Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Early-stage ground modelling in a mediterranean shelf margin: a sequence stratigraphic approach

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ABSTRACT: Quaternary stratigraphy of the Mediterranean shelves is largely controlled by glacial-interglacial eustatic cycles that defined the volume of sediment available for deposition and controlled sediment accommodation space, geometry and thickness of the soil units. To develop an early stage integrated ground model for a floating windfarm site in the southern Adriatic we adopt a simple sequence stratigraphic approach aiming to link shallow geophysical and geotechnical data into a coherent framework, allowing the distinction of mappable wedges interpreted to represent the depositional signature of distinct phases within sea-level cycles. Starting from a seismostratigraphic analysis of the site based on a dense grid of SBP and UHR data, we define three main fourth order (10^4 years) stratigraphic units bounded by erosional surfaces, each representing a full eustatic cycle. Individual units are in turn divided into separate sub-units encompassing all deposits accumulating during one phase of relative sea-level and preserved between specific primary chronostratigraphic surfaces. The stratigraphic process-response model pyBarSim, which uses event deposition to simulate stratigraphic response to changes in sea level and sediment supply, is used to qualitatively validate the results and favour the dissemination of specific stratigraphic concepts to non-specialists. Geotechnical data, including seabed CPTs and shallow vibrocore sampling, allow the ground-truthing of the stratigraphy and the definition of soil types unique to each main unit. Vertical and lateral trends in soil characteristics are found to correlate to sub-units whose depositional pattern was primarily controlled by the sea level cyclicity; this predictable behaviour facilitates a preliminary estimation of geotechnical properties away from CPT control points and an improved understanding of the geohazard processes.

Keywords: ground model; mediterranean; sequence stratigraphy; geohazards; floating offshore wind farm

1 INTRODUCTION

The development of offshore wind farms requires a comprehensive understanding of the seabed and subsurface conditions to ensure the safe, efficient, and cost-effective design and installation of foundations, cables, and other infrastructure. Integrated ground models (IGMs) provide a crucial framework for this understanding, incorporating geophysical, geotechnical, and geological data to create a three-dimensional representation of the site.

The Mediterranean, and particularly the southern Adriatic Sea, presents a unique set of challenges for IGM development due to its geological setting. The absence of glacially influenced deposits, characteristic of many offshore wind farm sites, necessitates a different approach to interpreting the stratigraphy and predicting the distribution of soil units. Furthermore, the site's history is marked by multiple sea-level cycles, resulting in a complex arrangement of sedimentary wedges with varying depositional environments and potentially significant lateral and vertical variability in geotechnical properties.

This paper presents a case study demonstrating how the application of sequence stratigraphic principles enhances the understanding of the subsurface conditions and informs the development of a robust and reliable IGM.

1.1 Sequence Stratigraphic Approach

Sequence stratigraphy examines the relationships between rock and soil bodies within a chronostratigraphic framework, focusing on repetitively arranged facies and stratal geometry

(Catuneanu et al., 2011). Sedimentary successions are divided into geometrical units with time-stratigraphic and genetic significance by identifying discontinuities as horizons in seismic datasets, complemented and validated by the analysis of core data. The fundamental unit in sequence stratigraphy is a sequence, representing a complete cycle of relative sea-level change, typically marked along the shelf by a prominent erosional unconformity and its seaward correlative conformity; within each sequence, one can differentiate four distinct phases, known as system tracts, each characterized by particular depositional patterns and resulting sediment layers.

Falling Stage systems tracts develop when the relative sea level is falling, forcing the shoreline to move seaward, irrespective of sediment supply, creating a forced regression. Lowstand systems tracts form when the sea level is at its lowest point; during this stage, the shelf edge also shifts seaward, and sediments are deposited in a downward-sloping manner towards the basin. Transgressive systems tracts are associated with a rising sea level; the sediment layers formed during this phase onlap onto the underlying surface and thicken landward. Highstand systems tracts form when sea level is high and stable, leading to the aggradation of sediments and the outward and upward building of layers towards the shelf edge.

The methodology employed in this paper integrates geophysical data (ultra-high resolution seismic, UHRS and sub-bottom profiler, SBP) with limited geotechnical data (Cone Penetration Tests, CPT and vibrocores, VC) within a sequence stratigraphic framework, validated through the use of a stratigraphic process-response model.

