THE EFFECT OF DRILLING FLUID INVASION ON THE GAS HYDRATE-BEARING SEDIMENTS

Fulong Ning*, Yibing Yu, Ling Zhang, Guosheng Jiang
Faculty of Engineering
China University of Geosciences
Wuhan, Hubei, 430074
China

Keni Zhang
Earth System Division
Lawrence Berkeley National Laboratory
1 Cyclotron Road, MS 90-1116, Berkeley, California, 94720
United States

ABSTRACT
When drilling through the oceanic gas hydrate-bearing sediments, the water-based drilling fluids under overbalanced drilling condition would invade into the borehole sediments and make gas hydrates unstable. This behavior will further influences the wellbore stability, drilling safety and well logging interpretation and evaluation. In this work, using TOUGH+HYDRATE V1.0 which developed by the Lawrence Berkeley National Laboratory, we performed the numerical simulations to study the effects of density (i.e., corresponding pressure), temperature, salt content of drilling fluids and the permeability of sediments on the hydrate stability around borehole. The results show that the drilling fluid invasion will enhance greatly the hydrate dissociation near wellbore sediments if the temperature of drilling fluids is higher than that of hydrate stability. When the temperature and salt content of drilling fluids are constants, the higher the pressure of the drilling fluid is, the greater degree of invasion and hydrate dissociation are. The gas and water produced from hydrate dissociation can re-form again at the certain depth in the radial sediments, and even the hydrate saturation in this place is higher than that in situ sediment due to the displacing effect of the drilling fluid invasion, which forms a high-saturation hydrate girdle band around the borehole. Under the same temperature and pressure of drilling fluids, the higher the salt concentration of the drilling fluid, the faster rate and greater degree of hydrate dissociation due to the stronger thermodynamic inhibition effect and heat transfer efficiency. The appearance of high-saturation hydrate girdle band mainly depends on the temperature and salinity of drilling fluids. Our simulations conclude that in order to keep wellbore stability and well logging accuracy during drilling through the hydrate-bearing sediments, it is better to adopt the managed pressure drilling and low-temperature mud circulation, and add kinetic inhibitors or anti-agglomerants instead of salts into drilling fluids for preventing hydrate re-formation in the well.

Keywords: gas hydrates, drilling fluid, invasion, secondary hydrates well logging, wellbore stability

* Corresponding author: Phone: +86 18963963512 Fax +86 2767883507 E-mail: nflzx@cug.edu.cn

This work was supported by National Natural Science Foundation of China (No.50704028,40974071, U0933004), Guangzhou Center for Gas Hydrate Research, Chinese Academy of Sciences (No.0807s2) and the Fundamental Research Funds for the Central Universities (No. CUGL100410).
INTRODUCTION
Gas hydrates are non-stoichiometry inclusion compounds which formed when small (<0.9nm) gas molecules (guest molecules) contact water (host molecules) under low temperature (typically<300K) and high pressure (typically >0.6MPa) [1]. As host molecules, the water molecules form water cages by hydrogen bonds then trap the guest small gas molecules, the latter usually are methane and carbon dioxide molecules, which can help to maintain the cage’s stability [2-3]. Thus, gas hydrate is also know as the natural gas hydrate, or simply as hydrate. There are three common types of gas hydrate structure: sI hydrate, sII hydrate, and sH hydrate. Although there are other structure types such as sT type and half hydrate cagelike hydrate [4-7], but so far they exist only in the laboratory. In the nature environment gas hydrate are mainly sI and sII type hydrate, later sH type hydrate was also confirmed that exist in nature, as in the Gulf of Mexico and Cascadia Margin [8-9]. Since the 1960s and 1980s gas hydrate was found in permafrost and marine area respectively [10-11], more and more governments, oil and gas companies and kinds of academic research institutions had paid enormous attention on it, for its important significance in the resources, environment and global change. Gas hydrate research has become one of the hot spots in the geosciences and energy field. As a result, the knowledge of gas hydrates achieved an explosive growth [12], its research field has been spreaded from the initial flow assurance for preventing the block in the oil and gas pipeline [13-14] to resource potential [15-17], safe drilling [18-19], geologic hazard [20], carbon cycle [21] and climatic change [22-23], even the outer space hydrate [24-25]. Recently, the National Energy Technology Laboratory of United States Department of Energy has made a remarkable progress in rapid forming gas hydrate [26], which bring an attractive application prospect for the hydrate technology to use in nature gas and hydrogen storage and transportation [27-29], CO₂ capture and geological burial [30], gas separation [31], cold-storage [32] and desalination of sea water [33]. So to some extent the gas hydrate research has reflected a country’s comprehensive scientific and technological competition and sustainable development potential [34].

