Invasion of drilling mud into gas-hydrate-bearing sediments. Part I: effect of drilling mud properties

Fulong Ning,1,2 Keni Zhang,3,4 Nengyou Wu,2 Ling Zhang,1 Gang Li,2 Guosheng Jiang,1 Yibing Yu,1 Li Liu1 and Yinghong Qin1

1Faculty of Engineering, China University of Geosciences, Wuhan, Hubei 430074, China. E-mail: nflzx770803@163.com
2Guangzhou Center for Gas Hydrate Research, Chinese Academy of Sciences, Guangzhou 510640, China
3Earth System Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
4College of Water Sciences, Beijing Normal University, Beijing, 100875, China

Accepted 2013 January 16. Received 2012 November 30; in original form 2011 November 12

SUMMARY
To our knowledge, this study is the first to perform a numerical simulation and analysis of the dynamic behaviour of drilling mud invasion into oceanic gas-hydrate-bearing sediment (GHBS) and to consider the effects of such an invasion on borehole stability and the reliability of well logging. As a case study, the simulation background sets up the conditions of mud temperature over hydrate equilibrium temperature and overbalanced drilling, considering the first Chinese expedition to drill gas hydrate (GMGS-1). The results show that dissociating gas may form secondary hydrates in the sediment around borehole by the combined effects of increased pore pressure (caused by mud invasion and flow resistance), endothermic cooling that accompanies hydrate dissociation compounded by the Joule–Thompson effect and the lagged effect of heat transfer in sediments. The secondary hydrate ring around the borehole may be more highly saturated than the in situ sediment. Mud invasion in GHBS is a dynamic process of thermal, fluid (mud invasion), chemical (hydrate dissociation and reformation) and mechanical couplings. All of these factors interact and influence the pore pressure, flow ability, saturation of fluid and hydrates, mechanical parameters and electrical properties of sediments around the borehole, thereby having a strong effect on borehole stability and the results of well logging. The effect is particularly clear in the borehole SH7 of GMGS-1 project. The borehole collapse and resistivity distortion were observed during practical drilling and wireline logging operations in borehole SH7 of the GMGS-1.mud density (i.e. the corresponding borehole pressure), temperature and salinity have a marked influence on the dynamics of mud invasion and on hydrate stability. Therefore, perhaps well-logging distortion caused by mud invasion, hydrate dissociation and reformation should be considered for identifying and evaluating gas hydrate reservoirs. And some suitable drilling measurements need to be adopted to reduce the risk of well-logging distortion and borehole instability.

Key words: Downhole methods; Geomechanics; Gas and hydrate systems; Ocean drilling; Phase transitions.

1 INTRODUCTION
Gas hydrates are non-stoichiometric inclusion compounds formed when hydrophobic gas molecules (usually methane and carbon dioxide) come into contact with water (host molecules) under conditions of low temperature (typically <300 K) and high pressure (typically >3.8 MPa at a temperature of 277 K; Sloan 2003). Gas hydrates are widely distributed in marine continental margin sediments and to a lesser degree in permafrost environments (Kvenvolden 1993).

Great advances have been made in the exploration for and exploitation of natural gas hydrates (Jaiswal et al. 2006; Priest et al. 2006; Weitemeyer et al. 2011). Yet further development is hampered by poor quantitative descriptions of in situ properties of hydrate deposits, immature exploration and production technology and high safety risk of geology and environment in exploitation. The problems of immature technology and safety risk are related to factors such as drilling safety (e.g. wellbore instability), formation deformation, geologic hazards and climate change. Especially for poorly consolidated hydrate deposits in marine environments (Birchwood...
et al. 2008), drilling induced wellbore instability is likely to occur if underbalanced drilling is adopted (Collett et al. 2009; Birchwood & Noeth 2012). Under such drilling conditions, gas hydrates tend to decompose because of the pressure decrease and further causes a sharp reduction in the strength of the sediment (Winters et al. 1999a,b, 2007), thereby placing the wellbore at risk of collapse (Freij-Ayoub et al. 2007). A practical way to reduce this risk is to maintain the wellbore pressure at a higher level than the pore pressure but lower than the formation fracture-opening pressure (Ning et al. 2008a). In such a case, mud (herein referred to as ‘water-based mud’) displaces the original pore fluid surrounding the borehole and invades the gas-hydrate-bearing sediment (abbreviated as GHBS) because of the pressure gradient between the mud and the surrounding sediment (Fig. 1). Mud invasion into drillholes has an effect on host-sediment properties, such as permeability, pore pressure and mechanical strength (Philips 1995; Chi et al. 2006), and it is also likely to influence the stability of gas hydrates. For example, the hydrate may dissociate due to the relative high temperature of the mud and due to frictional heat generated by the drilling tool.

