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The early Quaternary North Sea Basin

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Abstract: The onset of the Quaternary (2.58 Ma) corresponds to significant paleo-environmental events, such as the intensification and southward extension of Northern Hemisphere glaciation. In the North Sea Basin a significant late Cenozoic succession has been identified as a high-resolution archive of paleo-environmental changes during the Pliocene and Pleistocene. However, the identification of the base of the Quaternary has been a long-standing issue owing to lack of stratigraphic calibration. This study incorporates continuous, regional 3D seismic data with high-quality chronostratigraphic markers to map the base-Quaternary surface at high resolution across the entire North Sea. Depth conversion, backstripping, seismic geomorphology and sedimentation rate calculations are integrated to analyse the paleogeographical evolution of the North Sea Basin and its infill of *c.* 83×10^3 km^3 of northward prograding marine to deltaic sediments. The basin is 600 km long from SSE to NNW and largely localized above residual topography of the Mesozoic graben system. During the earliest Quaternary (2.58 – 2.35 Ma) paleo-water depths were *c.* 300 ± 50 m and solid sedimentation rates (calculated from 0% porosity) *c.* 32 km^3 ka^{-1}. The base-Quaternary provides an important marker for further studies of the changing environment of the Quaternary of NW Europe as well as resource and shallow geohazard analysis.

Supplementary material: A base Quaternary two-way travel time structure map is available at https://doi.org/10.6084/m9.figshare.c.3900343

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The onsets of cooling and widespread Northern Hemisphere glaciation at the Plio-Pleistocene transition are important markers for paleoclimate and paleo-environmental studies worldwide (Raymo 1994; Lisiecki & Raymo 2007). Climate records often vary strongly with latitude, and cooling trends such as the Plio-Pleistocene transition are often best preserved in mid- to high-latitude basins (Mudelsee & Raymo 2005; Rohling *et al.* 2012). In the North Sea Basin, a mid-latitude epicontinental basin, understanding the nature and extent of early Pleistocene cooling has previously been difficult owing to the poor definition and identification of the base Quaternary boundary. It has long been known that there is a considerable thickness (*c.* 1 km) of Quaternary deposits in the central North Sea (Holmes 1977; Cameron *et al.* 1987; Gatliff *et al.* 1994). However, the discrepancies among inconsistent lithostratigraphic and chronostratigraphic studies in the five bordering countries, combined with spatio-temporal changes in climate and sediment supply (Huuse 2002) and a strong glacial overprint, have impeded the accurate definition of the basal Quaternary (2.58 Ma) across the basin (Cameron *et al.* 1987).

Regional 3D seismic data acquired for deeper petroleum exploration have previously been used for glacial geomorphological studies on local to sub-regional scales (e.g. Praeg 1996, 2003; Kuhlmann & Wong 2008; Stewart & Lonergan 2011; Kristensen & Huuse 2012; Stewart *et al.* 2012, 2013; Moreau & Huuse 2014). The improved seismic resolution provided by these data has allowed previously hidden insights into the structure and stratigraphy of the Late Cenozoic succession. This study documents the shape and evolution of the earliest Quaternary North Sea Basin (2.58 – 2.35 Ma) through the integration of continuous, regional 3D seismic data with recent biostratigraphic studies from the southern North Sea. The Plio-Pleistocene boundary and sediment distribution patterns are accurately mapped across the entire central and southern North Sea for the first time. The newly mapped basin contains an expanded and largely complete record for paleoclimatological studies of the onset and history of glaciation in the Northern Hemisphere and will further contribute to an enhanced understanding of geohazards and resources constituted by shallow gas reservoirs.

Regional setting

The present-day North Sea is an epicontinental sea reaching average water depths of 100 m (outside the Norwegian Channel) and bordered by the NW European, Scandinavian and British landmasses. The North Sea Basin originated during episodic extensional rifting related to the unzipping of the Atlantic from the Paleozoic to the Early Cretaceous (Ziegler 1992). Rifting was followed by continuous subsidence throughout the Late Cretaceous and Cenozoic punctuated by basin inversion episodes during the Paleogene (Ziegler 1992; White & Lovell 1997; Stoker *et al.* 2005). The role of continued regional and local tectonic activity into the late Cenozoic is still debated. Most evidence favours a model of passive thermal subsidence enhanced by sediment loading in the central North Sea and marginal uplift owing to denudation and unloading of the Norwegian landmass (Huuse 2002; Nielsen *et al.* 2009; Anell *et al.* 2010; Goledowski *et al.* 2012).

In previous studies of the central North Sea, the early Quaternary stratigraphy in the North Sea has been mapped as one unit, the Aberdeen Ground Formation, of pro-deltaic to marine sediments (Gatliff *et al.* 1994; Stoker *et al.* 2011). The sediment was mostly sourced from the Rhine–Meuse and Baltic river systems of northern Europe and Scandinavia (Bijlsma 1981; Overeem *et al.* 2001; Busschers *et al.* 2007). The timing of onset of glaciation in the Quaternary remains unclear, although there is growing evidence for several ice sheet advances during the Middle and Late Pleistocene, sourced from the UK and Scandinavian landmasses (Graham *et al.* 2011), and evidence for iceberg scouring even in the southern North Sea Basin since the onset of the Quaternary (Kuhlmann *et al.* 2006;

Stuart & Huuse 2012; Dowdeswell & Ottesen 2013; Ottesen *et al.* 2014).

Data and methods

This study uses seismic stratigraphical and seismic geomorphological techniques (Mitchum *et al.* 1977*a*,*b*; Posamentier *et al.* 2007) to analyse a basin-scale 3D seismic dataset covering 128 000 km^2 of the central and southern North Sea. The study uses the continuous PGS central and southern North Sea and 3D seismic MegaSurveys with a subsampled bin size of 50 m and a sampling rate of 4 ms two-way travel time (TWT) to map the deepest part of the Quaternary North Sea Basin (Fig. 1). In areas not covered by the MegaSurvey, regional 2D seismic lines were used to resolve the basin shape. In the top 1.5 s TWT, the vertical resolution of the MegaSurveys is 8 – 16 m, whereas the vertical resolution of the 2D lines is between 10 and 18 m with variable line spacing between 1 and 15 km. Lithological descriptions, gamma-ray logs and time–depth calibration curves were accessed from a regional database of both public and private domain data provided by TNO and TGS respectively.

The base Quaternary stratigraphic surface, taken as 2.58 Ma, was correlated to a well-defined and continuous seismic reflection trough using the Dutch North Sea well A15-03, for which very detailed bio- and magneto-stratigraphic dating is available in the public domain (Kuhlmann *et al.* 2006; see discussion below). The horizon was picked at the well tie and then mapped down the depositional dip of the clinoforms into the basin, which minimized correlation errors to about half the dominant wavelength (20 – 35 m), using a diminishing grid size (200 m then 100 m then 50 m), which was then propagated in full three dimensions (Hart 1999). The base Quaternary was correlated and compared with the biostratigraphic record of the Josephine-1 well (Knudsen & Asbjörnsdóttir 1991), which is commonly used as a reference point for studies of the UK Continental Shelf (UKCS) Quaternary (Fig. 2), as well as Cenozoic studies from the southern North Sea including those by Thöle *et al.* (2014) for the German sector and Nielsen *et al.* (2008) for the Danish sector (Table 1). The mapped horizon was converted to a gridded surface with a 100 m interval and seismic attributes such as instantaneous and root mean square (RMS) amplitudes were extracted across the horizon to investigate evidence for paleogeographical context using seismic geomorphology. To convert the surface from TWT to depth, calibrated TWT–depth data from 1122 wells from the UK and Norwegian North Sea were plotted to find a simple but robust depth conversion equation (equation (1)) with defined data variability (Fig. 3):

$$\text{depth (m)} = 80.81 \times \text{TWT (s)}^2 + 863.85 \times \text{TWT (s)} + 25.91(\pm 120\ \text{m}). \quad (1)$$

Subsidence owing to differential loading and compaction leads to exaggeration of clinoform slopes as maximum deposition occurs on the slope rather than the topsets. Therefore the time–depth conversion or thickness maps alone cannot accurately estimate paleo-water depth. To provide realistic water depth estimates from buried clinoforms, they need to be back-rotated so their topsets are approximately horizontal and their height is de-compacted (Pekar *et al.* 2000; Patruno *et al.* 2014).

In this study, a series of transects representing the overall structure of the basin were identified for decompacting the sediment package and backstripping the clinoform heights. The sedimentary infill of the basin was first split into four seismic stratigraphic packages bounded by dated surfaces at 2.58, *c.* 2.35, 1.94, 1.1 and 0 Ma. The youngest or shallowest package (1.1 Ma to present day) was

