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3D Seismic investigation of a gas hydrate and fluid flow system on an active mid-ocean ridge; Svyatogor Ridge, Fram Strait

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Key Points:

- A gas hydrate system is imaged with 3-D seismic data south of Vestnesa Ridge and exists on young, warm crust near the plate boundary
- The system is seeping fluid at the seafloor episodically, likely controlled by seismic activity
- We identify fracture networks, which we suggest are a proxy to identify the extent of gas hydrate within the sediment column

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Abstract

Tectonic settings play a large role in the development of fluid flow pathways for gas migrating through sedimentary strata. Many gas hydrate systems worldwide are located on either passive continental margins, in large contourite deposits on the slopes of passive continental margins or on subduction margins. The Svyatogor Ridge, however, located at the northwestern flank of the Knipovich Ridge and south of the Molloy Transform Fault (Fram Strait), is a gas hydrate system which is located on an actively spreading margin. Svyatogor Ridge has evidence of shallow gas accumulations; a strong BSR indicating a gas hydrate and underlying free gas system, and fluid flow pathways to the seafloor culminating in pockmarks. Using a high-resolution P-Cable 3D seismic survey, we investigate how tectonic and sedimentary regimes have influenced the formation of this well-developed gas hydrate system. Large-scale basement faults identified in the seismic data are interpreted as detachment faults, which have exhumed relatively young ultramafic rocks. These detachment faults act as conduits for fluid flow, and are responsible for the formation of folds in the overlying sediments that are breached by faults. We propose a model for fluid flow within this system whereby as sedimentary faults breach upwards through the sedimentary strata, fluid is able to migrate further upwards. We find that the tectonic regime on Svyatogor Ridge is the dominant driver of fluid migration and episodic release at the seafloor.

1. Introduction

Gas hydrates are solid compounds of water and gas (i.e., dominantly methane) which are stable in marine sediments or permafrost regions at high pressures and low temperatures [i.e., *Sloan*, 1998]. Determinants for gas hydrate formation are salinity (high salinity inhibits hydrate formation), porosity and a sufficient gas input. The gas that sustains gas hydrate accumulations in shallow sediments has been found to be predominantly of microbial or thermogenic origin [*Klauda and Sandler*, 2005]. In the case of microbial in situ methane production, an input of organic matter into the system is also necessary [*Paull et al.*, 1994]. Therefore, many of the sub-aqueous gas hydrate and related fluid flow system occurrences worldwide are observed on TOC-rich sedimented continental margins (i.e. Hikurangi Margin [*Pecher et al.*, 2005], Cascadia Margin [*Suess et al.*, 1999] Gulf of Mexico [*Shipley et al.*, 1979]) or in large contourite deposits (i.e. Vestnesa Ridge [*Bünz et al.*, 2012], Blake Ridge [*Faugères et al.*, 1999]) as these settings generally meet all the conditions for both gas hydrate formation and stability. Distal settings (i.e. abyssal plains), on the other hand, are generally characterized by deposition of clays and silts, and lower organic matter fluxes to the seafloor [*Müller and Suess*, 1979; *Klauda and Sandler*, 2005] and the common assumption is that these are not ideal settings for gas hydrate formation, even though they may fall within the gas hydrate stability zone.

In the Fram Strait, the Western Svalbard Margin and Vestnesa Ridge are known for storing large quantities of methane within the sedimentary strata, where large amounts of this shallow gas is sequestrated as gas hydrate [*Vanneste et al.*, 2005; *Hustoft et al.*, 2009; *Bünz et al.*, 2012]. The Western Svalbard margin is a passive continental margin that evolved in connection with the onset of rifting in the North Atlantic [e.g., *Lundin and Doré*, 2002; *Engen et al*., 2008]. Vestnesa Ridge formed as a large contourite deposit that extends off the continental margin crossing the continental-oceanic crust transition [*Engen et al.*, 2008; *Bünz et al.*, 2012; *Eagles et al.*, 2015]. Although the distribution of fluid flow related features developed through the gas hydrate zone on Vestnesa Ridge is correlated with the presence of faults [*Plaza-Faverola et al.*, 2015], the gas hydrate system here is assumed to have developed post-rift [*Eiken and Hinz*, 1993; *Engen et al.*, 2008; *Bünz et al.*, 2012]. However, to the west of the Western Svalbard Margin and south of Vestnesa Ridge is the Knipovich

Ridge, which is an ultra-slow spreading ridge [*Dick et al.*, 2003]. In such ultra-slow settings, magmatism is limited and low-angle detachment faults accommodate the majority plate motion and can remain active for 1-3 Myr [*Tucholke et al*., 1998; *Escartin et al*., 2008]. The Arctic mid-ocean ridges are all ultra-slow and in particular, low angle detachment faults and exhumed serpentinized peridotites have been observed and/or sampled on the Gakkel Ridge, Lena Trough and Molloy Ridge *[Snow et al., 2001; Dick et al., 2003; Michael et al*., 2003]. Abiotic methane has been, in recent years, identified as another potential gas source available for gas hydrate formation in slow to ultra-slow spreading environments [*Rajan et al*, 2012; *Johnson et al.*, 2015], forming during serpentinization of ultra-mafic rocks [*Etiope and Sherwood Lollar*, 2013]. Serpentinites sampled on the seafloor in slow and ultra-slow spreading mid-ocean ridges are often found in close proximity to detachment faults [*Cann et al*., 1997; *Kelley et al*., 2001], which provide easy access for seawater to drive serpentinization reactions. Due to the limited life span of slip on a detachment fault and the temperature range for maximum serpentinization, the window to form serpentinized methane is limited to young crust close to the spreading axis [*Johnson et al*., 2015]. Additionally, serpentinites are commonly observed at the junctures between spreading ridges and transform faults, where detachment faults are well developed *[Tucholke et al*., 1998].

Due to the proximity of the Arctic mid-ocean ridges to the Western Svalbard Margin, and their ultraslow spreading rates, the Arctic mid-ocean ridges are often sedimented, and magma limited conditions create geothermal gradients lower than at intermediate to fast spreading ridges. The flanks of the Knipovich Ridge and Molloy Ridge are not only within the temperature and pressure regime required for gas hydrate stability, but also are characterized by having similar sedimentary depositional regimes [*Eiken and Hinz*, 1993] and potentially even their own methane source – serpentinized abiotic methane [*Johnson et al.*, 2015; *Rajan et al.*, 2012].

Svyatogor Ridge is a sedimented, elongated ridge located on the flank of the Knipovich Ridge at the inner junction with the Molloy Transform Fault. Previous work has documented the presence of a gas hydrate system on the Svyatogor Ridge [*Johnson et al*., 2015]. Unlike the other Fram Strait gas hydrate reservoirs, the gas hydrate system on the Svyatogor Ridge is on the flank of an actively spreading mid ocean ridge, implying that unlike the other Arctic gas hydrate systems, Svyatogor Ridge is in an actively rifting environment. Using high-resolution 3D seismic data, we investigate the first gas hydrate system identified on the flank of an actively rifting ultraslow spreading margin. Based on detailed descriptions of tectonic and sedimentary structures characterizing the gas hydrate bearing ridge we explore the implications that this tectonically active ultra-slow spreading setting has on the development of a gas hydrate system and associated seafloor seepage system.

2. Geologic Setting and Tectonic History

2.1 Study Area

Svyatogor Ridge is a contourite driven sedimented ridge with a length of 46 km and a width of ~5 km (Fig. 1) [*Johnson et al.*, 2015]. Our study focuses on the southernmost part of the ridge.

