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SCIENCE

A high-resolution DEM for the Top-Palaeogene surface of the Belgian Continental Shelf

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ABSTRACT
A 1:250,000 scale map of the surface of the Top-Palaeogene for the Belgian Continental Shelf was created based on extensive analyses of older and recent geological and geophysical datasets. The Top-Palaeogene surface is an important polygenetic unconformity that truncates older strata of the Palaeogene and to a smaller extent some of Neogene age from the overlying Quaternary deposits. As such it represents the base of the latter. The represented surface has been diachronously shaped and reworked through Late Quaternary times by different geological processes (e.g. fluvial, marine, estuarine, periglacial). Additionally, the offshore surface has been attached to the landward Top-Palaeogene surface and was transformed into a uniform 3D surface allowing new and better interpretations to be used in fundamental and applied research underpinning both scientific purposes (e.g. geology, archaeology, palaeogeography), and commercial applications (e.g. wind farms, aggregate extraction, dredging).

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1. Introduction

The Belgian Continental Shelf (BCS) is a sediment-depleted shallow shelf environment without a distinct shelf break and is located in the Southern Bight of the North Sea (De Batist, 1989). Its coastal plain is characterised by a small non-linear, glacio- and/or hydro-isostatic subsidence component that increases significantly towards the northeast in the direction of the Fennoscandian land mass (Kiden, Denys, & Johnston, 2002; Vink, Steffen, Reinhardt, & Kaufmann, 2007). As a consequence there is very little accommodation space to accumulate newer and preserve older sediments, which in turn caused important reworking and redistribution of these older sediments. The lack of accommodation space led to a complex thin, discontinuous and patchy Quaternary sediment cover. Still, it protects some significant palaeolandscape elements that connect the Strait of Dover in the south and the depositional north of the present Southern Bight (Hijma, Cohen, Roebroeks, Westerhoff, & Busschers, 2012). Knowledge of the location, preservation conditions and spatio-temporal distribution of the remaining Quaternary deposits is critical to provide a better stratigraphical context for past and future archaeological and palaeontological finds not only on the BCS but also in the surrounding areas of the Southern Bight (see Hijma et al., 2012 for the Dutch Continental Shelf).

In addition, the Top-Palaeogene surface in Belgium regained interest to meet new societal and economic challenges. On the one hand, the deposits directly above this surface might contain a unique archive of submerged cultural heritage. On the other hand, the Top-Palaeogene surface provides the base for this sedimentary archive that is economically exploited by the Belgian offshore industry. Two Belgian research projects now address these issues, each requiring detailed mapping of the Top-Palaeogene surface of the BCS. The 'SeArch' project (*Archaeological Heritage in the North Sea*, www.sea-arch.be) wants to provide the industry with an efficient survey methodology, a sustainable management framework and a practical guide for the assessment of submerged cultural sites. To characterise the preserved palaeolandscape elements and to quantify their depth distribution, a detailed map of the Top-Palaeogene unconformity was required. The main focus of the SeArch project has been on drowned river valleys, planation surfaces, and slope breaks and escarpments. A majority of these elements were already described in previous studies (e.g. Liu, 1990; Liu, Missiaen, & Henriet, 1992; Mathys, 2009; Mostaert et al., 1989), though often not in sufficient detail and/or precision, and a high-resolution digital elevation model (DEM) of the Top-Palaeogene surface was urgently needed to pinpoint areas with high geoarchaeological potential. For this purpose the offshore and landward Top-Palaeogene surfaces were fully integrated, resulting in a level of detail never reached before. Such a connection allows for better interpretations concerning landscape evolution of buried landscapes. The second research project 'TILES' (*Transnational and*