Enter the 21st century, with the reduction of recoverable oil and gas and their consumption increases, unconventional energies such as nature gas hydrate and shale gas exploration and exploitation were officially put on the agenda. However, controlled by the hydrate reservoir-forming conditions, the nature gas hydrates mainly occur in the oceans, permafrost and some deep-water sediments of inland lakes [22], where has rugged environment and seriously lacked infrastructure. Therefore, the exploration and exploitation of hydrates are far more difficult than those of conventional oil and gas reservoirs. In the marine areas, gas hydrates account for the vast majority of the amount of gas hydrates that have been found [35]. They distribute in the upheaval of active and passive continental margin and mainly are methane hydrates. According to Klauda and Sandler [36], there was 74,400 Gt of CH₄ trapped in hydrates buried in marine zone, which were three orders of magnitude larger than worldwide conventional natural gas reserves. Therefore, the exploration and exploitation of marine gas hydrates become a hot topic for present and future energy research. And now the commonly methods used for hydrate exploration include geophysical, geochemical and core-drilling. The first is the most widely used [37]. Normally it includes seismic detection technology [38], logging technology [39] and the newest marine electromagnetic technology [40]. The core-drilling is the most direct way for the hydrate reservoir’s identification and evaluation. So far, marine hydrate drilling activities have mainly operated in Blake Ridge [41], Hydrate Ridge in Cascadia Continental Margin [42], Gulf of Mexico [43], Nankai Trough [44], Northern Slope of South China Sea [45], Indian continental margin [46], the Ulleung Basin in the East Sea of South Korea [47]. As the marine hydrate deposits are less consolidation [48-49], it would result in wellbore instability if the under-balanced drilling technology is adopted. Further more, under the under-balanced drilling condition, gas hydrates will decompose because of pressure decline and cause a sharp strength decrease of the sediments [50-51], which would increase the risk of wellbore instability. For this reason, the suitable way is to maintain the wellbore pressure larger than the pore pressure but lower than fracture pressure when drilling in hydrate bearing sediments [52]. On the condition mentioned above, drilling fluid (here referring to water-based drilling fluid) will displace the original pore fluid surrounding the borehole and invade into the sediments because of pressure difference. Drilling practice
has proved that properties of the sediment around borehole are changed when drilling fluid invasion, such as strength and pore pressure [53]. When drilling fluid invasion occurs in hydrate-bearing sediments, the process likely is coupled with hydrate dissociation induced by the temperature of drilling fluid and the generation of heat by drilling tool’s friction. This is the mainly different from what the invasion take places in conventional oil and gas sediments. Moreover, among numerous geophysical logging properties, the resistivity and wave velocity of sediments are influenced greatly by gas hydrates occurrence [39,54-57]. In marine areas, hydrate bearing sediments are usually underconsolidated, while acoustic wave is influenced more greatly by consolidation than other logging methods, so resistivity well logging is more reliable than acoustic and other logging methods[58-59]. However, the circulation and invasion of drilling fluid have a significant influence on the resistivity well logging [60]. For the inhibition of hydrate formation in the wellbore and the protection of the marine environment, water-based drilling fluid system containing polymer and high concentration of salts are commonly used while drilling in deep water [61]. But the invasion of drilling fluid with high salinity will seriously affect the reservoir characteristics and the accuracy of the resistivity logging. Also the salts are thermodynamic inhibitors, with the invasion of drilling fluid they will cause hydrate dissociation and further influence the identify and evaluation of logging, wellbore stability and the security of borehole. Therefore, the investigation of dynamic characteristics of the water-based drilling fluid invasion coupled with hydrate decomposition and the influence for the formation is of great significance and value for the response of logging in hydrate sediment, evaluation of reservoirs, borehole stability, regional hydrate resources and environmental assessment and the hydrate dynamic observation system implementation in the well for the Integrated Ocean Drilling Program(IODP).

