Marine and Petroleum Geology 96 (2018) 501–521

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Early to middle Cenozoic paleoenvironment and erosion estimates of the southwestern Barents Sea: Insights from a regional mass-balance approach

Amando Lasabuda[a,b,*], Jan Sverre Laberg[b,a], Stig-Morten Knutsen[c], Gert Høgseth[a,b]

[a] Research Centre for Arctic Petroleum Exploration (ARCEx), Department of Geosciences, UiT–The Arctic University of Norway, NO-9037 Tromsø, Norway
[b] Department of Geosciences, UiT–The Arctic University of Norway, NO-9037 Tromsø, Norway
[c] Norwegian Petroleum Directorate (NPD), Harstad, Norway

ARTICLE INFO

Keywords:
Southwestern Barents sea
Uplift and erosion
Cenozoic evolution
Paleoenvironment
Norwegian Arctic

ABSTRACT

The Cenozoic pre-glacial development of the southwestern Barents Sea is discussed, with focus on the early to middle Cenozoic net erosion that was poorly constrained. From 2D and 3D seismic mapping, the western Barents Sea continental margin development shows a complex history of structural configuration of highs and basins related to the Greenland and Eurasian plate movement and subsequent seafloor spreading in the Norwegian-Greenland Sea. Our subdivision of the Sørvestsnaget Basin allows for a closer focus on the tectonostratigraphic development in an overall transtensional setting. To the west, the lower to middle Cenozoic sediments are observed to be systematically overlying the oceanic crust in the Lofoten Basin in accordance to the progressive seafloor's opening. Based on interpretation of five seismic units including sediment progradation (clinoforms) as well as lithology information from exploration wells, the paleoenvironments for the Paleocene, Eocene, Oligocene, and Neogene periods were reconstructed. The mass-balance approach has then been used to quantify the corresponding erosion of the southwestern Barents Sea source area. The Stappen High, the Loppa High, and part of mainland Northern Norway are proposed as the key drainage areas covering a combined area of 191,500 to 334,000 km^2, depending on the location of its eastern limit. Our result shows that an average net erosion of 858–1362 m and an average erosion rate of 0.014–0.021 m/k.y have characterized the Cenozoic pre-glacial period. The calculated sediment discharge is 8.7×10^6 t/y and the sediment yield is 26.2–45.7 t/km^2/y. Comparison with present-day fluvial systems shows a similar rate of sediment discharge suggesting that our estimates are reasonable. The pre-glacial sedimentation rate is estimated to be 0.026–0.071 m/k.y, which is on average one order of magnitude lower than for the preceding glacial period characterizing this area.

1. Introduction

Uplift and erosion have affected petroleum basins worldwide and these processes represent major challenges for hydrocarbon exploration (e.g. Knutsen et al., 2000; Henriksen et al., 2011). Moreover, the quantification of the average (net) erosion is an important input for basin modelling in order to estimate the maximum depth of burial of the petroleum system.

In the southwestern Barents Sea, earlier studies addressing uplift and erosion (e.g. Nøttvedt et al., 1988; Vorren et al., 1991; Vågnes et al., 1992; Fiedler and Faleide, 1996; Hjelstuen et al., 1996; Rasmussen and Fjeldskaar, 1996; Dimakis et al., 1998) and recent work utilizing a revised age, a new glaciation model (e.g. Knies et al., 2009; Laberg et al., 2010) as well as an expanded well database (e.g. Henriksen et al., 2011) have increased our understanding of this topic significantly.

The late Cenozoic glacial erosion, however, does not account for the total net Cenozoic erosion alone. It is likely that there has been a substantial pre-glacial erosion component that also has affected the Barents Sea area as indicated from a considerable amount of Cenozoic sediments overlying the oceanic crust beneath the glacial trough-mouth fans (TMF) (e.g. Vorren et al., 1991; Fiedler and Faleide, 1996). Though, the timing and amount of the erosion are still poorly constrained.