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Integrated Long-term Marine Exploitation Strategies, www.odnature.be/tiles) focuses on sustainable management of marine aggregate resources through the development of 4D resource models as decision support tools, linking 3D geological models, knowledge and concepts to numerical impact models. Here, voxel models of the Quaternary sediment are created in which lithological and other sedimentological characteristics are quantified to get a better understanding of the distribution, composition and dynamics of the sparsely available geological resources (Van Lancker et al., 2014). This will enable detailed and long-term calculations of the economic resource potential of the Quaternary deposits overlying the Top-Palaeogene surface. Both scientific projects fit well within the aims of the new recognised research field called Continental Shelf Prehistoric Research and the SPLASHCOS COST Action (2009–2013) to build a multidisciplinary research community in Europe through better knowledge on investigation methods, interpretation and management of underwater archaeological, geological and palaeoenvironmental evidence of prehistoric human activity. As such, an interdisciplinary and international research framework is provided to archaeologists, heritage professionals, scientists, government agencies, commercial organisations, policy-makers and the wider public.

2. Study area

The BCS extends to a maximum of 84 km from the present-day Belgian coastline (67 km long) and covers an area of 3454 km^2. The sea-floor topography is characterised by the presence of sandbanks and swales (Figure 1). In the swales, water depths reach 30–40 m below LAT (Lowest Astronomical Tide), whilst the offshore sandbanks shallow up to 5 m below LAT.

Previous studies highlighted that the Top-Palaeogene surface is polygenetic and that the sediments below this surface are composed of compacted clays and sands to sandy clays that were deposited in a near-coastal to outer shelf environment from the Eocene to the Neogene (between 53 and 2.6 Ma) (Le Bot, Van Lancker, Deleu, De Batist, & Henriet, 2003, for a synthesis). In areal extent, consolidated Ypresian clays from the Eocene dominate, but overall there is a lateral difference in lithology, both between and within the units. Farther offshore finer sediments such as silt and clay are predominant, but also silty sand, muddy sand and even calcareous sandstone beds occur (Le Bot et al., 2003). During the Quaternary (2.6 Ma to present) the surface was diachronously ‘reshaped’ in marine, fluvial, estuarine and periglacial circumstances influenced by different climatic conditions (Mathys, 2009).

3. Methodology

To construct a high-resolution (1:250,000 scale) DEM of the Top-Palaeogene surface, available offshore data, as well as relevant land data, were compiled (Figure 1). This comprised in-depth processing and re-interpretation of boreholes, in conjunction with extensive seismic records. The digital seismic database, acquired over the last 45 years, contains a total of over 7800 km seismic lines of which 2534 km were digitised from paper records. After quality assurance, a series of inconsistencies were revealed that caused problems in developing the model of the Top-Palaeogene surface. Apart from the uneven distribution of the data over the study area, some of these inconsistencies were related to incorrect or missing corrections for the tidal level, and poor positioning of the old analogue seismic lines, both causing a move or lift of the Top-Palaeogene surface by several metres. Additionally, a considerable area of low acoustic penetration was present in the nearshore area, due to shallow gas in the subsurface. Here, the modelled surface is mainly based on borehole data. From the 749 boreholes located on the BCS only 130 reached the Top-Palaeogene surface; most of them were only 2–3 m deep (i.e. vibrocores). In order to reconstruct the Top-Palaeogene surface, the boreholes together with ~6670 km of seismic data, were analysed in an industrial software package (Kingdom Software, v8.8). Dynamic depth conversion was used to integrate the interpreted horizons from the seismic data (in time) and borehole information (in depth) into a grid-based layered velocity model. The average velocity model was calculated using the depth from the boreholes in order to calculate the depth of the interpreted horizons. All available data were then plotted using Esri ArcGIS (v10.1), where the boreholes were combined with the calculated depth model. Nearest neighbour was used as the interpolation method.

To allow optimal reconstruction of the nearshore Top-Palaeogene surface, gridded data from land were incorporated in the geographical information system (GIS) model. The former, constructed on the basis of boreholes and cone penetration tests, is free for download and needed a transformation of the reference system from Belgian Lambert 72 (EPSG: 31370) to UTM WGS84 zone N31 (EPSG: 32631) (Matthijs et al., 2013). Since this grid was available at a 50×50 m resolution, the offshore data were interpolated to this resolution. The result is shown on the Main map.