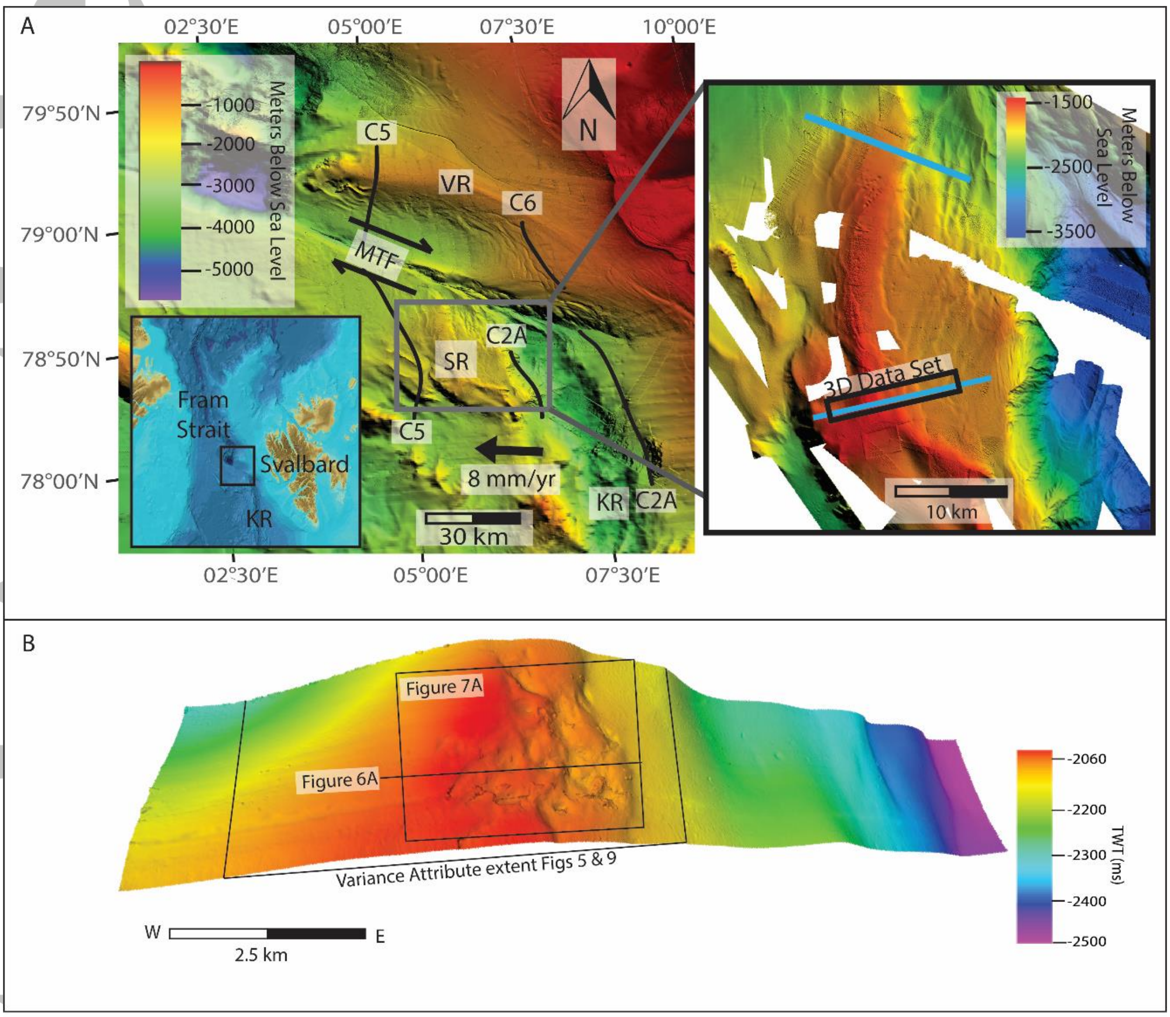

Figure 1. A) The Svyatogor Ridge is a 46 km long, ~5 km wide feature at the intersection between the Molloy Transform Fault (MTF) and the Knipovich Ridge (KR). The Knipovich Ridge has a spreading rate of ~8 mm/yr [*Ehlers & Jokat*, 2009]. Svyatogor Ridge is located between Chrons 5 and 2A (C2A, C5), correlating to 9.8 Ma and 2.8 Ma respectively [*Engen et al*., 2008]. The location of the 3D P-cable Seismic survey is marked by the black box in the inset and seismic examples from *Johnson et al*., [2015] are marked by blue lines. Other tectonic and geologic features in the Fram Strait are the Vestnesa Ridge (VR) Molloy Ridge (MR), Yermak Plateau (YP), Lena Trough (LT) and Gakkel Ridge (GR). B) Position of figures 5-7 and 9 in relation to the 3D seismic cube.

2.2 Tectonic Background

The ultra-slow spreading Knipovich Ridge extends for ~550 km in N-S direction [*Okino et al*., 2002], with a half-spreading rate for the Knipovich Ridge of 6.2 mm/yr, on the western, faster moving, side of the Ridge [*Ehlers and Jokat*, 2009]. The Knipovich Ridge connects the Gakkel Ridge in the Arctic Ocean to the Mohns Ridge through a number of transform faults and small spreading centres (Fig. 1). The Gakkel and Mohns Ridges most likely began spreading during Chron 24 at 53 Ma [*Vogt et al*., 1978; *Ehlers and Jokat*, 2009], and the Knipovich Ridge began propagating northwards at Chron 13, 33 Ma [*Talwani and Eldholm*, 1977; *Ehlers and Jokat*, 2009]. At the northernmost segment of Knipovich Ridge, magnetic anomaly C6 (19.6 Ma) is clearly delineated, and C5 (9.8 Ma) is present as a weaker lineation [*Engen et al*., 2008] on the western side of the Ridge. Conjugate magnetic anomalies are not present on the Svalbard side of the Ridge, leading *Engen et al*., [2008] to suggest that the junction between the Molloy Transform Fault and Knipovich Ridge has migrated northwards. Faults and rift escarpments further north suggest that the Knipovich ridge is continuing to propagate northwards under the West Svalbard Margin [*Crane et al*., 2001]. Due to the nature of the geologic and tectonic setting of the study area, close to the Knipovich Ridge, the crust is young and close to the seafloor [*Amundsen et al.*, 2011].

2.3 Seismic Stratigraphy

Three main stratigraphic units provide chronological constraints on the West Svalbard Margin *[Eiken and Hinz*, 1993]. YP-1 is the oldest unit, composed of syn- and post-rift sediments, which deposited directly on oceanic crust; YP-2 sequence comprises the onset of contourite facies with a basal age between 11 Ma and 14.6 Ma; and YP-3 corresponds to the onset of glacially transported sediments, where contourites and glaciomarine turbidites and debris flows are the predominant facies. Correlation to cores drilled during Ocean Drilling Program Leg 151 [*Geissler et al*., 2011] provides the age control for these seismic stratigraphic units. The boundary between YP-2 and YP-3 is estimated to be 2.7 Ma [*Eiken and Hinz*, 1993; *Mattingsdal et al*., 2014], and has been identified in the region comprising the Yermak Plateau, the Vestnesa Ridge and offshore Prins Karls Forland [*Eiken and Hinz*, 1993; *Hustoft et al*., 2009; *Mattingsdal et al*., 2014]. Based on the supposition that the Svyatogor Ridge was offset to the west during growth of Vestnesa Ridge across the MTF during the last 2-3 Ma [*Johnson et al*., 2015], YP-2 and YP-3 seismic stratigraphic units should also be present on the Svyatogor Ridge. YP-1 however is most likely too old compared to the estimated crustal age to be present on Svyatogor Ridge [*Engen et al.*, 2008; *Mattingsdal et al.*, 2014].

2.4 Oceanography

The Fram Strait channels warm, saline waters from the North Atlantic into the Arctic Ocean, and transports cold Arctic water southwards [*Beszczynska-Möller and Fahrbach*, 2012]. The West Spitsbergen Current brings North Atlantic water northwards, and is an important sediment supply system for the Western Svalbard Margin, having deposited the muddy-silty contourite deposits that dominate sedimentation [*Howe et al*., 2008; *Rebesco et al*., 2013]. Although paleo-current indications suggest the West Spitsbergen Current has migrated up the west-Svalbard Margin slope over time [*Eiken and Hinz*, 1993], this current may have been influencing the Svyatogor Ridge in the past [*Johnson et al*., 2015], thus, driving sedimentation that ultimately hosts the gas hydrate and free gas system observed there today. As the West Spitsbergen Current has migrated upslope through time, we expect the WSC influenced sedimentation to decrease through time on Svyatogor Ridge.

3. Data and Methods

A 2 x 10 km high-resolution P-Cable 3D seismic data set was acquired in 2014 aboard R/V Helmer Hanssen. P-Cable seismic data was recorded using 14, 25-m long streamers spaced 12.5 m apart with eight channels per streamer [e.g., *Planke et al*., 2009]. The source used was a mini-GI air gun with a capacity of 15/15 in^3, fired every 5 seconds with the ship maintaining a speed of 4 kn andsailing line spacing of ~60 m. Data processing steps included: Insertion of navigation data, CDP-Binning at 6.25 x 6.25 m (fold of approximately 7 traces per CDP bin), static corrections, bandpass filtering with a frequency of 10-20-400-500 Hz, attenuation and spherical divergence correction, NMO correction, stacking, interpolation in crossline direction and a 3D Stolt (post-stack) |Migration. We used a constant velocity of 1600 m/s for migration, constrained for the imaged sedimentary infill by Ritzmann et al. [2004], who used Ocean Bottom Seismometers for velocity analysis. Dominant frequency of this data is 120 Hz, so the vertical data resolution is <3.2 m (λ/4) at the seafloor assuming a water velocity of 1490 m/s (measured by CTD at beginning of surveying). Data penetration is restricted to 3200 ms TWT. Seismic interpretation used commercially available seismic interpretation software (Petrel). Variance maps were generated along major reflections for fault-analysis and depositional reconstruction carried out for constraining the evolution of the study area. Seismic results are analyzed together with bathymetry data with a resolution of ~10-20 m collected aboard the R/V Helmer Hanssen between 2014 and 2016. Repeated water column acoustic mapping (June 2014 and October 2015) during CAGE cruises 14-1, 14-2 and 15-6 reveled no active fluid expulsion above pockmarks on the crest of Svyatogor Ridge.

4. Results and Interpretations

4.1 Distinct depositional periods

Four main depositional periods (S1-S4) are identified in addition to the acoustic basement, based on: 1) the seismic character of the reflections; 2) faulting pattern; and time framework (i.e., syn-rift or post-rift deposition) (Fig. 2).

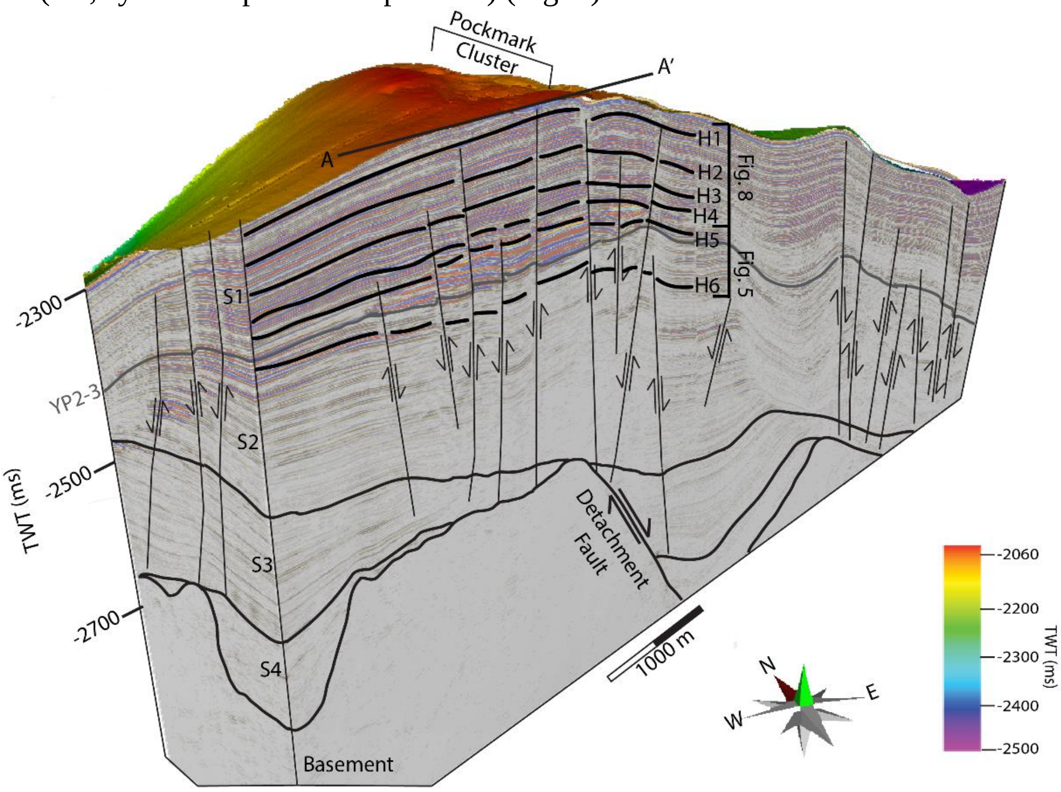

Figure 2. The data set is divided into four units representing depositional periods (S4-S1) and Basement. These depositional periods are defined based on seismic properties that indicated a change in depositional regime and rock/sediment properties. Locations of structural maps in Figures 5 and 8 are annotated on this section. WP and EP are the west and east basement peaks respectively.