Under over-balanced conditions, the temperature and salinity of drilling fluid are the major factors to determine the hydrate stability or not in the sediments during the invasion process. If temperature of drilling fluid is equal or lower than the hydrate equilibrium temperature (Point A in Figure 1) under the same salinity and pressure conditions, the mechanism of drilling fluid invasion in hydrate bearing sediments is similar to that in conventional oil and gas reservoirs. Compare to permafrost areas, the temperature of oceanic hydrate-bearing sediment is higher and closer to the phase equilibrium line. For example, in the Shenhu area of South China Sea, the temperature and pressure of hydrate bearing sediments are nearby the boundary of phase equilibrium [17]). Besides, drilling tool’s friction can generate heat and the presence of thermodynamics inhibitors in drilling fluid can drop the equilibrium temperature of gas hydrates. So these factors act together likely cause that the temperature of drilling fluid is higher than the t phase equilibrium temperature under the same condition(Point B in Figure 1), then the hydrate dissociation would occur around the borehole. That is to say, drilling fluid invasion coupled with hydrate dissociation often encounters when drilling through the marine hydrate-bearing sediments.

![Figure 1 The relations between the temperature of drilling fluid and the temperature of reservoir](image)

If ignore the minor factors, the main behaviors of drilling fluid invading into hydrate-bearing sediment can be described in the multi-phase flow of drilling fluids displacement induced by differential pressure and the hydrate dissociation induced by differential temperatures (between the temperature of drilling fluid and the temperature for hydrate phase equilibrium). So the dynamic invasion process coupled with hydrate dissociation can be approximately described as a opposite direction flow process of hydrate exploitation by pressure reducing and heat stimulating the hydrate reservoirs. We can use the existing numerical models for gas production from hydrate dissociation to investigate the invasion process of drilling fluid in the hydrate-bearing sediments. Merely the influence of invasion is smaller and
limited in an annular area around the borehole, and the hydrate dissociation also occur within a certain range around the borehole. Here, on the basis of the previous theoretical analysis and numerical simulations [62-63], we further simulated the characteristics of drilling fluid invasion and the influence on hydrate sediments around borehole by the TOUGH+HYDRATE code which was developed by Lawrence Berkeley National Laboratory [64].

**NUMERICAL MODELS**

**Simulation method**

The software, TOUGH + HYDRATE, is mainly used to simulate the gas recovery from hydrate reservoirs in marine or permafrost regions[65-67], which can be also used with other softwares (e.g. FLAC 3D) to simulate the wellbore stability and the sediment deformation during gas production from gas hydrates[68-69]. The model of this software is developed from the general groundwater seepage simulator (TOUGH V2.0) by combining with equation ofhydrate state (EOSHYDR). TOUGH+HYDRATE can model nonisothermal hydration reactions, phase behavior, and flow of fluids and heat under the conditions typical of natural CH4-hydrate deposits in complex geologic media. It includes both an equilibrium and a kinetic model of hydrate formation and dissociation [64]. The model accounts for heat and up to four mass components (i.e., water, CH4, hydrate, and water-soluble inhibitors such as salts or alcohols) that are partitioned among four possible phases: gas, aqueous liquid, ice, and hydrate. A total of 15 states (phase combinations) can be described by the code, which can handle any combination of hydrate dissociation mechanisms and can describe the phase changes and steep solution surfaces typical of hydrate problems [70]. Here we adopted the equilibrium model of hydrate formation and dissociation, and did not consider the chemical and mechanical coupling and diffusing effect. At the same time, we assumed that the drilling fluid only contained the thermodynamic inhibitor NaCl and the sediment was isotropic, so that the invasion problem was simplified as a one-dimensional radial displacement problem.

