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 the upper shelf at < 300 m to gas hydrate systems in the deep sea at > 1000 m. The Vestnesa sedimentary ridge, located on oceanic crust at 1000-1700 m water depth, hosts a perennial gas hydrate and associated free gas system. Present day seepage activity is restricted to the eastern segment of the sedimentary ridge, despite morphological and paleontological evidence for past seepage activity along the entire ridge. An eastward transition from the zone with clear morphological evidence of past seepage to the zone of present-day seepage coincides with a change in the faulting pattern of near-surface strata. We modelled the tectonic stress regime due to oblique spreading along the Molloy and Knipovich spreading ridges to investigate whether spatial and temporal variations in ridge push forces may correlate with patterns of seepage distribution. The model reveals a zone of tensile stress that extends northward from the Knipovich Ridge and encompasses a zone of active gas chimneys and pockmarks on the eastern Vestnesa Ridge. The seemingly inactive part of the Vestnesa Ridge is presently located in a strike-slip regime. Modelled stresses due to oblique spreading suggest that minimum principal stresses are perpendicular to mapped NW-SE oriented faults along the Vestnesa Ridge, thus favouring opening of pre-existing faults and fractures. Seepage may occur by leakage from the base of the gas hydrate stability zone if pore fluid pressure dominates over horizontal stresses. It is likely that glacial-related stress has contributed to the total state of stress during glaciations, possibly explaining multiple seepage events along the entire extent of the gas-charged Vestnesa Ridge. The contribution of other factors such as flexural bending to the total state of stress remains 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 is an important component of 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 that methane seepage has been occurring for millions of years, but we have a poor understanding of what forces it.

Present day seepage is identified as acoustic flares in the water column commonly originating at seafloor depressions, 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) 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 (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). 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?

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 postulated that the faults have a tectonic origin and that spatial and temporal tectonic stress variations may have a long-term effect on the distribution of fault-related gas migration and seepage evolution. In general, the total state of stress at passive continental margins is the result of diverse factors including bathymetry and subsurface density contrasts, subsidence due to sedimentary loading and lithospheric cooling, in addition to ridge-push (e.g., Turcotte et al., 1977). The state of stress at formerly glaciated margins (i.e., such as the west-Svalbard margin) has in addition the effect of flexural bending succeeding ice-sheet advances and retreats (e.g., Fjeldskaar and Amantov, 2018;Grunnaleite et al., 2009;Patton et al., 2016). The interaction between the above mentioned factors renders modelling of the total state of stress a complex problem that has not 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 may influence faults and associated seepage activity.

The effect of regional stresses on near-surface fluid dynamics has implications for seepage systems globally. Splay-faults are found to sustain shallow gas accumulations and seepage (Plaza-Faverola et al., 2016), 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 be 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 a passive Arctic margin.

2. STRUCTURAL AND STRATGRAPHIC SETTING OF THE VESTNESA RIDGE

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 of 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 Fram Strait started during the Miocene, ca. 17-10 Ma ago (Jakobsson et al., 2007;Ehlers and Jokat, 2009), establishing 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 narrow on the eastern segment to expanded 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 onset of 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 (Knies et al., 2018;Bünz et al., 2012). 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). Many transient seepage events are suspected and one 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 (Ambrose et al., 2015).

3. SEISMIC DATA

The description of faults and fluid flow related features along the Vestnesa Ridge is documented in Plaza-Faverola et al., 2015. The description is based on 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 (Fig. 3). 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). 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).

4. THE MODELING APPROACH

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. 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) mid-oceanic spreading, 2) depth of the brittle-ductile transition, and 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 only consider the orientations and relative magnitudes of stress.

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 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

5.1 PREDICTED 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 arises near the Vestnesa Ridge due to the interference of the stress from the two spreading ridges. A zone of tensile stress extends northward from the Knipovich Ridge, encompassing 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. 4). The sensitivity tests show that the tensile stress zone covering the eastern Vestnesa Ridge 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).

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. 4). 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. 4).

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), 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 stress from plate spreading and observed earthquake focal mechanisms shows an excellent agreement, both with regards to style and orientation of principal stresses. 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. 4). 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: 1. that the model, despite the simplicity of its assumptions, provides a correct first order prediction of the stress field in the upper crust, and 2. that stress from plate spreading may have a significant influence on the state of stress along the Vestnesa Ridge. Other possible sources of stress in the region will be discussed in more detail below.