In addition to its effect on wellbore stability, hydrate dissociation has a strong influence on geophysical well logging, especially the resistivity and wave velocity of sediments. That is because the resistivity and wave velocity of sediments are influenced greatly by occurrence of gas hydrates among numerous geophysical logging properties (Collett & Lee 2000; Collett 2001; Spangenberg 2001; Chand et al. 2006; Riedel et al. 2006; Waite et al. 2009). In marine areas, the acoustic logging method is more sensitive to formation consolidation than other logging methods, suggesting that resistivity well logging is more reliable than acoustic logging because gas hydrates normally occur in relatively unconsolidated sediments (Lee & Collett 2008; Lee & Collett 2009b). However, a water-based drilling mud system, containing polymer and specified concentrations of salts, is commonly used when drilling in deep water (Ebeltoft et al. 1997) or when drilling marine hydrate deposits (Collett et al. 2009; Jiang et al. 2011). In addition to borehole washout caused by this type of drilling mud circulation (Lee et al. 2012), mud filtrate invasion may also have a strong effect on the reliability of geophysical resistivity logging. Salts are thermodynamic inhibitors, and when carried with invading mud, they potentially cause hydrate dissociation (Dickens & Quinby-Hunt 1997), leading to wellbore instability and affecting logging data. Therefore, it is important to understand the dynamics of drilling mud invasion and to consider its influence on the GHBS, especially in terms of the response of geophysical well logging in the GHBS, the evaluation of reservoirs, borehole stability, regional hydrate resources and environmental assessment.

In the case of overbalanced conditions, the temperature and salinity of the drilling mud are major factors in determining hydrate stability in the sediments during mud invasion. If the temperature of the mud falls below the hydrate equilibrium temperature (Point A in Fig. 2) under given salinity and pressure conditions, the hydrate remains undissociated; consequently, the mud invasion influences the GHBS in a manner similar to the case of conventional oil/gas reservoirs. Compared with permafrost hydrate deposits, the temperature of an oceanic GHBS is higher and closer to the phase equilibrium line (Booth et al. 1996). For example, in the Shenhu area of the South China Sea, the temperature and pressure of GHBS are close to those of phase equilibrium (Ning et al. 2010). In such a case, borehole drilling may easily lead to hydrate dissociation around the borehole because drilling generated heat, salts as thermodynamic inhibitors in mud and originally higher mud temperature together may jointly result in the local temperature of mud crossing the phase equilibrium boundary (Point B in Fig. 2). Such conditions were encountered when drilling the WR 313-G well during the Gulf of Mexico Gas Hydrate Joint Industry Project Leg II (JIP Leg II) in May 2009 (Collett et al. 2009). Under this condition, the overall behaviour of mud invading, the GHBS can be described as a multiphase flow coupled with hydrate dissociation driven by differential pressure and differential temperature. Existing numerical models of multiphase fluid-flow for hydrate production may therefore be used to investigate the invasion process of drilling mud in the GHBS. The difference between gas production from the GHBS and mud invasion into the GHBS is that the influence range of mud invasion is small, limited to an annular area around the borehole, contrary direction of multiphase flow and hydrate dissociation occurs close to the borehole.

On the basis of a previous theoretical analysis (Ning et al. 2008b, 2009), we performed a series of numerical simulations to investigate the characteristics of drilling mud invasion and its influence on hydrate sediments around a borehole. This simulation
1372 F Ning et al.

considers the case of Project GMGS-1 in the South China Sea, using the TOUGH+HYDRATE code developed by Lawrence Berkeley National Laboratory (Moridis et al. 2009a). The effect of mud invasion on GHBS can be discussed from two aspects: the properties of drilling mud and the petrophysics of sediment. This paper considers the former, with the aim of identifying the invasion characteristics of drilling mud into GHBS and the key factors that affect the mud invasion. The results of this study may help in guiding well drilling, logging and the protection of hydrate reservoirs, especially correcting for the distortion of well logging induced by mud invasion.