2 GEOLOGICAL SETTINGS

The late Quaternary sedimentation on the southern Adriatic shelf (Figure 1) is characterized by the interplay of tectonics, glacio-eustasy, oceanographic currents, and sediment supply (Aiello, 2023).

The Middle Pleistocene witnessed the formation of forced-regression wedges, likely driven by the tectonic uplift of the Apulian foreland and 4th-order glacio-eustatic variations. This uplift is thought to have enhanced sediment supply by increasing erosion of coastal units, leading to significant progradation of the shelf (Aiello, 2023). The Late Pleistocene and Holocene saw a prominent role of short-eccentricity cycles, resulting in the formation of lowstand prograding wedges separated by transgressive surfaces of erosion (ravinement surfaces).

Further complexity is introduced by the presence of bottom currents like the Levantine Intermediate Water and the North Adriatic Dense Water, which have contributed to the formation of contourite deposits (Pellegrini et al., 2016).

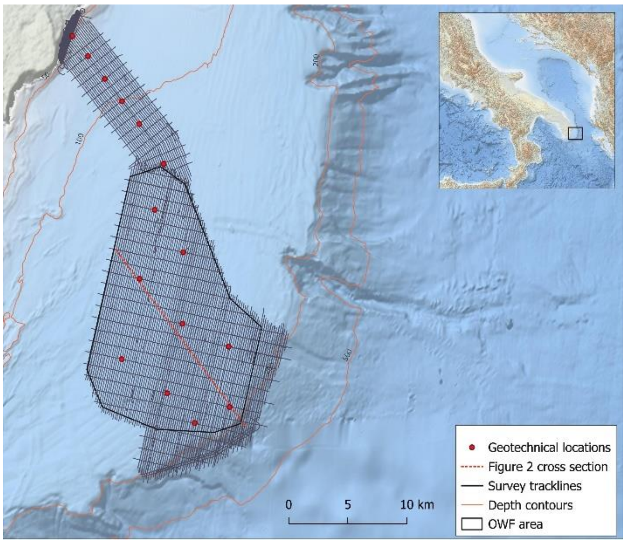

Figure 1 Location map of the study area and available geophysical and geotechnical data

3 IGM DEVELOPMENT

3.1 Seismic Stratigraphy

Interpretation of SBP and UHRS data (Figure 1) enabled the identification and mapping of key seismostratigraphic horizons, resulting in the delineation of five main wedge-shaped, non-channelized seismostratigraphic units and their sub-units (Figure 2) based on variations in seismic facies.

The age of each unit was determined by correlating the interpreted seismic horizons with the established chronology of Quaternary sea-level cycles, particularly the transgressive-regressive phases associated with glacial-interglacial periods as discussed in Aiello (2023).

The oldest unit, Unit E, is characterized by chaotic to steeply inclined reflectors and is interpreted as the engineering bedrock, likely consisting of Late Oligocene calcarenites.

Above Unit E is Unit D, a sediment wedge interpreted to predate the most recent fourth-order sea-level cycles, likely older than 230,000 years. In the western offshore wind farm area this unit shows large-scale deformation, with folding and faulting attributed to the Pleistocene uplift of the Apulian Platform.

Unit C, featuring south-eastward dipping parallel to sigmoidal reflectors, is subdivided into two sub-units (C1 and C2). This unit corresponds to the first complete fourth-order sea-level cycle analysed in this study, spanning approximately 230,000 to 120,000 years ago.

Unit B, also displaying parallel to sigmoidal reflectors, comprises four sub-units (B1-B4) distinguished by subtle variations in reflector geometry and features such as gas blanking and slumping. Unit B represents the subsequent fourth-order sea-level cycle, covering a period from roughly 120,000 to 18,000 years ago.

The youngest unit, Unit A, has a wedge shape that thickens toward the shore and is divided into two sub-units (A1 and A2). Unit A reflects the most recent, incomplete sea-level cycle, dating from approximately 18,000 years ago to the present. Sub-unit A2 is only observed in the nearshore area, while the widespread drape of Sub-unit A1 likely marks the onset of the Holocene sea-level highstand.

