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SCIENCE

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Geomorphology of the Axial Channel (Southern Bight, North Sea)

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ABSTRACT
This study presents a transnational geomorphological map of the Southern Bight, North Sea, using bathymetric data (EMODnet – c. 115 m horizontal resolution; UKHO – 4 m horizontal resolution). Based on the erosional and/or depositional relationship of the mapped features, a first step is established towards the reconstruction of the evolution of the Axial Channel, i.e. a major geomorphological feature on the southern North Sea seafloor. It reveals that the present-day Axial Channel reflects four distinct phases that occurred throughout the Pleistocene: a glacial phase, a major, regional scale fluvial dominated phase – that evolved after the glacial phase; a short-lived, high-energy drainage event; and a last, tidal dominated marine phase. These findings contribute to a refined understanding of the Southern Bight's geomorphological evolution and offer a framework for future palaeo-environmental and stratigraphic studies in the region.

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Southern Bight; Axial Channel; Quaternary geology; geomorphology; seafloor mapping

1. Introduction

The Axial Channel is a prominent geomorphological feature on the present-day southern North Sea seafloor (Main Map), believed to be a remnant of a long-lived, intermittently active, large drainage system. However, its origin and evolution remain unclear. Some studies suggest it formed during the Miocene, as a northern extension of the Lobourg Channel in the Dover Strait (Dingwall, 1975; Liu et al., 1992). Others propose it originated as an eastward branch of the Thames-Medway system during the Early to Middle Pleistocene, draining the uplifted Weald area in the south towards the at that time more northernly positioned North Sea (Balson & D'Olier, 1990; Gibbard & Lewin, 2016). During the Middle to Late Pleistocene, repeated glaciations caused a fall in global sea level, isolating the southern North Sea and leading to the formation of large proglacial lakes in front of the merged British and Fennoscandian ice sheets (e.g. Böse et al., 2012; Graham et al., 2011; Roberts et al., 2018). The West European rivers and glacial meltwater drained into these lakes (e.g. Busschers et al., 2008; Gibbard et al., 1988; Hijma et al., 2012). Indirect evidence for the existence of these lakes are the erosional features still preserved in the Dover Strait, which were created by catastrophic outburst floods at the end of the Elsterian/Anglian and Saalian/Wolstonian, recording the breaching of the land bridge connecting UK to mainland Europe (Collier et al., 2015; Gibbard & Cohen, 2015; Gupta et al., 2007). West European rivers subsequently flowed towards this southern outlet, turning the Axial Channel into a complex, southward running drainage system (Gibbard, 1995; Hijma et al., 2012). Its present-day seabed expression reflects multiple phases of drainage related to glacial and fluvial processes, and tidal erosion and reworking during interglacial periods (Cohen et al., 2017).

Previous studies of the geomorphology of the southern North Sea concentrated on local or national scales (Cohen et al., 2017; De Clercq et al., 2016; Dix & Sturt, 2011; Hijma et al., 2012; Limpenny et al., 2011). Here, we create a transnational geomorphological map of the southern North Sea (the Southern Bight; located roughly between 53° and 51° N, 5° and 1° E; Figure 1a). By mapping the bathymetry, we take a first step in re-evaluating the formation and evolution of the Axial Channel and associated geomorphological features, which will form the basis for future investigations into the sub-surface. The overall aim is to: (1) identify major geomorphological features; (2) make a first interpretation of their formation and evolution; (3) create a relative chronology of events that shaped the region of the Axial Channel.

2. Study area

The ~200 km long Axial Channel extends from the Norfolk Banks in the north towards the Lobourg

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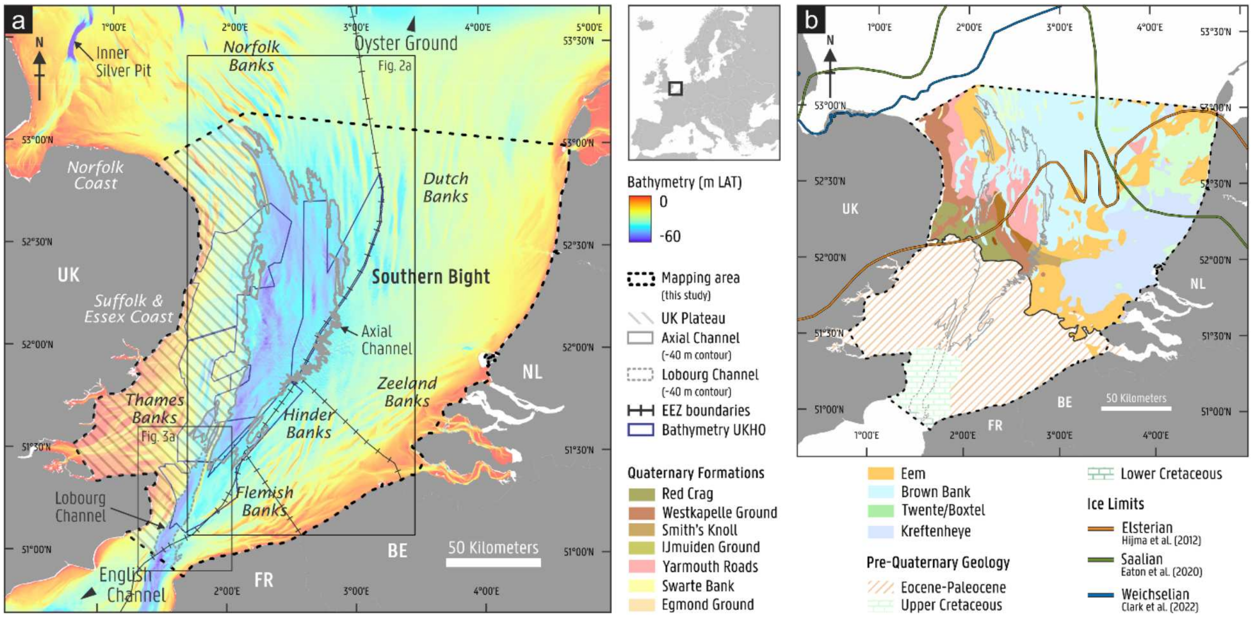

Figure 1. (a) Bathymetric map of the Southern Bight, southern North Sea. The mapped area is indicated, as well as the bathymetry blocks obtained from the UK Hydrographic Office (UKHO; ©The Crown). Geomorphological features (the Axial Channel and Lobourg Channel), geographic features (boundaries of the Exclusive Economic Zone (EEZ), Inner Silver Pit, English Channel, Oyster Ground) and tidal sandbanks (Dutch Banks, Zeeland Banks, Flemish Banks, Hinder Banks, Thames Banks and Norfolk Banks) are also indicated; (b) Pre-Holocene Geological map of the Southern Bight, compiled by the BGS (2000). The Pleistocene ice extents by Clark et al. (2022), Eaton et al. (2020) and Hijma et al. (2012) are also shown.

