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Excess Pore Pressure and Slope Failures Resulting From Gas-Hydrates Dissociation and Dissolution

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Abstract

Parameters affecting gas hydrate formation include temperature, pore pressure, gas chemistry, and pore-water salinity. Any change in the equilibrium of these parameters may result in dissociation (gas-hydrate turns into free gas/water mixture) and/or dissolution (gas-hydrate becomes mixture of water and dissolved gas) of the gas hydrate. While, gas-hydrate dissociation at the base of the Gas Hydrate Occurrence Zone (*GHOZ*) is often considered as a major cause of sediment deformation and submarine slope failures the consequence in terms of pore pressure and sediment deformation of the dissolution of the gas hydrate at the top of the *GHOZ* remains neglected. In this study, we quantify and compare the excess pore pressure resulting from gas hydrate dissociation and dissolution. Based on theoretical development it is demonstrated that excess pore pressure and shear discontinuities generated by hydrate dissociation is unlikely to be a hazardous factor. In natural environment, the excess pore pressure generated by hydrate dissociation is bounded by the gas hydrate stability law inducing for a natural temperature increase a limited amount of excess pore pressure and limited shear discontinuities at the base of the *GHOZ*. On the other hand, we show that under natural temperature changes hydrate dissolution at the top of the gas hydrate stability zone, which can occur at a regional scale, is a hazardous process that can lead to catastrophic landslides.

Introduction

For the last 3 decades, several authors have raised serious concerns regarding the possible link between gas hydrate and submarine slope failures. [McIver](#)¹ was amongst the first authors to speculate about this possible link. In the [McIver](#) conceptual model¹, the excess pore pressure generated by

hydrate dissociation and the sediment shear strength decreases (lost of hydrate playing the role of cementing agent between sediment grains) are the two key factors in the slope failure mechanism. The causal factor of the hydrate dissociation in [McIver](#)¹ model is the continuous sedimentation, which induces the upward migration of the base of the Gas Hydrate Stability Zone (*GHSZ*). Afterwards, [Kvenvolden](#)² has stated that an upward movement of the bottom of the *GHSZ* due to an increase of bottom water temperature may accelerate the process of slope failures associated to hydrate dissociation. Different authors have later developed several other hypotheses and theories supposing all that gas hydrate dissociation may lead to important excess pore pressure and lead to sediment deformations and slope instabilities^{3,4,5,6,7}. In the meantime, many large submarine landslides have been described worldwide in areas where gas hydrate occurrence was proved or suspected^{9,10,11,12,13}. [Paull and co-authors](#)⁶ have proposed that gas-hydrate is the main cause of the increased frequency of sea-floor slumping on continental margins containing gas hydrates during sea-level lowstands. While authors seem to agree about the association between gas-hydrate dissociation and submarine slope failures, few theoretical and mathematical works were developed to define accurately the mechanism associated to the slope failure process. In the last few years, some authors have tried to evaluate using different approaches the excess pore pressure due to hydrate dissociation^{14,15,16,17,18}. On the other hand, almost none or very few theoretical and experimental works were carried out to identify the decrease of the sediment shear strength with hydrate dissociation.

The process of hydrate dissolution and slope failure was described previously by [Sultan and co-authors](#)¹⁶ to illustrate one of the possible triggering mechanisms of the Storegga slide. More recently, it was shown that the excess pore pressure generated by hydrate dissolution seems to be in the same order of magnitude than the one generated by hydrate dissociation under undrained conditions and for a closed system¹⁷. On the other hand, the gas hydrate stability law bounds the amount of the excess pore pressure generated by gas-hydrate dissociation. By considering theoretically the two processes of hydrate dissolution and hydrate dissociation, our work aims to give an answer to the following major question: Under natural sea level and temperature changes as the one occurred since the last deglaciation where is the most hazardous area in the *GHOZ* of submarine slopes?

Excess pore pressure generated by hydrate dissolution and dissociation

The excess pore pressure generated by hydrate dissolution and dissociation in a closed system can be derived from the compressibility of the gas hydrate-bearing sediment system and the volume and expansion factor of each constituent (solid, liquid and gas)^{16,17,18}. While the volume expansion factor generated by the gas hydrate dissociation is much larger than the one generated by hydrate dissolution, the compressibility of a system containing free gas is much higher than the one containing just liquid. The amount of the excess pore pressure generated by the two processes of hydrate dissolution and dissociation is bounded by the gas hydrate stability law and the gas solubility respectively.

