

EFFECT OF CHANGES IN SEAFLOOR TEMPERATURE AND SEA-LEVEL ON GAS HYDRATE STABILITY

Sabodh K. Garg* and John W. Pritchett
Science Applications International Corporation
10260 Campus Point Drive, San Diego, CA, 92121
U. S. A.

ABSTRACT

We have developed a one-dimensional numerical computer model (simulator) to describe methane hydrate formation, decomposition, reformation, and distribution with depth below the seafloor in the marine environment. The simulator was used to model hydrate distributions at Blake Ridge (Site 997) and Hydrate Ridge (Site 1249). The numerical models for the two sites were conditioned by matching the sulfate, chlorinity, and hydrate distribution measurements. The constrained models were then used to investigate the effect of changes in seafloor temperature and sea-level on gas hydrate stability. For Blake Ridge (site 997), changes in hydrate concentration are small. Both the changes in seafloor temperature and sea-level lead to a substantial increase in gas venting at the seafloor for Hydrate Ridge (site 1249).

Keywords: gas hydrates, Blake Ridge, Hydrate Ridge, hydrate stability, gas venting

INTRODUCTION

Natural gas hydrates occur worldwide in oceanic sediments and to a lesser degree in terrestrial permafrost regions. Estimates of total carbon mass sequestered in methane hydrates globally range from 500 to 10,000 Gton [1-3]. For comparison, known fossil fuel resources contain about 5000 Gton of carbon [4]. Methane is a potent greenhouse gas, and a release of a large amount of methane from the global hydrate reservoir would have a significant impact on earth's climate [5, 6]. At present, the role of methane released by hydrate dissociation in climate change is uncertain. There is, however, little question that changes in global climate (e.g. glaciation, warming) can destabilize the hydrates.

During the last glacial maximum, sea level dropped about 100 meters. It has been suggested that the sea-level fall was associated with gas hydrate instability and seafloor slumping [7-8]. It is now almost universally accepted that global warming is a fact. The Intergovernmental Panel on Climate Change in its latest assessment [9] estimates that under certain

scenarios global temperatures will rise as much as 6 °C by the end of the twenty-first century. Although the increase in ocean temperature will be buffered by the high heat capacity of water, it is very likely that the stability of gas hydrates will be adversely affected by global warming.

In this paper, we investigate the effect of changes in seafloor temperature and sea level on gas hydrate stability and on gas venting at the seafloor. Previously, the authors [10] developed a one-dimensional numerical simulator to model hydrate formation and decomposition in the marine environment. This numerical model incorporates (i) the burial history of deep marine sediments and associated phenomena (e.g. sediment compaction and consequent reduction in sediment porosity and permeability, fluid expulsion, time evolution of temperature and pressure, changes in effective stress, heat flux), (ii) *in situ* generation of biogenic methane from buried organic carbon, and methane dissolution in formation brine, (iii) methane hydrate formation, decomposition, and re-distribution in response to changes in gas concentration, pressure,

* Corresponding author: Phone: +1 858 826 1615 Fax: +1 858 826 5115 E-mail: gargs@saic.com

temperature and fluid salinity, (iv) the role of the sulfate reduction zone in suppressing hydrate formation, (v) the possibility of a free-gas region beneath the hydrate stability zone (HSZ), and (vi) multi-phase (*i.e.* liquid brine with dissolved brine, free gas, gas hydrate) flow through a deformable porous matrix. Applications of the model to investigate hydrate distributions at Blake Ridge (site 997) and Hydrate Ridge (site 1249) are described by Garg *et al.* [10]. The numerical models for the two sites were developed by matching the sulfate, chlorinity, and hydrate distribution measurements. These constrained models are used in this study to investigate the effect of changes in seafloor temperature and sea level upon gas hydrate stability.

BLAKE RIDGE (SITE 997)

Ocean Drilling Program (ODP) Leg 164 was dedicated to characterizing the gas hydrates in the Blake Ridge area [11]. A transect of boreholes were drilled from an area lacking bottom-simulating reflectors (site 994) to site 997 where the BSR is well developed. The depth to the sea floor at site 997 is about 2780 m. The hydrate occurs at depths between 185 m below the seafloor (mbsf) and 450 mbsf [12]. The hydrate concentration is estimated to range from less than 4% up to 7%.