5.2 SPATIAL CORRELATION BETWEEN MODELLED TECTONIC STRESS REGIMES, FAULTING AND SEEPAGE ALONG THE VESTENSA RIDGE

The zone of tensile stress on the eastern Vestnesa Ridge coincides with a zone of faulting and where all the present day seepage is concentrated (Fig. 3, 4). 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. 4). However, the agreement is striking from a regional point of view. In the predicted tensile zone towards the east of the Vestnesa Ridge, the sub-seabed faults are generally NW-SE oriented (Fig. 2), near vertical and have a gentle normal throw (< 10 m). Normal faulting or tensile opening of these faults would be enhanced by NW-SE oriented maximum compressive stress σ_H (i.e., these faults are within the transition zone from a strike-slip regime with NW-SE oriented σ_H to a tensile regime with more WNW-ESE oriented σ_H (Fig. 2; 4)). These faults are thus possibly under a regime that makes them favourably permeable for fluids (Fig. 2). Indeed, these faults are spatially linked to gas chimneys and active seepage (Plaza-Faverola et al., 2015;Bünz et al., 2012). Some of the faults show thicker sediment thicknesses at the hanging wall, allowing identification of discrete periods of normal faulting (Plaza-Faverola et al., 2015).

The character of the faults changes towards the western Vestnesa Ridge where the model predicts a strike-slip regime (Fig. 2). The density of faulting and seismic definition decreases westward (Fig. 2, 3, 5). In this part of the ridge gas chimneys are narrower, stacked more vertically than active 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 faults. The fault segments are short; however, the 3D seismic data show that several of them extend from the surface to below the GHSZ. These structures are generally less favourably oriented for tensile opening by modelled NW-SE oriented σ_H than the structures imaged towards the east (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. 4). These extensional faults have been suggested to indicate the northward propagation of the Knipovich Ridge rift system (Crane et al., 2001;Vanneste et al., 2005). However, since the faults are located on the steep south slope of the Vestnesa Ridge, we consider it likely that their formation was influenced by gravitational stresses. Modelled maximum compressive stress vectors in this area are generally oblique to the fault planes (Fig. 4), making these faults less favourable for fluid migration. Interestingly, this is also a zone of pockmarks with no evidence of active seepage at present (e.g., Johnson et al., 2015; Hustoft et al., 2009; Vanneste et al., 2005).

5.3 MODELLED STRESSES IN RELATION TO THE TOTAL STATE OF STRESS ALONG THE VESTNESA RIDGE

Other sources of stress important in the region are gravitational stresses due to bathymetry/topography or subsurface density contrasts and flexural stresses due to cooling of the lithosphere or sedimentation. During the Quaternary, the west-Svalbard margin has furthermore been affected by glacially induced flexural stresses due to the glaciations (e.g., Patton et al., 2016;Fjeldskaar and Amantov, 2018).

A topography effect on the regional stress regime appears likely along the south-eastern flank of the Vestnesa basin were the bathymetry deepens from 1200-1600 m along the crest of the Vestnesa Ridge to Ca. 2000 m near the Molloy Transform Fault (Fig. 1). Small-scale slumps at the slope (Fig 1, 2) may be evidence of gravitational forcing. Gravitational stress would induce tensile horizontal stress perpendicular to the crest of the Vestnesa ridge. Thus, faulting and opening would be induced on NW-SE trending faults on the eastern Vestnesa Ridge and WNW-ESE trending faults on the western Vestnesa Ridge (Fig. 2). While gravitational stress may influence present day seepage along the Vestnesa Ridge, it offers no explanation as to why active seepage occurs exclusively on the eastern Vestnesa Ridge.

The effect of lithospheric bending on the total state of stress in the region remains poorly investigated. It is believed that 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;Plaza-Faverola et al., 2015). 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, only N-S oriented faults would be consistent with a deformation incited by density contrast related flexural bending (i.e., regional structural horses and grabens are N-S trending, reflecting the direction of major rift systems during basin evolution (Faleide et al., 1991;Faleide et al., 1996).The NW-SE to E-W oriented faults on the Vestnesa Ridge point towards a different origin.