Upper bound of the excess pore pressure resulting from hydrate dissociation process

Figure 1 shows the results of 1D calculation in terms of excess pore pressure generated by hydrate dissociation due to a temperature increase from an initial thermal state T_i to a final one T_f using the software developed by Sultan and co-authors¹⁶. In this calculation the transient thermal evolution from T_i to T_f is not considered in order to focus on the excess pore pressure generated between two limiting temperature states. Under T_i , gas hydrates are stable over the first 200 m (Figure 1-a). For a thermal steady state regime from T_i to T_f , the temperature increase induces the dissociation of the gas hydrate below the point A in Figure 1-a. However, the gas hydrates are not completely dissociated below the point A since the excess pore pressure generated by the hydrate dissociation re-crystallizes a part of the hydrate and delays hydrate dissociation process. This phenomenon creates a metastable thermodynamic state where the gas and the gas-hydrates coexist (Figure 1-b-c). The excess pore pressure cannot cross the hydrate stability curve as presented in Figure 1-d showing that the BHSZ which is often associated to the BSR is an area with a dynamic process where the free gas concentration and the excess pore pressure are the lowest. In such dynamic process where the gas hydrate is dissociating at the base of the gas hydrate stability zone, the sharp limit between gas hydrate and the free gas is not very clear as it can be seen from Figure 1. The subsequent dissipation of the pore pressure below the base of the GHSZ generates an additional dissociation of the gas hydrate. The time scale of this dissipation depends on the permeability of the sediment. At long term the gas hydrate below the GHSZ may disappear completely without the generation of a critical pore pressure at the base of the *GHOZ*.

The upper bound of the excess pore pressure Δu_{max} generated by hydrate dissociation can therefore be calculated from the following equation:

$$\Delta u_{max}|_{z(T)} = P(T) - z(T) \cdot \gamma_w \quad (1)$$

where $P(T)$ is the hydrate equilibrium pressure at a given temperature T , $z(T)$ is the depth corresponding to the same

temperature T and γ_w is the water unit weight.

Upper bound of the excess pore pressure resulting from the hydrate dissolution process

The upper bound of the excess pore pressure generated by hydrate dissolution is related to the solubility of the gas. The low solubility of the methane prevents to form easily in the laboratory methane-hydrate from a single-phase solution of dissolved methane in water. However, it was demonstrated theoretically that dissolution of methane hydrate in a closed system leads to a decrease of the mass density and therefore to an increase of the pore pressure¹⁷. For methane hydrate, the maximum excess pore pressure generated by hydrate dissolution can be evaluated using the analytical expressions given by Sultan¹⁷ and is presented in Figure 2. The maximum hydrate fraction able to be dissolved in seawater is presented as a function of depth in Figure 2-a. The maximum excess pore pressure generated by hydrate dissolution is presented in Figure 2-b.

Slope failure and Shear band propagation associated to gas hydrate dissolution and dissociation

The effect of hydrate formation on the increase of the shear resistance of hydrate-bearing sediments has been well recognized experimentally^{20,21}. This increase of the shear resistance depends mainly on the gas hydrate distribution (disseminated in the pores versus cementing grains) and the gas hydrate fraction. The increase of the shear resistance is optimal when gas hydrate acts as a cementing agent between grains. Sultan¹⁷ has recently carried out in-situ *CPT* (Cone Penetration Testing) measurements in hydrate-bearing sediments. In-situ mass density using a source of Cesium 137 was also acquired. From the mass-density and the cone resistance qt , it was possible to calculate the hydrate fraction η and the internal friction angle ϕ . Results from [17] have clearly shown the effect of the hydrate fraction on the increase of the internal friction angle. An important increase of the internal friction angle was observed at low hydrate fraction (< 2%).

On the other hand, hydrate formation impede the normal mechanical consolidation of the hydrate-bearing sediment leading to the formation of an open sediment structure. The phenomenon of hydrate dissolution and dissociation in the *GHSZ* is probably similar to destructure and softening of natural clay. Several authors have shown experimentally an important deformation and collapse due to the destructure of natural clay^{22,23}. Recently, Yun and Santamarina²¹ have observed that sediment with only 2% of cemented material may strengthen the sediment matrix and create an open structure. The subsequent mechanical loading of this cemented sediment has induced the collapse of the cemented structure. Hydrate dissolution/dissociation may lead to an important plastic deformation (collapse) of the sediment due to the loss of cementation. Therefore a localized shear strain at the top or the bottom of the *GHOZ* may create shear discontinuities.