To depict morphological elements in the terrain model a slope analysis was performed and is useful to define the differences between large- and small-scale features, which can be highlighted by changes in slope.

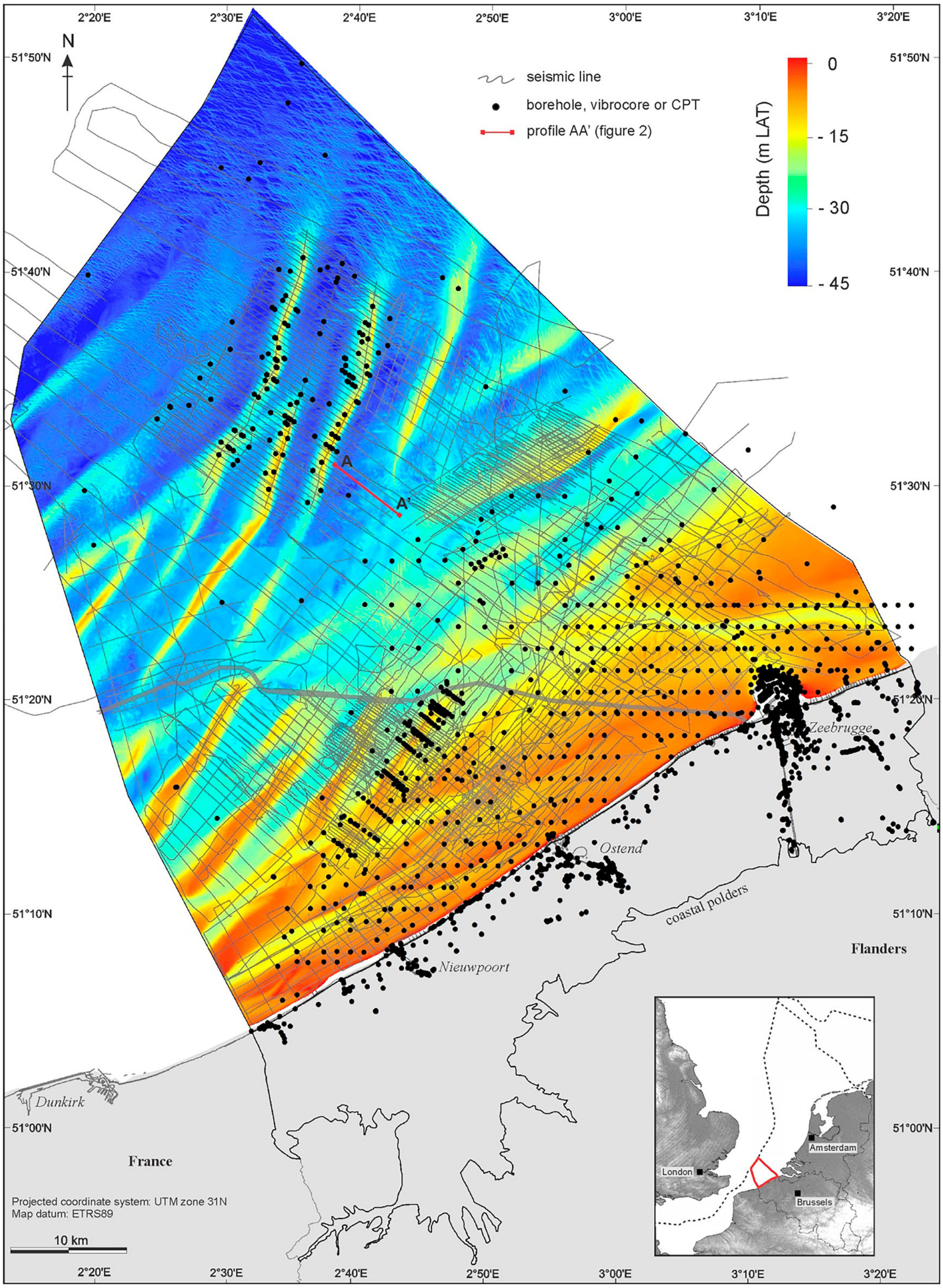

Figure 1. Database used to construct the Top-Palaeogene surface on the Main map, superimposed on a DEM of the present-day seafloor bathymetry (compiled from Flemish Hydrography and FPS Economy – Continental Shelf Service, 2015). A small number of onshore data (retrieved from Databank Ondergrond Vlaanderen) were added to the offshore dataset to better interpolate onshore and offshore surfaces. Grey lines are seismic data and black dots are information from boreholes, vibrocores and cone penetration measurements (no distinction made).