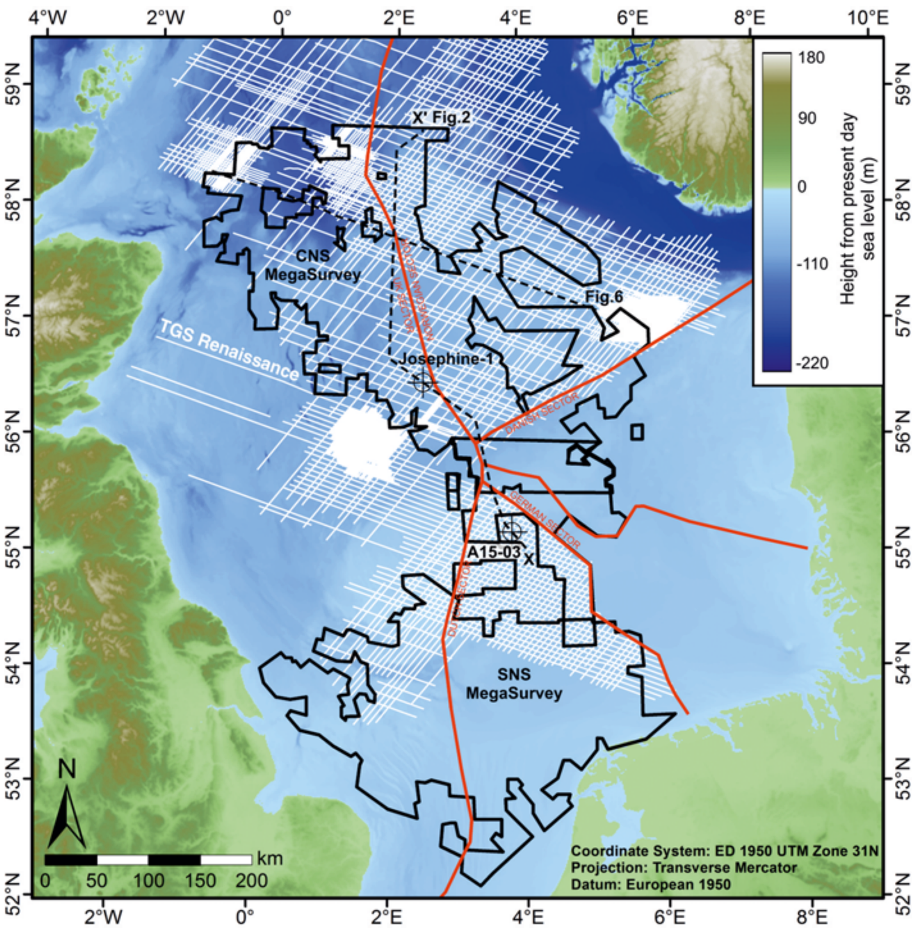

Fig. 1. Location map and datasets. Data shown are the PGS central North Sea and southern North Sea 3D seismic MegaSurveys, the TGS North Sea Renaissance 2D lines and the locations of the Josephine-1 and A15-03 wells used for dating of the basal Pleistocene. Bathymetry and topography data from Ryan *et al.* (2009). Location of Figures 2 and 6 seismic sections are indicated.

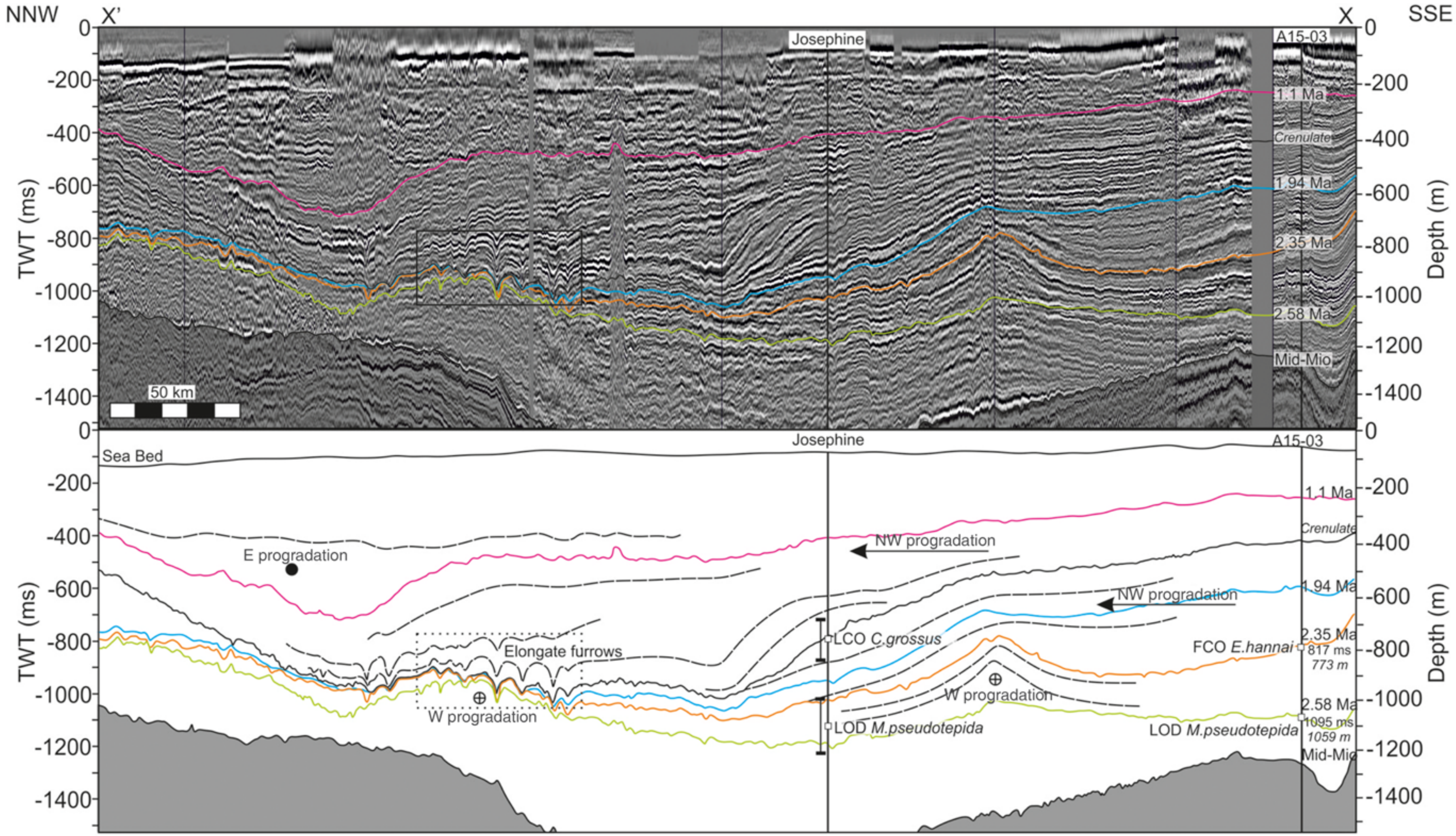

Fig. 2. Seismic section and line interpretation, at 75× vertical exaggeration, showing the location of Josephine-1 and A15-03 wells plus surfaces for the mid-Miocene (*c.* 17 – 14 Ma), 2.58 Ma (base Quaternary), 2.35, 1.9 and 1.1 Ma (base-Jaramillo paleomagnetic event). Key biostratigraphic events from Josephine-1 well identified after Knudsen & Asbjörnsdóttir (1991) with error range from depth conversion. Location is shown in Figure 1. FCO, first common occurrence; LCO, last common occurrence; LOD, last occurrence datum. Data courtesy of PGS.

Table 1. *Comparison of chronostratigraphic calibrations from five sectors of the North Sea, used in this study to identify the basal Quaternary surface*

Sector	Study	Marker	Well	Benthic Foraminifera	Unconformity	Date based on A15-03 (Ma)	Depth at A15-03 (mbsf)	Depth at Josephine-1 (mbsf)
UK	Knudsen & Asbjörnsdóttir (1991), Buckley (2012, 2017)	Crenulated reflector	Josephine-1	*Cibicides grossus*	n.a.	*c.* 1.8	400	771
Norwegian	Ottesen *et al.* (2014)	Base-NAUST	n.a.	n.a.	Top-Utsira unconformity	Cannot be correlated	Cannot be correlated	*c.* 950
Dutch	Kuhlmann *et al.* (2006)	Pollen climatic degradation	A15-03	*Monspeliensina pseudotepida*	n.a.	2.58	1059	1096
Dutch	Kuhlmann *et al.* (2006)	MIS 92	A15-03	*Melonis affinis*, *Elphidiella hannai* & *Cassidulina* assemblage	n.a.	*c.* 2.35	773	980
Danish	Nielsen *et al.* (2008)	Neogene–Quaternary hiatus	n.a.	n.a.	Southern North Sea regional unconformity	2.58	1059	1096
German	Thöle *et al.* (2014)	Dinocyst assemblage *I. multiplexum*	B-15-3, G-5-1, G-11-1	n.a.	Southern North Sea regional unconformity	2.58	1059	1096

Studies include Knudsen & Asbjörnsdóttir (1991); Kuhlmann *et al.* (2006); Nielsen *et al.* (2008); Buckley (2012, 2017); Ottesen *et al.* (2014) and Thöle *et al.* (2014). mbsf, metres below seafloor; n.a., not analysed.

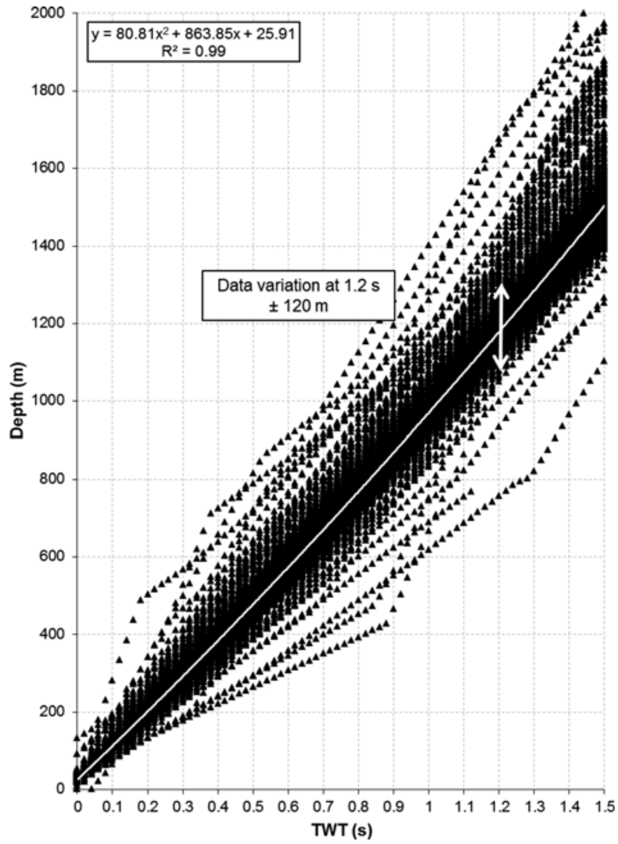

Fig. 3. Calibrated depth plotted against TWT for top 1.5 s TWT in 1122 wells across the UK and Norwegian sectors of the central North Sea MegaSurvey with regression line and R^2 value for depth conversion as well as maximum error margins. Data courtesy of TGS.

decompacted first along the chosen transects, using the decompaction equation of Allen & Allen (2013):

$$y'_2 - y'_1 = y_2 - y_1 - \frac{\phi_0}{c}\left(e^{-cy_1} - e^{-cy_2}\right) + \frac{\phi_0}{c}\left(e^{-cy'_1} - e^{-cy'_2}\right) \quad (2)$$

where y_1 is the depth to the top of the sediment layer, y_2 is the depth to the bottom of the sediment layer, y'_1 is the depth to the top of the decompacted sediment layer, y'_2 is the depth to the bottom of the decompacted sediment layer, ϕ_0 is the porosity of the sediment at the surface and c is a constant that defines the curve representing the change of porosity with depth. The values for ϕ_0 and c are taken from empirically derived values for sandy-shale lithology in the North Sea at 0.56 and 0.39 respectively (Allen & Allen 2013).

