Gas-driven tensile fracturing in shallow marine sediments

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Abstract

The flow of gas through shallow marine sediments is an important component of the global carbon cycle and affects methane release to the ocean and atmosphere as well as submarine slope stability. Seafloor methane venting is often linked to dissociating hydrates or gas migration from a deep source, and subsurface evidence of gas-driven tensile fracturing is abundant. However, the physical links among hydrate dissociation, gas flow, and fracturing has not been rigorously investigated. We used mercury intrusion data to model the capillary drainage curves of shallow marine muds as a function of clay content and porosity. We combined these with estimates of in situ tensile strength to determine the critical gas saturation at which the pressure of the gas phase would exceed the pressure required to generate tensile fractures. Our work demonstrates that tensile fracturing is more likely as clay content increases due to decreased pore sizes and increased capillary pressure, but tends to be restricted to the shallowest portion of the sediment column (<130 m below seafloor) except when the clay-sized fraction exceeds 50%. Dissociating hydrate may supply sufficient quantities of gas to cause fracturing, but this is only likely near the updip limit of the hydrate stability zone, where release of methane bubbles from discrete vents is to be expected due to the combination of weak sediments and significant gas expansion. Gas-driven tensile fracturing is probably a common occurrence near the seafloor, does not require much gas, and is not necessarily an indication of hydrate dissociation.

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Key points

- Gas-driven tensile fracturing can occur easily in near-seafloor sediments
- If the clay-sized fraction exceeds 60-70%, gas saturations <10% can generate tensile fractures in sediments as deep as 2 km below seafloor
- Hydrate dissociation can cause fracturing and venting near the updip limit of hydrate stability, but is not the only source of vented gas

Abstract

The flow of gas through shallow marine sediments is an important component of the global carbon cycle and affects methane release to the ocean and atmosphere as well as submarine slope stability. Seafloor methane venting is often linked to dissociating hydrates or gas migration from a deep source, and subsurface evidence of gas-driven tensile fracturing is abundant. However, the physical links among hydrate dissociation, gas flow, and fracturing has not been rigorously investigated. We used mercury intrusion data to model the capillary drainage curves of shallow marine muds as a function of clay content and porosity. We combined these with estimates of in situ tensile strength to determine the critical gas saturation at which the pressure of the gas phase would exceed the pressure required to generate tensile fractures. Our work demonstrates that tensile fracturing is more likely as clay content increases due to decreased pore sizes and increased capillary pressure, but tends to be restricted to the shallowest portion of the sediment column (<130 m below seafloor) except when the clay-sized fraction exceeds 50%. Dissociating hydrate may supply sufficient quantities of gas to cause fracturing, but this is only likely near the updip limit of the hydrate stability zone, where release of methane bubbles from discrete vents is to be expected due to the combination of weak sediments and significant gas expansion. Gas-driven tensile fracturing is probably a common occurrence near the seafloor, does not require much gas, and is not necessarily an indication of hydrate dissociation.

Keywords: hydrates, fracturing, gas, marine sediments

Plain language summary

Gas bubble emissions from discrete locations on the seafloor are observed at many locations worldwide. Bubble emissions are often be linked to hazards such as submarine landslides and may contribute to ocean acidification and release of methane and carbon dioxide to the atmosphere. Observations indicate that the gas tends to move through fractures or cracks, but the role of gas in potentially forming those fractures and the overall process of gas accumulation and flow in shallow marine sediments are not well understood. Using a new model based on laboratory data to predict how much gas is needed to generate fractures in shallow marine sediments, we show that gas can easily generate fractures near the seafloor, particularly when the sediments contain a significant amount of clay. Our results demonstrate that gas-driven fracturing is probably a common occurrence near the seafloor, does not require very much gas, and may not necessarily be an indication of gas hydrate melting caused by ocean temperature increase.

1. Introduction

Methane hydrates are ice-like, non-stoichiometric compounds of water and methane that are stable at high pressure and low temperatures, and occur in the shallow subsurface of continental margins and in sediments below permafrost [*Ruppel*, 2011]. There are three research foci associated with methane hydrates: (1) as an energy resource, (2) as a large reservoir of carbon with associated roles in climate change and carbon cycling, and (3) as a potential marine geohazard [*Maslin et al*., 2010; *Boswell and Collett*, 2011; *Collett et al.*, 2015; *Ruppel and Kessler*, 2017]. The geomechanical aspects of methane hydrate formation and associated gas migration in marine sediments has been an active area of research for many years [e.g., *Flemings* *et al*., 2003; *Nimblett and Ruppel*, 2003; *Hornbach et al.*, 2004; *Xu and Germanovich*, 2006; *Jain and Juanes*, 2009; *Daigle and Dugan*, 2010b; *Fauria and Rempel*, 2011; *Stranne et al*., 2017]. Particular interest has been given to hydrate that occurs as a filling in fractures and veins [*Nimblett and Ruppel*, 2003; *Cook and Goldberg*, 2008; *Cook et al*., 2008; *Daigle and Dugan*, 2010b; *Daigle and Dugan*, 2011; *Cook et al*., 2014; *Jin et al*., 2015]. These features tend to occur predominantly in clay-rich sediments, suggesting that they are related to low permeability and associated elevated fluid pressures [*Ginsburg and Soloviev*, 1997; *Sassen et al*., 2001; *Weinberger and Brown*, 2006; *Daigle and Dugan*, 2010b; *Daigle and Dugan*, 2011], or that they form as a result of capillary forces inhibiting nucleation of disseminated hydrate within the pore space [*Clennell et al*., 1999; *Rempel*, 2011; *Cook et al*., 2014; *You et al*., 2019]. The prospect that marine sediments may fail in tension or shear due to pore pressures associated with fluid flow and methane hydrate dissociation has significant implications for hydrates as a geohazard and release of methane to the water column.

Gas-driven tensile fracturing in association with methane hydrates has been investigated or suggested by many authors [*Wood et al*., 2002; *Flemings et al*., 2003; *Natzeband et al*., 2005; *Zühlsdorff and Spiess*, 2004; *Liu and Flemings*, 2007; *Hustoft et al*., 2009; *Jain and Juanes*, 2009; *Daigle and Dugan*, 2010a; *Choi et al*., 2011; *Daigle et al*., 2011; *Holtzman and Juanes*, 2011; *Rees et al*., 2011; *Sun et al*., 2012; *Sultan et al*., 2014; *Stranne et al*., 2017]. Fractures are high-permeability conduits that can lead to venting of methane at the seafloor [e.g., *Hustoft et al*., 2009], and the ability of gas generated from hydrate dissociation to fracture overlying sediments has important implications for predicting feedbacks between ocean warming and methane release [e.g., *Archer et al*., 2009]. Issues relating to gas-driven tensile fracturing extend to marine sediments outside the hydrate stability zone as well, with the movement of gas posing hazards to offshore infrastructure and contributing to sediment-ocean methane exchange [*Best et al.*, 2006]. The importance of gas-driven fracturing to shallow gas movement is overall poorly understood due to a lack of predictive models [*James et al.*, 2016].

We used high-pressure mercury intrusion (HPMI) measurements performed on marine sediments from around the world to constrain relationships between capillary pressure and gas saturation, and combined this with estimates of tensile strength to predict the conditions under which gas-driven tensile failure may occur. We show that any amount of gas will cause fracturing in sediments as deep as 500 m below sea floor (mbsf) if the fraction of clay-sized grains is larger than 70%, while fracturing will only occur in sediment shallower than 100 mbsf when the clay-sized fraction exceeds 20%. The predictive model we present for variation in capillary pressure curves with porosity and clay-sized fraction allows for detailed predictions of sealing capacity and mode of gas migration in heterogeneous lithologies. We finally demonstrate that hydrate dissociation near the landward limit of the hydrate stability zone can easily lead to gas-driven tensile fracturing and bubble emission.

