Dear Editor,

We are thankful for this round of constructive and highly relevant reviews that helped us to improve the manuscript significantly. We hereby resubmit the manuscript for your consideration. Please find below the answers to each raised point by the referees and how the changes were implemented. The main changes in the manuscript can be summarized as follow:

- We have performed additional sensitivity tests for the geometry of the ridges in the model. The result is included in the supplementary, this include an additional figure. The main outcome of the additional tests is also presented in the main text.
- We have changed the paper structure to show a clear separation between results and discussion.
- The section where the model results is presented (5.1) includes now a paragraph that develops on the assumption of coupling between deep crustal and near surface deformation.
- We explain in the introduction the use of the terminology active vs. inactive pockmarks and refer to the presence or not of acoustic flares when possible.
- The discussion has been significantly extended: we developed further the analysis of modelled tectonic stress in the context of the total state of stress in the region; and we present a more substantial description of how we envision the evolution of present day and past seepage activity along the VR (including the mechanical relation between gas chimneys and faults). We close the discussion by placing our study in a context of global implications.
- All the specific comments have been addressed.
- Several figures were edited to support implemented changes. A new inset was included in former figure 3. A new figure is included in the result section to illustrate the origin of the tensile zone that extends towards the eastern Vestnesa Ridge. The figure numbers was updated accordingly. A figure for illustrating the model geometry was re-inserted in the appendix (we believe we lost that figure in the previous submission).
- Abstract, Introduction and conclusion sections were edited accordingly.

Sincerely,

Andreia Plaza-Faverola and Marie Keiding

Referee #1

In this contribution the authors are trying to bring together tectonic modeling (stress/strain) and observations on fluid seepage at Vestensa, off Svalbard. Their model suggests a region of tensile stresses that mostly coincides with a region of actively degassing pockmarks on the Vestnesa Ridge, juxtaposed to zones of strike-slip stress and inactive pockmarks.

I am reviewing this contribution after a first initial set of reviews by different reviewers was completed. I am judging my response on (a) the scientific material presented in the revised manuscript and (b) the earlier comments made by one reviewer on the applicability of the model used.

I find the approach presented in this manuscript intriguing, results rather interesting, but remain skeptical on the conclusions drawn. The paper needs some modifications, especially more discussions and at least one other set of tests if the zone of tensile stress is indeed robust in its location by modifying plate boundary geometries (which can be drawn differently than what authors show).

A few general remarks that I think would help in getting this paper published:

(a) Pockmarks on the southern drift. The authors show faults mapped south of the MTF, where seismic and bathymetric data show abundant chains of pockmarks. Those pockmarks are inactive in the terminology of the authors (i.e. inactive= no degassing). I suggest the authors augment their discussion on how to explain those southern pockmark chains as well. The orientation of principle stresses is strikingly different south and north of the MTF, relative to mapped fault-orientations (parallel, perpendicular) and earthquake focal mechanisms. Why is this not important as well?

Answer: thanks for pointing out this. The original focus of the paper was entirely on the Vestnesa Ridge seepage system (we wanted to test the hypothesis put forward in Plaza-Faverola et al., 2015). Also Vestnesa Ridge is much better studied than any other sedimentary ridge in the area. Having said that, we reckon that the correlation of these areas with the modeled stress fields makes sense.

Changes: We have included the location of these pockmarks in the discussion. Projection of pockmarks south of the MTF and right north of it where acoustic flares have not been documented as for the eastern Vestnesa ridge (i.e., Waghorn et al., 2018; Johnson et al., 2015) and discuss the spatial correlation of these features with the predicted stress field. We do emphasize that the features are less well investigated and a poorer control exist on the activity of this system. Ongoing studies by colleagues will provide more information about the structural setting in these regions.

(b) Why only use degassing as sign of "activity"? Very recent heat-flow surveying (>100 measurements) taken across the pockmarks show that pockmarks may be still "active" even without gas discharge, as they can show a strong and localized heat-flow anomaly to the pockmark depressions themselves (and that occurs north and south of the MTF and the zone of tensile stress regime). The authors are aware of this study and data as well as preliminary results from the heat-flow study are available through the cruise report of expedition MSM57 and can be downloaded from the University of Bremen website.

Answer: We are aware of this recent heat flow study, yes. This is of course a relevant point in the sense that the terminology used is crucial. Despite anomalous heatflow measured nearby fault planes and pockmarks in the region (also Crane et al., in the late 90s show this), there is sufficient bubbling of gas only at discrete sites. The University of Tromsø goes to the region sometime 2 times a year, and vertical acoustical anomalies in the multibeam and echo-sounder profiles (so call acoustic gas flares) are observed systematically on the few pockmarks on the astern Vestnesa Ridge segment. The pockmarks at the Svyatogor ridge and north of the MTF have been surveyed also several years (despite having received much less attention so far). Here, acoustic flares have also not been observed. The terminology we use then uses "active" for sites where seepage is enough to cause a visible anomaly in water acoustic data. The inactive adjective does not rule out advection of fluids toward the near-surface nor degassing to a certain but minor degree compared to the "active" sites.

Changes: we have clarified this through the text and figures. We also use the direct formulation of "documented acoustic flares" when possible.

(c) Degassing could be completely unrelated to the deep-rooted stresses – microbial activity rates are changing; there is coupling between ocean phenomena and the sediment with free gas phases and gas hydrates (e.g. seen in tidal modulated gas fluxes or decadal oscillations). I think, using degassing alone is "too short" an argument to investigate the relationship between stress and the fluid flow regimes.

Answer and changes: We have provide additional background on the fluid flow and seepage system along the ridge to make clear why current changes in sea-level and temperature would not be sufficient to explain solely the dynamics in this deep marine system. Yes, microbial methane generation is always a contribution to the seepage system. Along the Vestensa Ridge thermogenic gas (methane, ethaen, propane, butane, etc) have been sampled in head space samples from gravity cores as well as from water column and gas hydrate samples (e.g., Smith et al., 2014). The fluid flow systems is well documented to be associated with faults that extend close to the seafloor; gas chimneys are indeed following the fault planes. Petroleum modeling suggest that a thermogenic gas source may have been charging the system since 2 Ma ago (Knies et al., 2018). In this paper we rely on all these studies to assume that the advection of thermogenic/warmer fluids into the near-surface is a key player in gas hydrates and seepage dynamic in the region. Whether there is in addition seepage controlled by local microbial methane generation and to a small degree gas hydrate dissociation, is not so critical for this study. Regardless the source of the gas the behavior of faults can be modulating gas release.

(d) Sediment drift bodies such as the Vestnesa Ridge are heavily dynamic and evolve quickly. Topography is steep across the ridge and vertical stresses thus change fast. While the authors do say and have indicated in the revised version of their manuscript that they do not reject other causes (and associated stresses) of the difference in vent activity, but I find the outcome or limitation of discussion only on the zone of tensile stress rather weak overall, given this very dynamic and regionally fast-changing zone of study.

Answer and changes: we have now significantly extended the discussion to present clearer why the proposed tectonic explanation is so relevant for the study area and we provide summary of observations (large number of cross disciplinary studies) that points toward a regional tectonic mechanism.

(e) The geometry of the plate boundaries, especially the MTF, seems to be fixed in all the discussion, but I could easily draw the MTF at a different angle (e.g. rotated by 5 degrees) by just looking at the bathymetry. Would this not affect the zone of tensile stress regime? The authors did look at parameter variations and assess effects in the actual zones of stresses, but they never changed the geometry. Maybe test quickly, if this is important or not?

Answer and changes: Thanks for this suggestion. We carried out additional tests of the geometry by rotating the MTF as well as the MR and KR. The geometry does influence the shape or position of the tensile zone. However, the zone persists approximately in place. We have included results of diverse tests on geometry in the supplementary material. We also clarify, by including a new figure, how the tensile zone results due to the interaction between the spreading force from the Molloy and Knipovich ridges.

(f) Coupling between crustal deformation and sediment load seems to have been assumed as 100%. Is that acceptable? Could those regimes be decoupled, i.e. the ridge-push is doing its own thing and sediment drape from contourites deposited during glacial/deglacial phases react to other forces?

Answer and changes: We agree that this is a crucial and exciting question related to the topic. Is there a full coupling between crustal deformation and near-surface deformation of quaternary sediments? We discuss our results assuming a certain degree of coupling, as pointed out by the referee. We argue the near-surface faults reflect coupling (we interpret them as tectonic faults). We added a paragraph in section 5.1 with arguments supporting the assumption of a certain degree of coupling. We also touch upon the implications of assuming the coupling for the current debate about activity across passive margins.

Overall, the manuscript has its contribution that is interesting and intriguing, fully worth of getting published at some point; but as of yet, it has too little result and discussion to be fully acceptable. After the initial revision, the authors modified and restated many points in their discussion and conclusion but need to go even further. I suggest a more diverse discussion taking some of my points above into account and possibly assess the "error" in the stress-regime mapping a step further.

Then, what are the larger implications of such process? Could you maybe name other regions where similar processes occur? What other studies would help assess this phenomenon further? Borehole stress measurements? Are there maybe wire-line image log (from resistivity) data from the old ODP boreholes to look at the borehole stress by mapping breakouts or fractures? Could you use the shear-wave splitting technique to look at the stress components by doing a polarization analysis of the first arrivals (e.g. Tonegawa et al., 2016)? Are those changing across Vestnesa and to the Svyatogor Ridge south of the MTF?

Answer: great suggestions here, thanks. We keep this in mind for further work on the topic. We have indeed on-going OBS experiments in the region. It would be interesting to further discuss the approach in the Tonegawa et al paper.

Changes: we added a paragraph on the discussion to place the outcome of the study into a global context, emphasizing other known seepage systems where a stress control can be applicable.

Tonegawa, T., Obana, K., Yamamoto, Y., Kodaira, S., Wang, K., Riedel, M., Kao, H., Spence, G.D., 2016. Fracture alignments in marine sediments off Vancouver Island from Ps splitting analysis, Bulletin of the Seismological Society of America, 10.1785/0120160090.

Referee #2

Dear Authors,

Understanding flow localisation patterns and location is a challenging entreprise. The submarine features leading to the expulsion of methane and other gases are widely reported, but currently the mechanisms remain still very unclear and discussed. In this context, this study tries to address a challenging point, constraining the flow localisation in Western Svalbard based on a analytical mechanical model of the complex lithospheric regional layout.

