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An Integrated Working Party Approach to Offshore Site Characterisation

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ABSTRACT: In 2019, the Engineering Group of the Geological Society of London established a Working Party in Offshore Engineering Geology, Geomorphology and Geohazards with the purpose of undertaking a comprehensive examination of offshore ground conditions and site characterisation from an engineering geological standpoint. The primary focus is on the shallow subsurface and associated geo-constraints relevant to ground engineering operations at depths less than 100 m below seafloor and in water depths over 10 m. This paper guides readers through each chapter using real-world data to unravel the optimal solutions to factual geological constraints and provides recommended approaches for every stage of the offshore site characterisation process. By progressing through the Working Party publication in a methodical, chapter-by-chapter approach, the authors will demonstrate how this valuable publication can be used by a wide range of practitioners, including early career professionals and those making a sector change. This study includes a worked example based on the Ten Noorden van de Waddeneilanden (TNW) Wind Farm Zone (Netherlands), explaining how to approach early phase assessments at the regional scale, guidance on undertaking site-specific ground modelling and geohazard assessment, how to ensure multidisciplinary data integration, what tools are available to each individual discipline within the 'geo-team' and finally how this translates into engineering design for offshore infrastructure projects.

Keywords: Offshore / Marine Site Characterisation; Engineering Geology; Geomorphology; Geohazard.

1 INTRODUCTION

In 2019, the Engineering Group of the Geological Society of London established a Working Party to undertake a state-of-the-art review of offshore ground conditions from an engineering geological viewpoint, focusing on shallow geology and processes significant to ground engineering activities (less than 100 m depth below seafloor, water depths of more than 10 m). The Working Party will integrate and disseminate a wealth of academic and industry experience in these challenging conditions to the public domain for the first time.

The resulting Engineering Geology Special Publication (Martin et al. in press) provides: an overview of the industry drivers for this project; some of the key geo-challenges facing offshore developments and the potential benefits of, and approach to, a holistic ground-model approach to site characterisation and geohazard assessment.

1.1 Uncertainty management strategies

Managing geological and geotechnical risks for developments such as offshore wind farm sites is vital for several reasons: identifying and mitigating geological hazards, such as subsea landslides or sediment mobility, is essential for ensuring the safety of construction activities and perfomance of the asset during its lifespan. Early identification and managment of geotechnical uncertainties can prevent unexpected costs and delays during construction and operation, including those related to unforeseen ground conditions. Figure 1 outlines the proposed uncertainty management process for offshore site characterisation.

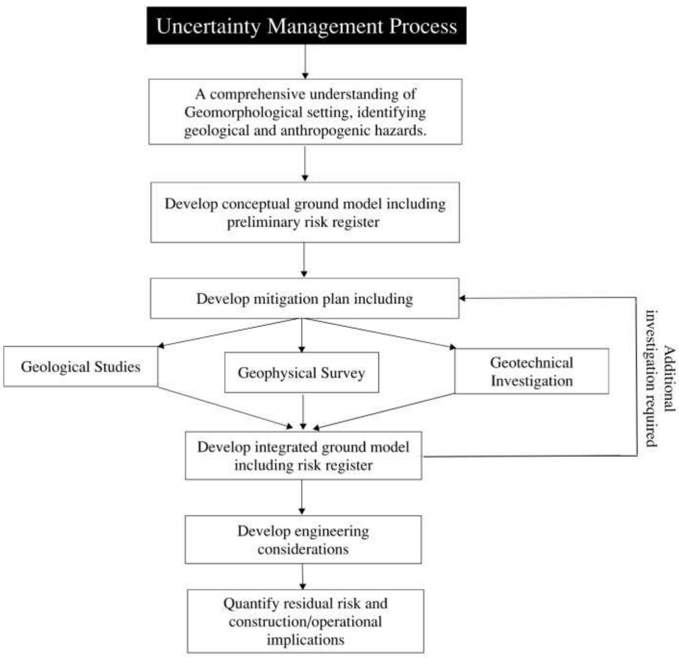

Figure 1 – Uncertainty management process for offshore site characterisation (Martin et al. in press).

1.2 Case Study – TNW Wind Farm Zone

The Ten Noorden van de Waddeneilanden (TNW) Wind Farm Zone is located about 67 km off the coast of Groningen, Netherlands. The new wind farm site within this zone is planned to have a capacity of 700 MW. The area covers approximately 120 km2. The Dutch government is in the process of issuing permits for its development, and the site is expected to be operational by 2027 (RVO, 2024).

