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Pockmarks and methanogenic carbonates above the giant Troll gas field in the Norwegian North Sea

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ABSTRACT

Acoustic imaging has revealed more than 7000 pockmarks on the seafloor above the Troll East gas field in the Norwegian North Sea. We present the first comprehensive study conducted on one of the World's largest pockmark fields complementing the acoustic data with extensive sampling, geochemical and petrographical studies. Specifically, we aimed at detecting possible active seepage still present over this vast area. The pockmarks are present as isolated structures, on average ~35 m wide and up to 100 m in size. In addition, smaller satellite pockmarks surround some of the pockmarks. In contrast to the muddy surroundings, parts of the investigated pockmarks contain laterally extensive carbonate deposits or meter sized carbonate blocks. These blocks provide shelter to abundant colonies of benthic megafauna. The carbonate blocks are comprised of micritic Mg-calcite and calcite, micritic aragonite, and botryoidal aragonite. Framboidal pyrite is also commonly present. Carbon isotopic values of the carbonates are ^{13}C-depleted (δ^{13}C as low as −59.7‰) and with δ^{18}O up to 4.5‰, indicating a methanogenic origin, possibly linked to gas hydrate dissociation. Pore water extracted from shallow cores from the centre and the flanks of the pockmarks show similar Cl and SO_4 profiles as the reference cores outside the pockmarks, ruling out active methane seepage. This conclusion is also supported by seafloor video observations that did not reveal any evidence of visual fluid seepage, and by the absence of microbial mats and by the fact that the carbonate blocks are exposed on the seafloor and party oxidized on the surface. We conclude that methane seepage formed this extensive gas field following to gas hydrate dissociation.

1. Introduction

There are three main settings where pockmarks are commonly present: 1) in offshore hydrocarbon provinces where fluids leaking from reservoirs reach the seafloor; 2) in gas hydrate regions as the result of ongoing or paleao dissociation of clathrates, and 3) in estuarine and delta regions where the constantly deposited organic-rich sediments or drowned wetlands trigger the production of shallow gas. Comparative studies show that the fields with the highest density of pockmarks are usually located at shallow depth associated with deltaic and estuarine settings (e.g. Kelley et al., 1994; Rogers et al., 2006; Brothers et al., 2012; Riboulot et al., 2013 and refs. therein). At these localities the presence of microbial methane is mostly recorded as opposed to thermogenic methane that is common at greater water depths especially in hydrocarbon-rich provinces (e.g. Nickel et al., 2013; Smith et al., 2014).

Former or ongoing methane seepage in pockmarks is commonly coupled to anaerobic methane oxidation operated by microbial colonies of archea and bacteria. This reaction releases CO_3^{2-} ions that bind with Ca present in the seawater ultimately resulting in authigenic carbonate precipitation (Valentine and Reeburgh, 2000; Boetius and Suess, 2004; Boetius and Wenzhöfer, 2013). Methanogenic carbonates are indeed common features at many pockmarks and seepage sites (Kocherla et al., 2015; Magalhães et al., 2012; Hovland et al., 1987; Naehr et al., 2000; Greinert et al., 2001; Gontharet et al., 2007; Akhmetzhanov et al., 2008; Greinert et al., 2010; Haas et al., 2010).

The presence of pockmarks in the North and Norwegian Seas and all the way north to the Barents Sea has been documented by several authors (e.g. Hovland and Judd, 1988; Andreassen et al., 2000; Bouriak et al., 2000; Bünz et al., 2003; Berndt et al., 2004; Hovland et al., 2005; Mazzini et al., 2005, 2006; Forsberg et al., 2007; Paull et al., 2008; Chand et al., 2012; Nickel et al., 2012). One of the largest pockmark fields is located at Nyegga, in the southern part of the Vøring Plateau. The first discovery of authigenic carbonates from this locality was reported by Mazzini et al. (2005). The first discovery of gas hydrates in the area was reported more recently (Ivanov et al., 2007). Although

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the features in the Nyegga region have always been described as pockmarks, a large part of them are not morphological depressions but rather positive structures containing large carbonate edifices in the central area. In order to describe these "seeping positive structure" Ivanov et al. (2010) coined the new term "seep mounds".

Large pockmark fields represent a window into the subsurface plumbing systems. They have been targeted for extensive geological and geophysical explorations offshore Norway in order to investigate the gas origin and if they are currently active or not. Active pockmarks and mud volcanoes represent oasis of unique chemosynthetic life (Olu et al., 1997; Sibuet and Olu, 1998; Menot et al., 2010; Ritt et al., 2011). However, numerous questions remain unanswered in particular for the pockmarks at northern latitudes. For example, is the seepage entirely related to gas hydrate dissociation? Or could the leakage from underlying gas and oil reservoirs represent the source of gas? Was the gas release catastrophic or did the fluid migration occur at slow mode? The climatic consequences of palaeo and modern seep-gas release to the shallow ocean and atmosphere is still an open question (Westbrook et al., 2009; Smith et al., 2014) and the discovery of new large pockmark fields is of relevance for future studies and global estimates.

