Two collocated seismic surveys acquired 8 years apart at Hydrate Ridge offshore Oregon, USA, show migration of free gas in a permeable conduit, Horizon A, feeding an active methane hydrate province. They also reveal transients in active gas venting to the water column. We propose that episodic gas migration and pressure fluctuations in the reservoir underlying the regional hydrate stability zone (RHSZ) at southern Hydrate Ridge influence methane supply to the RHSZ and are linked with periodic fracturing and release of methane into the water column by complex feedback processes. We model the effect of pore pressure variations within the deep methane source on fracturing behavior with a 1D model coupling multiphase flow, hydrate accumulation, and pore pressure buildup. Fractures open when the pore pressure exceeds the fracture criterion, which we assume is the vertical effective stress assuming hydrostatic conditions. We define a rate of pressure increase, which determines the time required to reach the fracture criterion, and a maximum pressure based on estimates of the reservoir size. Once fractures open, gas flows through the fractures until the maximum reservoir pressure is reached, after which the gas pressure is depleted quickly because the high gas pressure drives rapid gas flux through the fracture system. This results in gas venting at the seafloor and accumulation of hydrate in the fracture system. If the amplitude of pressure oscillation is near the vertical effective stress in Horizon A (~0.87 MPa) and the time for pressure increase is on the order of years, the gas pressure will meet the fracture criterion on a time scale of months to a few years. The high gas pressure is then depleted over a time scale of a few months. Thus we conclude that gas migration pathways at southern Hydrate Ridge may evolve on a time scale of months to years. This provides
important constraints on the time scale of transient effects on the methane hydrate system at southern Hydrate Ridge, and illustrates how pore pressure pulses affect fluid flow and fracturing behavior in active methane hydrate provinces.

**Keywords:** gas hydrates, hydraulic fracturing, Hydrate Ridge

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>$A$</td>
<td>Cross-sectional area of gas venting [m$^2$]</td>
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<td>$a$</td>
<td>Fracture aperture [m]</td>
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<tr>
<td>$c_x^j$</td>
<td>Mass fraction of component $x$ in phase $j$ [kg kg$^{-1}$]</td>
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<tr>
<td>$D_x^j$</td>
<td>Coefficient of molecular diffusion for component $x$ in phase $j$ [m$^2$ s$^{-1}$]</td>
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<td>$g$</td>
<td>Acceleration due to gravity [m s$^{-2}$]</td>
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<td>$J$</td>
<td>Dimensionless capillary drainage function</td>
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<tr>
<td>$k$</td>
<td>Intrinsic permeability [m$^2$]</td>
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<tr>
<td>$k_f$</td>
<td>Fracture system permeability [m$^2$]</td>
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<td>Relative permeability of phase $j$</td>
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<td>Porosity [m$^3$ m$^{-3}$]</td>
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<td>$\varphi_f$</td>
<td>Fracture porosity [m$^3$ m$^{-3}$]</td>
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**INTRODUCTION**

Hydrate Ridge is a bathymetric high ~25 km long and ~15 km wide oriented roughly NNE-SSW about 80 km offshore Oregon, USA landward of the Cascadia deformation front (Fig. 1). The northern and southern summits of Hydrate Ridge are areas of active methane seeps and gas vents [1,2,3]. Methane gas has been observed venting to the water column as discrete plumes and flares from several sites at northern and southern Hydrate Ridge [2,3], with the location of venting changing on time scales of months to years. Gas flow rates up to $10^7$ m/yr have been observed at discrete vents at the summit of southern Hydrate Ridge (SHR), representing methane flux up to 1000 mol/m$^2$·day [4,5]. Ocean Drilling Program (ODP) Leg 204 investigated 9 sites on SHR. The highest hydrate saturations ($S_h = 50\%$) were inferred near the summit of SHR, with hydrates present as veins, nodules, and fracture fill, as well as disseminated throughout the pore space [6].

![Figure 1. Location of Hydrate Ridge offshore Oregon, USA. NHR: Northern Hydrate Ridge; SHR: Southern Hydrate Ridge. Bathymetry contour interval 500 m. Rectangle at SHR shows approximate area of seismic survey shown in Figure 2.](image-url)
Figure 2. Seismic amplitude of Horizon A from seismic surveys acquired in 2008 (left) and 2000 (middle), and the amplitude difference between the two surveys (right). ODP Leg 204 sites are shown for reference. Three features are identifiable in both surveys, and are marked to show movement between the two surveys.

