

Multi-criteria characterisation of buried incised valleys and late Quaternary landscape evolution south of Dogger Bank, southern North Sea

Despina Kyriakoudi^{a,b,*}, Marc De Batist^b, Morgan Vervoort^{a,b}, Thomas Mestdagh^a,
Tine Missiaen^a, Ruth Plets^a

^a Flanders Marine Institute (VLIZ), Jacobsenstraat 1, Ostend, 8400, Belgium

^b Renard Centre of Marine Geology (RCMG) - Department of Geology, Ghent University, Krijgslaan 281, Ghent, 9000, Belgium

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ABSTRACT

Buried incised valleys are prominent features in the southern North Sea that preserve a detailed record of Quaternary landscape evolution, yet their origin, timing and infill remain poorly documented. Their presence provides key evidence for reconstructing the paleolandscape and for understanding the role of glacial-interglacial processes in both valley formation and regional evolution. Here, we integrate 2D high-resolution acoustic reflection data with extant 3D seismic data and multivariable morphometric clustering to map and classify a dense network of buried incisions south of Dogger Bank. Three morphostratigraphic generations of incised valleys are identified, each reflecting distinct erosional and depositional processes, with their chronology remaining relative and constrained by seismo-stratigraphic correlation. The oldest, Generation 1, forms linear V-shaped valleys interpreted as Weichselian subglacial channel systems formed by meltwater erosion, probably during a pre-Last Glacial Maximum (LGM) glaciation. Generation 2 comprises a U-shaped depression carved by direct ice-marginal processes probably at the LGM, and likely infilled with glaciolacustrine sediments. The youngest, Generation 3 forms a complex network of sinuous, branching channels that locally reoccupy older incisions developed under fluvial, estuarine or tidal conditions upon deglaciation during the late Weichselian to early Holocene. Together, these features record repeated phases of erosion and infill, progressing from subglacial to ice-marginal and finally subaerial settings, defining a three-stage landscape evolution from the Weichselian glaciation to the Holocene. The integrated approach applied here enables detailed mapping and an objective classification of buried incisions, revealing a more intricate valley network than previously documented. It demonstrates that landscape transformation in the southern North Sea was controlled by complex subglacial conditions, meltwater routing, ice-margin dynamics and post-glacial drainage reorganisation.

1. Introduction

Incised valleys are prominent geomorphological features in the stratigraphic record (Amorosi et al., 2023; Wagoner et al., 1990) that hold invaluable information on the erosional and depositional processes that shaped a region (Blum et al., 2013; Dubey et al., 2019). Such incised valleys preserved within the Quaternary record of the North Sea, spanning Marine Isotope Stages (MIS) 12-2 (e.g., Cameron et al., 1987; Ottesen et al., 2020; van der Vegt et al., 2012; Wingfield, 1990), although lithological and chronological data on their infill remain scarce (Prins and Andresen, 2019).

During the middle to late Quaternary, the southern North Sea region was influenced by three major glaciations – the Elsterian (MIS 12, ca.

480-410 ka), the Saalian (MIS 10-6, ca. 370-135 ka) and the Weichselian (MIS 5d-2, ca. 115-11.7 ka) — and three intervening interglacials – the Holsteinian (MIS 11, ca. 410-370 ka), the Eemian (MIS 5e, ca. 135-115 ka) and the Holocene (MIS 1, from ca. 11.7 ka to the present) (Bradwell et al., 2008; Gibbard and Cohen, 2015; Gibbard, 1995; Graham et al., 2011; Huuse and Lykke-Andersen, 2000; Kristensen et al., 2007; Sejrup et al., 2000). These climatic changes caused the depositional environment to shift between predominantly erosional and depositional phases (Clark et al., 2004, 2012; Cotterill et al., 2017a; Coughlan et al., 2018; Ottesen et al., 2014, 2018; Phillips et al., 2018; Praeg, 2003). One of the shifts marked by pronounced climatic and depositional change occurred during the last interglacial-to-glacial transition (MIS 5e to MIS 2) (Clark et al., 2012; Konradi et al., 2005; Lambeck et al., 2014; Peeters

* Corresponding author. Flanders Marine Institute (VLIZ), Jacobsenstraat 1, Ostend, 8400, Belgium.

E-mail address: despina.kyriakoudi@vliz.be (D. Kyriakoudi).

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et al., 2016; Zagwijn, 1983). During the Eemian interglacial, the North Sea was inundated by marine waters, with sea level reaching values close to those of today. In contrast, a major fall in global sea level during the Weichselian glaciation exposed extensive parts of the southern North Sea. The incised valley systems of the southern North Sea often hold a valuable record of this complex geological evolution (Cameron et al., 1992; Coughlan et al., 2018; Fitch et al., 2005; Hepp et al., 2012, 2017; Prins and Andresen, 2019; Roberts et al., 2018).

Many of the mapped incised valleys in the North Sea are linked to glacial processes associated with former ice-sheet cover. Most of them are described as tunnel valleys, a subset of subglacial channels typically found near former ice margins, with meltwater erosion beneath ice sheets considered as the main erosional process (Ehlers and Linke, 1989b; Jørgensen and Sandersen, 2006; Kirkham et al., 2024a,b; Ó'Cofaigh, 1996; Ottesen et al., 2020; Piotrowski, 1994; Russell et al., 2003; van der Vegt et al., 2012). Tunnel valleys are distinguished by their large dimensions (up to several km in length and width), undulating longitudinal morphology, and abrupt terminations (Ehlers et al., 1984; Jørgensen and Sandersen, 2006; Kehew et al., 2012; Kristensen et al., 2007; Sugden et al., 1991). In the North Sea, multiple generations of these tunnel valleys have been identified and correlated with the last three major glaciations (Kristensen et al., 2007; Stewart et al., 2013; Stewart and Lonergan, 2011; Wingfield, 1990). Yet, their exact age is uncertain due to the limited geochronological data of the infills, and/or the overprinting or re-occupation of younger incisions during subsequent glaciations (Andersen et al., 2012; Huuse and Lykke-Andersen, 2000; Lutz et al., 2009; Muther et al., 2012). Usually, cross-cutting relationships and seismo-stratigraphic interpretation are used as methods to assign relative chronology to these systems (Kirkham et al., 2024a,b; Kristensen et al., 2007; Stewart, 2009).

Apart from subglacial channels, other erosional incisions in the Quaternary succession of the North Sea are related to subaerial systems (Cotterill et al., 2017b; Gaffney et al., 2007; Prins and Andresen, 2019; van Heteren et al., 2014). In the southern North Sea, a complex system of fluvial, estuarine and tidal channels is preserved as a submerged late Quaternary landscape (Fitch et al., 2005; Prins and Andresen, 2019).

To distinguish and classify subglacial versus subaerial features in the geological record, plan view morphologies, morphometric dimensions and infill architecture can be used as criteria (Gibling, 2006). Morphological features such as braided and meandering forms, scroll bars, oxbow lakes and splays are expected in subaerial settings, while linear to low-sinuosity geometries are more commonly observed in subglacial environments (Kristensen et al., 2007; Ottesen et al., 2020; Prins and Andresen, 2019). Occasionally, complex anastomosing or dendritic patterns are observed in subglacial channels, but they are relatively rare (Lutz et al., 2009; Praeg, 2003; Stewart et al., 2013). Offshore, 2D reflection seismic data provide essential constraints on the geometry characterisation, stratigraphic relationships, and internal architecture of erosional features, but the wide line spacing limits spatial continuity (Fitch et al., 2005), whereas 3D seismic datasets offer a more continuous coverage across large regions, improving the geomorphological mapping of incisional features (Ottesen et al., 2020). In the North Sea specifically, the availability of 3D seismic data has significantly improved our general understanding of the Quaternary geological evolution (Bellwald et al., 2022; Kirkham et al., 2024a,b; Ottesen et al., 2018; Petrie et al., 2024).

This paper presents a high-resolution, detailed mapping and morphometric analysis of buried incised valleys in an area south of the Dogger Bank (southern North Sea). Taking advantage of available industrial 3D seismic data, we combine new 2D and existing 3D datasets to examine the spatial extent and seismic and morphological characteristics of different generations of incisions. By combining offshore stratigraphy with a systematic, data-driven methodology that uses quantitative multivariate analysis, the origin, timing and stratigraphic significance of the incisions are investigated. The results (i) provide new insights into the evolution of the buried Late Pleistocene to Holocene

landscape of the Dogger Bank area, and (ii) establish a stratigraphic-geomorphological classification system based on an objective, unsupervised approach.

2. Regional setting

Dogger Bank is a large, isolated bathymetric high in the central part of the southern North Sea (Fig. 1), forming an elongated southwest-northeast feature approximately 300 km long and 130 km wide. Water depths across the bank range from 20 to 40 m below sea level (mbsl), making it one of the shallower parts of the North Sea. To the southeast, between Dogger Bank and the Frisian Front, the seabed flattens into the Oyster Ground, a broad depression reaching depths of ~50 m mbsl. The Oyster Ground transitions westwards into the Outer Silver Pit, a narrower west-east oriented valley with maximum depths of ~80 mbsl.

The Dogger Bank itself consists of a core of Middle-to Late-Pleistocene deposits overlain by a layer of Holocene sediments and large sand ridges (Cameron et al., 1992; Cotterill et al., 2017b; Roberts et al., 2018). The stratigraphy and morphology of the region result from glacial and deglacial processes during the Weichselian glaciation, when global sea level was ca. 130 m lower than present during the Last Glacial Maximum (LGM) (Gibbard and Cohen, 2015; Lambeck et al., 2014). Large parts of the southern North Sea were then exposed as an extensive lowland plain with tundra vegetation (Andresen et al., 2022; Coles, 1998; Hughes et al., 2016). Between 30 and 24 ka, the British Irish (BIIS) and Fennoscandian Ice Sheet (FIS) converged across the North Sea Basin, followed by their separation ca. 24–20 ka (Bradwell et al., 2008; Carr et al., 2006; Clark et al., 2022; Graham et al., 2011; Hughes et al., 2016; Sejrup et al., 2009, 2016). During this merging phase, the margin of the Weichselian ice sheet reached into the area of Dogger Bank at the time of the LGM (Fig. 1) (Clark et al., 2022; Batchelor et al., 2019; Sejrup et al., 2016). The stratigraphy of the Dogger Bank's core is complex and results from successive episodes of folding and thrusting imposed by advancing ice lobes during the Weichselian (Carr et al., 2006; Cotterill et al., 2017a, 2017b; Emery et al., 2020; Phillips et al., 2022). This glaciotectionic complexity is absent further southeast towards the Oyster Ground (Emery et al., 2019a).

Post-LGM deglaciation of the area west and southwest of Dogger Bank was marked by several pulses of retreat and re-advance of major ice lobes (Bradwell et al., 2008; Carr et al., 2006; Clark et al., 2022; Dove et al., 2017 and references therein; Evans et al., 2019, 2021; Graham et al., 2011; Hughes et al., 2016; Livingstone et al., 2015; Sejrup et al., 2009, 2016). The timing of the deglaciation of Dogger Bank itself remains debated. Roberts et al. (2018) suggest it was ice-free after 23.1 ka, although till deposits to the west-southwest of Dogger Bank and in the Outer Silver Pit record a BIIS presence at 21–22 ka (Fig. 1) (Evans et al., 2019; Roberts et al., 2018). Other reconstructions indicate no ice cover on the central Dogger Bank after 19 ka (Clark et al., 2012; Evans et al., 2021; Sejrup et al., 2016). Later in the glacial cycle the rapid collapse of the ice sheet resulted in a progressive inundation of the southern North Sea basin (Clark et al., 2022), with major land loss around 11–10 ka (Hoebe et al., 2024) and complete submergence by 6 ka (Gaffney et al., 2007).

Remnants of the deglacial evolution of Dogger Bank, Oyster Ground and the Outer Silver Pit are preserved as extensive channel networks that incise older Pleistocene deposits. The channels interpreted as late-glacial to early-Holocene drainage systems (Andresen et al., 2022; Cotterill et al., 2017b; Fitch et al., 2005; Gaffney et al., 2017; Prins and Andresen, 2019). Some authors (Fitch et al., 2005; Prins and Andresen, 2019) suggest that parts of these channels initially formed subglacially during the last glaciation and were subsequently reused by proglacial and fluvial systems, while estuarine or intertidal environments may also have influenced their development.

While the area of Dogger Bank was essentially shaped during the Weichselian glaciation and subsequent deglaciation, the previous glacial-interglacial cycles also left their traces in the deeper stratigraphy

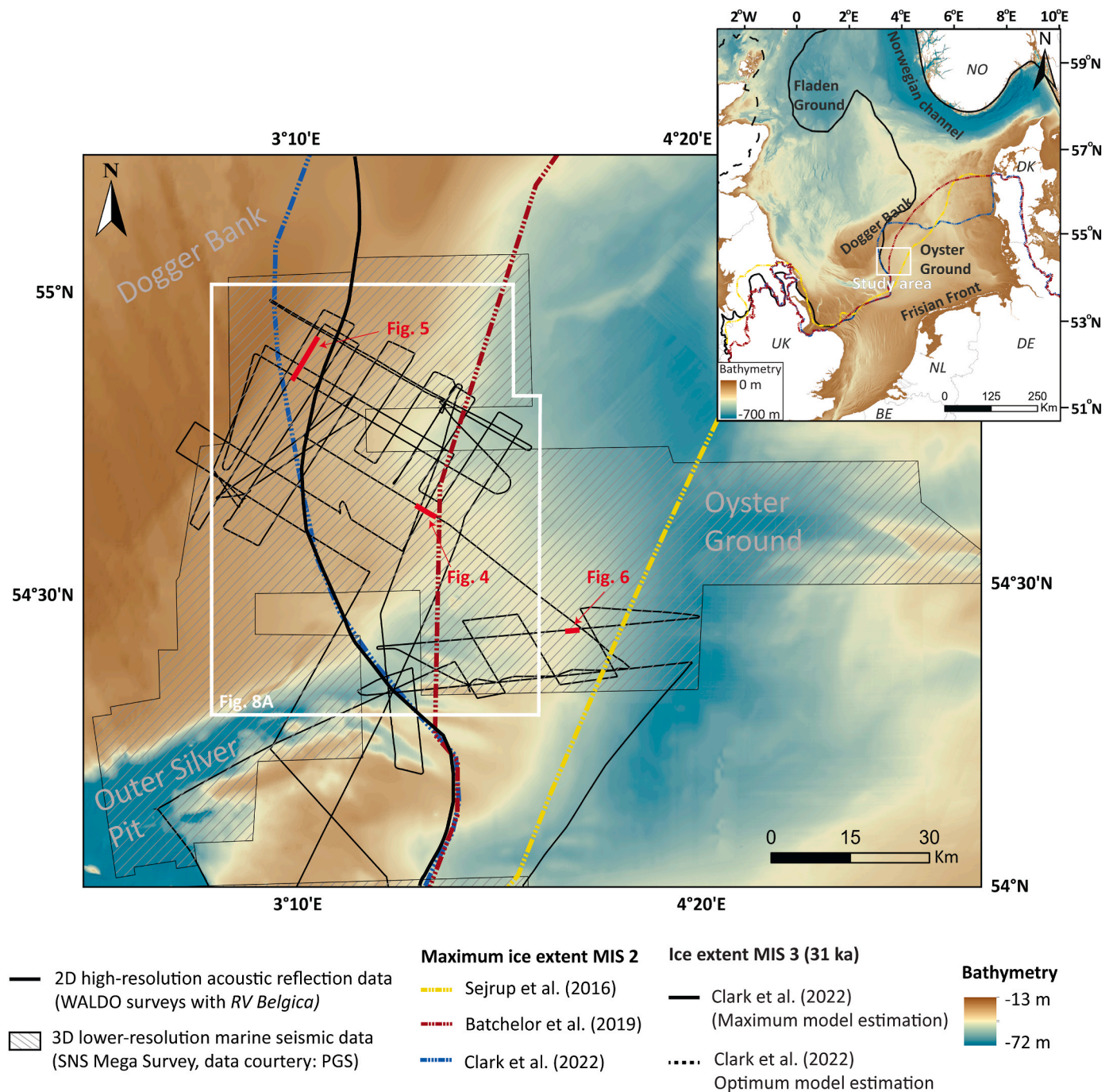


Fig. 1. Map of the study site in the southern North Sea showing the location of the 2D sub-bottom data collected during the surveys with the *RV Belgica* (black lines) and the 3D seismic data from the PGS 'SNS MegaSurvey' (hatched area). The maximum ice limits at LGM projected by Sejrup et al. (2016), Batchelor et al. (2019) and Clark et al. (2022) are indicated by dashed lines of different colours. Optimal and maximum ice extents at 31 ka are shown as solid and dashed black lines, respectively, following the reconstructions of Clark et al. (2022). Bathymetric data have been derived from the EMODnet Bathymetry portal.

of the region. The overall Middle-Pleistocene to Holocene stratigraphic framework of the region is summarised in Fig. 2. The oldest stratigraphic units are associated with the pre-Weichselian deposits of the Eem, Cleaver Bank, and Egmond Ground Formations. Deposits related to the last glaciation comprise the subglacial Bolders Bank Formation and the glacial to periglacial Dogger Bank Formation (DBF), which itself has been informally subdivided into three seismo-stratigraphic units: the Basal, Older and Younger DBF (Cotterill et al., 2017b). This subdivision is also adopted in the present work, as it has been widely used in previous studies (Andresen et al., 2022; Emery et al., 2019a, 2019b; Phillips et al., 2018, 2022; Roberts et al., 2018). Overlying these formations are

the subglacial, glaciolacustrine/marine Botney Cut (BCT) and periglacial Twente Formations, and a Holocene unit consisting of the brackish to intertidal Elbow Formation and the marine Southern Bight Formation (Cameron et al., 1992; Roberts et al., 2018; Stoker et al., 2011).