Johnson et al., [2015], define the basement in this study area, which is indicated by the transition in seismic response between sediments and oceanic basement. Using the nearest published seafloor sampling results, seismic refraction data, and the tectonic setting *Johnson et al.*, [2015] suggest that the basement in the study area is likely composed of serpentinized ultramafic rocks. The basement has two prominent highs (East Peak, West Peak; Fig. 3A), with a depression located in between. Associated with these two peaks, the acoustic basement tilts creating an additional two small basins at the western and eastern ends of the data set (Fig. 3). Within the unit defined as basement, there are no seismic indications of stratified reflections from sediments. We interpret the basement as young crust formed as part of the Knipovich Ridge spreading regime.

Pockets of sediments infilling acoustic basement lows (Fig. 2; Fig. 3A) characterize the first period of deposition (Unit S4). In the central depression between the two basement peaks, this unit appears to onlap against the East Peak but abruptly truncates against the West Peak. Amplitude of reflections in this unit are very low. All reflectors in this unit dip at similar angles to the acoustic basement (Fig. 3A). The reflector marking the top of unit S4 appears to be erosional (truncating lower reflectors) on the western side of West Peak. Unit S4 is interpreted to be sedimentation infilling the basement highs and lows. It is difficult to interpret further owing to the extremely low amplitudes. The rotation of the few reflectors we could identify suggests this unit has tilted because of tectonic event(s).

Unit S3 also infills basement lows, however it is not localized in the same manner as S4; the top reflections of this unit is nearly continuous throughout the entire dataset, except in one area (west peak) where the acoustic basement protrudes above this unit (Fig. 2; Fig. 3A). While in the west of the data-set reflectors are sub-horizontal to slightly rotated, the eastern half of this unit is rotated to conform to the dip trend of the acoustic basement (Fig. 2; Fig. 3A). Overall, the amplitudes and reflection frequency of this unit are low, however moving upwards through this unit reflectors appear to become increasingly less rotated (Fig 3A). We therefore interpret this unit to have continued to infill basement lows after the deposition of Unit S4.

Depositional period S2 consists of mostly sub-horizontal deposition in the west and dipping reflectors in the east. In this unit, there is thickening of sedimentary packages towards the east (Fig. 3). Disruption and vertical offset of reflections is prevalent within Unit S2. Based on correlation with regional seismic lines [e.g. *Hustoft et al*., 2009] we interpret that the top reflection of our S2 depositional period coincides with the YP2/YP3 boundary. This indicates that the sediment deposited in this unit is older than 2.7 Ma. In addition, the unit thickens eastward so this unit is interpreted to have deposited as the WSC was moving east, while simultaneously the Knipovich Ridge was propagating Svyatogor Ridge westward.

Depositional period S1 is composed of mostly sub-horizontal reflectors in the west and dipping reflectors in the east (Fig. 3). Unit S1 shows a clear thickening trend of sedimentary packages towards the east (Fig. 3B). The amplitudes in this depositional period also cycle from high amplitude to low amplitude, however the transition to low amplitude is abrupt and therefore there is a predominance of high amplitude (Fig. 3A). Frequency of reflections in this unit is high. Like Unit S2, disruption and vertical offset of reflections is common. The uppermost reflector in this unit is the seafloor and the base has been correlated as YP2/3 [e.g. *Hustoft et al*., 2009] therefore this unit must correlate to YP3 (<2.7 Ma) sediment. The eastward thickening of this unit is interpreted to result from the combined effects of the eastward migration of the WSC and the westward offset of the ridge along the MTF.

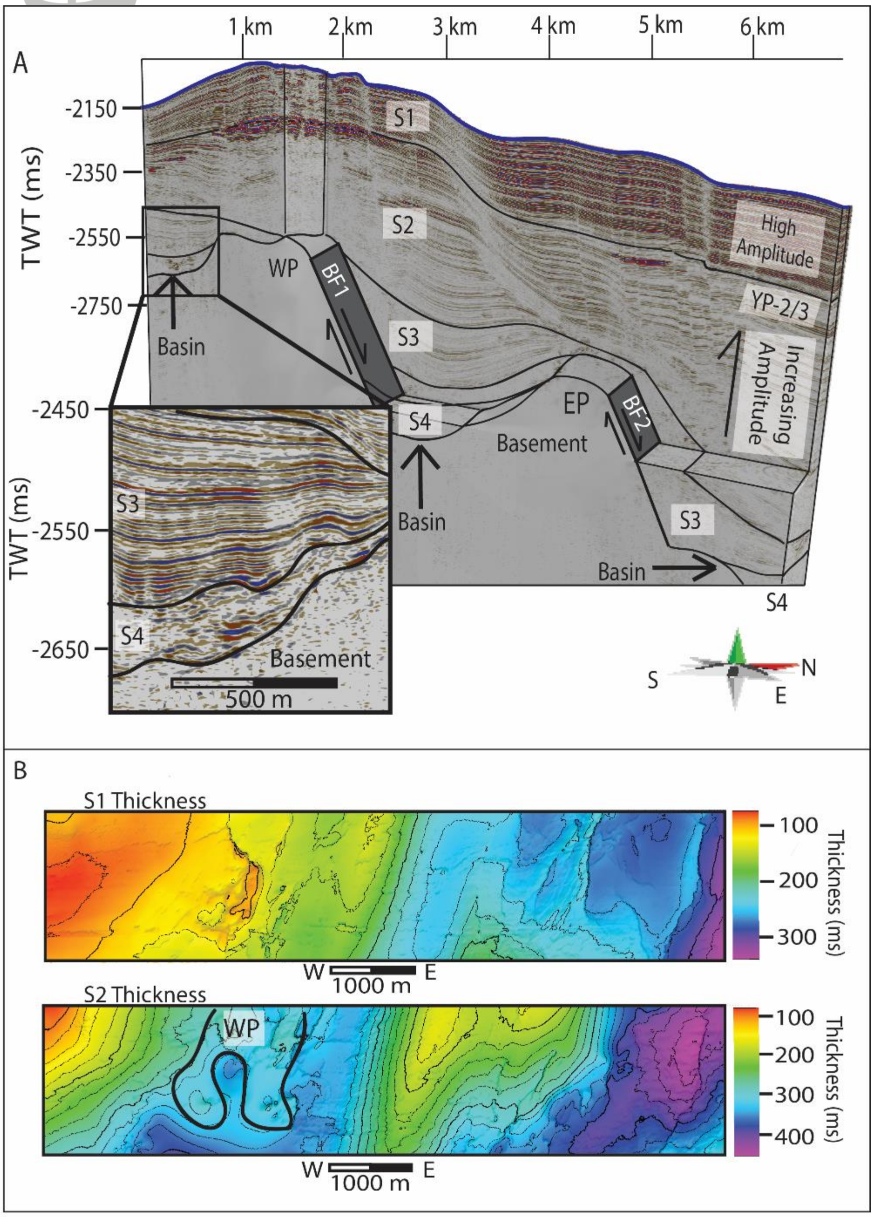

Figure 3. A) The acoustic basement has two main peaks (WP: West Peak, EP: East Peak) that are defined by two normal faults, with basins surrounding the peaks. Units S4 and S3 infill these basement highs. Units S2 and S1 are composed of mainly sub-horizontal reflectors in the west and dipping reflectors in the east. Inset: Units S4 and S3 are slightly rotated, and stretched, to conform to the tilt of the basement. This has led to the interpretation that these units have been deposited while these faults were active B) Isopach maps of units S1 and S2 show that eastward thickening of strata is most pronounced in S2. Section marked 'WP' is where the basement peak West Peak outcrops into S2.

4.2 Fault Analysis

4.2.1 Major tectonic faults

Two normal faults (BF1, BF2) were identified at the lower limit of penetration of the data set (Fig. 4). These faults occur in the acoustic basement and do not extend upwards into the sedimentary sequences (Fig. 4). The western-most fault (BF1) is the best imaged and closer to the surface. The eastern-most (BF2) is at the very edge of both lateral and vertical data extent; however, it is still possible to interpret a fault plane. The dip of BF1 and BF2 is calculated to be 30° and 20° respectively (based on a velocity of 1600 m/s adjacent to sedimentary sections), and dip azimuth of BF1 is ~80° while BF2 ~95°. Both faults conform to the regional tectonic setting. Offset of BF1 is at least 1200 m and the offset of BF2 at least 1000 m [*Amundsen et al*., 2011]. These faults are interpreted to be detachment faults, which are related to spreading on the Knipovich Ridge [*Amundsen et al*., 2011; *Johnson et al*., 2015].

