Abiotic methane from ultraslow-spreading ridges can charge Arctic gas hydrates

Joel E. Johnson[1,2]*, Jürgen Mienert[1], Andreia Plaza-Faverola[1], Sunil Vadakkepuliyambatta[1], Jochen Knies[1,3], Stefan Bünz[1], Karin Andreassen[1], and Bénédicte Ferré[1]

[1]CAGE–Centre for Arctic Gas Hydrate, Environment, and Climate, Department of Geology, UiT The Arctic University of Norway, Dramsveien 201, N-9037 Tromsø, Norway

[2]Department of Earth Sciences, University of New Hampshire, 56 College Road, Durham, New Hampshire 03824, USA

[3]Geological Survey of Norway, PO Box 6315 Sluppen, N-7491 Trondheim, Norway

ABSTRACT

Biotic gas generation from the degradation of organic carbon in marine sediments supplies and maintains gas hydrates throughout the world's oceans. In nascent, ultraslow-spreading ocean basins, methane generation can also be abiotic, occurring during the high-temperature (>200 °C) serpentinization of ultramafic rocks. Here, we report on the evolution of a growing Arctic gas- and gas hydrate–charged sediment drift on oceanic crust in eastern Fram Strait, a tectonically controlled, deep-water gateway between the subpolar North Atlantic and Arctic Oceans. Ultraslow-spreading ridges between northwest Svalbard and northeast Greenland permit the sustained interaction of a mid-ocean ridge transform fault and developing sediment drift, on both young (<10 Ma) and old (>10 Ma) oceanic crust, since the late Miocene. Geophysical data image the gas-charged drift and crustal structure and constrain the timing of a major 30 km lateral displacement of the drift across the Molloy transform fault. We describe the buildup of a 2 m.y., long-lived gas hydrate– and free gas–charged drift system on young oceanic crust that may be fed and maintained by a dominantly abiotic methane source. Ultraslow-spreading, sedimented ridge flanks represent a previously unrecognized carbon reservoir for abiotic methane that could supply and maintain deep-water methane hydrate systems throughout the Arctic.

INTRODUCTION

Marine gas hydrates are sustained by large quantities of biotic methane formed by microbial degradation and thermogenic decomposition of sedimentary organic matter (Kvenvolden, 1995). A recent global gas hydrate estimate by Dickens (2011) suggests that 170–12,700 Gt of carbon may be stored in modern marine gas hydrate systems. Abiotic methane has been recently recognized as an additional sub-seafloor gas source generated in slow- to ultraslow-spreading mid-ocean ridge environments during the serpentinization of ultramafic rocks (Proskurowski et al., 2008; Cannat et al., 2010). Serpentinization rates in ultramafic rocks are highest at temperatures between 200 °C and 350 °C (Martin and Fyfe, 1970) and occur within a permeability zone in the upper crust that may not exceed 3–4 km in depth (Cannat et al., 2010). In magma-limited slow and ultraslow ridges, serpentinization is focused along large detachment faults (e.g., Escartín et al., 2008), which can accommodate the majority (nearly 100%) of relative plate motion (e.g., Sauter et al., 2013) and are commonly well developed at the inside corners of ridge-transform intersections (Tucholke et al., 1998). Slow- to ultraslow-spreading ridge detachment faults form near the ridge axis and are believed to be active over a period of 1–4 m.y. (Tucholke et al., 1998; Tani et al., 2011), thus limiting active serpentinization and methane venting to the youngest crust near the ridge axis.

In the Arctic (Fig. 1), low-angle detachment faults and exhumed serpentinized peridotites have been observed and sampled on Gakkel Ridge (Dick et al., 2003; Michael et al., 2003), serpentinite and peridotite have been sampled on Lena Trough and Molloy Ridge (Snow et al., 2001), and black smokers and vent fauna have been observed at the junction of the Mohns and Knipovich Ridges near exhumed detachment surfaces or oceanic core complexes (Pedersen et al., 2010). Bottom simulating reflectors (BSRs) that indicate the base of the gas hydrate stability zone (GHSZ), identified in seismic sections above interpreted serpentinized ultramafic diapirs, are also documented on the sediment-covered eastern flank of Knipovich Ridge (Rajan et al., 2012). These observations establish the possibility of gas delivery for gas hydrates from an abiotic, serpentinized mantle source of methane throughout sediment-covered portions of the Arctic Ocean ultraslow-spreading ridge system.