2 SIMULATION METHOD

2.1 Background

The first Chinese expedition to drill gas hydrate, GMGS-1, was carried out in the Shenhu area of the South China Sea during 2007 April to 2007 June by the companies Fugro and Geotek for the Guangzhou Marine Geological Survey (GMGS), the China Geological Survey (CGS) and the Ministry of Land and Resources of P. R. China (Fig. 3). Eight sites were selected for drilling and well logging. Cores were recovered at five sites, among which gas hydrate occurrences were identified from Site SH2, SH3 and SH7 (Wu et al. 2009). In the three sites, hydrates occur at 153–229 m beneath the seafloor, with a thickness of 10–43 m and porosity of 33–48 per cent. The hydrate is mainly type I methane hydrate with a saturation of 26–48 per cent (estimated from well logging), and it is disseminated throughout the sediment. The produced gas consists of 96.1–99.82 per cent methane, which was of microorganism origin. In situ measurements indicate that the bottom-water temperature was 3.3–3.7 °C and the geothermal gradient was 43.0–67.7 °C km−1, corresponding to a sea-bottom heat flow of 74.0–78.0 mW m−2 (average 76.2 mW m−2).

During the GMGS-1 Project, drilling was performed from the vessel Bavenit (of the company AMIGE), which does not have a marine riser. The assembly for well drilling was as follows: Ø228.6 mm blade core bit + long-sealing pup joint + short-sealing pup joint + landing nipple + shut-off nipple + floating valve nipplet + Ø177.8-mm drill collar (×8) + Ø127-mm drilling pipe (×22) + Ø175-mm aluminium drilling pipe (×100) + Ø127-mm drilling pipe. Sea water was used as drilling mud with a rate of 70–80 rpm and displacement of 800–900 L/min. When the well reached the desired depth, sea water in the open-hole annulus was displaced by bentonite mud with a density of 1190 kg m−3 to improve wellbore stability. Well logging and coring were conducted to characterize the borehole (Hu et al. 2009). Mud invasion into the GHBS mainly occurred during the stage of mud displacement. During this stage, mud circulation occurred for only a short time, meaning that the mudcake effect did not necessarily need to be considered.

The software TOUGH+HYDRATE is widely used to simulate gas recovery from hydrate reservoirs in marine or permafrost regions (Moridis et al. 2007, 2009b; Li et al. 2010), and it can be used in tandem with other software (e.g. FLAC 3D) to simulate wellbore stability and sediment deformation during gas production from hydrate deposits (Rutqvist et al. 2008, 2009). TOUGH+HYDRATE can simulate non-isothermal hydration reactions, phase behaviour and the flow of fluids and heat under the conditions typical of natural CH4-hydrate deposits in complex geologic media. It includes both equilibrium and kinetic models of hydrate formation and dissociation. The model accounts for heat and up to four mass components (i.e. water, methane hydrate, gas and water-soluble inhibitors such as salts or alcohols) that are partitioned among four possible phases: gas, aqueous liquid, ice and hydrate (Moridis et al. 2009a). Up to 15 states (phase combinations) can be described by the code, and it is capable of simulating any combination of hydrate dissociation and of describing phase changes and heat mass transfer for sediment fluids, as well as considering other typical hydrate problems (Zhang et al. 2008). We adopted the equilibrium model of hydrate

Figure 3. (a) Location of the Shenhu GMGS-1 project on the north slope of the South China Sea. (b) Bathymetric map of the area of gas hydrate drilling, showing the locations of wells drilled in the research area (reproduced from Li et al. 2010).
formation and dissociation, and did not consider chemical and mechanical coupling of the diffusion effect. For simplification, we assumed that the mud only contained the thermodynamic inhibitor NaCl.

