Marine and Petroleum Geology 27 (2010) 1789–1803

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Late Cenozoic geological development of the south Vøring margin, mid-Norway

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ARTICLE INFO

Article history:
Received 20 May 2010
Received in revised form
27 August 2010
Accepted 1 September 2010
Available online 15 September 2010

Keywords:
Norwegian Sea
Vøring Plateau
Continental slope
Naust Formation
Pliocene
Pleistocene
Submarine slide

ABSTRACT

Late Cenozoic seismic stratigraphy of the Vøring continental margin has been studied in detail, with emphasis on the geological development of the Naust Formation deposited during the last 3 million years. The Kai Formation (15–3 Ma) comprises mainly biogenic ooze deposited in the Møre and Vøring Basins. In Naust time, there was a marked increase in supply of sediments from the inner shelf areas and the western part of the Scandinavian mountain range, and glaciers expanded to the shelf and reached the shelf edge several times during the last 1.5–2 million years. During early to mid Naust time the shelf was widened by westerly prograding sediment units, but for a long period the shallowest part of the Helland-Hansen Arch (HHA) formed a barrier preventing glacially derived debris from being distributed farther west. West of the HHA, mainly stratified marine and glacimarine sediments were deposited. A substantial part of these sediments were transported by the north-flowing Norwegian Atlantic Current, which redistributed suspended particles from ice streams, rivers, coastal erosion and seabed winnowing. After burial of the crest of the HHA at c. 0.5 Ma, glacial debris and slide deposits were also deposited west of this high. In the north, massive units of glacial debris were distributed beyond the crest of the HHA, also in mid Naust time, thinning westwards and interfingering with fine-grained sediments on the lower slope. The Sklinnadjupet Slide, inferred to be c. 250,000 years old, corresponds in age with an earlier huge slide in the Storegga area. An elongated area of uneven seabed topography previously interpreted as diapirs (Vigrid diapirs) on the slope west of the HHA is shown to be formed by ooze eruption from the crest of the arch and submarine sliding.

1. Introduction

The aim of this work has been to map stratigraphy and slide history offshore mid-Norway to provide knowledge of importance for deep-water hydrocarbon exploration licenses. Mid–late Cenozoic stratigraphy and stability assessment of the outer shelf/upper continental slope were also important topics in previous phases of the Seabed Project of the Norwegian Deepwater Programme (NDP) (McNeill et al., 1998; NDP, unpublished report, 2004a) and the Ormen Lange Project (Bryn et al., 2005a; Rise et al., 2005; Solheim et al., 2005a,b). In the present study, however, we had access to a much denser seismic grid than previously applied.

The study area is the continental slope off mid-Norway, including the Vøring Plateau (Fig. 1), which is part of one of the best investigated glacial margins in the world. As the giant Ormen Lange gas field was discovered below the Storegga Slide scar, extensive scientific studies were carried out to investigate if a safe development of the gas field was possible (Solheim et al., 2005a). One of these studies was to establish a stratigraphic framework of the Late Pliocene–Pleistocene succession (hereafter referred to as the Naust Formation) on the shelf and slope between the outlet of the Norwegian Channel (62°N) and Lofoten (68°N) (Rise et al., 2002, 2005). In Phase II of the Seabed Project, the area was extended to 61°N (Sognefjorden), and the seismic database increased from c. 40,000 km to about 100,000 km (NDP, unpublished report, 2004a). Only parts of this large regional study have been published (Bugge et al., 2004; Rise et al., 2006; Eidvin et al., 2007; Ottesen et al., 2009), but the regional stratigraphic framework served as an important basis for a more detailed interpretation in the present GANS Project (www.gans.no).

Seismic interpretation has included the Eocene to mid–late Pliocene succession (Brygge and Kai Formations). The pre-Naust Cenozoic stratigraphy with a particular emphasis of the area north of the Storegga Slide (Nyegga) is submitted for publication (Shyam Chand, pers. comm., 2010). The authors discuss features indicating gas/gas hydrates in the sediments and fluid flow to the seafloor (Buenz et al., 2003; Buenz and Mienert, 2004; Westbrook et al., 2008; Hustoft et al., 2009; Hjelstuen et al., 2009) in relation to the mid–late Cenozoic geological evolution.

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doi:10.1016/j.marpetgeo.2010.09.001