Our study area is located in the Arctic Fram Strait, the tectonically controlled oceanographic gateway to the Arctic Ocean (Fig. 1). Oblique rifting across a continental transform fault initiated the opening of Fram Strait in the early Oligocene (33 Ma) (Talwani and Eldholm, 1977). As a result, a narrow oceanographic gateway slowly developed due to the ultraslow-spreading Molloy and Knipovich Ridges, the last ridges created between the Gakkel Ridge–Lena Trough and the Mohns Ridge (Fig. 1) (Engen et al., 2008; Ehlers and Jokat, 2013). The Molloy transform fault (MTF) and Spitsbergen

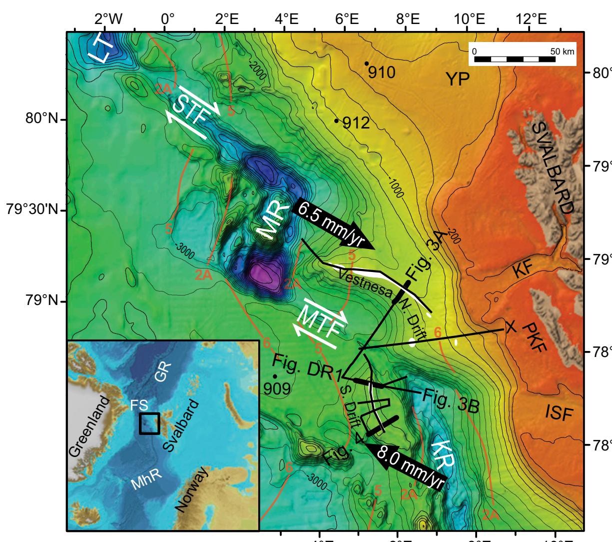

Figure 1. Tectonic setting of Vestnesa sediment drift (west of Svalbard). Color-shaded relief bathymetry (contours are in meters) from International Bathymetric Chart of the Arctic Ocean grid (Jakobsson et al., 2012). Magnetic anomaly chrons (in red): 2A—2.8 Ma; 5—9.8 Ma; 6—19.6 Ma (Engen et al. 2008). Half-spreading rates (arrows) from Ehlers and Jokat (2009). Pockmark fields in white; seismic track lines in black, bold where displayed in figures; Ocean Drilling Program core sites (black dots) as numbered. Seismic line X is shown in Vanneste et al. (2005). Figure DR1 is in the Data Repository (see footnote 1). FS—Fram Strait; KR—Knipovich Ridge; MR—Molloy Ridge; LT—Lena Trough; GR—Gakkel Ridge; MhR—Mohns Ridge; MTF—Molloy transform fault; STF—Spitsbergen transform fault; YP—Yermak Plateau; KF—Kongsfjorden Trough; PKF—Prins Karls Forland; ISF—Isfjorden Trough.

*E-mail: joel.johnson@unh.edu

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transform fault offset these spreading ridges by ~120 and ~150 km, respectively (Fig. 1). Initial exchanges of Arctic and Norwegian sea surface and deep-water masses through Fram Strait occurred at the earliest during the late early Miocene (ca. 17 Ma; Jakobsson et al., 2007; Ehlers and Jokat, 2013) or at the latest, during the late Miocene (ca. 10 Ma; Engen et al., 2008), creating an environment for the formation of sediment drifts throughout Fram Strait (Eiken and Hinz, 1993; Gebhardt et al., 2014). Vestnesa Ridge, a >100-km-long and 50-km-wide sediment drift between the northwest Svalbard margin and the MTF (Fig. 1), evolved within the West Spitsbergen Current (WSC) and grows on oceanic crust at the North American–Eurasian plate boundary. A gas hydrate reservoir and active free gas system within the Vestnesa sediment drift north of the MTF (Fig. 1) creates vents that release gas through the seafloor and into the ocean (Hustoft et al., 2009; Petersen et al., 2010; Bünz et al., 2012; Smith et al., 2014).