3. Data and methods

This study integrates newly acquired high-resolution 2D acoustic sub-bottom data with lower-resolution existing 3D seismic data to investigate the morphology, stratigraphy, internal architecture and

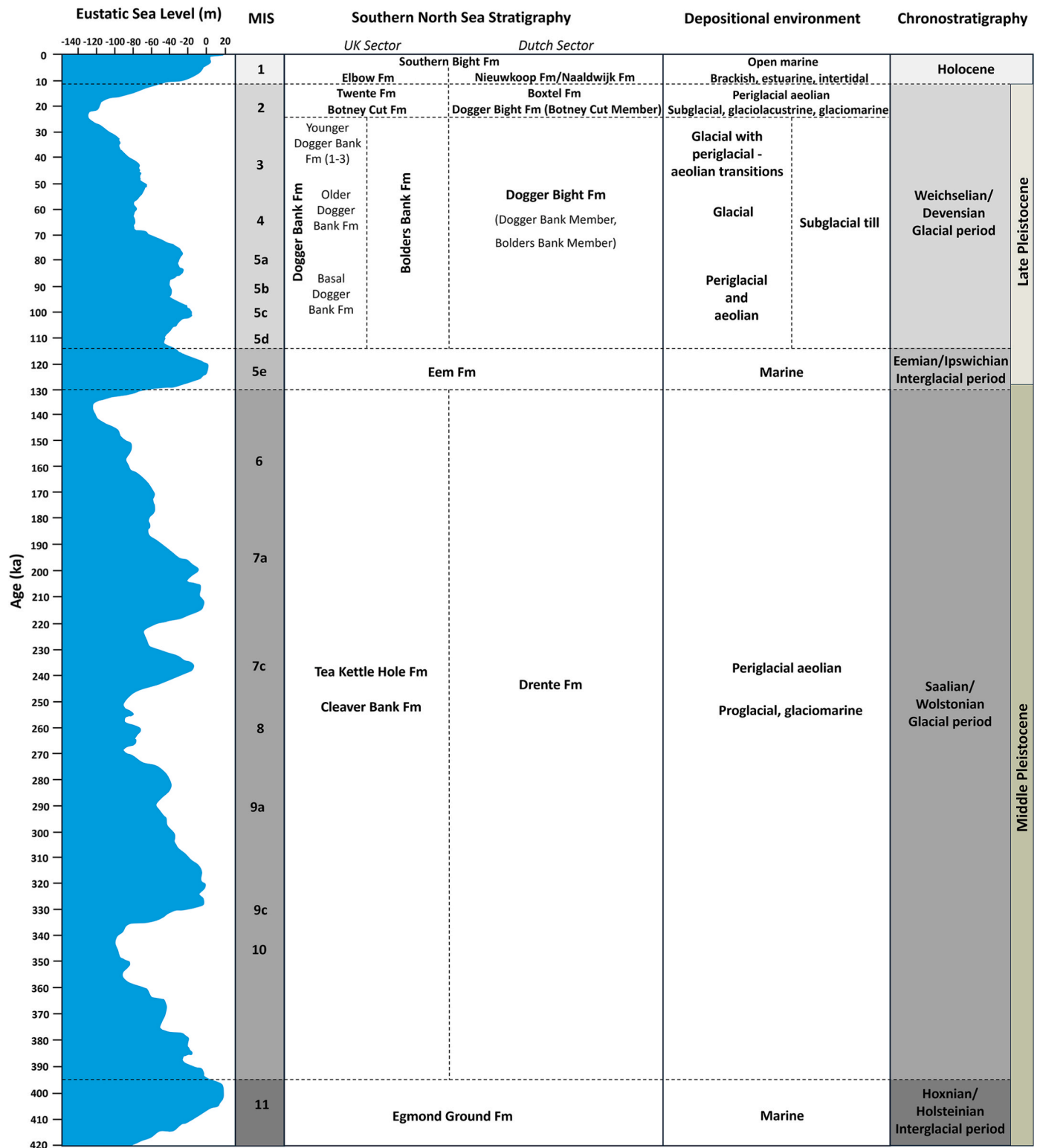


Fig. 2. Overview of the stratigraphic framework in the study area in relation to eustatic sea level estimates (Spratt and Lisiecki, 2016) and Marine Isotope Stages (Lisiecki and Raymo, 2005). The main formations listed above are correlated with the regionally established formations in the UK (Cameron et al., 1992; Cotterill et al., 2017b; Emery et al., 2019a, 2020; Phillips et al., 2018; Stoker et al., 2011) and the Netherlands (Laban, 1995; Rijdsdijk et al., 2005).

evolution stages of buried incisions in the area south of Dogger Bank. The 2D dataset was collected during surveys onboard the research vessel *Belgica* in 2022 and 2023 (cruises 2022/30 and 2023/19) in the framework of the WALDO project (Fig. 1). Sub-bottom data were acquired using a TOPAS PS18 parametric sub-bottom profiler operating at central frequencies of 2.0 to 4.0 kHz (Ricker wavelet) with a sampling

rate of 64 kHz, trace lengths of 120-130 ms and a ping interval of 200 ms. At an average vessel speed of 6 knots, this implies a horizontal ping spacing of 60 cm. The resulting vertical resolution is a few tens of centimetres. The 3D dataset was obtained as part of the Southern North Sea (SNS) 3D seismic MegaSurvey by Petroleum GeoServices (PGS) (Fig. 1). The dataset was retrieved from the open-access NLOG Datacenter,

managed by TNO. Covering an area of $\sim 7900 \text{ km}^2$, the 3D dataset features seismic data shot with Soderia G Gun airguns, with a bin spacing of $25 \times 25 \text{ m}$ and a sample interval of 2 ms. The vertical resolution of the 3D dataset is several metres. The 3D dataset was pre-processed and imported into PaleoScan 2023.1 software for visualisation and analysis. Amplitude time slices were extracted at 4 ms intervals starting from 60 to 70 ms two-way travel time (TWT), below the first seabed multiple reflection. Since the 3D dataset is thus investigated via multiple reflections, shallow stratigraphic horizons and geomorphological features appear at higher, approximately twice their primary-reflection TWT relative to their true depth observed in the 2D dataset (Fitch et al., 2005; van Heteren et al., 2014). This approach circumvents the issue that the shallower slices (through the primary reflections) are masked by ringing of the (strong) primary seafloor reflection. The advantage of this approach is that the deeper time slices generally show higher lateral amplitude contrasts and hence facilitate the identification of geomorphological elements present in the shallow subsurface (Prins and Andresen, 2019). These time slices were exported as GeoTIFF slices for further interpretation in a GIS environment. Processing of the 2D sub-bottom profiles was performed in RadExPro Seismic Software LLC (version 2022.4) and included signal-to-noise enhancement through the application of bandpass, burst-noise removal, and 2D spatial filters, together with vertical corrections for transducer depth and tides. Tidal corrections were based on sea-surface heights at the time and location of profile acquisition, as modelled by the Atlantic-European North West Shelf Ocean Physics Analysis and Forecast model (Copernicus Marine Service, 2023). The obtained values were converted to metres above Lowest Astronomical Tide (LAT) using MSL-LAT offset grids for the UK and Dutch continental shelves (provided through the ADMIRALTY Marine Data Portal and the Hydrographic Service of the Royal Netherlands Navy, respectively). Tidal heights in m LAT were then converted to TWT using a seawater velocity of 1500 m s^{-1} and subtracted from the acoustic depths, resulting in profiles referenced to LAT. All processed profiles were subsequently analysed in Kingdom™ Geoscience software (S&P Global, version 2023). All measurements and interpretations were performed in the time domain (TWT). For time-to-depth conversion, an average interval velocity of 1600 m s^{-1} was applied (Andresen et al., 2022; Cotterill et al., 2017b; Hepp et al., 2017) to assist in correlating the thickness of identified features and stratigraphic units. Note that internal velocities can vary between Holocene and glacial successions, with the cited studies reporting values $\sim 1600\text{--}1750 \text{ m s}^{-1}$, therefore, minor variations in depth and thickness estimates may exist. Seismic facies were classified according to the principles of seismic stratigraphy outlined by Mitchum Jr (1977). Spatial measurements and the creation of maps were performed in ArcGIS 10.7 (Esri).

Detailed morphometric analyses of the incised valleys were conducted on the high-resolution 2D sub-bottom profiles using a representative set of incisions across the study area. Measurements of width, depth, form ratio (width/depth), shape (b-value) and symmetry were taken for 28 vertical cross-sections. The cross-sections were selected to maximise spatial coverage across the study area, targeting different incisions to capture variability between features, and, where possible, widely spaced positions along individual incision systems. The symmetry index was defined as the ratio of horizontal distance from the incision centreline to its margins, where a value of 1 indicates a perfectly symmetrical cross-section (Noormets et al., 2009). The b-value factor reflects the cross-sectional shape of an incision, with values of 1 and 2 corresponding to V-shaped and U-shaped profiles, respectively. B-values exceeding 2 are associated with trapezoidal-shaped profiles, while values below 1 illustrate convex-upward incision flanks (Gales et al., 2013). B-values between 1 and 2 are typically associated with composite incision forms (intermediate between V- and U-shaped) (Kirkham et al., 2019). The calculation of b-values was derived using the General Power Law (GPL) method from Pattyn and Van Huele (1998), and is based on the following equation:

$$y - y_0 = a|x - x_0|^b$$

where x is the horizontal distance from the incision centreline, y is the vertical depth, x_0 and y_0 are the coordinates of the origin of the cross of the incision, a and b are constants.

An unsupervised multivariate statistical analysis was carried out to investigate relationships between all morphometric characteristics and seismo-stratigraphic unitisation (based on the acoustic facies analysis of the 2D vertical profiles), to allow their classification into clusters. Principal Component analysis (PCA) and clustering were performed in RStudio 4.4.2. PCA was performed to reduce dimensionality (Deisenroth et al., 2020) and identify dominant trends in the data, enabling more effective cluster classification. K-means and hierarchical clustering (Ward method) were conducted to identify coherent groups within the dataset. Lastly, the optimal number of clusters was determined using elbow and silhouette analyses, ensuring robust and reliable classification. All variables used in the PCA and clustering were standardised prior to analysis to ensure comparability across parameters.

Additional parameters such as length, sinuosity, and orientation were measured on selected incisions mapped in plan-view, derived from the 3D time slices. Slopes were calculated from 2D profiles and cross-checked against 3D time-slice mapping to verify spatial continuity of the measured incisions. Additional 2D cross-sectional profiles were selected across thalwegs for slope calculations, independent of the 28 cross-sections subset used for PCA analysis. Sinuosity is the ratio of the distance measured along the incision to the straight-line distance between its start and end points. It is given by the following equation:

$$\text{Sinuosity} = \text{length of thalweg} / \text{length of straight-line distance}$$

Based on the sinuosity values, the patterns are typically classified into straight (<1.1), sinuous ($1.1 - 1.5$) and meandering (>1.5) (Charlton, 2008).

Combination of the multi-resolution 2D and 3D datasets, along with morphometric and multivariate analyses, provided an effective framework for detailed and systematic mapping of these incised valley systems with complete spatial coverage. This approach enabled a robust interpretation of incision evolution and stratigraphic relationships, which are further explored in the following sections.

4. Results

4.1. Main stratigraphic units and features based on 2D sub-bottom profiles

Analysis of the high-resolution sub-bottom profiles has allowed the identification of several distinct acoustic facies (Fig. 3), which define eight main seismo-stratigraphic units, Units A-H (Figs. 4–6). For consistency, units are described from the oldest (Unit A) to the youngest (Unit H). Unit A corresponds to the deepest and stratigraphically oldest deposit that is imaged on the sub-bottom data and is consistently present in the entire study area. Units A, B and D represent deposits cut by large erosional features, indicating significant incision phases. Units C, E, F and G encompass infill of these incisions, preserved at different stratigraphic levels. Unit H comprises the most recent sedimentary deposits identified across the study area.

Unit A

Unit A is the lowest unit mapped in the study area (Figs. 4 and 6). Its acoustic facies consist of low-amplitude and low-frequency sub-parallel to hummocky reflections at the base and low-amplitude hummocky reflections at the top, which are separated by a transparent and structureless thin layer. A high-amplitude, continuous wavy reflection forms the top boundary of Unit A. The upper layer of Unit A has a complex acoustic character with sub-horizontal stratified deposits, with minor hummocky reflection geometries also present. Often, inclined

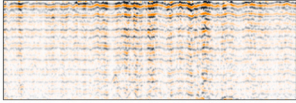
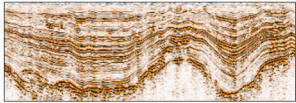
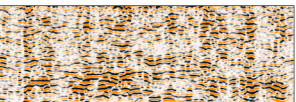
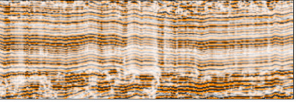
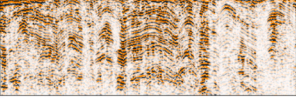
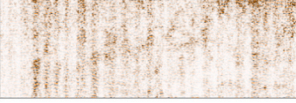
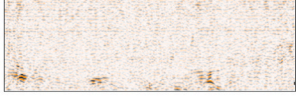
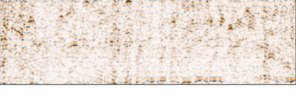
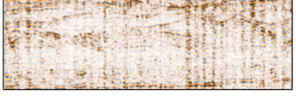
Stratigraphic unit	Example	Reflection pattern description	Regional stratigraphic correlation
<u>Unit H</u>	5 ms 70 m 	Parallel, low-amplitude, moderate frequency, continuous. Gently prograding sigmoidal in the northern part.	Southern Bight Fm
<u>Unit G</u>	11 ms 60 m 	Sub-parallel to oblique, high-amplitude and high-frequency, continuous. Strong amplitude reflector at the base. Stratified channel infills, onlapping.	Elbow Fm
<u>Unit F</u>	7 ms 60 m 	Medium- to high-amplitude hummocky reflectors.	Twente Fm
<u>Unit E</u>	17 ms 55 m 	Parallel to sub-parallel, high-amplitude and high-frequency, continuous. Hummocky reflectors at the base. Stratified basin infill.	Botney Cut Fm Upper Member
<u>Unit D</u> <u>Subunit D2</u>	9 ms 90 m 	Sub-parallel to hummocky, high-amplitude, wavy, continuous to discontinuous. Transparent to low-amplitude lenses are common.	Younger Dogger Bank Fm
<u>Unit D</u> <u>Subunit D1</u>	19 ms 80 m 	Massive, transparent, structureless.	Older Dogger Bank Fm
<u>Unit C</u>	18 ms 60 m 	Massive, transparent, structureless. Unstratified basin or channel infill. Mounded reflections at the base.	Botney Cut Fm Lower member
<u>Unit B</u>	10 ms 200 m 	Semi-transparent, structureless to very low-amplitude irregular discontinuous reflectors.	Basal Dogger Bank Fm
<u>Unit A</u>	11 ms 150 m 	Low-amplitude, hummocky to sub-parallel inclined discontinuous reflections, with a transparent layer in between.	Eem, Cleaver Bank, or/and Egmond Ground Fm

Fig. 3. Description of the main stratigraphic units and acoustic facies identified in the area.

reflections and oblique geometries can be observed, possibly indicating incised surfaces (e.g., Fig. 6). Unit A is overlain by Unit B, with the upper part of Unit A traceable across the region, except in the northern part, where acoustic penetration in the sub-bottom profiles was limited. Similarly, due to limited penetration, the base of Unit A is largely obscured within the region, preventing accurate estimation of its thickness.