One of the key parameters in the evaluation of the slope

instability enclosing gas hydrate is the lateral extension of the area where gas hydrate was dissolved or dissociated (shear discontinuities) due to the temperature and hydrostatic pressure changes. The amount of the excess pore pressure generated by hydrate dissolution/dissociation is also an important input to evaluate the danger of slope failures. In this work, the location of the hydrate dissolution/dissociation areas and the excess pore pressure generated by dissolution and dissociation was evaluated based on the theoretical development presented by Sultan and co-authors^{16,17}. In this work, hydrofracturing is supposed to occur in sediment whenever the excess pore pressure has exceeded 95% of the vertical effective stress. In the lack of experimental data and as a hypothesis, hydrofracturing was also considered to occur only in gas-hydrate marine sediment with hydrate fraction lower than 1. After hydrofracturing, the permeability of the hydrofractured sediment increases until the excess pore pressure becomes equal or less to 95% of the vertical effective stress.

Figure 3 shows the initial distribution of the hydrate fraction for a gentle submarine slope (slope angle of 2.2°) in water depths ranging between 450 and 850 m. Figure 4 illustrates the temperature and hydrostatic pressure increments applied at each time period and considered in this work as the source of the hydrate dissolution and dissociation along the considered submarine slope. The initial seawater temperature was taken equal to 3.2° and the temperature gradient equal to 40 °C/km (time 0 - Figure 4).

Figure 5 presents the amount and location of dissolved or dissociated hydrates (shear discontinuities), the pore pressure field and the base of the *GHSZ* generated after 0.8 ky, 1.2 ky, 2 ky and 4 ky of temperature and hydrostatic pressure increases. Excess pore pressure generated by hydrate dissolution is related to the increase of the gas solubility as the temperature and pressure increases^{16,17}. From Figure 5, one can see that critical pore pressure was first generated at the top of the *GHOZ*. The spatial extension of the pore pressure and the hydrate fraction decreases which define the extension of the shear discontinuities are much more important at the top of the *GHOZ* than at its base. This is due to the relatively fast temperature rises at the top of the *GHOZ* with respect to the bottom of the *GHOZ*. The excess pore pressure at the base of the *GHOZ* has delayed the dissociation process and it auto-controls the dissociation process preventing the generation of excess pore pressure exceeding the pressure of the thermodynamic stability of the gas hydrate (Figure 5).

The shear discontinuities corresponding to the hydrate dissolution and dissociation areas can be used to evaluate the danger of a catastrophic landslides generation. Puzrin and co-authors²⁴ have recently applied the fracture mechanics methods to evaluate the shear band propagation in soils and its consequence in terms of catastrophic landslides generation. Puzrin and co-authors²⁴ have combined limiting equilibrium to fracture mechanics and have showed clearly that the main parameters controlling the shear band propagation and the generation of catastrophic landslide are:

- the depth of the discontinuity surface h
- the length of the discontinuity surface L
- the residual shear strength along the discontinuity surface τ_r

- the gravitational shear stress τ_g which is equal to $\gamma'.h.\sin(\alpha)$: γ' is the submerged unit weight and α is the slope angle
- the average values of the active (P_a) and passive (P_p) lateral pressure in the considered layer.

To generate catastrophic landslides Puzrin and co-authors²⁴ have shown that the length of the discontinuity surface L must be greater than the length of the critical shear band l_f which is given by the following equation:

$$L > l_f = h \frac{P_p - P_a}{\tau_g - \tau_r} \quad (2)$$

Discussion

Observations on continental slopes in zones with proven or suspected gas hydrate occurrence and sediment deformations show that slope failure could be initiated inside or even at the top of the *GHSZ*^{25,26}. Pecher and co-authors²⁵ have described seafloor erosion associated to hydrate destabilization caused by depressurization during ridge uplift and fluctuating water temperatures. Brown and co-authors²⁶ have rejected gas hydrate dissociation as a triggering mechanism of the Storegga Slide, on the fact that the bottom simulating reflector (BSR) would have been deeper than the glide plane at the time of Storegga slope failure. Those examples show that in natural environment slope failures are not always associated to hydrate dissociation at the base of the *GHOZ* and that slope failure may occur due to hydrate dissociation at the top of the *GHOZ*.