In this study, we integrate existing data with newly collected high-resolution P-Cable™ two-dimensional (2-D) seismic and swath bathymetry data to (1) reconstruct both the buildup and breakup of the Vestnesa drift along the MTF with a significant 30 km offset; (2) constrain the age of an Arctic gas–gas hydrate system that concurrently developed within the growing sediment drift; and (3) image the link between crustal structure and gas migration pathways that suggest that the gas hydrate system south of the MTF is likely charged by a significant portion of abiotic gas.

STRATIGRAPHY OF THE VESTNESA SEDIMENT DRIFT

The stratigraphy of Vestnesa Ridge in the area north of the MTF has been divided into three seismostratigraphic units (YP-1, YP-2, and YP-3) (Eiken and Hinz, 1993; Hustoft et al., 2009), with age control based on correlation to Ocean Drilling Program (ODP) Leg 151 holes (Geissler et al., 2011; Mattingsdal et al., 2014). The YP-1 sequence shows synrift and post-rift sediments deposited directly on oceanic crust. Magnetic anomaly chrons 6 (19.6 Ma), 5 (9.8 Ma), and 2A (2.8 Ma) constrain the age of the ocean crust beneath Vestnesa Ridge (Engen et al., 2008) (Fig. 1). The YP-2 sequence exhibits contourites and YP-3 encompasses glaciomarine contourites and turbidites. The boundary between YP-2 and YP-3 lies at an estimated age of 2.7 Ma (Knies et al., 2009). The basal age of the YP-2 sequence beneath Vestnesa Ridge could be at least 11 Ma (Mattingsdal et al., 2014) and as old as 14.6 Ma (Geissler et al., 2011).

OFFSET ALONG THE MOLLOY TRANSFORM FAULT

We discovered a new, major southern extent of the Vestnesa sediment drift that rests on

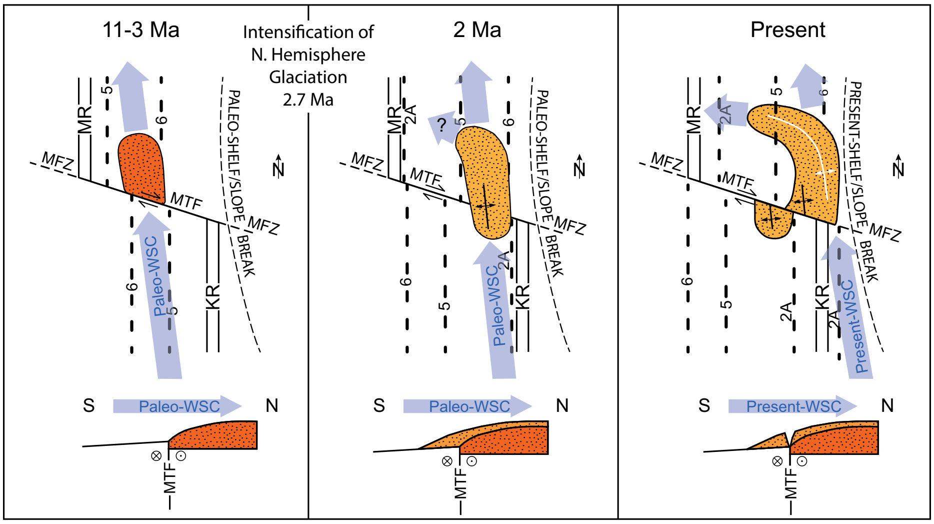

Figure 2. Tectonic reconstruction of Vestnesa sediment drift (west of Svalbard) during the past 11 m.y. MTF—Molloy transform fault; MFZ—Molloy fracture zone; MR—Molloy Ridge; KR—Knipovich Ridge; WSC—West Spitsbergen Current. Magnetic anomaly chrons (dashed lines) are as in Figure 1. South-north cross sections bisect the drift. An early crest of the growing drift (black axis in middle and right panels) across the MTF is observed today (Vanneste et al., 2005; Fig. DR1 [see footnote 1]), faulted and pockmarked, and serves as strain marker for offset. Continued eastward growth of the drift north of MTF within the WSC resulted in the development of a younger crest (white axis), also faulted and pockmarked.