Lithospheric bending is also associated with Quaternary isostasy during glacial and interglacial periods. Glacial isostasy results in significant stresses associated with subsidence and uplift of the crust as the ice-sheet advanced or retreated. Present uplift rates are stronger at the core of the ice-sheets where the ice thickness was at the maximum (e.g., ~700 m accumulated subsidence has been estimated for the last million year at formerly glaciated basins in the Barents Sea; (Fjeldskaar and Amantov, 2018). Subsidence and uplift rates decrease towards the former ice-sheet margin. Indeed, modelled present day uplift rates at the periphery of the Barents sea ice-sheet ranges from 0 to -1 mm/a, depending on the ice-sheet model used in the calculation (Auriac et al., 2016) compared to an uplift rate of up to 9 mm/a at the centre (i.e., maximum thickness zone) of the ice sheet (Auriac et al., 2016;Patton et al., 2016). Consistently, 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). The Vestnesa Ridge is located ~60 km from the shelf break (Fig. 1). It is actually closer to the Molloy mid-ocean ridge than to the shelf break. It is likely that the present day effect of glacial stresses on seepage activity in the region is more important towards the seep sites on the shelf break (i.e., PKF region; Fig. 1) than along the Vestensa Ridge. Wallmann et al., (2018) postulated that post glacial uplift lead to gas hydrate dissociation and associated seepage on the shelf break. Since no gas hydrates have been found despite deep drilling (Riedel et al., 2018), the influence of glacial stresses provides an alternative and previously not contemplated explanation for seepage in this area. It is also likely that glacial stresses as far off as the Vestnesa Ridge had a more significant effect in the past, as further discussed in section 5.5.

Since we focused exclusively on modelling the type of stresses potentially generated by oblique spreading at the Molloy and Knipovich ridges, and we have so far disregarded any other source of stress, the modelled stress field in this study cannot be understood as a representation of the total state of stress in the region. However, the striking correlation between the predicted tensile stress regime with favourably oriented faults, gas chimneys and current seepage on the eastern segment of the Vestnesa Ridge, suggests that tectonic stresses resulting from oblique spreading at the Molloy and the Knipovich ridges have the potential to influence near-surface sedimentary deformation and fluid dynamics in the study area. Tectonic processes at plate margins have a major influence on regional stress patterns (Heidbach et al., 2010). Given the proximity to the Molloy and Knipovich Ridges, and without neglecting that other sources of stress can have as well a significant effect on shallow fluid dynamics, we argue that tectonic stress (ridge push) is an important factor, perhaps even a dominant factor, modulating seepage activity along the Vestnesa Ridge.

5.4 PRESENT DAY SEEPAGE COUPLED TO STRESS CYCLING

Based on the correlation between tectonic stress regimes and seepage patterns, we postulate that current seepage on the eastern Vestnesa Ridge is favoured by the opening of pre-existing faults in a tensile stress regime (Fig. 2, 3b). Depending on the tectonic regime, 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).

It is likely that the steep NW-SE oriented faults mapped along the eastern Vestnesa Ridge formed in a strike-slip regime and became permeable to fluids over time. We envision that seepage is induced 1) by opening of faults favourably oriented with respect to the stress field and 2) by high pore fluid pressure at the base of the GHSZ (i.e., the shallowest reservoir holding gas from escaping to the seafloor). Thus, seepage along the Vestnesa Ridge may have been driven by cyclic changes in stress or pore fluid pressure. 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). A negative minimum effective stress and subsequent increase in secondary permeability in a tensile stress regime can be achieved particularly easy in the near-surface. Continued flow through opened faults and fractures would explain brecciation and development of the observed chimneys (Fig. 2b) (e.g., Sibson, 1994).

Seepage through gas chimneys has been dominantly advective and episodic (Fig. 2; Plaza-Faverola et al., 2015) likely due to consecutive decreases and increases in the pore fluid pressure at the base of the GHSZ in response to both, regional stress field variations, and also to local pressure alterations associated for example with hydrofracturing (e.g., Karstens and Berndt, 2015;Hustoft et al., 2010 and references therein). Pressure increases at the base of the GHSZ in this part of the ridge may be explained by a constant input of thermogenic gas from an Eocene reservoir since at least ca. 2 Ma ago (Knies et al., 2018).