The northernmost extent of the high amplitude region (red line) appears to have moved ~100 m to the southwest ( updip). Another high-amplitude region in the 2000 survey located southeast of Site 1247 (black line) migrated ~100 m south between surveys. The southernmost limit of the highest amplitudes in the 2000 survey (brown line) migrated ~350 m south, passing Sites 1249 and 1250. The map of amplitude difference (right) shows areas where seismic amplitudes increased between 2000 and 2008 (hot colors), which is interpreted to indicate an increase in gas saturation in Horizon A. The most notable increase occurred at the SHR summit region, and between Sites 1247 and 1249. This is interpreted as evidence of flux of gas into Horizon A beneath the summit region.

Pressure in Horizon A beneath the summit of SHR is inferred to be at or near the lithostatic pressure, and hydraulic fracturing has been invoked to explain the presence of hydrate-filled fractures and rapid gas flux that has been observed at SHR [7,8]. Model results have shown that formation of hydrate in sediment pore space at SHR can decrease permeability to the point that fluid pressure in excess of lithostatic pressure is required to maintain the observed flow rates by porous medium flow [9,10]. At flow rates of tens to hundreds of cm/yr inferred near vents and seeps at SHR [4], this process requires hundreds to a few thousand years to generate fractures [9]. However, fractures may be generated more quickly at much more rapid flow rates.

Two recent, co-located seismic surveys collected in 2000 and 2008 reveal the dynamic nature of the gas reservoir feeding Horizon A beneath SHR (Fig. 2). Differences in seismic amplitudes in Horizon A between the two surveys are inferred to result from migration of gas within Horizon A. In particular, a high-amplitude area northeast of the summit of SHR migrated ~100 m updip between the two surveys, and the amplitude of Horizon A directly beneath the summit region increased significantly (Fig. 2). From these features we interpret migration of gas through Horizon A towards the summit of SHR at a rate of roughly 12.5 m/yr.

We model the response of the sediments at the summit of SHR to an increase in gas pressure in Horizon A corresponding to the changes observed between the two seismic surveys. We use a 1-dimensional model ofhydrate formation coupling multiphase fluid flow, hydrate formation, and pore
pressure buildup to determine how changes in the deep methane reservoir affect fracturing behavior and methane discharge to the seafloor at SHR.

MODEL DETAILS
Domain and environmental parameters
Our model uses the methodology of [9]. We simulate fluid flow and methane hydrate formation in a 1-dimensional domain with fixed seafloor depth of 780 m, seafloor temperature of 277 K, and geothermal gradient of 0.053 K m⁻¹ [11]. These parameters are selected to represent the conditions near the southern summit of Hydrate Ridge. The seafloor temperature and geothermal gradient define the thickness of the RHSZ. We define a porosity-depth profile \( \phi \) and permeability-porosity relationship \( k \) [m²] [10]:

\[
\phi = 0.53e^{-z/1400},
\]

\[
k = e^{(3z-40)},
\]

where \( z \) is depth below the seafloor [m]. Our model includes three components (water [superscript w], methane [superscript m], salt [superscript s]) that may be present in three phases (aqueous [subscript w], hydrate [subscript h], gas [subscript g]). We conserve mass by solving mass balance equations:

\[
\frac{\partial}{\partial t} \left[ \phi S_j \rho_j c_x^j \right] - \frac{\partial}{\partial z} \left[ \bar{q}_j \rho_j c_x^j \right] = \frac{\partial}{\partial z} \left[ \phi S_j \rho_j D_x^j \frac{\partial c_x^j}{\partial z} \right]
\]

where \( S_j \) is the fraction of pore volume occupied by phase \( j \) (water, hydrate, gas), \( \rho_j \) is the bulk density of phase \( j \) [kg m⁻³], \( c_x^j \) is the mass concentration of component \( x \) in phase \( j \), \( \bar{q}_j \) is the flux of phase \( j \) [m s⁻¹], and \( D_x^j \) is the diffusion coefficient of component \( x \) in phase \( j \) [m² s⁻¹]. We assume \( \rho_w = 1024 \) kg m⁻³, \( \rho_h = 930 \) kg m⁻³, \( c_m^h = 0.134 \) [12], and \( D_m^w = D_s^w = 10^{-9} \) m² s⁻¹ [13]. Gas density is computed from the ideal gas law. Solubility of methane in water is computed using the method of [14], and we assume that \( c_m^w \) is initially 3.35% by mass. Equation (3) is solved explicitly for methane and implicitly for salt and water using a forward-in-time, centered-in-space finite difference scheme. We further assume that salt is only present in the aqueous phase; that dissolved methane does not affect the density of the pore fluid; that the mass fraction of water in the aqueous phase is close to unity and that the mass fraction of water in the hydrate phase is close to zero; that diffusion only occurs in the aqueous phase; and that the flux of the hydrate phase is zero.