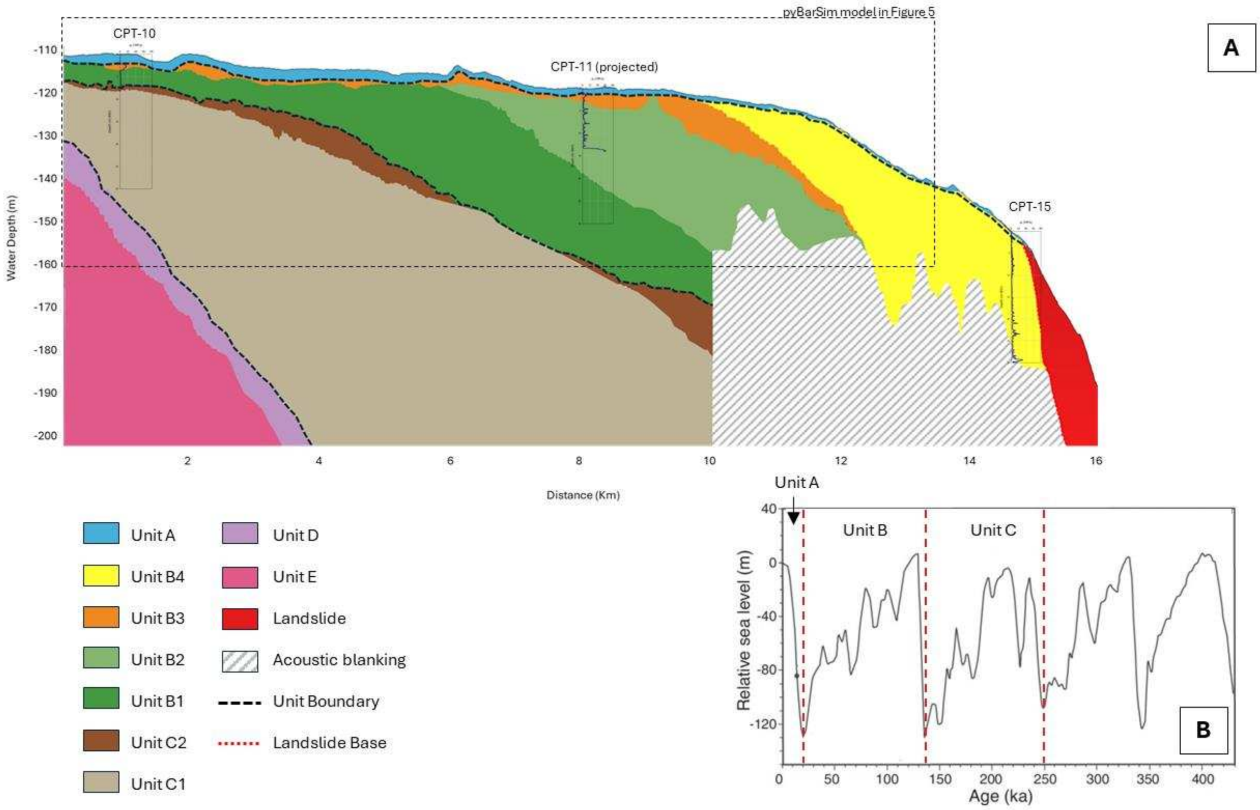

Figure 2 – A) Interpreted stratigraphic cross-section across the OWF area (location in Figure 1) including q_t CPT plots; B) Late Quaternary sea level curve modified from Wright (2000)

3.2 Geotechnical Unitisation

Geotechnical data provided ground-truthing for seismostratigraphic Units A to C, while Units D and E remained largely untested.

The geotechnical unitisation was primarily based on the analysis of a limited number (Figure 1) of Cone Penetration Test (CPT) to the depth of 30 m below seabed (BSB) and laboratory testing of retrieved shallow (up to 6 m BSB) soil samples.

This analysis led to the definition of four primary geotechnical soil types: CLAY, SAND, SAND MIXTURES, and SILT MIXTURES. These primary types were further divided into thirteen geotechnical units (GUs) based on their stratigraphic position and the observed variations in soil behaviour (e.g. Figure 3).