Although the model used seems to be correctly applied, the major simplifications and hypotheses the authors make in order to use it significantly limit the conclusion that can be drawn. This point was also discussed and criticised in the past round of revisions.

I will propose some broad suggestions that may enhance clarity and readability of the article, then address some specific amendments.

> Since the aim of this study is a modelling exercise, it would be nice to have a more rigorous model description. The model configuration is not very clear. It would be very helpful for the reader to see on the figure the initial and boundary conditions. On Fig. 4 as well, it would be very helpful to have these information present, as well as the highlight of the Vastness ridge.

Answer: We agree. In a previous version of the manuscript we had included a figure showing the model configuration, but that somehow slipped out.

Changes: We added in the appendix a figure showing model configuration, and added spreading vectors to Figure 1. The crest of the Vestnesa Ridge is shown by the seismic line, as described in the caption.

It would be very helpful for the reader to have a more structured result dissection and discussion. Maybe the authors could expose the full set of hypotheses and more quantitative facts in a first step, and then discuss and present their interpretation regarding the various aspects.

Changes: we have changed the structure to have separated result and discussion sections. Please see above for details about the changes in the discussion. The discussion should reflect better what the state-of-knowledge is about seepage in the region and where does the importance of the tectonic hypothesis we present reside.

Also, I would ask the authors to clearly distinguish between tectonic stress configuration optimal for enhanced fluid motion (extension regime) and actual mechanisms that may lead to flow focussing within chimneys and pockmarks. Fault planes will fail to produce pipe like features from a mechanical point of view.

Changes: Thank you for rising this point. The relation between the chimneys and the faults/fractures is intriguing. Although the mechanical evolution of the gas chimneys escape the scope of the present study we extended the discussion about the spatial relation between faults and chimneys and touch upon the mechanical requirements to form a chimney. We offer a solution for a close spatial link between these two features.

> The more specific comments are following:

L. 60-63: elastic stresses resulting from strain are instantaneous, thus I would be very careful using them to explain long term evolution and variations. They may be related to viscous creep rather than to purely elastic medium.

A: Thanks for pointing this out. In particular within the upper 50 m of sediments, the most recent interval through the gas chimneys towards the astern part of the ridge, have undulation features that remind features described in creep zones at other margins. However, there is a clear change with depth (from ca. 150 m) where the deformation is not expressed as chimneys but appear as near-vertical fault planes (documented in Plaza-Faverola et al). This paragraph was modified.

L. 73: please precise which fluids in the fluid dynamics you refer to.

A: done

L. 105-110: it is difficult to get the importance of the regional geology in the way it is brought to the reader. It would be very interesting to read about how these different geological formation impact the model, and the results.

A: The first section in the discussion links to the regional geological setting. The last 2 paragraphs were inserted in the discussion about the potential effect of tectonic stresses on near-surface faults.

L. 125-126: The last sentence is difficult to get, please rephrase.

A: done

L. 130: the GHSZ does not seem to be reported in Fig. 2, but rather in Fig. 3 ?

A: corrected

L. 134-138: What is the importance of those facts with regards to the proposed work ?

A: We have added a new reference here and elaborated on the idea for clarification. Thanks for pointing this out! The importance is that although the beginning of seepage is suspected to coincide with the onset of glaciations, the periodicity of the events does not correlate directly with either glacial or interglacials, but it seems to be more randomly controlled.

Section 4: Modelling approach. This section is about the aim of the paper, modelling. Thus, it would greatly benefit from enhanced details and a more rigorous model description, with regards to initial and boundary conditions especially.

A: A missing figure in the previous submission was re-inserted (appendix) and slightly edited. The appendix and the table in the supplementary material shall provide the necessary details about the modeling parameters.

L. 173: agreeing on the usage of a very simplified model, orientation of the stress field may be valid to interpret from the model, but I would be very careful regarding the magnitude of stresses, even if relative.

A: We reformulated for clarification. What we consider is rather the orientation of the principal stresses to determine the stress regime.

L. 210-213: Long and unclear sentence

A: Corrected.

L. 214: please precise style of principal stress

A: done

L. 218: please consider to rephrase avoiding the usage of “thing”

A: corrected. Apologies for that ☺

L. 219: please consider rephrasing as following “… provides a correct first order prediction of the stress field ORIENTATION in the upper crust…”

A: done: orientation and type

L. 221: consider the preferred usage of section number rather than below / above …

A: corrected

L. 236: consider rephrasing “thicker sediment thickness” to make it more clear

A: corrected

L. 240: what is seismic definition ?

A: changed to: delineation of faults in the seismic

L. 268: Gravitationnel stress would not only induce the suggested stress, but a complex pattern.

A: Right, the discussion was re-structured and this part was reformulated.

L. 292 what unit is mm/a ?

A: millimeters per year. For some reason the glacial isostatic modeling folk and also in chronology it is often used “a”. Must be from the latin annos. We changed to year

L. 234-235: Please make it clear to distinguish between tectonic stress that may enhance fluid circulation in specific location from the actually mechanism that will result in fluid localisation within pipes or chimneys. Faults and fractures will not be able to produce tubular like features, based on mechanics.

A: Thank you for pointing out this. Thinking about the distinction between chimneys and faults in terms of mechanics of fluids lead to further discuss about the timing of faulting vs. chimney formation. We have elaborated this idea further and introduced a couple of additional references.

L. 335: consider replacing above by the appropriate section number.

A: changed accordingly through the entire manuscript.

Fig. 2: missing BSR in legend ?

A: corrected

Fig. 4: add boundary conditions, highlight the Vestnesa Ridge

A: done

Based on the aforementioned arguments, I would suggest to publish this article but asking minor revision.

CORRELATION BETWEEN TECTONIC STRESS REGIMES AND METHANE SEEPAGE ON THE WEST-SVALBARD MARGIN

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Abstract. Methane seepage occurs across the west-Svalbard margin at water depths ranging from < 300 m, landward from the shelf break, to > 1000 m in regions just a few kilometres away from the mid-ocean ridges in the Fram Strait. The Vestnesa sedimentary ridge, located on oceanic crust at 1000-1700 m water depth, hosts a perennial gas hydrate and associated free gas system. The restricted occurrence of acoustic flares to the eastern segment of the sedimentary ridge, despite the presence of pockmarks along the entire ridge, indicates a spatial variation in seepage activity. This variation coincides with a change in the faulting pattern as well as in the characteristics of fluid flow features. Due to the position of the Vestnesa ridge with respect to the Molloy and Knipovich mid-ocean ridges, it has been suggested that seepage along the ridge has a tectonic control. We modelled the tectonic stress regime due to oblique spreading along the Molloy and Knipovich ridges to investigate whether spatial variations in the tectonic regime along the Vestnesa Ridge are plausible. The model predicts a zone of tensile stress that extends northward from the Knipovich Ridge and encompasses the zone of acoustic flares on the eastern Vestnesa Ridge. In this zone the orientation of the maximum principal stress is parallel to pre-existing faults. The model predicts a strike-slip stress regime in regions with pockmarks where acoustic flares have not been documented. If a certain degree of coupling is assumed between deep crustal and near-surface deformation, it is possible that ridge push forces have influenced seepage activity in the region by interacting with the pore-pressure regime at the base of the gas hydrate stability zone. More abundant seepage on the eastern Vestnesa Ridge at present may be facilitated by dilation of faults and fracture favourably oriented with respect to the stress field. A modified state of stress in the past, for instance due to more significant glacial stress, may have explained a more vigorous seepage activity along the entire Vestnesa Ridge. The contribution of other mechanisms to the state of stress (i.e., sedimentary loading and lithospheric flexure) remain to be investigated. Our study provides a first order assessment of how tectonic stresses may be influencing the kinematics of near-surface faults and associated seepage activity offshore the west-Svalbard margin.

1. Introduction

~~Seafloor seepage is a wide spread phenomenon which consists in the release of natural gases into the oceans.~~ Hundreds of gigatonnes of carbon are stored as gas hydrates and shallow gas reservoirs in continental margins (e.g., Hunter et al., 2013). The release of these carbons over geological time, a phenomenon known as methane seepage, is an important ~~component of~~contribution to the global carbon cycle. Understanding and quantifying seepage has important implications for ocean acidification, deep-sea ecology and global climate. Periods of massive methane release from gas hydrate systems (e.g., Dickens, 2011) or from large volcanic basins like that in the mid-Norwegian Margin (e.g., Svensen et al., 2004) have been linked to global warming events such as the Palaeocene-Eocene thermal maximum. ~~We know~~It is well known that ~~methane~~ seepage at continental margins has been occurring episodically for millions of years (e.g., Judd and Hovland, 2009), but ~~we have~~there is a poor understanding of what forces it.

Present day seepage is identified as acoustic flares in the water column commonly originating at seafloor depressions (e.g., Chand et al., 2012;Salomatin and Yusupov, 2011;Skarke et al., 2014;Smith et al., 2014;Westbrook et al., 2009), while authigenic carbonate mounds are used as indicators of longer-term seepage activity (e.g., Judd and Hovland, 2009). Seepage at the theoretical upstream termination of the gas hydrate stability zone (GHSZ) (i.e., coinciding with the shelf edge) at~~on~~ different continental margins, has been explained by temperature driven gas-hydrate dissociation (e.g., Skarke et al., 2014;Westbrook et al., 2009). On formerly glaciated regions off Svalbard and the Barents Sea, active seepage has been explained by gas hydrate dissociation either due- to pressure changes resulting from the retreat of the ice-sheet (e.g., Portnov et al., 2016;Andreassen et al., 2017) or to post-glacial uplift (Wallmann et al., 2018).