Pressures and fluxes
Fluxes of the water and gas phases are computed from Darcy’s law:

\[
\bar{q}_j = -\frac{k_{rj}}{\mu_j} \frac{\partial P^*}{\partial z},
\]

where \( k_{rj} \) is the relative permeability of phase \( j \), \( \mu_j \) is the dynamic viscosity of phase \( j \) [Pa s], and \( P^*_j \) is the pressure in excess of hydro- or gas-static of phase \( j \) [Pa]. Relative permeability is calculated using Corey’s model assuming residual water and gas saturations of 10% and 2%, respectively [13,15]. Water viscosity is 0.001 Pa s, and gas viscosity is computed from the Lennard-Jones potential [16]. We impose boundary conditions on water- and gas-phase overpressures at the base of the domain. As hydrate forms and constricts the pore space, the permeability is reduced by a factor of \((1-S_h)^2\) [10].

Below the RHSZ, gas accumulates at a rate determined by the reservoir pressure boundary condition. We assume that gas saturation must reach a value of 10% before the gas may form an interconnected phase and flow [7,13]. If gas is present, we assume that \( c_m^w \) is equal to the solubility value. Any methane in excess of solubility exists in the gas phase. Within the RHSZ, hydrate forms from methane in excess of the solubility value. As hydrate forms, the salinity of the surrounding pore fluid is increased since the hydrate crystal structure excludes salt ions [17]. The increased salinity depresses water activity, which causes an increase in the three-phase equilibrium temperature for hydrate, aqueous methane, and methane gas [18]. We compute the change in three-phase equilibrium temperature due
to salinity changes using the method of [19]. If salinity at a given point within the RHSZ increases to the value required for three-phase equilibrium at in situ temperature and pressure, formation of hydrate ceases and free gas may be present at that point. Previous studies of Hydrate Ridge have shown that this requires hydrate fill 40-80% of the pore space [9,20]. Methane gas may thus invade the RHSZ if sufficient salt is produced by hydrate formation and is not removed by flux of pore water [9,13,20].

The gas-phase pressure changes in the RHSZ as a result of the reservoir pressure boundary condition as well as formation of hydrate. Due to the curvature of the gas-water interface, the pressure of the gas phase is greater than the pressure of the water phase by an amount equal to the capillary pressure $P_c$ [Pa]. Capillary pressure is computed as

$$P_c = J \sigma_{gw} \frac{\phi}{k(1-S_h)},$$  

where $\sigma_{gw}$ is the interfacial tension of the gas-water interface [J m$^{-1}$] and $J$ is a dimensionless function that describes changes in capillary pressure during drainage as gas displaces water in the pore space [13,15]. We assume $\sigma_{gw} = 0.072$ J m$^{-1}$ [21] and use a $J$-function determined from mercury injection capillary pressure measurements [22].

When the gas pressure in Horizon A exceeds the total vertical stress, hydraulic fractures form. We assume that fractures propagate from Horizon A to the seafloor very rapidly [23], in less than one model time step (~1 hour). These fractures provide a conduit linking Horizon A with the seafloor. The permeability of the fracture system is given by [24]

$$k = \frac{12a^3}{l},$$  

where $a$ is the fracture aperture [m] and $l$ is the inter-fracture spacing [m]. We assume that the fractures have aperture of 1 mm and are spaced 1 m apart [e.g., 8]. As hydrate forms in the fractures, the permeability is reduced by a factor of $(1-S_h)^3$ [10]. We assume that the fracture aperture is large enough that the capillary pressure of the gas phase in fractures is negligible (e.g., for a fracture with

Figure 3. Model stages. (a) Stage 1: accumulation of gas and porous medium flow above Horizon A. (b) Stage 2: fractures form, gas front propagates through fractures as hydrate forms and increases local salinity. (c) Stage 3: gas vents to the seafloor until gas reservoir is exhausted.
aperture 1 mm, the capillary entry pressure is 144 Pa [25]).