Channel in the south. The – 40 m contour line delineates a crescent-shaped deep, curving southwestward towards the Dover Strait (Figure 1a). The Southern Bight area is covered by marine sands and gravel up to 5 m thick on the UK Continental Shelf and reaching up to 20 m on the Dutch Continental Shelf (Balson et al., 1991; Cameron et al., 1984b). Locally, these sediments are organised into extensive Holocene tidal sandbanks: the Dutch Banks, Zeeland Banks, Flemish Banks, Hinder Banks, Thames Banks and the Norfolk Banks (Balson et al., 1991; Balson & D'Olier, 1990; Johnson et al., 1982) (Figure 1a). The Axial Channel axis is located in between these sand ridge fields. It has an average depth of 50 m below lowest astronomical tide (LAT), locally down to 65 m, and is widest in the centre (around 55 km), between 52° N and 52°30' N, narrowing to ~10 km in the north and south (Figure 1a). The western margin of the Axial Channel consists of a plateau, here referred to as the UK Plateau. The (pre-) Quaternary geology of the southern North Sea has been compiled and published by the British Geological Survey (BGS, 2000) (Figure 1b). Across the Southern Bight, between East Anglia (UK) and Zeeland (the Netherlands), a clear geological change is observed (Figure 1b). In the north, thick packages of Quaternary sediments ranging from the Early to Late Pleistocene dominate (for individual formations see Figure 1b). In contrast, pre-Quaternary formations (Eocene-Paleocene and Cretaceous) are found close to the seabed in the south. Here, Quaternary sediments are discontinuous, concentrated in banks or depressions and valley incisions cut into the Paleogene (Balson & D'Olier, 1990; Cameron et al., 1984a; Harrison & Hopson, 1991; Laban et al., 1992) (Figure 1b).

3. Methodology

To map the present-day geomorphology of the Axial Channel, the EMODnet Digital Bathymetry data (EMODnet Bathymetry Consortium, 2022) were used. The current digital terrain model (DTM) is available as a gridded raster of c. 115 m with water depths in m below LAT. Additionally, bathymetry blocks from the UK Admiralty Seabed Mapping Service (United Kingdom Hydrographic Office (UKHO) data) were compiled for most of the (south-)western part of the study area. Each block has a different horizontal resolution, ranging from 1 up to 4 m. The blocks were merged, applying the same parameters as the original raster blocks, but reducing the horizontal resolution to a common cell size of 4 m. Subsequently, the EMODnet DTM and UKHO bathymetry blocks were incorporated into ArcGIS Pro and transformed to reference system UTM Zone 31N (WGS84). The mapping was performed on the lower resolution DTM and on the higher resolution UKHO data where available and all depths are expressed in m below sea level. Traditional hillshades (including at 0°, 90°, 180°, 270° azimuth and 20° altitude, no vertical exaggeration) and multidirectional hillshades (no scaling) were created. Slope angles were measured based on a slope map created from the EMODnet DTM. The term 'escarpment' is used to describe features with a slope drop of ≥ 10 m. For drops < 10 m, the term 'slope break' is used. Geomorphological features were subsequently delineated as polyline features and polygons, and their statistics (i.e. mean length, orientation) calculated in the ArcGIS Pro software. In places where too many features were present, the area was delineated and a subsection of features was selected to calculate their statistics. The result of the delineated features (and feature areas) is shown on the Main Map. Topographic profiles were created by adding the EMODnet DTM and merged UKHO blocks as elevation source layers.

4. Geomorphological features

4.1. The Axial Channel

The full Axial Channel's extent is only partly expressed in the bathymetry, with its northern and southern limits masked by extensive tidal sandbanks and wave fields (Figure 2a). In the north, the Axial Channel is discernible only to ~53° N, beyond which it becomes buried beneath the Norfolk and Dutch Banks (Figure 2a). There is no bathymetric

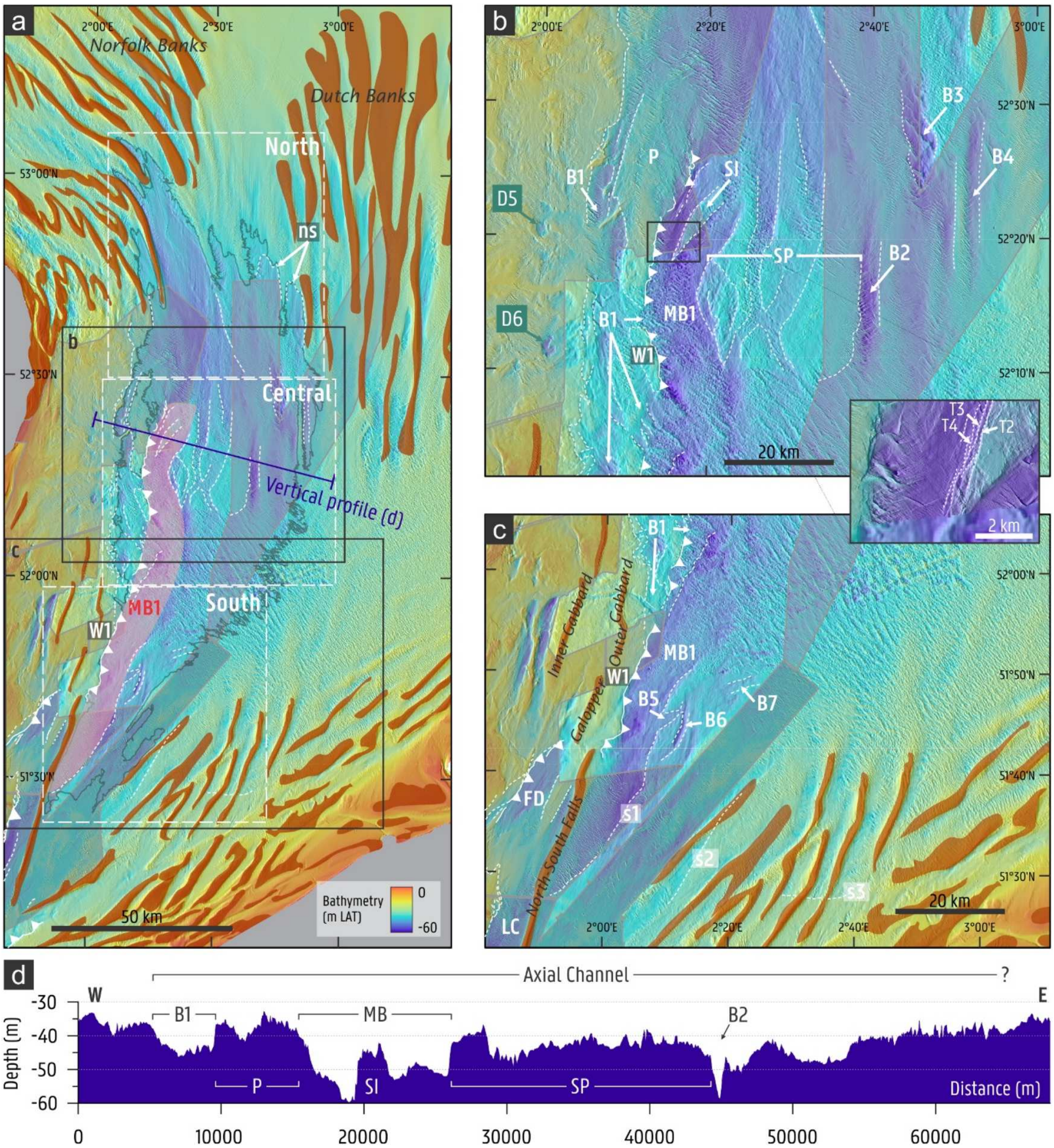

Figure 2. (a) Bathymetric map of the Axial Channel (map location indicated on Figure 1a) indicating the northern, central and southern sectors of the Axial Channel (white boxes). UKHO bathymetry data are indicated by the more shaded blocks. Breaks in slope are indicated by white dotted lines, escarpments by a white line with triangles. Tidal sandbanks are shown in brown and the main branch of the Axial Channel is overlain by red shading; (b) Zoom of the central Axial Channel sector; (c) Zoom of the southern Axial Channel sector. (d) Vertical profile over the central Axial Channel, location of the profile is shown by a dark blue line in (a). B1-7: side branches, D5-6: depressions, FD: Falls Deep, LC: Lobourg Channel, MB1: main branch, P: plateau, s1-3: slope-breaks, SI: streamlined island, SP: streamlined plateau, W1: western escarpment.