Calculations for site 997 [10] indicate that methane migration into the HSZ from a deep source (or a mixed methane source, *i.e.*, methane generation *in situ* and deep methane influx) is the most likely mechanism for the observed hydrate distribution. If the upflowing fluid is just saturated with methane, then the maximum computed free gas saturation below the HSZ does not exceed 3%, in line with saturation values derived from seismic data [13]. The upflow must contain some free gas in order to obtain larger free gas saturation beneath the HSZ as inferred from well logs [12]. In the following, we will restrict our attention to case 2 of Garg *et al.* [10]. In the latter case, no methane is generated *in situ*, and a brine influx – slightly supersaturated in methane – is imposed at the bottom boundary. The total upward fluxes of brine and methane are 0.284 kg/a-m² and 0.0475 moles/a-m², respectively. Starting from zero initial hydrate concentration, the calculation was carried forward in time for 10 Ma. The hydrate distribution with depth undergoes only small changes after 5 Ma [10]; for present purposes, we will adopt the computed distribution at 10 Ma as the initial hydrate concentration.

To assess the effects of an increase in temperature at the seafloor, it is assumed that the temperature increases linearly over a 100-year period; thereafter, the seafloor temperature is held constant. Calculations were performed for temperature increases of 2°C, 4°C, and 6°C. A single calculation was run to evaluate the effects of a decrease in sea-level (100 m over a 100-year time span).

The change in hydrate saturation corresponding to a temperature increase of 6°C is shown in Figure 1. It is apparent from Figure 1 that little or no decrease in hydrate saturation takes place for at least 200 years. Even after 200 years, decreases in hydrate concentration are both slow and small (see curves for 500 and 1000 years in Figure 1).

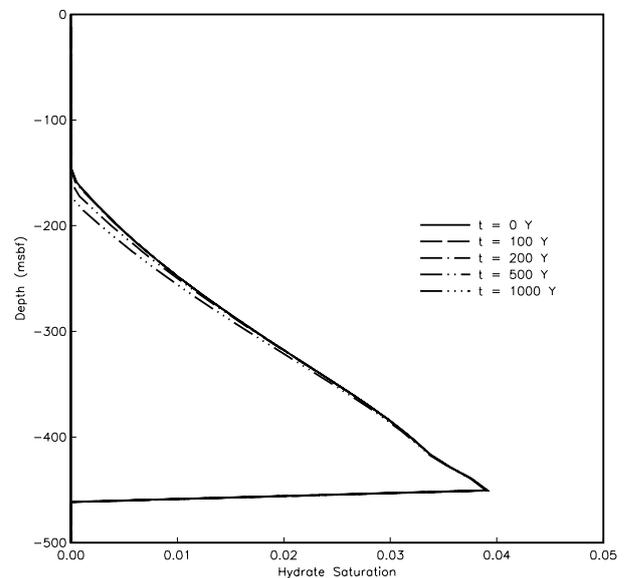


Figure 1: Changes in hydrate saturation at Blake Ridge site 997 due to a seafloor temperature increase of 6°C over a 100 year time period ($t = 0$ to $t = 100$ y). The curve labeled $t = 0$ y corresponds to the initial hydrate concentration.

The reason for the rather slow change in hydrate concentration may be found in the history of temperature below the seafloor (Figure 2). The imposed temperature increase at the seafloor propagates downwards principally as a result of conduction. Since thermal conduction is a relatively slow process, it takes a few hundred years for a significant temperature increase (and hence hydrate dissociation) to occur within the hydrate zone (below ~150 mbsf).

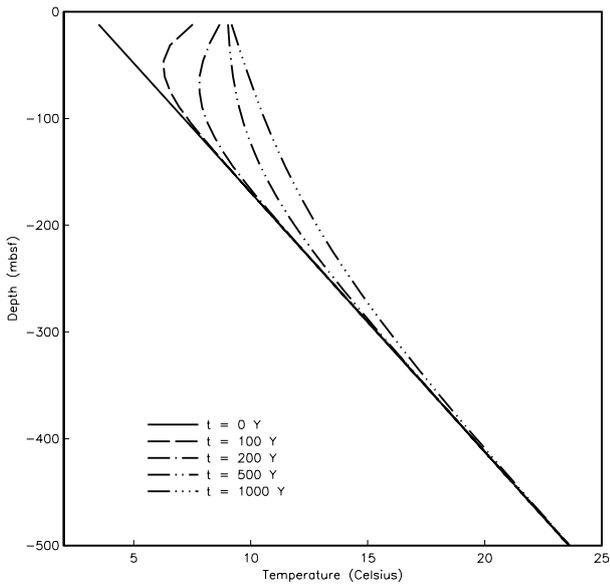


Figure 2: Computed temperature distribution below the seafloor at Blake Ridge site 997 associated with an increase in seafloor temperature of 6°C over a 100 year time period (t = 0 to t = 100 y). The curve labeled t = 0 y corresponds to the initial temperature distribution.