Unit B

Unit B exhibits a semi-transparent acoustic character with low-amplitude, irregular, discontinuous internal reflections. Unit B rests on the underlying Unit A throughout the area (Fig. 4 and Fig. 6). Its lower

boundary, which separates Unit B from Unit A, appears as a prominent high-amplitude mostly planar reflection. A high-amplitude, irregular, continuous reflection marks the top boundary of Unit B, which clearly separates it from the overlying units. Deposits covering Unit B are markedly variable across the area. Although internal reflection terminations within Unit B cannot be confidently identified due to its transparent character, local truncations at its upper boundary are visible, caused by incisional forms associated with Unit C. In areas where Unit C is absent, Unit D drapes over Unit B. Towards the northern part of the study area, the base of Unit B cannot be traced due to reduced penetration. The maximum visible thickness in the area reaches ~10 m.

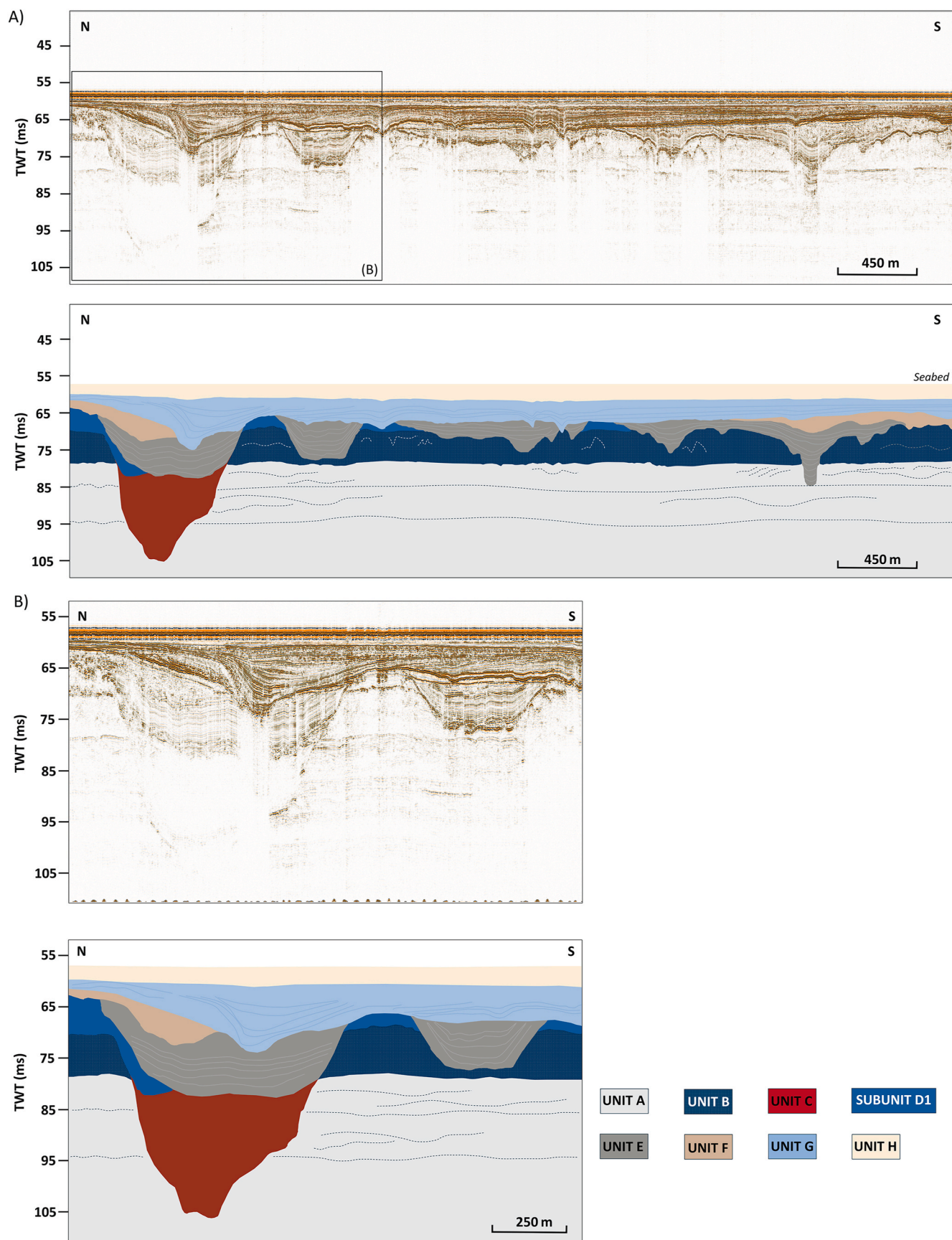


Fig. 4. (A) High-resolution sub-bottom profile depicting the main stratigraphic units identified (see Fig. 1 for location of profile). It displays an uninterpreted acoustic profile in the N-S direction (top) and the interpreted stratigraphy, with coloured intervals representing the units as defined in this study (bottom). (B) A detailed example along the line shown in 4A, displaying a series of densely distributed erosional features with complex infill incising into the older stratigraphic units.

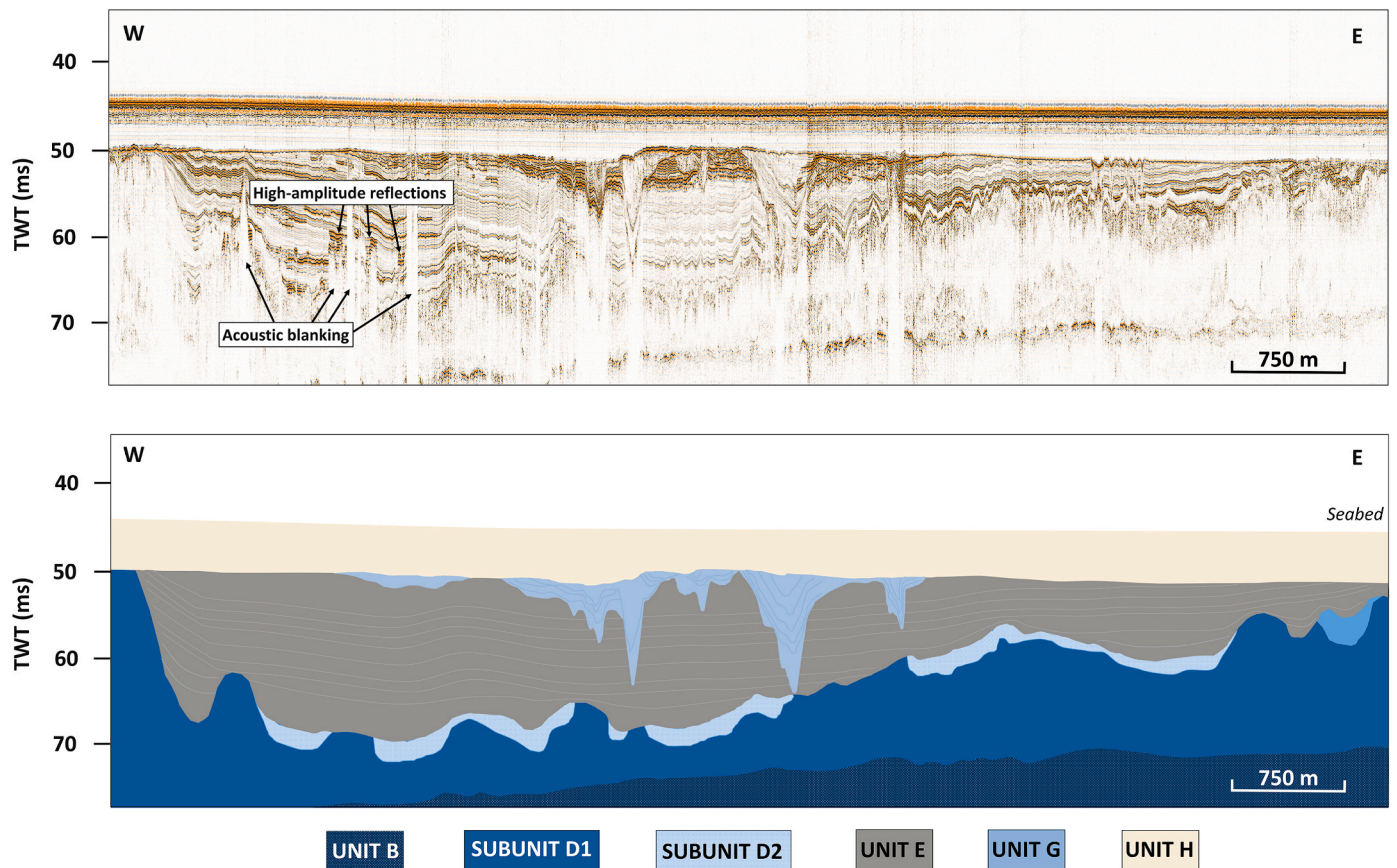


Fig. 5. Non-interpreted (top) and interpreted longitudinal acoustic profile (bottom) along a valley with laminated fill deposits, locally eroded at the top by younger channels. Vertical zones of acoustic blanking, possibly associated with the presence of gas, are visible (see Fig. 1 for position).

Unit C

Unit C consists of the lower infill of deep, V-shaped incisions (Fig. 4 and Fig. 6), predominantly found in the southern part of the study area. The incisional depth of these valleys ranges from approximately 20 to 35 m. Depending on the location, the erosional event that preceded the deposition of Unit C completely truncates Unit B and reaches into and erodes Unit A in all cases. The lower part of Unit C is consistently characterised by a transparent, unstratified and structureless reflection pattern, while the basal part, if discernible, is marked by low-amplitude, discontinuous, hummocky reflections. The internal infill of all mapped incisions maintains the transparent facies in their lower part, frequently overlain by deposits of Unit E and/or G. Sporadically, deposits of Unit D1 are found infilling the sides of incisions, overlying the deposits of Unit C.

Unit D

Unit D consists of two subunits, each characterised by a distinct acoustic facies.

Subunit D1 represents the lowermost part of Unit D and is present in large parts of the study area (Fig. 4 and Fig. 5). It has a massive, mostly transparent and structureless acoustic signature, with some patchy low-amplitude, discontinuous reflections appearing internally. The basal boundary of subunit D1 is characterised by a consistently high-to medium-amplitude wavy horizontal reflection, which appears to have more hummocky and discontinuous characteristics in some locations. Subunit D1 is either directly covered by Units F, G or H, its top boundary marked by a high-amplitude continuous reflection (unconformity) or is eroded and overlain by subunit D2. Subunit D1 is present across the area but exhibits significant variability in thickness, ranging from more than 25 m in the north to less than 2 m in the south.

Subunit D2 has a complex internal structure with higher reflection

amplitudes compared to subunit D1 (Fig. 5). The most frequently observed facies are characterised by sub-parallel to hummocky, high-amplitude, wavy continuous or discontinuous reflections. Often, transparent lenses are present. Subunit D2 has a greater thickness in the northern part (up to 12 m) and gradually thins towards the south, eventually becoming undetectable. It is bounded at the top by a high-amplitude, continuous reflection that usually marks the transition to Units E, G or H. Reflector geometries at the top of subunit D2 locally appear hummocky.

Both subunits D1 and D2 are cut by a series of variably sized and shaped incisions (filled with Units E and G), which locally truncate either their upper surface or the entire subunit.

Unit E

Unit E represents the infill of U-shaped incisions and displays a well-stratified internal structure (Figs. 4 and 5). The incisions have variable incisional depths between 8 and 31 m. Their main infill is characterised by parallel to sub-parallel, high-amplitude and high-frequency, continuous reflections, with high-amplitude hummocky reflections at the base. Sub-parallel onlapping patterns are observed along the margins of the incisions, reflecting a progressive and gradual sediment accumulation against the pre-existing topography. In some areas, toplap reflection terminations are detected at the upper boundary (e.g., Fig. 5), indicating erosion following infill completion or periods of non-deposition. The high-amplitude reflections indicated by arrows in Fig. 5 likely correspond to gas-charged zones, where local acoustic blanking is also observed. This led to reduced penetration and locally disrupted reflections, but internal architecture and stratigraphic continuity remained sufficient to allow reliable interpretation. Unit E mainly forms the infill of incisions eroded into Unit D (subunits D1 and D2) and occasionally overlain by Unit F. Unit E locally also fills the