The Working Party have chosen this site as it provides open-source data and studies with extensive preparatory work, including environmental impact assessments and site characterisation studies. These studies provide a wealth of data on the geological and geotechnical properties of the site, making it a rich resource for further research and development.

This approach is not intended to reassess the site characterisation previously implemented at the TNW site, but to assist readers in navigating each chapter utilising real-world data. It identifies optimal solutions to specific geological constraints and offers recommended best practices for each phase of the offshore site characterisation process.

By progressing through the Working Party publication in a methodical, chapter-by-chapter approach, the authors will demonstrate how this valuable publication can be used by a wide range of practitioners, including early career professionals and those making a sector change (i.e., from onshore to offshore site investigation).

2 OFFSHORE SETTING: METOCEAN, GEOMORPHOLOGY & GEOLOGY

Early investment in studies and site investigations is essential to mitigate the risks associated with geohazards (Moore et al. 2007, 2023). Understanding the regional geological and geomorphological settings of offshore sites helps in developing ground models, identifying hazards, guiding project planning, and interpreting site-specific data.

Recent advancements in subsea survey technologies have improved our understanding of the geology and geomorphology of the world's oceans (Hough et al. 2011). Despite mapping about 20% of the ocean floor in detail, large areas remain unexplored due to inaccessibility. Progress in remote imaging, testing, sampling, and monitoring has provided extensive data for evaluating oceanic features and processes. These data are crucial for identifying geological and geomorphological hazards (geohazards) that can impact offshore developments.

The recognition of scale for the characterisation of offshore sites in both space and time is of particular significance compared to terrestrial environments. Metocean conditions operate at scales that span the world's oceans, likewise active and passive continental margins, slopes, and ocean basins have evolved over geological time and cover vast areas of subsea landscape. Meso-scale structural, sedimentary, and discrete subaqueous geomorphology features such as landslides are found to share morphological similarities to their terrestrial analogues, yet they are typically many orders of magnitude greater in scale. Consequently, a full understanding of the features, materials, origins, stress history and sensitivity of offshore sites to future change processes and events can only be achieved in the wider context of the evolution of the continental margins and ocean basins.

The TNW wind farm site is located in the southern North Sea, a passive shelf environment. The seafloor is remarkably flat with the only morphological features being a few sand banks in the most eastern part of the site. The crests of the sand banks are aligned in a north-south direction, and are 1 to 5 km long, 500 to 700 m wide, and do not exceed 1 m above the surrounding seafloor (the "Visual Glossary" chapter of the Special Publication supports the reader with identification and classification of seabed and features).

The desk study was based on publicly available data from governmental online databases, including bathymetric data, logs from shallow and deep boreholes, and published literature, The stratigraphic framework for the site was extracted from geological maps.

The location did not experience ice loading during the most recent (Weichselian) glaciation, with the Last Glacial Maximum (LGM) across the southern North Sea (~23-22 ka) terminating to the north. In a regional context, the soil units deposited post-Eemian (i.e., younger than ~115 ka) were laid down in ice-distal (i.e. periglacial) terrestrial, glaciomarine and/or marine environments. Prior to this, during the preceding Eemian and Holsteinian interglacial, marine conditions dominated with typically shelly sands being deposited across the site. Pre-Eemian soils comprise subglacial, proglacial, periglacial, and glaciomarine deposits, associated with the Saalian and Elsterian glaciations.

This preliminary regional overview (following the approach advocated in Chapter 2 of the Special

Publication) characterises the site in the context of the previously glaciated NW European margin and allows the geo-team to build a picture of anticipated ground conditions and potential geohazards and geo-constraints for an early phase in the project (i.e., boulders in subglacial deposits, lateral and vertical variability created by subglacial and proglacial channel incision).

3 GROUND MODELS & GEOHAZARDS

To identify and address constraints, challenges, and opportunities in offshore engineering, it is essential to understand the processes shaping ground conditions at the proposed site. As mentioned in Section 2, this understanding is rooted in the site's geological evolution and its wider context, ranging from continent-wide tectonic forces to local, contemporary processes like tidal scour.

A Ground Model integrates various datasets to determine: i) how processes created the ground conditions; ii) how and why ground conditions vary; iii) which dynamic processes are active; iv) the implications for the engineering project; and v) potential design and mitigation measures.