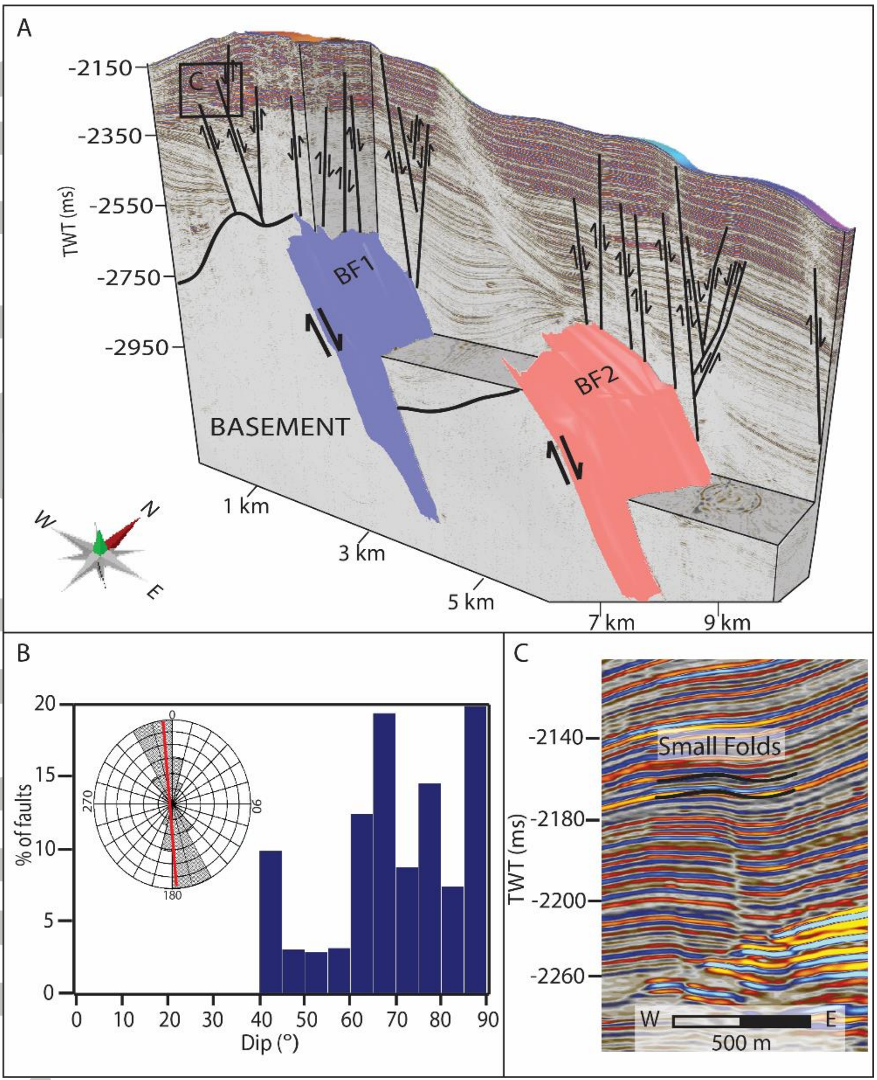

Figure 4. A) BF1 and BF2 are two large normal detachment faults identified within the data set. These faults do not extend beyond the basement however, sedimentary fault arrays occur exclusively around the area where the basement faults occur. B) The sedimentary faults mostly conform to the regional tectonic regime (strike of Knipovich Ridge marked in red on Stereonet, from *Peive and Chamov* [2008]). Dip of the sedimentary faults is between 40-90°. C) Sedimentary faults from the eastern-most group shown in (A) showing instances of small folds occurring above the fault termination, indicating that these are developing as growth faults.

4.2.2 Sedimentary faults

In the sedimentary strata, there are numerous steeply dipping normal faults present throughout the dataset. These faults are NNW-SSE oriented and have dips of between 40-90°, although most faults dip between 60-90° (Fig. 4). Most of the faults upwardly terminate in Unit S2 although a few terminate within Unit S1 or reach the seafloor. These faults are all concentrated around the two major tectonic faults, BF1 and BF2, in the acoustic basement (Fig. 4). These faults mostly comply with the regional tectonic setting although some at the apex of the ridge do not (Fig. 4) [*Peive and Chamov*, 2008]. Sedimentary faults nearly exclusively terminate against the basement. At the upward termination of the faults, there is often a very small fold which is indicative of a fault propagation folding [*Hardy and McClay*, 1999; *Jackson et al*., 2006]. We interpret folding at the upper terminus of sedimentary faults to indicate upward and lateral propagation of normal faults through ductile sediment deposited over more rigid basement material [e.g. *Corfield and Sharp*, 2000].

4.2.3 Radial Faults and Fracture networks

Structural maps reveal smaller scale faults forming at random azimuths between larger scale NW-SE trending faults (Fig. 5). We only identify this type of faulting in the area above West Peak. This type of faulting occurs in a linear, step-like fashion around a zone of acoustic blanking coincident above West Peak (Fig. 5). This type of faulting is interpreted as radial faulting, and similarly to the radial-type faulting around sediment remobilization features [e.g., *Hansen et al*., 2005], is interpreted to be a function of the sediment doming around the peaks associated with the two major detachment faults BF1 and BF2 (Fig 4a). In this case, we interpret the structure causing sediment doming to be uplift of West Peak into the sedimentary sequence. Lastly, we also identify even smaller scale features in variance attribute that are also forming at random azimuths, and sometimes as circular features, and are often barely recognizable in the seismic section (Fig 5). These features are mostly associated with a very small depression at the upward termination, which may be interpreted as fluid flow features i.e [*Hartwig et al*., 2012]. As the depression structure is at the limit of seismic resolution, it is difficult to interpret whether it is a paleo-pockmark or associated with syn-tectonic infill, however the circular features often form at intersections of the small scale, random azimuth features. Therefore, we interpret the random azimuth features as fracture networks.

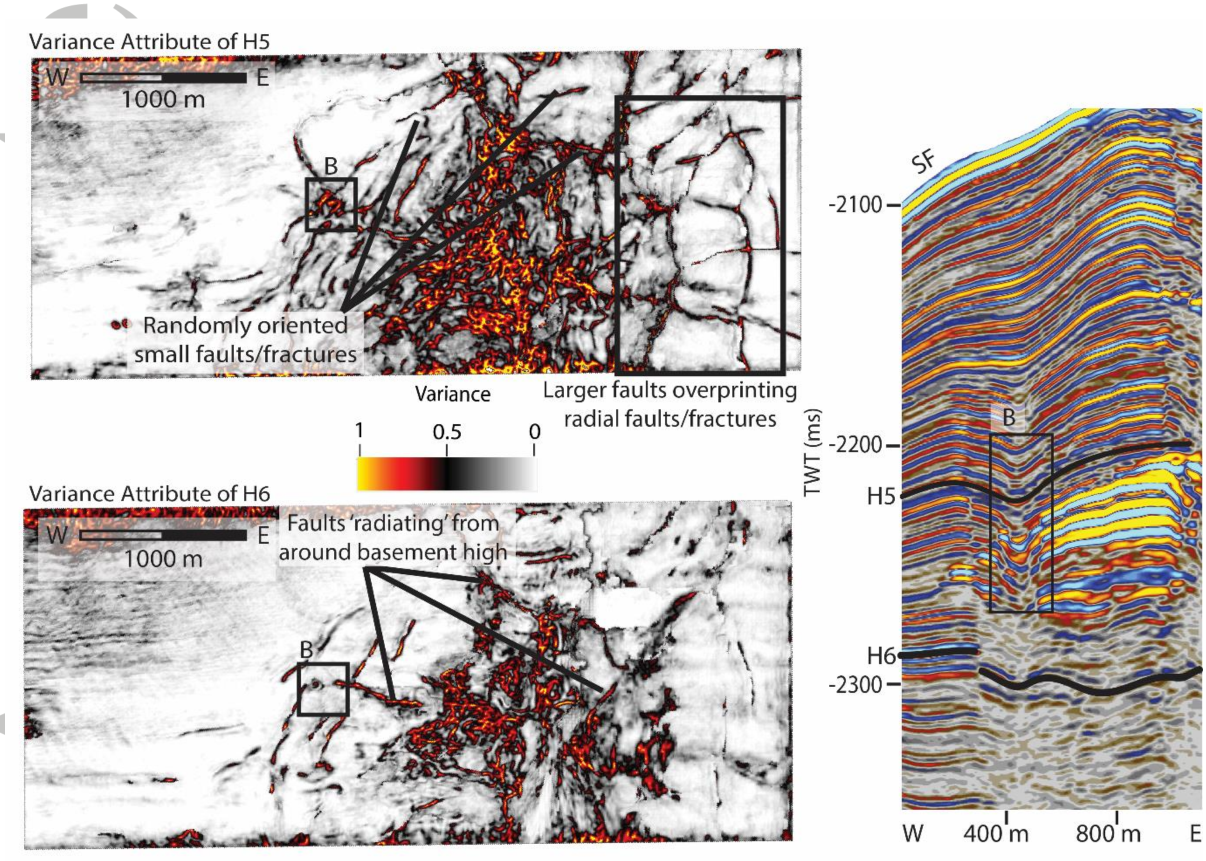

Figure 5. Structural maps (variance attribute) of horizons show radial faulting at depths greater than 2150 ms TWT. These are interpreted to be caused by the uplift of the basement West Peak into its current position. We also identified fracture networks (B) which often present as small circular features in variance attribute, however are often difficult to observe as faults in the seismic section. Location of horizons shown on Figure 2 and inset.

4.3 Fluid flow and associated gas hydrate system

In Unit S1, located 150 ms TWT beneath the seafloor, at the apex of Svyatogor Ridge, is a persistent crosscutting reflector with anomalously high amplitude, reverse polarity c.f. the seafloor that simulates the seafloor (Fig. 6A). Such a distinct crosscutting reflection is known as the bottom-simulating reflector (BSR) which indicates the base of the GHSZ [*Shipley et al*., 1979]. There is a zone (40-60 ms TWT thick) immediately below the BSR with enhanced amplitudes compared to the surrounding strata (Fig. 7B).