evidence of a northward connection to the Oyster Ground or Inner Silver Pit (Figure 1a, Figure 2a). Along the northwestern margin of the Axial Channel, two gentle slopes (< 1°) occur just west of the Dutch sandbanks (ns; Figure 2a). In its central and southern sector, the Axial Channel comprises a main branch (MB1) and multiple side branches (Figure 2a). The main branch reaches depths of up to 65 m and follows an s-shaped, meandering course (Figure 2b, d). Its western margin is defined by an escarpment (W1) that extends intermittently over ~150 km, from the central sector to the southern end of the channel (Figure 2a). This escarpment, with an average slope of ~4°, marks the eastern boundary of the UK Plateau, which itself dips gradually northeastward. The plateau sits at 10-15 m in the offshore Thames Estuary, 25-30 m near the Suffolk and Essex Coast, and ~35 m along its eastern margin (Figure 1a). Given that the main branch reaches 65 m depth, the height difference between the Axial Channel and the UK Platform is up to 30 m.

In the central sector of the main branch, a teardrop-shaped streamlined island (SI) crops out, with its apex oriented southwestward (Figure 2b). The feature is 10 km long and 2.5 km wide, with an average surface depth of 45.5 m, which is ~15 m above the base of the main branch on its western side and ~10 m on its eastern side (Figure 2d). At least six terraces are preserved along the western slope of the streamlined island (Figure 2b inset). The height difference between the second (T2) and third (T3) terrace is 7 m, while that between T3 and T4 is 5.5 m; the remaining terraces show a relief of 1-3 m. The eastern flank of the streamlined island forms a gradual slope of ~2° (Figure 2b inset).

Side branch B1 is separated from the main branch MB1 by a shallow plateau (P; Figure 2b, d). This side branch extends for ~70 km and curves broadly parallel to the main branch. Connection to the main branch occurs south of plateau P via three branches (white arrows in Figure 2b, c), creating interruptions in the otherwise continuous western escarpment W1. With depths reaching to 50 m, side branch B1 is shallower than the main branch of the Axial Channel.

East of the main branch, a streamlined plateau (SP) is present, preserving evidence of multiple – though less clearly defined – incisional stages resembling an anastomosing fluvial braid plain (Figure 2b, d). The plateau measures ~25 km in width and up to 20 km in length, with an average surface depth of 42 m. Its eastern and western flanks are well defined, reaching slopes of up to 3° (Figure 2b, d). The plateau is bounded on the east by side branch B2, which attains depths of 62 m. Northeast of B2, two additional, but shallower side branches, B3 and B4, occur at depths of 57 and 52 m, respectively. The eastern slope of B4 defines the easternmost margin of the Axial Channel, beyond which the morphology is obscured by the Dutch Banks (Figure 2b).

In the southern sector of the Axial Channel, the main branch MB1 is accompanied by three side branches (B5, B6, B7; Figure 2c). Two of these (B5, B7) are relatively shallow, reaching a depth of 46 m, whereas B6 is deeper at 54 m. Only B5 connects to the main branch. The western escarpment (W1) remains a prominent morphological feature; however, the Hinder and Flemish Banks prevent identification of a distinct eastern channel margin. A slope break of up to 2° occurs at the eastern edge of the main branch at 44 m (s1; Figure 2c). Further southeast, two additional slope breaks occur: one with a gradient of < 1° at a water depth of 35 m (s2; Figure 2c), and another with an E-W orientation and slope of < 1.5° at a depth of 30 m (s3; Figure 2c). The latter has previously been mapped by De Clercq et al. (2016).

At the southern end of the Axial Channel, the western escarpment is displaced ~8 km at the location of a depression, here termed Falls Deep (FD; Figure 2c). This feature reaches a depth of 49 m, extends ~20 km in length and is less than 5 km wide. South of Falls Deep, the escarpment is again displaced (~18 km southeastwards), marking the northern limit of the Lobourg Channel (Figure 2a, Figure 3a).

4.2. The Lobourg Channel

In the south, the Axial Channel is separated from the Lobourg Channel by the North-South Falls tidal sandbank (Figure 2c, Figure 3a). The southern Axial Channel is < 60 m deep, whereas the Lobourg Channel reaches depths to 65 m (Figure 3a).

The main branch (MB2) of the Lobourg Channel (Figure 3a, b) is bounded to the west by a continuous, 50 km-long escarpment (W2) with slopes up to 5°. Within this branch, two teardrop-shaped, streamlined islands (~1 km wide, ~3 km long) occur, with their apex pointing southwestward (SI; Figure 3c).

On the eastern margin, four slope breaks and three prominent escarpments are present (s1-4, E1-3; Figure 3b, c). The first escarpment (E1), with a slope of 1.5-2°, forms the western boundary of a streamlined plateau (SP: Figure 3c). This plateau is ~5 km wide, ~20 km long and separates the side branch (SB) from the main branch. The second escarpment, with a slope of 2.5-3°, defines the eastern slope of the side branch. The third escarpment, farther south in the Dover Strait, also has a slope of 2.5-3°.

4.3. Smaller channels connected to the Axial and Lobourg Channels

Several smaller channels connect to the Axial and Lobourg Channels and related geomorphological features (e.g. elongated deeps, see 4.4). Most occur