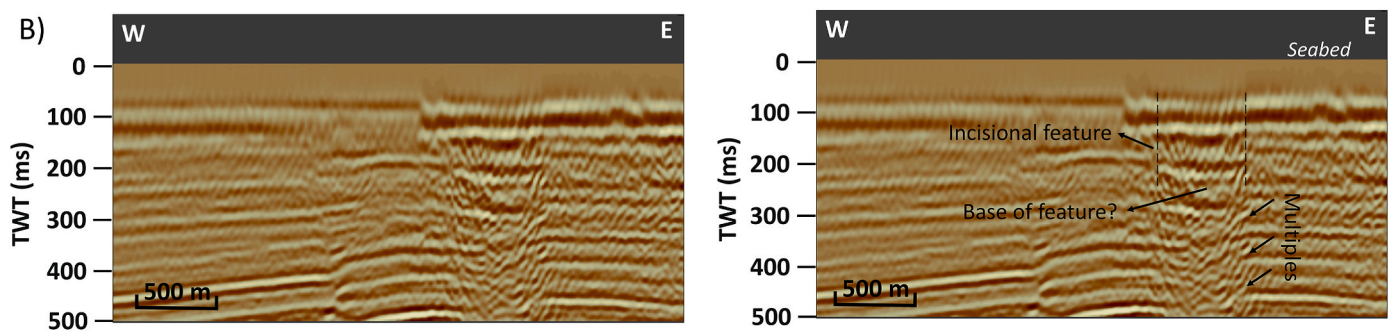
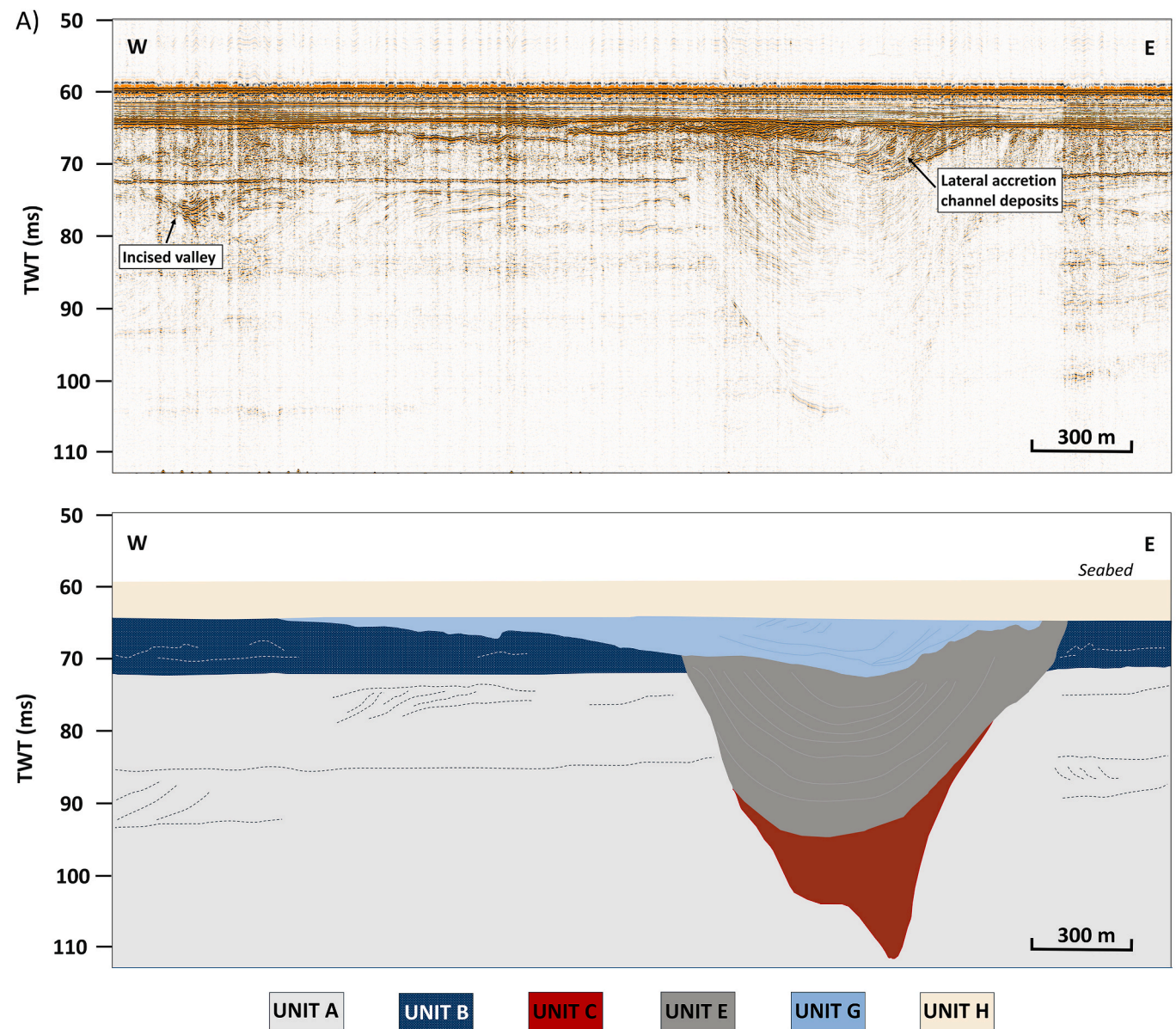


Fig. 6. (A) A high-resolution 2D sub-bottom profile in W-E orientation from the Oyster Ground, revealing one of the deepest incisional features mapped in the area, heavily eroding the oldest stratigraphic unit and exhibiting a three-stage infill. For location, see Fig. 1. This incision represents Incision ID “I05” in the morphometric data (Table 1). (B) A lower resolution profile extracted from the 3D data, which depicts the same location and units as in Fig. 6A, but with significantly reduced clarity, preventing reliable recognition of morphological and stratigraphic characteristics of units and features. Profiles derived from 3D data are displayed in approx. double time relative to the profile from 2D data (e.g., 100 ms in Fig. 6A corresponds to 200 ms in Fig. 6B).

stratigraphically older incisions that are partly infilled with Unit C. The upper part of the Unit E incisions is often eroded and infilled by deposits associated with Unit G. Where not eroded by Unit G, the top boundary of Unit E appears as a high-amplitude, wavy, continuous reflection and is directly covered by deposits of Unit H (Fig. 5).

Unit F

Unit F exhibits medium-to low-frequency, discontinuous, hummocky reflections, occasionally covered by transparent lenses. The lower boundary is not well-defined, but appears as discontinuous or disrupted, probably indicating erosional truncation of underlying deposits or an uneven depositional surface. On the contrary, the upper boundary is marked by a distinct, high-amplitude, continuous, flat reflection, except where it is heavily eroded by incisional features of Unit G. Unit F is restricted to the southeastern part of the area and rests on top of the stratified deposits of Unit E or Unit D (Fig. 4).

Unit G

Unit G occurs throughout the study area, but infill is confined to numerous incisions of variable shapes and depths. The incisions are considerably less deeply incised than bounding Units C and E, ranging from 5 to 15 m, with only a few reaching an incisional depth of 25 m. The main infill feature of Unit G is characterised by high-amplitude and high-frequency, sub-parallel, continuous reflections and its base is marked by a high-amplitude undulating reflection. Onlapping patterns are consistently observed against the incision flanks, while top lap terminations often occur at the top of the fill. Its top boundary is well-defined, marked by a high-amplitude, undulating, laterally extensive reflection. In some profiles, Unit G displays an asymmetrical stratification with marginal infills of sigmoidal to oblique (parallel and tangential) reflections that prograde towards the centre of the incision, suggesting lateral accretion and/or infill from the margins inwards (e.g., Fig. 6). Incisions of Unit G typically erode Unit E, but where Unit F occurs above Unit E, both units are incised. In other areas, Unit G is directly infilling erosional cuts into Unit D, while towards the south, where Unit D is absent, Unit G rests atop Unit B (Fig. 6).

Unit H

Unit H is the youngest deposit in the study area. It is mostly characterised by low-amplitude, moderate-frequency, parallel, continuous reflections. A sub-parallel sigmoidal geometry with gently prograding reflections is observed, restricted in the northern part. This unit overlies Units E, F and G, but in parts where these units are absent, it directly rests on Units D or B. Its basal boundary is marked by a strong flat reflection (unconformity), while a high-amplitude reflection at the top represents the active seafloor. Unit H varies considerably in thickness, being thicker in the north and progressively thinning towards the southeast (from 19 to 1 m) (Figs. 4–6).

4.2. Morphometric analysis from 2D sub-bottom profiles

A detailed morphometric analysis of the observed incisions was conducted on 2D vertical cross-sections to characterise and quantify their morphological variability. The results of this analysis were then used as input to derive a cluster-based classification.

The measured variables demonstrate that distinct morphometric patterns can be recognised, although the incisions display a wide range of geometric and morphological variations (Table 1, Fig. 7B–E). The incision depths are highly variable, with the majority having depths of less than 15 m and only a few reaching an incisional depth of 20 to 35 m. The width values cover a wide range, between 165 and 3700 m. Most features (68%) are less than 1200 m wide, although some incisions are wider than 2000 m. The form ratio (width/depth) ranges from 25 to 400, with most features having form ratios less than 50 (53%). Fewer features exhibit form ratios of 50–150 (29%), and only a small subset exceeds 150 (18%). Lower form ratio values are associated with narrower and steeper-sided incisions, while higher values are linked to broader, shallower forms with more gentle margins. Regarding symmetry, the symmetry-index values span from 0.4 to 3.8, with most incisions being symmetrical to moderately asymmetrical (79%) (values from 0.65 to 1.4), whereas only some features tend to be highly asymmetrical. B-value measurements (range: 0.53–3.26) exhibit considerable heterogeneity in shape, spanning from V-shaped to U-shaped, including more composite and trapezoidal forms.

Table 1
Morphometric characteristics of 28 examined incisions in 2D cross sections.

Incision ID	Width (m)	Depth (m)	Form ratio	Shape	Symmetry	Infill unit	Number of infill stages
I01	575	21.6	26.62	V	Highly asymmetric	Unit C, Unit E, Unit G	3
I02	983	28	35.11	V	Symmetric	Unit C, Unit E, Unit G	3
I03	1365	28.8	47.4	V	Symmetric	Unit C, Unit E, Unit G	3
I04	758	32	23.69	V	Moderately asymmetric	Unit C, Unit E, Unit G	3
I05	1197	34.4	34.8	V	Moderately asymmetric	Unit C, Unit E, Unit G	3
I06	1115	10.4	107.21	Trapezoidal	Symmetric	Unit E, Unit F	2
I07	250	16	15.6	V	Highly asymmetric	Unit E	1
I08	294	12	24.50	U	Symmetric	Unit E	1
I09	3065	20.8	147.36	U	Moderately asymmetric	Unit E	1
I10	432	8	54	U	Symmetric	Unit E	1
I11	260	11.2	23.21	Trapezoidal	Symmetric	Unit E, Unit F	2
I12	310	9.6	32.29	Trapezoidal	Symmetric	Unit E, Unit F	2
I13	2235	20	111.75	Composite	Symmetric	Unit E, Unit F	2
I14	1652	24.8	66.61	Composite	Symmetric	Unit E, Unit F	2
I15	263	4.8	54.79	Convex-flanked	Moderately asymmetric	Unit G	1
I16	2430	12.8	189.84	V	Symmetric	Unit G	1
I17	3165	14.4	219.79	V	Symmetric	Unit G	1
I18	275	9.6	28.65	Composite	Moderately asymmetric	Unit G	1
I19	490	11.2	43.75	Convex-flanked	Highly asymmetric	Unit G	1
I20	330	8	41.25	U	Highly asymmetric	Unit G	1
I21	812	8	101.50	Convex-flanked	Highly asymmetric	Unit G	1
I22	165	4.8	34.38	Composite	Moderately asymmetric	Unit G	1
I23	705	6.4	110.16	U	Moderately asymmetric	Unit G	1
I24	2300	8	287.50	Convex-flanked	Moderately asymmetric	Unit G	1
I25	3700	9.6	385.42	Trapezoidal	Symmetric	Unit G	1
I26	3510	11.2	313.39	Convex-flanked	Highly asymmetric	Unit G	1
I27	216	4.8	45.00	Convex-flanked	Symmetric	Unit G	1
I28	345	10.4	33.17	V	Symmetric	Unit E, Unit F	2

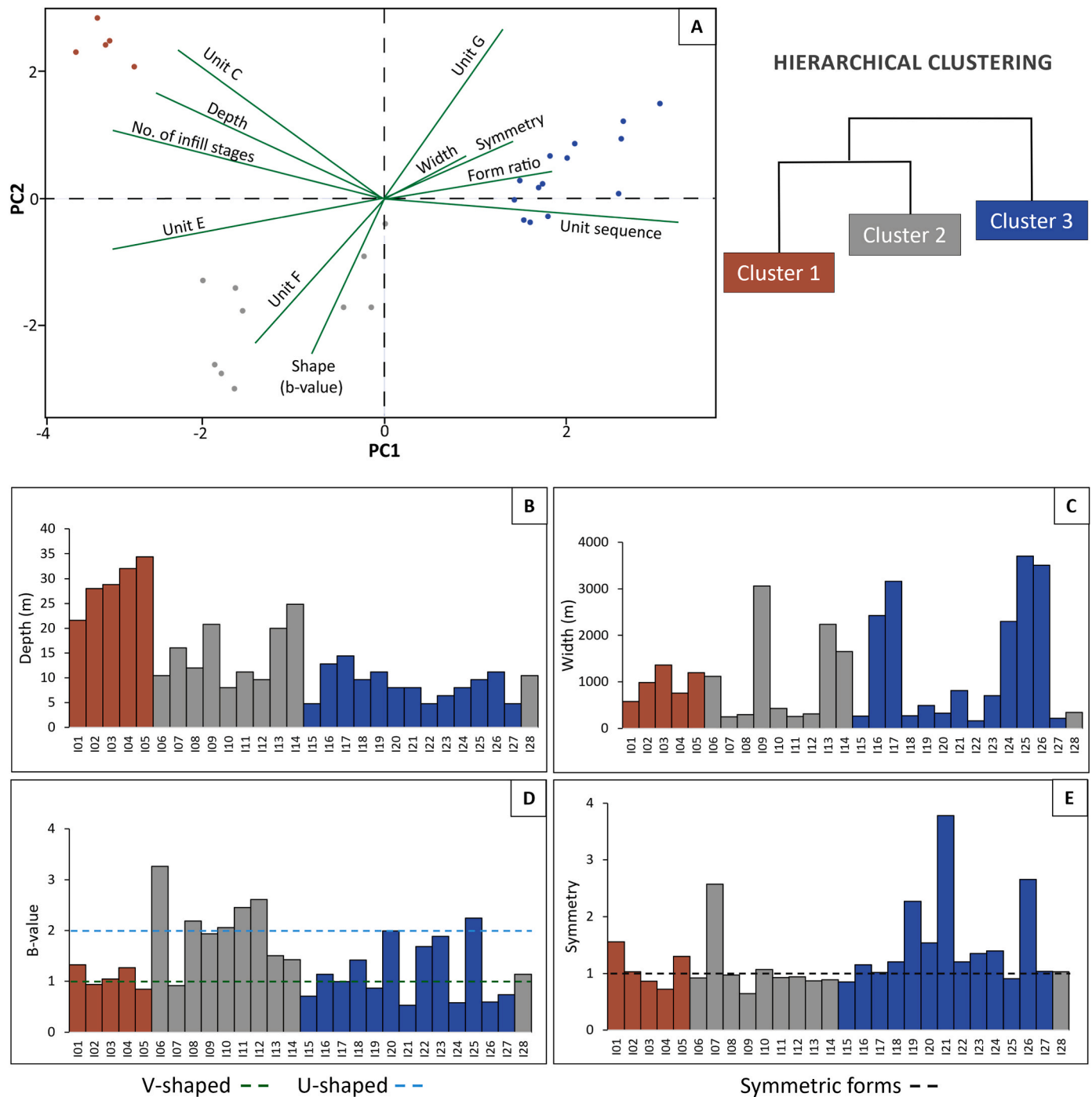


Fig. 7. (A) PCA biplot showing the clustering results based on the morphometric variables. Three main clusters were generated, indicated by different colours. Each dot represents one measured incision, and the green arrows indicate the active variables used to perform the PCA. (B to E) Distributions plots of width, depth, b-value (shape) and symmetry of incisions. The dashed lines in the b-value plot align with the representative geometries for V-shaped ($b = 1$) and U-shaped profiles ($b = 2$), and in the symmetry plot, value 1 corresponds to a totally symmetric feature.

PCA was performed on the five measured parameters (width, depth, form ratio, symmetry, b-value), the number of infill stages, infill units, and unit sequence. The variable ‘infill units’ represents the seismic units identified within each incision, whereas the variable ‘unit sequence’ describes the stratigraphic arrangement of these units within the incision infill. The first two components, PC1 and PC2, together explain 66.6% of the total variance (Fig. 7A). PC1 is dominated by unit sequence (score 0.46), unit E (s. -0.42), number of infill stages (s. -0.42), and incisional depth (s. -0.35). PC2 is primarily controlled by b-value (s. -0.44) and units G, C and F (s. 0.43, 0.43, and -0.42 , respectively). PC3

explains an additional 15.7% of the variance, which is primarily controlled by width (s. 0.70) and form ratio (s. 0.59). PC1 and PC2 capture dominant stratigraphic and morphometric variability between incisions, whereas PC3 reflects secondary variability in incision geometry, such as the proportional relationship between incision width and depth.