Figures 3 and 4 display the changes in the methane content of the computational grid for a temperature increase of 6°C and a sea-level decline of 100 m, respectively. The temperature increase is accompanied by a decrease in the hydrate content (Figure 3). Essentially all of the methane released by hydrate dissociation dissolves in the liquid, and the gas content remains more or less unchanged (Figure 3). A decline in sea-level leads to a decrease in the dissolved gas, and increases in the free gas and hydrate (Figure 4). All of the changes in methane content in Figure 4 are coincident in time with the decline in sea-level. Methane efflux is herein defined as the sum of the methane loss rates due to consumption in the sulfate reduction zone and to upflow and diffusion into the overlying ocean. It is evident from Figures 3 and 4 that the total methane content of the computational grid remains more or less unchanged. Therefore, any increase in methane efflux as a result of changes in seafloor temperature or decline in sea-level is likely to be exceedingly small. Also, the venting of methane gas at the seafloor remains negligible for the calculation time (1000 years).

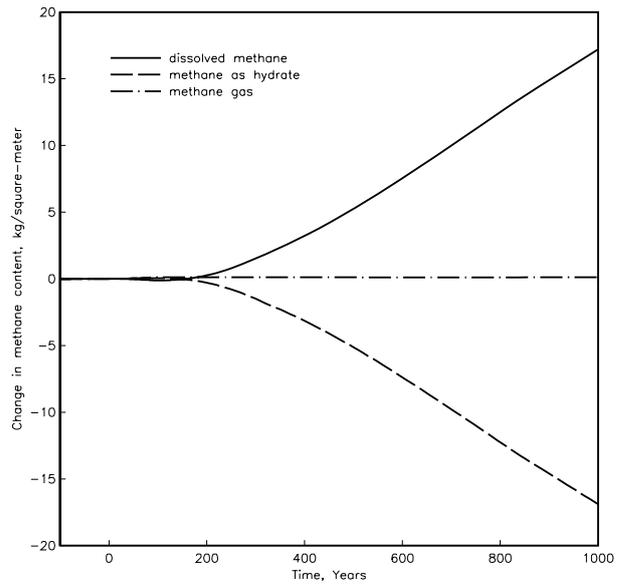


Figure 3: Change in methane content of the computational grid at Blake Ridge site 997 for a temperature increase of 6°C at the seafloor.

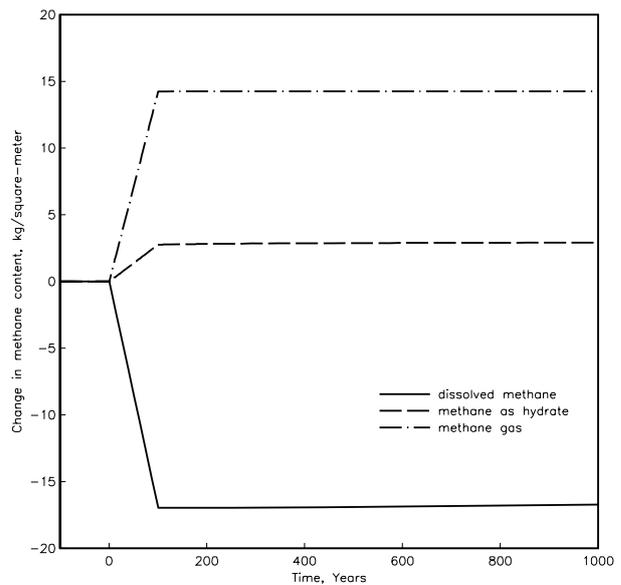


Figure 4: Change in methane content of the computational grid at Blake Ridge site 997 for a sea-level decline of 100 m.

HYDRATE RIDGE (SITE 1249)

Hydrate Ridge is a 25-km-long and 15-km-wide accretionary ridge on the Cascadia margin, located about 80 km off the Oregon coast. As part of ODP Leg 204, nine sites were drilled on and around the southern portion of Hydrate Ridge. Site 1249 was cored to 90 mbsf, and pore fluids with extremely high salinity were observed to depths of 20-40 mbsf; below this, salinity decreased to near

seawater concentrations [14, 15]. Milkov *et al.* [14] and Liu and Flemings [16] suggested that active gas venting at site 1249 may indicate the existence of free gas along with gas hydrate and brine at shallow depths where the high salinity of the pore fluids prevents additional hydrate formation. Seafloor observations [17] indicate that hydrate formation at site 1249 is extremely rapid (~ 100 moles/a-m²).

