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From Natural Variability to Industrial Legacy: Reconstructing Pre-Production Baselines and Modern Impacts on North Sea Benthic Ecosystems

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Environmental monitoring of abandoned and late-life hydrocarbon sites requires robust indicators that distinguish anthropogenic impacts from natural processes. We present a multidisciplinary environmental baseline for the Danish North Sea, integrating high-resolution geophysical surveys with ^{14}C-dated sediment core chronologies to assess seabed health over a 10,000-year timescale. By combining biological, geological, and geochemical proxies, we reconstruct pre-production conditions that are critical for evaluating marine recovery and restoration potential. We further examine site-specific features and potential long-term impacts on benthic communities.

Our analyses identify distinct geochemical and biological fingerprints that characterize sedimentary environments. Results from two mature oil-gas production sites and one off-platform control site reveal contrasting drivers of environmental variability, including naturally occurring gas seepage, trace-element anomalies linked to elemental mobility in platform-proximal sediments, and differences in faunal composition related to local environmental conditions.

We also integrate publicly available monitoring data from the North Sea Environmental Portal and isolate observations from 2009 at the same sites. Principal Component Analysis (PCA) of seabed indicators shows that one platform site is primarily associated with elevated trace metal concentrations (e.g., Ba, Cu, Pb). In contrast, the other is characterized by higher biological abundance and greater numbers of individuals, dominated by mussels.

When considering chemical and ecological data from a single platform across the period 1989-2024, PCA reveals temporally structured groupings, indicating time-specific environmental states. We observe a clear chronological development in key environmental indicators at this site, with a separation between earlier observations (2015, 2020, 2021) and the most recent data from 2024, as well as a distinct cluster for 2018. The 2024 confidence ellipsoid aligns strongly with vectors for several trace elements, with barium pointing toward this recent cluster, consistent with drilling-related inputs or produced water discharge.

Together, these results highlight the importance of higher-frequency monitoring and improved site-specific assessment frameworks to robustly evaluate long-term environmental impacts of offshore energy activities and to define realistic local pre-industrial baselines for restoration efforts.