**Model implementation**

System behavior can be divided into three distinct stages defined by the fluid flow regime (Fig. 3). In stage 1 (Fig. 3a), gas accumulates in Horizon A and the pressure of the gas phase increases. Fluid flow above Horizon A occurs through the sediment pore space. We specify the rate of gas pressure increase in Horizon A, and the rate of change in methane mass \( m \) [kg] in the gas reservoir is given by

\[
\frac{dm}{dt} = \rho_g A \phi S_g \frac{k_{rg}}{\mu_g} \frac{\partial}{\partial z} (P_g - \rho_g g z), \tag{7}
\]

where \( A [m^2] \) is the cross-sectional area through which fluid flow occurs above Horizon A.

Stage 2 begins when the gas-phase pressure in Horizon A exceeds the vertical effective stress (Fig. 3b). During this stage, gas propagates upwards through open fractures as hydrate precipitates in the fractures and the local salinity increases to the point required for three-phase equilibrium. During stage 2, gas pressure in Horizon A continues to increase at the specified rate since the gas cannot yet vent through the fracture system. The change in methane reservoir mass is given by replacing the matrix porosity and permeability in (7) with those of the fracture system (\( \phi_f, k_f \)):

\[
\frac{dm}{dt} = \rho_g A \phi_f S_g \frac{k_{rg}}{\mu_g} \frac{\partial}{\partial z} (P_g - \rho_g g z). \tag{8}
\]

When the gas front reaches the seafloor, stage 3 begins, during which gas vents through the fracture system, depleting the gas pressure in Horizon A (Fig. 3c). If the gas front reaches the seafloor before the gas pressure in Horizon A has reached its maximum value, gas vents to the seafloor at constant pressure gradient due to the high permeability of the fracture system \( (8.3 \times 10^{11} \text{ m}^2) \). Once the gas pressure in Horizon A has stopped increasing, stage 3 continues until the gas pressure in Horizon A drops below the vertical effective stress or the methane supply in the reservoir is exhausted. Pressure depletion during stage 3 is described by

\[
\frac{\partial P_g}{\partial t} = \frac{k_{rg}}{\mu_g} \frac{\partial}{\partial z} \left( P_g - \rho_g g z \right) A \phi_f \rho_g RT \frac{M_{\text{CH}_4}}{M_{\text{CH}_4}}, \tag{9}
\]

where \( M_{\text{CH}_4} \) is the molar mass of methane. Change in methane reservoir mass is described by (8). The simulation ends either when the reservoir pressure drops below the fracture criterion or the methane supply is exhausted.

**RESULTS**

**Determination of system parameters**

We assume that the methane gas reservoir feeding SHR is defined by the area of high amplitude in Horizon A. Based on the 2000 seismic survey, this area is roughly a rectangle with dimensions 1300 x 300 m (Fig. 2). We assume that Horizon A has an average thickness of 5 m, 50% porosity, and 50% \( S_g \), where gas is present. These parameters yield \( 4.88 \times 10^5 \text{ m}^3 \) of methane in the reservoir. Within the reservoir, Horizon A has an average depth of 170 m below seafloor (mbsf), which results in an average reservoir temperature of 286 K. From the methane equation of state of [26], the bulk density of the gas in the reservoir is \( 63 \text{ kg m}^3 \). Thus the reservoir initially contains \( 3.07 \times 10^7 \text{ kg} \) of methane. The reservoir pressure is 9.36 MPa from the ideal gas law.

The cross-sectional area through which flow occurs above Horizon A at SHR is an important parameter to constrain for reservoir depletion in (7) and (8). We assume that the area through which flow occurs at the summit of SHR corresponds with the area of dense microbial mats, mounded topography, and periodic gas release observed by [5] with the submersible Alvin. This area is a roughly 100 m x 100 m square. Our estimates of reservoir volume and cross-sectional area of flow are the most significant sources of error in our simulations.

We estimate the magnitude of pressure increase and the time over which the increase occurs from seismic data (Fig. 2). However, the shape of the pressure buildup over time is unconstrained. Therefore, we investigate system behavior in three different pressure increase scenarios (Fig. 4). We assume that the southern edge of the gas reservoir is initially just north of the SHR summit. At the estimated gas migration rate along Horizon A of
Figure 4. Pressure buildup scenarios.

12.5 m yr⁻¹, the center of the reservoir would move to the SHR summit after ~50 years. Thus we model the gas pressure increase at the SHR summit from 0 to the maximum pressure of 9.36 MPa over 50 years. In the first scenario, we model a linear pressure increase. In the second scenario, we model an initially slow pressure increase that increases exponentially with time. In the third scenario, we model an initially rapid pressure increase that decreases logarithmically with time.