The PCA and clustering analysis grouped the incisions into three main clusters based on their similarities. Fig. 7 illustrates the cluster associations with their corresponding measured geomorphic variables. Cluster 1 comprises incisions with the largest incisional depths (avg.

29 m), moderate widths (575 to 1365 m), V-shaped geometries, low form ratios, and diverse symmetries, ranging from symmetric to highly asymmetric. Cluster 1 exhibits three infill stages, primarily composed of Unit C deposits, which always infill the lowest part of incisions filled with Unit C. The bases of these incisions are measured between 73 and 89 m below LAT. Cluster 2 has shallower incisional depths (avg. 14.3 m) and a large range of widths, from very narrow to very wide (250 to 3065 m). It displays low to moderate form ratio values and a predominantly symmetrical geometry, with only a few asymmetrical features. U-shaped to trapezoidal geometries mainly dominate this cluster. It shows decreasing infill complexity, often filled with Unit E and occasionally Unit F. The base of the incisions is mapped at approx. 60–78 m below LAT. Cluster 3 represents the shallowest incisions (avg. 8.7 m) with a wide spectrum of widths (216 to 3700 m) and no clear trend in shapes. Symmetry and form ratio exhibit considerable variability, with the most asymmetric forms and largest form ratio values seen within this cluster. The incisions have a single infill stage filled with Unit G. Their base is at approx. 43 to 61 m below LAT.

Hierarchical clustering revealed three cluster groups, showing the formation and merging of these clusters across similarity thresholds. Clusters 1 and 2 merge at a relatively low height in the dendrogram, indicating a higher degree of similarity between them, while Cluster 3 branches off higher, reflecting lower similarity to the other clusters. This suggests that Clusters 1 and 2 have more comparable morphometrical characteristics compared to Cluster 3, which represents a more distinct group. The above PCA and clustering classification revealed three main incision groups (clusters), each marked by distinct morphometric characteristics and internal facies architecture.

4.3. Morphological mapping through the combination of 2D sub-bottom profiles and 3D derived time slices

Complex incision networks with distinct morphologies were revealed at multiple TWT intervals within the time slices derived from the 3D seismic data. As previously described, the TWT in the 3D time slices is approximately twice that of the 2D sub-bottom profiles due to interpretation through multiple reflections, causing shallow stratigraphic horizons and geomorphological features to appear at approximately twice their primary-reflection TWT. A comparison example is shown in Fig. 6b, where 100 ms in the 2D profile corresponds to 200 ms in the 3D profile. Incisions in 3D time slices were mapped at varying depths, with the deeper incisions appearing at 140–200 ms TWT and the shallower ones at 112–140 ms. This vertical distribution allowed a first-order grouping of incisions into older and younger systems, with their key geomorphological elements systematically identified and digitised (Fig. 8A–D). The older (deeper) incision forms include (a) wider, isolated, rounded to sub-rounded depressions concentrated in the northern part of the area (Fig. 8B) and (b) elongated valleys that form a densely spaced system towards the south (Fig. 8C and D). The older group can be further divided into discrete, narrow, deeper incisions with a predominantly NW-SE trend, and minor, subordinate N-S and WNW-ESE trends (yellow lines, Fig. 8C and D), while the wider, more densely spaced, elongated incisions have a general NE-SW orientation (white dotted lines, Fig. 8C). These are plan-view orientations derived from incision mapping on 3D time slices and represent general trends. Both older incision groups tend to have low sinuosity values (~ 1), pointing to straight planform geometries. 2D sub-bottom profiles were integrated with the mapped time-slice features to visualise both planform and vertical structure (Fig. 8E–G).

The limited continuous visibility of the deeper features on the 2D data (due to reduced acoustic penetration) resulted in detailed morphological measurements being carried out only on the 2D acoustic profiles for the younger (shallower) group of incisions. Three representative main channel bodies (Channel 1–3, Figs. 8A and 9 top right inset) were selected for further analysis. Measurements of channel slope were determined along their thalwegs using the 2D acoustic profiles,

whereas morphological characteristics and orientation were obtained from the 3D time slices. Based on the 2D analysis, all channels exhibited a general downstream gradient with gentle slopes. In contrast, the 3D time slice data revealed that these younger incisions form more complex and widespread channel systems, characterised by significant morphological variations along their longitudinal profiles. Fig. 9 shows an example of a southeast-flowing channel, and Table 1 lists the measured dimensions for all channels. Channel 1 is a 40 km-long sinuous system, oriented southeast, with a downslope gradient in that direction. It has a low-angle average slope of 0.05% without abrupt changes. It exhibits a dendritic drainage pattern with multiple tributaries forming a branching network and converging into the main channel (Figs. 8B and 9). Channel 2 has a sinuous planform, measuring ~ 30 km in length, following a gentle south-eastward downslope 0.12% gradient. In the northern part, segments are associated with distributary and/or tributary channels, pointing to connectivity with the primary channel body. Channel abandonment or avulsion indicators possibly linked to channel migration can be identified in the southern part (Fig. 8C). Channel 3 extends over 80 km in length, displaying a sinuous pattern with a southward orientation and several meanders. It is characterised by an overall low downstream slope gradient of 0.03%, although it exhibits major fluctuations along its thalweg trajectory. Several geomorphic elements are observed, including tributary and distributary systems, crevasse splays, abandoned channel segments, scroll bars and an oxbow lake (Fig. 8B and C). It clearly shows a morphological evolution with a complex configuration from north to south. The northern part is dominated by tributary junctions that merge into the main thalweg, splays, meander belts and abandoned parts (Fig. 8B). Further southwards, the channel evolves into a braided channel separated by bars and then transitioning to meandering patterns with cutoff and distributary/tributary channels (Fig. 8C).

Integrated 2D and 3D mapping revealed a complex system of numerous incisions that coincide spatially but occur vertically at different depth levels. Younger incisions are often mapped directly above or close to older ones, following similar alignments. This pattern is frequently observed, although 3D data continuity and resolution do not allow the identification of intersection geometries in all regions. Validation of observations made in the 3D dataset was achieved by integrating 2D profiles, which showed a strong morphological match, with the geometries and patterns described above.

4.4. Classification of systems

The integration of relative stratigraphic and 2D/3D morphological analyses results in an improved understanding of the overall incision morphology, acoustic character, spatial distribution and stratigraphic relationships. Stratigraphic and morphometric findings from the 2D sub-bottom profiles could be confidently traced in 3D mapping analysis, allowing the association of clusters and seismo-stratigraphic units with specific features. Based on this integration, Clusters 1 and 2 are associated with the older group of incisions as described in the morphological mapping, while Cluster 3 is tied to the morphologically younger set of incisions. However, locally, reoccupation and spatial overlap between features may blur the boundaries between generations. This combined approach has led to a robust classification of these incisions into three main generations (Fig. 10A).

- **Generation 1** corresponds to Cluster 1, which represents the oldest and deepest incisions stratigraphically. On the 2D acoustic profiles, these incisions are predominantly V-shaped, narrow, deep valleys (20.8–34.4 m) and have a three-stage infill with typically structureless basal deposits (Unit C) (Fig. 8G). The low form ratios also reflect their confined, steeper-sided nature. These valleys incise Units A and B. Spatial and stratigraphic overlaps by Generations 2 and 3 incisions are locally observed, indicating partial reoccupation of the same pathway. On the horizontal time slices, Generation 1 incisions

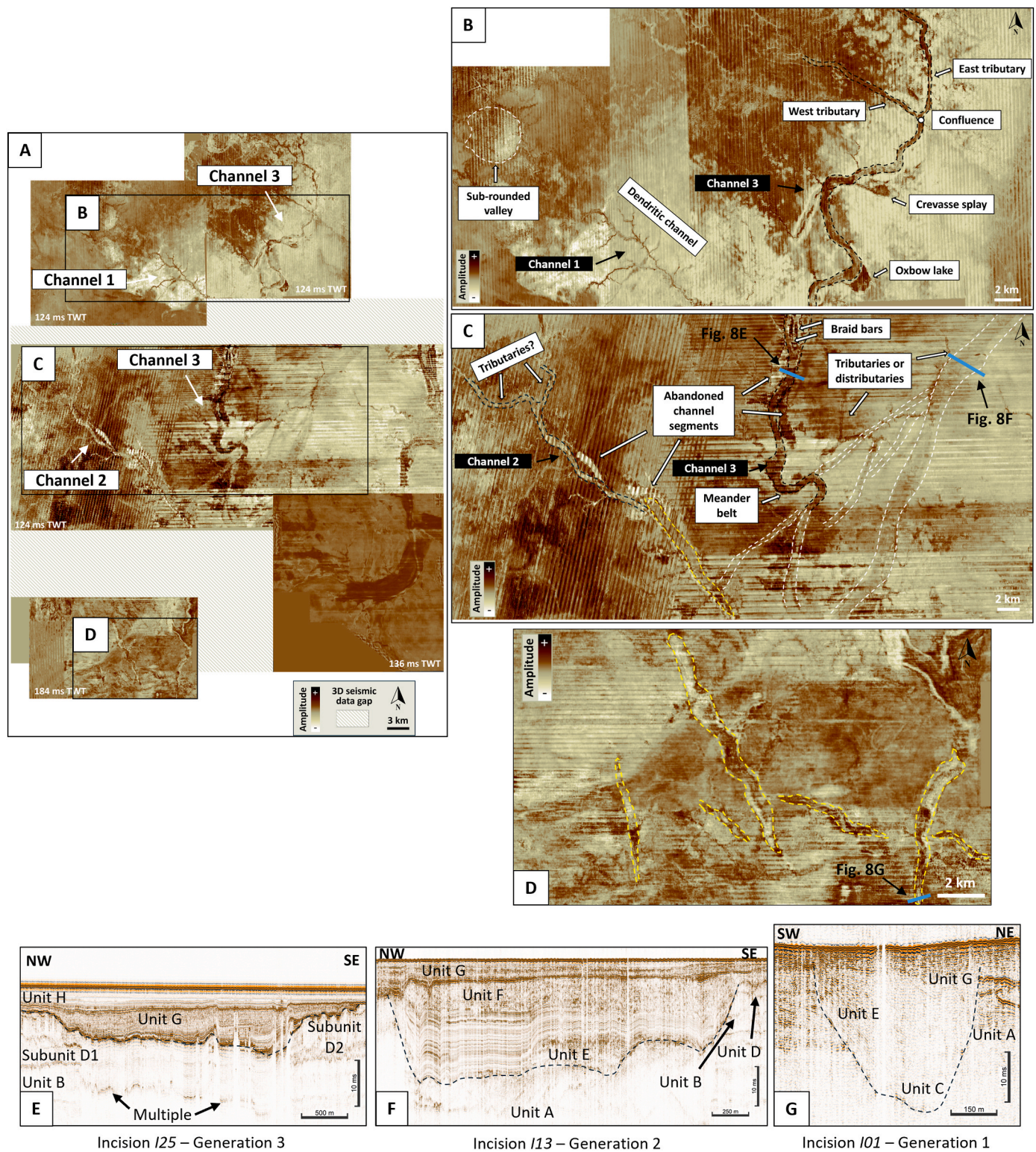


Fig. 8. (A) Amplitude time slices illustrating the presence of multiple incisions at different intervals (TWT) (see location in Fig. 1). (B to D) Plan view morphologies of incisions characterised by amplitude contrasts and visible intersecting relationships. Younger channel systems are outlined by dashed black lines (Generation 3), while older incisions by dashed yellow (Generation 1) and white lines (Generation 2). (B) and (C) Distinct morphological features related to the younger incisions showing the spatial development of the main channels and patterns. (E to G) Depict a comparison between the 2D acoustic profiles and seismic time slices, demonstrating the true dimensions, geometries and internal architecture of incisions in cross-sections. The dashed black line shows the base of each feature. The position of 2D profiles is indicated by blue lines on the time slices (see Fig. 8C and D) and measurements for each feature are shown in Fig. 7 and Table 1.

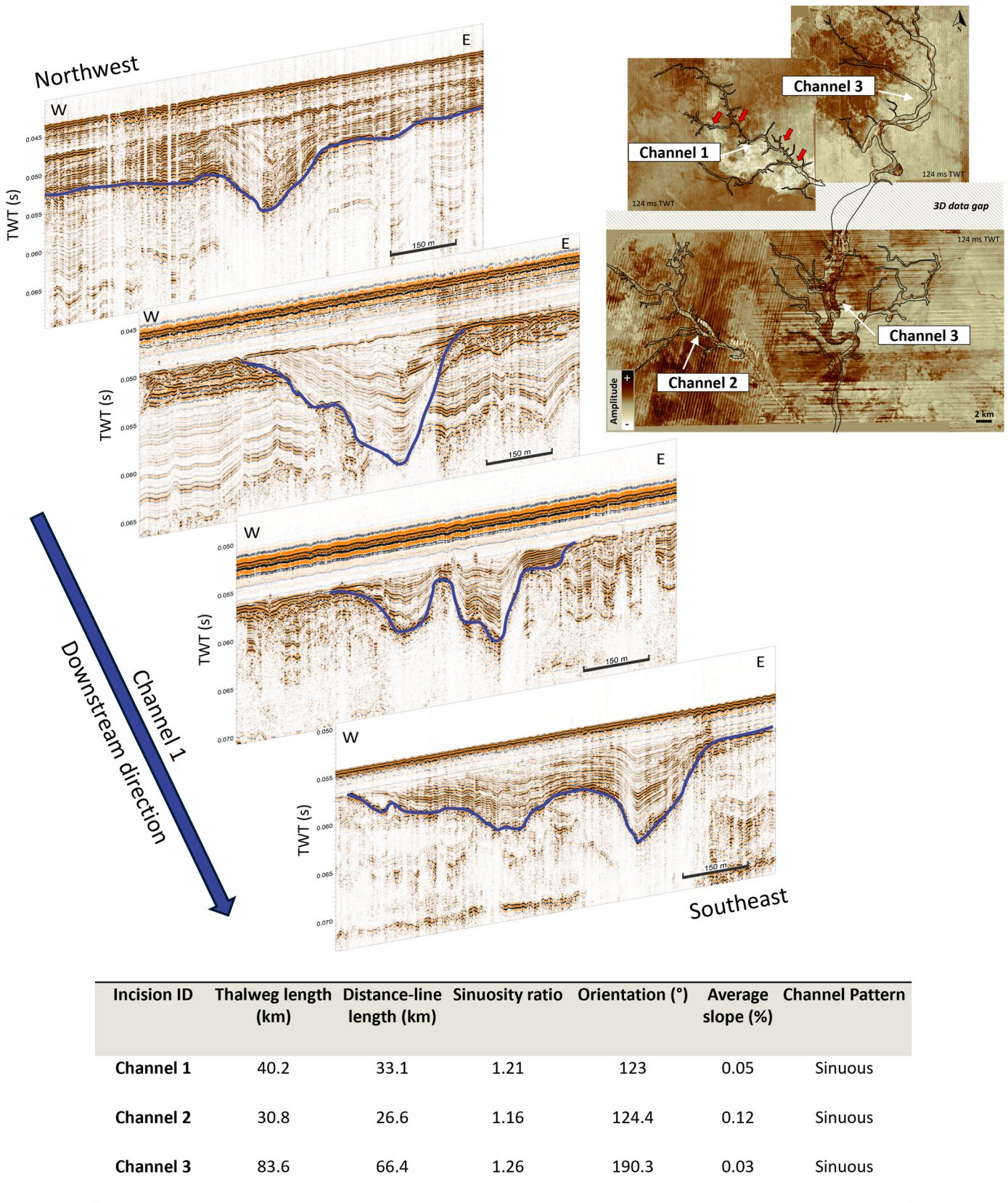


Fig. 9. Sketch portraying the NW to SE gradient trend of Channel 1 that exhibits a downstream flow direction (see location of channel in the right upper panel and Fig. 8A). The blue solid lines on the profiles mark the base of the channel. Red arrows on the map indicate the position of the four profiles along the channel. The table summarises the morphological measurements for each feature, highlighting their dominant sinuous patterns.