The term "Ground Model" can mean anything from a simple sketch to a detailed 3D digital rendering. It integrates geological, geomorphological, geotechnical, and geohazard data. As site-specific data are acquired, the model's detail and confidence increase. Key aims include: i) Managing project risks early; ii) Identifying opportunities for efficient planning and design; and iii) Providing evidence to support project progression.

This chapter introduces the Ground Model concept, its applications across various geological settings, and the importance of updating it with new data. It emphasises understanding geological conditions to manage geohazards, identify challenges early, and optimise site characterisation and engineering design.

The flat and benign-looking seafloor at the TNW site belies the complexity of geological and geotechnical conditions that lie within the depth of interest; hence, a ground model provides a valuable framework to communicate the lateral and vertical variability in ground conditions, the (un)certainty in extrapolation between sampled/tested locations, and to identify, manage and mitigate any constraints posed by the conditions inherited from its complex geological past. The ground model requires an understanding of the depositional (and erosional) history over multiple phases of glaciation and deglaciation that explain the nature of sediments emplaced, their often-complex post-depositional histories, including incision by subsequent phases of channelisation, loading and unloading, and that have involved various sea level changes that have modified the locus and mode of sediment accumulation from shallow marine to subaerially exposed glacially modified settings.

4 SITE CHARACTERISATION & DATA INTEGRATION

There is a plethora of data on seafloor and sub-seafloor conditions that can be accessed during desk studies for many, but importantly not all, areas of the world. In addition, there are a multitude of techniques, both non-intrusive and intrusive, to collect new data during ground investigations. Characterising a site requires the integration of these data in a consistent geological framework and is the main task in building a representative ground model to support engineering design and geohazard assessment. This chapter considers the key disciplines required to build a ground model (the ‘geo-team’), the role of the desk study in preliminary site characterisation and planning of site surveys and investigations, timescales and sequencing of site and desk-based work, data management and integration, key internal and external interfaces between the geo-team and end-users, and the technical and practical issues that must be considered.

At TNW, the integration of geology, geophysics and geotechnics was performed by the Norwegian Geotechnical Institute (NGI) and SAND Geophysics. The core team had broad experience with all the required disciplines, including seismic inversion and data science to obtain a 3D model of the area in a consistent geological framework that can be used for engineering design. Key aspects included: (i) seismic interpretation, taking into account the geological setting and complexities of sea-level oscillations and glacial processes into a geological ground model; (ii) careful planning of the geotechnical site surveys in order to obtain critical data from all identified formations across the site; (iii) ground model calibration using in situ and laboratory testing, refining the ground model into a structural model, with sub-units having specific lithologies and constraining geotechnical properties by linking in situ test results with laboratory results in a probabilistic framework; (iv) extraction of seismic attributes and performing seismic inversion: (v) training of a neural network to blindly predict Cone Penetration Tests (CPT) responses across the site; and (vi) use of geostatistical approaches to populate the entire area with CPT predictions (i.e., NGI 2022; Sauvin et al. 2024).

5 GEOPHYSICAL SURVEYS

Geophysical data forms an essential component in all aspects of site characterisation, contributing towards geohazard and risk assessment, the creation of data-driven ground models, and engineering applications. The main advantage of geophysical datasets is that they can cover extensive areas, providing laterally continuous, detailed information about the seafloor and sub-seafloor structures and processes, both active and passive. This forms an ideal complement to geological analysis and geotechnical investigation, which provide localized ground-truth to the indirect and non-intrusive geophysical methods. The chapter focuses on geophysical methods, from theory to applications, including acquisition, processing and inversion for site characterisation.

While there is a wealth of different geophysical methods available, the most used are seismo-acoustic methods, which can be readily acquired and processed. However, complementary geophysical methods will provide additional information that allow a better integrated understanding of the sub-surface and may provide a closer link with, i.e., geotechnical parameters. As such, we close the chapter by highlighting complementary methods as well as emerging technologies, particularly those with added value for shallow sub-surface characterisation, identifying limitations in our current abilities and areas for potential future development.