2. Tensile fracturing and capillary drainage

In a saturated porous medium, tensile failure will occur when the fluid pressure exceeds the sum of the minimum principal stress (σ_3) and the tensile strength of the medium (T) [*Jain and Juanes*, 2009; *Boudreau*, 2012] (all nomenclature is defined in Table 1). In a water-wet porous medium, a gas phase will always exist at a greater pressure than the water phase, with the pressure difference equal to the capillary pressure. In this situation, the gas phase will tend to be the phase initiating fracturing. The fracturing criterion can thus be written as

$$P_g > \sigma_3 + T, \qquad \text{(Eq. 1)}$$

where P_g is the gas phase pressure. Here, T is assumed to be positive as it represents a strength rather than a stress. Eq. 1 may be recast in terms of the capillary pressure P_c by subtracting the water phase pressure P_w from both sides:

$$P_g - P_w = P_c > \sigma_3 - P_w + T. \qquad \text{(Eq. 2)}$$

Note that the presence of two immiscible fluid phases requires the use of total, rather than effective, stress in Eqs. 1 and 2, since stress transfer across fluid-fluid interfaces changes the thermodynamic considerations of the relationships between fluid phase pressures and the deformation of the porous medium [*Bishop*, 1959; *Coussy*, 2004, 2007; *Nuth and Laloui*, 2008; *Boudreau*, 2012]. Indeed, if a thin film of water separates gas from the grain surface as expected in a water-wet medium [*Hirasaki*, 1991], the gas-phase pressure can only act on the rock through the water film, causing a local increase in the water-phase pressure. The use of the total stress removes the need to consider this effect. Eq. 2 thus establishes a fracture criterion based on capillary pressure.

The capillary pressure of the gas phase is related to the volume fraction of the pore space occupied by gas, which is the gas saturation S_g. As a nonwetting phase, gas must overcome an entry pressure for the curved gas-water interface to enter a pore and displace water. For a cylindrical pore of radius r, the entry pressure P_e for a completely nonwetting fluid is given by Washburn's equation [*Washburn*, 1921]:

$$P_e = \frac{2\gamma}{r}, \quad \text{(Eq. 3)}$$

where γ is the gas-water interfacial tension. Because sediments contain a range of pore sizes, different values of gas pressure will correspond to gas entering pores of different sizes. The capillary drainage curve describes the relationship between gas pressure and gas saturation with the assumption that gas will fill the largest pores at the lowest pressures and move into progressively smaller pores with increasing pressure [*Bear*, 1972]. During primary drainage, wherein the sediment begins fully saturated with water, gas must first overcome the entry pressure of the largest pores. After that, with each pressure increment it will displace water from any pore that has an entry pressure smaller than or equal to the new capillary pressure and has a connected pathway to existing gas-filled pores [*Larson and Morrow*, 1981]. The value of P_c that satisfies the tensile fracturing criterion in Eq. 2 may therefore be related to a critical gas saturation through the capillary drainage curve.

The potential for tensile fracturing due to excess gas pressure can be reduced if the gas pressure can dissipate by porous flow. Flow of a nonwetting phase in a porous medium can only occur if the gas saturation achieves a certain mobility threshold saturation. The mobility threshold depends on many different properties of the sediment, including pore structure and scale of heterogeneities. While numerical and laboratory pore network models have demonstrated that nonwetting phase flow occurs only after the saturation achieves the percolation threshold [*Chatzis and Dullien*, 1977; *Larson and Morrow*, 1981; *Lenormand et al*., 1983; *Diaz et al*., 1987; *Ewing and Gupta*, 1993; *Sahimi*, 2011], experiments on real muds and mudrocks have shown gas breakthrough at saturations far below the percolation threshold. *Schowalter* [1979] suggested a mobility threshold of 10%, while the experiments of *Hildenbrand* *et al.* [2002; 2004] suggest a much lower value around 2%. If the mobility threshold is reached before tensile failure occurs, then pressure can be dissipated by porous flow. The exception to this is the case where the rate of pressure buildup exceeds the rate of dissipation to the point where tensile fracture occurs. We note that our treatment of gas-driven tensile failure considers the coexistence of a wetting and nonwetting phase within a representative elementary volume of a porous medium. We are not considering dynamics of gas ganglia, thin fluid films, or other processes operating at the grain or pore scale. Since the capillary drainage curve is a macroscopic description of the relationship between nonwetting phase pressure and saturation [*Bear*, 1972], our approach to the fracturing criterion should be valid. More sophisticated models are needed to examine behavior at the grain scale [e.g., *Jain and Juanes*, 2009; *Bihani and Daigle*, 2019].

Finally, we note that we do not consider fracture propagation or any dynamic mechanical response after the fracturing criterion is met. *Johnson et al.* [2002] and *Barry et al.* [2010], among others, have shown that tensile failure and gas bubble rise in shallow marine sediments is described well by linear elastic fracture mechanics (LEFM). There are two pertinent items related to fracturing behavior. First, *Algar et al.* [2011] and *Boudreau* [2012] have shown that, after gas initially opens a fracture that then closes, subsequent gas escape will occur preferentially by reactivating the existing fracture surface. The fracture criterion we adopt in this work corresponds to initial fracturing, but it is important to remember that subsequent fracturing will be much easier and occur at lower gas pressures and saturations. Second, the opening of a tensile fracture compresses the surrounding, unfailed sediment, which inhibits additional tensile fracturing in the immediate vicinity of the original fracture due to the local increase in horizontal stress. This phenomenon is known as the stress shadow effect [*Warpinski and Teufel*, 1987; *Warpinski and Branagan*, 1989]. Tensile fractures will therefore have a characteristic spacing that is related to the material properties of the host sediments. This in turn may limit the gas flow rate as fracture spacing controls fracture system permeability along with fracture aperture [*Daigle and Dugan*, 2010b].

3. Methods

Determining the potential for gas-driven tensile fracturing requires (1) an estimate of in situ stresses, (2) an estimate of tensile strength, and (3) a capillary drainage curve. An illustration of this process with relevant parameters is shown in Fig. 1.

3.1 In situ stress estimation

We considered a generic marine sedimentary setting where the maximum principal stress was vertical (σ_v), and the sediments were vertically transversely isotropic such that the two horizontal stresses were equal to the minimum principal stress σ_h. We emphasize here that these are far-field stresses and not subject to any local perturbations that may arise from the presence of gas. Defining the vertical and horizontal effective stresses as $\sigma_v' = \sigma_v - P_w$ and $\sigma_h' = \sigma_h - P_w$ where P_w is the porewater pressure, from linear elasticity

$$\sigma_h' = \frac{\nu}{1-\nu}\sigma_v', \qquad \text{(Eq. 4)}$$

or

$$\sigma_h = \frac{\nu}{1-\nu}(\sigma_v - P_w) + P_w, \qquad \text{(Eq. 5)}$$

where v is Poisson's ratio. We acknowledge that there is longstanding disagreement in the literature as to how well Eqs. 4 and 5 represent the true in situ stresses in shallow marine sediments (see the discussion in *Zoback* [2007]). For example, *Eaton* [1969] used drilling data from the Gulf of Mexico to back-calculate Poisson's ratio from Eq. 4 and found that $v < 0.3$ was necessary to fit the data in the shallowest sediments. These values of v are much lower than typical values for shallow sediments (>0.4 [*Hamilton*, 1979; *Reynolds*, 1997]). On the other hand, leak-off test data from shallow sediments in the Gulf of Mexico [*Wojtanowicz et al*., 2000] and the South China Sea [*Yan et al.*, 2015] indicate that the minimum horizontal stress is very close to the vertical stress ($\sigma_h'/\sigma_v' > 0.8$) which is more consistent with expected values of v (i.e., $\sigma_h'/\sigma_v' = 0.8$ implies $v = 0.44$ from Eq. 4). Our use of Eqs. 4 and 5 is therefore consistent with evidence in the literature. If σ_h is overestimated, the result in our model will simply be that gas-driven tensile fracturing will be more likely.

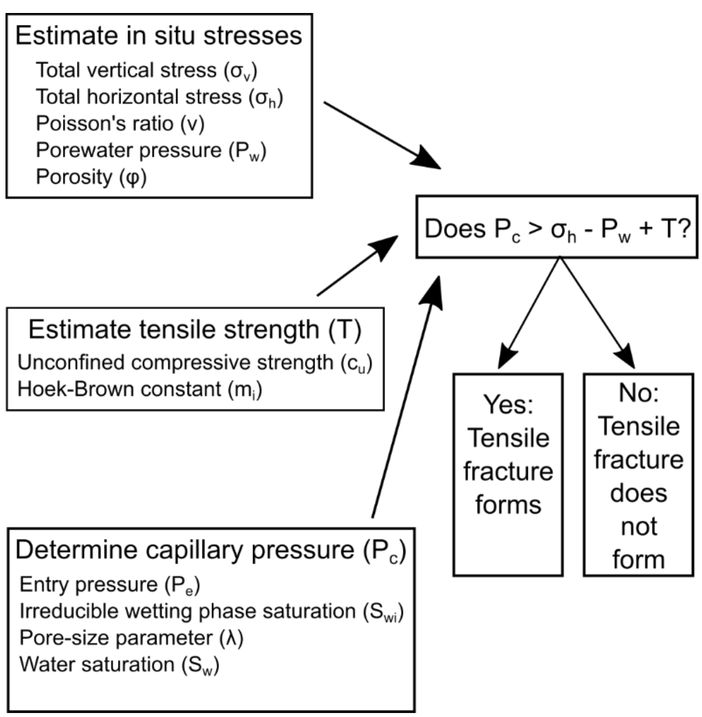

Figure 1. Illustration of process for determining the potential for tensile failure with relevant parameters.