The decompacted package was then backstripped using a simple Airy isostasy model and the strata below were unloaded accordingly. The process was repeated with each of the successive packages, in turn restoring the early Quaternary surfaces and finally the base Quaternary surface to its approximate structure at 2.58 Ma. This backstripping method is simple and robust but does not account for complexities such as eustatic changes, flexural responses to the sediment load, or heterogeneity of sediment within the packages, and should be taken as a first-order estimate. Many of the parameters for modelling such complexities are either unrealistic at a basin-wide scale (e.g. because of local variations in sedimentology) or poorly constrained (e.g. the flexural rigidity of the lithosphere), making more detailed calculations beyond the scope of this paper.

Sedimentation rates for the Quaternary were calculated from sediment thickness maps between the four seismic stratigraphical packages (2.58 – 2.35, 2.35 – 1.94, 1.94 – 1.1 and 1.1 Ma to present day). The volume of the principal depocentre was found and then compacted to a solid sediment volume (0% porosity) based on a standard porosity depth curve from Marcussen *et al.* (2010). From the solid sediment volume the average sedimentation rate for each period was calculated in cubic kilometres per thousand years.

The strata immediately below the base Quaternary surface were interpreted with regard to the age of the subcrop to identify features influencing the evolution of the earliest Quaternary basin. The mapping of the subcrop followed a standard geological mapping process in which geological contacts between units in contact with the base Quaternary surface were mapped on regional seismic lines and then interpreted across the study area to form a complete map. Seven geological units were identified according to the seismic packages defined by Evans *et al.* (2003) and included Mesozoic, Paleocene, Eocene, Oligocene, lower Miocene, middle–upper Miocene and Pliocene.

Chronostratigraphic calibration

In seismic reflection data from the UK sector of the central North Sea, the 2.58 Ma base Quaternary is usually identified as either the 'crenulated reflector' (Holmes 1977; Gatliff *et al.* 1994; Stoker *et al.* 2011), which is not regionally extensive, or the southern North Sea regional unconformity. The southern North Sea unconformity changes into a correlative conformity along the Plio-Pleistocene clinoform slope. Cameron *et al.* (1987, p. 46) stated: 'The base of the Quaternary is less easily identified in the centre of the North Sea Basin … The seismic boundary which we have used to define the base of the Quaternary offshore is almost certainly diachronous.'

Attempts at mapping into the UK sector from the Norwegian sector by Ottesen *et al.* (2014) identified the base Quaternary as equivalent to the base-NAUST at 2.7 Ma. This method correlated the two through the locally extensive unconformity at the top of the Upper Miocene to Lower Pliocene Utsira Formation, but this relationship assumes that middle to late Pliocene deposits are absent, which is not the case (Eidvin *et al.* 1999). Towards the southern half of the basin the Quaternary is preceded by an extensive Pliocene wedge (Cameron *et al.* 1992; Rasmussen *et al.* 2005; Thöle *et al.* 2014; Harding 2015; Table 1).

The identification of the basal Quaternary in the southern North Sea has been subject to recent integrated chronostratigraphy studies of the late Cenozoic. The chronostratigraphy of Kuhlmann *et al.* (2006) in Dutch exploration well A15-03 (55°18′N, 3°48′E; Fig. 1) can be correlated to the work of Köthe (2007, 2012) and Thöle *et al.* (2014) in the German sector of the North Sea, Nielsen *et al.* (2008) and Rasmussen *et al.* (2005) in the Danish sector, and Noorbergen *et al.* (2015) onshore Netherlands (Table 1; Harding 2015). The correlation provides a robust calibration across the topsets of the clinoform system, beyond the reach of the southern North Sea regional unconformity. The 2.58 Ma base Quaternary, as defined by Kuhlmann *et al.* (2006), is identified by an event in the pollen record that correlates with the climatic degradation at the Plio-Pleistocene transition, the paleomagnetic Gauss–Matuyama transition and the last occurrence of the benthic foraminifera species *Monspeliensina pseudotepida* (Table 1).

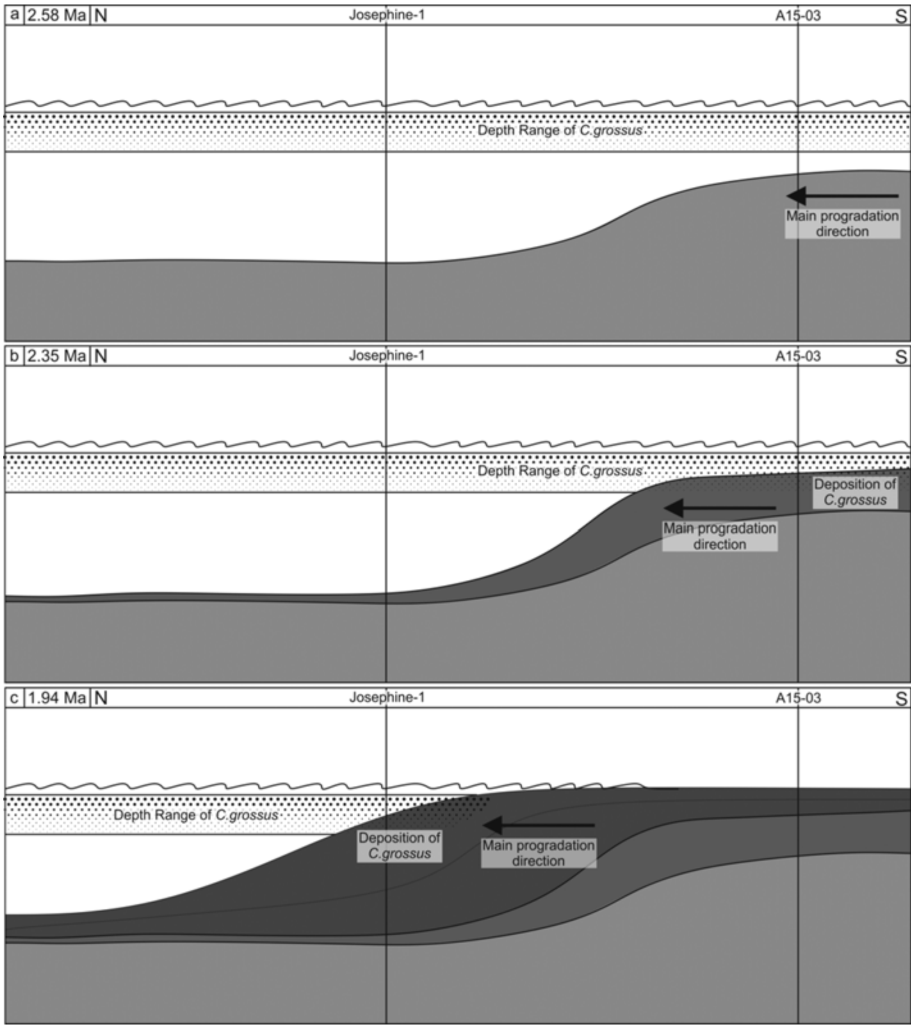

Fig. 4. Schematic illustration demonstrating the effect of rapid progradation during the earliest Quaternary on the distribution of depth-dependent benthic foraminifera species *Cibicides grossus*. (**a**) 2.58 Ma; *C. grossus* was not deposited in either well A15-03 or in Josephine-1. (**b**) 2.35 Ma; deposition of species closely related to *C. grossus* occurs in A15-03, indicating preferential depths for the species. (**c**) 1.94 Ma; progradation has extended significantly and deposition of *C. grossus* now occurs at Josephine-1 whereas A15-03 is close to or completely subaerial owing to infill of the basin.