**Scenario 1: Linear pressure increase**

With a linear increase in pressure, \( P_g \) reaches the vertical effective stress in Horizon A after 4.52 years (Fig. 5). Gas moves into the fracture system in the RHSZ as hydrate forms in the fractures and increases the local salinity to the conditions required for three-phase equilibrium. After an additional 78 days, the gas front reaches the seafloor and gas vents through the fracture system. Venting at the seafloor continues for 34.4 years until the methane reservoir is exhausted. The total time required from the start of the simulation to depletion of the methane reservoir is 39.2 years. No pressure depletion occurs in stage 3 of the simulation because the methane supply is exhausted before the entire time of pressure buildup (50 years) has elapsed, and the pressure in the system returns to hydrostatic.

**Scenario 2: Slow, exponentially increasing pressure increase**

In this scenario, \( P_g \) reaches the vertical effective stress in Horizon A after 24.7 years (Fig. 6). Gas moves through the fracture system and vents to the seafloor after an additional 78 days. Venting continues for 29.9 years. After 26.1 years of venting, the gas pressure in Horizon A stops increasing and the pressure is depleted through the fracture system. This pressure depletion takes 4.6 years. The gas pressure drops below the fracture criterion after a total time of 54.9 years from the start of the simulation.

**Scenario 3: Rapid, logarithmically decreasing pressure increase**

In this scenario, \( P_g \) reaches the vertical effective stress in Horizon A after 104 days, and the gas front reaches the seafloor through the fracture system after another 69 days (Fig. 7). Venting then occurs through the fracture system for 29.4 years, and the methane supply is exhausted after a total time of 29.9 years from the start of the simulation. As in scenario 1, in this case there is no pressure depletion since the methane supply is exhausted before the time for pressure buildup has elapsed.

**DISCUSSION**

**Effect of the shape of the buildup curve**

In scenarios 1 and 3, the methane supply was exhausted before the entire time for pressure buildup elapsed, while in scenario 2 the simulation progressed beyond the time for pressure buildup and included pressure depletion at the end of the simulation. This difference in behavior is driven by the difference in the rate of pressure increase, which affects the net flux of methane during the...
In scenario 1, enough methane is driven out of Horizon A during stage 1 that only 34.4 years of venting through the fracture system are required to exhaust the methane supply. In scenario 2, more time elapses during stage 1, but the gas pressure in Horizon A is generally lower in this scenario than in scenario 1, so less methane leaves the system during stage 1, and more time is required to exhaust the methane supply. In scenario 3, stage 1 is much shorter than in the other two scenarios. However, the rate of pressure increase is much faster during stage 2 than in the other two scenarios, so the gas pressure in Horizon A is much higher at the start of stage 3 (~1.4 MPa compared with 0.9 MPa for scenario 1 and 0.84 MPa for scenario 2). This drives correspondingly higher flux during stage 3, which exhausts the methane supply quickly.

Sensitivity to reservoir volume and venting area
Significant sources of error in our simulations are the estimates we made of the volume of methane in the reservoir, and the cross-sectional area through which flow occurs at the SHR summit. To investigate the sensitivity of our results to these parameters, we ran several simulations with different values of these parameters. For this sensitivity analysis we assumed a linear pressure buildup (scenario 1).

The cross-sectional area of flow at the SHR summit has an inverse relationship with the time venting occurs through the fracture system (simulation phase 3) (Fig. 8a). Our estimate of $10^4$ m$^2$ results in slightly less than 35 years of venting. Doubling this area decreases the venting time by a factor of 2; similarly, increasing the area by a factor of 4 decreases the venting time by a factor of 4. Based on the observations of [5], it is unlikely that the cross-sectional area of flow is larger than $9x10^4$ m$^2$, which would result in only ~3 years of venting. Our assumptions therefore make our results represent a maximum time for flow evolution and reservoir depletion.