We used the relationship reported by *Kominz et al.* [2011] for clay to determine porosity φ as a function of depth below seafloor z (m):

$$\varphi = 0.775e^{-\frac{z}{1251}}. \quad \text{(Eq. 6)}$$

Note that this differs from the form of the equation given by *Kominz et al.* [2011] as it has been modified to yield porosity in decimal rather than percent. Eq. 6 is valid for sediments shallower than 500 m below seafloor (mbsf) (Fig. 2a). We then determined the bulk density as a function of depth from the porosity with pore fluid density of 1024 kg/m^3 and sediment grain density of 2700 kg/m^3. The vertical effective stress was then calculated by integrating the bulk density with respect to depth with an assumption of hydrostatic pore pressure. To find σ_h, we determined ν as a function of depth by fitting a 6th-order polynomial to *Hamilton*'s [1979] compilation of ν in shallow marine sediments, and the total vertical stress was obtained from porosity or bulk density data (Fig. 2b).

3.2 Tensile strength estimation

In the framework of *Griffith* [1921], marine sediments may be considered as media filled with a number of existing flaws that increase in size and coalesce during fracturing. One method of obtaining the tensile strength in this framework is to determine the mode I fracture toughness and make an assumption of initial flaw size, thus determining the tensile strength using LEFM. Many studies have shown that this method can accurately describe the fracture initiation and propagation processes in marine sediments [*Johnson et al*., 2002; *Boudreau et al*., 2005; *Algar*

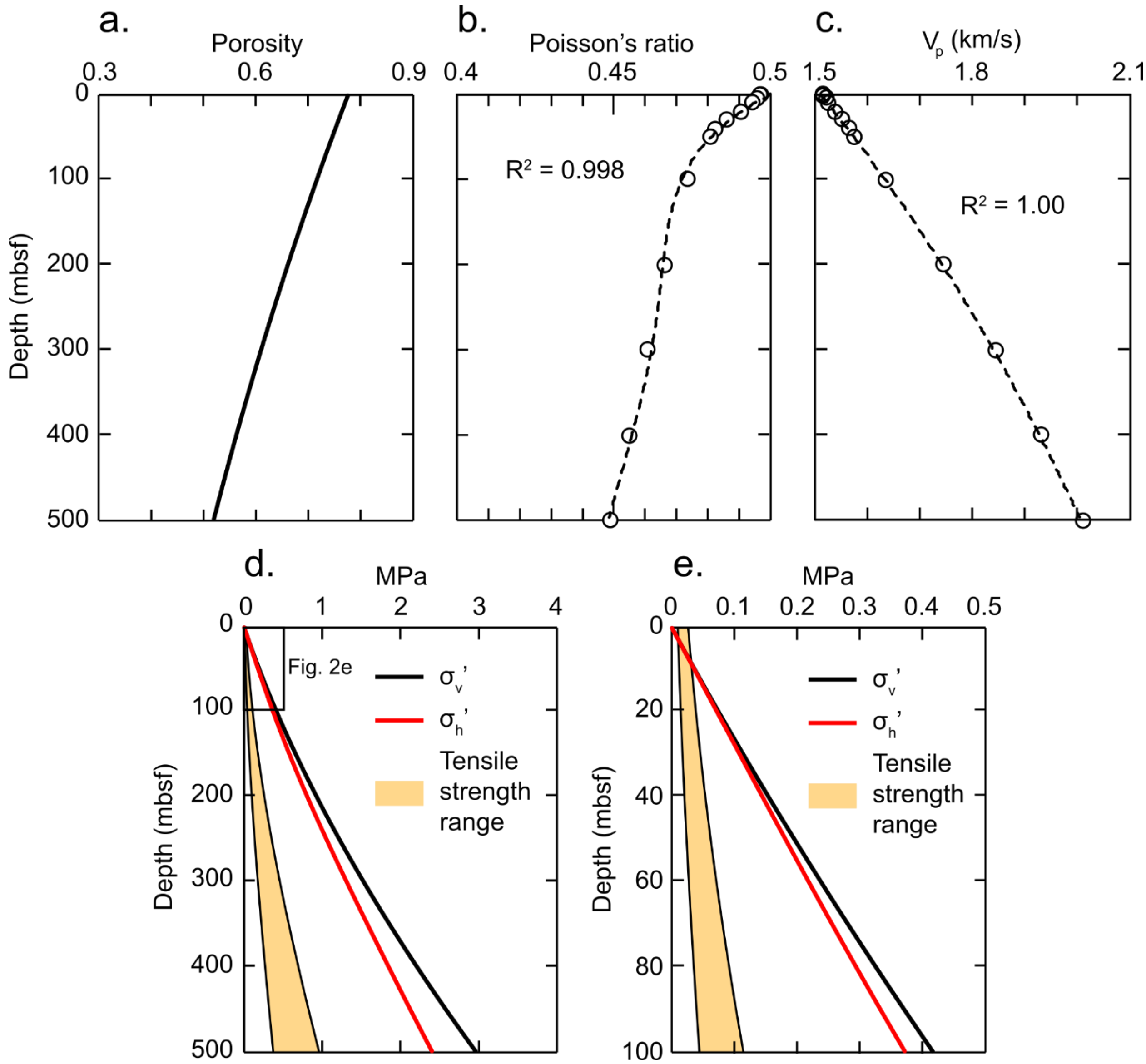

Figure 2. (a) Porosity-depth curve from *Kominz et al.* [2011]. (b) Polynomial fit for Poisson's ratio versus depth. (c) Polynomial fit for compressional wave velocity (V_p) versus depth. Data shown in (b) and (c) from *Hamilton* [1979]. (d) Vertical and horizontal effective stresses along with range of tensile strength for our generic passive margin sediments. (e) Close-up of (d) showing behavior at shallow depths.

and Boudreau, 2010; *Barry et al*., 2010; *Johnson et al*., 2012]. However, as *Boudreau* [2012] points out, the initial flaw size in marine sediments is usually unknown, which presents serious challenges in using LEFM as a predictive tool for tensile strength. Therefore, we adopted a simpler method of determining tensile strength based on the Hoek-Brown failure criterion [*Hoek and Brown*, 1997].

The Hoek-Brown failure criterion is an empirically derived, nonlinear Mohr-Coulomb failure envelope. For intact rocks, the tensile strength T is related to the unconfined compressive strength c_u by

$$T = -\frac{c_u}{2}\left(m_i - \sqrt{m_i^2 + 4}\right), \qquad \text{(Eq. 7)}$$

where m_i is the Hoek-Brown constant. *Hoek* [2006] gives a recommended value of $m_i = 4 \pm 2$ for claystones, and this value is consistent with results of triaxial shear experiments performed on marine muds and mudstones by *Silva et al*. [2000], *Moses et al*. [2003], *Dugan and Germaine* [2009], and *Schumann et al*. [2014]. Therefore we used this value for m_i. To determine c_u, we used the correlation of *Ingram and Urai* [1999] for muds and mudrocks:

$$\log_{10} c_u = -6.36 + 2.45 \log_{10}\left(0.86 V_p - 1172\right), \qquad \text{(Eq. 8)}$$

where c_u is given in MPa and V_p is compressional wave velocity in m/s. The vertical and horizontal effective stresses, as well as the range of tensile strength predicted from Eq. 7, are shown in Figs. 2d and 2e. Tensile strength ranges from 18.1±7.92 kPa at the sea floor to 679±297 kPa at 500 mbsf (with uncertainties corresponding to the possible range of m_i). The average value at 500 mbsf is 28% of the horizontal effective stress, and this ratio is relatively constant at 21-28% from 30 to 500 mbsf, above which the tensile strength corresponds to a greater fraction of the horizontal effective stress.

