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Research paper

Modelling persistent methane seepage offshore western Svalbard since early Pleistocene

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ABSTRACT

Recent observations of extensive methane release into the oceans and atmosphere have raised concern as to whether rising temperatures across the Arctic could drive rapid destabilization of gas hydrate reservoirs. Here, we report modelling results from hydrate-modulated methane seepage from Vestnesa Ridge, offshore western Svalbard, suggesting that continuous leakage has occurred from the seafloor since the early Pleistocene up until today. Sustained by modelled deep subsurface thermogenic sources of Miocene age, large scale hydrocarbon fluid migration started ~6 million years ago and reached the seafloor some 4 million years later. The modelling results indicate that widespread methane seepage offshore western Svalbard commenced in earnest during early Pleistocene, significantly older than late Holocene as previously reported. We propose that the onset of vertical hydrocarbon migration is the response of rapid burial of potential hydrocarbon sources induced by increased sediment deposition following the onset of Northern Hemisphere glaciations, ~2.7 million years ago. From the modelling results we propose that source rock intervals capable of generating hydrocarbons and hydrocarbon reservoirs buried kilometers deep have continuously fueled the gas hydrate system off western Svalbard for the past 2 million years. It is this hydrocarbon system that primarily controls the thermogenic methane fluxes and seepage variability at the seabed over geological times.

1. Introduction

Quantifying the release of methane and other potent greenhouse gases sequestered as submarine gas hydrates is critical for understanding the drivers of past and predicting future climate trajectories (Ruppel, 2011). Across the Arctic, recent discoveries of natural gas actively venting into the water column have been attributed to the thermal destabilization of shallow gas hydrate reservoirs due to ongoing thawing of offshore permafrost coupled with ocean bottom warming (Shakhova et al., 2014; Westbrook et al., 2009). It is estimated that current Arctic warming will release ~50 Gt of hydrate-sourced methane from the East Siberian Shelf into the atmosphere during our current decade up to 2025 (Whiteman et al., 2013), a flux that is apparently unprecedented during the Quaternary record (Loulergue et al., 2008). However, gas flares in the water column can also emerge from natural pathways that enable fluids to migrate from deep thermogenic hydrocarbon sources directly to the seabed over millions of years. Furthermore, recent geophysical evidence reveals that a prominent cluster of gas flares detected off the western Svalbard coast has existed for at least 3000 years (Berndt et al., 2014) implying that gas leakage into the ocean has continued throughout this time independent of climatic fluctuations (i.e.,the Little Ice Age and Medieval Optimum). To date, there are virtually no constraints on long-term variability in gas leakage rates across the Arctic or, specifically, on the origin of the leaking gas and the spatial and temporal evolution of hydrate-controlled methane seepage (Dumke et al., 2016; Plaza-Faverola et al., 2015, 2017).

In order to circumvent this problem and assess variability in long-term gas leakage we modelled a petroleum system that predicts methane generation and migration from thermogenic sources to the leakage points in the Atlantic-Arctic gateway region over millions of years. The model is constrained by one 2D seismic reflection profile (SV-3-97) tied to available borehole data (Fig. 1; Table 1). The seismic profile reveals a complete marine late Cenozoic sequence; at least ~17

