Pleistocene River Valleys and Glacial Tunnel Valleys in the Danish Sector of the North Sea

Introduction

The Quaternary geology of the North Sea Basin can be sub-divided in a deeper fluvio-deltaic succession and a shallow succession deposited during glacial and interglacial periods. The pre-Quaternary marine to deltaic succession is well studied using deep seismic data and wells from the oil and gas industry (Overeem et al., 2001; Gibbard & Lewin, 2016). Large scale glacial features such as tunnel valleys (Huuse and Lykke-Andersen, 2000a) and glaciotectonic deformation (Huuse and Lykke-Andersen, 2000b) have also been recognized on deep seismic data. For the development of offshore wind farms, increasingly large and detailed geophysical and geotechnical site investigations are performed which focus on the shallow subsurface (<100 m BSF). Here we present a large 2D ultra-ultra-high resolution seismic reflection dataset (2D-UUHRS), seafloor CPTs and geotechnical borehole data (sampling and CPTs) from the Energy Islands offshore wind farm site in the Danish Sector of the North Sea. At this site, 12 seismostratigraphic soil units were recognized which range in age from Miocene to Holocene. This paper focuses on three fluvial sand units (FL-I, FL-II and FL-III), which are incised by two sets of glacial tunnel valleys (GL-I and GL-II). These five units cover approximately 50 m depth below seafloor (BSF), which broadly corresponds with an expected depth range of primary interest for monopiles and jacket piles. Mapping, understanding, and predicting the geometry and variability of soil types and soil properties is important in site selection, layout design, foundation design and foundation installation for wind turbine generators, offshore converter platforms and artificial islands.

Datasets

The North Sea Energy Island wind farm site has an area 1052 km^2. 2D-UUHRS data with a penetration depth of approx. 200 below MSL (Mean Sea Level) and a total line length of 6071 km were acquired in 2021 (Fugro, 2022, 2023b; MMT, 2022). Seafloor CPT's were acquired at 269 locations and downhole CPTs and sampling data were acquired at 58 locations with a maximum penetration depth of 120 m BSF (below seafloor) in 2022 (Fugro, 2023a, 2023c).

Results

Unit FL-I overlies Miocene marine sediments, characterised by stratified seismic facies. Unit FL-I has a sheet-like geometry and is up to 90 m thick (figures 1a,b and 2a). This unit is absent in the north-east of the site where a glaciotectonic thrust-complex is present (Huuse and Lykke-Andersen, 2000b). The unit is characterised by various seismic facies, from chaotic to stratified, with horizontal and inclined reflectors, locally with acoustically transparent intervals and internal erosion surfaces. Based on 115 particle size distribution laboratory tests, it comprises on average 85% sand, 2% clay, 11% silt and 2% gravel. In the south-west of the site, strong amplitude reflectors with a negative polarity are present in this unit at multiple levels, covering areas up to ~5 km in diameter. Where sampled in boreholes, these anomalies correspond to beds of peat or organic rich clay. The internal seismic character, geometry and dominant lithology may suggest that Unit FL-I was deposited in channels and bars of a braided river. The presence of beds of peat and organic rich clay are interpreted to be deposited in peat mires. All these observations indicate deposition on a wide coastal plain of a prograding delta system (Gibbard & Lewin, 2016).

Unit GL-I incises into older units and forms the infill of relatively narrow (<5 km) and deep (170 m below MSL) valleys with a south-west to north-east orientation (figure 2c). Internally, the seismic character is chaotic, stratified or acoustically transparent (figures 1b). This unit contains poorly sorted sediments, from medium dense to very dense clayey and silty sand to very high strength to extremely high strength silty and sandy clay. Locally the sediment is gravelly.

Unit FL-II is locally present and is up to 20 m thick (figures 1a,b and 2b). In general, the base is undulating to locally channelised, where it reaches a maximum depth of 120 m below MSL. This unit contains internal erosion surfaces, horizontal and inclined stratification, and acoustically transparent intervals. Based on 33 particle size distribution laboratory tests, this unit comprises on average 85% sand, 3% clay, 10% silt and 4% gravel. It is interpreted that Unit FL-II was deposited in channels and bars of a braided river.

