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

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ABSTRACT

Biotic gas generation from the degradation of organic carbon in ocean sediments supplies and maintains gas hydrates throughout the world's oceans. In nascent, ultra-slow 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 Ocean. Ultraslow-spreading ridges between NW Svalbard and NE 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 build-up of

a 2 Ma, long-lived gas hydrate/free gas-charged drift system on young oceanic crust that may be fed and maintained by a dominantly abiotic methane source. Ultra-slow spreading, sedimented ridge flanks represent a previously unrecognized carbon reservoir for abiotic methane that may supply and maintain deep-water methane hydrate systems throughout the Arctic.

INTRODUCTION

Marine sediments contain large quantities of biotic methane formed by microbial degradation of organic matter occurring at high temperature (>80°C) (Claypool and Kvenvolden, 1983). About 500 -10000 Gt of methane carbon are stored in marine gas hydrate systems (Kvenvolden, 1988; Buffet and Archer, 2004). Abiotic methane has been recently recognized as a new fundamental source generated in slow to ultra-slow 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° 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 ultra-slow ridges, serpentinization is focused along large detachment faults (e.g. Escartín et al., 2008; Sauter et al., 2013), which can accommodate the majority (nearly 100%) of relative plate motion (e.g., Sauter et al., 2013), and are often well developed at the inside corners of ridge-transform intersections (Tucholke et al., 1998). Slow to ultra-slow 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, (Figure 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 sampled on Lena Trough and Molloy Ridge (Snow et al., 2001), and black smokers and vent fauna observed at the junction of the Mohn and Knipovich Ridges on an axial high that is flanked by exhumed detachment surfaces or oceanic core complexes (Pedersen et al., 2010). BSRs (bottom simulating reflectors) 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 the Knipovich Ridge (Rajan et al., 2012). These observations establish the possibility for gas delivery for gas hydrates from an abiotic, serpentinized mantle source of methane throughout sediment covered portions of the Arctic Ocean ultra-slow spreading ridges.

In the Arctic Fram Strait, the tectonic controlled oceanographic gateway to the Arctic Ocean, deep-water sediment drifts have formed over millions of years along the continental margins by interactions with geostrophic currents (i.e. Heezen et al., 1966). The Vestnesa Ridge, a >100 km long and 50 km wide sediment drift, developed under such geostrophic currents within Fram Strait (**Figure 1**). Prior to the Oligocene (33 Ma), Fram Strait was closed along a major continental transform plate boundary between the Arctic and Norwegian/Greenland Sea basins (Engen et al., 2008). A change in plate motion at 33 Ma resulted in oblique rifting across this continental transform and initiated the opening of Fram Strait (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 in the Arctic Ocean and the Mohns Ridge in the Norwegian Sea (Engen et al., 2008; Ehlers and Jokat, 2013). The active Molloy Transform Fault (MTF) and Spitsbergen Transform Fault (STF) clearly offset these spreading ridges by ~120 and ~150 km, respectively **(Figure 1).** This tectonic development controlled initial exchanges of Arctic and Norwegian sea surface and deep-water masses through Fram Strait, which likely occurred at the earliest during the late Early Miocene (~17 Ma; Jakobsson et al., 2007; Ehlers and Jokat, 2013) or at the latest, during the Late Miocene (~10 Ma; Engen et al., 2008).

Such a plate-tectonic development of Fram Strait, and subsequent water mass exchanges between the Arctic and subpolar North Atlantic, created an environment for the formation of sediment drifts throughout Fram Strait (Eiken and Hinz, 1993; Gebhardt et al., 2014). The Vestnesa sediment drift, between the NW Svalbard margin and the MTF, evolved within the West Spitsbergen Current (WSC, continuation of the Atlantic Current flowing north through the eastern side of Fram Strait), and grows on oceanic crust at the North American-Eurasian plate boundary and within the stability field for marine gas hydrate, an ice-like substance that forms under low temperature and high pressure conditions if enough microbial, thermogenic, and/or abiotic gas and water coexist in the pore space of sediments. A gas hydrate reservoir and active free gas system within the Vestnesa sediment drift north of the MTF (**Figure 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 reconstruct the tectono-sedimentary evolution of an Arctic gas hydrate system through time by integrating existing data with newly collected high resolution P-Cable 2-D seismic and swath bathymetry data to: (1) reconstruct both the build-up and break-up 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 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 ODP Leg 151 holes (Geissler et al., 2011; Mattingsdal et al., 2014). The YP-1 sequence shows syn-rift 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 (**Figure 1**). The YP-2 sequence exhibits contourites and YP-3 encompasses glaciomarine contourites and turbidites (Howe et al., 2008). 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); this range in age may be a consequence of the time transgressive nature of a migrating sediment drift.

OFFSET ALONG THE MOLLOY TRANSFORM FAULT

We discovered a new major southern extent of the Vestnesa sediment drift that rests on 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 (**Figure 1 and DR Figure 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 transform. 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 the Molloy Ridge, 6.5 mm/yr, and the western side of the 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 take ~2 Myr 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 break-up phase at 2 Ma. If the drift south of the MTF was much older than ~2 Ma, then the offset distance between the faulted and pockmarked apexes from south to north of the drift would increase 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 (**Figure 2**). First, the >2km thick sediment accumulation of Vestnesa Ridge, its onset during the Middle to Late Miocene, and its accumulation above old crust (~10–20 Ma) suggest that a N-S 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 (**Figure 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 (twofold) 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 (**Figure 2**), where continued seafloor spreading resulted in the 30 km offset of the Vestnesa drift during the last 2 Ma.