4. Geomorphological features

The Top-Palaeogene surface (Main map) of the BCS is defined by an angular unconformity marked by an overall strong seismostratigraphic reflector that cuts off the underlying sediments of the Palaeogene (De Batist, 1989; Liu, 1990; Mathys, 2009). This unconformity represents a significant stratigraphic hiatus, specifically here between the gently northeast dipping Lower- and Middle-Eocene formations (Thanetian to Rupelian in De Batist, 1989) and the overlying Quaternary deposits. The depth to the surface varies between 9 and 66 m below LAT and its geomorphology is characterised by a series of features ranging from planation surfaces, bounded by escarpments and slope breaks, to palaeovalleys and elongated depressions and ridges.

A number of the discussed morphological features have been described in the literature before (Liu, 1990; Liu et al., 1992; Mathys, 2009; Mostaert et al., 1989). New evidence from a denser borehole and seismic network however has allowed redefinition of some slopes and platform boundaries, including a new river valley. In order to link the offshore and onland situations, a single Top-Palaeogene surface was created that can now be used as a transition zone for palaeogeographical reconstructions between the depositional north of the present North Sea and the Strait of Dover. It is obvious that, regardless of the large amounts of data, some areas of the BCS are still poorly understood (i.e. the edges of the BCS). It is therefore necessary to connect the Top-Palaeogene DEM to the French, British and Dutch offshore grids.

4.1. Planation surfaces, escarpments and slope breaks

Three major planation surfaces have been mapped on the BCS. They are bounded by escarpments or slope breaks and are cut across different Palaeogene layers of varying resistance (Main map) indicating that lateral erosion processes were active at a successively lower base level. The overall orientation of the escarpments and slope breaks is southwest to northeast. The most nearshore platform, the Marginal Platform, is a remnant of the higher inland Top-Palaeogene surface that extends offshore. It is cut into three smaller platforms, each given an addition to their naming based on their geographic position (i.e. Western, Central and Eastern Marginal Platform). These platforms have little relief and have a total depth that varies between 10 and 20 m below LAT. At the edges, the slopes range from a steep 14.5% to less than 0.5%. The steepest slopes are cut by palaeovalleys whilst the gentlest slopes face north, away from past fluvial activity. The platforms themselves do not seem to have a straightforward relationship with the underlying Palaeogene lithostratigraphic units (Main map), however some contour lines, such as the 10 m and 22–24 m below LAT, locally follow the general geometry and distribution of the lower Palaeogene units (see Le Bot et al., 2003 for more information).

Offshore, the Middle Scarp gives way to the Middle Platform, which farther offshore prolongs into the Offshore Scarp and Offshore Platform. Both platforms and escarpments are more continuous compared to the Marginal Platform, which is dissected by large palaeovalleys with a distinct southeast to northwest orientation. An exception is the narrow Thornton Valley cutting the eastern side of the Middle Scarp, beneath the Thornton sandbank (Main map, number 6). The overall depth of the Middle Platform ranges between 28 and 33 m below LAT, whilst the escarpment displays a gentle drop of some 3 m. The northern boundary of the Marginal Platform, the Offshore Scarp, is characterised by a drop of 4 to locally 10 m. The depth of the Offshore Platform varies between 30 and 40 m below LAT and shows a greater variety in relief due to the presence of elongated depressions and ridges. Comparing the orientation of these morphological features to the underlying Palaeogene lithostratigraphic structures shows no obvious direct relationship of differential erosion (Main map) (De Batist, 1989). Beyond the Offshore Platform, the Top-Palaeogene surface almost resembles the present-day bathymetry with a maximum depth of 45 m below LAT and continues into a large palaeovalley known as the Axial Channel (Liu et al., 1992; Mostaert et al., 1989).