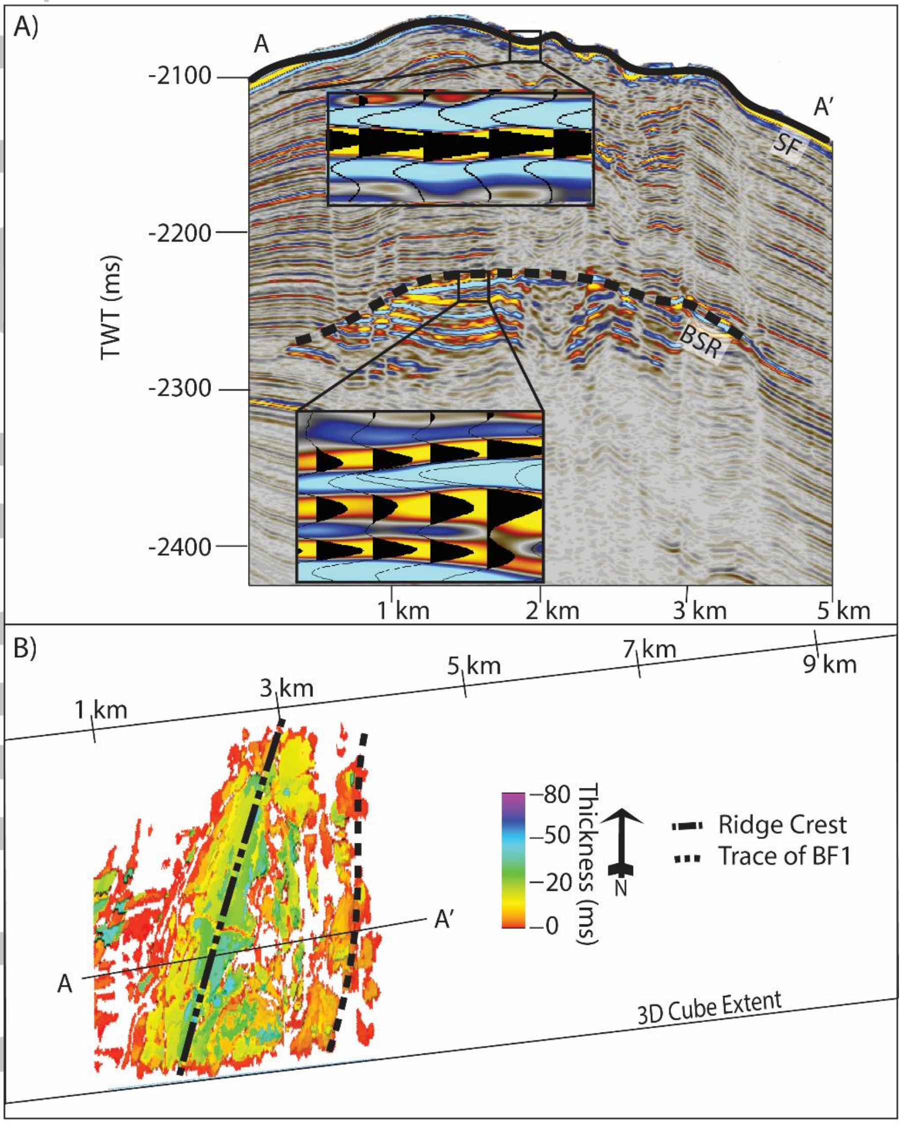

Figure 6. A) The reflection identified as a BSR is characterized by being reverse polarity and mimicking the seafloor as well as being notably higher in amplitude than the surrounding strata. B) The free gas zone beneath the BSR is relatively small in comparison to the extent of our 3D cube, however important to note that it is limited to the area west of the BF1 footwall and is thickest at the ridge crest axis.

This high amplitude zone is also a typical element of a gas hydrate system where free gas is trapped underneath gas hydrate bearing sediments [e.g., *Holbrook et al*., 1996]. The free gas zone in Svyatogor ridge is contained to the west of the BF1 footwall (Fig. 6B), becoming thinner toward the flanks of the sedimentary ridge until disappearing ~1 km away from the axis of the ridge (Fig. 6B). Beneath the enhanced reflection zone is a diminished amplitude zone extending through units 2, 3 and 4 (Fig. 7B). This zone characterized by amplitude blanking is the result of energy attenuation and scattering when the waves travel through gas-bearing sediments [*Anderson and Hampton*, 1980; *Løseth et al.*, 2009; *Cartwright and Santamarina*, 2015].

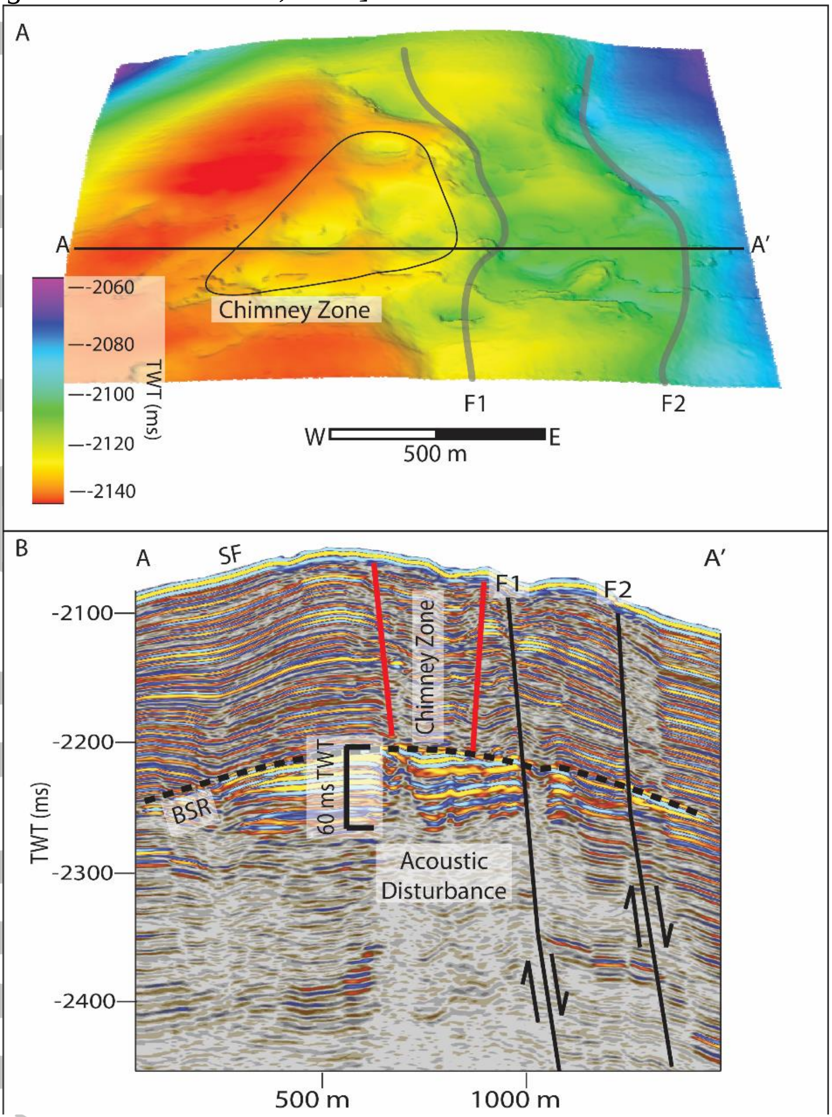

Figure 7. A) Seafloor map (interpreted from the 3D seismic) shows two groups of pockmarks are observed, those above the chimney zone, and those which are underlain by the western most sedimentary fault (F1). B) The chimney zone is immediately adjacent to F1. It is delineated by a change between regular sub-horizontal deposition to hummocky irregular deposition. The free gas zone is 60 ms TWT thickest at the thickest point.

A number of circular-elliptical depression structures (90-350 m diameter) disturb the seafloor at the apex of Svyatogor Ridge (Fig. 7A). We interpret these features as pockmarks related to fluid expulsion at the seafloor. There are two distinct fluid migration pathways leading to these seafloor pockmarks. Firstly, underlying the apex of the ridge (Fig. 7B) is a zone of hummocky, non-conformant reflections, which are notably lower in amplitude than the rest of unit S1 (section 4.1.5). This zone is interpreted to be a zone of focused fluid migration, referred to as a chimney zone here. The second fluid migration pathway are faults that upwardly terminate at the base of pockmarks. Spatially, pockmarks with a chimney beneath occur at the crest of the ridge while pockmarks underlain by a fault occur <100m east of the ridge crest (Fig. 7A, B).

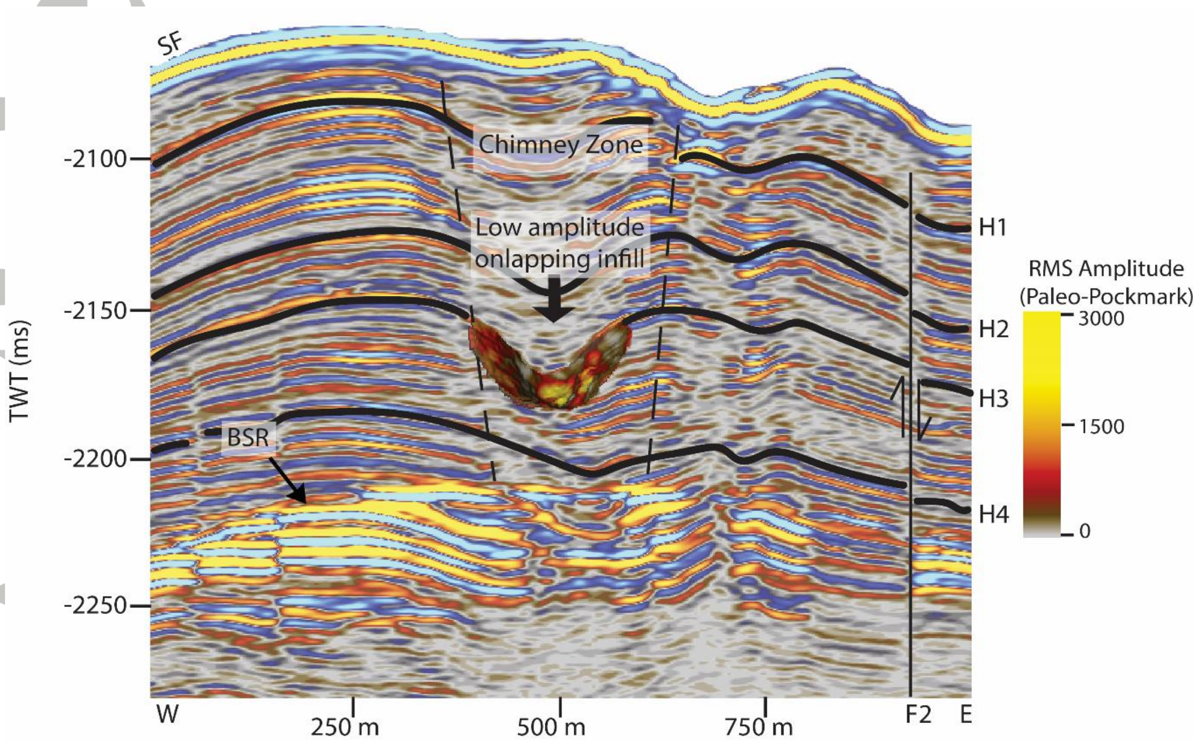

Figure 8. Paleo-Pockmarks occur only within the Chimney zone, bordered by two sedimentary faults which are pervasive through the data, F1 and F2 (F2 annotated here). The paleo-pockmarks occur beneath the crest of the ridge, where the BSR is shallowest. One paleo-pockmark is highlighted in this figure, with the base of the paleo pockmark displayed using RMS amplitude attribute to highlight that the paleo-pockmarks are circular-elliptical in shape and have a higher amplitude base than infill. Additionally, there is a higher amplitude at the base of the depression than the flanks, indicated by the RMS amplitude attribute. The infill is characterized by being onlapping against the base of the pockmark.