significantly younger oceanic crust, between magnetic anomaly chrons 5 and 2A, compared to the drift north of the MTF, and lies offset to the west across the MTF (Fig. 1; Fig. DR1 in the GSA Data Repository[1]). The offset of the drift is significant (30 km) and is accurately measured using the lateral displacement of the faulted and pockmarked apex of the drift bodies, imaged by seismic and seabed mapping, both north and south of the MTF. Restoration of the two portions of the drift to their original position, when they first encountered the transform fault, is based on the most recently published half-spreading rates from the eastern side of Molloy Ridge, 6.5 mm/yr, and the western side of Knipovich Ridge, 8 mm/yr (Ehlers and Jokat, 2009). These half-spreading rates yield a full plate slip rate on the MTF of 14.5 mm/yr. This slip rate implies that the 30 km offset of the Vestnesa sediment drift by the MTF would have taken ~2 m.y. to reach the present configuration.

Our reconstruction of the entire drift suggests that the southern part of the Vestnesa sediment drift must have started to grow just prior to the beginning of its breakup phase at 2 Ma. If the drift south of the MTF was much older than ca. 2 Ma, then the offset distance between the faulted and pockmarked apexes north and south of the MTF would have increased with age and the observed separation would be significantly larger. To explain the age contrast in deposition of the drift across the MTF, we propose a two-phase evolution for the drift in space and time (Fig. 2). First, the >2-km-thick sediment accumulation of Vestnesa Ridge, its onset during the middle to late Miocene, and its accumulation above old crust (ca. 10–20 Ma) suggest that a north-south–oriented depocenter (i.e., Eiken and Hinz, 1993) developed north of the MTF, building the drift here from at least 11 Ma to 3 Ma (Fig. 2). Second, the intensification of Northern Hemisphere glaciation at 2.7 Ma (Knies et al., 2014) and the subsequent increase in continental-shelf-edge glaciation of the Svalbard margin caused a rapid increase in sedimentation rates (two-fold) throughout eastern Fram Strait (Mattingsdal et al., 2014). The increased sedimentation rates promoted drift growth throughout Fram Strait (Gebhardt et al., 2014), including both sides of the MTF (Fig. 2), where continued seafloor spreading resulted in the 30 km offset of the Vestnesa drift during the last 2 m.y.

GAS HYDRATE SYSTEMS ON YOUNG AND OLD CRUST ACROSS THE MTF

A well-documented gas hydrate and free gas system on Vestnesa Ridge north of the transform (Hustoft et al., 2009; Petersen et al., 2010; Bünz et al., 2012) indicated also thermogenic gas hydrates (Smith et al., 2014). South of the MTF, our new high-resolution seismic data reveal an equally well-developed gas hydrate and free gas system, including a strong BSR (Fig. 3; Fig. DR1). It is noteworthy that the water depth is ~450 m deeper at the crest of the drift south of the MTF, but that the depth of the BSR is shal-

[1]GSA Data Repository item 2015132, supplemental seismic line (Figure DR1) and methods description, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