The fact that there is not active seepage at present along the western Vestnesa Ridge segment (i.e., being under a strike-slip regime according to the models) is interesting, and somehow supports the notion that the tensile regime affects the fluid flow system towards the eastern segment. The lack of seepage at present in the western segment suggests that p_f at the base of the GHSZ is not high enough to overcome the minimum horizontal stress (i.e., σ_h' is positive) (Fig. 3a).

5.5- PAST AND FUTURE SEEPAGE –ADITIONAL INFLUENCE FROM GLACIAL-RELATED STRESS AND PLATE SPREADING?

What triggered then seepage on the western Vestnesa Ridge and what caused the system to shut down? While tectonic stresses are constant over short geological time spans, chimney development and seafloor seepage has been a transient process because of slight variations in pore-fluid pressure (as discussed above) or the influence of other stress generating mechanisms that have repeatedly brought the system out of equilibrium. Geophysical and paleontological data indicate that there was once 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., 2018).

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, the bending forcing due to ice-loading on the lithosphere was much more significant 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 most likely 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 is, dominantly 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. 5). 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., 2018).

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. 6). In future, the eastern Vestnesa Ridge may temporarily move out of the tensile zone, while the western Vestnesa Ridge moves into it (Fig. 6). This suggests that a negative effective stress and subsequent active seepage may reappear at pockmarks to the west of the currently active seepage zone.

6- 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, our analysis of how stress from plate spreading may affect mapped faults along the Vestnesa

Ridge suggests that a spatial variation in the tectonic stress regime favours fluid migration through faults on the eastern Vestnesa Ridge where active seepage occurs. We suggest that present-day seepage is facilitated by opening of faults and fractures in a tensile stress regime or dilation on faults favourably oriented with respect to principal stresses, 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 is for reconstructing seepage activity in Arctic passive margins.

7- OUTLOOK

The effect of glacial stresses on fluid flow dynamics off west-Svalbard will be further tested (at least for the Weichselian period) by implementing the models by Lund and Schmidt (2011) 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