Across the west-Svalbard margin, active seepage extends beyond the shelf break and the region formerly covered by ice. As a matter of fact, active seepage sites have been identified from inside Isfjorden (Roy et al., 2014) to water depths of ~1200 m (Smith et al., 2014) where the Vestnesa Ridge hosts a perennially stable gas hydrate system > 50 km seaward from the ice-sheet grounding line. The Vestnesa Ridge is a NW-SE oriented contourite deposit located between the northward termination of the Knipovich Ridge and the eastern flank of the Molloy spreading ridge in the Fram Strait (Fig. 1). Seafloor pockmarks along the Vestnesa Ridge, first documented by Vogt et al., (1994), exist along the entire ridge. However, acoustic flares have been observed to originate exclusively at large pockmarks located on the eastern part of the sedimentary ridge (Fig. 2, 3). A clear increase in

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seepage activity towards the easternmost part of the ridge is thus evident from multiple year's water-column acoustic surveys (Petersen et al., 2010;Bünz et al., 2012;Plaza-Faverola et al., 2017;Smith et al., 2014). In this paper, we use the terminology "active" and "inactive" to differentiate between sites with and without documented acoustic flares. Even though methane advection and methanogenesis are likely to be active processes along the entire Vestnesa Ridge, ~~T~~the presence of inactive pockmarks~~ –~~ adjacent to a zone of active seepage~~ along the Vestnesa Ridge~~, raises the question what ~~stopped previously active seepage sites~~controls temporal and spatial variations in seepage activity along the ridge?

Plaza-Faverola et al., (2015) documented seismic differences in the orientation and type of faulting along the ridge and showed a link between the distribution of gas chimneys and faults. They hypothesised that seepage activity may be explained by spatial variation in tectonic stress field across the margin (Plaza-Faverola et al., 2015)~~.~~. However, the state of stress across Arctic passive margins has not been investigated. The total state of stress at formerly glaciated continental margins can be the result of diverse factors including bathymetry and subsurface density contrasts, subsidence due to glacial or sedimentary loading and lithospheric cooling,~~ –~~ in addition to ~~-~~ridge-push forces (Fejerskov and Lindholm, 2000;Lindholm et al., 2000;Olesen et al., 2013;Stein et al., 1989;Grunnaleite et al., 2009).

The interaction between the above mentioned factors renders modelling of the total state of stress a complex problem that has not yet been tackled. In this study, we focus exclusively on the potential contribution of oblique spreading at the Molloy and the Knipovich ridges to the total state of stress along the Vestnesa Ridge and do a qualitative analysis of how ~~tectonic stress~~stress generated by mid-ocean ridge spreading may influence near-surface faulting~~s~~ and associated seepage activity. The study of the effect of ridge push forces on near-surface deformation across the west-Svalbard margin contributes to the current debate about neo-tectonism and stress field variations across passive margins (Olesen et al., 2013;Salomon et al., 2015) and has implications for understanding the mechanisms that control seepage at continental margins globally. Splay-faults are found to drive fluid migration at subduction margins and to sustain shallow gas accumulations and seepage~~ –~~ (e.g., Plaza-Faverola et al., 2016;Minshull and White, 1989;Moore and Vrolijk, 1992;Crutchley et al., 2013), and the relationship between fault kinematics and fluid migration has been documented specially at accretionary margins where earthquake-induced seafloor seepage has been observed (e.g., Geersen et al., 2016). So far, the information about the present day stress regime in the Fram Strait has been limited to large scale lithospheric density models

(Schiffer et al., 2018) and a limited number of poorly constrained stress vectors from earthquake focal mechanisms (Heidbach et al., 2016). Our study provides a first order assessment of how stresses from slow spreading mid-ocean ridges may be influencing the kinematics of near-surface faults and associated seepage activity in an Arctic passive margin.

~~1.~~2. Structural and strat~~r~~igraphic setting

In the Fram Strait, sedimentary basins are within tens of kilometres from ultra-slow spreading Arctic mid-ocean ridges (Fig. 1). The opening of the Fram Strait was initiated 33 Ma ago and evolved as a result of slow spreading of the Molloy and Knipovich Ridges (Engen et al., 2008). An important transpressional event deformed the sedimentary sequences off western Svalbard, resulting in folds and thrustbelts, during the Paleocene-Eocene dextral movement of Spitsbergen with respect to Greenland. Transpression stopped in the early Oligocene when the tectonic regime became dominated by extension (Myhre and Eldholm, 1988). The circulation of deep water masses through the Fram Strait started during the Miocene, ca. 17-10 Ma ago (Jakobsson et al., 2007;Ehlers and Jokat, 2009), and established~~ing~~ the environmental conditions for the evolution of bottom current-driven sedimentary drifts (Eiken and Hinz, 1993;Johnson et al., 2015). It has been suggested that the opening of the northern Norwegian–Greenland Sea was initiated by the northward propagation of the Knipovich ridge into the ancient Spitsbergen Shear Zone (Crane et al., 1991) .

The continental crust beneath the western coast of Svalbard thins towards the Hornsund Fault zone indicating extension following the opening of the Greenland Sea (Faleide et al., 1991). Late Miocene and Pliocene sedimentation, driven by bottom currents, resulted in the formation of the ca. 100 km long Vestnesa Ridge between the shelf break off west-Svalbard and oceanic crust highs at the eastern flank of the Molloy mid-ocean ridge (Eiken and Hinz, 1993;Vogt et al., 1994). The sedimentary ridge is oriented parallel to the Molloy Transform Fault and its crest experiences a change in morphology from ~~being~~ narrow on the eastern segment to ~~be more like a plain~~~~expanded~~broader on the western Vestnesa Ridge segment (Fig. 2). The exact location of the continental-ocean transition remains ~~somewhat~~ uncertain (Eldholm et al., 1987) but it is inferred to be nearby the transition from the eastern to the western segments (Engen et al., 2008).

The total sedimentary thickness along the Vestnesa Ridge remains unconstrained. Based on one available regional profile it can be inferred that the ridge is > 5 km thick in places (Eiken and Hinz, 1993). It has been divided into three main stratigraphic units (Eiken and Hinz, 1993;Hustoft, 2009): the deepest sequence, YP1,

consists of synrift and post-rift sediments deposited directly on oceanic crust; YP2 consists of contourites; and YP3, corresponding to the onset of Pleistocene glaciations (ca. 2.7 Ma ago) (Mattingsdal et al., 2014), is a mix of glaciomarine contourites and turbidites. The effect of ice-sheet dynamics on the west-Svalbard margin (Patton et al., 2016;Knies et al., 2009) has influenced the stratigraphy, and most likely the morphology, of the Vestnesa Ridge and adjacent sedimentary basins. In this Arctic region, glaciations are believed to have started even earlier than 5 Ma ago. The local intensification of glaciations is inferred to have started ca. 2.7 Ma ago (e.g., Faleide et al., 1996;Mattingsdal et al., 2014). Strong climatic fluctuations characterized by intercalating colder, intense glaciations with warmer and longer interglacials, dominated the last ca. 1 Ma. (e.g., Jansen et al., 1990;Jansen and Sjøholm, 1991).

~~A set of N-S to NNE-SSE trending faults cut the recent strata at a narrow zone between the Vestnesa Ridge and the northern termination of the Knipovich Ridge (Fig 1). Due to their structural connection with the Knipovich Ridge they have been suggested to indicate ongoing northward propagation of the rift system~~ (Crane et al., 2001;Vanneste et al., 2005)~~. High resolution 3D seismic data collected on the eastern Vestnesa Ridge revealed sub seafloor NW-SE oriented faults (i.e., near vertical and parallel to the sedimentary ridge axis) that could be genetically associated with the outcropping faults (Plaza-Faverola et al., 2015; Fig. 2). Comparison of similar high resolution 3D seismic data from the western Vestnesa Ridge shows that the style of faulting has been radically different from that of the eastern segment. Here, only randomly oriented short fault segments are revealed in nevertheless pockmarked Holocene strata (Fig. 2).~~

~~The gas hydrate system dynamics along the Vestnesa Ridge seems to be highly influenced by spatial variations in the geothermal gradient and the gas composition~~ (Plaza-Faverola et al., 2017)~~. Thermogenic gas accumulations at the base of the GHSZ (Fig. 2) are structurally controlled (i.e., the gas migrates towards the crest of the sedimentary drift) and part of this gas sustains present day seepage activity~~ (Bünz et al., 2012;Plaza-Faverola et al., 2017;Knies et al., 2018)~~. Reservoir modelling shows that source rock deposited north of the Molloy Transform Fault has potentially started to generate thermogenic gas 6 Ma ago and that migrating fluids reached the Vestnesa Ridge crest at the active seepage site ca. 2 Ma ago~~ (Knies et al., 2018)~~. It is suspected that seepage has been occurring, episodically, at least since the onset of the Pleistocene glaciations c. 2.7 Ma ago leaving buried pockmarks and authigenic carbonate crusts as footprint~~ (Plaza-Faverola et al., 2015)~~.~~ (Schneider et al., 2018a)~~Many transient seepage events are suspected and one was dated to ca. 17.000 years based on the presence~~

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~~of a ~1000 years old methane dependent bivalve community possibly sustained by a gas pulse through a fault~~ (Ambrose et al., 2015)~~.~~

~~2.~~3. Seismic data

The description of faults and fluid flow related features along the Vestnesa Ridge is documented ~~in~~ by several authors (Bünz et al., 2012;Hustoft, 2009;Petersen et al., 2010;Plaza-Faverola et al., 2015;Plaza-Faverola et al., 2017)~~Plaza-Faverola et al., 2015~~. ~~The description is based on t~~Two-3D high resolution seismic data sets acquired on the western and the eastern Vestnesa Ridge respectively (Fig. 2), and one 2D seismic line acquired along the entire Vestnesa Ridge extent have been particularly useful in the description of the structures along the ridge (Fig. 5). These data have been previously used for the investigation of the bottom simulating reflection dynamics (i.e., the seismic indicator of the base of the gas hydrate stability zone) (Plaza-Faverola et al., 2017) and documentation of gas chimneys and faults in the region (Petersen et al., 2010;Plaza-Faverola et al., 2015;Bünz et al., 2012). The data were acquired on board R/V Helmer Hanssen using the 3D P-Cable system (Planke et al., 2009). Final lateral resolution of the 3D data sets is given by a bin size of 6.25x6.25 m^2 and the vertical resolution is > 3 m with a dominant frequency of 130 Hz. Details about acquisition and processing can be found in Petersen et al., 2010 and Plaza-Faverola et al., 2015. For the 2D survey the dominant frequency was ~80 Hz resulting in a vertical resolution > 4.5 m (assumed as λ/4 with an acoustic velocity in water of 1469 m/s given by CTD data; Plaza-Faverola et al., 2017).