3.3 Capillary drainage curves

We used the Brooks-Corey parameterization of the capillary drainage curve:

$$P_c(S_w) = P_e\left(\frac{S_w - S_{wi}}{1 - S_{wi}}\right)^{-\frac{1}{\lambda}}, \qquad \text{(Eq. 9)}$$

where S_w is the wetting phase saturation (assumed to be water), S_{wi} is the irreducible wetting phase saturation, P_e is the capillary entry pressure, and λ is the pore-size parameter [*Brooks and Corey*, 1964]. To constrain the Brooks-Corey parameters (P_e, S_{wi}, and λ), we used previously published mercury intrusion capillary pressure (MICP) performed on natural and resedimented samples of marine muds from various locations around the world [*Daigle and Dugan*, 2014; *Daigle et al*., 2019]. The Brooks-Corey parameters are expected to vary with grain size and porosity. We found the following correlations for P_e and λ:

$$\ln P_e = (6.59 \pm 0.584)(1 - \varphi + S_{wi})f_c - (2.76 \pm 0.224), \qquad \text{(Eq. 10)}$$

where P_e is in MPa, φ is total porosity (determined independently for all samples by the moisture-and-density method), and f_c is the mass fraction of the solid matrix composed of clay-sized grains (smaller than 2 μm in diameter). Eq. 10 calculates P_e for methane invading a water-saturated pore, while the pressures measured in the MICP tests corresponded to mercury entering an evacuated pore. The mercury pressures were converted to equivalent methane-water pressures by multiplying by $-(\gamma_{CH4,W}\cos\theta_{CH4,W})/(\gamma_{Hg,V}\cos\theta_{Hg,V})$ where $\gamma_{CH4,W}$ is the methane-water interfacial tension (0.072 N/m), $\theta_{CH4,W}$ is the contact angle of the methane-water interface on solid grains (0°) [*Henry et al.*, 1999], $\gamma_{Hg,V}$ is the mercury-vacuum interfacial tension (0.480 N/m), and $\theta_{Hg,V}$ is the contact angle of the mercury-vacuum interface on solid grains (140°) [*Purcell*, 1949]. The minus sign in this expression is necessary since $\cos\theta_{Hg,V} < 0$. The correlation for the pore-size parameter was found to be

$$\ln\lambda = (1.64 \pm 0.162)f_c - (0.921 \pm 0.0774). \qquad \text{(Eq. 11)}$$

These correlations had R^2 of 0.81 and 0.46, respectively (Fig. 3). The reported errors in the regression coefficients are ±1 standard deviation.

The S_{wi} determined from an MICP test is not the true irreducible wetting phase saturation (i.e., the wetting phase volume fraction trapped irretrievably by capillary forces) because during the MICP test mercury (assumed to be the nonwetting phase) displaces air or vacuum (assumed to be the wetting phase). Therefore, some independent estimate of S_{wi} is necessary to be able to predict the behavior of a gas-water system. *Daigle et al.* [2015] showed that the volume of clay-bound water in marine muds can be determined from porosity and fraction of clay-sized (<2 μm) grains. Since S_{wi} represents the amount of water remaining in the pore system at infinite capillary pressure, the amount of clay-bound water can be used as a reasonable proxy. Therefore we determined S_{wi} following *Daigle et al.* [2015] as

$$S_{wi} = (0.326 \pm 0.0220)f_c^{0.219\pm0.103} + (0.0262 \pm 0.00915)/\varphi, \qquad \text{(Eq. 12)}$$

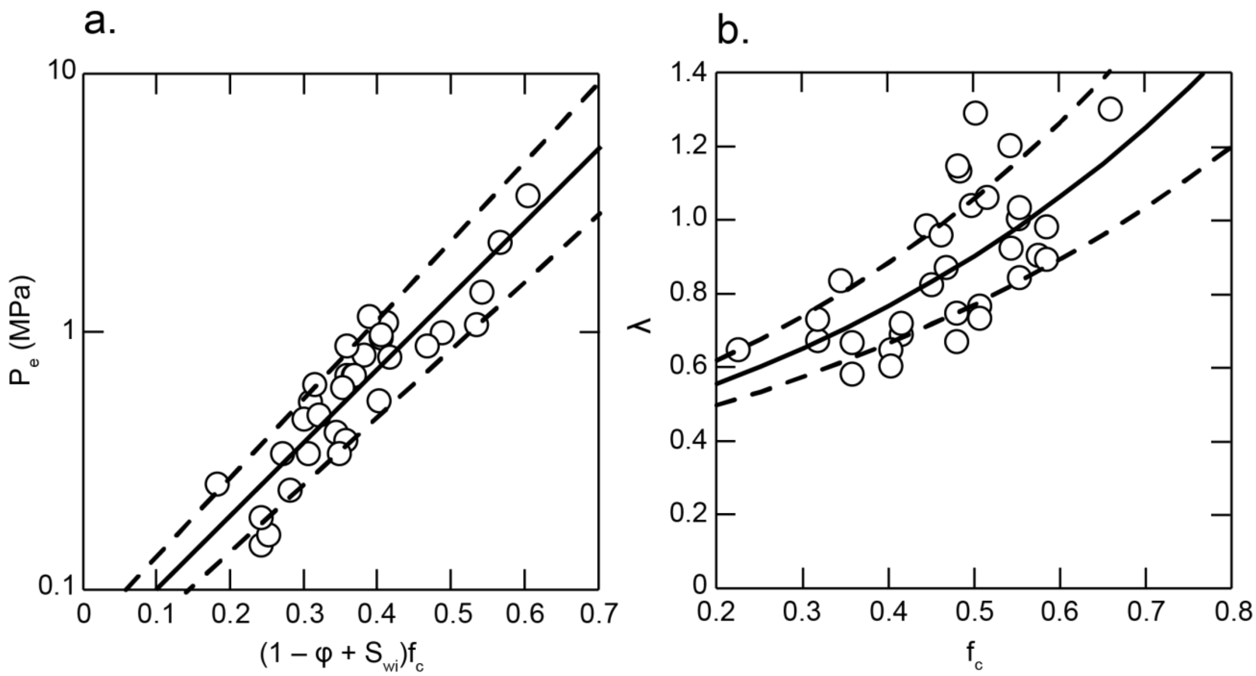

Figure 3. (a) Correlation for predicting entry pressure. (b) Correlation for predicting λ. Solid lines in both plots are best fit, while the dashed lines are ±1 standard deviation.

where the reported errors are ±1 standard deviation. The Brooks-Corey capillary drainage curves with parameters determined from Eqs. 10-12 are shown in Figure 4 for $\varphi = 0.7$ and 0.4 and $f_c =$ 0.7 and 0.2. Our approach differs from that of *Leverett* [1941] in that knowledge of permeability is not necessary. Indeed, formulating the capillary pressure curve in terms of porosity and clay-size fraction allows more direct facies-based prediction using empirical models that are specific to shallow marine sediments.

3.4 Fracture versus flow

Gas will migrate by porous flow instead of initiating tensile fractures if it achieves the mobility threshold at a capillary pressure below the fracturing criterion given by Eq. 2 and the intrinsic sediment permeability and gas-phase relative permeability are large enough to allow flow without additional pressure buildup. Based on the work of *Schowalter* [1979], we assumed a mobility threshold gas saturation of 10%, where the gas saturation $S_g = 1 - S_w$. If the fracturing criterion is achieved at gas saturations lower than this value, then tensile fracturing will occur before porous flow (Fig. 5a). If the capillary pressure at 10% gas saturation is smaller than the fracture criterion, this does not necessarily preclude tensile fracturing. Rather, it indicates that a rapid, transient increase in gas saturation would be required to generate fractures, as this could allow the gas pressure to reach the fracture criterion before being dissipated by porous flow (Fig. 5). Note that using a 10% mobility threshold will give more conservative estimates of fracturing behavior than using the percolation threshold, which is considerably larger than 10% in shallow