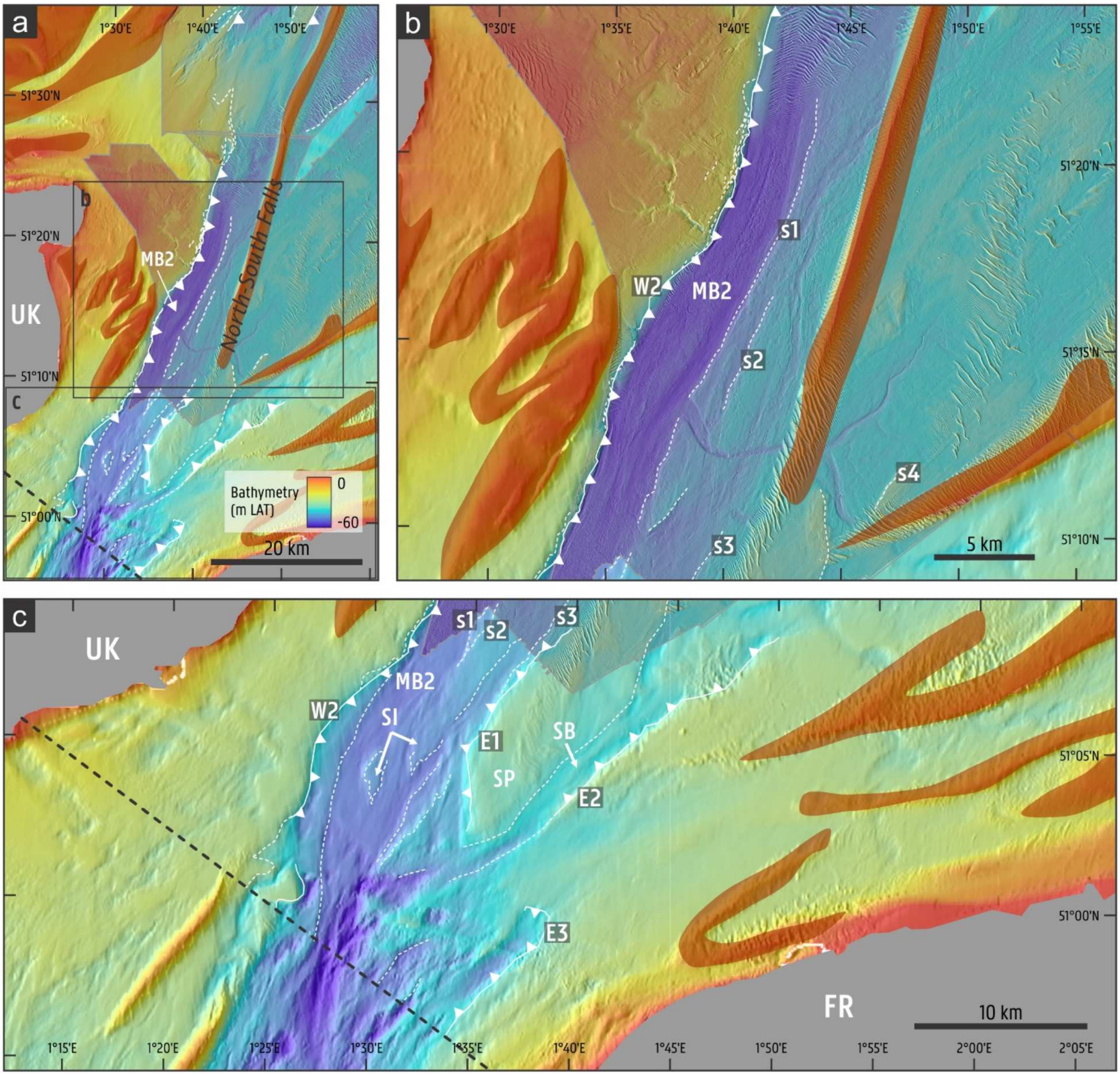

Figure 3. (a) Bathymetric map of the Lobourg Channel, map location indicated on Figure 1a. UKHO bathymetry data are indicated by the more shaded blocks. Breaks in slope are indicated by white dotted lines, escarpments by a white line with triangles. Tidal sandbanks are shown in brown; (b) Zoom of the northern Lobourg Channel valley; (c) Zoom of the southern Lobourg Channel valley. MB2: main branch, SB: side branch, W2: western escarpment, E1-3: eastern escarpments, SP: streamlined plateau, SI: streamlined island, s1-4: slope-breaks.

along the western margin, except for two systems on the eastern margin (Figure 4a). Channel depths are reported relative to the surrounding bathymetry.

In the north of the study area, just off the Norfolk coast (UK), a > 30 km-long (palaeo-)channel is preserved on the UK Plateau (p1; Figure 4b). Previously described by Limpenny et al. (2011) and Tizzard et al. (2014), this meandering channel is up to 2 km wide and 8 m deep. Small-scale linear bedforms are abundant and point bars occur in the two widest meander bends (PB; Figure 4b). At its east-west bend, a streamlined island is present with its apex pointing southeastward (SI; Figure 4b). Channel remnants extend eastward towards the western side branch of the Axial Channel (B1; Figure 4b). Northeast of the bend, linear bedforms suggest the presence of a tributary channel system (Figure 4b, encircled area), while farther northeast, a second channel system is preserved. This latter channel is ~7 km long, ~1.5 km wide, and incised 2 m into the UK Plateau (Figure 4b).

Further south on the UK Plateau, two channel systems are present (p3-4; Figure 4c), which were previously described by Dix and Sturt (2011), Henriet and Moor (1989) and Sturt and Dix (2009). P3 is a narrow, east-west-oriented channel, ~20 km long, ~400 m wide and only a few metres deep (Figure 4c). Two north-south tributaries join its northern flank: a ~5 km-long tributary at its eastern end and a shorter, ~1 km-long tributary at the west. The channel shows no connection to the western side branch (B1; Figures