The characterisation of these GUs relied on the integration of CPT data with laboratory tests, including classification tests and index properties such as particle size distribution and Atterberg limits.

The differentiation and classification of the interbedded layers, particularly within the SAND MIXTURES and SILT MIXTURES, presented challenges due to the limited availability of soil samples and relied on literature CPT based soil behaviour type (SBT) charts (Robertson, 2016; Schneider et al., 2008). Minor discrepancies observed between these two methods, particularly in classifying fine-grained soils, are tentatively attributed to the low sleeve friction values measured at the site, possibly due to the presence of silt or the relatively high carbonate content. Based on the available laboratory classification test results, the Schneider approach seems to provide a more consistent classification of soil units for the site and it was preferred over results provided by the Robertson approach. However, it should be noted that more laboratory classification tests would be required to provide a conclusive answer and have a more robust geotechnical soil classification.

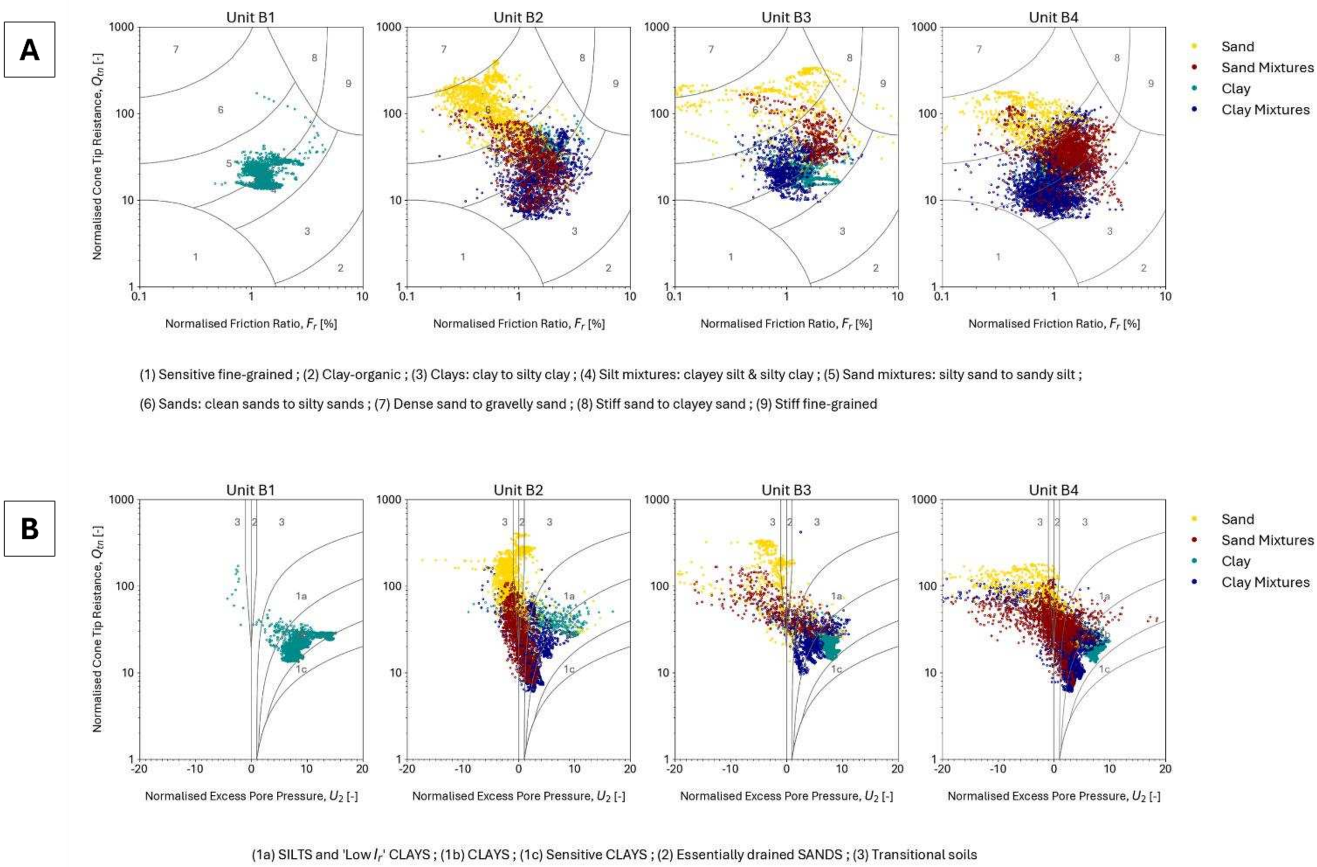

Figure 3 CPT based Soil Behaviour Type for Unit B deposits based on A) Robertson (2016) and B) Schneider et al. (2008) classification