~~3.~~4. The modelling approach

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The modelling carried out in this study deals exclusively with tectonic stress due to ridge push. We use the approach by Keiding et al. (2009) based on the analytical solutions derived by Okada (1985), to model the plate motion and tectonic stress field due to spreading along the Molloy and Knipovich Ridges.

The Okada model and our derivation of the stress field from it is described in more detail in appendix A. The Molloy and Knipovich Ridges are modelled as rectangular planes with opening and transform motion in a flat Earth model with elastic, homogeneous, isotropic rheology (Fig. A1 in appendix). Each rectangular plane is defined by ten model parameters used to approximate the location, geometry and deformation of the spreading ridges (Okada, 1985; see supplement Table 1). The locations of the two spreading ridges were constrained from bathymetry maps (Fig. 1). The two spreading ridges are assumed to have continuous, symmetric deformation below the brittle-ductile transition, with a half spreading rate of 7 mm/yr and a spreading direction of N125°E,

according to recent plate motion models (DeMets et al., 2010). Because the spreading direction is not perpendicular to the trends of the spreading ridges, this results in both opening and right-lateral motion; that is, oblique spreading on the Molloy and Knipovich Ridges. The Molloy Transform Fault, which connects the two spreading ridges, trends N133°E, thus a spreading direction of N125°E implies extension across the transform zone. We use a depth of 10 km for the brittle-ductile transition and 900 km for the lower boundary of the deforming planes, to avoid boundary effects. For the elastic rheology, we assume typical crustal values of Poisson's ratio = 0.25 and shear modulus = 30 GPa (Turcotte and Schubert, 2002). We perform sensitivity tests for realistic variations in 1) model geometry 2~~1~~) spreading direction, 3~~2~~) depth of the brittle-ductile transition, and 4~~3~~) Poisson's ratio –(Supplementary material). Variations in shear modulus, e.g. reflecting differences in elastic parameters of crust and sediments, would not influence the results, because we do not consider the magnitude of the stresses~~o~~.

Asymmetric spreading has been postulated for the Knipovich Ridge based on heat flow data (Crane et al., 1991), and for other ultraslow spreading ridges based on magnetic data (e.g., Gaina et al., 2015). However, the evidence for asymmetry along the Knipovich Ridge remains inconclusive and debatable in terms, for example, of the relative speeds suggested for the North American (faster) and the Eurasian (slower) plates (Crane et al., 1991;Morgan, 1981;Vogt et al., 1994). This reflects that the currently available magnetic data from the west-Svalbard margin is not of a quality that allows an assessment of possible asymmetry of the spreading in the Fram Strait (Nasuti and Olesen, 2014). Symmetry is thus conveniently assumed for the purpose of the present study.

We focus on the stress field in the upper part of the crust (where the GHSZ is) and characterise the stress regime based on the ~~relative magnitudes of the~~relationship between the horizontal and vertical stresses. We refer to the stresses as σ_v (vertical stress), σ_H (maximum horizontal stress) and σ_h (minimum horizontal stress), where compressive stress is positive (Zoback and Zoback, 2002). A tensile stress regime ($\sigma_v > \sigma_H > \sigma_h$) favours the opening of steep faults that can provide pathways for fluids. Favourable orientation of stresses with respect to existing faults and/or pore fluid pressures increasing beyond hydrostatic pressures are additional conditions for leading to opening for fluids under strike-slip ($\sigma_H > \sigma_v > \sigma_h$) and compressive ($\sigma_H > \sigma_h > \sigma_v$) regimes (e.g., Grauls and Baleix, 1994).

5. Results ~~and discussion~~

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5.1 Predicted type and orientation of stress fields due to oblique spreading at the Molloy and the Knipovich ridges

The model predicts zones of tensile stress near the spreading ridges, and strike-slip at larger distances from the ridges. An unexpected pattern of tensile stress arises from the northward termination and the southward termination of the Knipovich and Molloy ridges respectively (Fig. 3). The zone of tensile stress that extends northward from the Knipovich Ridge, encompasses the eastern part of the Vestnesa Ridge. The western Vestnesa Ridge, on the other hand, lies entirely in a zone of strike-slip stress (Fig. 3). The sensitivity tests show that the tensile stress zone is a robust feature of the model, that is, variations in the parameters result in a change of the extent and shape of the tensile zone but the zone remains in place (Supplementary material). It appears that the tensile zone is a result of the interference of the stress from the two spreading ridges. To illustrate this, we ran the model for the Molloy Ridge and the Knipovich Ridge independently. In the model with Knipovich Ridge alone, a large tensile zone extends northeast from the ridge's northern end, covering only the easternmost part of Vestnesa Ridge (Fig. 4). Under the influence of the strike-slip field from the Molloy Ridge, this zone is deflected and split into two lobes, of which one extends to the eastern Vestnesa Ridge.

To investigate the geometric relationship between the predicted stress field and mapped faults, we calculated the orientations of maximum compressive horizontal stress (Lund and Townend, 2007). The maximum horizontal stresses (σ_H) approximately align with the spreading axes within the tensile regime and are perpendicular to the axes within the strike-slip regime (Fig. 3). Spreading along the Molloy ridge causes NW-SE orientation of the maximum compressive stress along most of the Vestnesa Ridge, except for the eastern segment where the influence of the Knipovich Ridge results in a rotation of the stress towards E-W (Fig. 3).

The simplifying assumptions involved in our model imply that the calculated stresses in the upper crust are unconstrained to a certain degree. However, the predicted stress directions are in general agreement with other models of plate tectonic forces (e.g., Gölke and Coblentz, 1996;Naliboff et al., 2012). In addition, and Árnadóttir et al. (2009) demonstrated that the deformation field from the complex plate boundary in Iceland could be modelled using Okada's models. More importantly, a comparison of the predicted strike-slip and tensile stress fields from plate spreading and observed earthquake focal mechanisms shows an excellent agreement, both with regards to style stress regime and orientation of principal stressesmaximum compressive stress. The earthquake focal mechanisms are mostly normal along the spreading ridges and strike-slip along the transform faults, and the focal mechanism pressure axes align nicely with the predicted directions of maximum compressive stress (Fig.

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3). The good agreement between Okada's model and other modelling approaches as well as between the resulting stresses and focal mechanisms in the area ~~indicates two things~~indicates ~~: 1.~~ that the model, despite the simplicity of its assumptions, provides a correct first order prediction of orientation and type of the~~the~~ stress field in the upper crust~~., and 2. that stress from plate spreading may~~ be transferred have a significant influence ~~towards the near-surface sediments influencing on the state of stress~~deformation ~~along the Vestnesa Ridge.~~(~~-~~Other possible sources of stress in the region will be discussed in more detail in section 6.1)~~l below.~~ . It remains an open question to which degree the crustal stresses are transferred to the sedimentary successions of the Vestnesa Ridge. For compacted stratigraphic formations in the Norwegian Sea, a comparison of shallow *in situ* stress measurements and deeper observations from earthquake focal mechanisms indicates that the stress field is homogeneous in direction over a large depth range (Fejerskov and Lindholm, 2000). For an overburden constituted of Quaternary sediments, though, the stress coupling between the crust and the near-surface depends on the shear strength of the sediments. The upper 200 m of hemipelagic sediment along the Vestnesa Ridge arerelatively young (< 2 Ma)and is not expectedto be highly consolidated. However, the fact that a large number of faults extend several hundred meters through the sediments suggests that compaction of the sediments has been large enough to build up some amount of shear strength. Geotechnical studies from different continental margins indicate that deep marine sediments can experience high compressibility due to the homogeneity in the grain structure (i.e., large areas made of a single type of sediment), providing favourable conditions for shear failure (Urlaub et al., 2015;DeVore and Sawyer, 2016). We, therefore, consider it possible that the upper sediments along the Vestnesa Ridge can be deformed by tectonic stress.

5.2 Distribution of fault~~sing~~ and seepage activity along the Vestensa Ridge with respect to modelled tectonic stress

High-resolution 3D seismic data collected on the eastern Vestnesa Ridge revealed sub-seabed NW-SE oriented, near-vertical faults with a gentle normal throw (< 10 m). In this part of the Vestnesa Ridge, gas chimneys and seafloor pockmarks are ca. 500 m in diameter. On structural maps extracted along surfaces within the gas hydrate stability zone (GHSZ) gas chimneys project over fault planes or at the intersection between fractures (Fig. 2). ~~The faults mapped in this part of the ridge structures mapped could be genetically associated with a~~A set of N-S to NNE-SSE trending faults ~~that~~ outcrop at the seafloor at a narrow zone between the Vestnesa Ridge and the northern termination of the Knipovich Ridge (Fig 1, 2). These faults could be genetically associated with the faults on the crest of Vestnesa Ridge (Plaza-Faverola et al., 2015; Fig. 2), but they have also~~Due to their~~

~~structural connection with the Knipovich Ridge the outcropping faults have~~ been suggested to indicate ongoing northward propagation of the Knipovich rift system (Crane et al., 2001;Vanneste et al., 2005).

Most of the outcropping N-S to NNE-SSE oriented faults north of the Knipovich Ridge and the sub-seafloor NW-SE oriented faults on the eastern Vestnesa Ridge are located within the zone of modelled tensile regime that extends northward from the Knipovich Ridge (Fig. 3). The orientation of σ_H rotates from being perpendicular to the Molloy ridge nearby sub-seafloor faults at the eastern Vestensa Ridge, to be perpendicular to the Knipovich Ridge in places within the tensile zone (Fig. 3). Interestingly, documented acoustic flares along the Vestensa Ridge are also located within the zone of modelled tensile stress regime (Fig. 3). ~~-~~The match between the extent of the modelled tensile zone and the active pockmarks is not exact; active pockmarks exist a few kilometres westward from the termination of the tensile zone (Fig. 3). However, the agreement is striking from a regional point of view. Some of the outcropping faults north of the Knipovich Ridge and south of the Molloy transform fault appear located outside the modelled tensile zone (Fig. 3; Fig. S1-S4 in the supplement). Inactive pockmarks (i.e., no acoustic flares have been observed during several visits to the area) are visible on high resolution bathymetry maps over these faulted regions (Dumke et al., 2016;Hustoft, 2009;Johnson et al., 2015;Waghorn et al., 2018).

