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High-resolution seismic stratigraphy, sedimentary processes and the origin of seabed cracks and pockmarks at Nyegga, mid-Norwegian margin

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ABSTRACT

Densely spaced high-resolution TOPAS seismic profiles and EM1002 bathymetric data reveal the presence of numerous pockmarks, mound-like structures and elongated seabed cracks at Nyegga, offshore mid-Norway. The seabed cracks are located adjacent to the northern escarpment of the Storegga Slide, appearing as graben-like structures in the TOPAS data. Unlike the cracks, pockmarks and mound-structures are largely associated with vertical zones of acoustic blanking at depth, interpreted as pathways for vertically migrating gaseous fluids. Based on the TOPAS data, a new seismostratigraphic framework has been established and correlated to previously published age models of IMAGES cores MD99-2291 and MD99-2289. Seismic facies interpretation suggests repeated and rapid deposition of up to 40 m thick glacigenic wedges in the eastern part of the study area around 18.2 ^{14}C ka BP (21.8 cal. ka), 17.5 ^{14}C ka BP (20.8 cal. ka) and 16.9 ^{14}C ka BP (20 cal. ka). Towards the west, glacimarine deposition has prevailed, characterized by progressively increasing sedimentation rates with peak values of 30 m/ka during the period from 15.0 ^{14}C ka BP (18.2 cal. ka) to 15.8 ^{14}C ka BP (19 cal. ka). As the distribution of the Nyegga pockmarks closely coincides with the main Late Weichselian sediment depocenters, we suggest a relation between rapid and repeated sedimentation and periodic overpressure generation at depth, ultimately leading to fluid expulsion at the seabed and the formation of the Nyegga pockmark field. In contrast, seabed cracks at Nyegga appear to have formed due to local extension which we relate to horizontal stress reduction as a consequence of the Storegga Slide event. Potentially, this event has been accompanied by renewed vertical fluid migration and the most recent stage of pockmark development.

1. Introduction

During the last decade, advances in marine survey technology and improved data coverage have increasingly shown that continental shelf and slope deposits are frequently subject to small-scale processes like vertical fluid migration, mud diapirism or seabed cracking (e.g. Driscoll et al., 2000; Perez-Garcia et al., 2009; Jané et al., 2010). Commonly, such processes affect the seafloor morphology, by forming features like pockmarks, topographically positive mound-structures or elongated seabed cracks (Hustoft et al., 2007; Talukder et al., 2007; Mienert et al., 2010).

Previous studies have shown that these processes often require certain geological pre-conditions. For instance, the formation of pockmarks has been related to the presence of gas hydrates/free gas, sufficiently permeable pathways for gas-rich fluids to reach the seabed and, as observed for many pockmark provinces, an external triggering mechanism, such as rapid sediment loading, faulting or seismic activity (Hasiotis et al., 1996; Rise et al., 1999; Gay and Berndt, 2007; Hustoft et al., 2007, 2009; Pilcher and Argent, 2007; Sultan et al., 2010). In contrast, seabed cracks have been associated with past or present-day slope instability or with the presence of thick sedimentary successions which undergo compaction driven dewatering and polygonal faulting (Wattrus et al., 2003; Blum et al., 2010).

The Nyegga area, offshore mid-Norway, represents a well known and intensively studied pockmark-province, being associated with many of these geological parameters such as the presence of gas hydrates (Andreassen et al., 2000; Bünz et al., 2003), shallow gas reservoirs (Plaza-Faverola et al., 2010a), repetitive large-scale sliding (Solheim et al., 2005) and rapid late-glacial sediment loading (Hjelstuen et al., 2004). Consequently, this area has been targeted by a number of studies, frequently using multichannel seismic data to link the seafloor pockmarks to underlying gas hydrates, free gas accumulations, polygonal faults and buried slide scars (Berndt et al., 2003; Hovland et al., 2005; Solheim et al., 2005; Hustoft et al., 2007, 2010; Hjelstuen et al., 2010; Plaza-Faverola et al., 2010a). Yet, little knowledge exists about the relation between more recent, Late Weichselian sedimentary processes and the formation of pockmarks at Nyegga (Hustoft et al., 2009; Hjelstuen et al., 2010). Additionally, previous authors have largely focused on the formation of the Nyegga pockmark field, whereas few

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studies have recognized the presence of several seabed cracks at Nyegga (Evans et al., 1996; Gravdal et al., 2003; Hjelstuen et al., 2010).