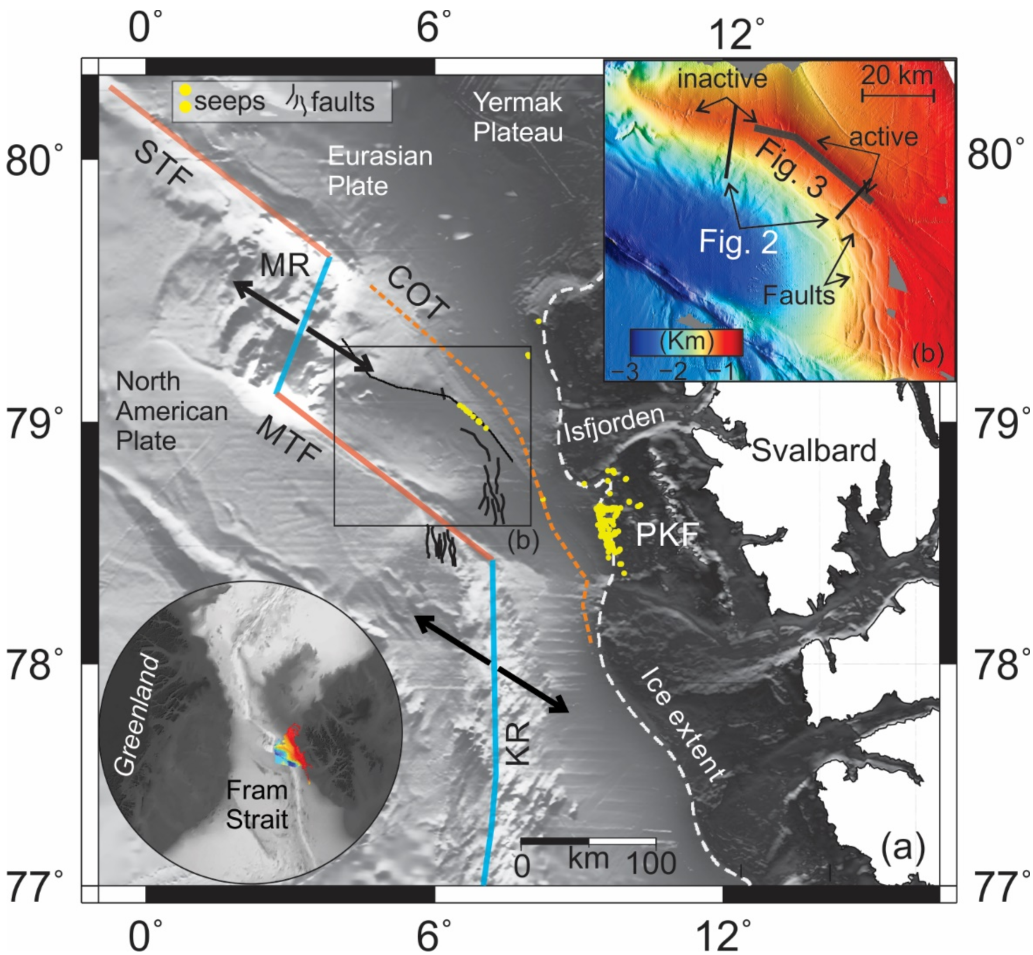

Figure 1: (a) International Bathymetry Chart of the Arctic Ocean (IBCAO) showing the geometry of mid-ocean ridges offshore the west-Svalbard margin; (b) High resolution bathymetry along the Vestnesa Ridge (UiT, R/V HH multi-beam system). Seafloor pockmarks are observed along the entire ridge but active 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).