In this paper we document the structure and nature of a giant pockmark field in the Norwegian North Sea (Fig. 1) where large carbonate blocks have been identified and sampled. These results are part of a large Statoil-funded project aiming at investigating gas migration around the Troll A platform. The aim of the paper is to describe the characteristics of this new discovery and to determine if active seepage is occurring in the region based on a large sampling campaign inside and outside the pockmarks. This issue has important implications for the fluid flow and hazard aspects of the area. If the pockmarks are actively leaking, there is a potential risk for formation of new pockmarks with a possible influence on platform stability. The second important

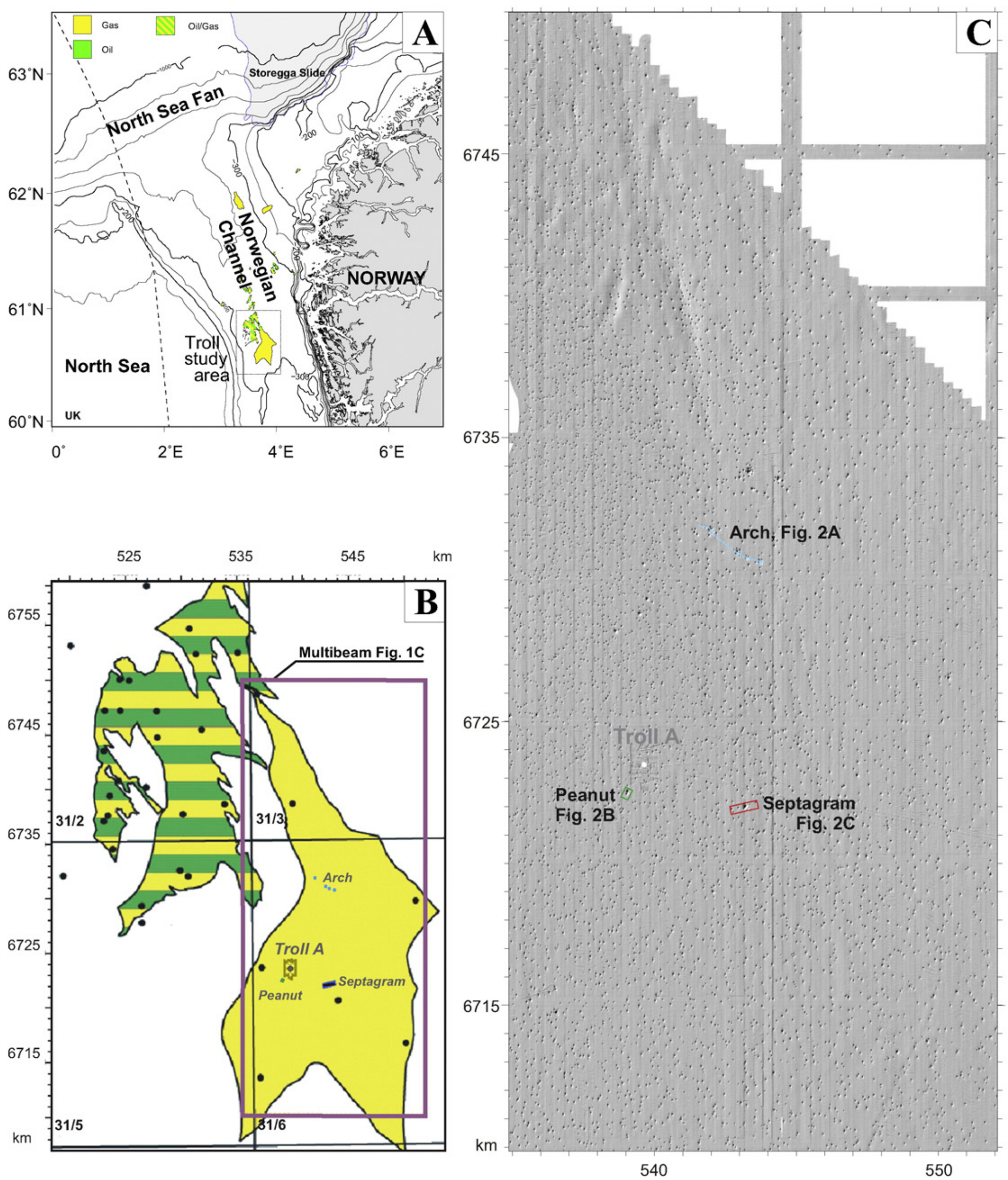

Fig. 1. (A) Inset map of Norwegian channel and North Sea, framed the Troll study area. (B) Detail of the Troll East gas field (yellow) covered with an extensive multibeam survey (purple line). (C) Troll field multibeam data. Note the large number of pockmarks (about 7500 in total). UTM Zone 31, WGS84 datum. Indicated the *Troll A* platform and the location of the three main ROV pockmark study areas: in red (Septagram), green (Peanut), and blue (Arch).