Within the chimney cluster, interleaved between sections of low amplitude, hummocky reflections are four horizons that have higher amplitude, are semi-continuous and appear undulating in 2D. In 3D, these undulations are circular depressions, the flanks of which are truncating reflectors beneath (Fig. 8). These depression structures are infilled with a low amplitude material which onlaps against the flanks of the depression (Fig. 8). We interpret these features as buried pockmarks, with the disturbed, low amplitude zones beneath being individual chimneys. Buried pockmarks occur only in the chimney cluster. Although reflections are highly disturbed in the chimney cluster, we are unable to discern any faults leading to buried pockmarks. Buried pockmarks occur specifically on four stratigraphic intervals (Fig. 9), however they are not vertically stacked, nor are they of consistent size, either within the same stratigraphic interval or vertically throughout the data set, therefore they are not velocity artefacts. Due to their locations on four specific stratigraphic intervals, these are interpreted to be recording episodic fluid expulsion at paleo-seafloors.

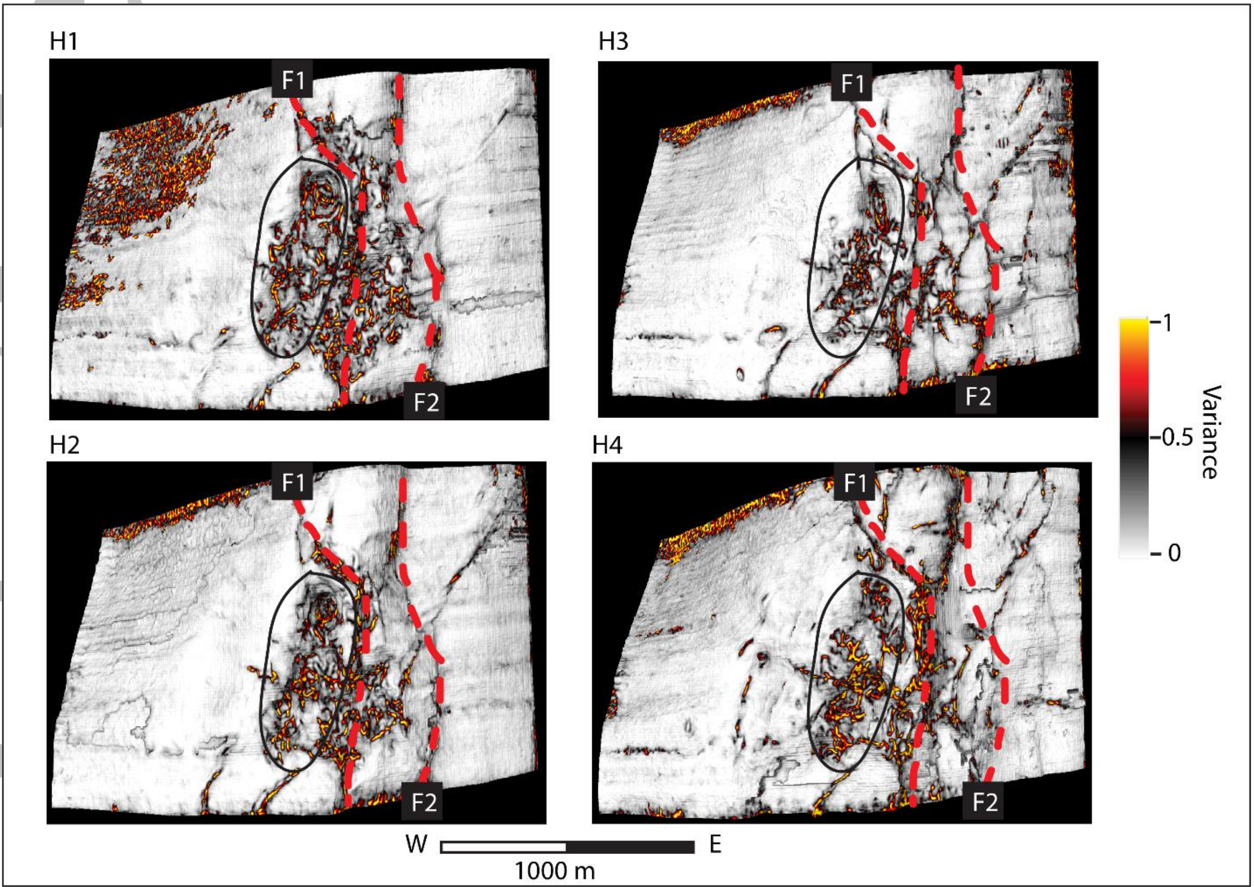

Figure 9. In variance attribute taken across horizons, the chimney zone (black oval) is characterized by being highly variant, but chaotic. The first two pervasive sedimentary faults (F1 and F2, red dotted lines) are clear in all four variance maps, and border the chimney zone to the east. Locations of horizons shown on Figure 2 and 8.

5. Discussion

5.1 Structural and stratigraphic evolution of Svyatogor Ridge

The Svyatogor Ridge has undergone much deformation as indicated by the numerous faults present in the data set. The configuration of reflections within the individual units provides information on the style and possible timing of faulting and deformation on the Svyatogor Ridge. The rotation angles and onlap/termination patterns of Units S4 and S3 indicate that these packages have undergone rotation during phases of movement on BF1 and BF2 (Fig. 3). Units S2 and S1 are highly faulted, especially around the basement highs (Fig. 2; Fig. 5). This is indicative that there was still movement on the basement faults during or after deposition of these units. As the West Spitsbergen Current is the dominant sediment supply current to the West Svalbard Margin and Yermak Plateau [*Eiken and Hinz*, 1993], and that Svyatogor Ridge is isolated from down-slope processes by the Knipovich Ridge axial valley, the West Spitsbergen Current has likely dominated sediment supply to Svyatogor Ridge in the past. Given that the West Spitsbergen Current has migrated upslope, away from the Svyatogor Ridge [*Eiken and Hinz*, 1993; *Johnson et al.*, 2015], the Svyatogor Ridge has likely been sediment-limited since spreading began on the northern Knipovich Ridge [*Johnson et al*., 2015].

Two styles of faulting present in the data can be attributed to regional tectonism – the detachment faults, which are directly linked to spreading on the Knipovich Ridge *[Amundsen et al*., 2011; *Johnson et al*., 2015], and the sedimentary faults, which based on the strike of these faults, conform to the regional tectonic setting [*Crane et al*., 2001]. There are two main possible mechanisms for the formation of such faults in this environment.

Firstly, the creation of accommodation space as the Knipovich Ridge spreads can result in gravity driven extension [*Bodego and Agirrezabala*, 2013; *Peel*, 2014]. Secondly, growth faulting, which occurs when a mechanically weaker material (sediment) overlies a mechanically stronger material (basement), and the stronger material faults [*Hardy and McClay*, 1999; *Tvedt* et al., 2013]. As a fault in the basement moves, the sediment overlying the basement accommodates this by folding (Fig. 10); however, as offset on the basement fault increases, the folds may become breached, forming the sedimentary faults [*Hardy and McClay*, 1999; *Ferrill et al.*, 2012]. The process of sedimentary fault propagation through this mechanism will occur at a rate determined by the movement of the basement fault [*Allmendinger and Shaw*, 2000; *Ferrill et al.*, 2012]. In this study area, the basement faults are accommodating the stress from the ultraslow extension at the plate boundary. Therefore, we would expect episodic movement on the basement faults implying that the sedimentary faults would have also grown over a much longer period than in a faster spreading environment. We suggest that this has also had consequences for fluid migration within this system.