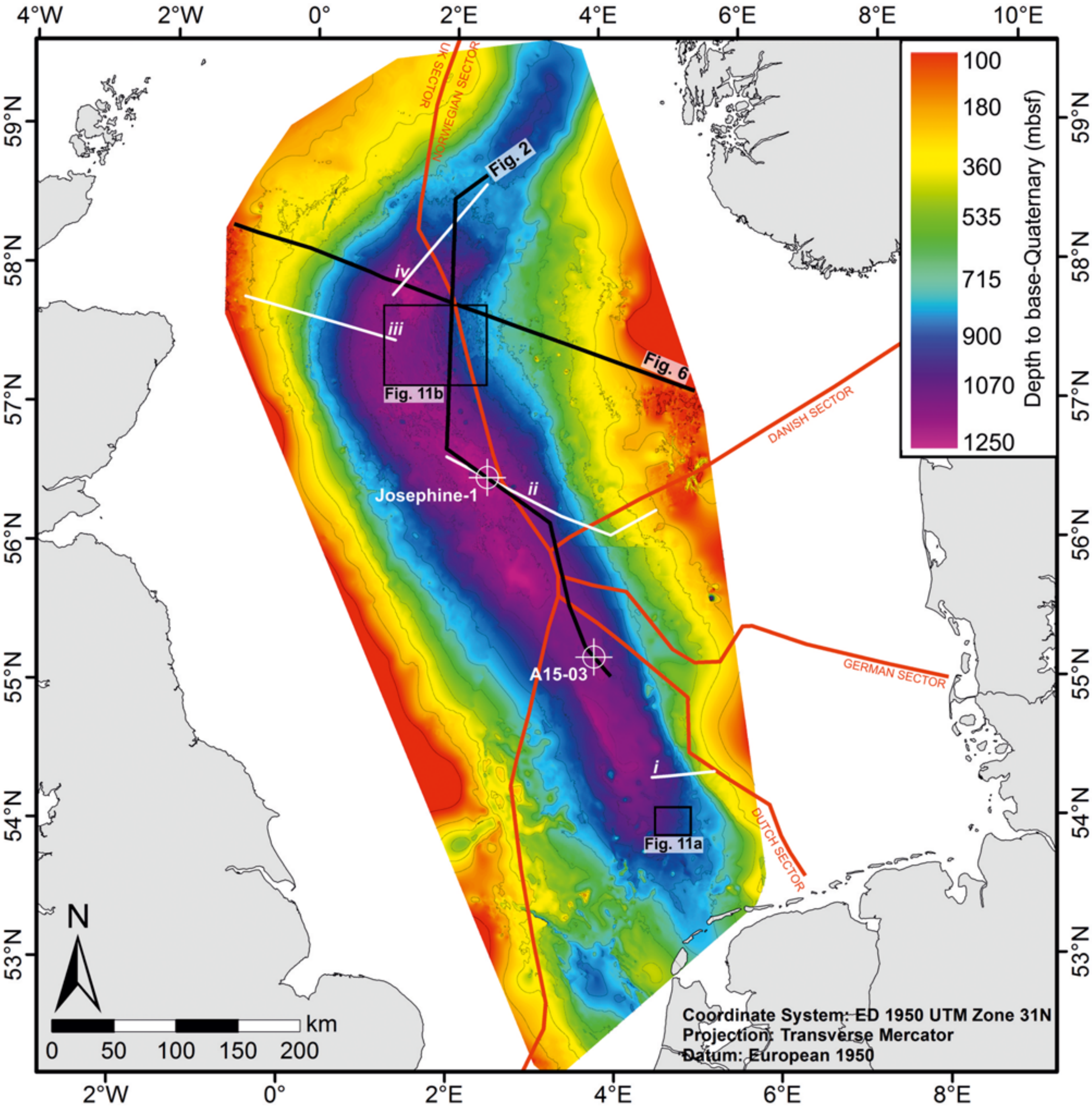

Fig. 5. Depth converted 2.58 Ma surface using velocity function derived in Figure 4. Contours are every 100 m. Locations of Josephine-1 and A15-03 wells, the seismic sections in Figures 2 and 6, transects for Figure 9i–iv and geomorphological features shown in Figure 11 are shown.

The extensive work on the southern North Sea has yet to be correlated northwards into the UK and Norwegian sectors of the North Sea; however, the agreement between multiple studies from across all three regions of the southern North Sea makes it a strong contender for solving the issues of mapping the basal Quaternary across the central North Sea. Correlating from the southern North Sea into the central North Sea involves mapping the clinoforms downdip in the direction of progradation into the basin, which reduces the risk of mapping errors, and allows correlation of the clinoform geometries to well log and core sample data in the central North Sea, notably the Josephine-1 well (56°36.11′N, 2°27.09′E; Fig. 1), which has a complete biostratigraphic record for benthic foraminifera species (Knudsen & Asbjörnsdóttir 1991). The correlation allows the *M. pseudotepida* event to be checked to ensure its preservation through mapping, within the depth conversion error range.

For comparison, the basal Quaternary as defined at Josephine-1 by Knudsen & Asbjörnsdóttir (1991) and correlated to the ‘crenulate reflector’ by Buckley (2012, 2017) using the first occurrence of benthic foraminifera species *Cibicides grossus*, was also mapped across the dataset. *C. grossus* was identified as a marker species for the North Sea by King (1983), who calibrated *C. grossus* and its related species *Elphidiella hannai* to the Gauss–Matuyama Reversal, and hence the 2.58 Ma boundary. The *C. grossus* event is known to be diachronous across the North Sea Basin owing to the depth dependence of the species but is still considered, in mid- to outer-neritic environments (i.e. the clinoform topsets of the southern North Sea) to correspond to the onset of the Quaternary (King 2016; Fig. 4). The *C. grossus* event mapped from the Josephine-1 well south towards A15-03, however, correlated more closely with a date of 1.94 Ma based solely on seismic geometries from the 3D mapping (Table 1; Figs 2 and 4). *C. grossus* was not present in A15-03 according to Kuhlmann *et al.* (2006). However, species such as *Melonis affinis* and *Cassidulina* species are observed in A15-03, which are known to exist in close association with *C.*

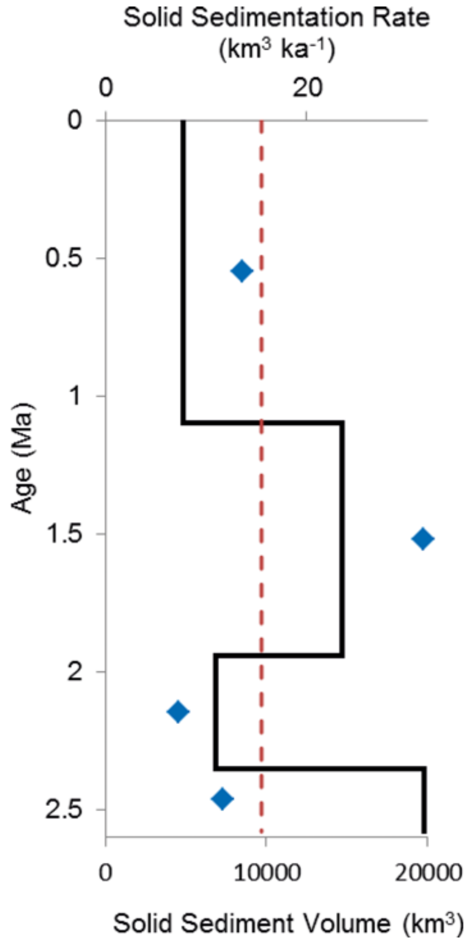

Fig. 6. Average solid sedimentation rates for the Quaternary period (2.58 Ma to present); black line represents sedimentation during the periods 2.58 – 2.35 Ma, 2.35 – 1.94 Ma, 1.94 – 1.09 Ma and 1.09 Ma to present day; red line represents average sedimentation rate between 2.58 Ma and present day. Blue diamonds indicate the total solid sediment volume for each of the four time periods.

grossus in the Danish offshore (Kuhlmann *et al.* 2006). The first common occurrence of *E. hannai* can also be used to define the interval in which *C. grossus* might be expected and is observed in A15-03 (King 1983; Table 1). The interval defined by these indicator species, in A15-03, corresponds to a date of *c.* 2.35 Ma, demonstrating the diachronous distribution of *C. grossus* (Table 1; Figs 2 and 4; Harding 2015).

It is likely that the difference between the *C. grossus* dates is due to the significant differences in water depth at the onset of the Quaternary across the basin. There is a north–south trend to the age of the first occurrence of *C. grossus*, which follows the progradation of the clinoforms and thus the progression of local water depths (Fig. 4). Thus, *C. grossus* is not considered to be a good marker for the basal Quaternary (King 2016). As the *M. pseudotepida* event is well preserved to the Josephine-1 borehole and correlated across the entire southern North Sea to the basal Quaternary, unlike *C. grossus*, this event was used to map the basal Quaternary across the rest of the basin for the first time (Figs 2 and 5).

The early Quaternary North Sea Basin

Basin structure

The base Quaternary event defined in the southern North Sea has been mapped across the southern and central North Sea Basin and depth converted according to the borehole-derived velocity function provided above (Fig. 5). The base Quaternary follows the structural form of the underlying Mesozoic Central Graben, with a central basin trough that is elongated NW–SE until 57°30′N, where the northern portion of the trough switches to a NE–SW trend. The maximum depth of the base Quaternary is 1248 ms TWT (1230 m). The minimum depth along the basin axis is 812 ms (781 m), found in the northernmost part of the basin, where a relatively shallow connection exists into the northern North Sea and eventually the North Atlantic. The central basin trough has a maximum width of 130 km and axial length of about 600 km. This surface defines the complete Quaternary depocentre, apart from a thin veneer present beyond the flanks of the trough. The volume of sediment within the trough is *c.* 83×10^3 km^3 (*c.* 40×10^3 km^3 solid sediment volume, Fig. 6).

The base Quaternary surface overlies Pliocene sediments, in the main part of the Early Quaternary intra-shelf basin, as shown by the subcrop section and map (Figs 7 and 8). The Pliocene is characterized by an expansive clinoform set which prograded from the south and east into the basin (Figs 7 and 8). This clinoform set, known as the Southern North Sea Deltaic Formation (Cameron *et al.* 1992; Stoker *et al.* 2011) constitutes a significant shelf system which continues to prograde NW and north well into the Quaternary period (Sørensen *et al.* 1997; Overeem *et al.* 2001; Thöle *et al.* 2014, Harding 2015). To the north and east of the basin, the Quaternary sediments unconformably overlie older formations, principally the Late Miocene to Early Pliocene Utsira Formation but also older strata from most of the Cenozoic and into parts of the Mesozoic towards the basin margins, reflecting the overall basin structure and the basin-fill history (Figs 7 and 8).

Clinoform height

The mapped base Quaternary surface has been progressively backstripped to produce transects of the changing basin geometry and architecture through time (Fig. 9). These results for the southern

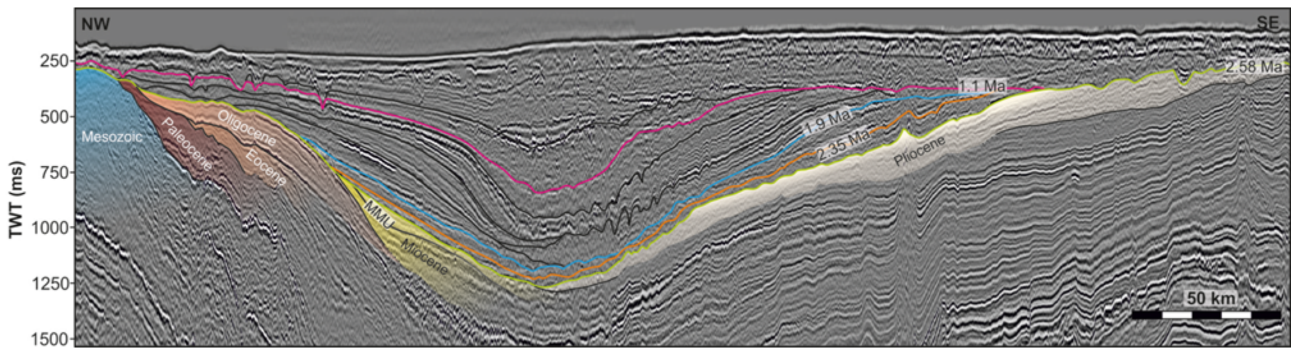

Fig. 7. Seismic section showing interpretation of subcrop beneath the 2.58 Ma surface used to produce subcrop map (Fig. 8). Packages separated by age after Evans *et al.* 2003. (See Fig. 1 for location.) MMU, Mid-Miocene Unconformity. Data courtesy of TGS.