It can be concluded that both the Middle and Offshore Scarps are larger features that traverse the whole width of the BCS. Based on studies from the southern North Sea it can be concluded that both scarps are believed to be remnants of ancient river terraces of the Rhine and Meuse rivers (Bridgland & D'Olier, 1995; Busschers et al., 2005, 2007, 2008; Gibbard, 1995; Hijma et al., 2012; Peeters, Busschers, & Stouthamer, 2015; Rijsdijk et al., 2013). This conclusion is similar to what Mathys (2009) suggested about the Offshore Platform being the valley floor of an incised river valley.

4.2. Elongated depressions and ridges

On top of the Offshore Platform a group of tidal sandbanks, referred to as the Hinderbanks, is located. Beneath this group of sandbanks several SW to NE oriented elongated depressions and ridges can be recognised in the Top-Palaeogene surface. Comparison between digitised analogue data from the 1980s and the present-day bathymetry revealed a direct link with the sandbanks. The elongated ridges are (largely) located beneath the actual sandbanks, while the depressions are located in the swales between or on the edges beneath the sandbanks. Generally the depressions are semi-parallel and typically a few km wide, 10–20 km long and scoured down 5–10 m lower than the surrounding planation surface. The south-eastern depression is long and narrow (2.3–4.9 km wide, 20 km long) and reaches a depth up to 25 m below the surrounding planation surface. This depression is responsible for two local steep elevation drops in the Offshore Platform just north of the Offshore Scarp (see Figure 2). These 'secondary and tertiary escarpments', as revealed by recent seismic data from April 2015, are 3.8 km long and marked by a local drop of ca. 10 m (from the surrounding planation surface to the secondary scarp) and ca. 11.5 m (from the

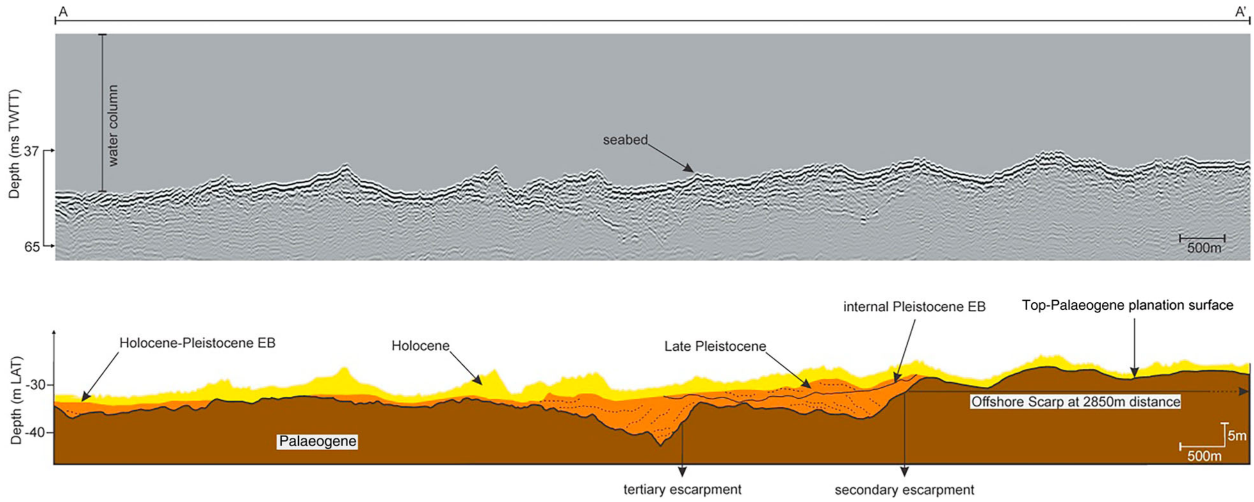

Figure 2. Seismic reflection profile shot with a GSO 360 tips Sparker (top) and interpreted panel (below) illustrating seismic facies character and association for deposits overlying the Top-Palaeogene surface Erosional Boundary (EB). The location of profile A-A′ is depicted on Figure 1.