4 PYBARSIM MODEL

The stratigraphic interpretation of the IGM is complemented by the use of the rule-based, 2D forward-stratigraphic model pyBarSim, that simulates the long-term coastal evolution and stratigraphic architecture of wave-dominated systems using Storms (2003) BarSim model.

The main inputs required by the model are initially estimated from the IGM and site-specific literature, and include initial shelf geometry, wave-height regime, sea level history (Wright, 2000; Figure 2B) and sediment supply. Although sediment budgets are not fully constrained, regional studies suggest that tectonic uplift in the Apulian foreland during the Pleistocene, combined with glacio-eustatic sea-level falls, likely increased the gradients of rivers draining into the Adriatic, leading to increased erosion and a higher sediment supply to the shelf during lowstands (Aiello, 2023 and references therein).

Following initial model runs, best-fit sediment supply data are refined trough a trial and error approach; preliminary results are firstly adjusted to match the overall 2D margin architecture derived from the seismostratigraphic mapping, and successively updated to reproduce the main stratigraphic features observed in 1D VC and CPT data, such as the thickness and depth of prominent sand packages, at different water depths (Figure 4).

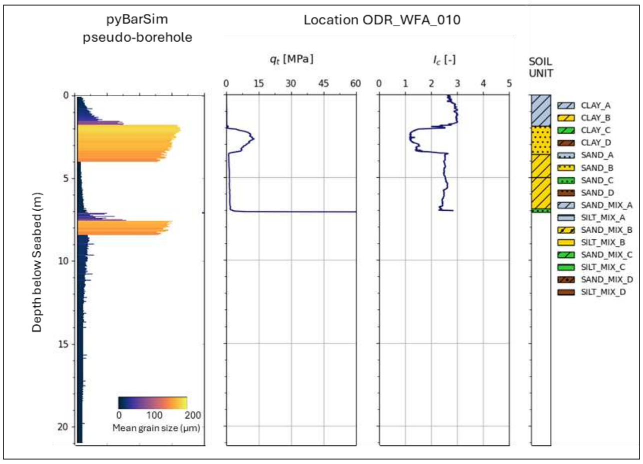

Figure 4 Comparison of mean grain size extracted as a pseudo-borehole from the pyBarSim model at -115 m WD with CPT-derived data (q_t and I_c) and geotechnical units from location ODR_WFA_010 (-114.4 m WD)

The model results qualitatively match the IGM observations, but provides further insight into the origin of sediment packages and their sequence stratigraphic significance (Figure 5B), together with a better understanding of their lateral distribution away from geotechnical control points (Figure 5A).