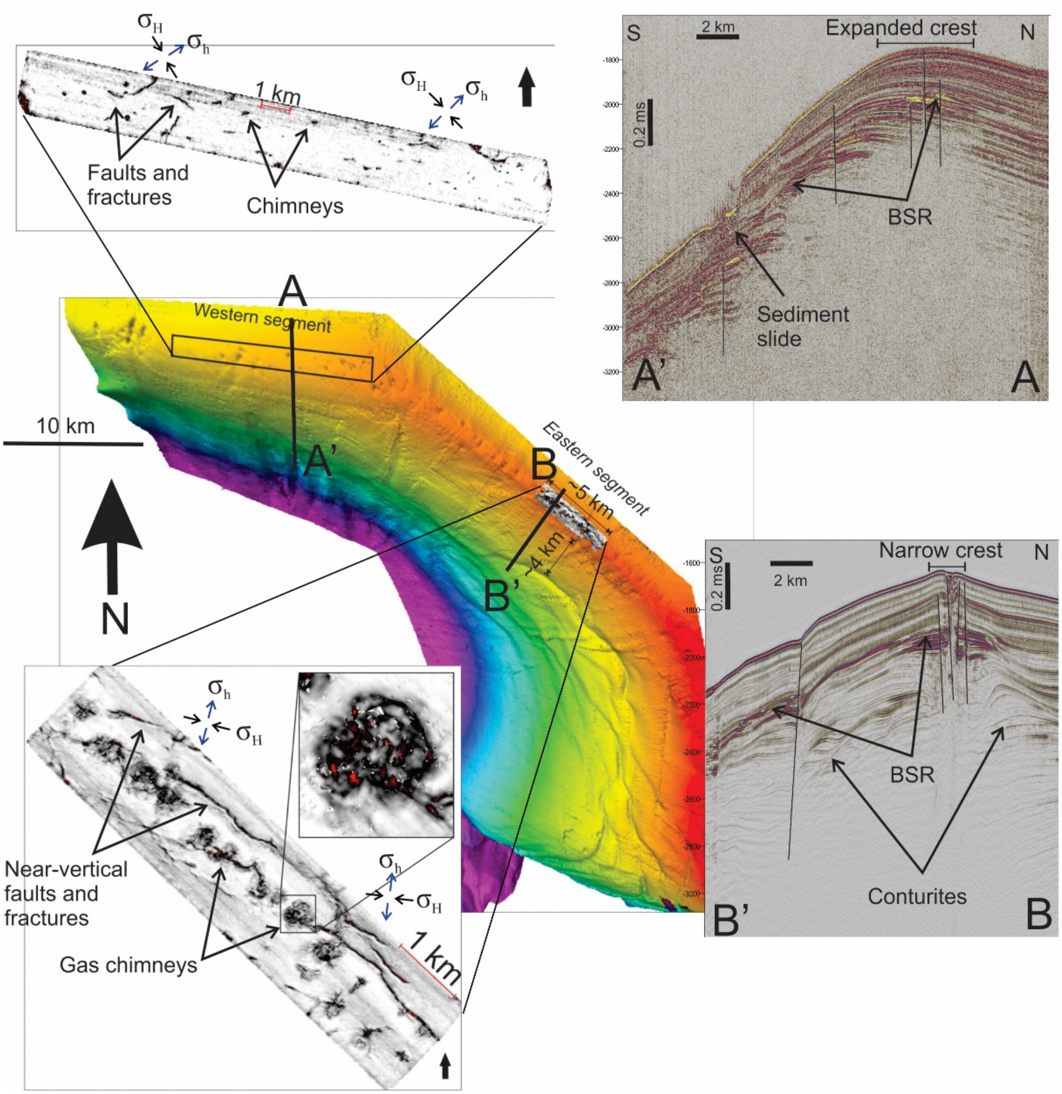

Figure 2: Composite figure with bathymetry and variance maps from 3D seismic data along the eastern and the western Vestnesa Ridge segments (modified from Plaza-Faverola et al., 2015). The orientation of maximum compressive horizontal stress (σ_H) and minimum horizontal stress (σ_h) predicted by the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

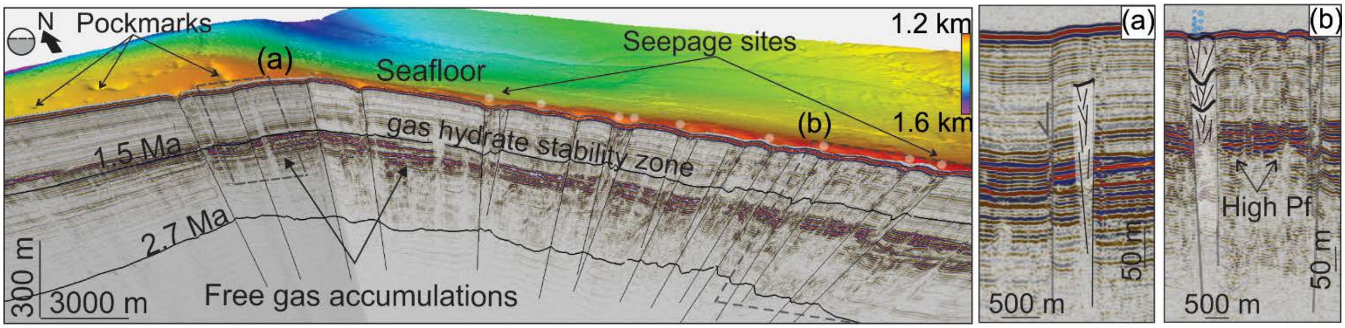

Figure 3: Integrated seismic and bathymetry image of the gas hydrate system along the Vestnesa Ridge. (a) Outcropping fault located at the transition from the active to the currently inactive pockmark region; (b) Gas chimneys with active seepage and inferred high pore-fluid pressure (Pf) zone.