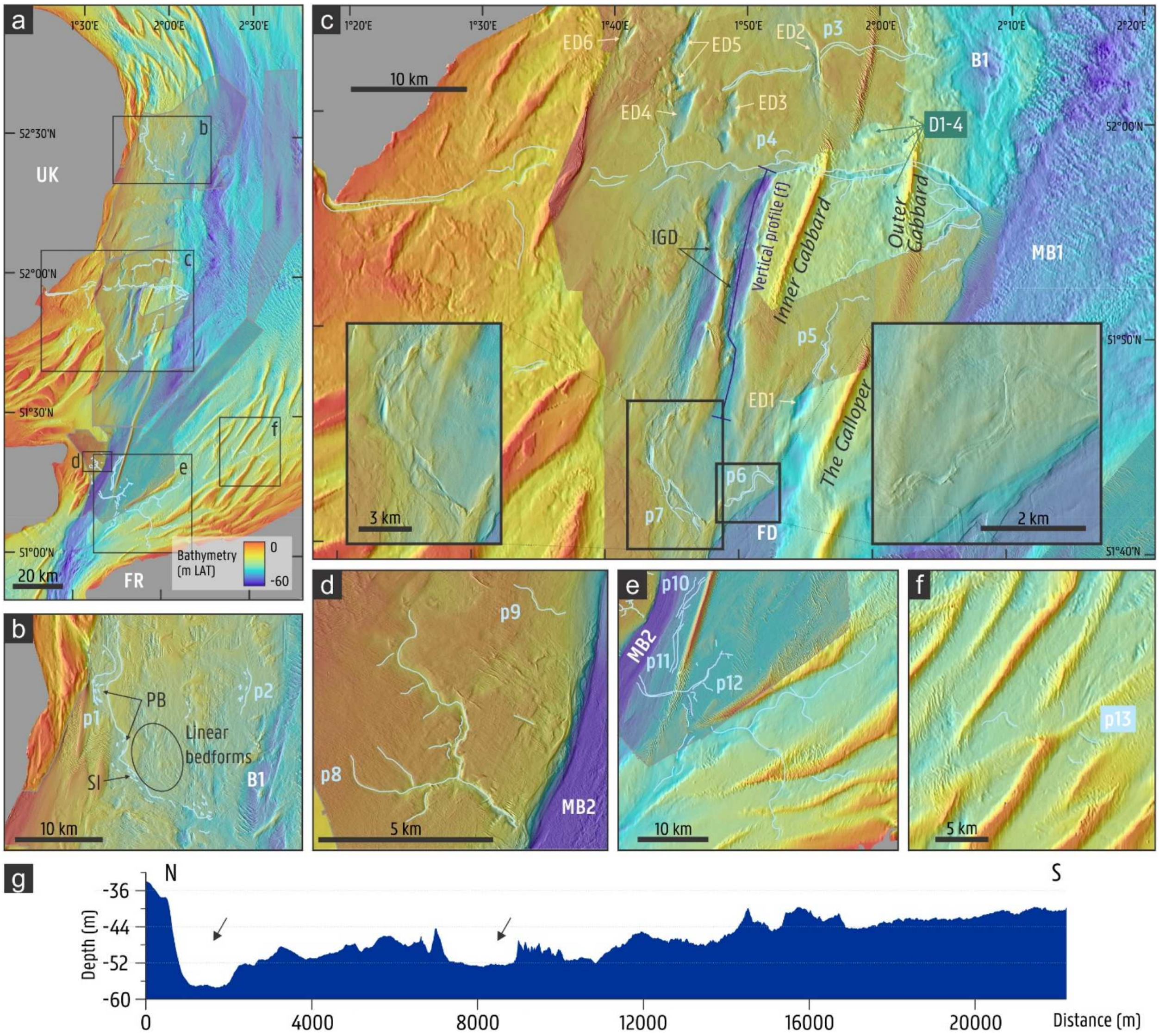

Figure 4. (a) Palaeochannels connected to the Axial Channel and Lobourg Channel (indicated in light blue lines). (b) Zoom of palaeochannels p1 and p2; (c) Zoom of palaeochannels p4-7, as well as Inner Gabbard Deeps, elongated deeps and depressions on the UK Plateau; (d) Zoom of palaeochannels p8 and p9; (e) Zoom of palaeochannels p10-12; (f) Zoom of palaeochannel p13; (g) Vertical profile over the eastern Inner Gabbard Deep, location of the profile is shown by a dark blue line in (c), arrows indicate overdeepend areas. UKHO bathymetry data are indicated by the more shaded blocks. B1: western side branch of Axial Channel, D1-4: depressions, ED1-6: Elongated deeps, IGD: Inner Gabbard Deep, MB1: main branch of Axial Channel, MB2: main branch of Lobourg Channel, PB: point bar, SI: streamlined island.

4c), the Axial Channel to the east or the elongated deeps to the west (see 4.4). Instead, it is truncated by a north-south oriented elongated deep (see 4.4; Figure 4c). Approximately 10 km to the south, channel p4 extends from the mainland towards the western escarpment of the Axial Channel (Figure 4c). Although partly obscured by the Inner and Outer Gabbard sandbanks, the system displays a clear, low-sinuous main channel with multiple tributaries on its southern bank. The main channel is ~50 km long, ~500 m wide, with banks up to 10 m above the channel floor and slopes of ~3°. It widens towards the eastern margin of the UK Plateau, reaching a width of ~2 km at its mouth, where it joins the main branch of the Axial Channel (Figure 4c).

Three smaller channels are present further south on the UK Plateau (p5-7; Figure 4c). p5 is a north-south-oriented, low-sinuous channel, ~8 km long, that has been previously described by Sturt and Dix (2009) and Dix and Sturt (2011). It connects at its southern end to the elongated deep west of the Galloper sandbank (see 4.4; Figure 4c) but shows no connection to the tributaries of p4 to the north (Figure 4c). South of the western Inner Gabbard Deep (see 4.4), channel p7 extends ~15 km southeastward. This complex system displays braided channels and overdeepend sections, reaching depths of up to 12 m, and widths of up to 1 km (Figure 4c inset). While connected to the western Inner Gabbard Deep, no clear connection to the Falls Deep (FD; Figure 4c) is observed. Approximately 2.5 km to the northeast, on the UK Plateau, a meandering channel (p6) extends for ~5 km with widths between 80 and 320 m (Figure 4c inset). It appears isolated from p7, and any connection to FD remains uncertain due to a lack of high-resolution bathymetry (Figure 4c).

On the western margin of the Lobourg Channel, a small dendritic channel system is present (p8; Figure 4d). Its sinuous main branch runs NW-SE for 8.8 km and is joined by multiple tributaries. The channel base lies ~6 m below the surrounding plateau. There is no distinct mouth or connection to the Lobourg Channel; instead, the system terminates just before a > 20 m drop into the Lobourg Channel floor. North of this system, a single sinuous channel (p9) extends for ~2 km with a depth of ~2 m. It also lacks any visible connection to the Lobourg Channel (Figure 4d).

Parallel to the main branch of the Lobourg Channel, east of slopes s1 and s2 (Figure 3b), two additional channel systems are present (p10-11; Figure 3b, Figure 4e). The northernmost channel (p10) is ~6 km long and up to 700 m wide. It incises and overprints channel p11, which is ~9 km long and up to 600 m wide. Depths reach ~3 m in p10 and ~4 m in p11. Channel p10 can be traced southwards into the Lobourg Channel, while to the north it disappears beneath the North-South Falls sandbank. Channel p11 displays a braid plain to the north, also partly buried beneath the sandbank, but shows no connection southwards to either the Lobourg Channel or channel system p12.

Approximately 3 km further south, an extensive, intricate channel system (p12) is present, partly buried beneath the Flemish Banks (Figure 4a, e), previously described by García-Moreno et al., (2019). Two branches can be discerned – one originating at the French coast and another draining NE-SW from the Belgian Continental Shelf – that converge into an E-W channel, ultimately connecting to the Lobourg Channel. A southern tributary extends southwestward towards the English Channel. In total, the system comprises > 60 km of channels, with depths reaching up to 10 m.

Additional remnants are exposed or partly buried beneath the Flemish Banks, representing a larger, now fragmented system (p13; Figure 4f).

4.4. Deeps and depressions on the UK Plateau

Two parallel, elongated deeps occur on the UK Plateau, west of the Inner Gabbard sandbank (Inner Gabbard Deeps, IGD; Figure 4c). Previously described by Sturt and Dix (2009) and Dix and Sturt (2011), these NNE-SSW trending features are 21.6 km (eastern IGD) and 16.8 km (western IGD) long, with widths up to 2.2 km. Maximum depths are located at their northern margins, reaching 24 m in the eastern and 21 m in the western deep, with corresponding slopes of ~7° and ~6.5°. Both deeps shallow southwards, their undulating floors containing two distinct overdeepend sections (Figure 4c, g).

Five similar, albeit smaller elongated deeps (ED2-6) occur on the UK Plateau north of the IGDs; a sixth deep (ED1) is located east of the IGDs. Although previously mapped (Dix & Sturt, 2011; Sturt & Dix, 2009), their geomorphology has not yet been described. These roughly N-S oriented features average ~4 km in length, ~900 m in width and 8-18 m in depth. All exhibit an elongated form, except the westernmost, heart-shaped deep (ED6, Figure 4c). The deep located ~3 km north of the Inner Gabbard sandbank (ED2, Figure 4c) differs in showing shallow slopes at both ends and truncating an E-W channel (p3; Figure 4c; see 4.3). Since 2015, this area is designated as an aggregates site, with associated disturbance features obscuring the original morphology.

Between the Inner and Outer Gabbard sandbanks, on the flanks of channel p4, four irregular depressions are present (D1-4; Figure 4c). These features are 5-10 m deep and up to 2.5 km wide. On the southern flank, one depression appears connected to p4 by a ~900 m long, shallow (~2 m deep) channel. The deeps on the northern flank show no clear connection to either p4 or p3. Further north on the UK Plateau, two circular depressions (D5-6; Figure 2b) occur, each 1.5-2 km wide and ~15 m deep.