For this study, we use high-resolution TOPAS seismic profiles and EM1002 bathymetric data, providing particularly detailed insight into the seabed landscape and the shallow subsurface at Nyegga. We primarily aim (1) to establish a new seismic stratigraphy, (2) to constrain the age of the resolved sedimentary succession at Nyegga, (3) to get detailed insight into the distribution, morphology and acoustic characteristics of the Nyegga seabed features and (4) we attempt to present a new conceptual model in order to contribute to the ongoing discussion about the age and origin of the Nyegga seabed features.

2. Geological background

Since Pliocene times, the depositional environment off mid-Norway has been predominately influenced by the glacial–interglacial climate cyclicity, culminating in repeated shelf edge advances of the Fennoscandian Ice Sheet since 0.5 Ma (Dahlgren et al., 2002; Hjelstuen et al., 2005). Whereas during periods of glacial expansion, fast-flowing ice streams delivered large amounts of glacigenic sediments to the mid-Norwegian continental margin, hemipelagic and contouritic deposition prevailed during interglacial times (Dahlgren et al., 2002; Hjelstuen et al., 2004; Rise et al., 2005). At Nyegga, the Late Plio-Pleistocene Naust Formation (Fm.) reaches a maximum thickness of 1500 ms(twt), consisting primarily of stacked, prograding debris flows which are separated by thin layers of hemipelagic sediments (Hjelstuen et al., 2004, 2005; Rise et al., 2005, 2010). Based on the most recently suggested stratigraphy by Rise et al. (2006), the Naust Fm. may be subdivided into five distinct units, defined as N, A, U, S and T (where Naust T is the youngest one).

Recurrently changing depositional processes have influenced the slope stability off mid-Norway. With Nyegga being located at the northern escarpment of the Storegga Slide (Fig. 1), repeated large-scale failures have affected the study area since about 0.5 Ma (Solheim et al., 2005). The present-day exposed Storegga Slide represents the most recent event in a series of several pre-Holocene submarine mega-slides (Haflidason et al., 2005; Solheim et al., 2005). Dating of several cores from the Storegga Slide area by Haflidason et al. (2004, 2005) revealed an age of 7 250 ± 250 ^{14}C yrs BP (8100 cal. yrs) for the sliding event.

Geophysical surveys, targeting the northern flank of the Storegga Slide, have reported the presence of small-scale faults, slightly offsetting reflectors within the uppermost stratified sediments of the Naust Fm. (Evans et al., 1996; Gravdal et al., 2003; Hjelstuen et al., 2010; Mienert et al., 2010). Such cracks are evident from the shelf break to water depths of 1300 m and have commonly been described as 150 m to 250 m wide and up to 10 m deep graben-like structures (Gravdal, 1999; Mienert et al., 2010). Mienert et al. (2010) have studied a series of seabed cracks, trending from the northeastern tip of the Storegga Slide scar approximately 60 km towards north, closely following the 500 m depth contour (Fig. 6 in Mienert et al., 2010). Radiocarbon dating the base of their infilling sediments yielded an age of 7350 ^{14}C yrs (8180 cal. yrs) (Haflidason et al., 2004). Based on a close coincidence between the location of the cracks and the present-day limit of the gas hydrate stability zone (GHSZ), Mienert et al. (2010) suggest these features to have formed due to gas hydrate dissociation.