The early to middle Cenozoic evolution of the southwestern Barents Sea continental margin is closely linked to the rifting, breakup, and seafloor spreading forming the Norwegian-Greenland Sea (Talwani and Eldholm, 1977; Lundin and Doré, 2002; Tsikalas et al., 2005; Faleide et al., 2008). A shear-dominated setting, episodic magmatic activity, and salt tectonics add to the geological complexity of the margin.

* Corresponding author. Research Centre for Arctic Petroleum Exploration (ARCEx), Department of Geosciences, University of Tromsø - The Arctic University of Norway, NO-9037 Tromsø, Norway.
E-mail address: amando.lasabuda@uit.no (A. Lasabuda).

https://doi.org/10.1016/j.marpetgeo.2018.05.039
Received 29 October 2017; Received in revised form 17 May 2018; Accepted 31 May 2018
Available online 02 June 2018

Sparse well distribution is also one of the main challenges when reconstructing the regional development of the southwestern Barents Sea area during the Cenozoic.

A mass-balance approach (Doré et al., 2002; Anell et al., 2009; Helland-Hansen et al., 2016) is useful to directly link the offshore deposits to their source area and quantify the amount of erosion, especially for regional studies. This technique has been proven to be useful for the estimation of erosion in the late Cenozoic (e.g. Dowdeswell et al., 2010; Laberg et al., 2012), early–middle Cenozoic (e.g. Lasabuda et al., 2018), and even older systems (e.g. Sømme and Jackson, 2013; Eide et al., 2017). The integration of this method with plate reconstruction will better constrain the dynamic size of the source and sink areas of the southwestern Barents Sea continental margin that was largely affected by the early–middle Cenozoic tectonic.

In this paper, we aim to: 1) describe and discuss the spatial distribution and temporal evolution of the Paleogene–Neogene strata along the southwestern Barents Sea continental margin (to about 74°N) and in the adjacent Lofoten Basin; 2) discuss the factors that have controlled the development of the succession; and 3) quantify the average erosion and sediment yield of the sediment source areas and discuss the processes involved.

2. Geological setting

The southwestern margin of Barents Sea shelf is characterized by a series of highs and basins (Fig. 1a and b). These predominantly Mesozoic and early to middle Cenozoic highs and basins are related to repeated episodes of continental rifting that are culminated by the NE Atlantic continental separation, and to the onset of sea-floor spreading from early Cenozoic forming the present Norwegian-Greenland Sea (Talwani and Eldholm, 1977; Faleide et al., 1993, 2008; Tsikalas et al., 2002). In the Middle Jurassic to Early Cretaceous times, an extensional setting governed the tectonic activity (Faleide et al., 2008). Most of the basins of the western Barents Sea shelf experienced various degrees of subsidence. During the Late Cretaceous, the Northern Atlantic realm as well as the southwestern Barents Sea have been dominated by renewed rifting that also affected the Tromsø, Sørvestsnaget, and Harstad Basins (Gabrielsen et al., 1990). The Svalbard Archipelago underwent a more compressional setting and most likely experienced uplift at that time (Bergh et al., 1997).

During the earliest Eocene (from ca. 55 Ma), sea-floor spreading in the Norwegian-Greenland Sea gradually expanded northwards. For the western Barents Sea continental margin, this resulted in the development of a transform setting (Kristoffersen and Talwani, 1977). A major change in plate organization took place in the earliest Oligocene time (ca. 33 Ma) when the Greenland plate started to move in the same direction as the North American plate (Kristoffersen and Talwani, 1977; Faleide et al., 1993). In the Norwegian-Greenland Sea, this event resulted in a readjustment of the relative seafloor spreading motion from NNW-SSE to NW-SE (Faleide et al., 2008).