There is a significant trade-off between acquiring a 2D geophysical survey and a 3D ultra-high-resolution (UHR) geophysical survey in terms of the subsurface imaging and characterization. A 2D survey is generally more cost-effective and quicker to conduct but offers a limited view, which may not capture smaller or intricate geological features (largely pending on line spacing and geological complexity). In contrast, a 3D UHR survey can produce a comprehensive volume of data, providing superior sub-surface information, although it requires more time for acquisition and processing. However, when the technology is available, using 3D over 2D may ultimately shorten the windfarm development time, as no additional geophysical surveys will be required, and therefore, the geological ground model can be created much earlier in the process.

When complemented with seismic inversion and machine learning techniques, the 3D data will result in higher-resolution CPT or soil parameter predictions with constrained uncertainty, which will aid the engineering design. Underprediction of geotechnical strength/stiffness parameters can lead to over-design, necessitating larger volumes of steel and increasing costs. Conversely, overprediction can lead to under-design, causing issues with foundation capacity.

However, there is currently significant uncertainty regarding the empirical relationships between geotechnical parameters obtained from CPT, which the industry has learned to accept in order to minimise costs. The application of predictive CPTs presents a promising solution to enhancing the spatial coverage of geotechnical parameter estimations, reducing scope for geotechnical survey. Ultimately, the aim is to mitigate and manage uncertainty, rather than add it.

At TNW, the seismo-acoustic data consisted of seafloor data (multi-beam echo-sound, side-scan sonar, backscatter) and sub-seafloor data (sub-bottom profiling, multi-channel seismic reflection data), in addition to magnetometer data for UXO clearance before CPT and BHs. The data were fully interpretated and integrated with the geotechnical data. Further, the seismic data was inverted for acoustic impedance, using a genetic algorithm, and seismic attributes were extracted which were used as input in a probabilistic artificial neural network to predict CPT responses (see NGI, 2022).

A 3D UHR survey (with 0.5 m bin length) was collected over a sub-set of the area and used to extract geomorphological and
stratigraphic information (Figure 3). Despite the wealth of geophysical data available, the complex geological history would warrant a site-wide 3D survey to improve our understanding of the processes and geospatial distribution of key formations and soil units (i.e., Sauvin et al. 2023).
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An UHR 3D survey (with 0.5 m bin length) was collected over a sub-set of the area and used to extract geomorphological and stratigraphic information (Figure 2). Despite the wealth of geophysical data available, the complex geological history would warrant a site-wide 3D survey to improve our understanding of the processes and geospatial distribution of key formations and soil units (Sauvin et al. 2023).

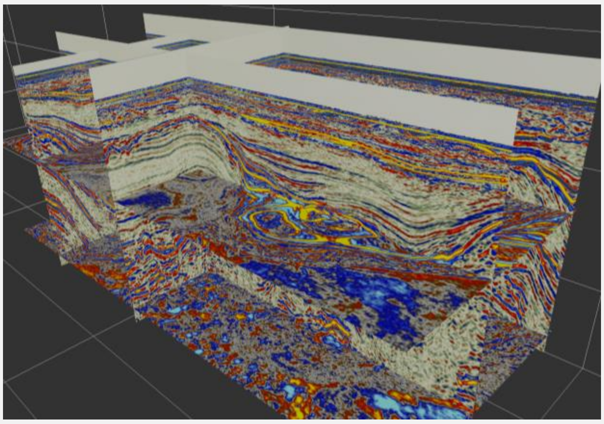

Figure 2 – 3D seismic data volume collected over TNW, illustrating the complex stratigraphy affected by glacial processes and sea-level fluctuations.

6 GEOTECHNICAL INVESTIGATION

The demands on marine site characterisation have grown over time with advancing ambitions in offshore developments, progressing in size, water depth, geological complexity. The energy transition brings further advancing technical ambition while increasing demand for cost-effectiveness of offshore foundations.

Ground truthing, meaning the acquisition of detailed knowledge about the material properties of the seafloor and sub-seafloor, and achieved through geotechnical investigation, is key to characterisation. This chapter describes best practice of marine geotechnical investigation and interpretation, mapping out the current equipment, tools, testing and interpretation methods. It guides practitioners in selecting equipment, tools, and methods to suit project needs and outlines ongoing innovations and future trends, focusing on improving operational efficiency and safety (in field operations or the data delivery cycle), or as developments which improve the fidelity of geotechnical characterisation.