**Simulation parameters**

The cylindrical coordinate was adopted for the simulations. The well has a diameter of 150mm and lies at the center of the cylinder, and the drilling pole diameter is assigned a value 90mm, so the annular space is 30mm. The range of study here is 3m around the borehole. Then a thin layer with a thickness of 0.1m was taken from the center of the hydrate bearing sediments, and it was divided into 90 elements along the radial direction. The drilling fluid in the annular space was treated as one element, which was set as a fixed internal boundary, i.e., the temperature and pressure of drilling fluid in this place kept constant (Figure 2). The in-situ temperature and pressure were set at 8°C and 10MPa, which met the condition of hydrate stability in the sediment. The drilling fluid had a temperature of 15°C and a pressure of 12 MPa. The conductivity of marine sediment (saturated by water) is set 3.1 W.m⁻¹.°C⁻¹, and the conductivity of marine sediment (without water) is 0.85 W. m⁻¹.°C⁻¹. Under the initial condition, the hydrate bearing sediments contained two phases, hydrate phase and liquid phase. The hydrate saturation is 50% (vol) and the liquid saturation is also 50% (vol). The density of the marine sediment is about 2600kg/m³, the porosity is 35%, and the permeability coefficient is 2.96×10⁻¹⁵m².

The primary parameters and physical properties of the sediments in the simulations were shown in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Temperature($T_i$)</td>
<td>8°C</td>
<td>grain density ($\rho_g$)</td>
<td>2600kg/m³</td>
</tr>
<tr>
<td>Initial Pressure($P_i$)</td>
<td>10MPa</td>
<td>grain Specific Heat($C_i$)</td>
<td>1000J.kg⁻¹.°C⁻¹</td>
</tr>
<tr>
<td>Pore water salinity($X_w$)</td>
<td>3.5%</td>
<td>Wet conductivity of sediment(saturated water) ($\lambda_s$)</td>
<td>3.1 W. m⁻¹.°C⁻¹</td>
</tr>
</tbody>
</table>

![Figure 2 A schematic of drilling fluid invasion during drilling in the hydrate-bearing sediment](image-url)
RESULTS AND DISCUSSIONS

Time-dependent geophysical properties during the invasion of drilling fluid

From Figure 3 and 4, it can be found that when the borehole in the gas hydrate-bearing sediment is open, the drilling fluid filters swiftly into the wellbore and displaces the original fluids so that the pore pressure, temperature and water content increase in the sediment around the borehole. At the same time, the hydrates in the sediment are heated to decompose into water and gas. As time goes on, the infiltration amount increases, the temperature and pressure gradually transmit around. At the beginning stage, there is a big pressure difference between borehole and the sediment, but later the pressure line become smooth with the pressure diffusion. Near the borehole(within 1m, shown in Figure 3), the increasing water and gas content by hydrate dissociation cause higher pressure than that without hydrate dissociation[71], i.e., the drop in pressure become smooth, the increase degree of pore pressure caused by drilling fluid invasion coupled with hydrate dissociation is larger than that in the conventional oil and gas sediments. While away from the borehole (beyond 1m), since there is no hydrate dissociation, the diffusion rule of pore pressure is similar to the invasion of drilling fluid into the conventional sediment. Besides, the hydrate dissociation is an endothermic reaction, which causes the sharp drop of sediment temperature near the borehole. Furthermore, the drilling fluid invasion can increase the pore. The two factors make water and gas forming hydrates again in the sediment. The re-formed hydrates are also called secondary hydrates. Because the hydrate formation process is an exothermic reaction, the temperature line become smooth within the radial distance of 0.75m-2.25m (shown in Figure 4).