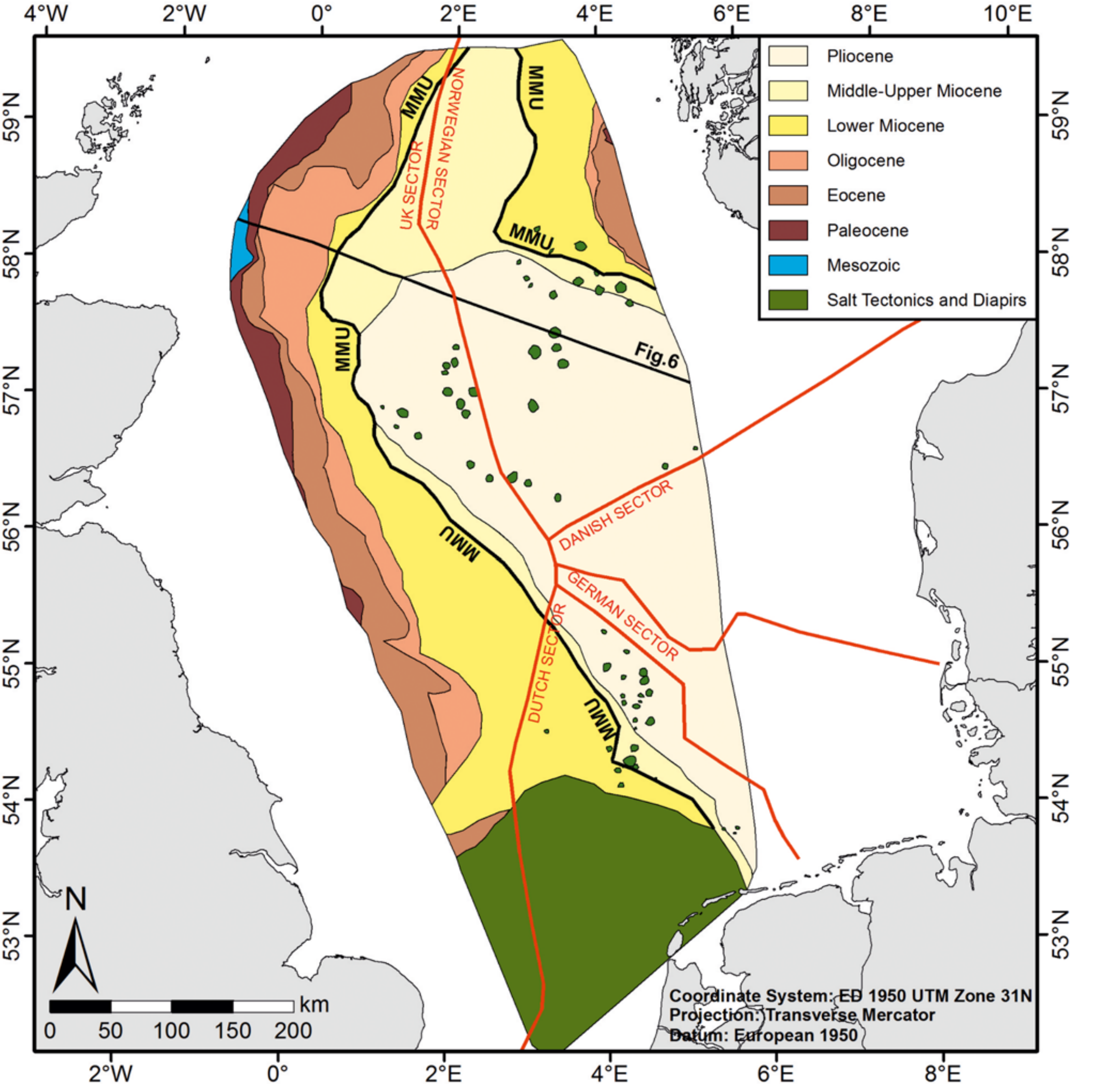

Fig. 8. Simplified map of the base Quaternary subcrop indicating areas of sediment hiatus particularly on the western side of the basin. In the southern North Sea the subcrop becomes extremely complex owing to the presence of large-scale salt tectonic features, which heavily disturb the seismic reflection correlated to the base Quaternary. MMU, Mid-Miocene Unconformity.

(Fig. 9i), central (Fig. 9ii) and northern (Fig. 9iii and iv) parts of the basin are discussed below.

Southern basin

The calculations indicate a maximum backstripped clinoform height at the onset of the Quaternary of 250 ± 50 m (Fig. 9i) in the southern part of the basin, although this reaches 300 ± 50 m away from the main transect. Between 2.58 and 2.35 Ma the southern clinoform set accumulated 480 ± 50 m of sediment as the clinoforms prograded 110 km westwards (Fig. 10), almost infilling the southernmost part of the basin by 2.35 Ma and resulting in a backstripped clinoform height of <20 m by 2.35 Ma. Progradation of the clinoforms follows this pattern with a progradation direction toward the SW until *c.* 2.35 Ma when the progradation direction of the southern clinoform set turns towards the NW (Figs 2 and 10a).

Central basin

The central part of the eastern clinoform set has an initial backstripped clinoform height of 200 m (Fig. 9ii) at the onset of the Quaternary. Between 2.58 and 2.35 Ma 70 m of sediment was accumulated (Figs 9ii and 10), producing a sigmoidal geometry with a backstripped clinoform height of 80 m. Progradation in the central part of the basin was in an eastwards direction, advancing to a maximum clinoform height of 50 m between 2.58 and 2.35 Ma.

Northern basin

The northern clinoform set consists of two parts, one to the NW and one to the NE (Fig. 9iii and iv); the northwestern part of the clinoform package is inherited from older Cenozoic clinoforms, which were not active during the earliest part of the Quaternary.

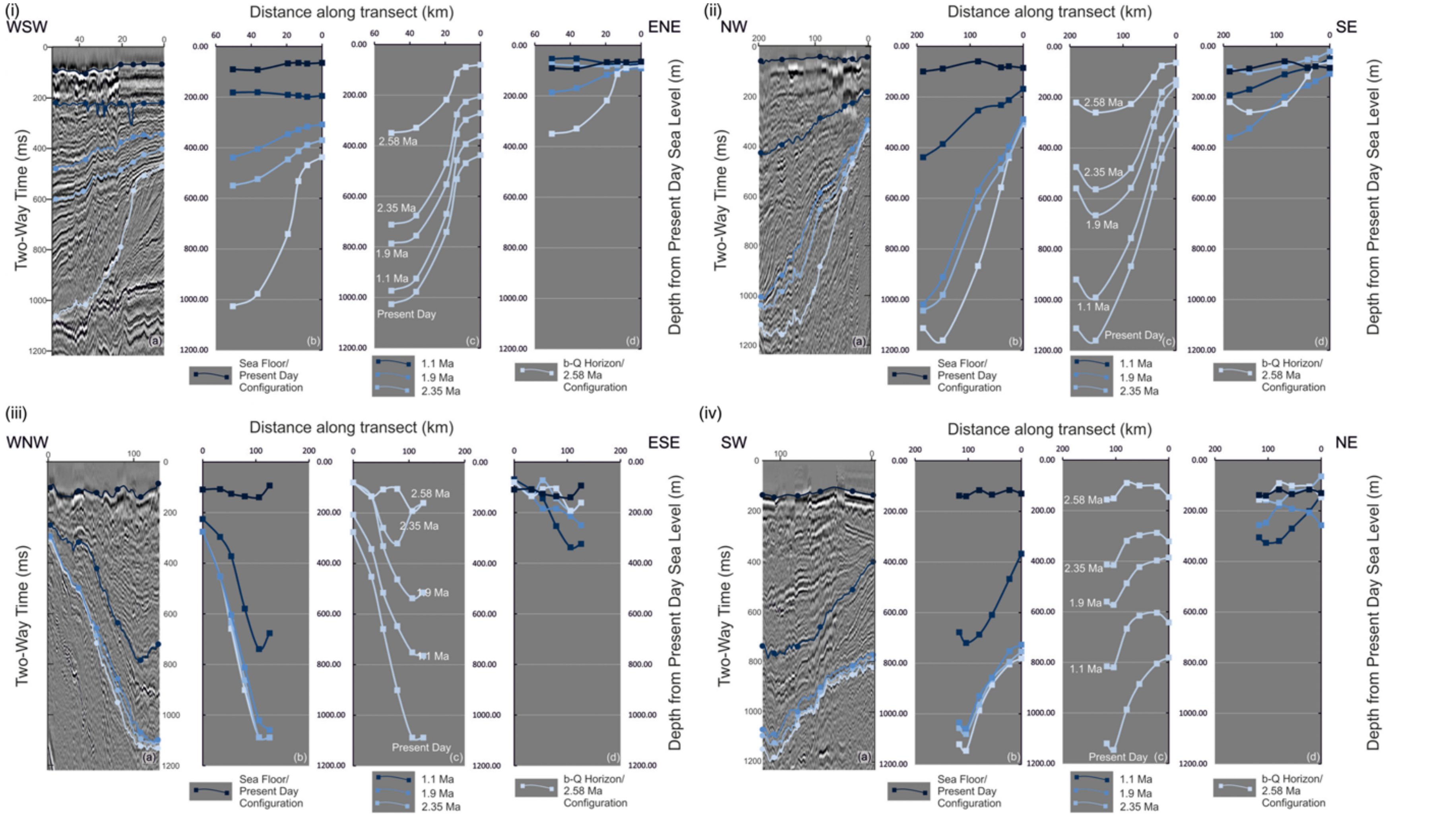

Fig. 9. Simplified sections from transects i–iv (locations shown in Fig. 5) used in the backstripping process; each point along the transect was used in the calculations and positioned according to distance along the transect. (**a**) Seismic data along the transect with current configuration of dated horizons, courtesy of PGS. (**b**) Simplified current configuration of dated horizons. (**c**) Burial history of the base Quaternary horizon. (**d**) The changing backstripped basin configuration through time.