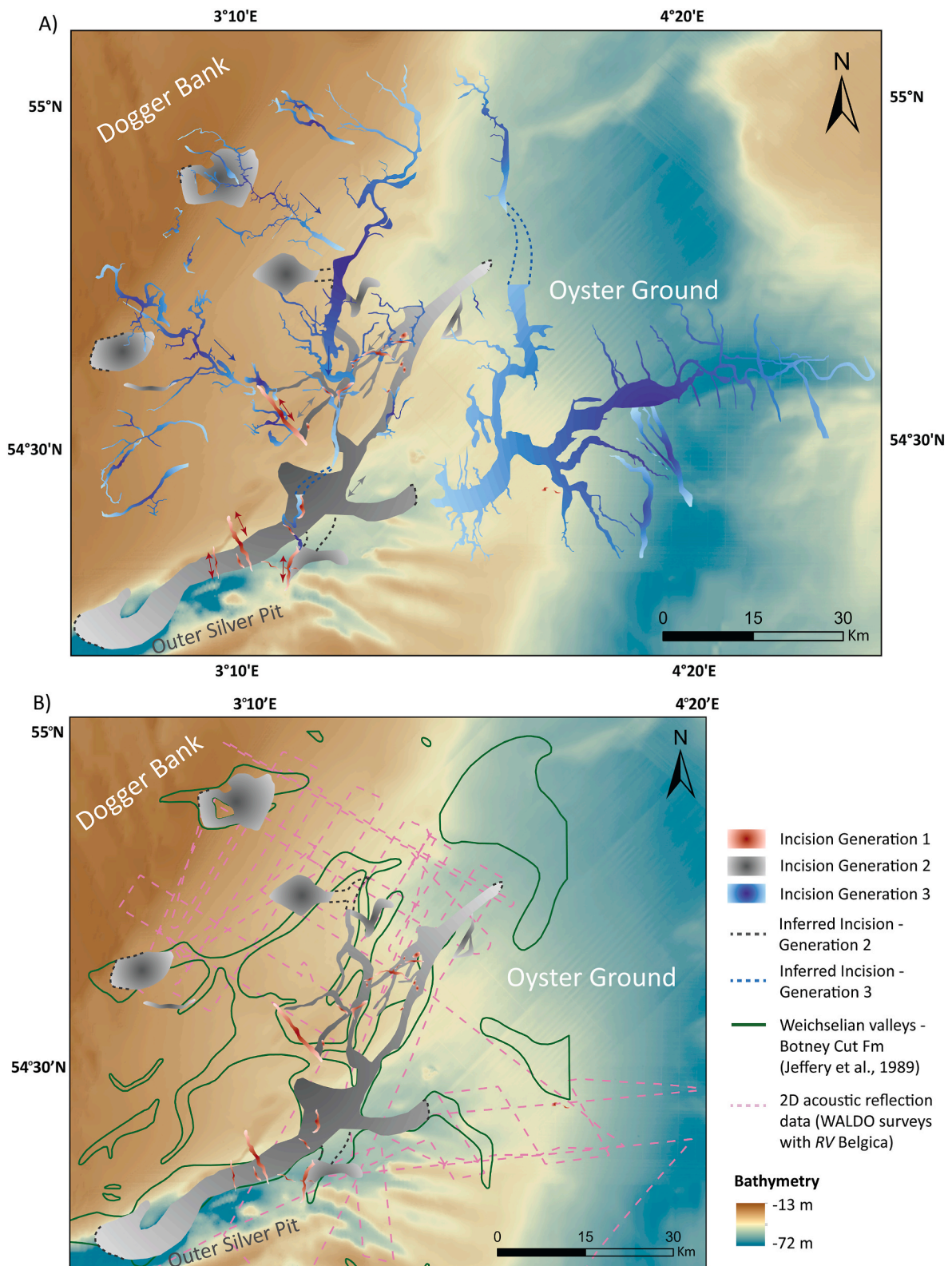


Fig. 10. (A) Synthesis and classification of mapped incisions into three main generations. The map summarises their overall shapes, dimensions and spatial distribution across the study area. Features are colour-coded according to generation and categorised based on their acoustic facies, morphological characteristics, and clustering analysis. Generation 1, marked by red, is associated with the stratigraphically older valleys, mainly of V-shaped, narrow, and elongated forms. Generation 2, shown in grey, is linked to wider valleys with straight forms in the south and subrounded shapes in the north. Generation 3, displayed in blue, shows younger channel systems with complex and interconnected forms extending throughout the area. (B) Comparison of mapped valleys associated with Botney Cut Fm from this study (Generations 1 & 2) and earlier studies (green lines) (Jeffery et al., 1989), illustrating updates on their extent, geometry and distribution within areas of available 2D acoustic data (outlined by pink dashed lines).

display discrete, linear features, spatially concentrated in the southern part of the area (Fig. 8C and D).

- **Generation 2** incisions are associated with Cluster 2. On the 2D acoustic profiles, they are trapezoidal to U-shaped incisions of intermediate depths (8–24.8 m). Morphologically, they are mostly symmetrical with moderate form ratios and are wider than the older incisions of Generation 1. They erode the underlying Units B and D, often infilling the upper part of Generation 1 incisions (above Unit C). Their infill is typically dominated by parallel laminated deposits (Unit E), occurring in single or two-stage successions (Fig. 8F). On the 3D time slices, these valleys appear as more densely arranged, elongated incisions in the southern part, while in the northern part, they are expressed as isolated, rounded to sub-rounded forms (Fig. 8B and C).
- **Generation 3** is linked to features described in Cluster 3. It includes the shallowest (4.8–14.4 m) and stratigraphically youngest group of incisions (infilled with Unit G) (Fig. 8E). The 2D acoustic profiles are characterised by diverse shapes and symmetries, forming a morphologically complex network of channel systems. The channels often follow and truncate the pre-existing Generation 2 valleys (Unit E), and otherwise incise Units D and F. On the 3D time slices, these channels are seen to be well-distributed across the area, showing sinuous to moderately meandering patterns (Fig. 8B and C).

Each generation represents a group of morphologically and stratigraphically related incisions defined through seismo-stratigraphic unit architecture, stratigraphic position, and morphometric clustering, reflecting a discrete erosional phase.

5. Interpretation and discussion

5.1. Morphology and genesis of incisions

Quantitative morphometric and morphological analysis revealed three distinct generations of incisions, differentiated by their stratigraphic signatures, geometries, shapes, and spatial distribution patterns (Figs. 7 and 10). These groups are stratigraphically constrained to different subunits, distinguished by multiple morphotypes, indicating differing formation mechanisms and chronostratigraphic contexts.

Generation 1 incisions are linear, laterally discrete depressions with deep and narrow V-shaped cross-sections, typical of a subglacial meltwater erosion mechanism (Jørgensen and Sandersen, 2006; Kirkham et al., 2019, 2024; Kristensen et al., 2007). Their characteristic morphometry, such as low form ratios (24–48), low sinuosity, higher incisional depth (20.8–34.4 m), and steeper base and sides, supports the interpretation that these formed under subglacial conditions. However, the absence of long profiles demonstrating an undulating thalweg limits confidence in this interpretation. Based on the valley classification proposed by Gibling (2006), the dimensions of subglacial and proglacial channels exhibit low form ratios (2.5–42), larger depths (7–400 m), and narrow widths (25 m–6 km), with commonly steep-sided flanks. Other studies also demonstrate the highly variable nature of subglacial channels (e.g., tunnel valleys), with depths spanning from tens to several hundred meters (<400 m) and widths ranging from <100 m to >5 km (Ehlers and Linke, 1989a; Jørgensen and Sandersen, 2006; Kristensen et al., 2007; Lutz et al., 2009; Moores, 1989). Subglacial meltwater erosion, catastrophic meltwater flow and direct glacial erosion are the main mechanisms by which tunnel valleys are theorised to be formed (Ehlers and Linke, 1989b; Gibling, 2006; Huuse and Lykke-Andersen, 2000; Praeg, 2003), though competing theories also attribute valley incision to fluvial erosional processes (Donovan and Foster, 1972; Salomonsen and Jensen, 1994; Sørensen and Michelsen, 1995). Although an undulating longitudinal profile is an important morphological characteristic diagnostic of subglacial features formed by meltwater under pressure (Kristensen et al., 2007; van der Vegt et al., 2012), spatial limitations in this dataset prevent a full evaluation of this

criterion. However, the cross-sectional shape might play a significant role in revealing the initial formation mechanism. Both U- and V-shaped morphologies are associated with glacial valleys, yet they reflect differing influences, with U-shaped implying direct glacial scouring and V-shaped reflecting erosion by subglacial meltwater (Dewald et al., 2022; Huuse and Lykke-Andersen, 2000; Jørgensen and Sandersen, 2006; van der Vegt et al., 2012). Several glaciated V-shaped valleys have been described as products of subglacial meltwater erosion under high hydrostatic pressure flows (Eyles et al., 1991; Lenz et al., 2023; Mullins and Hinchey, 1989; Sugden et al., 1991). The morphological proportions of Generation 1 incisions fit with the proposed spectrum, supporting their interpretation as smaller-scale subglacial channel forms and therefore tentatively attributed to a subglacial meltwater origin.

Generation 2 is characterised mostly by moderately to highly symmetrical incisions with U-shaped to trapezoidal cross-sectional shapes with flat bottoms. These features occur mostly as spatially separate, elongated depressions extending over several kilometres, with limited branching/joining in the southern sector. These forms display key characteristics consistent with glacial troughs carved by direct glacial erosion (i.e. due to direct movement and erosive action of the ice, rather than subglacial meltwater processes) (Benn and Evans, 2010; Patton et al., 2016; Pattyn and Van Huel, 1998; Rose et al., 2014; van der Vegt et al., 2012), with glacial abrasion and quarrying as the primary shaping mechanisms (Bennett and Glasser, 2009). Typical glacial troughs generally have straight longitudinal profiles, flat valley floors, symmetrical and roughly parabolic cross-sectional shapes (Dobhal, 2011). The incisional depth (8–24.8 m) and width (250–3065 m) of Generation 2 align with the dimensional framework introduced above by Gibling (2006), although the observed form ratios here (15.6–147.4) indicate some deviation. However, the valley morphometrics can also be influenced by ice sheet characteristics like ice thickness or the resistance of the underlying substrate to glacial erosion (Moores, 1989; van der Vegt et al., 2012; Woodland, 1970), which can lead to shallower valley depths (Ehlers and Linke, 1989b; Russell et al., 2003). The presence of local branching or merging segments could reflect glacial tributary patterns, similar to those described in glacially incised valleys in the central North Sea, which are inferred to have formed during Weichselian and older glaciations (Stewart et al., 2013). In the northern part, discrete subrounded to rounded morphologies are observed (e.g., Fig. 8B), closely resembling basin-like hollows. The regional context suggests that a kettle-hole origin is likely (Kirkham et al., 2021). Former ice sheets are likely to form depressions due to the subsidence caused by the melting of remnant buried ice (Benn and Evans, 2010; Knight, 2009). Kettles are known as ice-marginal, relatively circular landforms that form small flat-floor basins, ranging in diameter from a few meters to several hundred meters (Eilertsen et al., 2016; Knight, 2009). Such features commonly accumulate water, evolving into kettle lakes (Benn and Evans, 2010; Knight, 2009). Given the enclosed morphology and independent occurrence in a low-relief setting, the depressions associated with the Generation 2 incisions could be kettle holes. However, their larger sizes may imply an enlargement beyond the classical kettle dimensions or a different formative process. Alternatively, these closed depressions could reflect formation as subglacial basins, produced by localised overdeepening. This process is well-documented in landscapes shaped by ice sheets, creating enclosed topographic basins, carved by glacial erosion (Cook and Swift, 2012). These basins can range in length from several kilometres to hundreds of kilometres, primarily controlled by ice flux and glacial occupancy time (Cook and Swift, 2012). In this context, the scale and morphology of the depressions observed in this study plausibly reflect enlarged kettle holes or subglacial basins, formed by processes near the ice margin.

The Generation 3 incisions form spatially extensive, closely spaced channel systems with well-developed sinuosity, widely distributed across the area. These channels display predominantly sinuous plan-forms with localised meander belts, accompanied by a dense network of smaller tributaries and/or distributaries connected directly to the

principal channel body. Their cross-sectional shapes vary considerably, ranging from classic U- and V-shaped profiles to more convex flanked geometries, with no clear trend identified in cross-sectional asymmetry. A relationship between incision width and form ratio is also observed, with wider channels tending to display higher form ratios, which may reflect variable flow discharge or sediment load (Gales et al., 2013). The measured dimensions of Generation 3 incisions (form ratio: 33–385; width: 165–3700 m; thickness: 4.8–14.4 m) align well with channels formed under subaerial conditions (Gibling, 2006). Variations in cross-sectional shapes and the lack of a consistent symmetry trend further suggest laterally variable, shallow, sinuous channel systems formed under fluvial, estuarine, or tidal conditions. The complex plan-form morphologies of Generation 3, including meander belts, cut-offs, splays, abandoned channel remnants, and dendritic forms, suggest formation through subaerial (fluvial) incision, followed by subsequent transitions to estuarine and tidal regimes influenced by regional sea-level rise and isostatic adjustment (Andresen et al., 2022; Fitch et al., 2005; Gaffney et al., 2007; Petrie et al., 2024; Prins and Andresen, 2019).

Morphological findings highlight the polygenetic origin of the incisions in the study area, proposing a plausible subglacial and glacial origin for the valleys of Generations 1 and 2, and a subaerial model of genesis for Generation 3 channels. The interpretation of contrasting formative mechanisms is further supported by pronounced differences in scale, with Generation 1 exhibiting, on average, notably larger depths than Generation 3.

5.2. Correlation to the regional stratigraphy

Seismic facies analysis, stratigraphic position, and spatial context form the basis for correlating the identified units of this study to the established stratigraphic formations in the southern North Sea (Figs. 4–6). These interpretations integrate findings from adjacent areas, contributing to a broader understanding of the depositional history.

Unit A shows seismic similarities to the Eem, Cleaver Bank or Egmond Ground Formations identified previously in the Dogger Bank area (Cotterill et al., 2017a, 2017b; Roberts et al., 2018). Existing borehole data show that this unit consists of sand-dominated marine sediment sequences, compatible with the classification of either the Eem Formation or the Egmond Ground Formation (boreholes 81/52A; Cameron et al., 1992; ABH1101, ABH1134, BH1224, BH1282; Cotterill et al., 2017b), while proglacial clays of the Cleaver Bank Formation might be present between the Egmond and Eem Formations (borehole BH1207, Cotterill et al., 2017b). Deposits associated with the Weichselian glaciation (spanning the period from MIS 5d to MIS 2) are found to lie either conformably on top of the Eem Formation or, in areas with significant erosion, rest on the Egmond Ground Formation (Cotterill et al., 2017b). In conclusion, Unit A is interpreted here as a pre-Weichselian deposit, likely linked to the Eem, Cleaver, and/or Egmond Ground Formations, spanning the Holsteinian to the Eemian periods.