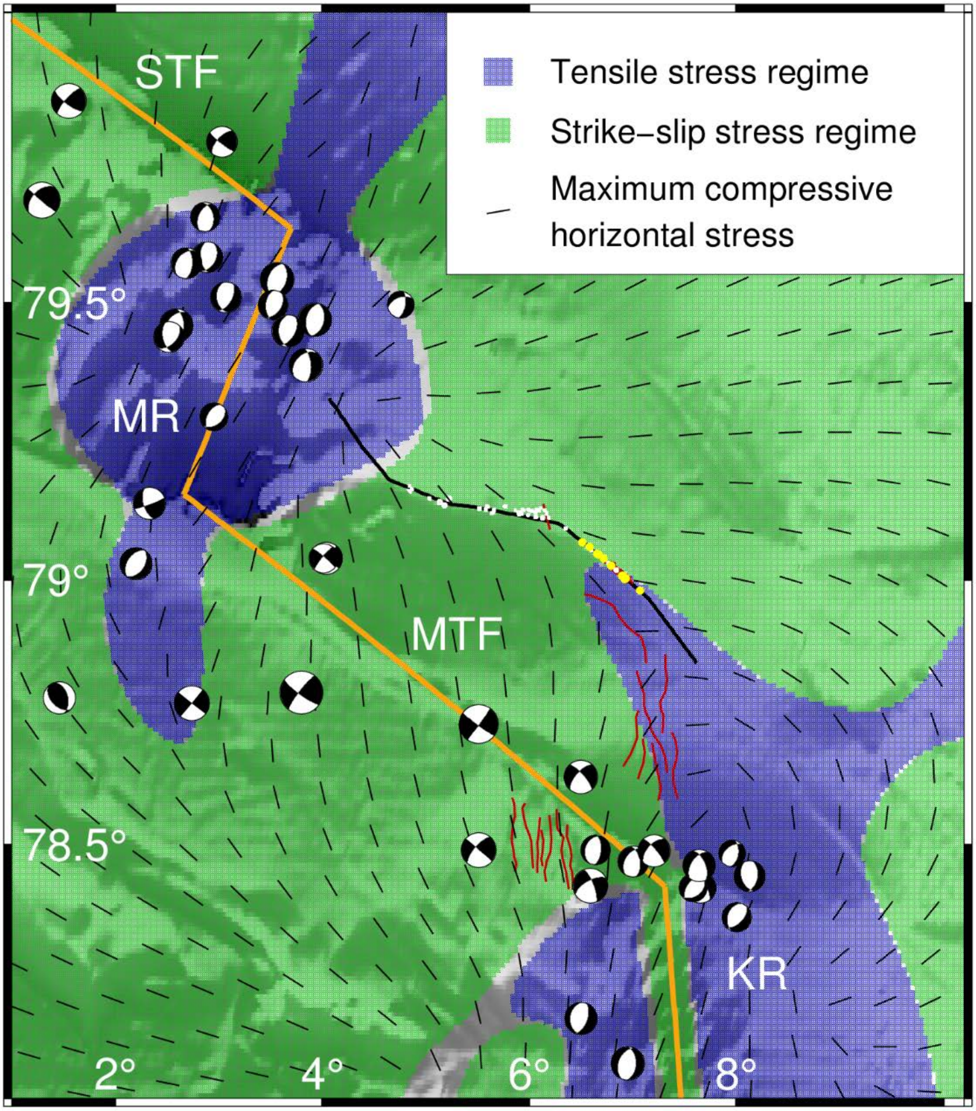

Figure 4: Modelled upper crustal tectonic stress field (blue – tensile and green - strike-slip regime) and stress orientations, due to oblique spreading at Molloy Ridge (MR) and Knipovich Ridge (KR). The seismic line is projected as reference for the crest of the Vestnesa Ridge. Red lines are faults, yellow dots seeps and white circles inactive pockmarks. The focal mechanisms are from the ISC Online Bulletin (http://www.isc.ac.uk).