As time goes on, the hydrate dissociation degree increases gradually and the dissociation front moves gradually into the deep sediment(shown in Figure 5-7). In the beginning, the gas from hydrate dissociation dissolves in the pore water. With the hydrate dissociation increases, the free gas increases gradually and then some of them form gas hydrates again somewhere in the sediment. At the same time, the hydrate dissociation will also dilute the salinity of pore water, sequentially the drop of the water mineralization in the sediment will take place. (shown in Figure 8).

<table>
<thead>
<tr>
<th>Hydrate saturation in situ($S_H$)</th>
<th>0.5</th>
<th>Dry thermal conductivity (no water) ($\lambda_{HH}$)</th>
<th>0.85 W.m$^{-1}$. °C$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore water saturation in situ($S_A$)</td>
<td>0.5</td>
<td>Thermal conductivity of hydrate($\lambda_H$)</td>
<td>0.5 W. m$^{-1}$°C$^{-1}$</td>
</tr>
<tr>
<td>Temperature of drilling fluid($T_m$)</td>
<td>15°C</td>
<td>intrinsic permeability ($K$)</td>
<td>2.96$\times$10$^{-11}$ m$^2$</td>
</tr>
<tr>
<td>Pressure of drilling fluid ($P_m$)</td>
<td>12 MPa</td>
<td>hydrate Density ($\rho_H$)</td>
<td>920 kg/m$^3$</td>
</tr>
<tr>
<td>Porosity($\phi$)</td>
<td>0.35</td>
<td>Specific Heat of hydrate($C_H$)</td>
<td>2100 J.kg$^{-1}$. °C$^{-1}$</td>
</tr>
</tbody>
</table>

Table 1 Parameters of formation in simulation

<table>
<thead>
<tr>
<th>Pressure(MPa)</th>
<th>r(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>1min</td>
</tr>
<tr>
<td>10.5</td>
<td>10min</td>
</tr>
<tr>
<td>11.0</td>
<td>2h</td>
</tr>
<tr>
<td>11.5</td>
<td>5h</td>
</tr>
<tr>
<td>12.0</td>
<td>12h</td>
</tr>
<tr>
<td>12.5</td>
<td>17h</td>
</tr>
<tr>
<td>13.0</td>
<td>20h</td>
</tr>
<tr>
<td>13.5</td>
<td>24h</td>
</tr>
</tbody>
</table>

Figure 3. The pore pressure of sediment around borehole as a function of time during the invasion

<table>
<thead>
<tr>
<th>Temperature(°C)</th>
<th>r(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>1.0</td>
</tr>
<tr>
<td>9</td>
<td>1.5</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
</tr>
<tr>
<td>11</td>
<td>2.5</td>
</tr>
<tr>
<td>12</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Figure 4. The temperature of sediment around borehole as a function of time during the invasion
The effect of drilling fluid density on the invasion behaviors
Under the same temperature and drilling fluid's salinity, the borehole pressure (i.e., density of drilling fluid) is changed in the simulations. It can be found that the higher the pressure, the deeper the invasion, and the speed and depth of heat transfer increases, and the larger degree of hydrate dissociation (shown in fig.9-14). And the higher pressure will quicken the pressure diffusion so that the influence of pores pressure increase induced by the hydrate can be partly reduced (shown in Figure 10). Besides, to some extent the higher pressure will also inhibit the hydrates dissociation and result in the smaller drop of sediment temperature while the higher increase of sediment temperature when secondary hydrates form (shown in Figure 10). Even the higher pressure can cause the whole gas from hydrate dissociation to be dissolved into the pore water (shown in Figure 13). There would form a relatively higher resistivity girdle band induced by the water dilution and free gas from hydrate dissociation in the sediment around the borehole comparing with the original sediment. The longer the invasion time and the higher the density, the deeper the girdle band(shown in Figure 14).