Unit GL-II incises into older units. This unit is the infill of relatively narrow (<2 km) and deep (up to 130 m) valleys with a north-west to south-east orientation (figures 1a,b and 2d). Internally the seismic character is chaotic, stratified or acoustically transparent. This unit contains poorly sorted sediments, from medium dense to very dense clayey and silty sand to very high strength to extremely high strength silty and sandy clay. Locally the sediment is gravelly.

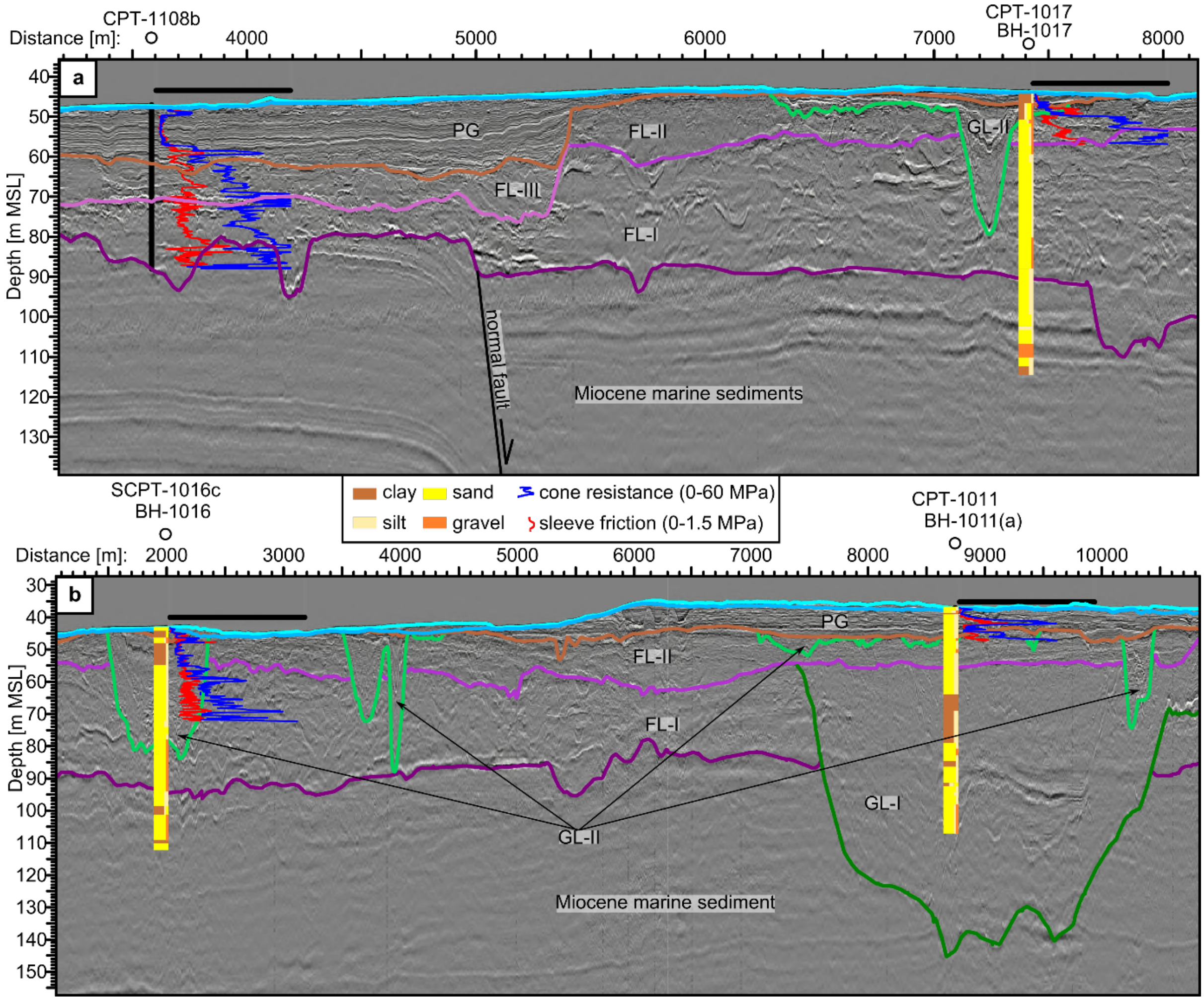

__Figure 1__ Data examples of the seismostratigraphic units including CPT and soil data.

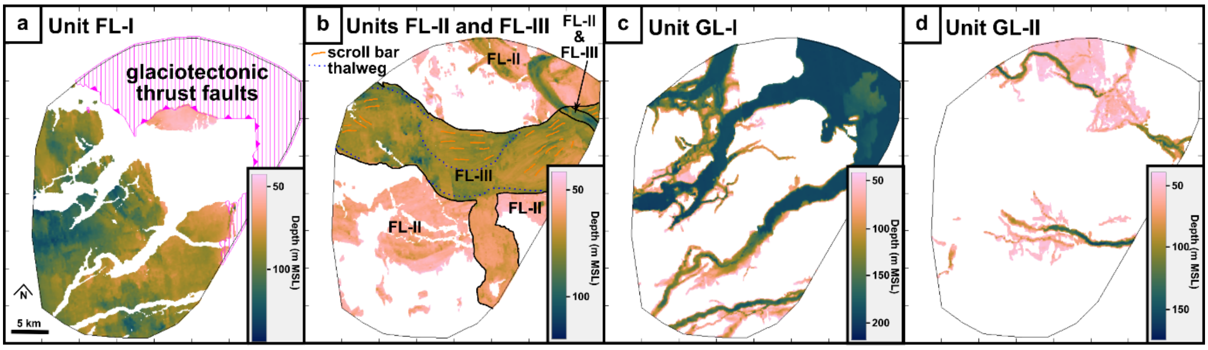

__Figure 2__ Maps of the depth of the base of the seismostratigraphic units in meters below MSL.

Unit FL-III forms the infill of relatively wide (up to 15 km) and shallow (~30 m) main valley and smaller-scale side valley (figure 2b). In plan view, these valleys have a meandering geometry, deeper (up to 60 m MSL) narrow channels (thalwegs) are visible at the margin of the wide valley, and this unit contains a morphology similar to scroll bars. This unit contains internal erosion surfaces, horizontal and inclined stratification, and acoustically transparent intervals (figures 1a). Based on 30 particle size distribution laboratory tests, this unit comprises on average 86% sand, 1% clay, 5% silt and 10% gravel. The lithology and internal seismic character may suggest that Unit FL-II was deposited in fluvial channels and bars within a river valley.

These five units are overlain by various pro-glacial lake clays and outwash plain sands from the last glacial period (Weichselian), which are partially glaciotectonically deformed, and post-glacial Holocene estuarine and shallow marine deposits. In figure 1 these younger deposits are indicated as "PG".