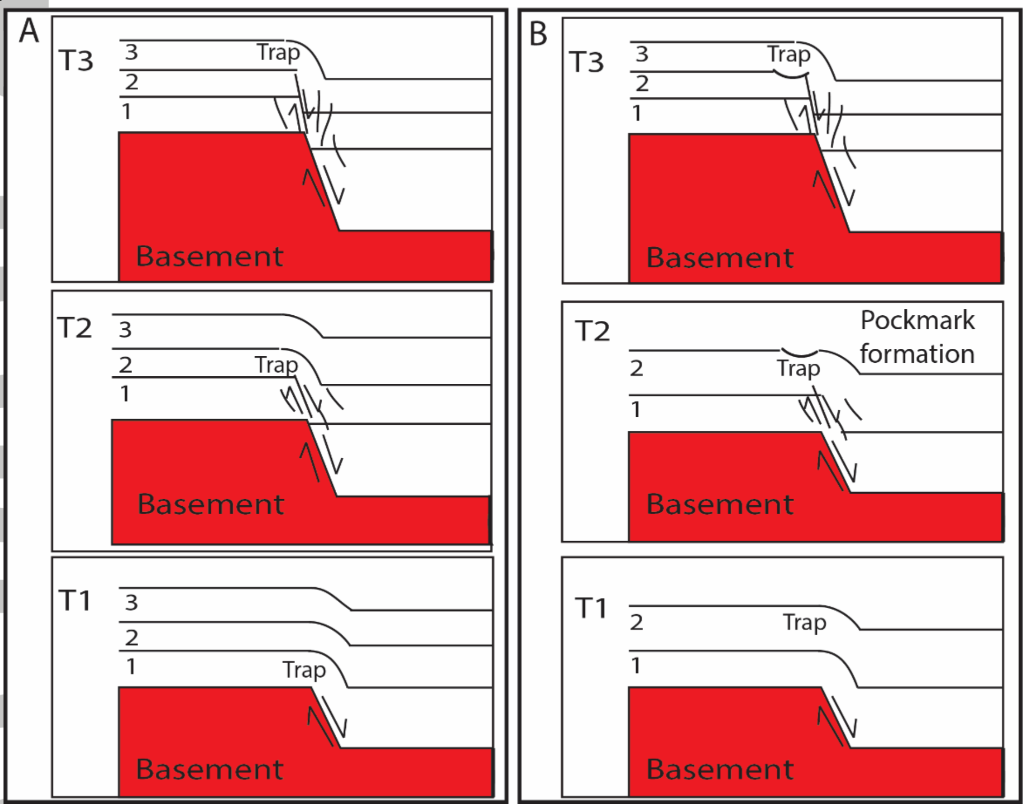

Figure 10. A) Conceptual diagram of fault growth where a mechanically stronger basement, covered by a mechanically weaker strata, faults and causes folds to develop, and with continued movement on the basement fault these folds breach into faults. In this simple scenario, fluid () can utilize the faulted sections to migrate but may become trapped (labelled 'trap') by the unfaulted strata [After Hardy & McClay, 1999]. B) When this process occurs close to the seafloor, fluid seepage across the seafloor results in pockmark formation. With continued syn-deformation sedimentation, pockmarks get buried and the process continues

5.2 Fluid Migration Evolution

The fluid migration system on Svyatogor Ridge is unique in that it occurs in a sedimented mid-ocean ridge system where the basement rock is identified only ~500 ms TWT beneath the seafloor. Additionally, all the fluid flow features, such as the BSR and pockmarks, occur exclusively above the basement faults. Although it is not clear whether the system is still actively leaking fluid today, buried pockmarks occurring along certain stratigraphic horizons would indicate episodic fluid release events. In such large water depths temperature and pressure changes due to sea-level fluctuations during glacial cycles are unlikely to have had a significant effect on the dynamics of a gas hydrate and associated fluid flow system here. However, it remains uncertain whether glacial related isostatic adjustments as modelled on the West Svalbard shelf [*Wallmann et al.*, 2018] may have influenced fault activity and fluid migration on Svyatogor Ridge.

Johnson et al., [2015] propose that the basement faults imaged on Svyatogor Ridge are acting as fluid migration pathways for fluids from the mid ocean ridge system to reach the shallow subsurface. In this scenario, periods of fluid activity (migration and release from the seafloor) are most likely tectonically controlled. As noted previously, faulting events on BF1 and BF2 have occurred as recently as the time Unit S2 was deposited.

On the seafloor, pockmarks occur above both the chimney zone and above faults 50-100 m east of the chimney zone. Buried pockmarks, however, occur only within the chimney zone and not associated with the faults to the east (Fig. 8, 9). This indicates that fluids bypassing the GHSZ have found an additional pathway over time; from releasing at paleo-seafloor(s) at the apex of the ridge indicated by paleo-pockmarks within the chimney zone to utilizing zones of weakness and fault planes, which culminates in pockmarks above faults. We interpret that this is a function of the time taken for sedimentary faults to develop. As shown in Figure 11, below the GHSZ fluid is able to utilize faults as migration pathways to the point of encountering the fold at the upper termination- the fold is acting as a structural seal. If the pore spaces of the sediment become over-pressurized before another section of folded strata breaches into faults, fluid release to the seafloor will be characterized by 'blow-out' type seal bypass systems [*Cartwright et al*., 2007] such as a chimney. As sedimentary faults propagate upwards towards the seafloor they provide an additional seal bypass pathway (Fig. 11). We have also identified small fracture networks, which are important in transporting fluid through the GHSZ. These fracture networks have randomly oriented strikes and therefore are not a consequence of the regional tectonic regime. We suggest that fracture networks are a consequence of hydraulic fracturing, occurring as fluids migrate through the subsurface. Small faults themselves have random strikes, but to the east of the free gas zone, these faults become integrated with sedimentary faults striking in compliance with the regional tectonic regime. Fracture networks appear to be restricted to a zone immediately above and within the free gas zone. We suggest that this is evidence for how fluid bypassed a seal created by hydrate clogging the pore space, a model consistent with *Hornbach et al.*, [2004]. We suggest that faults or planes of weakness were created in the past when the radial faulting formed, that were then re-activated as the free gas zone became critically thick [*Hornbach et al.*, 2004]. In this scenario, planes of weakness across the seal need only be reactivated so that overpressure is released, and fluid can migrate upwards without obstruction. We cannot determine from seismic data alone the type of brittle failure that is occurring to create these fractures (i.e. hydraulic extension fractures, extensional shear fractures or meshes [*Sibson*, 2003]. However, we propose that in this case gas hydrate within the pore space of the sediment and the natural anticlinal structure of the ridge acts as an effective seal or cap rock. The fracture networks we identify here could be seismic evidence for the extent of the seal trapping free gas in this study location [*Hornbach et al.*, 2004; *Sibson*, 2003].

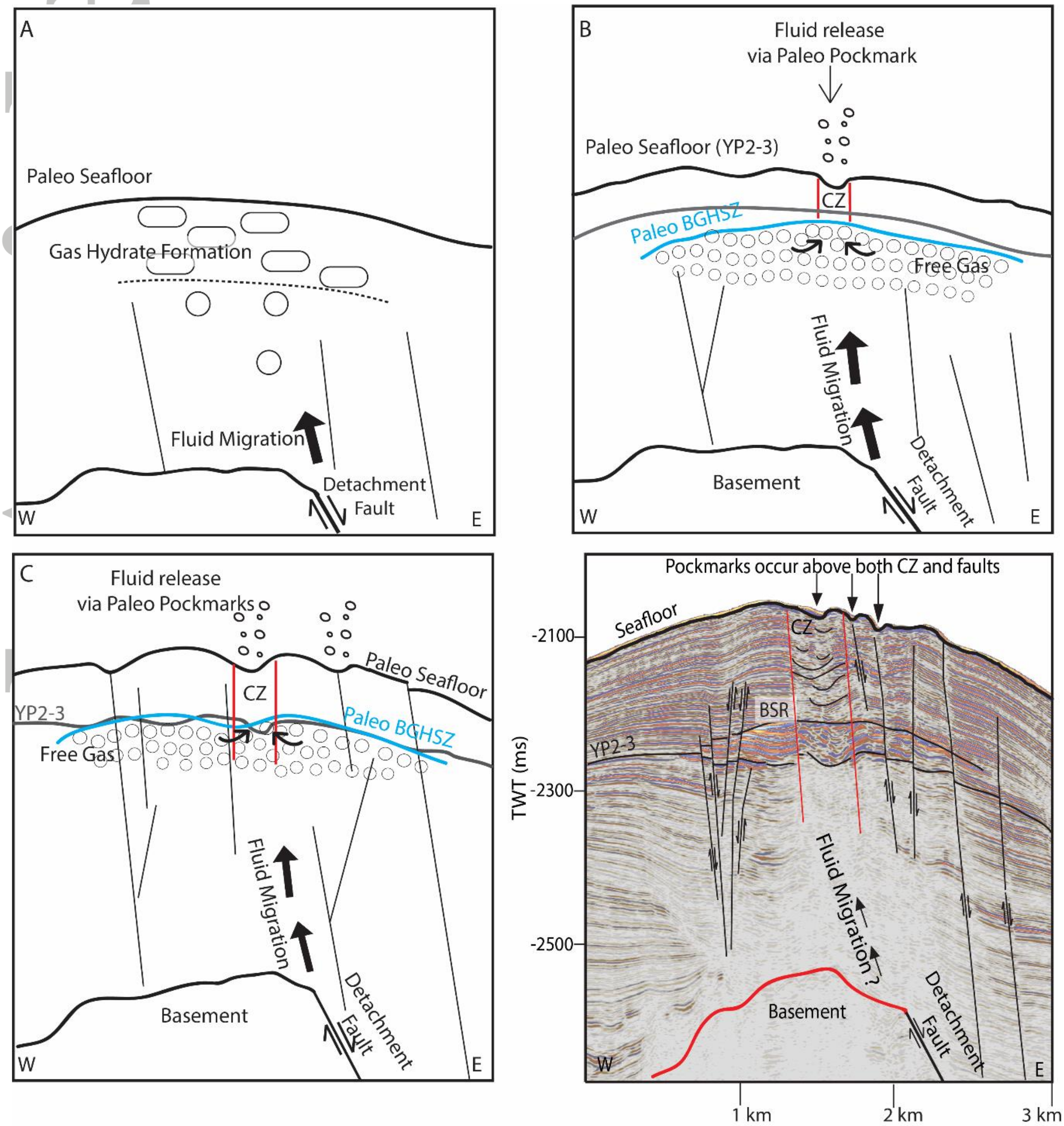

Figure 11. A) During initial activation of the detachment fault, faults in the sedimentary strata had not propagated far through the sedimentary column so they were not fluid migration pathways to the seafloor. However, gas hydrate can develop as can a free gas zone. B) With prolonged fluid migration into the system, fluids in the FGZ can become overpressurized and force the chimney zone to form C) As additional material deposited, the BGHSZ is able to migrate upwards, and sedimentary faults propagated further due to further movement on detachment fault. This means that fluid migrating to the seafloor is able to use faults as fluid migration pathways to the seafloor. D) Today, it is not clear whether the detachment faults are supplying fluid to Svyatogor Ridge; however, the evidence of past fluid migration and release is preserved.