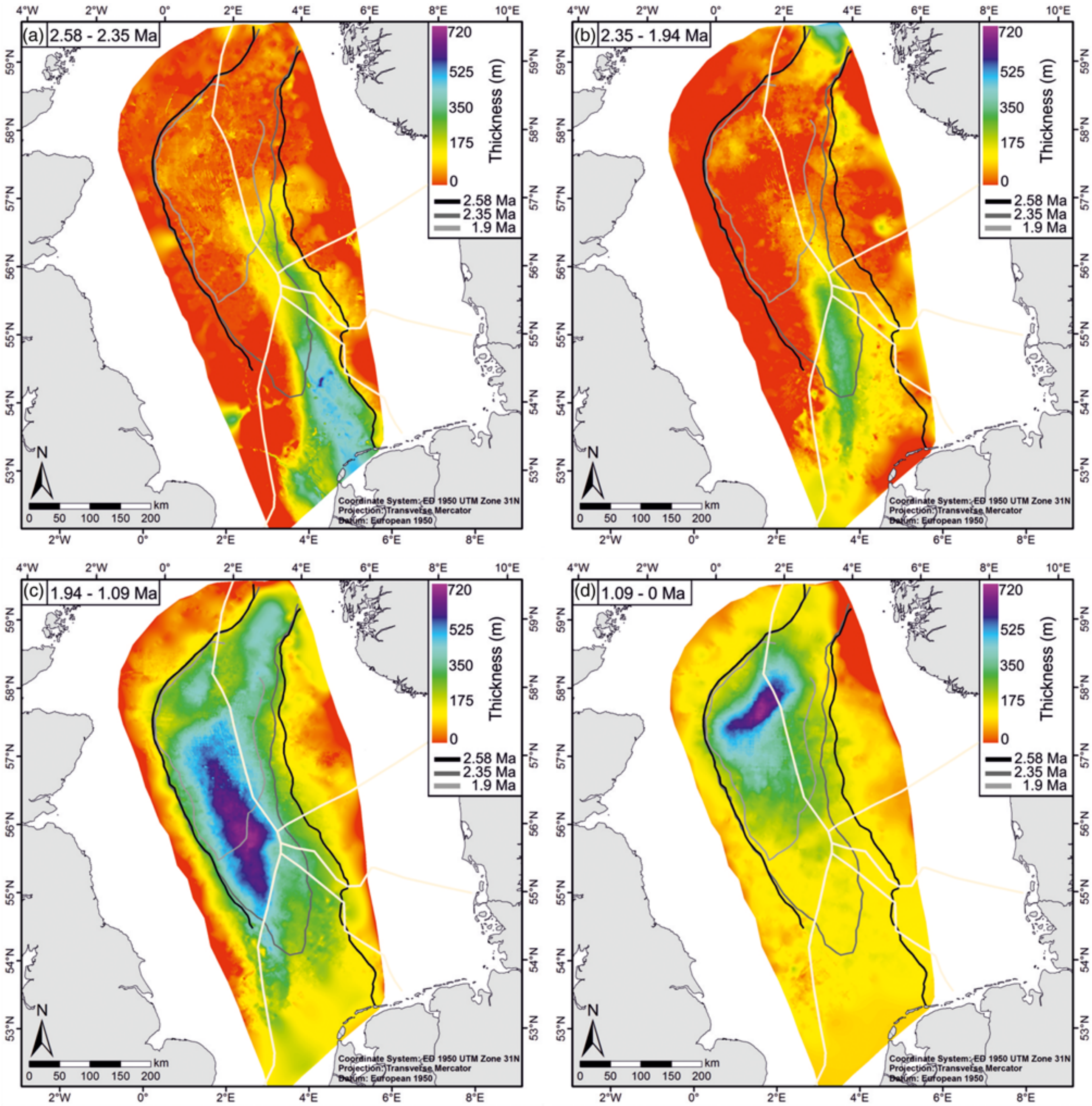

Fig. 10. Present-day thickness maps of compacted Quaternary strata used to estimate sedimentation rates: (**a**) 2.58 – 2.35 Ma; (**b**) 2.35 – 1.94 Ma; (**c**) 1.94 – 1.09 Ma; (**d**) 1.09 Ma to present-day sea floor. Location of clinoform breakpoints at 2.58, 2.35 and 1.94 Ma is shown.

Backstripped clinoform heights at the onset of the Quaternary are in the region of 110 m and remain so until after 2.35 Ma. To the NE, the clinoforms are flatter, almost horizontal, and form part of the shallow sill connecting the North Sea Basin to the North Atlantic. Here backstripped clinoform height is minimal at the onset of the Quaternary, increasing to 100 m by 2.35 Ma. The northern clinoforms do not prograde between 2.58 and 2.35 Ma.

Sedimentation and basin infill

Borehole lithological descriptions indicate that the late Pliocene and early Quaternary sediments of the North Sea consist of sequences of fine clay to silt with infrequent sands. Gamma log responses are found to be typical of mudstones (FMB v3.4 2014; 60 – 150 API; Rider 2002), in agreement with previous descriptions of the Quaternary Aberdeen Ground Formation as deltaic to marine muds (Cameron *et al.* 1987; Gatliff *et al.* 1994; Stoker *et al.* 2011). The sediment infill is observed to form three geographically separate clinoform sets of differing provenance, one to the south prograding first west and then NW, one to the east prograding westwards before merging with the southern set, and another to the NW, which progrades broadly southwards during the Quaternary. The clinoforms vary between high-angle (4 – 5°) sigmoidal or oblique reflections with well-defined break points, principally in the southern clinoform set between 2.58 and 2.35 Ma, to very low angle (<0.5°), in the northern clinoform set and in the southern set post-1.94 Ma (Fig. 9). Each clinoform represents a suite of paleo-environmental conditions, from the shallow shelf to the bathyal environment, with associated variations in sediment grain-size distribution (Posamentier & Allen 1993; Stuart & Huuse 2012; Patruno *et al.* 2014, 2015).

The three clinoform packages formed two main depocentres, with the southern and eastern clinoform packages sharing one extensive depocentre in the south and centre of the basin and the northern clinoform package consisting of a smaller depocentre to the north

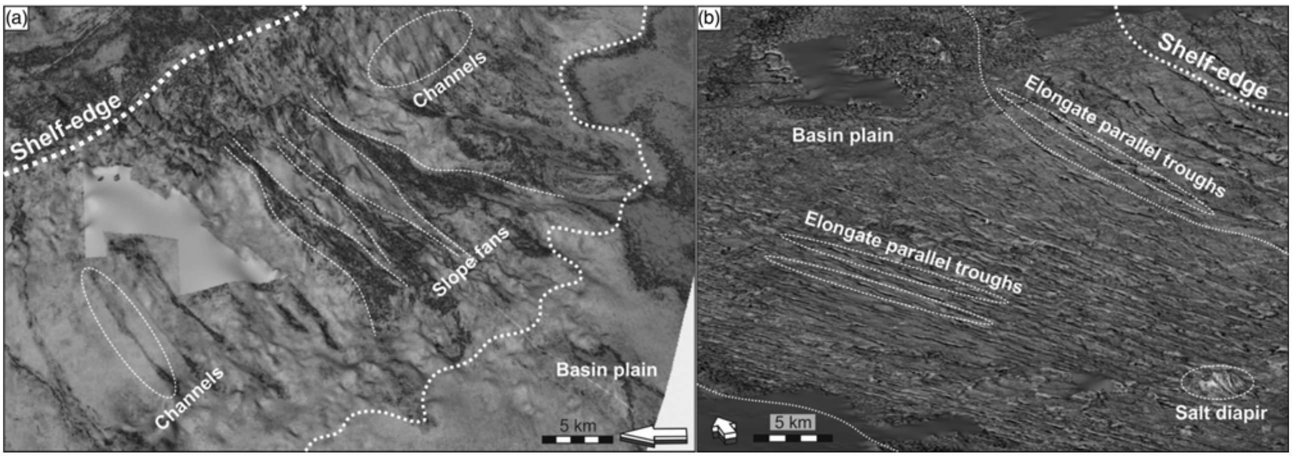

Fig. 11. (**a**) Seismic amplitude extraction of horizon within the earliest (2.58 – 2.35 Ma) Quaternary package in the southern North Sea showing downslope channels and fan deposits on the clinoform slopes and toesets. (**b**) Seismic amplitude extraction across base Quaternary (2.58 Ma) surface in the central North Sea showing elongate, semi-parallel furrows linked to deep-water processes.

(Fig. 10). The northern depocentre was not active during the very earliest Quaternary (2.58 – 2.35 Ma; Table 1) and only began to show signs of deposition from 2.35 Ma, merging with the southern depocentre by 1.94 Ma (Fig. 10c). The southern depocentre covers an area of just over 6000 km^2, defined by the 40 m thickness contour, with a solid sediment volume of over 7000 km^3, giving an average sedimentation rate for the earliest Quaternary (2.58 – 2.35 Ma) of 31.6 $km^3\ ka^{-1}$. In comparison, the entirety of the Quaternary saw an overall average sedimentation rate of 15.5 $km^3\ ka^{-1}$ (between 2.58 Ma and present day), with rates of 11 $km^3\ ka^{-1}$, 23.5 $km^3\ ka^{-1}$ and 7.7 $km^3\ ka^{-1}$ respectively for the periods of 2.35–1.94 Ma, 1.94–1.1 Ma and 1.1 Ma to present day (Fig. 6).