Both Units B and D are characterised by a diverse acoustic nature and are interpreted to correspond to the Dogger Bank Formation (DBF), based on regional stratigraphic correlation. DBF has historically been described as consisting of glaciogenic sediments deposited in glaciolacustrine or proglacial settings (Cameron et al., 1992), with recent studies revealing greater complexity than earlier assumed. Cotterill et al. (2017a, 2017b) and Phillips et al. (2018) informally classified the DBF into basal, older and younger subunits, appointing a glaciolacustrine and glaciofluvial origin across Dogger Bank. Comparable seismic facies have been identified in other studies from adjacent areas, with their interpretation aligning with the proposed framework (Andresen et al., 2022; Roberts et al., 2018). Correlating with the established framework, Unit B, subunits D1 and D2 are assigned to the basal, older and younger DBF, respectively (Cotterill et al., 2017b; Phillips et al., 2018). Unit B matches the basal DBF as it illustrates a massive, brighter acoustic

appearance with a strong upper surface reflector, located above the underlying Unit A. Unit B forms the oldest preserved deposit within the DBF, which is locally eroded by incisions subsequently infilled with Unit C. The acoustically highly variable subunit D1 is similar to the older DBF, ranging from massive, structureless to sub-horizontally stratified reflections, and is clearly separated from Unit B by a prominent horizon. This reflector is interpreted as a desiccation/subaerial exposure surface (Phillips et al., 2018). In central Dogger Bank, dated cores from the uppermost part of the older DBF yielded ages of 26.2 and 29.5 ka, implying they could be preserved glaciolacustrine deposits (cores 150VC and 151VC; Roberts et al., 2018). Subunit D2 corresponds to the younger DBF, recognised as an outwash sediment sequence (Phillips et al., 2018, 2022). The distinctive transparent lenses in subunit D2 could reflect patterned ground (desiccated or subaerial surfaces), as the area was believed to be a large periglacial or tundra region during the LGM (Cotterill et al., 2017b; Roberts et al., 2018).

The identified incisions, Generations 1 to 3, are associated with three distinct infill sequences, Units C, E and G, and have therefore been interpreted as linked to three erosional events. The stratigraphically older infill phases associated with Units C and E are likely affiliated with the Botney Cut (BCT) Formation, representing Generation 1 and Generation 2, respectively. On the contrary, the upper Unit G is correlated to the Elbow Formation, associated with channels of Generation 3.

The BCT Formation is a widespread unit infilling mainly scaphiform valleys across the Dogger Bank. Incising into Weichselian and pre-Weichselian deposits, these valleys typically do not exceed 80 m in depth and 8 km in width, and their infill is divided into two main members (Cameron et al., 1992; Cotterill et al., 2017b). According to these earlier studies, the valleys partially eroded the Dogger Bank Formation, showing strong similarities with the distribution of incisions infilled with Unit C or Unit E as seen in this study. The lower infill member has been described in the literature as exhibiting a structureless seismic character (Jeffery et al., 1989), which is compatible with the observations of Unit C (Generation 1). Based on existing BGS boreholes, the lowermost part of the BCT valley infill contains diamicton linked to the lower member of the BCT Formation (Cameron et al., 1992; Roberts et al., 2018). This deposit may represent reworked sediments of the Bolders Bank Formation (Cameron et al., 1992), hence giving its transparent acoustic appearance reflected in Unit C. In contrast, the upper member of the BCT Formation is described in the literature as displaying planar bedding with locally gas-charged sediments (Cameron et al., 1992; Jeffery et al., 1989; Schroot and Schüttenhelm, 2003), which is analogous to the Unit E deposits (Generation 2). BGS boreholes revealed that the upper part consists of fine-grained sediments, likely deposited in glaciolacustrine settings (Cameron et al., 1992; Cotterill et al., 2017b; Roberts et al., 2018). Although there is a strong association between the BCT members and Generations 1 and 2 incisions, it is apparent from the present study that these incisions represent two distinct valley systems, rather than successive stages of a single valley, as mentioned in the existing stratigraphy. Many authors attributed the formation of the valleys to subglacial erosion (Cameron et al., 1992; Dove et al., 2017; Ehlers and Wingfield, 1991). Some incisional features identified are capped by till reflecting deposition synchronous with glaciation, or infilled with glaciolacustrine sediments, showing proglacial conditions (Roberts et al., 2018). On Dogger Bank, the BCT Formation has also been interpreted to represent proglacial lake sediments, suggesting that these valleys may have also been created as a proglacial drainage network (Cotterill et al., 2017b; Emery et al., 2019a). However, the mapped valleys in this study are largely isolated, elongated depressions with uniform base levels and limited connectivity, which is inconsistent with the morphology of typical drainage systems and the radial nature reported by Cotterill et al. (2017b). This suggests that the formation of a proglacial drainage network is unlikely in this part of the area.

Unit F shows an irregular, hummocky reflection character consistent with the regional descriptions of the Twente Formation, which is interpreted as a late Weichselian periglacial deposit formed close to the

ice margin. Previous studies describe this unit as comprising wind-blown (aeolian) sands that overlie the Botney Cut, Dogger Bank and Eem Formations and are overlain by the Southern Bight Formation (Cameron et al., 1992; Rijdsdijk et al., 2005; Stoker et al., 2011), a stratigraphic relationship also observed here.

The acoustically stratified Unit G covers the deeper incisions. The base of the unit consists of a distinct network of Generation 3 channels, locally reoccupying and infilling the older incisions of Generations 1 and 2. Based on its geometry and distribution, Unit G is interpreted to represent the post-glacial sequence of the Elbow Formation, in agreement with published regional stratigraphic correlations. This formation is known to comprise early Holocene sediments that were deposited under brackish, intertidal or coastal conditions and comprise muddy sands with clay layers and regionally basal peats (Cotterill et al., 2017b; Fitch et al., 2005; Stoker et al., 2011). To the east and south of the study area, a series of similar channel networks has also been identified as being infilled with BCT and Elbow Formations (Andresen et al., 2022; Coughlan et al., 2018; Hepp et al., 2017; Roberts et al., 2018), suggesting that the incision and infill mechanisms were active on a much larger scale.

The uppermost Unit H represents homogeneous and acoustically stratified deposits associated with the Holocene marine sequences of the Southern Bight Formation (Cotterill et al., 2017b; Rijdsdijk et al., 2005; Roberts et al., 2018; Stoker et al., 2011). It unconformably overlies the glacial DBF deposits (Unit D) and the late-glacial to Holocene sequences of the BCT and Elbow Formations (Units C, E and G).

5.3. Limitations

Due to the lack of ground-truth data in this study, interpretations rely on seismic facies and regional correlations. A relative chronology for the features was derived based on their stratigraphic level, a method also used in similar geomorphological studies (Kirkham et al., 2021; Kristensen et al., 2007; Ottesen et al., 2020; Stewart et al., 2013), with MIS correlations remaining interpretative and are not based on direct ground-truth or absolute dating. Although the 2D dataset provided detailed cross-sectional views of the incision systems, its spatial coverage was locally limited by the large extent of the study area. This data limitation introduces uncertainty in interpreting Generation 1 as subglacial meltwater features, given the absence of evidence for an undulating thalweg, highlighting the need for additional data to confirm this interpretation. The 2D dataset's insufficient spatial coverage hindered continuous mapping of buried features, reducing the ability to capture their full geometries and morphologies accurately. This also prevented the production of thickness maps for each generation, as the extent and continuity of the incisions could not be reliably constrained, particularly for Generations 1 and 2, which also may have resulted in incomplete mapping in some locations (Fig. 10B). To mitigate this, multiple adjacent time slices from the 3D dataset were incorporated to illustrate their complete spatial configuration. The 3D data quality also introduced uncertainties, particularly where features exhibited overlapping or reoccupation. Mapping incisions spatially extending in the same positions but at varying intervals became more challenging due to amplitude changes and data gaps. The poor resolution of the 3D cross-sections prevented accurate measurements of the dimensions and stratigraphic characteristics of incisions (Fig. 6B). These limitations were partially overcome by performing cross-validation with intersecting high-resolution 2D profiles, which provided additional constraints to ensure robust measurements and interpretation (Fig. 6A). Overall, the integration of 2D and 3D mapping has proven a highly effective strategy for depicting a better spatial extent, morphological and stratigraphic characteristics and evolutionary trends of the incision systems. Combining mapping with PCA analysis and clustering has enabled an objective classification of incisions, making this framework a powerful tool for characterising these features in greater detail. It is proposed that the integrated approach applied here can be transferable to other

offshore settings where multiple generations of incision are present, provided that sufficient 2D and 3D seismic coverage, high-quality datasets, and adequate stratigraphic control are available, as demonstrated in this study.

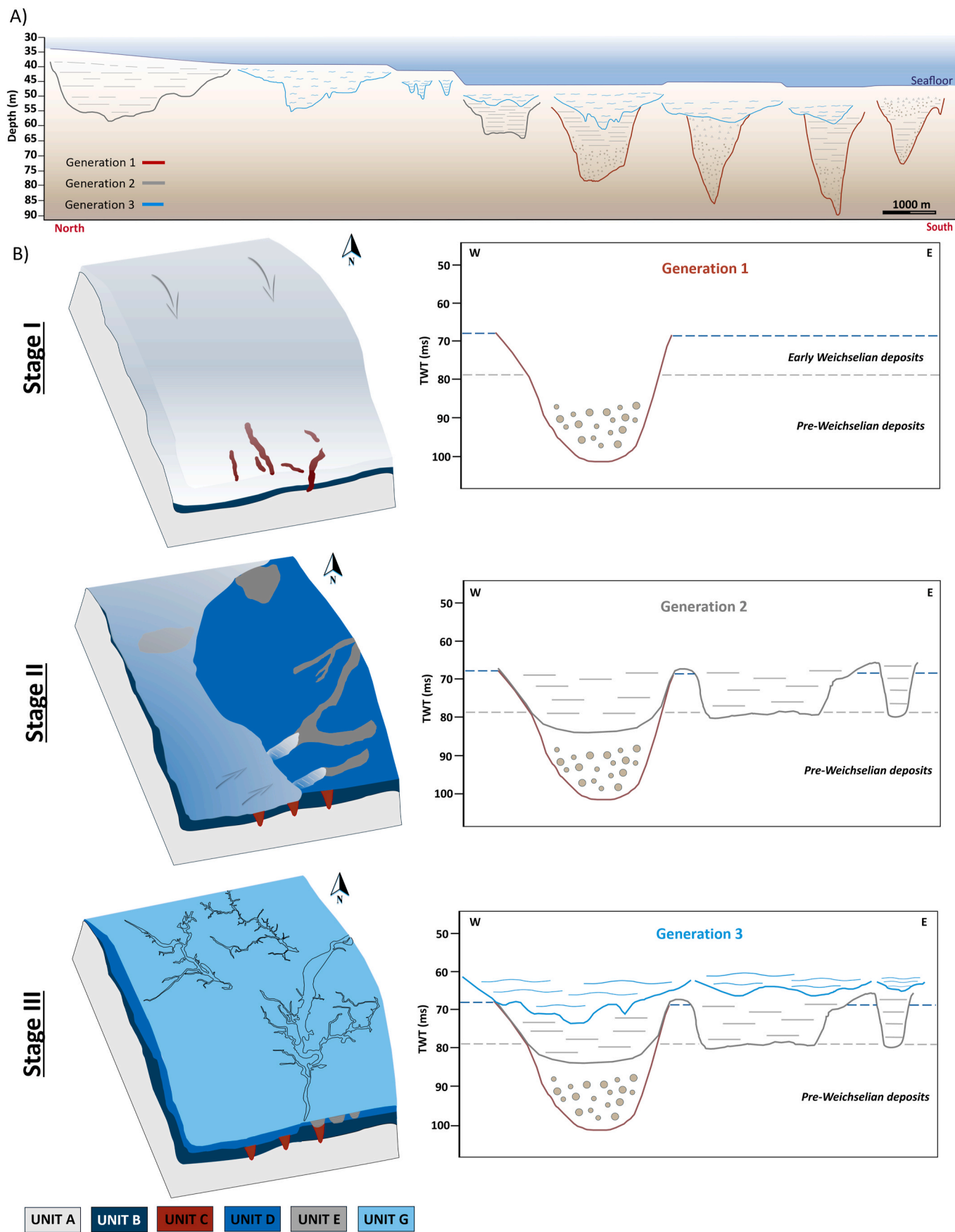
5.4. Stages of landscape evolution

The key advances of this study are the recognition of three distinct generations of incisions preserved south of Dogger Bank through an integrated morphometric and stratigraphic workflow, together with the refinement of the existing Botney Cut Formation framework by demonstrating its more complex nature and proposing the presence of two separate valley systems. Based on integrated stratigraphic interpretation, clustering analysis and detailed geomorphological mapping, a three-stage evolutionary model is suggested for the study area (Fig. 11). Due to the lack of direct ground-truth data and absolute age determinations, the proposed MIS chronology is relative, based primarily on correlation with the established stratigraphic framework and published ground-truth data.

5.4.1. Stage I: early subglacial incision phase

The oldest Generation 1 incisions are interpreted to represent an early phase of subglacial meltwater erosion, comparable in scale and morphology to small subglacial channels seen in other glaciated regions (Gibling, 2006; Moores, 1989; van der Vegt et al., 2012). Complex networks of subglacial channels (tunnel valleys) of multiple generations have been identified in the North Sea, most linked to the Elsterian, Saalian or Weichselian glaciation, but their ages are poorly constrained (Huuse and Lykke-Andersen, 2000; Kristensen et al., 2007; Ottesen et al., 2020; Stewart et al., 2013; Wingfield, 1990). In the southern North Sea, Weichselian valleys appear buried or remain exposed at the surface, often tending to be less extensive compared to the Elsterian and Saalian features (Ehlers and Wingfield, 1991; Huuse and Lykke-Andersen, 2000; Laban, 1995). The proposed subglacial valleys mapped in this study are smaller in scale than the tunnel valleys reported in the southern North Sea formed during earlier glaciations (Kirkham et al., 2024a,b; Lutz et al., 2009; Ottesen et al., 2020). Their significantly smaller dimensions compared to those from older glaciations, along with their seismo-stratigraphic position, support their formation during the Weichselian. On Dogger Bank itself, a previously described buried tunnel valley has been interpreted to be of Weichselian age based on its morphology and shallow burial depth, although its age is not firmly established (Fitch et al., 2005). It exhibits morphological similarities to Generation 1 valleys, but the mapped valleys of this study are characterised by shallower incisional depths. Smaller dimensions of Generation 1 valleys could be explained if they formed closer to the ice-sheet margin, where thinner ice could reduce the erosive capacity of subglacial meltwater (Cotterill et al., 2017b; van der Vegt et al., 2012).

Spatially restricted to the southern sector of the study area, encompassing the Oyster Ground and the eastern Outer Silver Pit, these Generation 1 valleys erode the basal Dogger Bank Formation (Unit B), while often the older Dogger Bank Formation (Unit D1) is found infilling part of the valleys. These units regionally are correlated with a pre-LGM ice advance (Cotterill et al., 2017b; Roberts et al., 2018), implying that the valley incision possibly occurred during MIS 3. The base of these valleys is generally attributed to the lower member of the Botney Cut Formation, but the infill composition appears less well documented. While some authors interpreted them to be infilled with the diamictites of the Botney Cut Formation (Stoker et al., 2011), others assign them to the diamictites of the Bolders Bank Formation (Cameron et al., 1992; Roberts et al., 2018). In contrast, the latter has been the focus of recent studies, providing more detailed stratigraphic and chronological information (Dove et al., 2017; Roberts et al., 2018). In this area, OSL dating on sediments lying above the Bolders Bank Formation suggested that the two diamict deposits beneath were deposited before 31.6 and 25.8 ka, respectively (cores 178VC and 179VC; Roberts et al., 2018), placing



(caption on next page)

Fig. 11. (A) A conceptual illustration of cross-sections showing the regional distribution and interaction of incision generation from North to South within the study area. (B) Schematic representation of incisions evolution from the last glaciation to the early Holocene in the areas SE of Dogger Bank and the Oyster Ground. **Stage I:** Linear V-shaped subglacial valleys formed beneath advancing ice during a pre-LGM glaciation phase. The inferred ice flow configuration is marked with grey arrows. Incisions erode into pre-Weichselian and Weichselian sediments, infilled at their base with diamictons (Generation 1). **Stage II:** U-to-trapezoidal valleys were created due to direct ice flow erosion during the LGM, with grey arrows showing the inferred flow configuration. Spatially, they coexist with Stage I, but stratigraphically at distinct levels, indicating formation during a separate glacial advance. They form a denser network of incisions, probably filled with glaciolacustrine deposits indicative of later phases of ice retreat in the region (Generation 2). **Stage III:** The youngest set of incisions, showing a complex interconnected system of channels formed under subaerial processes during the late glacial to early Holocene transition (Generation 3). Their infill likely reflects a fluvial, estuarine or tidal depositional setting. Together, these three stages reveal the polyphasic nature of channel incision, reflecting the shift from subglacial and direct glacial control to glaciolacustrine reworking, and then to post-glacial marine transgression.

their timing of deposition in MIS 3. Morphologically similar Weichselian subglacial channels capped by diamicton have been mapped south of Dogger Bank, proposing that incision of channels and diamicton deposits occurred contemporaneously (Dove et al., 2017; Roberts et al., 2018). Such relationships reflect sustained glacial influence in the area with repeated phases of ice advance and retreat prior to the LGM. Therefore, Generation 1 valleys likely formed during a glacial advance before the LGM, while the basal part of their infill, assigned to the lower Botney Cut member, could include reworked sediments from the Bolders Bank Formation.