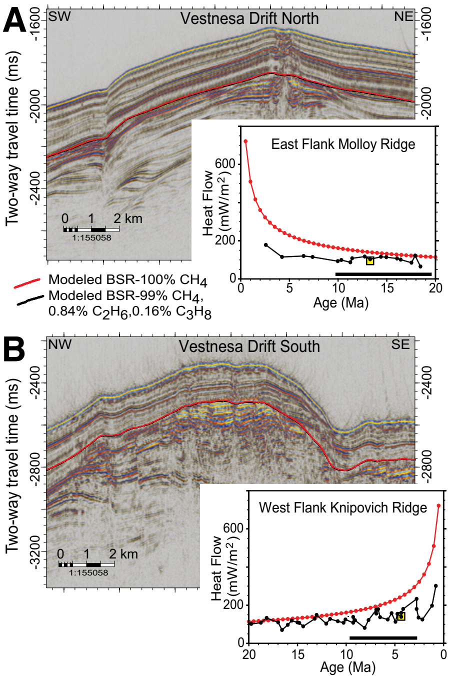

Figure 3. High-resolution P-cable seismic profiles across the crest of Vestnesa sediment drift (west of Svalbard), north (A) and south (B) of Molloy transform fault (MTF). Seismic line locations shown bold in Figure 1. Modeled bottom-simulating reflectors (BSRs) are described in the Data Repository (see footnote 1). Insets: Theoretical heat flow data (red) (Stein and Stein, 1992) and measured heat flow data (black) (Crane et al., 1991) versus age for east flank of Molloy Ridge (inset in A) and west flank of Knipovich Ridge (inset in B). Note the reversed *x* axis in B inset. BSR–derived heat flow values shown as yellow boxes. Black bars designate age of crust beneath Vestnesa drift on each side of MTF.

lower (~140 m) compared to the north (~200 m) (Fig. 3). This 60 m difference is consistent with younger and hotter crust as indicated by higher measured heat flow in the south (139 ± 2 mW/m^2) versus the north (103 ± 3 mW/m^2) (Crane et al., 1991) (Fig. 3, insets). To confirm that the BSR is gas hydrate related, we calculate the heat flow based on the BSR depth both north (95 mW/m^2) and south (141 mW/m^2) of the MTF, and document remarkable agreements with the measured heat flow in each region (Fig. 3, insets).

GAS SOURCES NORTH AND SOUTH OF THE MTF

Scientific drilling on the Vestnesa sediment drift on both sides of the MTF has not yet been accomplished, but shallow gas hydrates in the Vestnesa drift north of the MTF are derived from thermogenic gas sources (Smith et al., 2014). Biotic gas–producing source rocks do exist in older Miocene-age sediments (Knies and Mann, 2002) recovered from the base of ODP Site 909 ~50 km to the west (Fig. 1) and may also exist in the equivalent-age sediments beneath Vestnesa drift north of the MTF. The absence of sediment of this age south of the MTF may exclude comparable biotic gas sources here, although one cannot rule out contributions from lateral gas migration via undiscovered stratigraphic and/or structural conduits. Given the magma-limited, ultraslow-spreading environment in the Arctic, we also do not expect in situ thermal maturation of organic carbon driven by shallow magmatic sources (i.e., Lizarralde et al., 2011) to be significant in this region. The well-constrained age (ca. 2 Ma) and thickness (~700 m) of the drift deposit south of the MTF compared to the north (ca. 11 Ma, >2 km), yet the similar, extensive gas hydrate–free gas system, suggests that an additional gas source may be required south of the MTF. Seismic data across the drift south of the MTF image large offset normal faults in the oceanic crust that are interpreted as detachment faults (Fig. 4). Above one of these detachments, high-amplitude reflectors, a gas wipe-out zone, and a large free gas accumulation are visible directly beneath a BSR (Fig. 4), suggesting a likely contribution from abiotic methane, produced by the serpentinization of these exhumed ultramafic rocks (see the Data Repository). We suggest that the preservation of the drift deposit south of the MTF (1) in a region of asymmetric ultraslow spreading, (2) at the elevated inside corner of a ridge transform discontinuity (Fig. 1), (3) above relatively young underlying crust (2.8–9.8 Ma), (4) with large offset faults imaged beneath the sedimentary cover (Fig. 4), and (5) with the onset of its deposition in this region at 2–3 Ma, creates a very high potential for abiotic methane production from the serpentinization of ultramafic rocks.