The effect of drilling fluid temperature on the invasion behaviors
Under the same density and salinity of drilling fluid, when its temperature is higher than that of the hydrate stability, the higher its temperature, the larger degree of hydrate dissociation (shown in Figure 15) and the farther the influenced depth(shown in Figure 16-19). The displacement or push by the invasion will cause gas and water to gather somewhere in the sediment and the pore pressure to increase. In addition, such factors as the rapid drop of sediment temperature by hydrate dissociation and the lag of heat transfer will together cause the gas to form hydrates again even whose saturation is higher than that of the original hydrates and then form a "highly saturated hydrate
ring” around the borehole. It can be speculated that the higher the temperature difference between the drilling fluid and the sediment, the more obviously this character is.

Figure 9. The hydrate left as a function of time
Figure 10. The pore pressure as a function of distance (t=2h)

Figure 11. The temperature as a function of distance
Figure 12. The distribution of hydrate saturation (t=2h)

Figure 13. The distribution of free gas saturation
Figure 14. The distribution of NaCl concentration (t=2h)

The effect of drilling fluid salinity on the invasion behaviors
Under the same conditions, the higher the drilling fluid’s salinity, the greater the hydrate dissociation by the invasion (shown in Figure 20), which can be explained by two reasons: one is that the salt as thermodynamic inhibitor can cause phase equilibrium shift which benefits the dissociation, the other is that the increasing salinity will also benefit the heat transfer because of the higher heat conductivity of salts. The invasion of the drilling fluid with high concentration salt will also bring a “highly saturated hydrate ring” around the borehole, which is similar to that by the
temperature (shown in Figure 21-24). Because of the formation of secondary hydrate, the pressure diffusion is retarded and the invasion process is obstructed (Figure 25).

Figure 15. The accumulative gas from hydrate dissociation under different temperature of drilling fluid

Figure 16. The distribution of hydrate saturation Figure 17. The distribution of water saturation (t=2h)

Figure 18. The distribution of free gas saturation Figure 19. The distribution of NaCl concentration (t=2h)

**Discussions**

Obviously, the hydrate stability around borehole depend on the density, temperature and salinity of the drilling fluid during the course of invasion. While the main factors which affect the drilling fluid invasion is the positive pressure difference between the borehole and sediment, the penetrability and the invasion time. Therefore, such an interesting question appears that what the location relation is between the front of the drilling fluid invasion and that of the hydrate dissociation (shown in Figure 26). In other words, what is the main factor deciding their location when the invasion front edge exceeds the decomposition front edge or when the latter exceeds the former? According to our simulations, we speculate that when there is hydrate dissociation around the borehole, if there is small pressure difference, large
temperature difference and low sediment penetrability, the invasion front lags the hydrate dissociation front. If the condition is converse, the invasion front exceeds the hydrate dissociation front. But if there have big pressure difference, great temperature difference and big sediment penetrability, the situation is complicated because the secondary hydrate will disturb the invasion process. In general conditions, the hydrate dissociation front lags the invasion front of drilling fluid.

![Figure 20](image1.png) The accumulative gas from hydrate dissociation

![Figure 21](image2.png) The pore pressure distribution (t=2h)

![Figure 22](image3.png) The distribution of hydrate saturation

![Figure 23](image4.png) The distribution of water saturation (t=2h)

![Figure 24](image5.png) The distribution of free gas saturation

![Figure 25](image6.png) The distribution of pore pressure
In addition, the gas hydrate is similar to ice which is dielectric. Therefore, the sediment appears high apparent resistivity on the dynamic responding characters\[54-59\]. But in the drilling of marine hydrates, normally high-containing salts such as NaCl and KCl are added into the drilling fluid in order to inhibit the hydrate formation in the BOP and keep the wellbore stability. Therefore, there is a higher mineralization of the drilling fluid. When it invades, the dynamic responding characters of resistivity well logging appear a resistivity drop with the increasing water content by the hydrate dissociation. But the water will dilute the pore water to some degree and the gas from the hydrate dissociation will increase the resistivity, so the dynamic responding characters of the resistivity well logging accompanied by drilling fluid invasion and hydrate dissociation are more complicated than that of the conventional sediment. The above mentioned problems need to be investigated by further simulations and extra experiments.