4.5. Linear features in the Southern Bight

On the UK Plateau, parallel to the western side branch of the Axial Channel (B1), linear ridges occur (Figure 5a, b). Channel p1 incises these ridges (Figure 5a). The ridges exhibit a parallel, near N-S orientation (mean: 190°) and range in length from 100 m to 2 km. Intervening scour pits reach depths of up to 10 m and widths of up to 450 m. Smaller-scale linear features with a mean length of 350 m and a comparable orientation are superimposed (mean: 195°; Figure 5b). The features are situated in or near aggregates sites, where seabed morphology may have been modified by extraction activities.

At the base of the main branch of the Lobourg Channel (MB2), similar linear ridges and scour pits are present, though at smaller scale (Figure 5a, f). The ridges average 244 m in length and 10-20 m in width, with a mean orientation of 210°. Intervening scour pits reach depths of up to 2 m and widths of 20-60 m. These features are further superimposed by smaller linear features, averaging 70 m in length and sharing a comparable orientation (mean: 212°; Figure 5a, f).

Smaller-scale linear features are also present on the plateau (P) and streamlined island (SI) in the central sector of the Axial Channel (Figure 5a, c), east of the Kentish Knock sandbank (Figure 5a, d) and at the dendritic channel p8 (Figure 5a, e). Their mean lengths are 200, 566 and 240 m, with mean

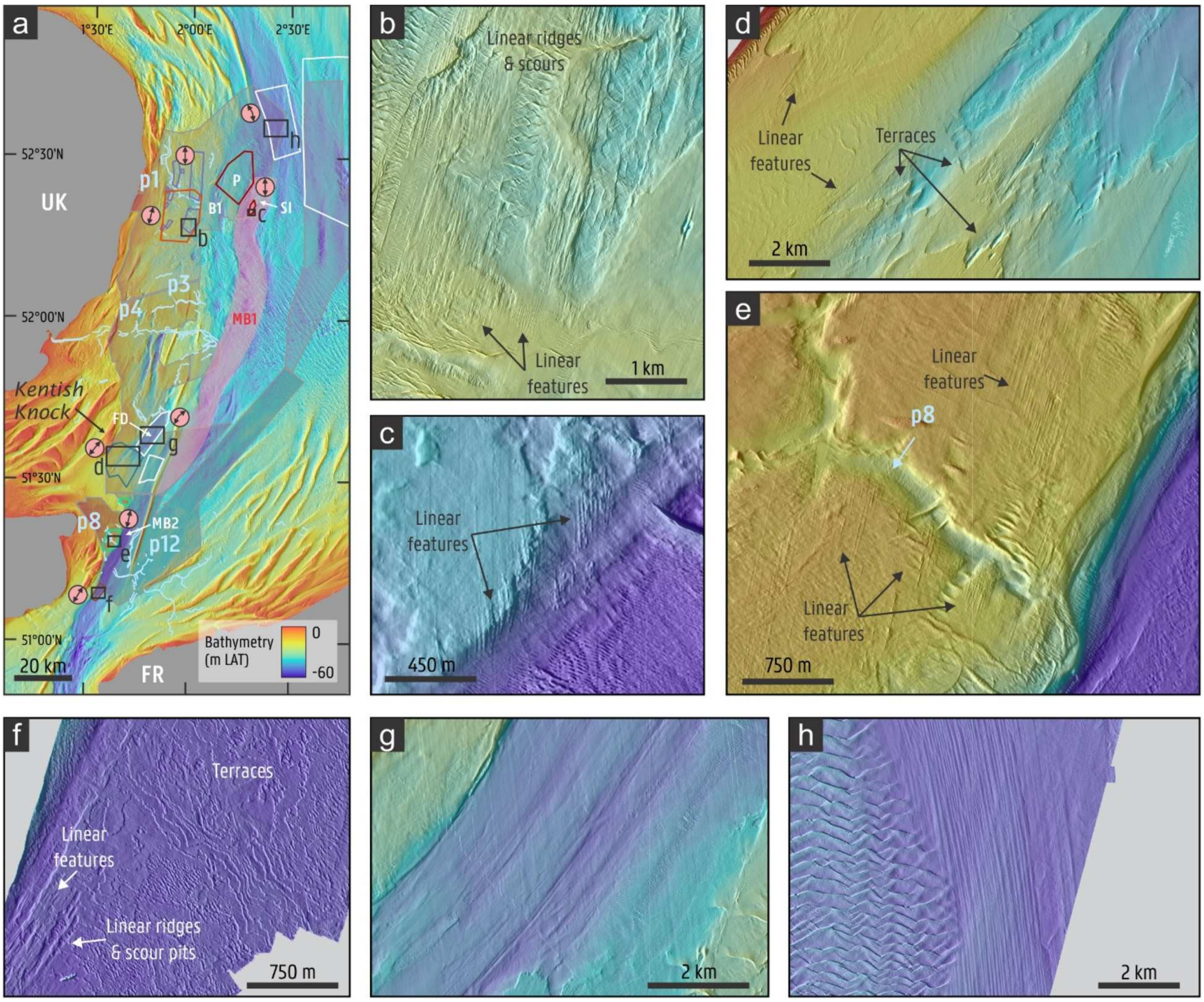

Figure 5. (a) Linear feature areas in the Southern Bight (indicated by different coloured polygons), with the orientation of the linear features indicated by pink encircled arrows. UKHO bathymetry data are indicated by the more shaded blocks; (b) Linear ridges and scour pits on the UK Plateau (a: purple polygons), superimposed by linear features (a: orange polygon); (c) Linear features upstanding from the seabed on the plateau and streamlined island in the central Axial Channel (a: dark red polygons); (d) Linear features in a step-like terraced landscape in the Falls Deep (a: blue polygon); (e) Linear features upstanding from the seabed at the dendritic palaeochannel p8 (a: light green polygons); (f) Linear ridges and scour pits, superimposed by linear features, in a step like terraced landscape, at the base of the main branch of the Lobourg Channel (a: brown polygon); (g, h) Linear features at the base of the Axial Channel valley and Falls Deep (a: white polygons). B1: western side branch of Axial Channel, FD: Falls Deep, MB1: main branch of Axial Channel, MB2: main branch of Lobourg Channel, p1, 3, 4, 8, 12: smaller channels connecting to the Axial and Lobourg Channels, P: plateau, SI: streamlined island.

orientations of 179°, 219° and 192°, respectively. It remains unclear whether these features are depositional or represent erosional remnants protruding the surrounding seabed.

Another type of linear feature occurs at the base of Falls Deep (FD), west of the North-South Falls sandbank, and in the Axial Channel (Figure 5a, white boxes). The largest lineations are found in the Axial Channel, particularly towards the Dutch Banks, where they reach 2-3 km in length and 70-200 m in width (Figure 5h). These features show slight curvature, following the channel axis (Figure 5h). Comparable lineations at the base of Falls Deep are up to five times shorter (~600 m) but exhibit wider spacing (~100 m compared to ~50 m in the Axial Channel; Figure 5g).