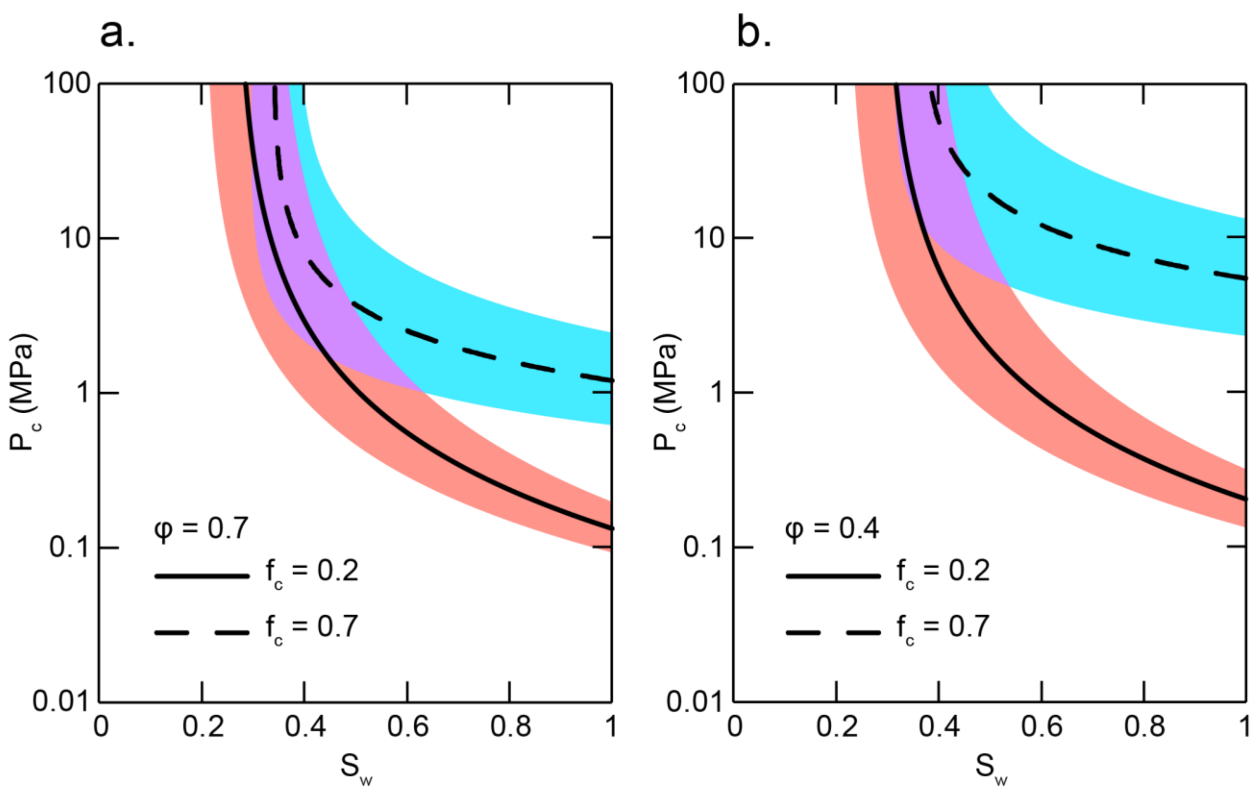

Figure 4. Predicted capillary drainage curves for porosities of 0.7 (a) and 0.4 (b) at clay fractions of 0.2 and 0.7. The shaded regions represent the overall uncertainty based on the uncertainties of the input parameters.

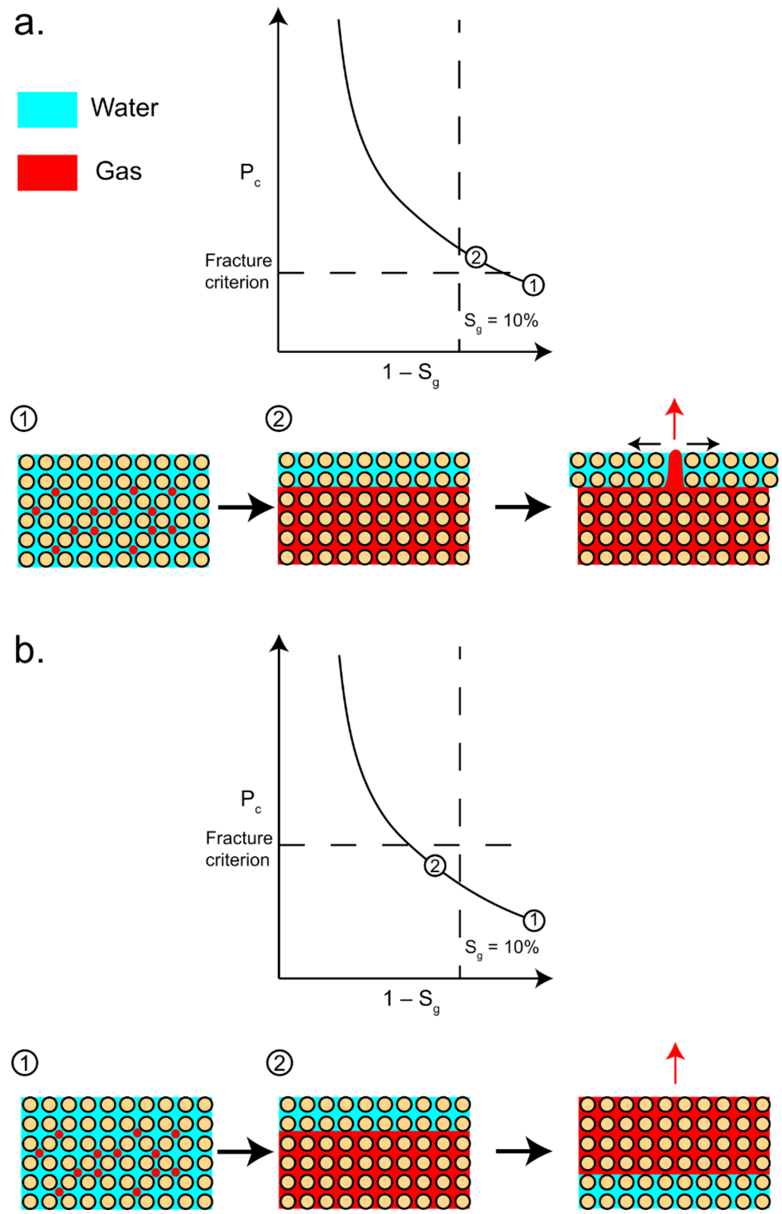

Figure 5. (a) Capillary pressure at the fracture criterion corresponding to a gas saturation smaller than the mobility threshold. At point 1, gas (red) starts accumulating in the sediment. This could be due to local microbial methanogenesis, hydrate dissociation, or buoyant migration of discrete bubbles from a deeper source. The gas continues accumulating to a gas saturation and capillary pressure represented by point 2. At this point, the fracture criterion is exceeded and the gas opens a tensile fracture, allowing buoyant migration. (b) Capillary pressure at the fracture criterion corresponding to a gas saturation larger than the mobility threshold. Gas starts accumulating (point 1) to a saturation and capillary pressure corresponding to point 2. Since this saturation is larger than the mobility threshold and the capillary pressure is smaller than the fracture criterion, the gas can move by porous flow.

marine muds [*Daigle et al*., 2019]. Future research should investigate gas mobility thresholds specific to marine muds, and how this threshold varies during burial.

4. Results

4.1 Generic marine hydrate system

We considered the tensile fracturing behavior of a generic marine hydrate system. The seafloor depth and temperature were 2000 m and 3°C, and the geothermal gradient was 40°C/km. These values were selected to represent a deepwater, passive continental margin. The water density and salinity were 1024 kg/m^3 and 3.5 wt% NaCl equivalent and the water-phase pressure was assumed hydrostatic. Based on the sI methane hydrate equilibrium temperature-pressure curve obtained from the CSMHYD program [*Sloan*, 1998], the base of the hydrate stability zone (BHSZ) was located at 403 mbsf.