Scoping, meaning definition of sampling and in-situ testing quantities, needs to reflect the above-mentioned drive for increased cost effectiveness, noting that this also applies to the geotechnical investigation cost itself. Scaling-up investigation scopes, as would be applied for single-structure oil and gas developments, to wind energy projects having a hundred or more wind turbine structures is simply not feasible from cost, time and market availability perspectives. Hence the offshore wind industry has developed complex strategies for phasing and scoping geotechnical investigations as described in the chapter, balancing expenditure with the required level of definition of soil properties over time.

The phasing for offshore wind farms usually has an initial reconnaissance survey performed before the wind turbine layout is known, followed by detailed investigation at each turbine location once the layout has been confirmed. Aims of the reconnaissance investigation include: i) constraining the ground model, which to this point has been established purely on geophysical survey data and regional geological knowledge; ii) developing correlations between in-situ geotechnical readings and laboratory-measured properties from recovered samples; and iii) enabling concept-level foundation and cable design.

The TNW investigation included the above objectives yet was atypical in its ambition as a reconnaissance survey. This was partly due to the funding model, with the investigation paid for by RVO as opposed to a prospective developer and associated normal commercial drivers. The extensive scope also enabled RVO's background aims of scientific furtherment, for example geotechnical profile generation at any non-investigated location via the seismic inversion described above. This required a more extensive PCPT dataset than would otherwise be acquired – some 130 locations were investigated with a deep-push seabed PCPT unit or a borehole, possibly a factor of three or more on a typical reconnaissance investigation scope for a wind farm of this size.

7 GEOLOGICAL INVESTIGATION

It may be warranted to acquire further samples for geological analysis to provide information to feed into the site characterisation and/or risk assessment that cannot be provided solely by geophysical surveys or geotechnical investigations. This may include ground truthing of geophysical data interpretations, providing temporal information on past geohazard processes such as the frequency of events using age dating, or numerical modelling to understand the behaviour and impact of seafloor processes on infrastructure.

The extent of sampling and testing is dictated by the findings of early-stage assessments. Such geological analysis provides additional information that allows for various potential geohazards to be ruled out and offers information needed for geohazard-resistant design, provides the basis for monitoring strategies or for re-routing/avoidance.

Value is added by including geological analysis, without advocation of a prescriptive approach, and each site should be considered with respect to its interpreted risk profile, the nature and type of anticipated geohazards. In the chapter we will discuss a range of different geological methods and analyses that provide information to provide temporal constraints to deposition and geohazard recurrence, calibrate geophysical interpretation, better understand geotechnical behaviour of sediments, and to enhance confidence in site characterisation and reduce the exposure of the proposed development of geohazards.

Based on the desk study and recommendations for site survey, TNW was investigated by MBES (Multibeam Echo Sounder) including backscatter, SSS (Side Scan Sonar), SBP (Sub-bottom Profiler), MAG (Magnetometer), Seismic Survey with 2D UHRS and sediment grab sampling.

8 ENGINEERING & DESIGN CONSIDERATIONS.

The 3D quantitative ground model underpins the engineering design for wind farm infrastructure, including foundations, anchoring systems, and routing /protection measures for interarray and export cables.

The 3D ground model of geotechnical parameters is a platform for engineering analyses to be overlain through gridded design calculations to create design outcome maps as layers in the GIS. This approach capitalises on the availability of computing power and software automation, that allow a potentially unlimited number of geotechnical analyses to be performed (Doherty et al. 2018, Putuhena et al. 2023).

Benefits from integration, automation and upscaling include i) a wider range of design cases can be explored to optimise the outcome ii) the geotechnical design outcomes become part of the ground model GIS, helping to share information among the geo-team and to update outcomes if input parameters change as the ground model evolves.

This improved ability to compare design options allows the geoscience considerations to be weighed against, and respond to, the many other constraints and opportunities that influence the optimal project solution as illustrated in Figure 3. The optimum geotechnical infrastructure is not determined from geoscience considerations alone, i.e., the choice of concrete gravity-base or steel piled foundations may be influenced by available port and construction infrastructure, and local content and environmental impact considerations. Also, cable routing and array layouts can be influenced by existing infrastructure, other ocean activity and ecological interactions. The design inputs and risks differ for different geotechnical infrastructure, affecting the required ground model detail.

However, the process of building and using the ground model, risk register, and risk management are similar for all sites whether small or large, and straightforward or complex. Geoscience best practice enables the right geotechnical solutions to be found for optimisation of the overall project.