Garg *et al.* [10] modeled the formation of hydrate at site 1249. The best match to the observed salinity distribution (see case 4 in [10]) was obtained by assuming that hydrate is formed by methane influx through the bottom boundary (i.e. sediment-basement). The methane influx (~ 128 moles/a-m²) was chosen so as to yield an outflow at the seafloor of ~ 100 moles/a-m² once quasi-steady state conditions are attained. In the following, we shall adopt the computed hydrate distribution at $t = 3000$ years (case 4 in [10]) as the initial hydrate concentration.

Like the Blake Ridge example, calculations were run for seafloor temperature increases of 2°C, 4°C, and 6°C, and a sea-level decline of 100 m. All the changes in seafloor temperature and sea-level are assumed to take place over a 100-year span. Computed changes in hydrate saturation for a seafloor temperature increase of 6°C are shown in Figure 5. In contrast to the Blake Ridge example discussed above (Figure 1), substantial changes in hydrate concentration are seen in Figure 5. At Hydrate Ridge site 1249, gas hydrate is present at shallow depths below the seafloor; consequently, the temperature increase at the seafloor propagates downwards in a relatively short time to the hydrate stability zone (Figure 6).

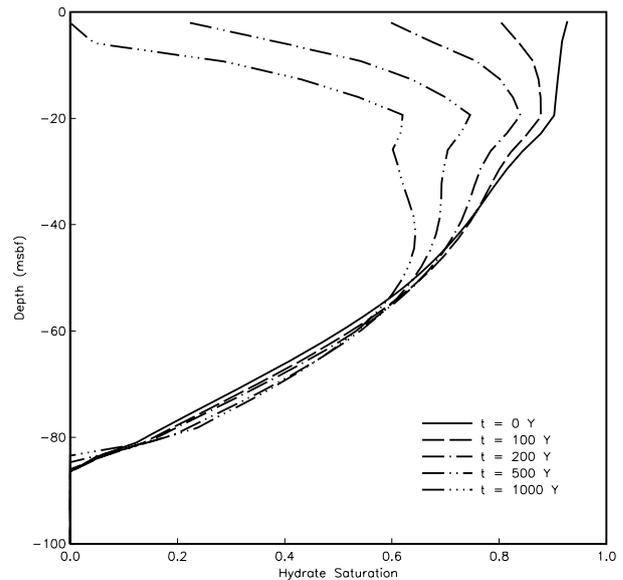


Figure 5: Changes in hydrate saturation at Hydrate Ridge site 1249 due to an increase in seafloor temperature of 6 °C over a 100 year time period. The curve labeled $t = 0$ y corresponds to the initial hydrate concentration (case 4 in [10]).

Computed methane efflux at Hydrate Ridge site 1249 for temperature increases of 2, 4, and 6°C at the seafloor, and a sea-level decline of 100 m is plotted in Figure 7. Unlike Blake Ridge site 997, substantial increases in methane efflux are predicted for Hydrate Ridge site 1249. The methane efflux peaks at $t = 100$ years (at the end of the period during which seafloor temperature or sea-level changes occur), and then declines. Both the initial increase and subsequent decline in methane efflux are most rapid for a decline in sea-level. The discontinuity in methane efflux at about $t = 700$ years in the curve labeled $\Delta T = 6^\circ\text{C}$ is due to spatial discretization. An important feature of the computed increase in methane efflux is that it persists long after the temperature (or the sea-level) stabilizes.

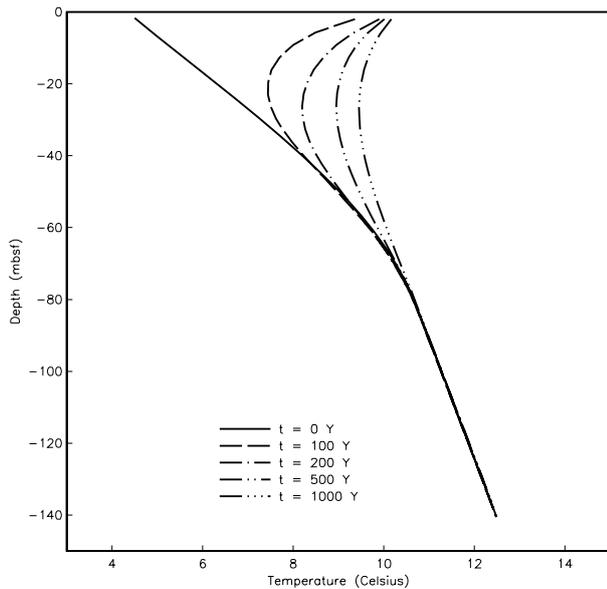


Figure 6: Computed temperature distribution below seafloor at Hydrate Ridge site 1249 associated with an increase in seafloor temperature of 6 °C over a 100 year time period. The curve labeled t = 0 y corresponds to the initial temperature distribution.