secondary to the tertiary scarp) respectively. They merge with the Offshore Scarp in the southwest but divert from it when going northeast (maximum 1.2 km). These features clearly provide evidence that this depression is both related to the current hydrodynamic processes and other non-recent geological processes. The north-western depression in the Offshore Platform is generally less narrow (2.2–6 km wide) and not as elongated (17 km long). Farther towards the northeast both elongated depressions connect and create a wider depression in the Top-Palaeogene surface, continuing into Dutch waters. Other depressions on the western side of the Offshore Platform also seem to have a relationship with the present-day bathymetry and continue into French waters. This is not surprising considering the overall limited Quaternary cover (less than 3 m in the swales) and the strong hydrodynamic currents present in these zones (Van Lancker et al., 2015).

4.3. Palaeovalleys

Besides elongated depressions and ridges several large palaeovalleys occur in the Top-Palaeogene surface. Three of these palaeovalleys, the Ostend, Zeebrugge and Yser valleys, cross the present-day Belgian coastline and can be related to (formerly) active rivers. All three valleys are marked by a general N-NW to S-SE orientation, with an increasing E-W orientation towards the west, that is, the Strait of Dover. The most prominent palaeovalley is the funnel shaped Ostend Valley (Main map, number 3). It is connected to the inland ancient Scheldt pathway through the Coastal Valley (Main map, number 1), which runs parallel to the present-day coastline. The Ostend Valley cuts its pathway deep through the Marginal Platform, locally eroding up to almost 70 m into the Palaeogene sediments. The slopes of the valley are variable, but generally the western slope is much more gentle (<0.5%) than the eastern slope which is marked by an internal channel. Here the slope varies between 2% and locally 8%. Two deeply incised channels occur within the valley, respectively 20/10 km long and reaching up to 58/66 m below LAT at their deepest incisions. These two internal channels are characterised by three deep depressions (so-called Sepia Pits) in which the deepest depths are found (Mostaert et al., 1989).

The Zeebrugge Valley (Main map, number 2) is a smaller outflow of the ancient Scheldt pathway (38 km^2, compared to 280 km^2 of the Ostend Valley) and is mapped for the first time. The valley separates the Central and Eastern Marginal Platform. Similar to the Ostend Valley, it's eastern slope is much steeper (14.5%) than its western slope (>1%), which can be directly related to the presence of the very hard and compact erosion-resistant Bartonian clay (Jacobs et al., 2002). The deepest point in this valley is located in a centralised depression called the Zeebrugge Pit (Liu, 1990), reaching up to 34 m below LAT.

The last palaeovalley that is buried beneath the present coastline is the Yser Valley (Main map, number 4). This palaeovalley is still active and is connected to a separate drainage system, the Yser river (Baeteman, 1999). The Western Marginal Platform separates it from the Scheldt drainage system. Seismic evidence offshore of the Yser Valley is at best difficult to interpret (biogenic gas combined with shallow geology, and low water depths creating a strong multiple effect), but the general contours of the valley can be distinguished. It is clear that the Western Marginal Platform blocks the pathway north of the Yser palaeovalley, diverting it westwards into the French part of the North Sea (i.e.

the Western Valley, Main map, number 5 after Liu, 1990). The deepest parts of this shallow palaeovalley locally reach 30 m below LAT, but generally range between 17 and 25 m below LAT.