In a similar high-resolution 3D seismic data set from the western Vestnesa Ridge the faults have different characteristics compared to those of the eastern segment. In this part of the ridge gas chimneys are narrower, buried pockmarks are stacked more vertically than the chimneys towards the east and it is possible to recognise more faults reaching the present-day seafloor (Plaza-Faverola et al., 2015). Fault segments are more randomly oriented with a tendency for WNW-ESE and E-W orientations (Fig. 2). These structures coincide with a modelled strike-slip stress regime with σ_H oriented nearly perpendicular to the Molloy Ridge (Fig. 3).

6. Discussion

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T~~t~~he striking ~~correlation~~coincidence between the spatial variation in ~~predicted tensile~~ modelled stress regimes and the pattern of faulting and seepage activity along the Vestnesa Ridge leads to the discussion whether ~~,~~ tectonic stresses resulting from plate~~oblique~~ spreading at the Molloy and the Knipovich ridges~~-~~ have the potential to influence near-surface ~~-~~deformation and fluid dynamics in the study area. We discuss first the modelling results

in the context of the total state of stress across passive margins and to which extent regional stresses can influence near-surface deformation. Assuming that tectonic stress can potentially influence near-surface deformation, we discuss then the effect that the modelled stress fields would have on pre-existing faults and associated fluid migration. Finally, we propose a model for explaining seepage evolution along the Vestnesa Ridge coupled to stress field variations. We close the discussion with a note on the implications of the present study for understanding near-surface fluid dynamics across passive margins globally.

6.1 Modelled stress in the context of the total state of stress along the Vestnesa Ridge

~~Since~~ In this study we focused exclusively on modelling the type and orientation of stresses potentially generated by ~~oblique~~ spreading at the Molloy and Knipovich ridges. ~~, and we have~~ Other sources of stress have been so far disregarded. ~~any other source of stress,~~ Hence, ~~the~~ the modelled stress field documented in this study cannot be understood as a representation of the total state of stress in the region. Modelling studies from Atlantic-type passive margins, suggest that from all the possible sources of stress across passive margins (i.e., sediment loading, glacial flexure, spatial density contrasts, and ridge push as well as basal drag forces) sediment loading (assuming elastic deformation) appears to be the mechanism with the potential of generating the largest magnitudes of stresses across passive margins(Stein et al., 1989;Turcotte et al., 1977). However, stress information derived from seismological and in-situ data (Fjeldskaar and Amantov, 2018;Grunnaleite et al., 2009;Lindholm et al., 2000;Olesen et al., 2013) and paleo-stress field analyses based on dip and azimuth of fault planes (Salomon et al., 2015) point towards a dominant effect of ridge push forces on the state of stress across passive continental margins. Given the proximity of the Vestnesa Ridge to the Molloy and the Knipovich ridges (Fig. 1), we argue that tectonic stress from spreading can be an important factor, perhaps even a dominant factor, controlling near-surface deformation along the Vestnesa Ridge.

The contemporary stress field across the west-Svalbard passive margin is presumably the result of an interaction between large-scale tectonic stress mechanisms (i.e., ridge push, basal drag) overprinted by regional (i.e., density contrasts, glacial related flexure, sediment loading) and local mechanisms (e.g., topography, pore-fluid pressure variations, faulting). In the concrete case of the Vestnesa Ridge, a change in the faulting pattern, the distribution of shallow gas and gas hydrates, as well as differences in the topographic characteristics of the ridge crest (Fig. 2), are all factors likely to induce local changes in near-surface stress. We discuss in the following sections how local stress-generating mechanisms may interact with tectonic forcing to control fluid dynamics and seepage.

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The Vestnesa sedimentary Ridge sits over relatively young oceanic crust, < 19 Ma old (Eiken and Hinz, 1993;Hustoft, 2009). The oceanic-continental transition is not well constrained but its inferred location crosses the Vestnesa Ridge at its easternmost end (Engen et al., 2008;Hustoft, 2009). This is a zone prone to flexural subsidence due to cooling during the evolution of the margin and the oceanic crust may have experienced syn-sedimentary subsidence nearby the oceanic-continental transition, as suggested for Atlantic passive margins (Turcotte et al., 1977). However, syn-sedimentary subsidence would result in N-S oriented faults (i.e., reflecting the main direction of major rift systems during basin evolution) (Faleide et al., 1991;Faleide et al., 1996). Although one N-S oriented fault outcrops in bathymetry data at the transition from the eastern to the western Vestnesa Ridge segments (Fig. 5a), most of the sub-seabed faults and associated fluid migration features in 3D seismic data are~~The~~ NW-SE to E-W oriented (Fig. 1, 2) ~~faults on the Vestnesa Ridge point towards a different origin.~~ Similarly, the weight of the contourite ridge over the oceanic crust may have generated additional stress on the Vestnesa Ridge. However, for a sedimentary load to generate large contemporaneous stress sedimentation would need to occur at fast rates (e.g., > 1 mm/year) so the stress builds up faster than it relaxes at the crust (Stein et al., 1989). Sedimentation rates on the Vestnesa Ridge are estimated to have fluctuated between 0.1-0.6 mm/year since the onset of glaciations 2.7 Ma ago (Plaza-Faverola et al., 2017;Knies et al., 2018;Mattingsdal et al., 2014).

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Glacial isostasy results in significant stresses associated with flexure of the lithosphere as the ice-sheet advances or retreats. Present uplift rates are highest at the centre of the formerly glaciated region where the ice thickness was at the maximum (Fjeldskaar and Amantov, 2018). Modelled present day uplift rates at the periphery of the Barents sea ice-sheet ranges from 0 to -1 mm/year, depending on the ice-sheet model used in the calculation (Auriac et al., 2016) compared to an uplift rate of up to 9 mm/year at the centre of the ice sheet (Auriac et al., 2016;Patton et al., 2016). Modelled glacial stresses induced by the Fennoscandian ice sheet on the mid-Norwegian margin are close to zero at present day (Lund et al., 2009;Steffen et al., 2006). By analogy, present day stress at the Vestnesa Ridge - located ~60 km from the shelf break - may be insignificant. It is likely that glacial stresses as far off as the Vestnesa Ridge had a more significant effect in the past, as further discussed in section 6.3 and 6.4.

~~6.3~~

Finally, ~~spreading~~ridge push forcing has the potential of being a dominant factor on the state of stress across the west-Svalbard margin as observed for Norwegian margins (Fejerskov and Lindholm, 2000;Lindholm et al.,

2000). Specifically, the Vestnesa Ridge has the particularity that it is located within the expected range of maximum influence of ridge push forces on the stress regime (Fejerskov and Lindholm, 2000) and that forces from two spreading ridges influence it from different directions (i.e., the Molloy Ridge from the west and the Knipovich Ridge from the south-east). The intriguing stress pattern appears to be caused by the interaction of the stress generated by the two spreading ridges, as described above (section 5.1).

6.2 Effect of the modelled stress fields on pre-existing faults and present day seepage

Bearing in mind that several factors contribute to the total state of stress at different scales across passive margins we assume that an influence on near-surface deformation by mid-ocean ridge stresses is plausible and discuss their potential effect on seepage activity. Depending on the tectonic regime, the permeability through faults and fractures may be enhanced or inhibited (e.g., Sibson, 1994;Hillis, 2001;Faulkner et al., 2010). Thus, spatial and temporal variations in the tectonic stress regime may control the transient release of gas from the seafloor over geological time as documented, for example, for CO_2 analogues in the Colorado Plateau (e.g., Jung et al., 2014).

A gas hydrate system is well developed and shallow gas accumulates at the base of the GHSZ along the entire Vestnesa Ridge (Plaza-Faverola et al., 2017). Thermogenic gas accumulations at the base of the GHSZ (Fig. 5) are structurally controlled (i.e., the gas migrates towards the crest of the sedimentary drift) and together with microbial methane this gas sustains present day seepage activity (Bünz et al., 2012;Plaza-Faverola et al., 2017;Knies et al., 2018). All the conditions are given for sustaining seepage along the entire ridge. However, seepage is focused and restricted. Some of the mechanisms commonly invoked to explain seepage activity across passive margins include climate related gas hydrate dissociation, tidal or seasonal sea-level changes, and pressure increases in shallow reservoirs due to fast sedimentation - (e.g., Bünz et al., 2003;Hustoft et al., 2010;Karstens et al., 2018;Riboulot et al., 2014;Skarke et al., 2014;Berndt et al., 2014;Wallmann et al., 2018;Westbrook et al., 2009;Franek et al., 2017). While all of these mechanisms may influence ~~to a certain degree~~ seepage systems as deep as the Vestnesa Ridge (> 1000 m deep; as discussed further in section 6.3) they offer no explanation as to why seepage activity is more substantial within chimney sites proximal to or at fault planes and why seepage is at a minimum or stopped elsewhere along the ridge (Fig. 2). –Overall, the pattern of seepage activity along the Vestnesa Ridge is strikingly consistent with the modelled tectonic stress field pattern. Acoustic flares have been documented to originate from < 10 m broad zones (Panieri et al., 2017) within pockmarks located exclusively

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along faults. We suggest that these faults are favourably oriented with respect to a tectonic σ_H (Fig. 2) and that opening of fault segments favourably oriented with respect to the stress field is one controlling factor of present day seepage.

Present day seepage activity is less ~~favourable~~pronounced towards the western Vestnesa Ridge. Despite available gas trapped at the base of the GHSZ (Fig. 5) the faults are generally less favourably oriented for tensile opening (i.e., NW-SE oriented σ_H) and are under a strike-slip regime (Fig. 2). The cluster of larger scale N-S to NNW-SSE trending extensional faults that outcrop at the southern slope of the Vestnesa Ridge (Fig. 1, 2), also coincides with the zone of predicted tensile stress (Fig. 3). However, the modelled maximum compressive stress in this area is generally oblique to the fault planes ~~(Fig. 3)~~, making these faults less open for gas. Interestingly, this is also a zone of pockmarks where acoustic flares have not been observed (e.g., Johnson et al., 2015; Hustoft et al., 2009; Vanneste et al., 2005). A set of N-S oriented structures south of the Molloy Transform Fault and a train of pockmarks at the crest of a ridge west of the Knipovich Ridge axis are located under a strike-slip regime with N-S oriented σ_H (Fig. 3). Although gas accumulations and gas hydrates have been identified at the crest of this ridge, acoustic flares have so far not been documented ~~in the region~~ (Johnson et al., 2015;Waghorn et al., 2018). We suggest that the N-S trending faults in this region may be impermeable for fluids despite a parallel σ_H, if the stress regime is transpressive. Transpression has been documented at different stages of opening of the Fram Strait (Jokat et al., 2016) and is thus a plausible tectonic mechanism for holding the gas from escaping. Ongoing studies will shed light into the structural evolution of this near-surface system.

