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A climatic trigger for the giant Troll pockmark field in the northern North Sea

Adriano Mazzini[a,*], Henrik H. Svensen[a], Carl Fredrik Forsberg[b], Henriette Linge[c,d], Stein-Erik Lauritzen[c,d], Haflidi Haflidason[c,d], Øyvind Hammer[e], Sverre Planke[a,f], Tor Inge Tjelta[g]

[a] CEED, University of Oslo, Oslo, Norway
[b] NGI, Oslo, Norway
[c] University of Bergen, Bergen, Norway
[d] Bjerknes Centre for Climate Research, University of Bergen, Allégaten 41, N-5007 Bergen, Norway
[e] Natural History Museum, University of Oslo, Norway
[f] VBPR, Oslo, Norway
[g] Statoil, Stavanger, Norway

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ABSTRACT

Pockmarks are seafloor craters usually formed during methane release on continental margins. However, the mechanisms behind their formation and dynamics remain elusive. Here we report detailed investigations on one of the World's largest pockmark fields located in the Troll region in the northern North Sea. Seafloor investigations show that >7000 pockmarks are present in a ∼600 km^2 area. A similar density of pockmarks is likely present over a 15,000 km^2 region outside our study area. Based on extensive monitoring, coring, geophysical and geochemical analyses, no indications of active gas seepage were found. Still, geochemical data from carbonate blocks collected from these pockmarks indicate a methanogenic origin linked to gas hydrate dissociation and past fluid venting at the seafloor. We have dated the carbonates using the U–Th method in order to constrain the pockmark formation. The carbonates gave an isochron age of 9.59 ± 1.38 ka, i.e. belonging to the initial Holocene. Moreover, radiocarbon dating of microfossils in the sediments inside the pockmarks is consistent with the ages derived from the carbonates. Based on pressure and temperature modelling, we show that the last deglaciation could have triggered dissociation of gas hydrates present in the region of the northern part of the Norwegian Channel, causing degassing of 0.26 Mt$_{CH4}$/km^2 at the seafloor. Our results stress the importance of external climatic forcing of the dynamics of the seafloor, and the role of the rapid warming following the Younger Dryas in pacing the marine gas hydrate reservoir.

1. Introduction

Despite several decades of research on pockmarks, many features and mechanisms controlling their activity remain poorly understood. Key aspects such as 1) timing of formation and 2) external (climatic) versus internal (overpressure) forcing are still debated. Part of the reason for this is the limited availability of large-scale high resolution bathymetry and monitoring data from continental margins, and the lack of accurate pockmark ages.

Pockmarks often display gas flares, gas-rich sediments, gas hydrate deposits or contain carbonates originating from the seepage of thermogenic or microbial methane (e.g. Mazzini et al., 2005; Haas et al., 2010; Nickel et al., 2013). They have been found in a large variety of geological settings at continental margins (e.g. Gontharet et al., 2007; Greinert et al., 2010; Kocherla et al., 2015). Although exceptions exist, it is commonly accepted that the driving force for pockmark formation is linked to methane migration and degassing. The methane may ultimately be sourced from deep hydrocarbon-rich reservoirs or from dissociating shallow gas hydrate deposits (e.g. Solheim and Elverhøi, 1993; Naehr et al., 2000; Smith et al., 2014). A common assumption is that some of the pockmarks offshore Norway were formed at some stage after the Last Glacial Maximum (e.g., about 21 ka ago), maybe even quite recently (e.g. Jung and Vogt, 2004; Paull et al., 2008; Hustoft et al., 2009; Plaza-Faverola et al., 2011). Cremiere et al. (2016) recently published a study on pockmarks in the Barents Sea, where

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[*] Corresponding author.
E-mail address: adriano.mazzini@geo.uio.no (A. Mazzini).

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methanogenic carbonates from pockmarks were dated. The results suggest methane seepage between 17–2 ka, linked to initial gas hydrates dissociation after the deglaciation of the southwest Barents Sea (∼18–16 ka).

By investigating one of the World's largest pockmark fields offshore Norway, located above a giant gas reservoir (Fig. 1A), we aim at resolving if the degassing was driven by deep or external forcing, and if the last deglaciation was the ultimate pockmark trigger. The main difference between this study and those previously done in the same region (e.g. Vogt et al., 1994; Bunz et al., 2005; Mazzini et al., 2006; Ivanov et al., 2010; Reiche et al., 2011; Chand et al., 2012), is that we have access to petroleum industry data including seismic profiles and bathymetry, ROV video observations and cores and sea floor carbonate samples, providing the necessary regional coverage, and statistical analyses in addition to stratigraphic details from a selection of pockmarks.

2. Study area and Quaternary geology

The Norwegian Channel is a distinct trough separating the Norwegian mainland from the shallower parts of the North Sea Shelf to the south and west. The water depths in the central part of the trough increase gently from around 305 m in the Troll area to about 400 m at the shelf break. Fast flowing ice streams are believed to have given the Norwegian Channel its characteristic physiography (Sejrup et al., 2003; Ottesen et al., 2005). During the LGM, ice streams probably extended all the way to the shelf edge where the North Sea Trough Mouth Fan was deposited (Nygard et al., 2007). The Troll area was thus situated below an ice stream, about 200 km from its terminus during these periods. Present day Antarctic ice streams show that analogous settings have subglacial water pressures that are approximately equivalent to the glacial overburden (e.g. Alley et al., 1989) and that the ice rides on a layer of deforming sediments (deformation till). The temperature and pressure regime imposed by the presence of the ice streams provides an important constraint for understanding the possible contribution of gas hydrates to the formation of pockmarks in the Norwegian Channel.