Paleogeography

Paleogeographical information is contained within borehole records of lithofacies and biostratigraphy coupled with seismic geomorphological evidence usually extracted from analysis of extractions of seismic attributes across the mapped surface. Features are interpreted relative to methods of formation and sorted by paleogeographical context; for example, slope channels (Fig. 11a) indicating modes of sediment distribution downslope.

In this study, seismic amplitude extractions of the base Quaternary surface reveal little evidence for slope features such as channels or basinal fans. Instead, the slopes of the base Quaternary surface are characterized by a relatively consistent, medium- to low-amplitude seismic facies with little evidence of facies changes between the roll-over and the slopes of the basal clinoform. The topsets of the clinoform package are typically strongly influenced by velocity effects from tunnel valleys in the overburden (Fig. 2a) or by survey imprints, although when clearly imaged in local areas the topsets do demonstrate a more chaotic seismic facies. Tunnel valleys are subglacial drainage conduits and are common in the Middle to Late Quaternary of the North Sea (Praeg 1996, 2003; Stewart & Lonergan 2011; Kristensen & Huuse 2012; Stewart *et al.* 2012, 2013; Moreau & Huuse 2014). Artefacts caused by tunnel valleys and survey imprints are relatively easily to detect by comparing reflection patterns through successive horizontal time slices, with systematically repeating patterns more likely to be artefacts. In vertical cross-sections, the topsets of the eastern clinoform package show small truncational depressions on the base Quaternary surface that are closely connected with a series of elongated, near-linear features with U-shaped cross-sections oriented broadly downslope in map and perspective views (Fig. 11b). The linear features imprint on the basal Quaternary surface in the deepest parts of the basin although they initially incise from a shallower horizon (Fig. 2). In comparison with the base Quaternary surface, horizons within the 2.58 – 2.35 Ma package show multiple preserved downslope channels and mass transport deposits on the slopes and toesets, principally in the southern portion of the Quaternary basin (e.g. Fig. 11a).

Discussion

Onset of the Quaternary

Structural mapping, backstripping calculations and seismic amplitude extractions of the basal Quaternary reflection reveal that the North Sea Basin, at the beginning of the Quaternary, consisted of an elongate basin, 600 km long, with maximum water depths in the region of 300 m. This basin is enclosed by the NW European landmasses on three sides, with a narrow marine connection to the north (Fig. 12). At the onset of the Quaternary the basin showed a distinct lack of slope features, such as mass transport deposits or downslope channels, with limited evidence for a change in facies between the topsets of the basin shelf and the slope. Mapping of the subcrop beneath the basal Quaternary horizon reveals a pattern of early Cenozoic sediments in the north and west of the basin gradually increasing in age towards the edge of the basin and forming an unconformity between the Quaternary basin infill and the older subcrop strata (Figs 7 and 8). Towards the south and east the slopes of the basin are formed of Pliocene clinoformal sediments and are conformable with the Quaternary basin infill (Figs 7 and 8). The primary reasons for the asymmetry in subcrop age relate to the regional structural controls of the underlying central graben and the eastern North Sea Basin offering greater accommodation to sediments supplied from around the basin and the relative sediment inputs through time between southern Norway, the Scottish mainland and NW Europe. These factors gave rise to the clockwise arrangement of clinoform breakpoints through the Cenozoic (e.g. Huuse *et al.* 2001), which set up the template on which the base Quaternary formed, with the southeastern part being a conformable continuation of the Neogene progradation from the Baltic region whereas the western and northern parts are characterized by greater hiati owing to erosion and onlap.

The structure of the subcrop leads to an asymmetry in the age of the underlying sediments (Fig. 7), which is likely to have some influence on the compaction pattern of the Quaternary sediments. The Pliocene subcrop was deposited quickly, retaining the potential to compact under the Pleistocene load; however, the Mesozoic and Paleogene strata to the NW are exhumed and thus already

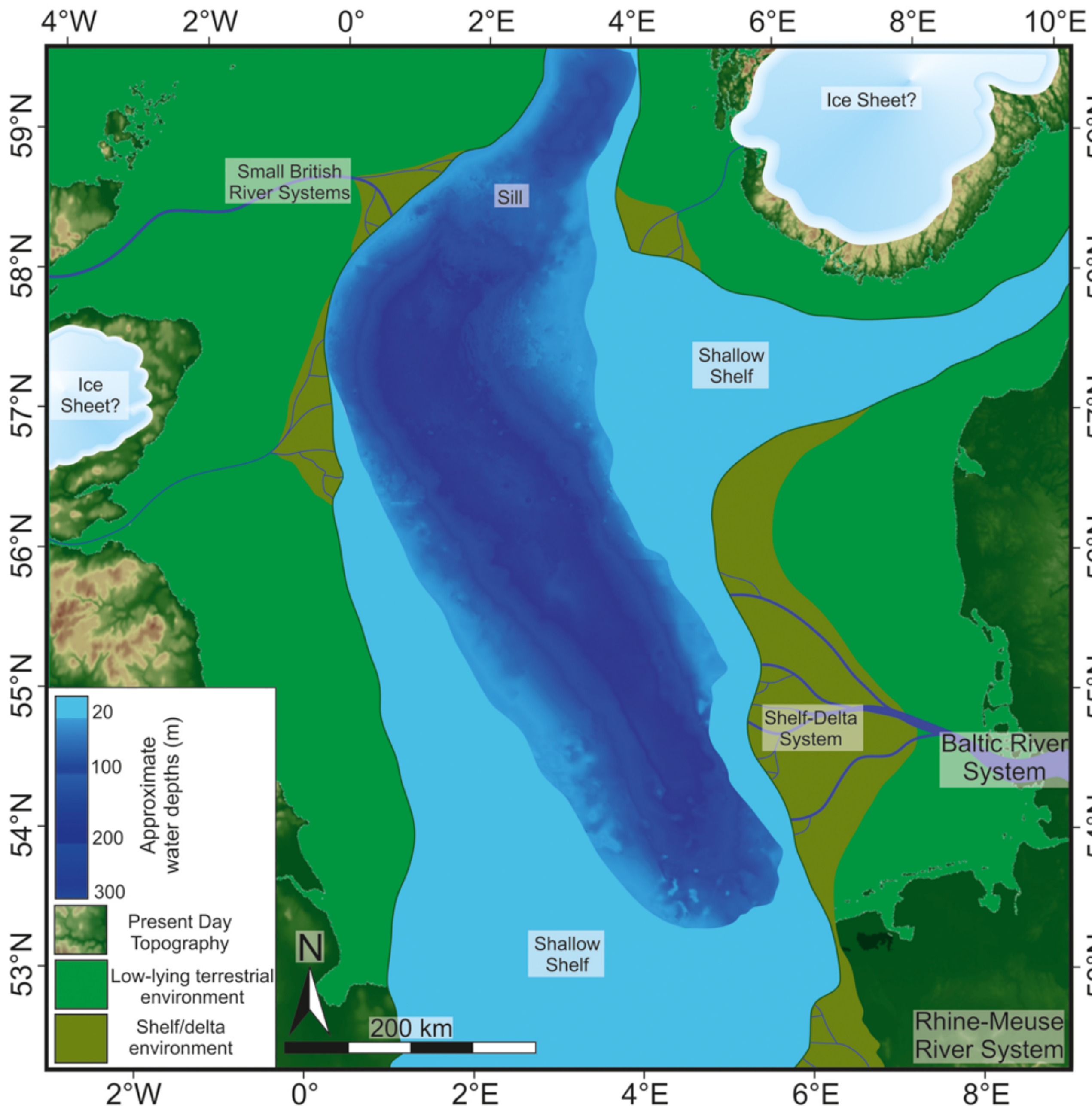

Fig. 12. Reconstructed paleo-environmental map of 2.58 Ma North Sea based on results of this study, Overeem *et al.* (2001), McMillan *et al.* (2005), Busschers *et al.* (2007), Rose (2009) and Noorbergen *et al.* (2015). Large parts of the present-day North Sea would have been flooded under the highstand conditions at the onset of the Quaternary, creating a very shallow shelf, but were otherwise terrestrial.

compacted, with minimal potential for further compaction. Late Cenozoic Zechstein salt diapirs are observed to have deformed pre-Quaternary sediments, resulting in elevation of Mesozoic to Late Permian deposits to the base or even into the fill of the Quaternary North Sea Basin (Figs 7, 8 and 11b). The shallow sill to the north coincides with an area where the relatively narrow South Viking Graben has been overfilled by Tertiary sediments, leaving a relatively narrow and shallow seaway between the broader and comparatively under-filled Central Graben and North Viking Graben (Ziegler 1992).

The observations of the North Sea Basin, as it was at the onset of the Quaternary, are found to be in agreement with a number of other early Quaternary paleo-environmental studies. Thickness maps of Quaternary sediments have previously identified the elongate depocentre (e.g. Holmes 1977; Cameron *et al.* 1987; Gatliff *et al.* 1994), although its true shape is only now revealed because of the much greater density of seismic data used in this study. Biostratigraphic studies and clinoform geometries reported in previous more localized studies suggest paleo-water depths of 100 – 300 m in the deepest part of the basin (e.g. Overeem *et al.* 2001; Huuse 2002; Kuhlmann 2004; King 2016), in agreement with the present study. The lack of slope features on the basal Quaternary surface, as well as limited evidence for extensive facies change between the topset and the slope, is suggestive of the sediment source for the clinoforms being located a significant distance from the clinoform break point (Posamentier & Vail 1988; Mulder & Alexander 2001; Mulder *et al.* 2003). If the delta is a significant distance from the slope breakpoint then coarser material does not as easily reach the slope, limiting facies changes between topsets and slope, and reducing the possibility of slope feature formation (Posamentier & Vail 1988). This interpretation of the observations is supported by the onshore stratigraphy from southeastern Britain, which suggests that the basal Quaternary was deposited in a shallow-marine environment (McMillan *et al.* 2005; Rose 2009), and a peak in sea-level observed at 2.58 Ma in the global sea-level curve (Miller *et al.* 2011), suggesting a flooding event at the onset of the Quaternary. This flooding surface is observed in studies of seismic stratigraphy in the Dutch sector southern North Sea at the top of the MIS 103 interglacial, marked by a large transgression within the seismic geomorphology and a marked shift in the depocentre (Funnell 1996; Harding 2015). A significant flooding event at the onset of the Quaternary created an extensive shallow marine environment on the shelf (clinoform topset), possibly as shallow as 20 m water depth, increasing sharply at the clinoform breakpoint of the shelf prism into the elongate basin (Fig. 12).