The bathymetry of the southern flank of the Vestnesa Ridge deepens from 1200-1600 m along the crest of the Vestnesa Ridge to ca. 2000 m near the Molloy Transform Fault (Fig. 1). Thus, an additional effect of gravitational stress on near-surface deformation and seepage in the region cannot be ruled out. In particular, although the faults at the steep slope north of the Knipovich Ridge have been suggested to reflect the northward propagation of the Knipovich Ridge rift system (Crane et al., 2001;Vanneste et al., 2005), it is likely that their formation was influenced by gravitational stresses. Small-scale slumps at the slope (Fig 1, 2) could be also evidence of gravitational forcing at the steep southern flank of the Vestnesa Ridge. However, sub-seabed faults on the eastern Vestnesa Ridge dip towards the NE (Fig. 5c), suggesting that gravitational forcing is not necessarily influencing the behaviour of faults and current seepage activity on the eastern Vestensa Ridge.

6.3 Seepage evolution coupled to stress field variations

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The seepage systems along the Vestnesa Ridge has been highly dynamic over geological time. Both microbial and thermogenic gas contribute to the gas hydrate and seepage system (Hong et al., 2016;Panieri et al., 2017;Plaza-Faverola et al., 2017;Smith et al., 2014). Reservoir modelling shows that source rock deposited north of the Molloy Transform Fault has potentially started to generate thermogenic gas 6 Ma ago and that migrating fluids reached the Vestnesa Ridge crest at the active seepage site ca. 2 Ma ago (Knies et al., 2018). Seepage has been occurring, episodically, at least since the onset of the Pleistocene glaciations directly through faults, and a deformation typical of gas chimneys (i.e., where periodicity is evidenced by buried pockmarks and authigenic carbonate crusts) ~~,~~ seems to have started later (Plaza-Faverola et al., 2015). However, the periodicity of seepage events documented since the Last Glacial Maximum seems to correlate indistinctively with glacials or interglacials (Consolaro et al., 2015;Schneider et al., 2018a;Sztybor and Rasmussen, 2017). One transient event was dated to ca. 17.000 years based on the presence of a ~1000 years old methane-dependent bivalve community possibly sustained by a gas pulse through a fault or chimney (Ambrose et al., 2015). A tectonic control on the evolution of near-surface fluid flow systems and seepage along the Vestensa Ridge is an explanation that reconciles the numerous cross-disciplinary observations in the area.

The spatial relation between gas chimneys at the crest of the ridge and fault planes (Fig. 2, 3c) (Bünz et al., 2012;Plaza-Faverola et al., 2015) is intriguing and raises the question whether the faulting was posterior to brecciation (fracturing) of the strata during chimney formation. Gas chimneys form by hydrofracturing generated at a zone of overpressure in a reservoir (e.g., Karstens and Berndt, 2015;Hustoft et al., 2010 and references therein;Davies et al., 2012). From the mechanical point of view the tensile faults at the eastern Vestnesa Ridge would not be a favourable setting for the generation of hydrofracturing and chimney formation right at the fault planes as observed in the seismic (Fig. 2, 3c). For gas chimneys to be the youngest features fault segments would have to become tight and permeable at certain periods of times, allowing pore fluid pressure at the free gas zone beneath the GHSZ to build up (Fig. 5). This is a plausible scenario. The faults may get locally plugged with gas hydrates and authigenic carbonate and activate~~d~~ a self-sealing mechanism similar to that suggested for chimneys at other margin (e.g., Hovland, 2002). Nevertheless, where gas chimneys do not disturb the seismic response, fault planes are observed to extend near the seafloor (Fig. 5c). This observation suggests that latest faulting periods may have broken through already brecciated regions connecting thus gas chimneys that were already in place~~d~~. Both cases are consistent with the fact that ~~–~~acoustic flares and seepage bubbles are restricted to focused weakness zones (Panieri et al., 2017). We suggest that an interaction between pore fluid pressure at the base of

the GHSZ and tectonic stress has led to local stress field variations and controlled seepage evolution. Opening of fractures is facilitated if the minimum horizontal stress is smaller than the pore-fluid pressure (p_f), that is, the minimum effective stress is negative ($\sigma_h' = \sigma_h - p_f < 0$) (e.g., Grauls and Baleix, 1994). Secondary permeability may increase by formation of tension fractures near damaged fault zones (Faulkner et al., 2010). Cycles of negative minimum effective stress and subsequent increase in secondary permeability in a tensile stress regime can be achieved particularly easy in the near-surface and would provide an explanation for the development of chimneys coupled to near-surface tectonic deformation. A constant input of thermogenic gas from an Eocene reservoir since at least ca. 2 Ma ago would have contributed to localized pore-fluid pressure increases (Knies et al., 2018).

Geophysical and paleontological data indicate that there was once more prominent seepage and active chimney development on the western Vestnesa Ridge segment (e.g., Consolaro et al., 2015;Plaza-Faverola et al., 2015;Schneider et al., 2018b). An interaction between pore-fluid pressure and tectonic stress would explain variations in the amount of seepage activity over geological time. Following the same explanation as for the present day seepage, the negative σ_h' condition could have been attained anywhere along the Vestensa Ridge in the past due to pore fluid pressure increases at the base of the GHSZ or due to favourable stress conditions. During glacial periods, flexural stresses should have been significantly higher than at present day (Lund and Schmidt, 2011). According to recent models of glacial isostasy by the Barents Sea Ice sheet during the last glacial maximum, the Vesntesa Ridge laid in a zone where subsidence could have been of tens of meters (Patton et al., 2016). At other times, before and after glacial maximums, the Vestnesa Ridge was possibly located within the isostatic forebulge.

In general, it is expected that maximum glacial-induced horizontal stresses (σ_H) would be dominantly oriented parallel to the shelf break (Björn Lund personal communication; Lund et al., 2009). ~~. This~~that is, ~~dominantly~~ oriented N-S in the area of the Vestnesa Ridge (Fig. 1). Such stress orientation would not favour opening for fluids along pre-exiting NW-SE oriented faults associated with seepage activity at present (i.e., N-S oriented faults would be the more vulnerable for opening). It is likely, though, that the repeated waxing and waning of the ice sheet caused a cyclic modulation of the stress field (varying magnitude and orientation) and influenced the dynamics of gas accumulations and favourably oriented faults along the Vestnesa Ridge in the past. Past glacial stresses may provide then an alternative explanation for seepage along the entire Vestensa Ridge extent at given periods of time (Fig. 6). This explanation is in line with the correlation between seepage and glacial-interglacial

events postulated for different continental margins e.g., for chimneys off the mid-Norwegian margin (Plaza-Faverola et al., 2011), the Gulf of Lion (Riboulot et al., 2014), but also along the Vestnesa Ridge (Plaza-Faverola et al., 2015;Schneider et al., 2018b).

A temporal variation in the stress field along the Vestnesa Ridge is also caused by its location on a constantly growing plate. As the oceanic plate grows, the Vestnesa Ridge moves eastward with respect to the Molloy and Knipovich Ridges, causing a westward shift in the regional stress field on the Vestnesa Ridge (Fig. 7). In future, the eastern Vestnesa Ridge may temporarily move out of the tensile zone, while the western Vestnesa Ridge moves into it (Fig. 7). This suggests that a negative effective stress and subsequent active seepage may reappear at pockmarks to the west of the currently active seepage zone.

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6.4 Implications for the understanding of near-surface deformation across passive margins

Our study is a first step in the investigation of the effect of regional stress on the dynamics of near-surface fluid flow systems across passive margins. Analytical modelling of the spreading at the Molloy and the Knipovich ridges shows that complex stress fields may arise from the interaction of the dynamics ~~at~~of plate boundaries and exert an effect across passive margins. Although the Vestnesa Ridge is a unique case study due to its remarkable proximity to the Arctic mid-ocean ridges, stresses generated by plate tectonic forces are expected to extend for thousands of km (Fejerskov and Lindholm, 2000). Across a single passive margin a range of regional and local factors may result in spatial stress field variations that can explain focusing of gas seepage at specific regions. For instance, the pervasive seepage zone west of Prins Karl Fordland (PKF) on the west-Svalbard margin shelf break (Fig. 1) could be under a stress regime where glacial rebound have had a more significant contribution to the total stress field than it has had over the Vestensa Ridge area. Wallmann et al., (2018) offered as explanation for seepage at PKF that post glacial uplift lead to gas hydrate dissociation and associated seepage. Previously, several other restudies argued for a gas-hydrate control on seepage in this region (e.g., Berndt et al., 2014;Portnov et al., 2016;Westbrook et al., 2009). Since no gas hydrates have been found despite deep drilling (Riedel et al., 2018), the influence of regional stresses provides an alternative and previously not contemplated explanation for seepage in this area. The interactions between tectonic stress regimes and pore-fluid pressure we propose for explaining seepage evolution along the Vestensa Ridge may be applicable to seepage systems along other passive margins, in particular along Atlantic passive margins where leakage from hydrocarbon reservoirs is prominent (e.g., the mid-Norwegian margin, the Barents Sea, the North Sea, the north-east Greenland margin, the Mediterranean and

even the Scotia plate between Argentina and Antarctica) (e.g., Andreassen et al., 2017;Bünz et al., 2003;Hovland and Sommerville, 1985;Riboulot et al., 2014;Somoza et al., 2014;Vis, 2017).

The intriguing, potential correlation between tectonic stress fields from mid-ocean ridge spreading and seepage evolution along the Vestnesa Ridge~~, is an intriguing result that~~ adds to the current debate about the quietness of passive margins and the relation between deep crustal and near-surface deformation (Fejerskov and Lindholm, 2000;Fjeldskaar and Amantov, 2018;Lindholm et al., 2000;Olesen et al., 2013;Stein et al., 1989).