Given that there are buried pockmarks found at ~30 ms TWT (~22 m) above the current BSR, and ~60 ms TWT (~45 m) above YP2-3 (Fig. 9; Fig. 11), gas migration into the free gas zone, gas hydrate formation and migration to the (paleo-)seafloor has been ongoing during most of S1 deposition (Fig. 2; Fig. 11). *Johnson et al*., [2015] proposed that abiotic methane from serpentinization could be the origin of much of the gas here on Svyatogor Ridge. Our research suggests that the detachment faults here have indeed played a major role in driving fluid migration and expulsion in the subsurface and that methane may well have originated within these faults through serpentinization.

5.3 Consequence of Active Margin, Deep Ocean setting on the Gas Hydrate and Fluid Flow system

The location of the Svyatogor Ridge on the flank of the Knipovich Ridge, atop detachment faults (which accommodate rifting), makes it a unique location for a gas hydrate and fluid flow system. In general the types of fluid flow systems normally identified on the flanks of spreading ridges are high temperature basalt hosted hydrothermal vent systems, generated by the increased heat flow provided by magmatic centers along axis (e.g. Guaymas Basin [*Lizarralde et al.*, 2011]) or lower temperature peridotite hosted hydrothermal systems sustained by water-rock serpentinization reactions (e.g. Lost City Hydrothermal Field [*Kelley et al.*, 2005]). In the case of the northern Knipovich Ridge, the ultraslow spreading regime, accommodated by observed detachment faults, implies it is a magma-limited environment, which would be inherently a lower temperature sub-seafloor regime, suitable for the development of the observed, stable gas hydrate system. There is documentation of magmatic instrusive bodies on the eastern flank of the Northern Knipovich Ridge [*Ritzmann et al.*, 2004], which would have presumably formed in conjunction with rifting on either the Molloy Ridge or the Knipovich Ridge, in a mixed mode scenario of detachment fault and magmatic spreading in the past, however other studies have not found evidence for magmatic instrusive bodies associated with the northern section of the Knipovich Ridge [i.e. *Amundsen et al.*, 2011; *Crane et al.*, 2001]. Partial serpentinization of the crust at this location is supported by *Ritzmann et al.*, [2004] who observe crustal velocities of ~7.6 km/s south of the Molloy Transform Fault. Hydrothermal system studies further south along the Knipovich Ridge also suggest that there is some methane flux from serpentinization along with other hydrothermally generated fluids [*Cannat et al.*, 2010]. That a fluid flow system exists on a spreading ridge is not unique in itself due to the abundance of hydrothermal systems present on mid-ocean ridges, but the lack of significant heat flow and therefore, potential for a stable gas hydrate stability zone, is an interesting case for Svyatogor Ridge, as gas hydrate systems are normally identified on passive continental margins, far from spreading ridges. Most of the world's oceans deeper than approximately 300 mbsl have potential for gas hydrate stability [*Kvenvolden*, 1993]. However, distal setting are commonly excluded from global gas hydrate concentration models due to a lack of organic matter deposition [*Klauda and Sandler*, 2005]. A possible exception to this is of course in the case where the Continental-Oceanic crust boundary is proximal to a sediment source and has been for a long period of time, for example in the Gulf of Mexico or in the Fram Strait at Vestnesa Ridge. On the Svyatogor Ridge however, asymmetric, ultra-slow spreading of the Knipovich Ridge means that the Svyatogor Ridge has, since the underlying crust formed, been in proximity to the West Svalbard Margin and West Spitsbergen Current, allowing sedimentation at the northern extent of the Knipovich Ridge flanks [*Eiken and Hinz*, 1993; *Johnson et al.*, 2015] and therefore providing suitable reservoir material for fluids generated by crustal processes.

The occurrence of a gas hydrate system on the flank of an actively spreading margin presents an interesting case because active margin hydrate systems are better studied and more prolific on subduction margins, for example the Hikurangi [*Pecher et al.*, 2005; *Faure et al.*, 2006; *Barnes et al., 2010; Crutchley et al.*, 2010] and Cascadia margins [*Bohrmann et al.*, 1998; *Suess et al.*, 1999; *Riedel and Collett*, 2005; *Pohlman et al.*, 2009]. In a compressional tectonic system we expect to identify particular structural fabrics related to the regional tectonic regime. However, these structural fabrics will differ in an extensional regime, and while we can compare a gas hydrate system in an extensional setting to, for example, a hydrothermal system in terms of fluid flow pathway development, the Svyatogor Ridge setting may be confounded by two additional factors; 1) the location proximal to a strike-slip tectonic setting could be influencing the tectonic setting and 2) it is difficult to determine what effect, if any, an ultra-slow spreading regime has on the coupling between fluid migration pathway development, seepage and tectonic development. In this initial investigation of Svyatogor Ridge, we have not been able to determine with precision if the Molloy Transform Fault has an influence on the structural fabric and therefore fluid flow regime, however we have posited that the ultra-slow nature of the Knipovich Ridge might have played a role in the timing of fluid release on the Svyatogor Ridge. In contrast to the tectonic setting on Vestnesa Ridge, which is a contourite drift developed close to the mid-ocean ridge but on a passive margin slope, [*Vanneste et al.*, 2005; *Bünz et al.*, 2012; *Plaza-Faverola et al.*, 2015], Svyatogor Ridge appears to be unique in that sedimentary sequences, the gas hydrate system and the tectonic setting are developing in unison, particularly reliant on the tectonic setting to form as they have.

5.4 A note on gas origin

Shallow penetrating gravity cores collected on Svyatogor Ridge during CAGE expeditions have yet to recover enough gas for isotopic analysis. As there are no other gas samples from the Svyatogor Ridge available to the authors, we note from the 3D seismic survey that 1) faults appear to be controlling where and how the gas hydrate system has formed and that 2) the detachment faults are the major linking factor to all the processes occurring on the Svyatogor Ridge (sedimentary fault development, fluid flow pathway development and ridge topography). With regards to thermogenic gas production, we posit that there has been no thermogenic methane produced within the sediments on the Svyatogor Ridge itself as the criterion for generation (normally depths greater than 1000 m below seafloor [*Floodgate and Judd*, 1992]) is not met. We cannot rule out that there is gas migrating from another source, for example across the Molloy Transform Fault [*Smith et al.*, 2014] or from Hovgård Ridge [*Knies et al.*, 2018], which has also been shown to have some source rock present [*Knies and Mann*, 2002]. We do note, however that methane is generated in serpentinization reactions [*Etiope and Sherwood Lollar*, 2013] and that *Cannat et al.*, [2010] and *Proskurowski et al.* [2008] show methane production from serpentinization is produced in slow to ultraslow spreading ridge settings. Additionally, *Ritzmann et al.*, [2004] shows that there is potential for partially serpentinized crust beneath Svyatogor Ridge. Given that the detachment faults are key for the dynamics of this gas hydrate system, we would not rule out some contribution from serpentinization produced methane. Active methane production via serpentinization beneath the study location today may be unlikely, however, as the detachment faults now are approaching the end, or are at the end, of their typical duration of activity (1- 3 My), sedimentation above the oceanic crust restricts seawater peridotite interaction, and continued spreading and offset along the MTF has nearly removed Svyatogor Ridge sediments from the serpentinization driven abiotic methane window suggested by *Johnson et al.* [2015]. Thus, any abiotic methane present within the gas hydrate system here today, must have formed while the detachment faults were active, Svyatogor Ridge was within the abiotic methane production window, and there was sufficient sedimentation to trap the gases. In this scenario, methane generated through serpentinization may be preserved in early developing gas hydrate systems, like Svyatogor Ridge, but with continued development, the influence of crustal sources of fluids and gases may be minimized. Given the history here, we associate the modern fluid flow system in this study area as a sediment hosted gas hydrate system that developed over the last ~3 million years.

6. Conclusion

The Svyatogor Ridge has developed on the North Western flank of the Knipovich Ridge in an active margin setting. The majority of sedimentation on the Svyatogor Ridge has been interpreted to have deposited during the YP-2 and YP-3 sedimentation regimes, while the Svyatogor Ridge was still close to the spreading center and an active sediment supply. The tectonic environment here has greatly controlled all aspects of development in this setting, from sedimentary evolution to fluid flow system evolution. Sedimentary faults in the 3D seismic data are directly linked to the movement on spreading related detachment faults and the seismic stratigraphy is largely based on changes of reflection patterns linked to phases of faulting on detachment faults. The gas hydrate system on the Svyatogor Ridge is located on the flank of the Knipovich ridge axis – in a natural trapping type structure along the crest of the Svyatogor Ridge. Seepage from this system to the water column has been episodic in nature, occurring at four distinct intervals throughout the last ~2.7 Ma. Tectonism appears to be the major driver of fluid flow on Svyatogor Ridge, with movement on detachment faults shown to be impacting both the fluid flow into the gas hydrate and free gas zones, and release of at the (paleo-)seafloor.

Subaqueous gas hydrate reservoirs are generally found in settings with thick sedimentary sequences; on passive continental margins, contourite deposits or active (subducting) continental margins. Svyatogor Ridge, however, is a sediment limited, deep water drift located on an actively spreading plate boundary. Worldwide, this setting type is generally dominated by hydrothermal fluid systems sustained by seawater circulation in basalt or peridotite dominated crust. Due to the amagmatic nature of the northern Knipovich Ridge, there is no significant heat source for a magmatically heated hydrothermal system. Hydrothermal systems further south along the Knipovich Ridge have been shown to have methane as a fluid constituent, due to serpentinization reactions, and on the Svyatogor Ridge studies have shown that the acoustic velocity of basement material give a likelihood of serpentinitized mantle beneath the Svyatogor Ridge. Therefore, we conclude that the Svyatogor Ridge has developed a gas hydrate system in this ultra-slow, amagmatic spreading setting largely due to the presence of detachment faults, which accommodate seafloor spreading and deformation of the overlying sediment column, enable seawater rock reactions to drive serpentinization, and serve as pathways for crustal fluid and gas migration to the overlying sediments.

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