Earliest Quaternary (2.58 – 2.35 Ma)

Observations of the earliest Quaternary package from structural and seismic amplitude mapping, backstripping and calculations of sedimentation rates show a different picture to conditions at the Pliocene–Pleistocene boundary. During the earliest Quaternary, the extent of the basin long axis was reduced by over 100 km, primarily as a result of infill of the basin from the south and rapid northwards progradation of clinoform packages (Fig. 10). This progradation is highlighted in the sedimentation rates for this period, with the main depocentre for the earliest Quaternary lying in the south of the basin and low to no sedimentation in the north of the basin (Fig. 10). On the NW slopes of the basin older, remnant, clinoform packages from earlier Cenozoic depositional systems existed but were not active during 2.35 – 2.58 Ma (Fig. 10). Backstripping calculations also reflect the disparate sedimentation and infill of the basin, with the basin occupying the present-day southern North Sea being almost completely infilled by 2.35 Ma, leaving water depths of less than 50 m (Fig. 9i). In comparison, towards the northern end of the basin, the clinoforms either do not change in height, or marginally increase in height during the earliest Quaternary (Fig. 9iii and iv). Finally, unlike the basal Quaternary horizon, throughout the 2.58 – 2.35 Ma package, mass transport deposits, slope channels and fans are present on the southern clinoform slope, although not on the northern slopes (e.g. Fig. 11).

These observations fit with the general model of fluvial input into the North Sea during the early Quaternary and late Cenozoic. Evidence from the southern North Sea and from onshore NW Europe indicates that the dominant river systems during this time were the Baltic (Bijlsma 1981) and Rhine–Meuse (Busschers *et al.* 2007) river systems, which fed into the North Sea from Denmark, northern Germany and the Netherlands respectively (Fig. 12). The two river systems drained large areas of northern Europe during this time, including the Fennoscandian shield, the Baltic platform and large areas of NW Europe from the Alps to the present-day mouth of the Rhine (Overeem *et al.* 2001; Busschers *et al.* 2007). This drainage pattern would cause the high sedimentation rate in the south and the low sedimentation rate to the north, as the southwards drainage pattern of the Fennoscandian shield into the Baltic river systems bypasses the northern part of the basin. This bypass of the northern basin during the earliest Quaternary means that any correlation between the Norwegian and North Sea depositional systems, such as that presented by Ottesen *et al.* (2014), is difficult to test using the present-day distribution of high-quality chronostratigraphic calibrations. The two depocentres could, in fact, indicate completely separate depositional systems: one preserving solely the Scandinavian climate signal from the western coast of Norway, which drained into the northern North Sea, and the other the Northern European signal, or a mixed signal, from eastern Norway draining into the Baltic river system, routed through the southern clinoform set. Rapid northward progradation during this part of the early Quaternary has been noted in the southern North Sea previously, and has been linked with climatic cooling and increased sediment supply owing to glacial activity in the sediment source areas (Overeem *et al.* 2001; Huuse 2002).

The disparate sedimentation rates between north and south are highlighted in the backstripping results, which indicate that sedimentation rate must have far outstripped the formation of accommodation space by subsidence in the south of the basin during the earliest Quaternary (Fig. 9). Subsidence owing to loading is a continuous process, allowing far more sediment to be deposited in a depocentre than the initial accommodation space, and in a basin fully adjusted for isostasy it is not uncommon for up to three times the initial accommodation to be accumulated (Sclater & Christie 1980; Allen & Allen 2013). In the southern end of the basin, however, with an initial water depth of *c.* 300 m, only 350 m of sediment accumulated to fill the earliest Pleistocene accommodation. This part of the basin fill is a direct continuation of the rapid progradation that filled in the southeastern North Sea Basin during the post-middle Miocene (Clausen *et al.* 1999; Harding 2015). It is thus likely that flexural loading by the Pliocene clinoforms may have already preloaded this part of the basin, thus limiting the vertical isostatic component.

Additional to this the North Sea is noted to have been influenced by large-scale ice sheets at various points during the Quaternary (Graham *et al.* 2011, and references therein). Ice sheets are known to have an impact on isostasy both through the loading of the ice sheet itself (James & Bent 1994; Klemann & Wolf 1998; Davis *et al.* 1999; James *et al.* 2000; Stewart *et al.* 2000) and the changes to groundwater conditions affecting compaction of sediment (Boulton & Dobbie 1993; Sættem *et al.* 1996; Piotrowski & Kraus 1997; O'Regan *et al.* 2010, 2016). The effects of changes to groundwater drainage under a significant ice load can result in strongly differential compaction. Over-consolidation of sediment is common in glacially loaded regions, as the weight of the ice forces dewatering and effective stress increases dramatically (Boulton & Dobbie 1993; Sættem *et al.* 1996; Piotrowski & Kraus 1997; O'Regan *et al.* 2010, 2016). However, restricted meltwater discharge has been known to cause excess pore pressures and thus under-consolidation of sediment, particularly in fast-moving ice (Boulton & Dobbie 1993; Sættem *et al.* 1996; Piotrowski & Kraus 1997; O'Regan *et al.* 2010, 2016). There are very limited data available on how deep the compaction effects of glacial loading can penetrate into the substrate. Isostatic loading from an ice sheet is equally complex, with vertical and horizontal stresses placed on the strata even well beyond the extent of the ice sheet. Although modern postglacial rebound models, constrained by field-based investigations, have improved greatly over the years they are reliant on knowing the extent and thickness of the ice sheet in question (James & Bent 1994; Klemann & Wolf 1998; Davis *et al.* 1999; James *et al.* 2000; Stewart *et al.* 2000), for which the data are truly available only in the North Sea for the last glacial maximum (Huuse & Lykke-Andersen 2000; Graham *et al.* 2011). Additionally, modern rebound models may not fully account for the cumulative effect of repeated glaciations, which the North Sea is known to be subject to (Klemann & Wolf 1998; Stewart *et al.* 2000). With a limited understanding of ice extents prior to the last glacial maximum and lacking any direct measurements of potential over- or under-consolidation the impact of glacial loading on the Quaternary stratigraphy remains uncertain.

The presence of slope fan deposits and downslope channels on the slopes of the southern clinoforms during the 2.58 – 2.35 Ma package are typical of a shelf system in which material is transported to the shelf break. Coarser material remains on the topsets, forming a delta system, whereas finer sediment is carried down the slope by strong downslope currents into the basin (Posamentier & Vail 1988; Cartwright 1995; Mulder & Alexander 2001; Mulder *et al.* 2003). The elongate U-shaped features seen incising into the basal Quaternary in the central part of the basin are a particularly notable example of this process, and are interpreted as troughs formed by strong downslope currents under the high influx of sediment-laden water; that is, turbidites (Cartwright 1995; Lamb *et al*. 2017). These observations fit with the interpretation of the North Sea as a highly dynamic basin during the earliest Quaternary.

Implications

The mapping of the basal Quaternary surface and analysis of the earliest Quaternary sedimentary package define an expanded mid-latitude record of global climatic cooling. The onset of the Quaternary saw much of the shallow shelf flooded; however, the majority of deposition occured within the early Quaternary North Sea Basin. Rapid sediment deposition during the earliest Quaternary in the southern part of the basin caused both infill of the basin and differential subsidence, reducing accommodation in the south while maintaining accommodation towards the north, driving the depocentre northwards. This north–south deposition pattern allowed a significant thickness of Quaternary sediments to build up, leading to a thick and laterally expanded sedimentary succession of 1.2 km for the entire Quaternary and almost 600 m for the earliest Quaternary across the entire North Sea Basin. By correlating chronostratigraphic studies from the southern North Sea into the central North Sea and mapping continuously in full three dimensions this study provides a powerful chronostratigraphic calibration for the early Quaternary. If this base-Quaternary surface is combined with analysis of seismic geomorphology and drilling of the marine toesets from the rapidly prograding southern clinoform system, one of the most complete and detailed mid-latitude paleoclimate records for the early Quaternary could be produced.

In addition to the interpretations of the paleo-environmental record, the structural map of the basal Quaternary horizon can be combined with backstripping calculations to create a proxy that represents the pre-glacial paleobathymetry of the North Sea, which is one of the more poorly defined boundary conditions in ice sheet modelling (Peltier 1994). The Base Quaternary surface mapped here at 50×50 m resolution across the entire Quaternary North Sea Basin provides a uniform framework horizon that highlights the diachroneity of some previous correlations based on seismic facies or perceived stratal relations. The continuously mapped surface should thus help constrain future assessments of shallow geohazards and shallow gas resources in the North Sea Basin.

Conclusion

The basal Quaternary surface (2.58 Ma) has been mapped across the central and southern North Sea through the integration of chronostratigraphic studies with basin-wide 3D seismic data. The surface defines a highly elongate Quaternary depocentre comprising some 83×10^3 km^3 of sediments deposited in an elongated semi-enclosed deep marine basin with paleowater depths throughout the early Quaternary of up to 300 ± 50 m. Based on facies analysis and seismic geomorphological analysis it is suggested that the marine basin was initially flooded at the onset of the Quaternary but during the first 230 kyr was strongly influenced by a high sediment input from Northern Europe. The high sediment input created a dynamic and rapidly changing paleo-environment dominated by turbidites, channels and fans as well as shelf-margin deltas. Under this high sediment supply regime the basin shape changed dramatically during the first 230 kyr of the Quaternary, leading to the near-infill of the southern North Sea by 2.35 Ma. Estimates of sedimentation rates suggest a maximum sedimentation rate of over 30 km^3 ka^{-1} for the earliest Quaternary. The map of the base Quaternary and the early Pleistocene depocentre define a record of preserved paleoclimate information reaching up to 1.2 km thickness, which has implications for further study of the paleoclimate evolution of the Plio-Pleistocene transition, shallow geohazard analysis and resource assessments.

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