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~~6~~7- CONCLUSIONS

Analytical modelling of the stress field generated by oblique spreading at the Molloy and Knipovich ridges in the Fram Strait, suggests that tectonic forcing may be an important factor controlling faulting and seepage distribution along the Vestnesa Ridge, off the west-Svalbard margin. Other important sources of stress such as bathymetry and lithospheric bending, contributing to the actual state of stress off Svalbard, are not considered in the modelling exercise presented here; thus, we cannot quantitatively assess whether ridge push has a dominant effect on seepage activity. However, provided a certain degree of coupling between ~~our analysis of how~~ crustal and near-surface deformation, it is plausible that stresses from plate spreading may~~.~~ affect the behaviour of ~~mapped~~ Quaternary faults along the Vestnesa Ridge. ~~-~~Spreading at the Molloy and Knipovich ridges leads to a spatial variation in the tectonic stress regime~~ exerted along the Vestnesa Ridge~~, that may favour fluid migration through pre-existing faults and fractures on the~~. The~~ eastern Vestnee~~n~~sa Ridge~~ is under a stress regime that is favourable favours for fluid migration through pre-existing faults and fractures. on the eastern Vestnesa Ridge where active seepage occurs. We suggest that p~~Our study supports a tectonic explanation for the observed seepage pattern in the region. The ~~resent day seepage is facilitated by~~ opening of faults and fractures favourably oriented with respect to principal stresses in a tensile stress regime ~~or dilation on faults favourably oriented with respect to principal stresses,~~ facilitates the release of gas from zones of relatively high-pore fluid pressure at the base of the gas hydrate stability zone. ~~where pore fluid pressure overcomes the minimum horizontal stress.~~ Multiple seepage events along the entire extent of the Vestensa Ridge, may have been induced by additional sources of stress likely associated with glacial isostasy. Future reactivation of currently dormant pockmarks is likely following the gradual westward propagation of the tensile stress zone on the Vestnesa Ridge as the Eurasian plate drift towards the south-east. Despite the simplifying assumptions by the analytical model approach

implemented here, this study provides a first ~~order~~ assessment of how important understanding the state of stress may be~~is~~ for reconstructing seepage activity in Arctic passive margins.

7- OUTLOOK

The effect of glacial stresses over the fluid flow system off west-Svalbard will be further tested (at least for the Weichselian period) by implementing Lund et al., models using newly constrained Barents Sea ice-sheet models (Patton et al., 2016). Additional sources of stress related to topography/bathymetry should be further investigated as well to gain a comprehensive assessment of the effect of the total stress field on near-surface fluid migration in the region.

Figures

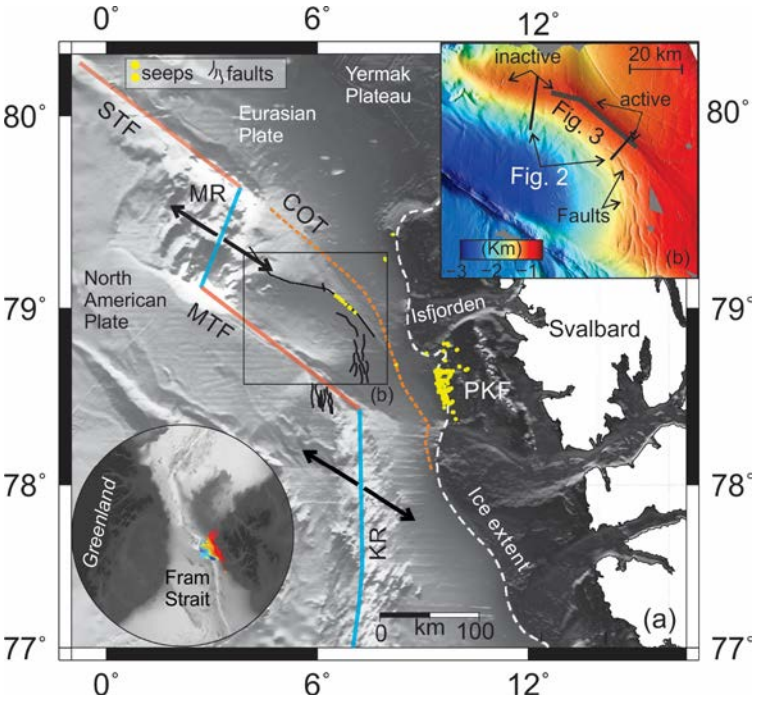

Figure 1: (a) International Bathymetry Chart of the Arctic Ocean (IBCAO) showing the geometry of mid-ocean ridges offshore the west-Svalbard margin; (b) High resolution bathymetry along the Vestnesa Ridge (UiT, R/V HH multi-beam system). Seafloor pockmarks are observed along the entire ridge but active seep sites are restricted to its eastern segment; PKF=Prins Karl Foreland; STF=Spitsbergen Transform Fault; MR=Molloy Ridge; MTF=Molloy Transform Fault; KR=Knipovich Ridge; COT=Continental-Oceanic Transition (Engen et al., 2008); Ice-Sheet Extent (Patton et al., 2016).

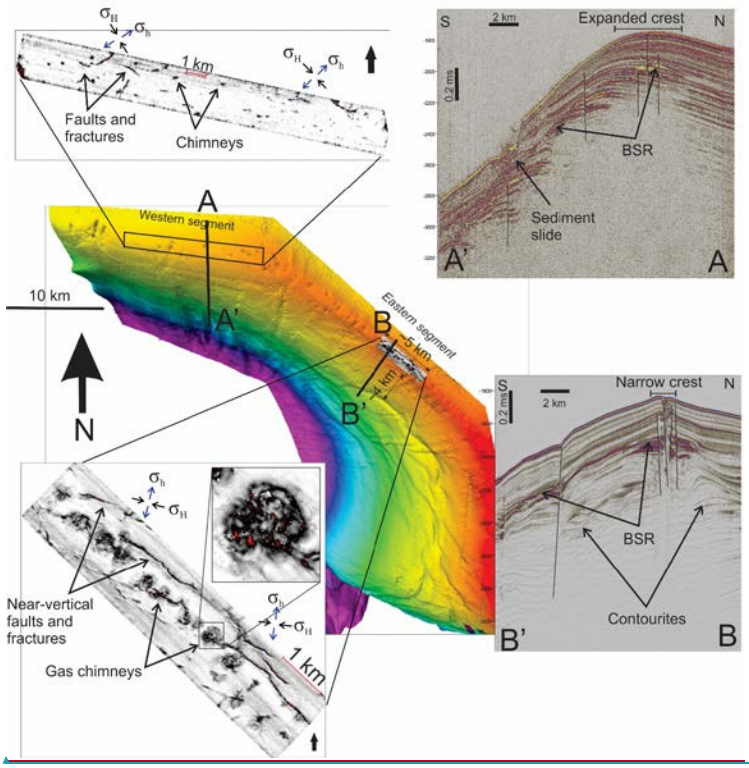

Figure 2: Composite figure with bathymetry and variance maps from 3D seismic data along the eastern and the western Vestnesa Ridge segments (modified from Plaza-Faverola et al., 2015). The orientation of maximum compressive horizontal stress (σ_H) and minimum horizontal stress (σ_h) predicted by the model are projected for

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comparison with the orientation of fault segments. Notice favourable orientation for opening to fluids on the eastern Vestnesa Ridge segment. Two-2D seismic transects (A-A' - Bünz et al., 2012 and B-B' – Johnson et al., 2015) illustrate the morphological difference of the crest of the Vestnesa Ridge (i.e., narrow vs. extended) believed to be determined by bottom current dominated deposition and erosion (Eiken and Hinz, 1993). BSR=bottom simulating reflector.

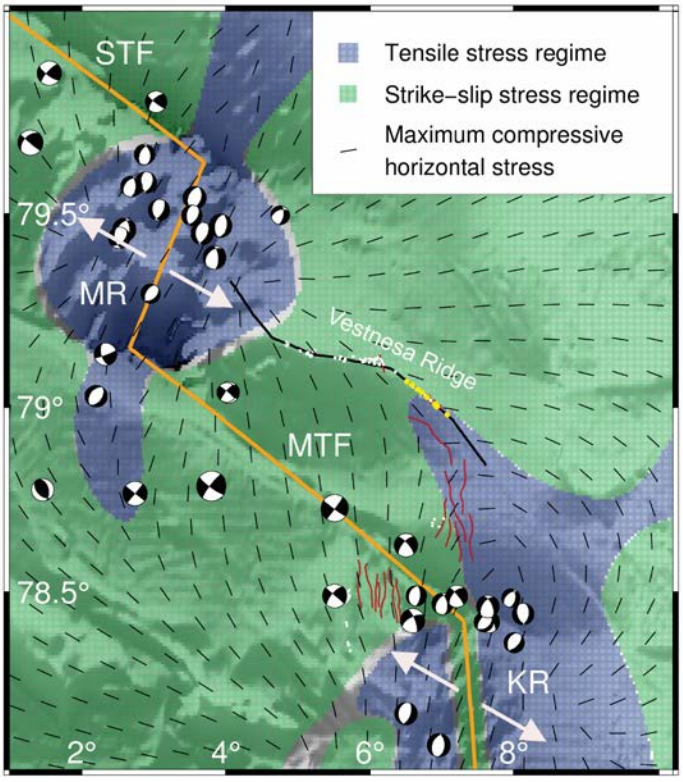

Figure 3: Modelled upper crustal tectonic stress field (blue – tensile and green - strike-slip regime) and stress orientations, due to oblique spreading at Molloy Ridge (MR) and Knipovich Ridge (KR). The seismic line is projected as reference for the crest of the Vestnesa Ridge. Red lines are faults, yellow dots seeps and white circles inactive pockmarks. The focal mechanisms are from the ISC Online Bulletin (http://www.isc.ac.uk).