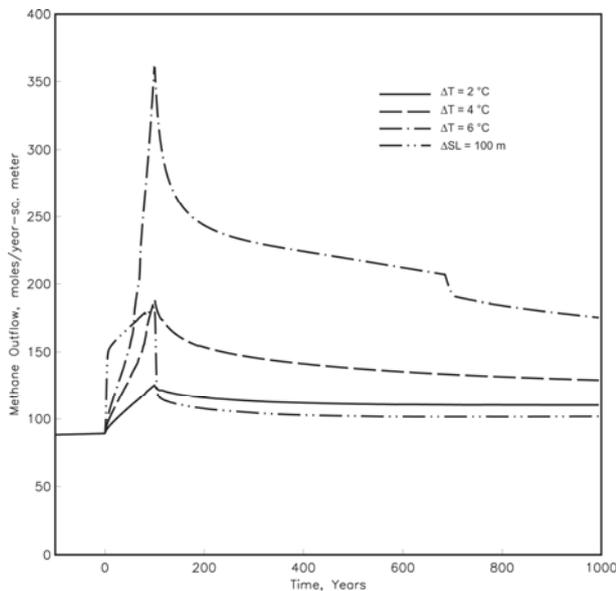


Figure 7: Methane efflux at Hydrate Ridge site 1249 for temperature increases of 2, 4, and 6 °C at the seafloor, and a sea-level decline of 100 m.

Changes in seafloor temperature or in sea-level are unlikely to be accompanied by sediment failure and a catastrophic release of methane gas to the seafloor. As a matter of fact, an increase in seafloor temperature leads to an increase in the

magnitude of the compressive effective stress (Figure 8), and thus lends additional stability to the sediments.

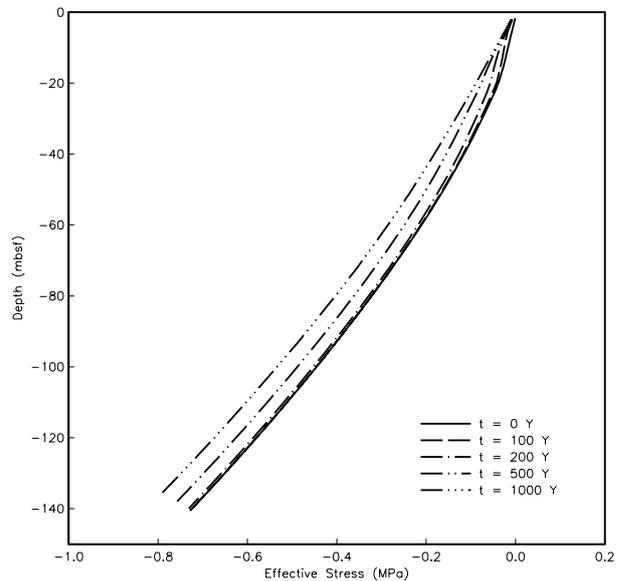


Figure 8: Computed effective stress (= vertical stress + gas pressure, negative in compression) distribution below seafloor at Hydrate Ridge site 1249 associated with an increase in seafloor temperature of 6°C over a 100 year time period. The curve labeled t = 0 y corresponds to the initial effective stress distribution.

CONCLUDING REMARKS

Our calculations for Blake Ridge site 997 and Hydrate Ridge site 1249 are intended to highlight the effect of changes in seafloor temperature and in sea-level on hydrate stability and methane efflux at the seafloor. For methane accumulations like Blake Ridge site 997 with hydrate occurring at considerable depth (100 meters or more below the seafloor), the changes in hydrate concentration are rather slow to occur, and methane efflux at the seafloor does not show an increase. At Hydrate Ridge site 1249, the hydrate occurs close to the seafloor; in this case, an increase in seafloor temperature or a decline in sea-level result in a relatively rapid decrease in hydrate concentration and a concomitant increase in methane efflux at the seafloor. The computed increase in methane efflux is not catastrophic. Also, the enhanced methane efflux persists for a long time even after the seafloor temperature or sea-level have stabilized.

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