Generation 1 valleys display a main NW-SE orientation, with secondary N-S and ESE-WNW trends, likely indicating an alignment primarily controlled by ice-sheet movement (Moreau et al., 2012). Subglacial channels (tunnel valleys) are typically aligned sub-parallel to former ice-flow directions and oriented roughly perpendicular to the ice margin in the southern North Sea (Huuse and Lykke-Andersen, 2000; Praeg, 2003; van der Vegt et al., 2012), although this orientation may differ in other regions (e.g., Ottesen et al., 2020).

Based on the findings of this work, it is proposed that Generation 1 incisions were initiated subglacially, near the ice margin, most likely during MIS 3. Their geographic positions imply that the ice sheet covered most of the study area at that time, while their orientation likely records the prevailing direction of ice flow, i.e. generally flowing from northwest to southeast, with some local deviations. Recently published reconstructions of the ice extent from 31 ka onwards in the North Sea differ in their interpretation of whether the ice reached the study area (Clark et al., 2022). Based on the optimum empirical reconstruction by Clark et al. (2022), the ice limit extended this far south only by 22 ka, whereas their maximum reconstruction suggests that the ice reached the study area as early as 31 ka (Fig. 1). While direct ages are lacking, the position of mapped valleys could represent evidence for a more extensive MIS 3 ice advance, in line with the published maximum reconstructions. Overall, this stage highlights the impact of early glacial erosion before the LGM in shaping the buried geomorphology of the wider area south of Dogger Bank.

5.4.2. Stage II: glacial phase (late Weichselian - LGM)

The Generation 2 valleys are inferred to result from erosion through direct movement of glacial ice, producing spatially broad, elongated valleys in the south and subrounded shapes in the north. Based on morphological characteristics, their formation is most plausibly associated with ice-marginal processes (Benn and Evans, 2010; Bennett and Glasser, 2009).

Stratigraphically, Generation 2 valleys occur above the confined Generation 1 features, and they are observed to incise the Weichselian deposits of the older and younger Dogger Bank Formation (Unit D). The older DBF (Unit D1) has been dated to 26.2 and 29.5 ka in previous studies (cores 150VC and 151VC; Roberts et al., 2018). As Generation 2 directly incises Unit D, their formation must postdate this deposit. Therefore, until more absolute dates become available, we tentatively attribute the creation of the Generation 2 valleys to ice advances during the LGM sometime after ca. 26 ka. Similar to the basin-like features mapped in the northern part, broad and irregular features eroding the top of the younger Dogger Bank Formation have previously been identified, with their origin still undetermined (Cameron et al., 1992) but

suggested to be related to glacial action near the ice margin. Recent reconstructions indicate that the last maximum extent of the North Sea Ice Sheet occurred around 22 ka, with the ice sheet advancing sufficiently close to the study area during that time (Batchelor et al., 2019; Clark et al., 2022; Dove et al., 2017; Sejrup et al., 2016). This is further supported by the existence of Generation 2 valleys, which provide geomorphological evidence for the presence of ice action in the study area near the LGM. As discussed earlier, the basins in the north show morphologies consistent with kettle holes or small-scale subglacial basins, implying erosional processes close to the ice margin (Bennett and Glasser, 2009). In the south, the mapped elongated features are linked to carving by direct ice flow, indicating that the maximum extent of the ice must have reached this part. If these elongated features prove to be ice-marginal meltwater channels instead, their formation still indicates direct ice involvement, showing the position of an ice margin in the area (Bennett and Glasser, 2009). Based on the orientation of Generation 2 valleys, ice movement might have occurred primarily in a SW-NE direction.

Regional indicators showed that ice flowed south to southeast along the east coast of England into the North Sea during the LGM (Boston et al., 2010; Boulton and Hagdorn, 2006; Busfield et al., 2015). Several advances and re-advances have been reported for the North Sea Lobe (Dove et al., 2017), with an eastward inferred flow configuration from Britain over Dogger Bank (Phillips et al., 2022; Sejrup et al., 2016). Although no direct flow indicators exist for this site, relationships between valley orientation and ice-flow configuration have been identified elsewhere, where glacial U-shaped valleys align parallel to the forward movement of ice flow (Lenz et al., 2023). The valleys in the southern part show a dominant SW-NE trend, possibly reflecting the dominant ice flow direction of this North Sea Lobe in the area during the LGM. Generation 2 occurs stratigraphically above Generation 1 incisions with overall different orientations but locally at similar spatial positions (Fig. 10A), implying a strong influence by pre-existing topography or easily erodible layers (Boulton and Hindmarsh, 1987; Hepp et al., 2012). V-shaped valleys overlain by U-shaped forms have been reported as a result of overdeepening during subsequent glacial re-occupation (Jørgensen and Sandersen, 2006; Kirkham et al., 2024a,b; Piotrowski, 1994). Although lateral widening of the older V-shaped Generation 1 by Generation 2 cannot be confirmed in this study, the scenario of a slight widening cannot be excluded.

The infill of the Generation 2 valleys (Unit E) is associated with the upper part of the BCT Formation, a parallel-bedded unit deposited in a glaciolacustrine setting in the late Weichselian (Cameron et al., 1992; Cameron and Holmes, 1999; Jeffery et al., 1989; Schroot and Schüttenhelm, 2003). Lacustrine sediments within this formation have been widely mapped in similar features in adjacent areas, suggestive of ice-marginal or deglacial proglacial conditions (Cameron et al., 1992; Cotterill et al., 2017b; Jeffery et al., 1989; Roberts et al., 2018). The laminated sediments composing this sequence indicate low-energy conditions, possibly deposited following ice retreat. During this phase of deglaciation, the landscape transformed into a proglacial environment (Fitch et al., 2005), filling valleys and depressions with glaciolacustrine deposits, recording the end of the last glacial period in this area.

Previous mapping efforts had already identified the Botney Cut valleys in this region (Fig. 10B) and had broadly attributed them to the

late Weichselian (Jeffery et al., 1989). The mapping in this study generally aligns spatially and stratigraphically with earlier observations (Cameron et al., 1992; Roberts et al., 2018). However, the integration of 2D and 3D seismic data, combined with quantitative clustering, has allowed a more detailed morphostratigraphic characterisation. The higher-resolution perspective reveals higher stratigraphic complexity than previously documented, demonstrating multiple episodes and processes of valley formation, rather than a single formative episode. Through re-evaluation conducted in this study, Generations 1 and 2 are seismically attributed to Botney Cut Formation members, but represent two distinct valleys, formed by different formation mechanisms. A holistic consideration of stratigraphic relationships, infill stages, and other orientations provided evidence for classifying the system as two separate systems, formed in distinct glacial phases. This interpretation was reinforced using time slices, which allowed the visualisation of complete morphologies showing association with two valley types (see comparison in Fig. 10B). Therefore, based on the updated mapping, spatial distribution, distinct orientations and more precise morphologies provided for each feature, we propose classification of the Botney Cut valleys into two generations in this area.

5.4.3. Stage III: late glacial-Holocene incision phase

The Generation 3 incisions are interpreted as a complex of large sinuous channel systems, originating under postglacial fluvial to estuarine or tidal conditions across an exposed landscape. Incising into the Weichselian deposits of the DBF Formation (Unit D) and the valleys of Generation 2, infilled with the Upper BCT Formation (Unit E), the infill of the youngest channels is linked to the Elbow Formation (Unit G). In the southern part, these channels are frequently observed incising into Unit F, attributed here to the periglacial aeolian deposits of the Twente Formation.

The Elbow Formation represents a transition from brackish intertidal to shallow marine settings, typically including basal peats overlain by brackish muddy sands and clays (Cameron et al., 1992; Cameron and Holmes, 1999; Stoker et al., 2011). On top, the channels are covered by marine deposits of the Southern Bight Formation. These features preserve diachronous transgressive deposits formed at ca. 8 ka (Stoker et al., 2011). This relationship suggests that the time of channel formation is consistent with the closing phase of the Weichselian and the early Holocene.

Sinuous channels with distinct morphological geometries, such as dendritic plan views, meanders, cutoffs, oxbow lakes and abandoned parts are common in fluvial landscapes (Leopold, 1964; Prins and Andresen, 2019). However, recent studies have shown that fluvial and tidal systems can share analogous planform morphologies (Gao et al., 2024 and references therein). A dendritic plan view geometry with tributaries is often observed within the area, where Channel 1 provides a typical example of this configuration (Fig. 8B and 9). Although it is usually challenging to distinguish tributary and distributary systems, Channel 1 likely exhibits a tributary system directing into the main channel in a SE direction. Distributary systems are mostly linked to deltas or alluvial fans, features that are absent in this study (Prins and Andresen, 2019). The main channels exhibit a south or southeast orientation with gentle slopes, indicative of a low-gradient setting. Based on their meandering morphology, these systems may have been formed under relatively lower energy conditions (Andresen et al., 2022). Also, they often exhibit a general asymmetry, a typical geometry of subaerial channel systems, suggesting some degree of lateral channel shift associated with their erosional development (Lewin and Macklin, 2003). The abandonment of the channel parts could reflect variations in the hydrological regime, possibly resulting from regional rising sea levels (Gaffney et al., 2007). The sub-parallel and continuous high-amplitude reflections of Generation 3 channel infills are indicative of a period of stratified deposition, likely driven by rising relative sea level (Andresen et al., 2022). In the North Sea, similar patterns were explained by a gradual transition from tidal to marine conditions (Hepp

et al., 2017; Prins and Andresen, 2019).

A large channel system has been mapped in the wider Dogger Bank and Outer Silver Pit area, with the majority showing a highly developed sinuous system with a predominant south-eastward trend (Gaffney et al., 2007). These channels are interpreted as a fluvial drainage system of the Late Pleistocene to Holocene incising into the Dogger Bank Formation, a relationship also observed here. Given their proximal location and comparable geometries, it is plausible that part of these channels shows an upstream continuation of the incisional features of Generation 3. The observed downstream direction suggests a north-to-south/southeast drainage direction towards the Outer Silver Pit and Oyster Ground, broadly consistent with the regional flow pattern proposed by Gaffney et al. (2007). Morphologically similar forms have been mapped on the Dogger Bank by other studies, with their origin also attributed to a meandering fluvial channel network (Andresen et al., 2022; Cotterill et al., 2017b; Fitch et al., 2005; Prins and Andresen, 2019). Alternative origins were discussed previously, where a brackish or estuarine setting was considered plausible. These major channel systems may also represent tidal mudflats or fluvial channels within a tide-dominated estuary, reflecting a possible fluvial-tidal interaction (Carling, 1981; Dalrymple et al., 1992; Fitch et al., 2005). At the eastern Dogger Bank, a channel system was hypothesised to have initiated in a fluvial setting with a later shift to estuarine, tidal and shallow marine environments (Andresen et al., 2022; Prins and Andresen, 2019).

Following the onset of the deglaciation phase, the Dogger Bank region experienced a period of major climatic and environmental changes, transforming the area into a dynamic postglacial setting (Cotterill et al., 2017b). Subsequent incision by the younger channel systems of Generation 3 reflects the post-glacial phase. Glacio-isostatic adjustments and drainage pathways following deglaciation (Prins and Andresen, 2019) caused the development of channels, reoccupying previously incised topographic lows (Fig. 11A). These channel networks developed before the complete marine inundation, which took place around 7.5 and 8 ka (Cohen et al., 2017; Cotterill et al., 2017b; Fitch et al., 2005; Sturt et al., 2013), during a period of stabilisation in tidal dynamics and minimal variation in tidal range from 6 ka to the present (Shennan et al., 2000). This shift shows the final transition to fully marine conditions, with processes that mirror the present-day North Sea system.

6. Conclusion

The approach of combining 2D and 3D seismic datasets has facilitated precise and coherent mapping of incisional features in the southern North Sea. Based on their stratigraphic architecture, morphology, and spatial distribution, three main generations of incisions were distinguished, revealing a significant heterogeneity in these buried Weichselian-Holocene systems (Fig. 10A and 11).

In this study, from a methodological perspective, stratigraphic and morphometric clustering analyses were employed as a means to objectivise the interpretation of different incisional generations. The results demonstrate systematic contrasts between generations and formation mechanisms, proposing three main stages of landscape evolution in the area (Fig. 11B). Generation 1 systems are linear, V-shaped depressions showing the deepest cuts among all generations, initiated as subglacial channels during a glacial period that occurred before the LGM (Stage I). As the stratigraphically oldest features, these valleys truncate early Weichselian and pre-Weichselian deposits, containing three stages of infill. However, uncertainties persist regarding the timing of formation, and the absence of thalweg measurements precludes confirmation of a subglacial origin by meltwater under pressure. Generation 1 channels display distinct N-S/NW-SE orientations and stratigraphic relationships reflect an ice advance that reached the area southeast of Dogger Bank and Oyster Ground likely during MIS 3. Higher in the stratigraphy, U-shaped to trapezoidal Generation 2 features appear incising the Weichselian glacial and periglacial deposits, carved by direct ice flow action around the LGM (Stage II). The presence of basin-like hollows in

the north and elongated valleys in the south reinforces the evidence of glacial marginal processes in the region. The SW-NE orientational trend of Generation 2 possibly reflects the regional ice-flow direction during the LGM advance in the southern part, and they most likely represent glaciolacustrine infill deposited in a deglacial or proglacial environment post-LGM. Together, Generations 1 and 2 exhibit multiple different erosional processes possibly occurring within the time window from MIS 3 to MIS 2, demonstrating that the area experienced various re-advances during this time. Although orientations of Generations 1 and 2 represent general trends rather than precise directional constraints. These two generations are resolved here as overlapping valleys, rather than a single valley as mapped in previous studies (e.g., Cameron et al., 1992; Jeffery et al., 1989) (Fig. 10B), highlighting a more intricate incision history than previously documented in the area. The last Weichselian to early Holocene transition is recorded by the presence of the younger, complex branching channel systems of Generation 3 (Stage III). These systems developed sinuous to meandering morphologies with their pathways tending to be partially controlled by pre-existing depressions. Their formation likely reflects reoccupation of the landscape under subaerial conditions, presenting either a fluvial origin or a more distal estuarine or intertidal environment.

The lack of ground-truth data, together with data gaps and lower-resolution coverage in some locations, introduce a degree of uncertainty in interpreting both the depositional environment of the features and timing. However, compared with earlier mappings, this study refines the spatial distribution of valleys and provides new quantitative constraints on their morphology and stratigraphic context, offering a more robust understanding of the late Quaternary landscape evolution of the southern North Sea.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All used 3D seismic data and survey information are available for download from NLOG, the Dutch Oil and Gas portal datacentre (<https://www.nlog.nl/datacenter>).

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