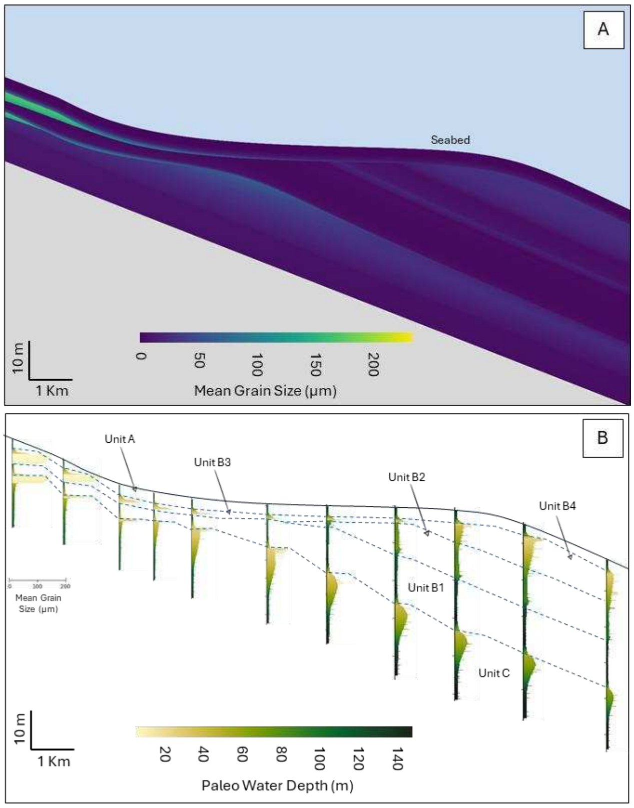

Figure 5 pyBarSim model of the OWF area (location in figure 2). A) Distribution of the mean grain size classes, B) Correlation panel. Pseudo-boreholes extracted from the model outputs, color-coded according to the water depth at the time of deposition

Tectonic effects and subsidence are not included in the available model capability; for this reason, only the most recent strongly progradational units (units C, B and A), deposited during the late Pleistocene sea level cycles (up to 230'000 years before present) and not influenced by tectonic deformation, are modelled.

Following initial model runs, best-fit sediment supply data are refined through a trial and error approach; preliminary results are firstly adjusted to match the overall 2D margin architecture derived from the seismostratigraphic mapping, and successively updated to reproduce the main stratigraphic features observed in 1D VC and CPT data, such as the thickness and depth of prominent sand packages, at different water depths (Figure 4).

4.1 ENHANCING UNDERSTANDING THROUGH SEQUENCE STRATIGRAPHY

The application of sequence stratigraphic concepts enhances the understanding of geotechnical conditions at the site, partially overcoming the limitations posed by the paucity of available geotechnical data, by providing a framework for explaining observed patterns and making informed predictions. In the stratigraphic scheme developed for this project we define a stratigraphic unit as equivalent to a full sequence, and a sub-unit as roughly equivalent to a system tract. As an example, the stratigraphic interpretation of the four subunits comprised in Unit B are discussed below.

Sub-unit B1 represents transgressive and high-stand marine deposits deposited at paleo-water depths > 80 m in the outer shelf (Figure 5B). It is consistently characterized as a homogeneous clay-rich unit in both core and CPT data (Figure 3). The sequence stratigraphic approach allows for the prediction of this clay-rich unit's lateral extent (Figure 5A) and its relatively uniform geotechnical properties based on its depositional setting.

The strongly progradational (Figure 2) sub-unit B2, formed during the falling stage system tract (Figure 5B, paleo-water depth decreasing from -80 to -40 m), exhibits greater variability in its geotechnical properties (Figure 2, Figure 3). While typically represented by thinly interbedded sands and silts as predicted (CPT-11 in Figure 2 and Figure 5B), CPT data across the site reveal lateral variations in grain size and composition not fully captured by the pyBarSim model, that could be explained by the influence of bottom currents on the outer shelf leading to variations in sediment transport and deposition.

Sub-unit B3, consistently recognized as a sand-rich layer in CPT and VC samples in the inner shelf and becoming finer-grained toward the shelf edge (Figure 2), was deposited during a forced regression and subsequent transgression (Figure 5B); the forced regression led to the deposition of sands across the inner shelf (CPT-10 in Figure 2), which were later reworked by wave action during the transgression (i.e. ravinement), resulting in a laterally continuous, relatively clean sand unit. The sequence stratigraphic interpretation also highlights gradual lateral changes in grain size not captured by the few available soil samples and provides a basis to interpret local CPT refusals as possible cemented layers formed during the subaerial exposure of the shelf.

Sub-unit B4, the younger forced regression / low stand deposit mapped, presents a unique set of geotechnical conditions due to the presence of possible shallow gas accumulations (Figure 2). This unit consists of interbedded sands, silts, and clays (Figure 3, Figure 5), with potential variations in composition due to the presence of gas and associated features like pockmarks. The sequence stratigraphic interpretation (Figure 5B) provides crucial context for understanding the origin of the gas, its spatial distribution, and its potential impact on the geotechnical properties of the unit and geohazards.

4.2 Geohazards

The outer shelf exhibits several features indicative of active or previously active geohazard processes.