EARLY GAS CHARGE TO A DEEP-WATER SEDIMENT DRIFT

We propose an early gas charge, and thus a long-lived (~2 m.y.) gas hydrate system, at the portion of the drift south of the MTF, for two reasons. First, if abiotic gases are a dominant source for methane in this region, its production is likely to have been ongoing during the past ~1–4 m.y., during active detachment faulting and when the seafloor crust was young, sufficiently warm, and infiltrated with seawater to drive serpentinization (Fig. 4B). This early-formed methane would have likely escaped into the water column until significant sediment accumulation began (at 2.7 Ma) south of the MTF and the drift sediments became an available reservoir for this methane and subsequent gas hydrate. Second, the close association of high-angle faults and fluid-escape features (chimneys and seafloor pockmarks) both north (e.g., Hustoft et al., 2009) and south (e.g., Fig. DR1) of the MTF suggests that faults play a critical role as conduits for methane produced at depth and transferred upward into the GHSZ. South of the MTF, these faults are syndepositional (Fig. 4; Fig. DR1), forming effective conduits for advective methane delivery to the overlying sediment drift as it grows through time. South of the MTF, early-formed abiotic methane would have encountered a GHSZ that expanded pro-

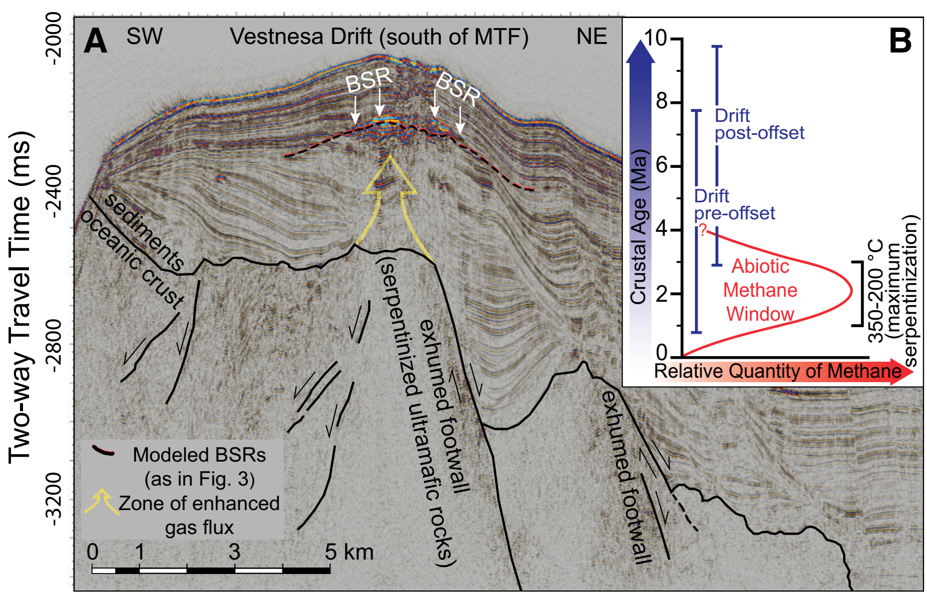

Figure 4. A: High-resolution seismic profile across the Vestnesa sediment drift (west of Svalbard) south of the Molloy transform fault (MTF). Oceanic crustal structures on western flank of Knipovich Ridge are shown. The observed bottom-simulating reflector (BSR), restricted to crest of drift, shows vertical offset with the modeled BSRs (parameters as in Fig. 3), consistent with advection-driven shoaling of the BSR. B: Conceptual diagram of an abiotic methane window for serpentinized oceanic crust in an ultraslow-spreading ridge environment. Temperature and crustal age constraints are described in text. Positions of the sediment drift south of MTF pre- and post-offset are shown.

gressively with continued translation of the drift into deeper water above a cooling crust.

CONCLUSIONS

Our geophysical results suggest that abiotic-dominated gas–gas hydrate systems can initiate, develop, and survive on tectonic time scales near young, sedimented, ultraslow-spreading mid-ocean ridge transform intersections. These active tectonic environments may not only provide an additional, serpentinized crustal source of methane for gas hydrate, but serve as a newly identified and stable tectonic setting for the long-term storage of methane carbon in deep-marine sediments. Future scientific ocean drilling and isotopic characterization of the recovered gases is necessary to quantify the proportion of biotic and abiotic gases stored in these deep-water reservoirs throughout the ultraslow-spreading Arctic Ocean ridges.

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