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 bottom simulating reflection (BSR), representing the base of the GHSZ **(Figure 3; DR methods).** Noteworthy, the water depth is ~450 m deeper at the crest of the drift south of the MTF, but the depth of the BSR is shallower (~140 m) compared to the north (~200 m) (**Figure 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) (**Figure 3 insets)**. To confirm 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 (**Figure 3 insets**).

GAS SOURCES NORTH AND SOUTH OF THE TRANSFORM

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 sediment 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 (**Figure 1**), which also may exist in equivalent age sediments beneath Vestnesa drift, north of the MTF. However, the absence of this age sediment south of the MTF may exclude comparable biotic gas sources here, although one cannot rule out contributions from lateral gas migration via undiscovered stratigraphic/structural conduits. Given an Arctic tectonic setting in a magma-limited ultra-slow spreading environment, we also do not expect i*n situ* thermal maturation of organic carbon driven by shallow magmatic sources (e.g., Gulf of California, Lizarralde et al., 2007). The well constrained age (~2 Ma) and thickness (~700 m) of the drift deposit south of the MTF compared to the north (~11 Ma, >2 km), yet showing a similar extensive gas hydrate/free gas system, suggests an additional gas source, beyond biotic sources.. Seismic data south of the MTF image large offset normal faults in the oceanic crust that are interpreted as detachment faults (**Figure 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 (**Figure 4**), suggesting a likely contribution from abiotic methane sources, formed by the serpentinization of these exhumed ultramafic rocks. We suggest that the preservation of the drift deposit south of the MTF in (1) a region of asymmetric ultra-slow spreading, (2) at the elevated inside corner of a ridge transform discontinuity (**Figure 1**), (3) above relatively young underlying crust (2.8–9.8 Ma), (4) with large offset faults imaged beneath the sedimentary cover (**Figure 4**), and (5) the onset of its deposition in this region 2–3 Ma, creates a very high potential for abiotic methane production from the serpentinization of ultramafic rocks. This production may provide a significant source of abiotic methane to the overlying sediments in this Arctic ultra-slow spreading ridge environment within the Fram Strait deep-water gateway.

EARLY GAS CHARGE TO DEEP-WATER SEDIMENT DRIFT

We propose an early gas charge, and thus a long lived (~2 Ma) 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 last ~1-4 m.y., during active detachment faulting and when the seafloor crust was young, sufficiently warm, and infiltrated with seawater to drive serpentinization (**Figure 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., **DR Figure 1**) of the MTF, suggests 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 syn-depositional (**Figure 4; DR Figure 1)** and thus developed early during drift sedimentation, 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 gas hydrate stability zone that expanded progressively with continued translation of the drift into deeper water above a cooling crust.

CONCLUSIONS

Our geophysical results suggest that mixed biotic and abiotic gas/gas hydrate systems can initiate, develop, and survive on tectonic timescales 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 large amounts 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 ultra-slow spreading Arctic Ocean ridges. .

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FIGURE CAPTIONS

Figure 1. **[[No “A” label seen]]** Tectonic setting of the Vestnesa Sediment Drift. Bathymetry from IBCAO grid; magnetic anomaly chrons (in red) 2A: 2.8 Ma, 5: 9.8 Ma, 6: 19.6 Ma (Engen et al. 2008); half-spreading rates from Ehlers and Jokat (2009); pockmark fields in white; seismic lines in black-bold where shown; ODP core sites as numbered; seismic line X shown in Vanneste et al. (2005). 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.

Figure 2. Tectonic reconstruction of the Vestnesa sediment drift during the last 11 Ma. MTF-Molloy Transform Fault, MFZ-Molloy Fracture Zone, WSC-West Spitsbergen Current, magnetic anomaly chrons as in Figure 1. An early crest of the growing drift (black axis in middle and right panel) across the MTF is observed today (Vanneste et al., 2005, and Supplemental Figure 1**)**, faulted and pockmarked, and serves as a strain marker for the measured 30 km offset. Continued eastward growth of the drift north of the MTF within the WSC resulted in the development of a younger crest (white axis), which is also faulted and pockmarked today.

Figure 3. High-resolution p-cable seismic profiles across (A) the crest of Vestnesa Drift, north (A) and south (B) of the MTF. Map locations shown bold in Figure 1. Insets: Theoretical heat flow data (Stein and Stein, 1992) and measured heat flow data (Crane et al., 1991) vs age for the east flank of Molloy Ridge (inset in A) and west flank of Knipovich Ridge (inset in B). BSR-derived heat flow values shown as yellow boxes. Black bars designate the age of the crust beneath the Vestnesa drift on each side of the MTF.

Figure 4. A. High-resolution seismic profile across the drift south of the MTF. Oceanic crustal structures on the western flank of the Knipovich Ridge are shown and interpreted as large offset detachment faults that exhume probable serpentinized ultramafic rock (**DR Crustal Structure)**. A broad gas wipeout zone, high amplitude (gas charged) reflectors, free gas zone and observed BSR are present above the largest offset detachment fault. The observed BSR is restricted to the crest of the drift and shows a vertical offset with the modeled BSRs (parameters as in Figure 3), consistent with advection-driven shoaling of the BSR. B. Conceptual diagram of an abiotic methane window for serpentinized oceanic crust in an ultra-slow spreading ridge environment. Temperature and crustal age constraints described in the text. Position of the sediment drift south of the MTF pre- and post-offset are shown as purple age brackets. The drift clearly evolved initially above crust within the abiotic methane window and, as we propose developed its gas hydrate system early. Continued offset into deeper water will eventually result in diminished serpentinization sources of methane, but much of the early-formed abiotic methane could be retained in long-lived, deep-water gas hydrate.

[1] GSA Data Repository item 2015xxx, xxxxxxxx, 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.