Southwest of Falls Deep and at the base of the main branch of the Lobourg Channel a terraced, step-like morphology is observed (Figure 5d, f). Terrace dimensions vary: those at Falls Deep show height differences of up to 15 m, whereas in the Lobourg Channel they do not exceed 1 m.

4.6. Depositional bedforms: sand waves and sand ridges

The occurrence of sand waves in the Southern Bight has been described by e.g. Van Veen (1935); McCave (1971) and Van Der Veen et al. (2006). In this study, six distinct sand-wave fields are described in the Southern Bight (Figure 6a). Sand waves in areas 3–6 share a NW-SE orientation (~127°; Figure 6b). Area

1 is unique compared to the other areas, as it displays symmetrical sand waves with a contrasting orientation and associated larger sand ridges. The ridges have a mean orientation of 143°, while the sand waves are nearly perpendicular to them (~72° and 80°; Figure 6b). In area 2, two orientations are present: sand waves at the base of the Axial Channel trend ~93°, perpendicular to the curvature of the main branch, whereas those on the streamlined plateau align with the general NW-SE orientation (~123°; Figure 6b).

4.7. Depositional bedforms: transverse ridges

Within the western side branch of the Axial Channel (B1; Figure 2b), four ridges are present: one crossing the side branch (R1), one isolated within the side branch (R2) and two along its western margin (R3-R4; Figure 6c). Ridges R1-R3 were previously described by Limpenny et al. (2011). Despite differences in shape and size, all share an ENE-WSW orientation (~50-60°), contrasting with the N-S orientation of the sandbanks and the NW-SE orientation of the sand waves (see 4.6). Ridge R1, the southernmost, is narrow and elongated (4.3 km long, ≤ 600 m wide, 15 m high). Its northeastern end is dome-shaped with smooth, near-symmetrical slopes (~3°; Figure 6c, d), while the southwestern end has a crest with a steeper NW slope (4°) and a terraced SE slope. Ridge R2 is smaller (1.6 km long, 800 m wide, 13 m high), more circular and contains a summit depression. Its western slope is the steepest (up to 6°), contrasting with the terraced SE slopes (Figure 6d). Ridge R3, situated on the margin of the side branch, is the largest (3.5 km long, > 1 km wide, 17 m high). It has a steep southern (up to 7°) and less steep northern slope (up to 4°) and a plateau-like crest bearing small sand waves, with a similar orientation as the ridge itself, to the north (Figure 6c, d). A N-S oriented, S-shaped ridge may represent its

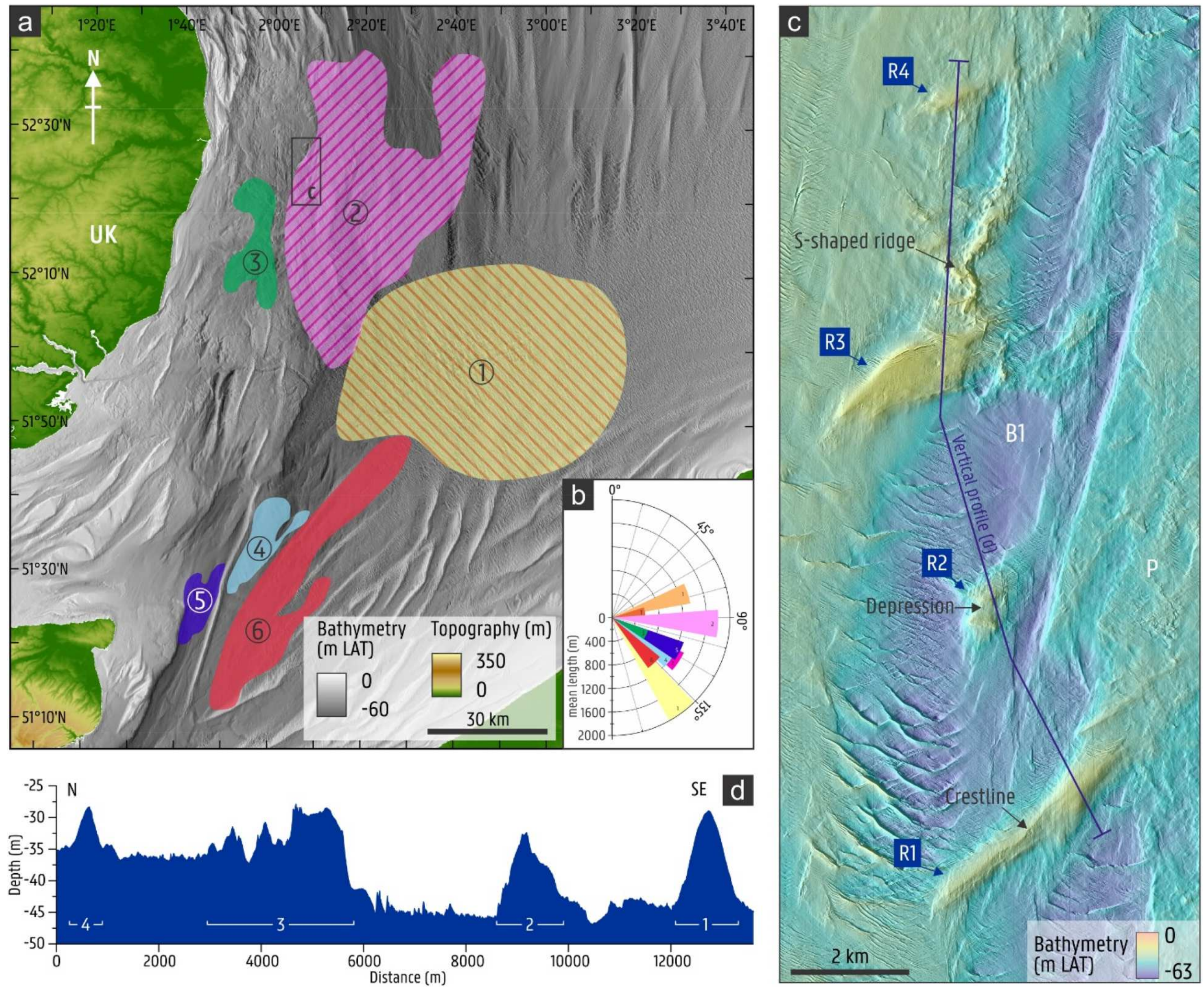

Figure 6. Depositional bedforms in the Southern Bight: (a) Sand wave field areas indicated by encircled numbers 1-6; (b) Rose plot with the mean orientation and mean length of the different sand waves. Area 1: yellow, light orange and dark orange, Area 2: dark and light pink, Area 3: green, Area 4: light blue, Area 5: dark blue, Area 6: red; (c) Transverse ridges (R1-4), west of plateau (P) and crossing the western side branch (B1) of the Axial Channel; (d) Vertical profile over the transverse ridges, location of the profile is shown by a dark blue line in (c).

northern extension, but this is uncertain (Figure 6c). Ridge R4, the northernmost, is the smallest (1.2 km long, 700 m wide and 7 m high) with gentle, symmetrical slopes (~2°; Figure 6c, d).