Calculation results obtained in this work and presented in Figure 5 demonstrate that hydrate dissolution at the top of the *GHOZ* occurs earlier than the hydrate dissociation at the base of the *GHOZ*. In this work, the Puzrin and co-authors²⁴ criterion was used to evaluate the danger of a catastrophic landslides generation after 0.8 ky of temperature and pressure increase (Figure 6). It is clear from Figure 6, that the length of the shear discontinuity at the top of the *GHOZ* is much more important than the one at the base of the *GHOZ* ($L_b < L_t$). Moreover, the critical length of the shear band l_f needed to generate catastrophic landslides is much lower at the top than

at the base of the *GHSZ* $\left(l_f|_{base} > l_f|_{top} \right)$ since:

- The value of the passive lateral pressure in the hydrate layer (P_{pb}) is more important than the one in the saturated soil (P_{pl}): the passive lateral pressure depends on the shear strength of the medium which increases with the hydrate fraction;
- The value of the active lateral pressure P_a in the hydrate layer is equivalent to the one in the saturated soil (Figure 6);
- The depth of the discontinuity surface h_t at the top of the *GHSZ* is greater than the one at the base of the *GHSZ* h_b (Figure 6);
- The residual shear strength along the top τ_t is lower than the τ_b due to the increase of the effective stress with depth. Moreover, the amplitude of the excess

pore pressure which can reduce the shear strength significantly seems to be more important at the top than the bottom of the *GHOZ*.

- The gravitational shear stress τ_g increases with depth due to the load of the sediment above the discontinuity surface. However and due to the low slope angle of submarine slopes the increase of τ_g could be considered as negligible with respect to the other parameters of equation 1: for a slope angle of 2.2° and a mean submerged unit weight of 5 kN/m^3 at the dissolution level and 7 kN/m^3 at the dissociation one, the value of $\frac{\tau_g}{h}$ is equal to 0.26 kN/m at the dissolution level while it is equal to 0.192 kN/m at the dissociation one.

From the above 5 observations derived from Figure 5, Figure 6 and equation 2, it is clear that catastrophic slope failure is more likely to happen at the top than the bottom of the *GHOZ*. Moreover, sediment deformation associated to the hydrate dynamic under a natural temperature and pressure increase as the one occurred since the last deglaciation is expected to occur first at the top of the *GHOZ*.

Conclusion

The main aim of this paper was to evaluate the danger related to the gas hydrate dissociation and dissolution under natural sea level and temperature changes as the one occurred since the last deglaciation. Based on theoretical calculation, it was clear that the top of the *GHOZ* is much more hazardous than its bottom:

- The excess pore pressure generated at the base of the *GHOZ* can re-crystallise the gas hydrate and delay the dissociation process.
- Gas hydrate dissociation under natural sea level and temperature changes seems to be a slow process rather than a catastrophic event and it plays an auto-controlling role in the hydrate dissociation progression.
- The lateral extension of the gas hydrate dissolved area is much larger and more regional than the dissociated one.
- Geometrical and mechanical conditions of the propagation of the shear band, which is the main factor in generating catastrophic event, seems to be more likely to happen at the top rather than the bottom of the *GHOZ*.

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Nomenclature

α	slope angle
ΔP	hydrostatic pore pressure increment
Δu_{max}	maximum excess pore pressure
ϕ	internal friction angle
GHSZ	gas hydrate stability zone
GHOZ	gas hydrate occurrence zone
γ_w	water unit weight
γ'	submerged unit weight
h	depth of the discontinuity surface
η	hydrate fraction
L	length of the discontinuity surface
l_f	length of the critical shear band
P_a	active lateral pressure
P_p	passive lateral pressure
$P(T)$	hydrate equilibrium pressure for a given temperature
T	
qt	corrected cone resistance
T	temperature
τ_g	gravitational shear stress
τ_r	residual shear stress
$z(T)$	vertical depth for a given temperature T