Figure 6 shows the range of gas saturations necessary to form tensile fractures (±1 standard deviation), taking into account the uncertainties in the Brooks-Corey parameters and Hoek-Brown tensile strength estimate. In each panel of Fig. 6, the mobility threshold is marked with a dashed vertical line. Tensile fracturing will be favored over porous flow wherever the gas saturation necessary for fracture (dark black line) is to the left of the mobility threshold line. For sediments with f_c = 0.2, fracturing occurs at gas saturations less than 10% shallower than 38 mbsf for the median case, indicating that gas accumulation in the shallowest 38 m of sediment will tend to result in tensile fracturing rather than porous flow (Fig. 6a). As f_c increases, fracturing is favored over more of the hydrate stability zone. For f_c = 0.5, fracturing is possible in the median case shallower than 132 mbsf (Fig. 6b), and for f_c = 0.7 fracturing is possible in the median case over the entire hydrate stability zone (Fig. 6c). Increasing the clay-sized fraction of

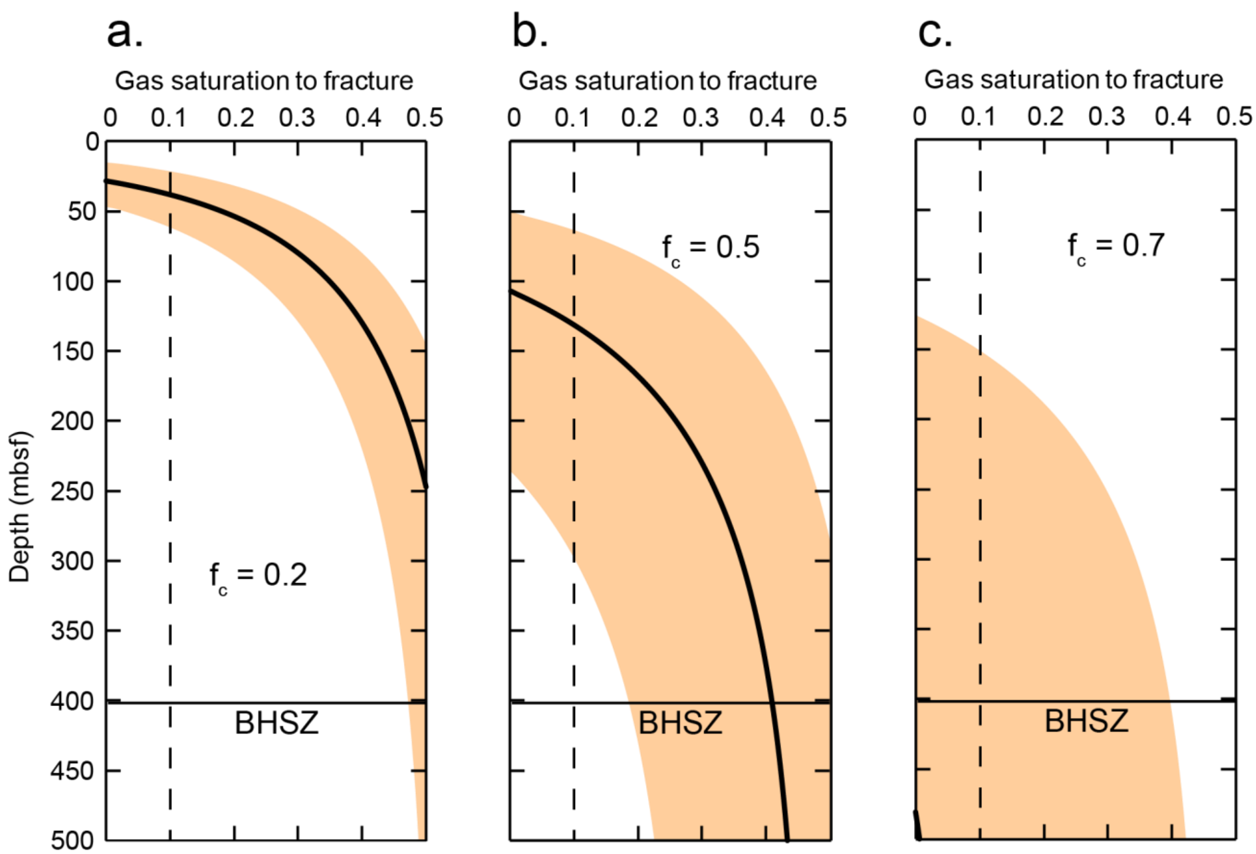

Figure 6. Gas saturation required to reach the fracture criterion in our generic passive margin sediments for clay fractions of 0.2 (a), 0.5 (b), and 0.7 (c). The solid black line represents the median prediction, while the shaded region shows the uncertainty. The vertical dashed line indicates the gas mobility threshold. Fracturing will happen whenever the solid black line is to the left of the vertical dashed line.

the sediment thus makes gas-driven tensile fracturing more likely. Since the absolute permeability of marine muds decreases with increasing clay-sized fraction at constant porosity [*Daigle and Screaton*, 2015], higher clay-sized fraction will also decrease the rate of excess pore pressure dissipation, which would further promote tensile fracturing at gas saturations above the mobility threshold in the case of sufficiently rapid gas evolution from hydrate dissociation or an external source.

4.2 Fracturing caused by hydrate dissociation at the BHSZ

While we have demonstrated the conditions that favor gas-driven tensile fracturing within the hydrate stability zone, a more pertinent question for hydrate-bearing sediments is the potential for gas-driven fracturing at the BHSZ, as this is where hydrate will first dissociate as a result of an increase in the steady-state temperature profile [*Ruppel*, 2011]. Indeed, many locations around the world already have thick gas columns trapped beneath the BHSZ [*Flemings et al*., 2003; *Hornbach et al*., 2004; *Tréhu et al.*, 2004], which raises the possibility that the sediments in these locations may already be near or at the conditions required for tensile failure.

We considered a generic passive margin setting in water depths ranging from 500 to 3000 m. The seawater density and salinity and geothermal gradient were the same as those assumed in Section 4.1. For the temperature at the sea floor, we interpolated the temperature-depth data presented by *Phrampus and Hornbach* [2012] based on conductivity-temperature-depth (CTD) casts in the vicinity of the Blake Ridge outside the influence of the Gulf Stream. While these data are specific to Blake Ridge, *Phrampus and Hornbach* [2012] compared the data to similar data from the eastern Pacific Ocean and found agreement to within 1.5°C, suggesting that these data are representative of a generic sea floor temperature. Using the seafloor temperature, specified geothermal gradient, and hydrostatic pressure, we determined the depth of the BHSZ by comparing the in situ temperature with the equilibrium temperature-pressure data from CSMHYD (Fig. 7a). No hydrate stability zone exists in the sediments at water depths shallower than 523 m, and this water depth represents the updip limit or feather edge of the hydrate stability zone, so called because thickness of the hydrate stability zone within the sediments decreases to zero at this water depth [*McIver*, 1982; *Ruppel*, 2011]. At greater water depths, the hydrate stability zone thickens, reaching a thickness of 483 m at 3000 m water depth.

Since the tensile strength of marine muds increases with depth, as does the minimum principal stress, greater amounts of gas are required to initiate tensile fractures at the BHSZ in deeper water. For sediments with f_c = 0.2, the median gas saturation necessary to fracture at the BHSZ is smaller than 10% only for water depths shallower than 560 m (Fig. 7b), indicating that tensile failure of coarser-grained marine muds at the BHSZ is unlikely except right at the feather edge of the hydrate stability zone. As clay-sized fraction increases, fracturing at the BHSZ becomes easier. At f_c = 0.5, the median gas saturation required for fracturing at the BHSZ is less than 10% for water depths shallower than 670 m (Fig. 7c), and 1670 m for f_c = 0.7 (Fig. 7d).

We also determined the minimum clay-sized fraction necessary for gas-driven tensile failure at the BHSZ, defined as the value of f_c that yields a median capillary pressure at 10% gas saturation equal to the median fracturing criterion. This value increases rapidly from zero to around 0.6 as water depth increases from 523 m to 1000 m, and increases only slightly with further increase in water depth. For a water depth of 3000 m, the sediments at the BHSZ must have f_c > 0.69 for gas-driven tensile failure (Fig. 7e). At the updip limit of the hydrate stability zone, fracturing is much easier. Our modeling suggests that fracturing will always occur, regardless of clay-size fraction, at the feather edge and in water depths as deep as 540 m (Fig. 7f).

