Spatial distribution and morphology of methane-derived authigenic carbonates, or 'bubbling reefs' in the Danish offshore environment.

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Methane-derived authigenic carbonates (MDACs) are lithified structures that form due to methane-rich fluid seepage. Carbonate precipitates as a result of anaerobic methane oxidation, facilitated by sulphate-reducing bacteria, and cements loose sediments. The methane generally has a microbial or geothermal origin. MDACs appear all around the world, from deeper to shallower seas, throughout the geological record as palaeostructures and they form actively in present-day marine environments.

MDACs occur in the Danish marine area, where their exposure is likely linked to (glacio-isostatic) uplift and removal of unconsolidated sediment around the structures. They appear in different morphologies, such as sheets, slabs, pillars or mushroom-like structures. A great variety of fish species spawn, nurse, shelter and feed in cavities and on the hard substrate and these structures. In addition, the hard substrates allow for bivalves, annelid worms, crabs, lobsters, anemones and sponges to live on and are therefore an important habitat for marine biodiversity. They are commonly also referred to as 'bubbling reefs'. The EU Habitats Directive (HD) and Annex I stress the importance of 'submarine structures made by leaking gasses', including 'bubbling reefs' (habitat type 1180) as natural habitats and aim to protect them. MDACs are also listed as one of the habitat types in the EU's Nature Restoration Regulation Annex II. EU's Nature Restoration Regulation aims to restore nature by 2030 in at least 20% of marine environments. It is therefore important to locate and assess the conditions of MDACs.

MDACs have been documented in the Danish offshore area in the North Sea. Their spatial distribution and morphology are mapped by geophysical seabed mapping, using a combination of side-scan sonar, multibeam echosounder and sub-bottom profiler data. They are further verified with underwater videos and images acquired by remotely operated vehicle (ROV) or taken by divers. Many of the identified MDACs have been observed in the Trans-European Suture Zone (or Sorgenfrei-Tornquist Zone), indicating a link to the

subsurface geology. Neotectonics may have activated methane seepage along fault zones. The methane seepage in this area has a microbial origin, as indicated with a distinct stable carbon isotopic ($\delta^{13}C$) signature and presumably originates from Late Quaternary marine deposits. However, a clear correlation between the subsurface geology and surface processes remains to be demonstrated. This study aims to provide detailed maps of the spatial distribution and morphology of the MDACs and to assess the potential link of their appearance to the subsurface geology.

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