The transform system of the western Barents Sea continental margin occurred at an angle to the spreading axis that created segmentation over a large area (Faleide et al., 1993). The Senja Fracture Zone and the Hornsund Fault Zone are the two large shear segments of this transform separated by the Vestbakken volcanic province as the central segment (Fig. 1c). To the south, the Senja Fracture Zone experienced dextral oblique shear that resulted in an overall transtensional regime of the Sørvestsnaget Basin (Faleide et al., 1993; Kristensen et al., 2017). The transtension mechanism has been explained by strain partitioning into shortening and extension that formed coevally, particularly in the southern and central part of the Sørvestnaget Basin (Kristensen et al., 2017). To the northeast, part of the Stappen High was part of the Cretaceous Bjørnøya Basin before it was inverted in the early Cenozoic (Blaich et al., 2017). However, in the northwestern part, the transition from the Sørvestsnaget Basin towards the Vestbakken volcanic province is less understood.

The Vestbakken volcanic province (Gabrielsen et al., 1990) marks the relay zone with significant volcanism and lava intrusion in a pull-apart basinal setting (Faleide et al., 2008) (Fig. 2). The Eocene rifting included the extensional faulting in the Knølegga Fault Complex. Possible fault reactivation in the earliest Oligocene (Eidvin et al., 2014) may contribute to a regional compression event (Blaich et al., 2017). Moreover, widespread salt diapirs in the Sørvestsnaget and Trømsø Basins are suggested to be developed in the early Cenozoic and have affected the tectonosedimentary style in those basins (Perez-Garcia et al., 2013).

Parts of the Hornsund Fault Zone near Svalbard appeared to have been compressed during the Paleocene–Eocene transition, later becoming a sheared margin and subsequently rifted in the Oligocene (Lundin and Doré, 2002; Bergh and Grogan, 2003). Significant parts of Svalbard were uplifted due to crustal shortening and subsequent exhumation, which caused it to be the most eroded part in the wider Barents Sea (Faleide et al., 2008; Henriksen et al., 2011). This early Cenozoic event resulted in the formation of West Spitsbergen Fold-Thrust Belt and the development of the Central Basin as a foreland basin to the east (e.g. Braathen et al., 1995; Bergh et al., 1997).

During the Plio–Pleistocene, multiple phases of glacial development have been identified in the Barents Sea area (Knies et al., 2009). During the glacial maxima, large quantities of sediments were eroded from the land and/or shallow shelf areas and deposited along the deeper continental shelf and slope. Laberg et al. (2010) interpreted the paleoenvironment in the early stage as dominated by glaciofluvial processes of erosion and sediment transport. Later, subglacial erosion and deposition of deformation till beneath and in front of fast-flowing ice streams were the most important processes. The glacial erosional product deposited along the continental slope led to the development of the Bear Island TMF (Laberg and Vorren, 1993, 1995, 1996; Faleide et al., 1996; Fiedler and Faleide, 1996).

3. Cenozoic uplift and erosion

The present-day morphology and depth of the southwestern Barents Sea are suggested to be a result of several episodes of Cenozoic uplift and erosion. Different approaches have been applied to estimate the timing and to quantify the erosion in the southwestern Barents Sea (Cavanagh et al., 2006; Henriksen et al., 2011). The results of these studies, including estimates of the erosion for each period, are summarized below.

3.1. Estimates of the total net erosion

Net erosion is defined as the total difference between the maximum burial and the current depth of a succession (Riis and Jensen, 1992; Doré and Jensen, 1996). Henriksen et al. (2011) compiled a Cenozoic net erosion map for the wider Barents Sea area based on weighted-average results from well data including vitrinite reflectance, sandstone diagenesis, apatite fission track, and shale compaction. They estimated that the net erosion affecting the sedimentary basins of the southwestern Barents Sea is between 900 and 1400 m. Recently, Ktenas et al. (2017) presented an updated net erosion map for the southwestern Barents Sea area based on sonic velocities and shale-sand compaction trends with higher values of net erosion, 1400–1750 m for most of the area south of ~72°30′N and east of 18°E. Baig et al. (2016) using shot gathers, well logs, and thermal maturity data suggested maximum values of average net erosion of up to 1950 m and 2100 m for the Loppa High and the Stappen High areas, respectively. Furthermore, studies from Bjørnøya (the exposed part of the Stappen High) show that up to 3000–4200 m of net erosion has affected this area (Wood et al., 1989; Ritter et al., 1996).