5. Discussion

5.1 How much hydrate needs to dissociate?

Gas-driven tensile fracturing is important to understand in the context of the global carbon cycle. Fractures that breach the sea floor and allow venting of gas from below the BHSZ provide important nutrients for chemosynthetic communities at the sea floor [e.g., *Torres et al.*,

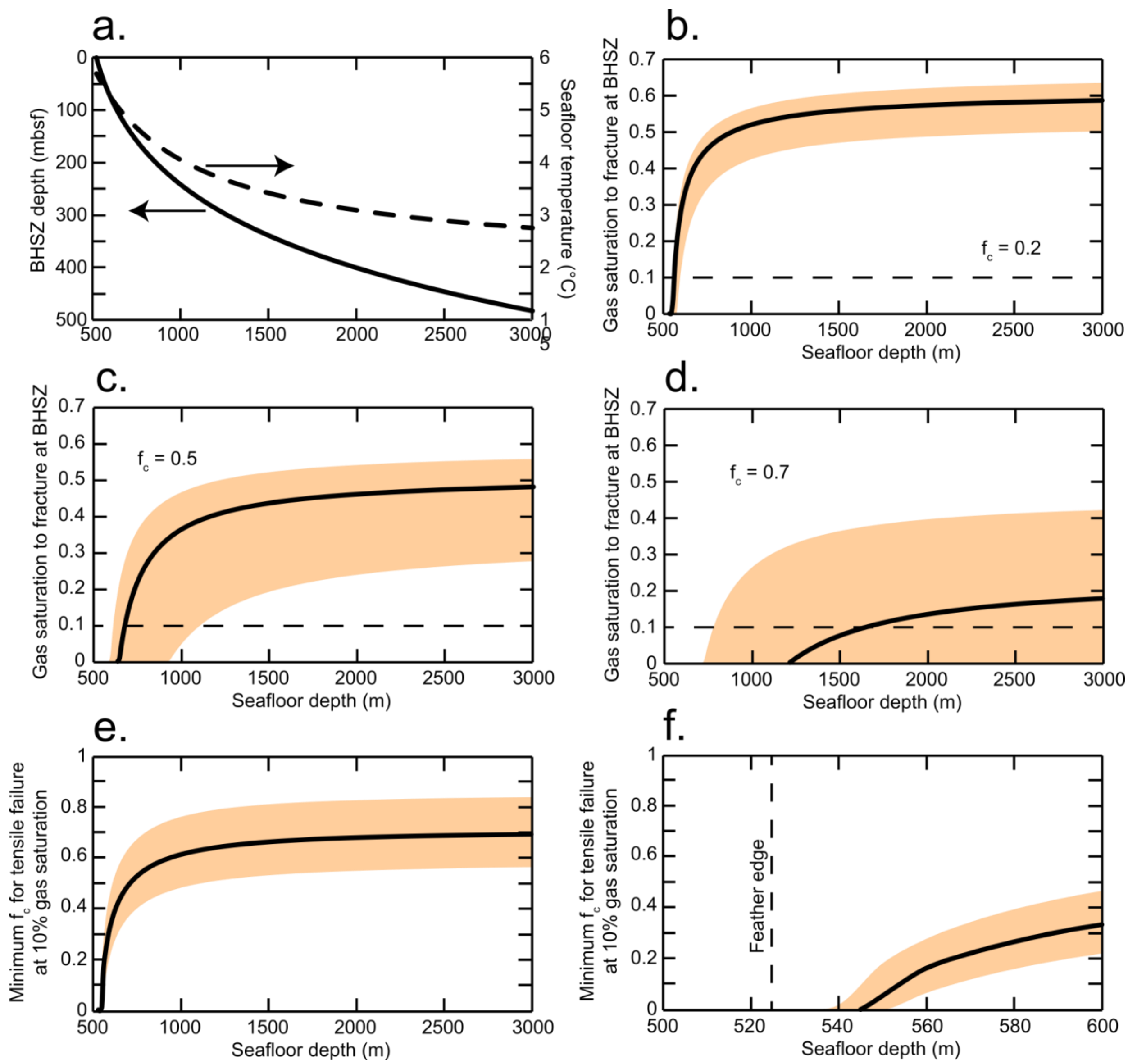

Figure 7. (a) Seafloor temperature and BHSZ depth as a function of water depth for our modeled case. Temperature based on data from *Phrampus and Hornbach* [2012]. The arrows indicate that BHSZ depth (solid line) is plotted on the left-hand y-axis while seafloor temperature (dashed line) is plotted on the right-hand y-axis. (b,c,d) Critical gas saturations to cause fracturing at the BHSZ for clay fractions of 0.2, 0.5, and 0.7. The gas mobility threshold is marked with a dashed line. (e) Minimum clay fraction that will result in fracturing at the BHSZ at 10% gas saturation. (f) Close-up of (e) showing the vicinity of the feather edge (523 m seafloor depth; dashed line). Solid black lines in all plots represent the median prediction, while the shaded regions represent the uncertainty.

2002; *Tryon et al.*, 2002]. Over larger spatial and time scales, gas hydrate can act as a capacitor in the global carbon cycle, holding carbon for long periods of time and releasing it in response to external perturbations [*Dickens*, 2003]. The factors governing the evolution of gas from hydrates are well understood, but the fate of that gas, including what determines its rate of transfer to the ocean, is not. Gas venting at the sea floor inferred to emanate from dissociating hydrates is observed at many locations worldwide, in response to both postglacial isostatic rebound and ocean temperature changes and anthropogenic warming [*Ruppel and Kessler*, 2017]. This venting may result from a combination of dissociation-derived gas accumulation and migration of gas from depth and accumulation at the BSHZ [e.g., *Daigle et al.*, 2011; *Plaza-Faverola and Keiding*, 2019]. Understanding the role of hydrate-derived gas in this process is central to predicting how hydrate systems respond to external perturbations.

The question arises, then, about how much hydrate needs to dissociate to generate the gas volumes required to initiate tensile fractures. At standard temperature and pressure, the molar volume of methane gas is roughly 164 times that of sI methane hydrate [*Collett et al.*, 2015], but at in situ conditions this ratio is much smaller. For instance, using the modified Lee-Kesler equation of state for methane described by *Duan et al.* [1992], at the in situ pressure and temperature in the vicinity of the BHSZ at Ocean Drilling Program (ODP) Site 997 on Blake Ridge (roughly 34.5 MPa and 21°C [*Ruppel*, 1997; *Flemings et al.*, 2003]), the molar volume of methane gas is only about 0.51 times that of sI methane hydrate. At these conditions, the initial hydrate saturation would be nearly twice the corresponding gas saturation following dissociation. In porous media the situation is slightly more complicated since the capillary pressure of the gas phase must also be considered.

If porosity does not change upon hydrate dissociation, the hydrate saturation S_h necessary to yield a particular gas saturation S_g is given by

$$S_h = S_g \frac{V_{m,h}}{V_{m,g}}, \qquad \text{(Eq. 13)}$$

where $V_{m,h}$ and $V_{m,g}$ are the molar volumes of hydrate and gas. We considered the hydrate saturation necessary to yield the gas saturation required to generate tensile fracturing at the BHSZ. $V_{m,g}$ was calculated using the equation of state of *Duan et al.* [1992] at the in situ temperature and a gas pressure equal to hydrostatic pressure plus the capillary pressure corresponding to the critical gas saturation for fracture. $V_{m,h}$ was assumed constant and was determined as 1.29 x 10^{-4} m^3/mol based on a molar mass for sI hydrate ($CH_4 \cdot 5.75H_2O$) of 0.1192 kg/mol and a hydrate bulk density of 925 kg/m^3 [*Waite et al.*, 2009].

Figure 8 shows the hydrate saturations required to generate fractures at f_c = 0.2 and f_c = 0.7. Since capillary pressures are lower when less clay is present, more gas and correspondingly more dissociated hydrate are required to generate fractures. In water depths greater than 1000 m when f_c = 0.2, a hydrate saturation of greater than 50% would need to dissociate to generate a sufficient amount of gas to cause tensile fractures (Fig. 8a). However, the larger capillary pressures in sediments with more clay will reduce the molar volume of methane gas, which means that more hydrate will need to dissociate to generate the required gas saturation. This explains the wide range of required hydrate saturations at f_c = 0.7 (Fig. 8b). Hydrate saturations in marine muds rarely exceed 10% except in localized cases [*Boswell and Collett*, 2006], and so it appears unlikely that hydrate dissociation at the BHSZ in deepwater settings (water depths greater than about 1500 m) would lead to gas-driven tensile fracturing, except in cases of