Discussion and Conclusions

Unit GL-I and GL-II form the infill of glacial tunnel valleys. These tunnel valleys are relatively narrow and deep. The infill comprises overconsolidated, poorly sorted clay and sand. The presence of tunnel valleys in the Danish Sector of the North Sea was recognized before (Huuse and Lykke-Andersen, 2000a). We recognised and were able to map out two generations of tunnel valleys. The site was covered by ice during the Elsterian and Saalian glacial periods. Therefore, Units GL-I and GL-II are interpreted to have formed during these two glacial periods respectively.

The glacial valleys are incising into sand units that are interpreted to be of fluvial origin. The fluvial units are sand dominated and show a decrease in the proportion of fines (clay and silt) and an increase in gravel content from Unit FL-I to FL-III. Also, Unit FL-I is unconfined and forms a thick planar unit interpreted to be deposited on a coastal plain (where glaciotectonic deformation is not present, see figure 2a). In contrast, Unit FL-II is only locally present, and Unit FL-III is confined to a well demarcated main river valley and side valley. The base of Unit FL-III has the morphology of a meandering river, with scroll bars and thalwegs (figure 2b). Internally Unit FL-II has a more complex infill of internal erosion surfaces and inclined stratification which indicates deposition on bars and channels of braided rivers. This suggests a change in processes forcing the fluvial morphology (Gábris & Nádor, 2007; Erkens et al., 2011; Woolderink, et al., 2018).