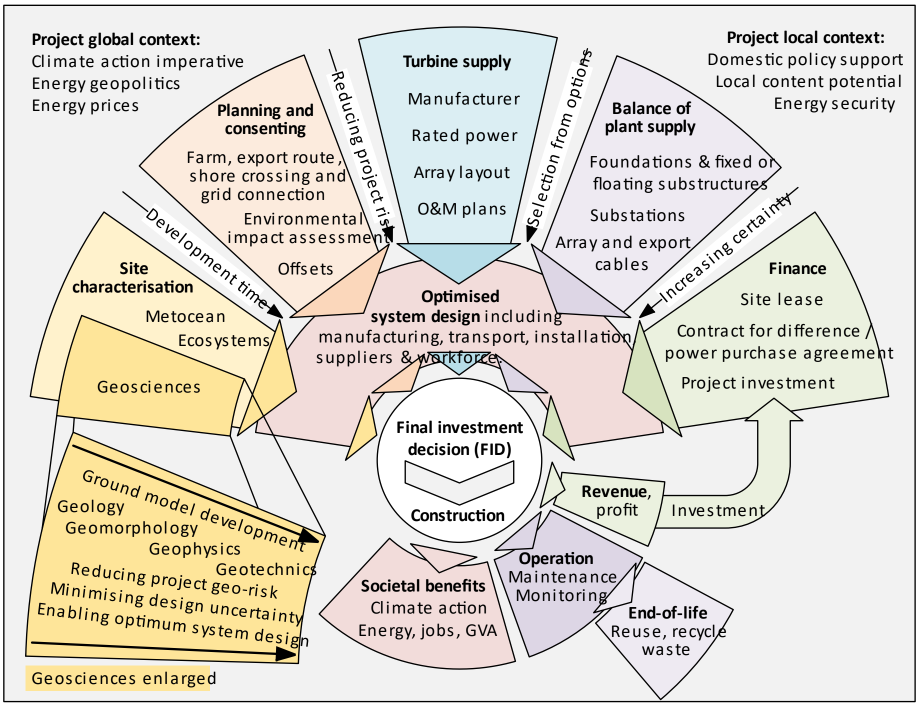

Figure 3 – Geoscience activities in wider project context (Martin et al. in press)

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It is expected that conventional monopiles would be appropriate at the TNW site due to the water depth and ground condtions presented and would be a finanically viable foundation solution. Figure 3 is from the NGI (2022) report and separates the site into seven zones that group the soil conditions and the geo-constraints into soil provinces. An assessment was made to convey required normalised pile length (i.e., length/diameter) for each zone to demonstrate optimum areas for development.

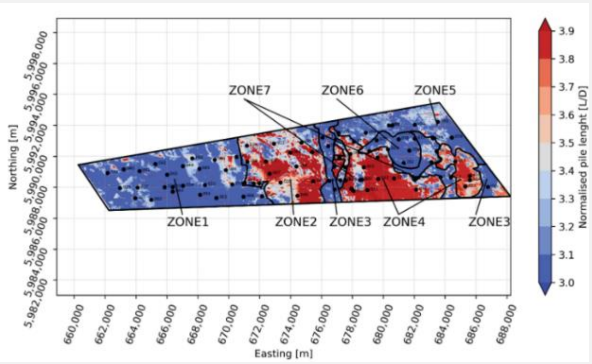

Figure 4 – Normalised pile lengths anticipated across TNW dependant on ground conditions (NGI, 2022)

9 CONCLUSIONS

This paper serves as a comprehensive guide for offshore site characterisation, emphasising the importance of a multidisciplinary approach to address geological constraints and geohazards. By providing practical examples and detailed methodologies, it aims to equip practitioners with the necessary tools and knowledge to manage uncertainties and integrate data across various geoscience disciplines. Ultimately, this publication aspires to enhance the proficiency of engineers at all career stages, fostering improved engineering design and safer offshore infrastructure project. By following the best practices outlined, geoscientists have a role to play in reducing the cost and timescale required for the new offshore energy developments and to unlock the energy transition.

10 AUTHOR CONTRIBUTION STATEMENT

P. Lipp: Conceptualisation, Supervision, Writing, Reviewing and Editing, **C.J. Martin:** Conceptualisation & Reviewing, **G. Carter, J. Griffiths, R. Moore, M. Clare, L. O'Leary, B. Mackenzie, M. Vanneste, S. Gourvenec and D. J. White:** Writing, Reviewing and Editing.

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