Pockmarks and seabed depressions are widespread, and spatially correlated to a mapped weak acoustic blanking observed in seismic data (Figure 6) interpreted as the remnant of a shallow gas front. Large-scale submarine landslides are mapped at the shelf break (Figure 6).

The above features are primarily located within the younger sediment wedge mapped, Sub-unit B4, deposited at the Last Glacial Maximum (LGM) and characterised by the rapid sedimentation (up to 2 m/Kyr or more) of thinly interbedded (see CPT-15 in Figure 2), predominantly fine-grained deposits (Figure 5A).

This rapid sedimentation likely increased both the gravitational load and the shear stress on the slope (Canals et al., 2004), and exceeded the rate of consolidation, possibly resulting in the formation of under-consolidated, weak layers characterized by high porosity and low shear strength.

The rapid sedimentation is also inferred to have caused the accumulation of biogenic gas in Units B2 and B4; in turn, rapid post-LGM sea level rise may have altered hydrostatic pressure conditions, potentially triggering gas exsolution from pore fluids and upward migration through the sediment column (Riboulot et al., 2016).

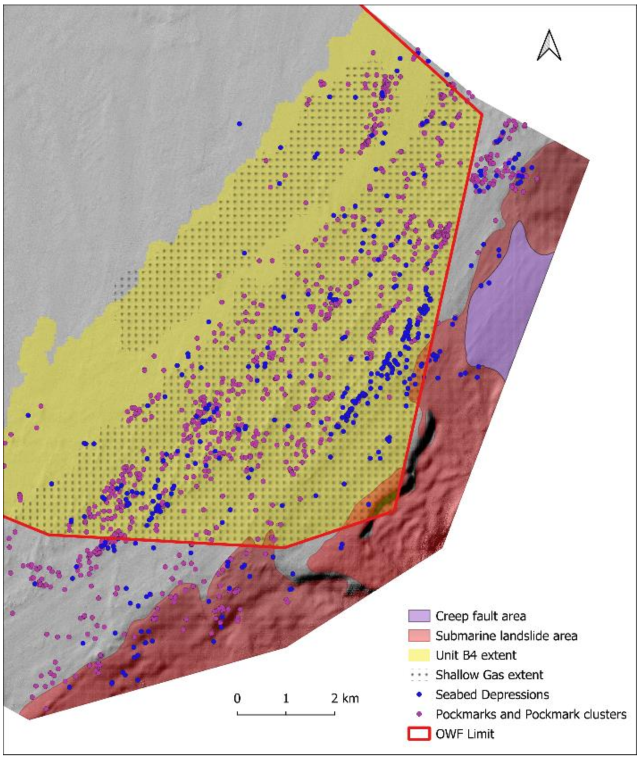

Figure 6. Geohazard map of the outer shelf area

The above factors likely acted as preconditioning factors for the landslides, ultimately triggered by rare but potentially strong earthquakes (e.g. the known 1743 BC Earthquake, Galli and Naso, 2008), with the pockmarks forming as a result of pressure release. This association between gas fronts, pockmarks, and landslides has also been observed in other areas of the central Adriatic Sea (Trincardi et al., 2004).

5 CONCLUSIONS

The findings from the presented case study underscore the value of incorporating sequence stratigraphic principles into IGM development for offshore wind farm projects, particularly in non-glaciated margins characterized by complex depositional histories.

Perhaps more importantly, this approach demonstrates that a comprehensive understanding of the site's depositional history leads to a clearer insight into subsurface conditions, even at a preliminary project stage. This, in turn, provides a foundation for identifying key geohazards and supports more reliable engineering design and decision-making.

AUTHOR CONTRIBUTION STATEMENT

Giuseppe Malgesini: Methodology, Software, Conceptualization, Data curation, Investigation, Writing- Original draft. **Ana Branco Fernandes**: Investigation, Data curation. **David Middleton**: Data curation. **Carlo Brandolini**: Investigation, Data curation. **Omar Zanoli**: Project Administration, Investigation, Writing- Reviewing and Editing.

ACKNOWLEDGEMENTS

The authors acknowledge Nadara / BlueFloat Energy for granting permission to publish this work.

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