5. Interpretation and conclusions

The geomorphological mapping of the Southern Bight provides a first step towards reconstructing the evolution of the Axial and Lobourg Channels. Based on cross-cutting and erosional relationships of the mapped features a relative chronological framework is established, while their morphology allows for a tentative depositional and environmental interpretation. These interpretations are illustrated in Figure 7. In the absence of absolute chronological constraints, however, this relative timeline cannot yet be placed within the broader Pleistocene evolution of the southern North Sea Basin.

The majority of geomorphological features identified on the UK Plateau – including the Inner Gabbard Deeps (IGDs), elongated deeps (ED1-6) and Falls Deep (FD) – were previously described and interpreted by Sturt and Dix (2009). Based on morphological similarities, we here follow the interpretation of Sturt and Dix (2009) and suggest that these features are (shallow) subglacial tunnel valleys (e.g. Huuse & Lykke-Andersen, 2000; Kristensen et al., 2007; Ottesen et al., 2020; Praeg, 2003; see also discussion in Sturt & Dix, 2009). The presence of such subglacial features indicates a glacially influenced landscape. This interpretation is further supported by the morphology of the – in this study identified – depressions (especially D5-6, Figure 2b) as well as the parallel linear ridges and scour pits north of the IGDs (purple polygons Figure 5a) which resemble subglacial landforms such as kettle holes (e.g. Bennett & Glasser, 2009; Maizels, 1977) and mega-scale glacial lineations (MSGL's; e.g. Spagnolo et al., 2014), respectively. On the same UK-Plateau, channels p3 and p4 provide evidence for a fluvial landscape, representing a different, terrestrial phase. This phase predates the glacial phase, as demonstrated by the erosional relationship between p3-4 and the IGDs (see 4.4; see also discussion in Sturt & Dix, 2009).

The western escarpment (W1) delineates the margin of the UK Plateau, showing the erosional relationship between the plateau and the younger, incised main branch (MB1). Following the earlier phases, a third, more prolonged terrestrial phase is inferred from the fluvially shaped main branch of the Axial Channel (MB1), its side branches (B1-7) and associated streamlined landforms (SI, SP). This phase may include base level changes and an eastward migration of the Axial Channel, expressed by terrace formation on the streamlined island (SI) and the presence of an anastomosing fluvial braid plain on the streamlined plateau (SP). Although the origin of the transverse ridges R1-4 is unclear, they may be associated with the eastward migration of the system. We tentatively interpret these ridges as (river) dunes formed after the western side branch (B1) was abandoned. The (re-)activation of several channels (p1-7, p13) is

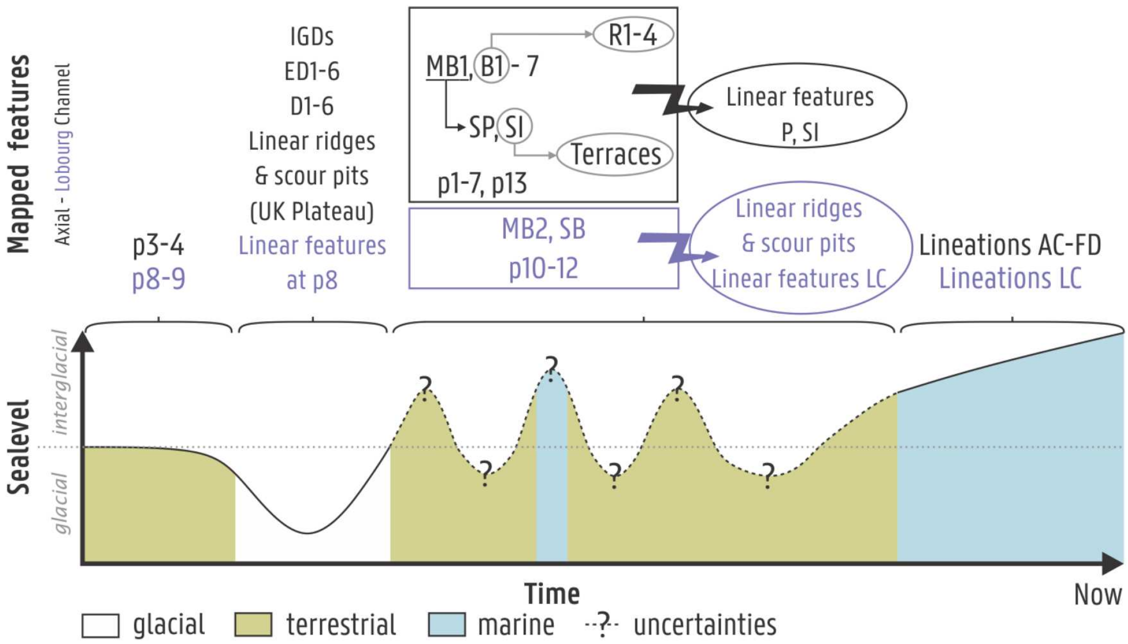

Figure 7. Schematic representation of the proposed evolution of the Axial (black) and Lobourg (purple) Channels, including relative chronology and simplified environmental interpretation. There are still many uncertainties due to the absence of absolute chronological constraints (question marks and dotted lined curve). AC: Axial Channel, B1-7: side branches of the Axial Channel, D1-6: depressions, ED1-6: elongated deeps, FD: Falls Deep, IGDs: Inner Gabbard Deeps, LC: Lobourg Channel, MB1: main branch Axial Channel, MB2: main branch Lobourg Channel, p1-13: channels connected to the Axial and Lobourg Channels, P: plateau, R1-4: transverse ridges, SB: side branch of the Lobourg Channel, SI: streamlined island; SP: streamlined plateau.

tentatively interpreted to indicate additional or renewed fluvial activity.

Linear features preserved on the plateau (P) and streamlined island (SI) may instead reflect a short-lived event. Depending on whether these features are depositional in nature or represent erosional remnants protruding the surrounding seabed, a different formational setting is inferred. In the latter case, they could be associated with a release of water from the north-northwest, potentially involving catastrophic flooding responsible for the preserved lineations. The timing of this short-lived phase relative to the prolonged terrestrial phase is uncertain, although it must postdate the formation of both the plateau (P) and streamlined island (SI).

The youngest geomorphological features are depositional, reflecting full marine conditions. These include sand waves and ridges, as well as furrows on the floors of the Axial Channel and Falls Deep, formed by tidal currents. The marine regime of the Outer Thames Estuary may also account for the linear features and terraces observed east of the Kentish Knock sandbank. The Lobourg Channel shows a parallel evolution, as the mapped features therein also reflect a glacio-fluvial imprint followed by a final marine phase (Figure 7).

Within the Pleistocene context of the southern North Sea, these phases predominantly reflect a non-inundated, terrestrial landscape. The interpreted glacial and fluvial phases are therefore more likely associated with glacial rather than interglacial periods. Nevertheless, as this study only shows the mapping of seabed expression of preserved geomorphological features, sub-bottom profiling and ground-truth data are required to fully resolve their extent, formative processes, and potential links to (inter)glacial periods.

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Data availability statement

The data that support the findings of this study are available through EMODnet Bathymetry and through the United Kingdom Hydrographic Office. These data were derived from the following resources available in the public domain: https://emodnet.ec.europa.eu/geoviewer/; https://seabed.admiralty.co.uk/. The data that was produced of this study, i.e. GIS shapefiles, are available in the Integrated Marine Information System (IMIS) at https://doi.org/10.14284/780.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Software

ArcGIS Pro 3.5.2 © 2025 Esri Inc.

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