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Research paper

Isostatic response to glacial erosion, deposition and ice loading. Impact on hydrocarbon traps of the southwestern Barents Sea

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ABSTRACT

Previous work indicates that a part of hydrocarbon loss from traps in the Barents Sea is attributed to the Pleistocene (glacially-related) spillage due to isostatically-driven depth changes and tilting. It is, however, unknown how severe the Pleistocene spillage was and how much hydrocarbons were depleted due to other mechanisms including leakage and pre-glacial spillage. In addition, it remains uncertain how much the orientation of the hydrocarbon traps and thus trap capacities and spill directions was affected by glacial sediment redistribution and ice loading.

The effect of the Pleistocene burial history on trap capacity and spillage is addressed by using a combination of the flexural isostasy and secondary migration modelling. The impact is modelled in three trap structures in the Bjørnøyrenna Fault Complex.

The results show that the Pleistocene burial history led to either increase or decrease the trap capacities in the range of 5–14%. The geometrical changes also affected the spill directions of some of the traps. Apart from the tilt magnitude the most important factor controlling the trap capacity change and spill directions in the analyzed traps was the initial geometric setting of the traps. The traps in the western Barents Sea with present spill points to the west and south experienced trap capacity increase and were not susceptible to spillage during the Pleistocene. Location of the pre-glacial spill points determines whether the traps with the present spill points to the east and north experienced capacity increase or reduction. Structural changes of the traps caused only by the tilting could not have resulted in major loss of oil and gas. The tilting together with gas volume expansion might however have been responsible for some part of the hydrocarbon loss during the Cenozoic.

1. Introduction

Spillage and remigration of hydrocarbons in the Barents Sea is often attributed to isostatic adjustments and related tilting of hydrocarbon traps during the Cenozoic. It is suggested that these processes might explain previously larger degrees of trap filling demonstrated by palaeo-oil shows (Cavanagh et al., 2006; Doré, 1995; Doré and Jensen, 1996; Duran et al., 2013; Henriksen et al., 2011; Nyland et al., 1992). Some of the hydrocarbon spillage is linked to isostatic movements due to cycles of Pliocene-Pleistocene ice-sheet loading/unloading and glacial sediment redistribution (Cavanagh et al., 2006; Doré and Jensen, 1996; Duran et al., 2013; Kjemperud and Fjeldskaar, 1992; Lerche et al., 1997). It is however uncertain what was the magnitude of isostatic response caused by these processes and how, as a result, the processes affected the orientation of hydrocarbon traps. Reconstructed trap orientation together with a complete Pleistocene burial history can provide an insight into how much of the hydrocarbons were spilled out of the traps due to the glaciations, and how much of the loss is attributed to other processes including leakage and pre-glacial spillage.

Literature considered problem of the isostatic response to the ice sheet loading in the Barents Sea (Amantov and Fjeldskaar, 2016; Fjeldskaar et al., 2000; Kjemperud and Fjeldskaar, 1992; Landvik et al., 1998; Lerche et al., 1997) and isostatic response to glacial sediment redistribution (Amantov et al., 2011; Butt et al., 2002; Dimakis et al., 1998; Rasmussen and Fjeldskaar, 1995; Riis and Fjeldskaar, 1992). Existing literature lacks however a coherent Pleistocene burial history model that demonstrates vertical movements of the stratigraphic units over long time scales (1–2

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Ma) incorporating recent ice sheet models (e.g. Peltier et al., 2015) and the newest findings regarding regional erosion-deposition trends (Laberg et al., 2012).

In a synthetic case it was shown that the glacially induced tilting could have had a pronounced impact on the Barents Sea trap capacities leading to up to 30% of hydrocarbon loss (Kjemperud and Fjeldskaar, 1992). In addition the study points out the importance of the initial trap geometry on hydrocarbon loss. Different trap geometries make some traps more sensitive to tilt-driven spillage than the others. This issue was however not addressed before in connection to the trap structures in the Barents Sea, and as a result the actual glacial impact on the hydrocarbon loss is uncertain. Moreover, it has been proposed that the Cenozoic spillage might have resulted in a major hydrocarbon remigration from central to peripheral parts of the Barents Sea basins (Lerche et al., 1997; Ohm et al., 2008). Detailed understanding of the pre-glacial migration patterns and locations of oil and gas accumulations are however challenged by uncertain hydrocarbon trap orientation and basin geometry prior to the ice ages.

Hydrocarbon trap orientation at the onset of glaciations (at ~1.50 Ma) and the impact of subsequent burial history on the traps will be addressed here by using a combination of flexural isostasy and secondary migration modelling. The study has been undertaken with data from the Bjørnøyrenna Fault Complex (western Barents Sea), one of the most active hydrocarbon exploration areas on the Norwegian Continental Shelf (Fig. 1). Besides major discoveries including for example 7220/4-1 and 7220/8-1, many of the traps are dry showing thick palaeo-oil columns (e.g. 7219/9-1) suggesting hydrocarbon depletion due to spillage and/or leakage. By using these trap structures it will be shown how much of the hydrocarbons might have been lost due to the Pleistocene spillage alone challenged by non-uniform vertical movements of the lithosphere and changes of the hydrocarbon densities.