Following the break-up of the Norwegian Channel Ice Stream, the pressure history is determined by the interaction of eustatic sea level changes and isostatic rebound. Relatively rapid Late Glacial, glacial marine sedimentation has allowed the determination of a detailed seafloor temperature history for the Troll area (Sejrup et al., 2003, 2004).

The base of the sediments from this period is separated from the underlying gravelly and sandy sediments (Unit L3) by a glacial erosion surface at 74 m depth (i.e. 8903/8904 borehole in Sejrup et al., 1995, 2003). The sediments above consist of tills, probably deformation tills, deposited by the latest Norwegian Channel Ice Stream (NCIS). The top of the till at 16.9 mbsf is crenulated by iceberg plough marks and overlain by glacial marine deposits that merge into Holocene marine deposits at ∼3 mbsf.

3. Methods

3.1. Marine expeditions, petrography, and geochemical and geotechnical analyses

During the period 2005–2007 large seismic and multibeam echo-sounder surveys and several sampling campaigns were conducted over the Troll gas field in the Norwegian Channel to better understand the gas transfer processes from deeper levels to the seafloor (Fig. 1A). Additional high-resolution multibeam lines, video stills, and subbottom profiler (SBP) records were later acquired during several ROV dives (some examples in Fig. 1B–C). Forty-five cores and a large collection of sea floor carbonate blocks were collected from three selected pockmark complexes (Septagram, Arch, Peanut) and the surrounding areas (e.g. Fig. 1D). The data collected at these localities is used for a broader interpretation of the whole area. Carbonates were studied using optical and electron microscopy, carbon and oxygen isotope analyses and complemented with the data presented by Mazzini et al. (2016). The composition of the pore waters extracted from the sediment cores was also analysed. Cone penetration tests (CPT) were performed at six locations respectively outside, on the sloping edge and inside the targeted pockmarks.

3.2. Statistical analyses

A selected region of 296 km^2 from high-resolution bathymetric data was subjected to a range of data analysis methods using PAST, v. 3.04 (Hammer et al., 2001) and in-house software.

Point pattern analysis can give information about the mode, timing and structural control of pockmarks (e.g. Hammer et al., 2009; Cartwright et al., 2011; Moss et al., 2012; Hillman et al., 2015). The analysis was limited to a rectangular region south of Troll A with relatively stationary point density (3189 pockmarks). Nearest-neighbour analysis (Clark and Evans, 1954) is a simple technique using the distance from each point to its nearest neighbour. The average neighbour distance is compared with the one expected for Complete Spatial Randomness (CSR). Donnelly's edge correction (Donnelly, 1978) was applied. The average nearest neighbour distance is 173.0 m, compared with 152.4 expected from CSR. CSR can thus be rejected at $p < 0.0001$ (t test). This indicates a lateral inhibition mechanism where points tend to avoid each other.

Nearest neighbour analysis only gives information on the local scale. To investigate point density at a range of scales, Ripley's K analysis was applied (Ripley, 1976). The number $R(d)$ of points within circles of radius d centred on one point is computed, and averaged over all points. For CSR, a quadratic $R(d)$ is expected, as the number of points is proportional to area. A normalised function $L(d)$, square root of $R(d)$, is expected to follow $L(d) = d$ for CSR. The function $L(d) - d$ thus represents departure from CSR at any scale d. An estimate of fractal dimension was obtained from the asymptotic linear slope in a log–log plot of $R(d)$. The main feature of the Ripley's K curve (Fig. 2A) is a dip at small scales (up to ca. 250 m), indicating local lateral inhibition. At larger scales, the pattern drifts towards CSR. A region of elevated values, corresponding to clustering, occurs at scales from 1000 to 1500 m. The estimated fractal dimension value of $D = 2.0$ coincides with that of CSR (Fig. 2B), and thus does not give any indication of fractal geometry as might be expected from an underlying fractal pattern of faults or cracks.

Local alignment of points along straight lines was assessed following Amorese et al. (1999). A rectangular blade with length 1.6 km was centred on each point, and rotated through a full revolution. Point counts within these blades were compared with the expected count for CSR and tested using a binomial distribution with a significance level of 0.05 (not corrected for multiple comparison). The alignments were filtered using the dispersion index, mean index and butterfly bow criteria of Amorese et al. (1999). The linear alignment analysis is shown in Fig. 2C. A strong preference for NNW–SSE orientation is evident in the rose plot, with an average orientation of 347 degrees (geographical), random orientation rejected at $p < 0.01$ (Rayleigh test).

Morphological parameters were computed as follows. For each position in the $N = 7243$ data set, a square with sides 150 m was extracted from the grid data, and smoothed with a Gaussian filter. The local regional depth was estimated from the median depth of the corners. The depth of the pockmark was estimated as the