when DO was on a research visit at OGS in Trieste in April 2024. The authors declare that they have no known interest of relationship, financial or otherwise, that is considered a potential source of conflict of interest. We thank two anonymous reviewers for thorough and helpful reviews of the manuscript. Matt O'Reagan and Nicolaj K. Larsen (Guest Editors) and Jan A. Piotrowski (Editor-in-Chief) also provided helpful suggestions that improved the manuscript. To all these institutions and persons, we extend our sincere thanks.

Author contributions. – DO: conceptualisation; formal analysis; investigation; visualisation; writing – original draft; writing – review and editing. JDK: conceptualisation; formal analysis; investigation; visualisation; writing – original draft; writing – review and editing. JAD: investigation, writing – original draft, writing – review and editing. HB and MH: investigation; review and editing.

Data availability statement. – The data needed to evaluate the conclusions in the paper are present in the paper. However, access to the original seismic data is not possible due to commercial interests.

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