The reservoir volume has a roughly linear relationship with total time required for reservoir exhaustion (Fig. 8b). Increasing the volume by an order of magnitude from our initial estimate of $4.88x10^5$ m$^3$ causes the total time to increase by a factor of ~6.5, while decreasing the volume by an order of magnitude decreases the total time by a factor of ~4.8. The effect of reservoir volume is
Sensitivity analysis assuming linear pressure increase (scenario 1). Our estimated parameters are represented by red circles. (a) Effect of venting area on duration of venting at the seafloor (phase 3). (b) Effect of reservoir volume on total time for methane reservoir exhaustion. Thus less significant than the effect of venting area. However, our estimate of reservoir volume is affected not only by the map dimensions, but also gas saturation and porosity. In reality, the true reservoir volume is probably less than the volume we estimated, since gas saturation is likely lower towards the edges of the reservoir, and the reservoir is somewhat smaller and more irregularly shaped than the rectangle we used for the estimate. Considering this, our results again represent upper limits on the time required for reservoir depletion.

Implications for evolution of fluid flow at southern Hydrate Ridge
Our results have important implications for understanding the current state of flow at SHR and predicting how the flow will evolve in the future. At the gas migration rate estimated from differences between the 2000 and 2008 seismic surveys, the gas reservoir roughly defined by the high-amplitude region in Horizon A will be exhausted on a time scale of years to a few decades once the gas is able to vent to the seafloor through a fracture system developed at the summit of SHR. Our sensitivity analysis shows that variations in reservoir volume or cross-sectional area of fluid flow at the SHR summit region yield variations in the total time required to exhaust the methane supply on the order of decades to a few centuries. However, given our best estimates of these parameters, venting should occur for only 30-50 years. Thus, the venting that has been observed at the summit of SHR [3,4,5] should continue for a few more decades.

During the active venting phase of our simulations (phase 3), we compute methane fluxes through the fracture system in the range $1.6-3.8 \times 10^4$ m yr$^{-1}$ depending on the pressure buildup curve. This is extremely rapid flux compared to the background fluid flux on the order of centimeters to decimeters per year measured away from active venting sites [4,5]. However, flow rates up to $10^7$ m yr$^{-1}$ have been measured at some active sites at northern Hydrate Ridge [4], and it is likely that similar flow rates may occur at discrete discharge points at SHR. However, flow rates at active vents are highly variable on time scales from hours to days [5]. During the phase of active venting through the fracture system, it is probably more realistic to assume that high flux occurs episodically rather than continuously as we assume in our model. This situation would require more time to exhaust the methane supply.

Our results show that the gas front propagates through the fracture system in 70-80 days as hydrate forms in the fractures and increases the local salinity. Assuming the formation of the fractures themselves is a relatively rapid process (scale of hours to days [23]), gas venting may not necessarily occur through the same fractures over the entire duration of gas venting. In the case of transient venting, fractures will be held open by gas pressure during active venting, and then will close when venting stops. Once venting resumes, the gas may exploit an entirely new set of fractures that may propagate and be exploited within a few months. This scenario may explain the abundant hydrate-filled fractures encountered in image logs from SHR [8] that coexist with active gas venting. The hydrate-filled fractures may be remnants of previous active venting episodes.
Overall, our results show that gas migration, fracture formation, and methane venting at the seafloor are highly transient events that can change over time scales of days to years at SHR, and that any observed features are likely to persist for only a few months to years, while any active venting of gas is likely to continue only for a few more decades. These results have broader implications for methane hydrate deposits worldwide since they demonstrate rapid formation of features and variations in methane supply over short time scales.

CONCLUSIONS
We model methane migration and fracture generation at southern Hydrate Ridge with a one-dimensional model that incorporates fluid flow, methane hydrate formation, and fracturing behavior. Our model inputs are based on geophysical observations from two seismic surveys acquired 8 years apart that show changes in the methane gas reservoir that feeds active methane venting near the summit of southern Hydrate Ridge. We show that, for our estimates of reservoir size, migration rate, and venting area at the seafloor, fractures will form within a few years of the onset of pressure buildup. Once fractures form, gas is able to move upwards through the RHSZ by formation of some hydrate in the fractures (40-80% of the fracture volume), which reduces the local salinity to the conditions required for the presence of gas within the RHSZ. Gas reaches the seafloor by this process after 70-80 days. The methane reservoir is then depleted by venting through the fracture system to the seafloor after an additional 30-50 years. Reasonable variations in reservoir volume or venting area from our estimates may increase or decrease this time roughly by a factor of 5. Our results show that the observed activity at southern Hydrate Ridge is part of a highly transient process involving methane gas migration, fracture genesis, and seafloor venting with variations on time scales of years to decades. In a broader sense, we illustrate the dynamic nature of hydrate deposits and the potential transience of many observed features.

REFERENCES