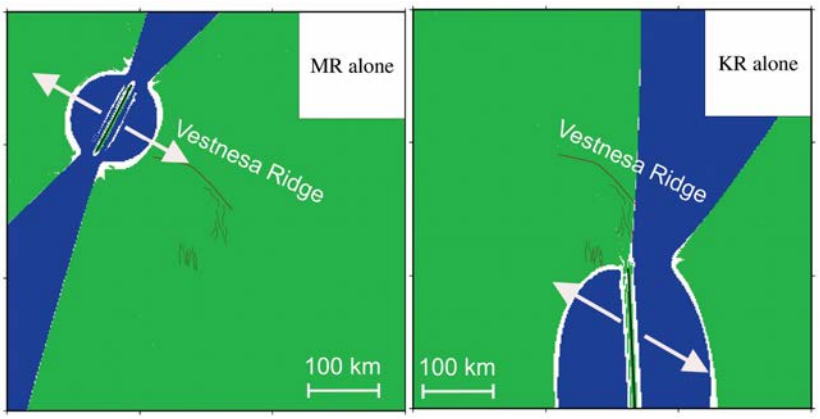

Figure 4: Stress field resulting from model runs with Molloy Ridge and Knipovich Ridge, respectively.

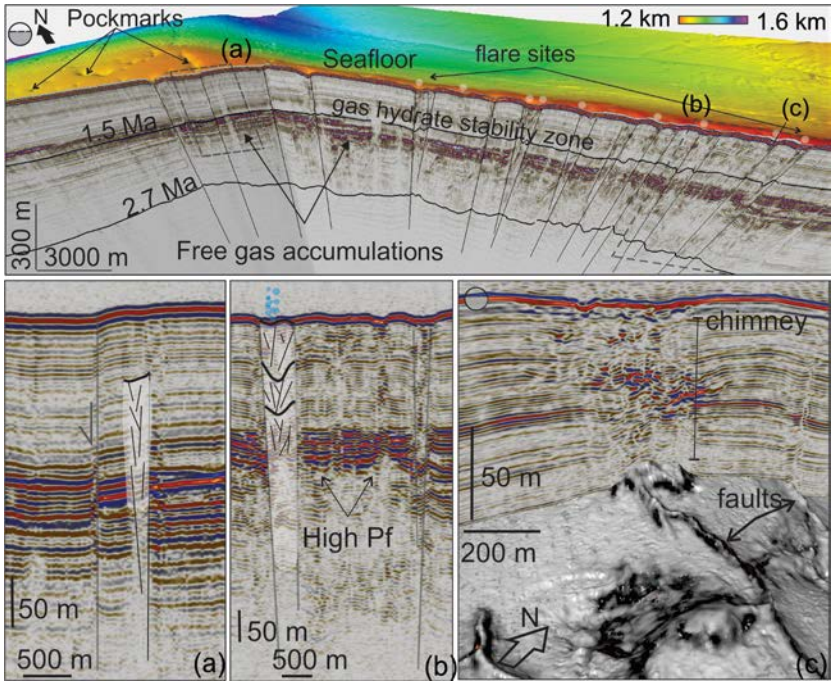

Figure 5: Integrated seismic and bathymetry image of the gas hydrate system along the Vestnesa Ridge. (a) Outcropping N-S oriented fault located at the transition from the region where acoustic flares have been documented to the region where no flares have been observed at pockmarks; (b) Gas chimneys with acoustic flare associated and inferred high pore-fluid pressure (Pf) zone at the base of the gas hydrate stability zone; (c) Gas chimney associated with faults and faults extending to near-surface strata. The same variance map in figure 2 is projected at the depth where the map was extracted along a surface interpreted on the 3D seismic volume.

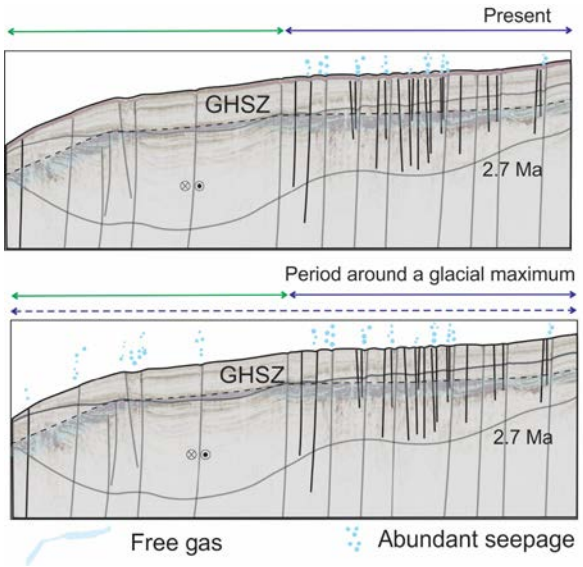

Figure 6: Conceptual model of the evolution of seepage coupled to faulting and spatial variations in the stress regime (tensile=blue; strike-slip=green) along the Vestensa Ridge, offshore the west-Svalbard margin. At present day, tensile stress from mid-ocean ridge spreading (blue solid line) favours seepage exclusively on the eastern segment of the Vestnesa Ridge. Seepage on the western Vestnesa Ridge and other regions may have been induced repeatedly since the onset of glaciations 2.7 Ma ago (Mattingsdal et al., 2014), due to tensional flexural stresses in the isostatic forebulge around the time of glacial maximums.

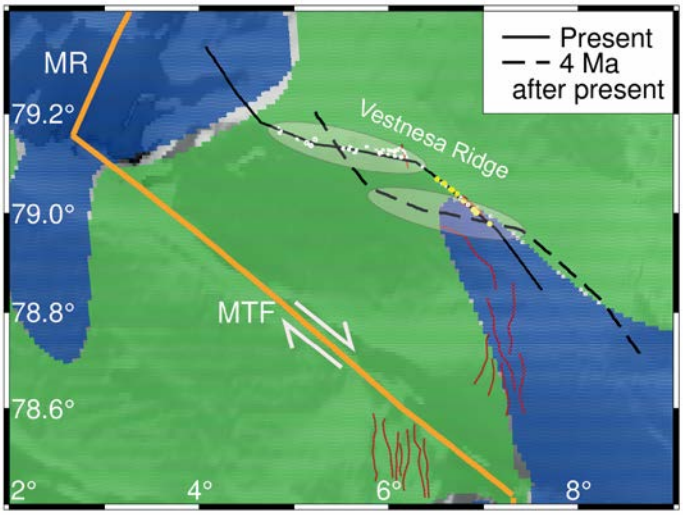

Figure 7: Stress field in figure 3 showing the location of the Vestnesa Ridge at present and 4 Ma after present time, assuming a constant spreading velocity of 7 mm/yr in the direction N125°E. The black polygon corresponds to the seismic line in Plaza-Faverola et al., 2017 and partly shown in figure 3. It is presented as reference for the crest of the eastern and western Vestnesa Ridge segments

Appendix A

Model description

We use the analytical formulations of Okada (1985) for a finite rectangular dislocation source in elastic homogeneous isotropic half-space (Fig. A.1). The dislocation source can be used to approximate deformation along planar surfaces, such as volcanic dykes (e.g. Wright et al., 2006), sills (e.g. Pedersen and Sigmundsson, 2004), faults (e.g. Massonet et al, 1993) and spreading ridges (e.g. Keiding et al., 2009). More than one dislocations can be combined to obtain more complex geometry of the source or varying deformation along a planar source. The deformation of the source can be defined as either lateral shear (strike-slip for faults), vertical shear (dip-slip at faults) or tensile opening.

The Okada model assumes flat Earth without inhomogeneities. While the flat-earth assumption is usually adequate for regional studies (e.g. Wolf, 1984), the lateral inhomogeneities can sometimes cause considerable effect on the deformation field (e.g. Okada, 1985). However, the dislocation model is useful as a first approximation to the problem.

At mid-ocean ridges, deformation is driven by the continuous spreading caused primarily by gravitational stress due to the elevation of the ridges, but also basal drag and possibly slab pull. Deformation occurs continuously in the ductile part of the crust. Meanwhile, elastic strain builds in the upper, brittle part of the crust. To model this setting, the upper boundary of the dislocation source must be located at the depth of the brittle-ductile transition zone. The lower boundary of the source is set to some arbitrary large depth to avoid boundary effects.

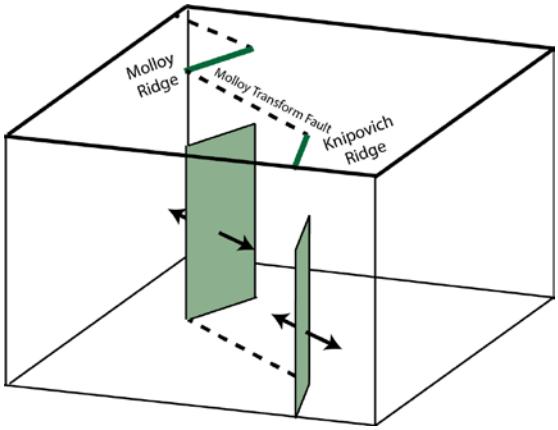

Fig A.1 Extract of model showing the location of the dislocation sources (light green) for Molloy and Knipovich ridges. Note that the model is an infinite half-space, i.e. it has no lateral or lower boundary.

The Okada model provides the displacements u_x, u_y, u_z (or velocities if deformation is time-dependent) at defined grid points at the surface and subsurface. It also provides strain (or strain rates) defined as:

The stress field can then be calculated from the predicted strain rates. In homogeneous isotropic media, stress is related to strain as:

where δ_{ij} if the Kronecker delta, λ is Lamé's first parameter, and μ is the shear modulus. Lamé's first parameter does not have a physical meaning but is related to the shear modulus and Poisson's ratio (ν) as .

The absolute values of stress are in general difficult to model (e.g. Hergert and Heidbach, 2011), and not possible with our analytical model. However, the model provides us with the orientations and relative magnitude of the stresses. That is, we know the relative magnitudes of the vertical stress (σ_v), maximum horizontal stress (σ_H) and minimum horizontal stress (σ_h). From this, the stress regime can be defined as either tensile ($\sigma_v > \sigma_H > \sigma_h$), strike-slip ($\sigma_H > \sigma_v > \sigma_h$) or compressive ($\sigma_H > \sigma_h > \sigma_v$).

Author contribution

Andreia Plaza-Faverola conceived the paper idea. She is responsible for seismic data processing and interpretation. Marie Keiding did the tectonic modelling. The paper is the result of integrated work between both.

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