The presence of gas hydrates at Nyegga has been recognized by several studies, inferred from a prominent bottom simulating reflector (BSR) (Mienert et al., 1998; Andreassen et al., 2000; Bünz et al., 2003; Bünz and Mienert, 2004). Bünz et al. (2003) have shown that gas hydrate occurrence appears to be geologically confined to stratified sediments of the Naust Fm. within the limit of the GHSZ. Beneath the BSR, seismic investigations from the Nyegga area have recently detected a clearly pronounced low-velocity zone, indicating the presence of free-gas beneath the Nyegga pockmark field (Plaza-Faverola et al., 2010a). Commonly, the pockmarks are connected to vertical zones of acoustic blanking (Hustoft et al., 2007; Westbrook et al., 2008) which are frequently (ca. 60%) rooted in this free-gas layer (Hustoft et al., 2010). Consequently, the acoustic wipe-out zones are suggested to represent focussed fluid flow conduits, providing preferential pathways for upward migrating gaseous fluids (Hustoft et al., 2007, 2010). This is confirmed by the recovery of gas hydrates and authigenic carbonates from the Nyegga pockmarks (Hovland et al., 2005; Mazzini et al., 2006; Ivanov et al., 2007; Paull et al., 2008). Geochemical investigations of gas hydrates and pore waters point towards a microbial origin of vertically migrating gaseous fluids (Chen et al., 2010; Ivanov et al., 2010; Vaular et al., 2010). Based on AMS ^{14}C measurements on planktonic foraminifera, recovered from one of the pockmarks, Paull et al. (2008) suggest that such fluid flow activity has been active at Nyegga prior to 14 ^{14}C ka BP (16.5 cal. ka).

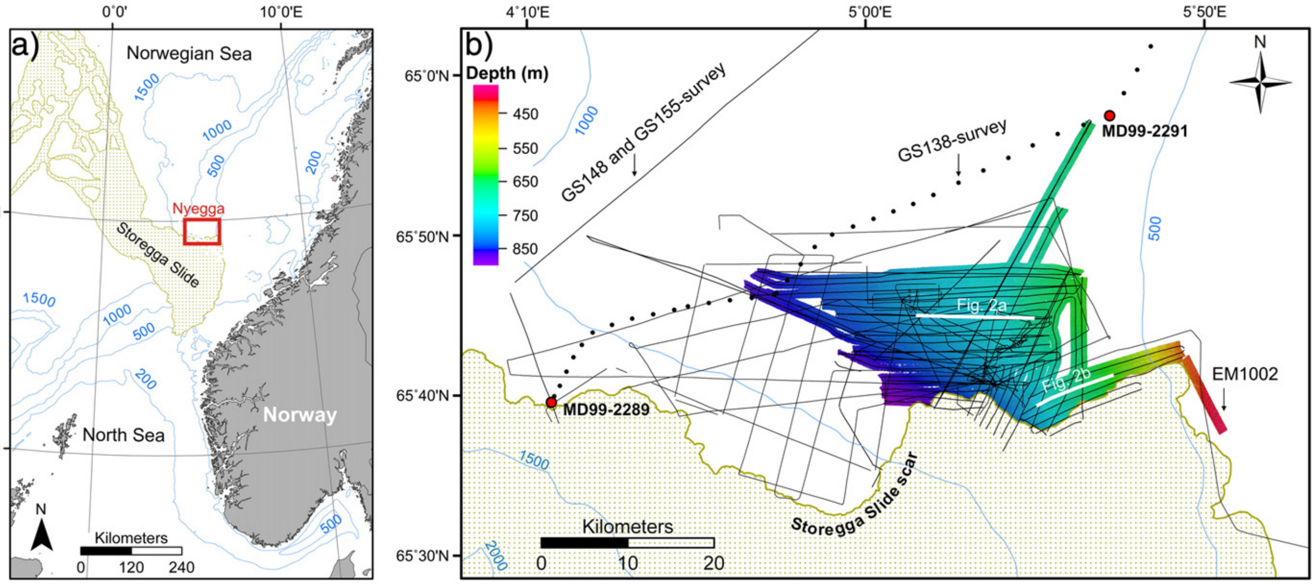

Fig. 1. a) Overview of the northeast Atlantic and North Sea region. The Nyegga area is delineated by the red box. b) Overview of the data set used for the present study. Black lines indicate the location of TOPAS seismic profiles. IMAGES cores MD99-2291 and MD99-2289 are shown by the red dots.