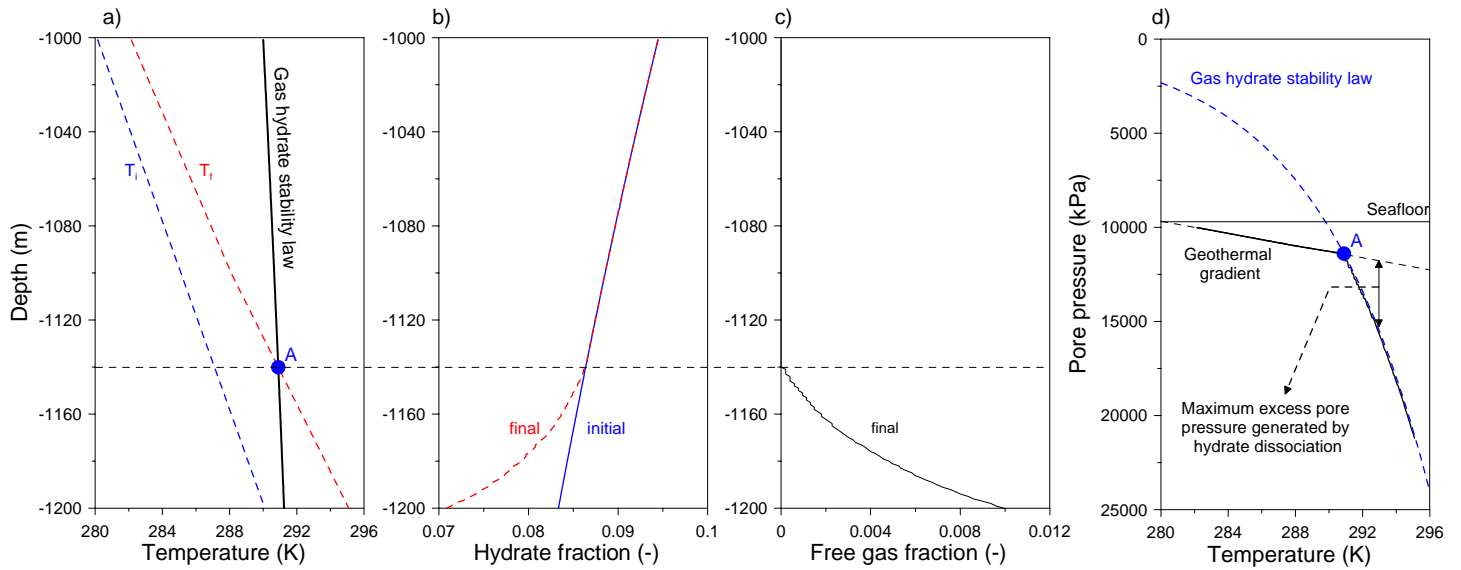


Figure 1. a) 1D calculation of gas hydrate bearing sediment system under two limiting thermal state showing a) the two temperature distributions T_i and T_f b) hydrate fraction profiles under T_i and T_f c) the free gas fraction profile under T_f and d) the maximum possible excess pore pressure generated by hydrate dissociation for the considered calculation. The excess pore pressure and the free gas fraction generated by hydrate dissociation at the base of the hydrate stability zone (point A) is the lowest below the base of the *GHSZ* in a transient regime. The excess pore pressures re-crystallize the hydrate and induce a thermodynamic metastable state where the gas and the gas hydrate coexist.

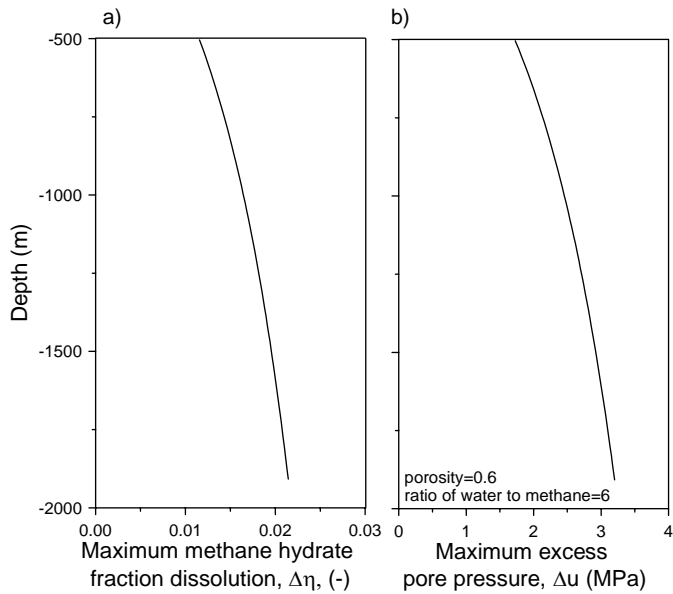


Figure 2. a) Maximum hydrate fraction dissolution as a function of water depth and b) maximum excess pore pressure generated by methane hydrate dissolution as a function of depth.