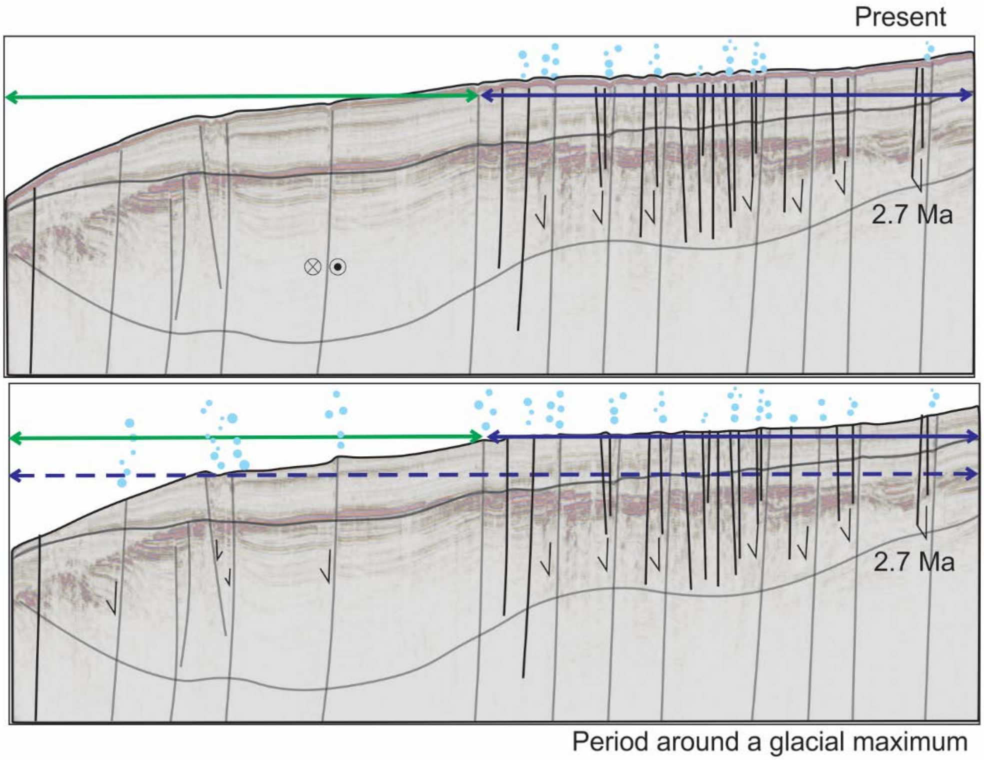

Figure 5: Conceptual model of the evolution of seepage coupled to faulting and spatial variations in the stress regime (tensile=blue; strike-slip=green) along the Vestensa Ridge, offshore the west-Svalbard margin. At present day, tensile stress from mid-ocean ridge spreading (blue solid line) favours 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.

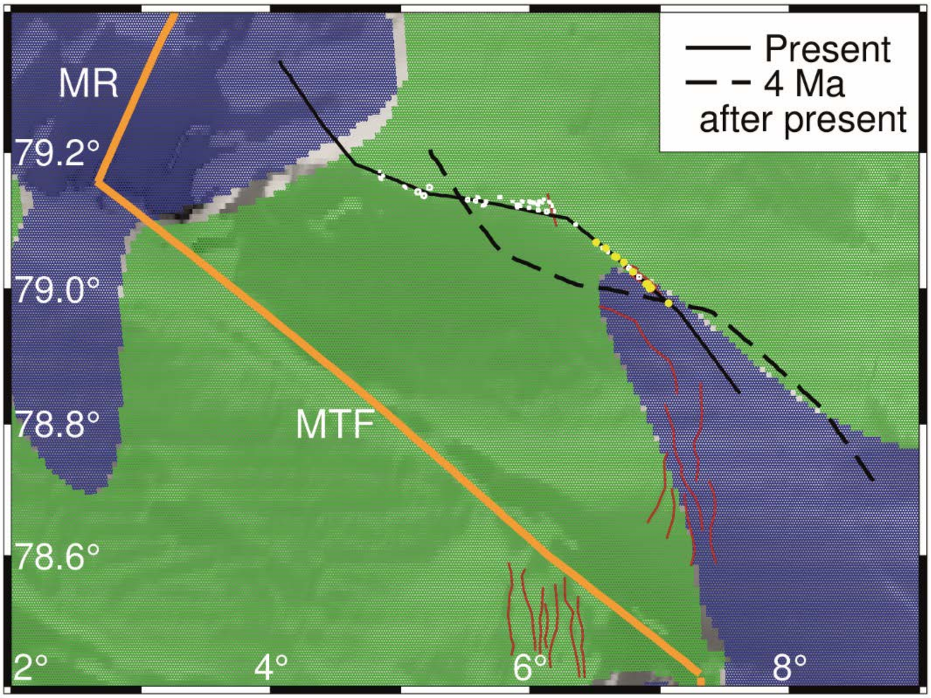

Figure 6: Stress field in figure 3 showing the location of the Vestnesa Ridge at present and 4 Ma after present time, assuming a constant spreading velocity of 7 mm/yr in the direction N125°E. The black polygon corresponds to the seismic line in Plaza-Faverola et al., (2017) and partly shown in figure 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:

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right)$$

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

$$\sigma_{ij} = \lambda\delta_{ij}\varepsilon_{kk} + 2\mu\varepsilon_{ij}$$

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 $\lambda = \frac{2\mu\nu}{1-2\nu}$.
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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