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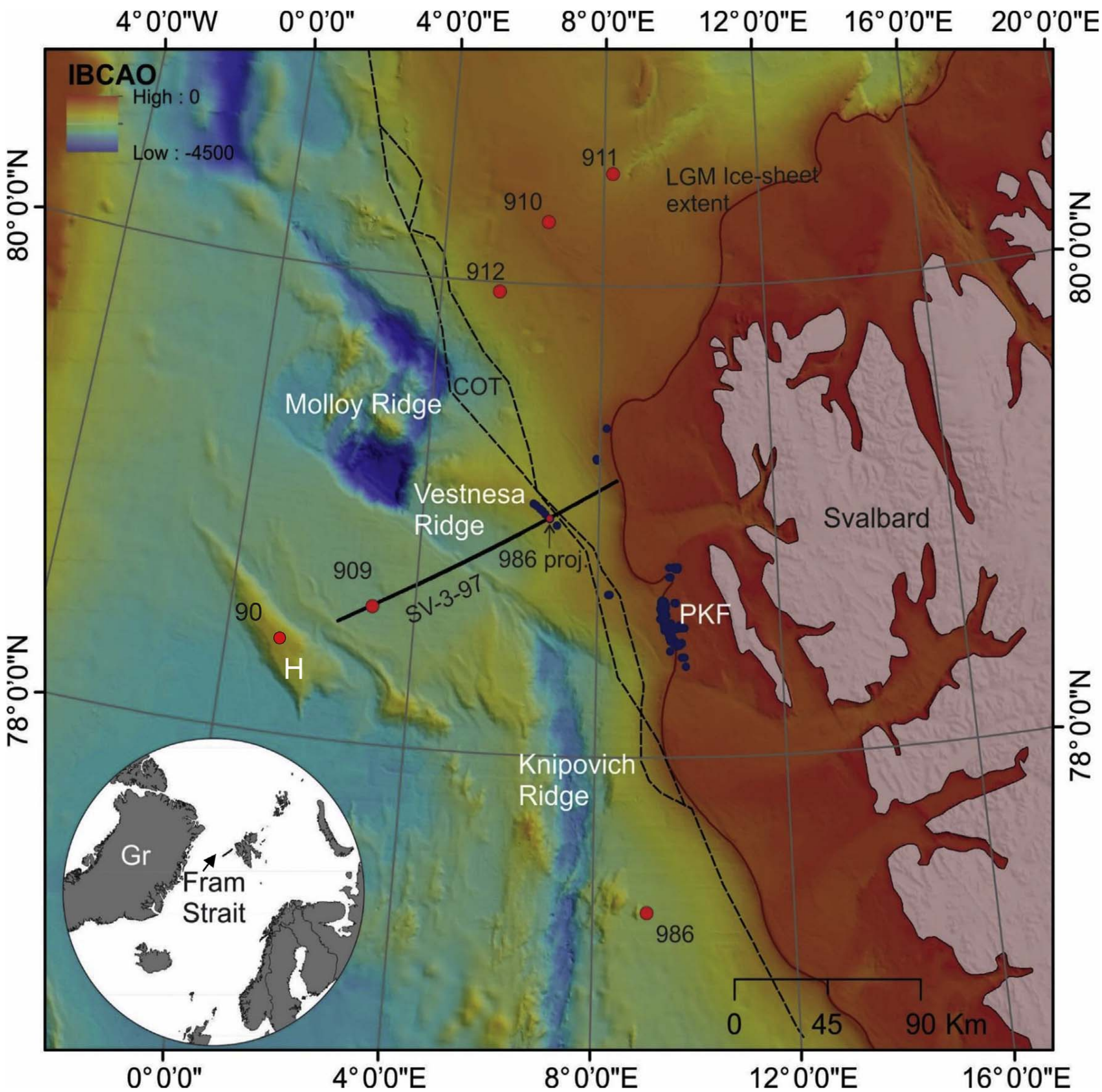

Fig. 1. The Arctic-Atlantic gateway (Fram Strait) in the Nordic Seas (inset), bathymetry (IBCAO, International Bathymetric Chart of the Arctic Ocean) (Jakobsson et al., 2012), and location of 2D seismic profile SV-3-97 and Ocean Drilling Program (ODP) Sites 910–912 (Yermak Plateau), 909–908 (Fram Strait), and 986 (western Svalbard). Detected gas flares on Vestnesa Ridge and Prins Karls Forland (PKF) are indicated by blue dots. The projection of Site 986 on seismic profile SV-3-97 is indicated. Continent-ocean boundary (COB) is modified from Engen et al. (2008) Gr: Greenland, HR: Hovgård Ridge. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Applied Ocean Drilling Program (ODP) borehole information for the basin modelling.

Borehole	Longitude	Latidude	Water Depth
ODP 910C	80°15.882 N	6°35.405 E	556.4 m
ODP 911A	80°28.466 N	8°13.640 E	901.6 m
ODP 912A	79°57.557 N	5°27.360 E	1036.8 m
ODP 909C	78°35.096 N	3°4.222 E	2519 m
ODP 908A	78°23.112 N	1°21.637 E	1273.6 m
ODP 986C	77°20.431 N	9°04.664 E	2051.5 m
ODP 986D	77°20.408 N	9°04.654 E	2051.5 m

million years of sedimentary section is inferred from Ocean Drilling Program (ODP) Site 909 biostratigraphic data compilation (Matthiessen et al., 2009; Myhre et al., 1995; Winkler et al., 2002; Wolf-Welling et al., 1996), that crosses a region with active methane seepage located along the western Svalbard margin (Figs. 1 and 2) (Bünz et al., 2012). In the west, the 2D seismic reflection profile SV-3-97 is tied to ODP Site 909, in which organic-rich (> 2 wt.%) deposits of largely terrigenous origin and free gas anomalies have been detected (Stein et al., 1995). In the east, the same 2D profile crosses the gas hydrate reservoir and associated seepage system of the easternmost segment of the Vestnesa Ridge, which is defined as a contourite drift located north of the Molloy transform fault (Fig. 2) (Bünz et al., 2012; Fisher et al., 2011; Hustoft et al., 2009; Smith et al., 2014). See: separate Fig. 2.

The main objectives of this study are two-fold: (A) To improve our understanding of the spatial and temporal evolution of the potential hydrocarbon sources in the eastern Fram Strait and (B) to apply a migration modelling approach to better determine the timing of initial onset and duration of methane seepage on the Vestnesa Ridge gas hydrate system and identify the potential controlling factors for this evolution. This region is particularly well-suited for the study of long-term variations of methane seepage because (1) it is located within the spatial and temporal extent of a petroleum system (Dumke et al., 2016; Knies and Mann, 2002); (2) there are known migration pathways through faults and fractures (Plaza-Faverola et al., 2015); and (3) deep carbon sourced gas hydrate formations (Smith et al., 2014) with a prominent bottom simulating reflector (BSR) (Hustoft et al., 2009) exist in regions of extensive gas seepage at the seafloor (Bünz et al., 2012).