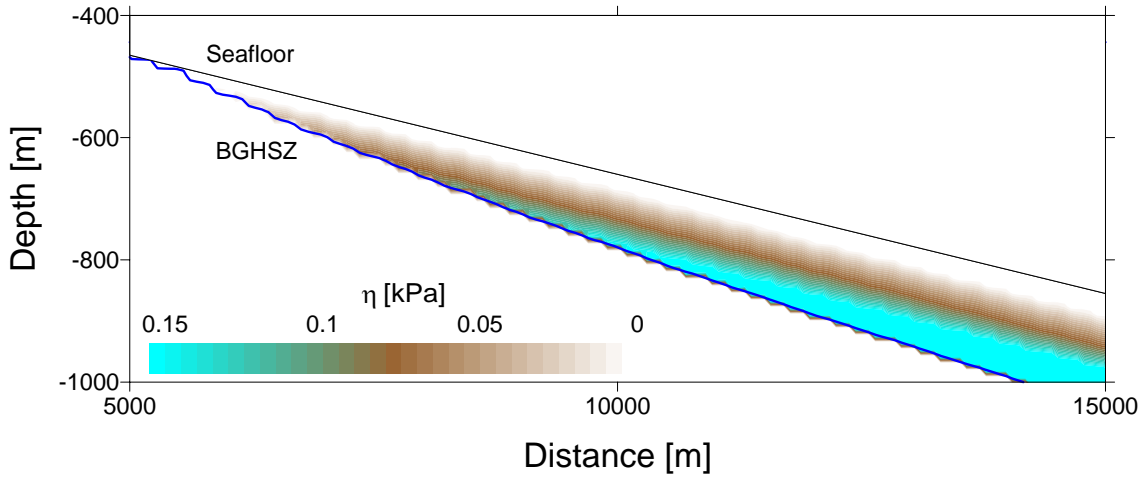


Figure 3. Initial hydrate fraction distribution

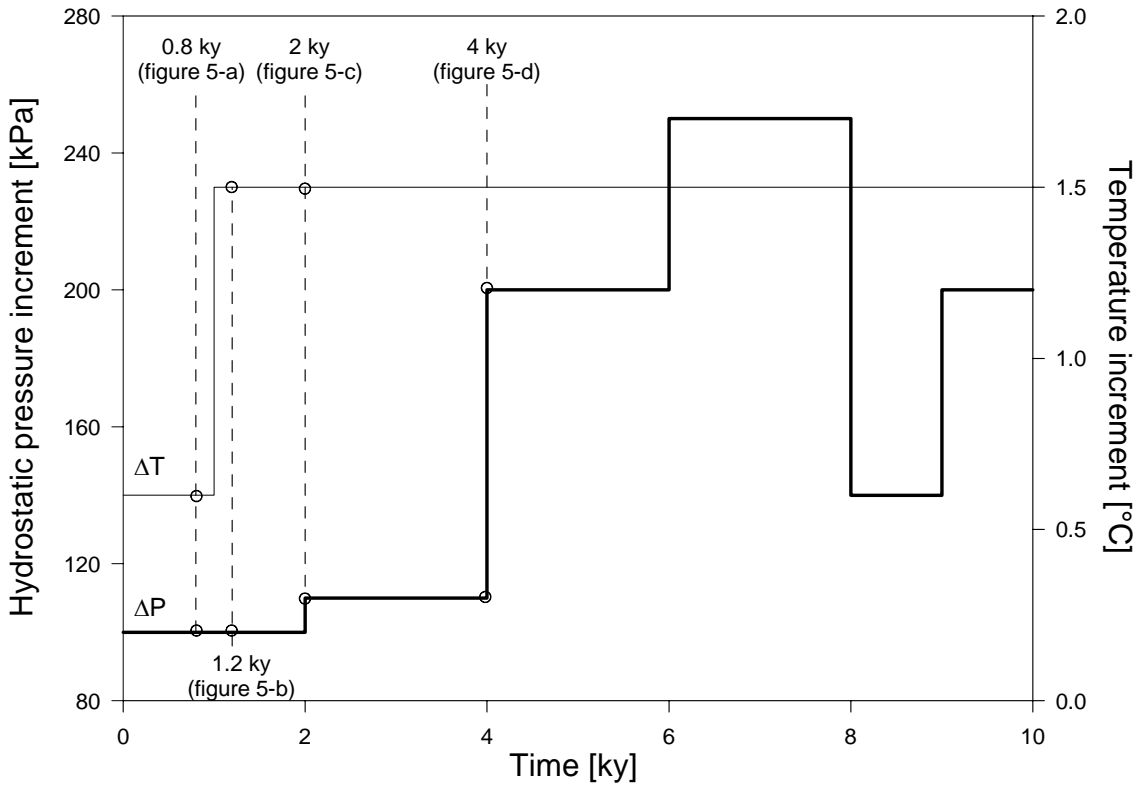


Figure 4. Temperature and pressure increments as a function of time.