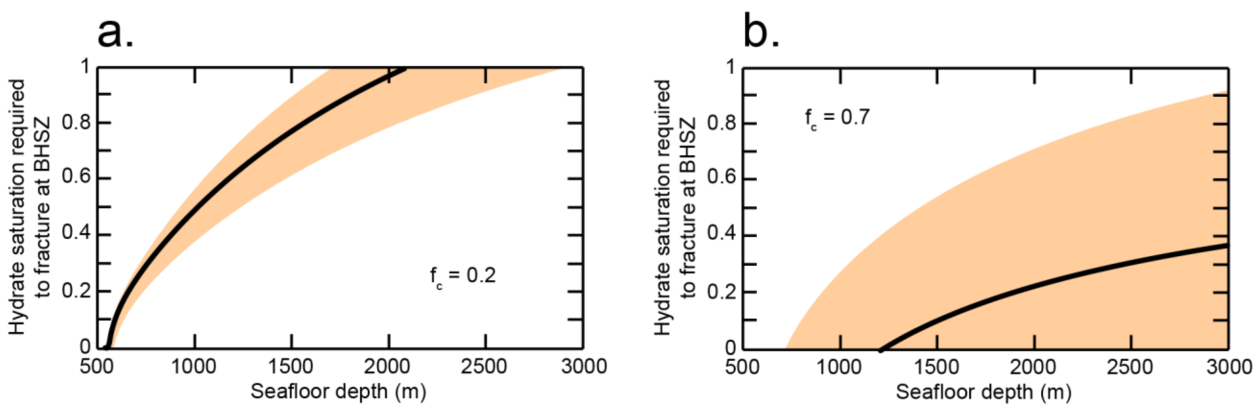

Figure 8. Initial hydrate saturation that would need to dissociate to cause fracturing at the BHSZ as a function of water depth for clay fractions of 0.2 (a) and 0.7 (b). The solid black lines represent the median prediction, while the shaded regions represent the uncertainty.

localized, high-saturation accumulations of hydrate. On the other hand, near the feather edge, any amount of dissociated hydrate can lead to tensile fracturing.

This analysis assumes that any excess pore pressure that develops following hydrate dissociation dissipates rapidly. If excess pore pressure is retained at least partially for some time, this will reduce the molar volume of methane gas and further increase the amount of hydrate needed to generate the necessary gas saturation. Likewise, we ignore the endothermic nature of hydrate dissociation [*Waite et al.*, 2009], which would perturb the in situ temperature.

5.2 Venting at the feather edge

Seafloor methane venting has been observed on many continental margins close to the feather edge where the BHSZ outcrops at the seafloor and may be related to changes in water temperature or depth on time scales ranging from seasonal to glacial-interglacial, including since the onset of the Industrial Age [*Ruppel and Kessler*, 2017]. Changes in ocean temperature will tend to affect hydrates nearest the seafloor first, and in this context the observed methane venting near the feather edge is not surprising [e.g., *Phrampus and Hornbach*, 2012], although it may be possible for gas derived from dissociation downdip of the feather edge or from a deep non-hydrate source to migrate updip [e.g., *Darnell and Flemings*, 2015]. Our calculations indicate that any sediment, regardless of clay-size fraction, is susceptible to tensile failure at the feather edge, and that any amount of hydrate dissociation will preferentially form fractures as the evolved gas vents to the water column. Observable seafloor gas venting at the feather edge does not require very much hydrate to dissociate because of gas expansion. At the pressure and temperature we considered at the feather edge (5.3 MPa, 5.7°C), 1 mol of methane gas occupies 3.0 times the volume of 1 mol of methane hydrate. With a seafloor sediment porosity of 0.775 based on the *Kominz et al.* [2011] model, dissociation of 1% hydrate saturation would produce 23.5 L of methane gas per m^3 of sediment. Widespread observations of seafloor methane bubble discharge from discrete vents near the feather edge are consistent with our predictions and require only small amounts of hydrate dissociation to appear. However, we caution that venting near the feather edge is not necessarily an indication of hydrate dissociation, since microbial methanogenesis in sediments outside the hydrate stability zone can still produce gas that can cause fracturing and venting [e.g., *Naudts et al.*, 2009; *Skarke et al.*, 2014].

5.3 The role of lithologic heterogeneity

The predicted critical gas saturations for tensile failure shown in Figures 6-8 all assume a uniform lithology (i.e., constant f_c) between the BHSZ and seafloor. The marine subsurface is more complicated than this, often exhibiting mixtures of lithologies (clay-rich, silty, sandy) in vertical and lateral successions. At a given porosity, sediments with less clay will be less prone to fracture, and it is conceivable that a propagating fracture may be arrested upon intersecting a coarser-grained layer since the capillary pressure will be lower in the coarser-grained layer. A similar fracture-arresting phenomenon due to contrasts in mechanical properties is well known in lithified sediments, for example hydrocarbon reservoirs [e.g., *Rijken and Cooke*, 2001], and may provide a migration pathway for gas to form hydrates in coarser-grained layers within the hydrate stability zone [*Cook et al*., 2008]. Although the expansion of gas as it rises buoyantly will tend to promote a fracture's propagation once it initiates, extreme cases like chimneys that reach from the BHSZ to the seafloor are likely to form only in relatively homogeneous sediments.

6. Conclusions

We demonstrated that gas-driven tensile fracturing is generally only possible in the shallowest sediments, although the lower depth limit of tensile fracturing increases with increasing clay content. With f_c = 0.2, fracturing is only favored in the shallowest 38 m of sediment, but fracturing may be possible to a depth of 132 mbsf when f_c = 0.5 and to a depth of nearly 500 mbsf when f_c = 0.7. This means that the potential for gas-driven tensile fracturing caused by dissociation of hydrate at the BHSZ is greatest in shallower water, where the BHSZ is closer to the seafloor.

Dissociating hydrate at the BHSZ can be a source of gas that can in turn cause tensile failure. We found that in clay-poor sediments (f_c = 0.2), more than 20% initial hydrate saturation would need to dissociate to generate gas-driven tensile fractures for all but the very shallowest water depths considered (<600 m). However, when the sediments have more clay, much less dissociated hydrate is necessary. At f_c = 0.7, any amount of dissociated hydrate can generate tensile fractures at the BHSZ in water depths as great as 1000 m. Fracturing potential is greatest near the feather edge of the hydrate stability zone: any amount of gas can generate fractures, regardless of the clay-sized fraction. This ease of fracturing combines with significant gas expansion relative to original hydrate volume (roughly a factor of 3) to allow seafloor gas venting near the feather edge with even minor amounts of hydrate dissociation.

Our work overall has shown the conditions under which gas-driven tensile fracturing may occur. The results presented here were based on simplifying assumptions and an idealized case of a passive continental margin, and predicting fracturing behavior at specific sites around the world would require more detailed knowledge of many different factors. However, the general conclusion that gas-driven tensile failure is probably a common occurrence near the seafloor and does not require much gas is important to consider in future studies of the source and fate of gas in the shallow marine subsurface.

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Symbol	Definition	Dimensions
c_u	Unconfined compressive strength	M/LT^2
f_c	Mass fraction of solid matrix composed of clay-sized grains	M/M
m_i	Hoek-Brown constant	-
P_c	Capillary pressure	M/LT^2
P_e	Capillary entry pressure	M/LT^2
P_g	Gas phase pressure	M/LT^2
P_w	Water phase pressure	M/LT^2
r	Pore radius	L
S_g	Gas saturation	L^3/L^3
S_h	Hydrate saturation	L^3/L^3
S_w	Water saturation	L^3/L^3
S_{wi}	Irreducible wetting phase saturation	L^3/L^3
T	Tensile strength	M/LT^2
$V_{m,g}$	Gas molar volume	L^3/mol
$V_{m,h}$	Hydrate molar volume	L^3/mol
V_p	Compressional wave velocity	L/T
z	Depth below seafloor	L
γ	Gas-water interfacial tension	M/T^2
$\gamma_{CH4,W}$	Methane-water interfacial tension	M/T^2
$\gamma_{Hg,V}$	Mercury-vacuum interfacial tension	M/T^2
$\theta_{CH4,W}$	Contact angle of methane-water interface on solid grains	-
$\theta_{Hg,V}$	Contact angle of mercury-vacuum interface on solid grains	-
λ	Pore-size parameter	-
ν	Poisson's ratio	-
σ_3	Minimum principal stress	M/LT^2
σ_h	Total horizontal stress	M/LT^2
σ_h'	Horizontal effective stress	M/LT^2
σ_v	Total vertical stress	M/LT^2
σ_v'	Vertical effective stress	M/LT^2
ϕ	Porosity	L^3/L^3

Table 1. Nomenclature