Offshore, two more palaeovalleys occur near the Belgian–Dutch border, the Thornton and Northern Valley (Main map, numbers 7 and 8). The Thornton Valley is a small and narrow (0.5–1 km wide) incision that cuts through the Middle Scarp and up to 12 m deep through a small high in the Top-Palaeogene surface below the Thornton sandbank. The maximum depth of this valley is 41 m below LAT whilst its flanks reach up to 30 m below LAT. The slopes of the valley vary between 2% and 6%. Beyond the Middle Scarp this valley opens up to a 6 km wide open low-lying plain, and bifurcates in two 2.5 km wide valleys with their deepest points ca. 11 m below the surrounding planation surface (see number 7, Main map). The cross-cutting relationship of the Thornton Valley with the Middle Scarp indicates that the latter is older. This has import implications for future palaeogeographical reconstructions of the area (e.g. Busschers et al., 2005, 2007, 2008; Hijma et al., 2012; Peeters et al., 2015; Rijsdijk et al., 2013). Farther north the Thornton Valley connects to the Northern Valley (see Main map). This palaeovalley is very shallow and ranges between 30 and 34 m below LAT, with a maximum of locally 38 m below LAT in a depression to the north. The width of the valley varies between 0.8 km just off the Thornton Valley and 3 km farther north where it connects to the south-eastern elongated depression of the Offshore Platform. The slopes of the valley reach up to 1.5% in the south, but are generally less than 1% further to the north. The northern part of this river valley is marked by a small cuesta with a length of 1–1.5 km and a local drop of 3–3.5 m making an angle of 135° with the axis of the valley. At its northern edge the valley seems to be cut off by a swale in-between the present-day Hinder sandbanks indicating that erosion took place at a later phase.

Recent seismic data revealed a narrow elongated buried valley on the western border of the BCS that enters the French Continental Shelf ca. 20 km offshore the present coastline (Liu, 1990; Main map, number 6). The valley runs semi-parallel to the Belgian–French border and widens from 0.8 km to ca. 3 km over a distance of 13.6 km. The depth of the valley is variable and changes between 8.2 and 13.2 m below the surrounding planation surface. The V-shaped valley in the south changes abruptly (after only 1.4 km) to a flat-floored valley towards the north. In the north, beneath the Fairy Bank, the valley shallows and seems to terminate just north of the Offshore Scarp. The origin and nature of the deepening of the Top-Palaeogene in the northwestern part of the BCS is until now unclear, but is likely related to the proximity of the Axial Channel (see Liu, 1990). This 'new' western valley appears to cut off the Offshore Scarp at the western edge of the BCS beneath the Fairy Bank where, according to Mathys (2009), it is supposed to connect with the Quaternary Basin in French waters. It suggests that the palaeovalley is younger than the Offshore Scarp and the Quaternary Basin. In analogy with the Thornton Valley, located beneath the Thornton sandbank, this valley was named the Fairy Valley. The S-N orientation of the valley is parallel to the lithological variability of the underlying Palaeogene layers possibly indicating a relationship. The orientation of the valley seems to differ somewhat from the other valleys on the BCS. No explanation for this orientation can be given yet. A larger scale view beyond the study area might provide more information on this detail.

5. Conclusions

A digital high-resolution elevation model of the Top-Palaeogene surface of the BCS and neighbouring coastal zone has been constructed based on extensive data comprising offshore boreholes and seismic records, together with onshore boreholes and cone penetration tests.

The mapping allowed quantifying the depth and extent of existing and new morphological features in detail, which is important for assessing the geoarchaeological potential of the area, as well as to provide an accurate base level of the Quaternary deposits, being a resource with economic viability.

The relative heights of a series of drowned river valleys, platforms, slopes and scarps were better defined, and for the first time, a smaller valley below the harbour of Zeebrugge was mapped, as well as a valley near the Belgian–French border.

Linking the relative height of the Quaternary deposits on top of these geomorphological features to sea-level changes will shed new light on the timing of their formation. In the near future, the digital surface will be merged with data from The Netherlands to re-evaluate the evolution of the Rhine and Meuse rivers on the BCS, two rivers that controlled sedimentation and erosion processes in the Southern Bight of the North Sea.

Software

The seismic and borehole database were processed using seismic the software package Kingdom v8.8. All available data were plotted using Esri ArcGIS v10.1, with CorelDRAW X7 used to produce the final layout of the map.

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