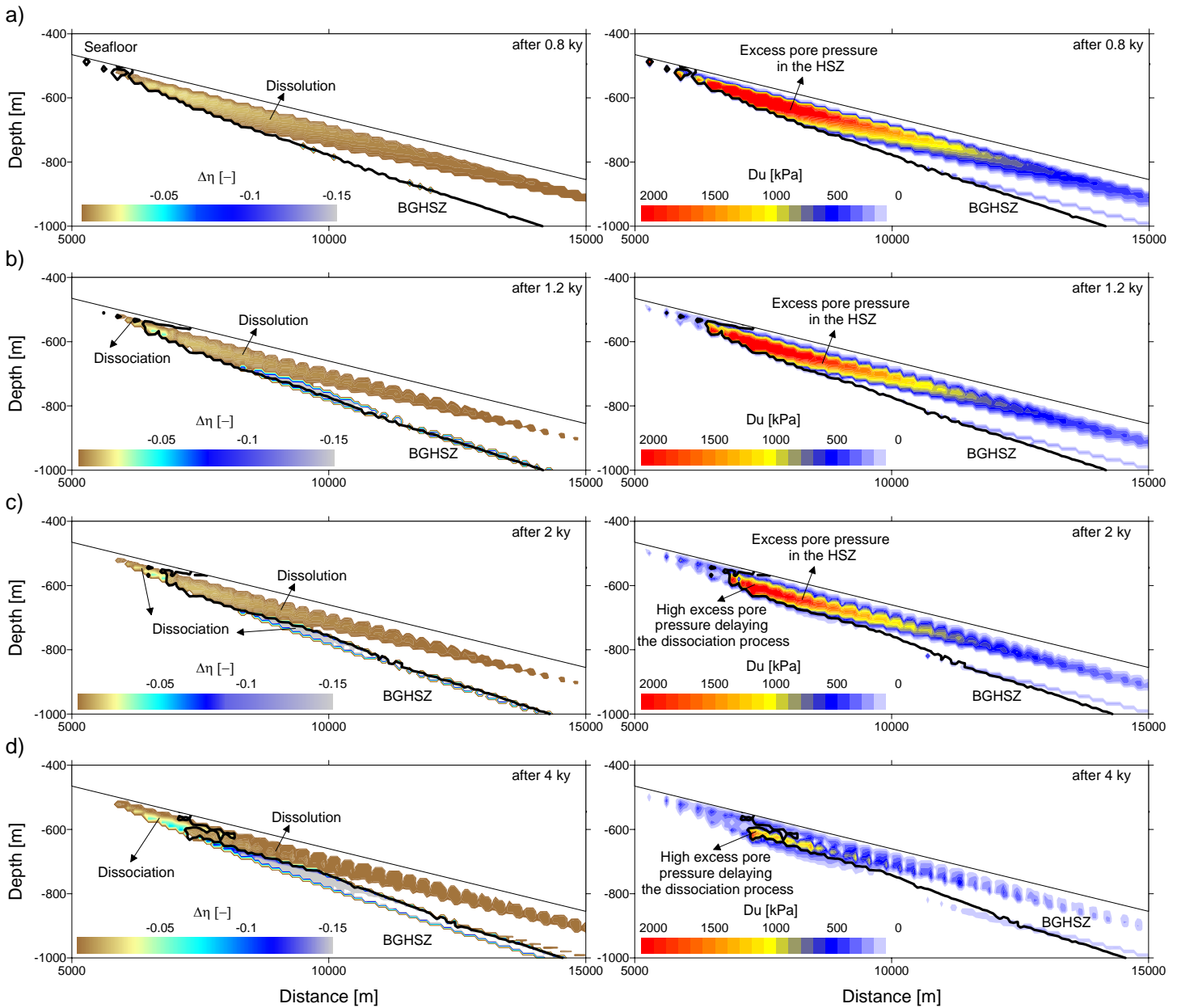


Figure 5. Amount and location of dissolved or dissociated hydrates (shear discontinuities), the pore pressure field and the base of the GHSZ generated after a) 0.8 ky b) 1.2 ky, c) 2 ky and d) 4 ky of temperature and hydrostatic pressure increases.