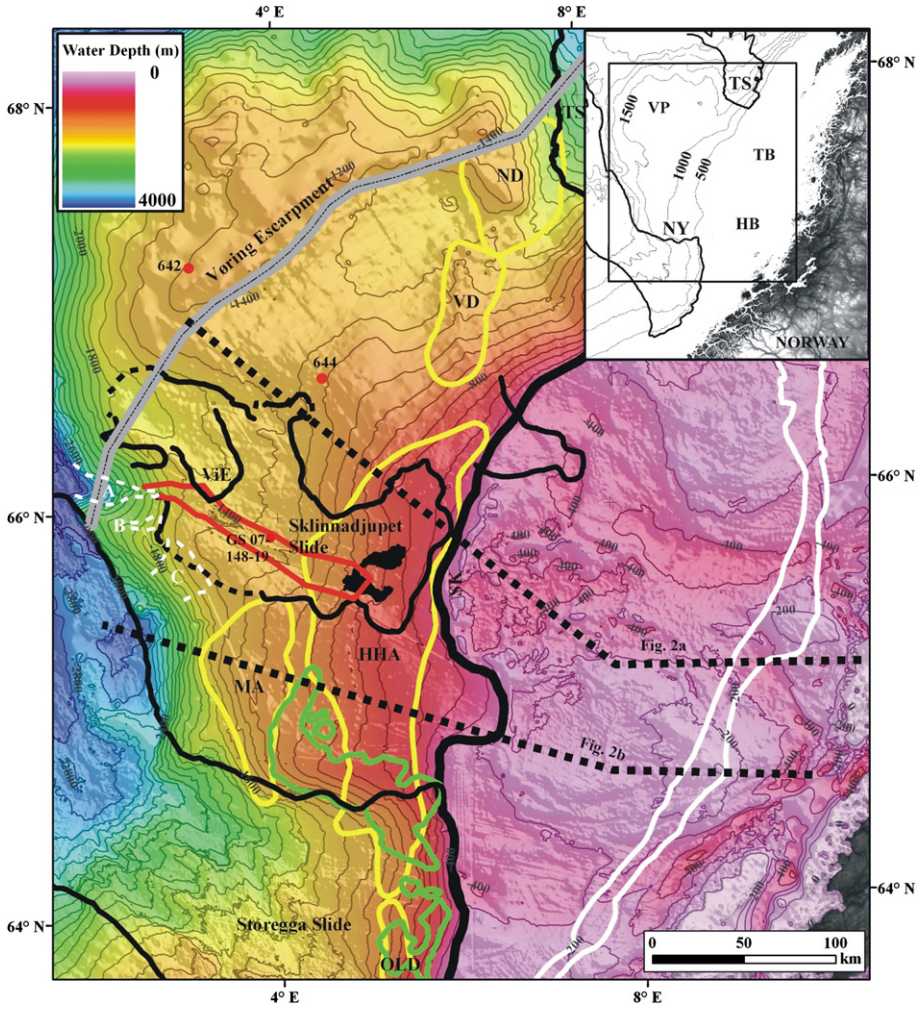

Fig. 1. Shaded relief bathymetry of the mid-Norwegian margin enclosing the study area (contours in metres) showing the locations of the five prominent domal structures (yellow polygons; HHA – Helland-Hansen Arch; MA – Modgunn Arch; VD – Vema Dome; ND – Nagelfar Dome; OLD – Ormen Lange Dome), SK – Skjoldryggen moraine ridge; large slides (black polygons), slides A, B, C (dashed white polygons), evacuation craters (black areas), gas hydrate Bottom Simulating Reflector (BSR, green polygons), ODP boreholes and pistoncore GS07-148-19PC (red dots), shelf edge (thick black line), Vigrid ridge and mound area (red polygon), subcrop Molo Formation (white polygon) and locations of regional seismo-geological sections in Fig. 2. The boundaries for the Vigrid Escarpment (ViE, previously interpreted as the Vigrid Slide) and the Sklinnadjupet Slide are also shown. The locations where the boundaries are not clear are indicated by dashed lines. Inset figure shows Trænabanken (TB), Trænadjupet Slide (TS), Nyegga (NY), Haltenbanken (HB) and Vøring Plateau (VP). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

The main purpose of the present paper has been to establish a detailed stratigraphic framework of the Naust Formation (the last c. 2.8 Ma) on the western mid-Norwegian continental margin (Fig. 1), and to study depositional processes and sediment sources in order to improve the understanding of the palaeogeographic and geological development. Compared to previous studies of the Late Pliocene–Pleistocene succession on the mid-Norwegian slope (McNeill et al., 1998; Dahlgren et al., 2002a; Hjelstuen et al., 2004a,b; Rise et al., 2005, 2006), the large database has enabled a much more detailed interpretation of depositional environments and processes. Other objectives have been to make more detailed maps and improve the understanding of the Sklinnadjupet and Vigrid Slides. Finally, the origin of the mounds and ridges in the south Vøring margin has been addressed based on new data. These features have earlier been interpreted as diapirs (Hjelstuen et al., 1997) or slide deposits (Riis et al., 2005; Rise et al., 2006).

2. Geological background

The study area lies mainly west of the shelf break between 64°30′N and 67°N, and includes most of the Vøring Plateau and the continental slope north of the Storegga Slide (Fig. 1). A substantial part of the Vøring Basin, as well as the northernmost part of the Møre Basin lies within the study area. Two Cenozoic structural highs, the Modgunn Arch (MA) and the Helland-Hansen Arch (HHA) (Figs. 2 and 3), had large influence on the Cenozoic depositional pattern (Rise et al., 2006). Seismic sections crossing the mid-Norwegian margin (Fig. 2) show the main structural elements, and give a regional view of the Brygge, Kai, Molo and Naust Formations deposited during the last c. 55 million years (Dalland et al., 1988; Eidvin et al., 1998). The interpretations of the Cenozoic succession (Hjelstuen et al., 1999; NDP, unpublished report, 2004a; Bugge et al., 2004) have recently been strengthened by additional biostratigraphical investigations of existing core and well samples, shedding new light to the chronology and geological evolution (Eidvin et al., 2007).

The Brygge Formation was deposited from Early Eocene to Early Miocene time (c. 55–18 Ma) (Eidvin et al., 2007). It is widely distributed and comprises mainly clay on the present day shelf and ooze-dominated sediments in the Møre and Vøring Basins where the thickest accumulations occur (Eldholm et al., 1987; NDP, unpublished report, 2004a; Eidvin et al., 2007) (Fig. 2).