A similar pattern of incision and an increase of confinement over time is observed as series of river terraces in for example the Rhine (Erkens et al., 2011), Meuse (Woolderink, et al., 2018; da Silva Guimarães et al., 2024), Danube and Tisza Rivers (Gábris & Nádor, 2007). The valley width of Unit FL-III (~10 to 15 km) is similar to the width of the channel belt of the Rhine and Danube Rivers (Gábris & Nádor, 2007; Erkens et al., 2011). Therefore, the fluvial units may have formed by a major river such as the Eridanos River, which drained the Baltic Sea Basin, in addition to smaller tributary rivers from Denmark and northern Germany (Gibbard & Lewin, 2016).

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References

da Silva Guimarães, E., Busschers, F.S., Kasse, C., van Haren, T., Menkovic, A., and van Balen, R.T. [2024]. Quaternary tectonic and climatic forcing on the spatio-temporal evolution of the Meuse fluvial terrace staircase. *Geomorphology*, **459**, 109270.

Erkens, G., Hoffmann, T., Gerlach, R., and Klostermann, J. [2011]. Complex fluvial response to Lateglacial and Holocene allogenic forcing in the Lower Rhine Valley (Germany). *Quaternary Science Reviews*, **30**(5-6), 611-627.

Fugro. [2022]. *Geophysical Results Report – North Sea OWF Zone West (Lot 2) Geophysical Survey – Danish North Sea*. Report Number F176286-REP-GEOP-001 issue 05.

Fugro. [2023a]. *Energy Islands – North Sea Artificial Island – Investigation Results – Geotechnics*. Report Number F191074/01issue 04.

Fugro. [2023b]. *Geophysical Survey Data Integration Report – 3GW Project Area Geophysical Surveys Integration – Danish North Sea*. Report Number F176286-REP-GEOP-002 issue 03.

Fugro. [2023c]. *Energy Islands – North Sea Offshore Wind Farm Area – Investigation Results – Geotechnics*. Report Number F191074/02 issue 04.

Gábris, G., and Nádor, A. [2007]. Long-term fluvial archives in Hungary: response of the Danube and Tisza rivers to tectonic movements and climatic changes during the Quaternary: a review and new synthesis. *Quaternary Science Reviews*, **26**(22-24), 2758-2782.

Gibbard, P.L. and Lewin, J. [2016]. Filling the North Sea Basin: Cenozoic sediment sources and river styles. *Geologica Belgica*, **19**(3-4), 201-217.

Huuse, M., and Lykke-Andersen, H. [2000a]. Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. *Quaternary Science Reviews*, **19**(12), 1233-1253.

Huuse, M., and Lykke-Andersen, H. [2000b]. Large-scale glaciotectonic thrust structures in the eastern Danish North Sea. In: Maltman, A.J., Hubbard, B., and Hambrey, M.J. (Eds.), Deformation of Glacial Material. *Geological Society, London, Special Publications*, **176**, 293-305.

MMT [2022]. *North Sea OWF and Energy Islands – Geophysical Survey Report*. Report Number: 103783-ENN-MMT-SUR-REP-SURVWPA.

Overeem, I., Weltje, G.J., Bishop-Kay, C. and Kroonenberg, S.B. [2001]. The Late Cenozoic Eridanos delta system in the Southern North Sea Basin: a climate signal in sediment supply? *Basin Research*, **13**, 293-312.

Woolderink, H.A.G., Kasse, C., Cohen, K.M., Hoek, W.Z., and van Balen, R.T. [2019]. Spatial and temporal variations in river terrace formation, preservation, and morphology in the Lower Meuse Valley, The Netherlands. *Quaternary Research*, **91**(2), 548-569.