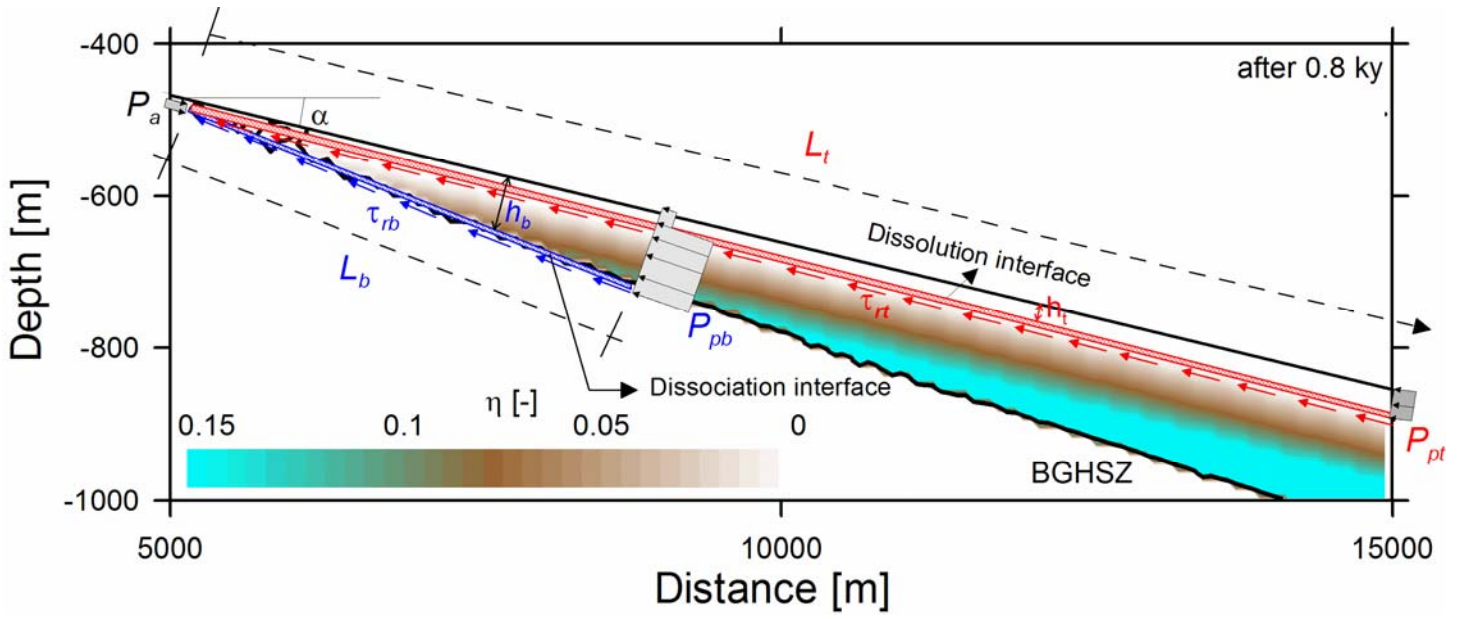


Figure 6. Shear band propagation caused by gas hydrate dissociation (at the bottom of the GHOS) and dissolution (at the top of the GHOS) after 0.8 ky of sea level and temperature changes.