2. Methods and data

2.1. Isostatic response to ice loading and sediment redistribution

2.1.1. Flexural isostasy modelling

The elastic lithosphere is thought to float on a denser viscous substratum – the asthenosphere (Vening-Meinesz, 1941). An applied load (positive or negative) causes bending (flexure) of the lithospheric plate. The applied load is partly supported by the shear stress of the lithosphere and partly by the buoyant forces of the asthenosphere. In this paper, the elastic plate is considered as 2500×2500 km flat structure with fixed sides (no displacement at the sides is modelled). Horizontal forces acting on the plate are not considered. The isostatic deflection is not an immediate process since the mantle is of low viscosity (e.g. Turcotte and Schubert, 2002). The time-dependent deflection is related to mantle relaxation time before which a state of the isostatic equilibrium is not reached. The relaxation time of the Scandinavia region is usually estimated as a few thousand years (Fjeldskaar, 1997; van den Berg et al., 2008). In this paper the time-dependent deflection is not considered. Time-dependency might be neglected for modelling of erosional/depositional processes lasting for 10^{-1} - 10^{0} Ma because flexural equilibrium is rather achieved during such long timespans. For short-time glaciations (lasting for thousands of years) the equilibrium might not been fully achieved. For longer periods including the Last Glacial Maximum (LGM) shelf-edge glaciation, lasting for 7 ka (Peltier et al., 2015) the equilibrium can be achieved.

Flexure calculations were performed by using the Matlab script of Cardozo (2009). The calculations were performed on a 10 km grid resolution. The elastic thickness is assumed to be 20 km, uniformly distributed in the study area following Fjeldskaar (1997) and van den Berg et al. (2008). Values of 5 km and 50 km were also tested. For the sake of simplicity, the density of the eroded sediments is considered to be the same as that of the deposited sediments (2200 kg/m^3). Density of the mantle is assumed as 3300 kg/m^3, water 1025 kg/m^3 and ice 917 kg/m^3.

2.1.2. Erosion/deposition and ice thickness models

Modelling of the isostatic response due to sediment redistribution was conducted by using erosion/deposition model of Laberg et al. (2012). The model was created by using a mass-balance method where volumes of glacial deposits are compared with their drainage area and the thickness of removed sediments is calculated accordingly. The drainage area used for calculation of the erosion thickness was estimated based on structure-contour map of the upper regional unconformity and the present-day

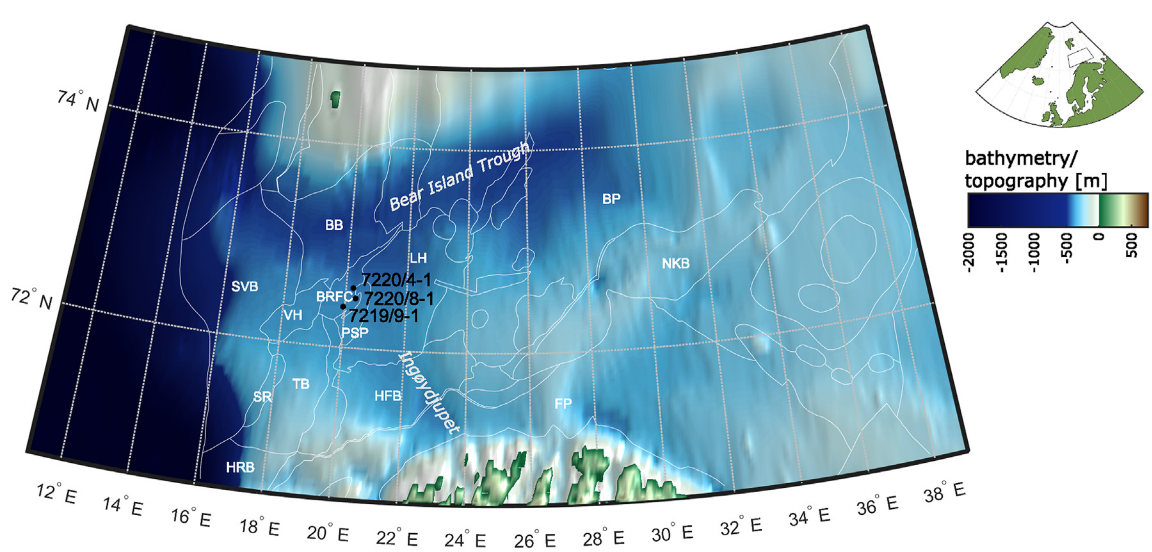

Fig. 1. The location of the study area overlaid by bathymetry/topography (ETOPO5, http://www.ngdc.noaa.gov/mgg/global/etopo5.html). The figure shows main structural elements, and well names of the hydrocarbon trap structures analyzed in this paper. BB: Bjørnøya Basin, BP: Bjarmeland Platform, BRFC: Bjørnøyrenna Fault Complex, HFB: Hammerfest Basin, FP: Finnmark Platform, HRB: Harstad Basin, LH: Loppa High, NKB: Nordkapp Basin, PSP: Polheim Subplatform, SR: Senja Ridge, SVB: Sørvestsnaget Basin, VH: Veslemøy High.