CONCLUSIONS AND SUGGESTIONS

The dynamic characteristics of water-based drilling fluid invading into hydrate-bearing sediment were investigated by employing the TOUGH+HYDRATE code developed by LBNL. The preliminary results are shown as follows according to the simulations.

(1) Under the overbalanced drilling condition, the invasion of drilling fluid into hydrate-bearing sediment is coupled with hydrate dissociation and reformation if the temperature of drilling fluid containing salts is higher than the equilibrium temperature of gas hydrate under the same salt concentration condition. They interact on each other and together determine the degree of drilling fluid invasion and hydrate dissociation, which further influences the mechanical properties, pore pressure, water/gas/hydrate saturation, permeability, resistivity and wave velocity of the sediment around borehole. Both the invasion of drilling fluid and hydrate dissociation will increase the pore pressure and water content and correspondingly decrease the effective stress and intergranular cohesion of sediment, which would cause wellbore instability.

(2) When the density and salinity of drilling fluid keep constant, the higher the temperature of drilling fluid, the larger degree of hydrate dissociation. At the same time, the gas and water produced from hydrate dissociation can re-form again at the certain depth in the radial sediments due to the pore pressure increase caused by drilling fluid invasion, the heat adsorption of hydrate dissociation and the heat diffusion delay of sediment, etc. Even the hydrate saturation in this place is higher than that in situ sediment and thus it forms a high-saturation hydrate girdle band around the borehole. The reason for this is that the gas from hydrate dissociation is squeezed by the displacement of the drilling fluid invasion and cumulates to a larger concentration at the certain depth in the sediment.

(3) When the salinity of drilling fluid is same with that of the pore water in the sediment near the borehole, the larger the density of drilling fluid, the deeper invasion and heat transfer, and the more hydrate dissociation. There would form a relatively higher resistivity girdle band induced by the water dilution and free gas from hydrate dissociation in the sediment around the borehole comparing with the original sediment.

(4) When the density and temperature of drilling fluid keep constant, the higher salinity of drilling fluid, the larger degree of hydrate dissociation due to the stronger thermodynamic inhibition effect and heat transfer efficiency during the invasion process. The high salt concentration of drilling fluid invasion would cause the similar high-saturation hydrate girdle band around borehole like the high temperature of drilling fluid. The final salinity distribution around borehole depends on the salinity of drilling fluids and the degree of hydrate dissociation and reformation.

(5) Under the simulation conditions, it is found that the appearance of high-saturation hydrate girdle band mainly depends on the temperature and salinity of drilling fluids. Therefore, when drilling in the hydrate-bearing sediment, managed pressure drilling operation should be employed to keep the suitable downhole...
pressure difference and ensure wellbore stabilization, well drilling safety and well logging accuracy. Our simulation results also show that even the LWD method might not be accurate in the hydrate-bearing sediment if the invasion condition is out of hydrate stability zone because the drilling fluid invasion and hydrate dissociation are very quick. The best way to avoid this is to adopt the deep laterolog method. In addition, it is better to select low salinity drilling fluid system for drilling, i.e., reducing the addition of salts which would influence the resistivity logging and hydrate stability around borehole. At the same time, the drilling fluid should be kept cool and fast circulation. However, the low temperature of drilling fluid circulation would cause the gas spilled from hydrate dissociation near the borehole re-form and aggregate in the borehole. So it is best to add the kinetic inhibitors or kinetic inhibitors (KHSs) or anti-agglomerants (AAs) into drilling fluids rather than salts that are thermodynamic inhibitors. In the future work, we will investigate the influence of drilling fluid invasion on the geophysical properties of hydrates bearing sediment and the resistivity logging by integrating with the practical drilling operations and experimental tests.

ACKNOWLEDGEMENTS
The authors would like to thank Dr. George Moridis for valuable suggestions on our models and theoretical analysis.

REFERENCES