2.2 Simulation model and parameters

The simulations were based on data retrieved from borehole SH7, where the seafloor is at a water depth of 1108 m. The GHBS mainly occurred in fine-grained sediment at 155–177 m below the seafloor (mbsf), including sandy clay at drillhole depths of 155.0–159.4 mbsf, silty clay at 159.4–168.9 mbsf and firm olive-grey clay at 168.9–177 mbsf. The hydrate concentration at the site is variable, with a maximum value of 44 per cent of pore volume calculated from porewater freshening. Here 44 per cent is selected as the original hydrate saturation for the simulations. A thickness of 0.1 m in the middle of the GHBS (about 166 mbsf) is investigated. In this thin layer, the GHBS is regarded as isotropic sediment in which hydrates occur as pore filling habit. The methane hydrates and water coexist in the in situ sediment. An axisymmetric cylinder with a radius of 5 m is adopted for the model domain, with the borehole located in the centre of the cylinder. The investigated thin layer was discretized into 100 radial grid cells. The drilling tools assembly used a borehole with a diameter of 228.6 mm, a drilling pipe with a diameter of 177.8 mm and an annular with a clearance of 25.4 mm. The mud in the borehole is treated as a fixed inner boundary; that is, the temperature and pressure remained stable in this thin mud layer. The process of mud invasion is simplified as a 1-D radial displacement problem. The physical model is shown schematically in Fig. 4.

Because natural gas hydrates are mainly distributed in poorly consolidated sediments near the seafloor, pore water in the sediment can be considered to communicate with sea-bottom water. Then the hydrostatic pore-water pressure can be calculated on basis of well depth and average sea water density. The geothermal gradient at borehole SH7 was 43.2 °C km⁻¹ and the sea-bottom temperature at the site was about 3.5 °C (Li et al. 2010). The temperature and pressure at the thin layer were calculated to be 13.74 °C and 13.2 MPa, respectively, which is within the stability field of hydrate.

The drilling mud temperature at the simulation depth was estimated to be close to 15 °C, based on the borehole conditions of logging at the depth of hydrate occurrence (Nakai et al. 2007), and mud pressure was estimated from the pressure of overlying sea water and mud in the borehole, as follows:

\[ P_t = P_{atm} + g(\rho_{sw}h + \rho_f(z)) \times 10^{-6}, \]

where \( P_t \) is mud pressure, MPa; and \( \rho_t \) is mud density, kg m⁻³; \( P_{atm} \) is standard atmospheric pressure, 0.101325 MPa; \( h \) is water depth, m; \( z \) is the depth of sediment from the sea bottom, m; \( g \) is the acceleration of gravity, m s⁻²; and \( \rho_{sw} \) is the average sea water density, which is a function of water depth, temperature and salinity, kg m⁻³. The calculated \( P_t \) was about 13.54 MPa, at which the corresponding equilibrium temperature was about 14.7 °C for a NaCl concentration of 3.05 per cent, suggesting that the mud temperature crosses the gas hydrate stability phase boundary. The model parameters are listed in Table 1.

3 RESULTS AND ANALYSES

3.1 Characteristics of drilling mud invasion into GHBS

The simulated distributions of pressure and temperature around the borehole during mud invasion are shown in Figs 5a and b. During drilling through the GHBS, mud filters moved swiftly into the borehole wall and displaced the original fluids, causing a rapid pressure increase in the local sediment. With the ongoing infiltration of mud, the zone of enhanced temperature and pressure gradually extended farther into the surrounding sediment. The temperature spread, which reached 0.5 m from the borehole at 5 h and 0.5 m at 24 h, lagged behind the pressure spread (Figs 5a and b), which reached 5 m from the borehole at 5 h. During mud invasion, the temperature and pressure developed in a similar manner to that in conventional oil and/or gas sediment.

Despite this similarity, during hydrate drilling the mud invasion was accompanied by phase changes, as indicated by variations in the saturation of the hydrate, aqueous and gas phases around the borehole. This differs from mud invasion in conventional sediment and GHBS. For example, in the present simulation, hydrate dissociation occurred during mud invasion and led to a reduction in saturation, concomitant with an increase in water and free-gas saturation around the borehole (Fig. 5c). The increase in water content is due to mud invasion and hydrate dissociation. Fig. 5c also shows that the mud invasion causes hydrate dissociation accompanied by hydrate reformation under the simulation conditions. Such reformed hydrates are called ‘secondary hydrates’ (Moridis & Reagan 2007), and these have been predicted by numerical simulations (Moridis & Reagan 2007; Li et al. 2010) and validated in experiments (Kneafsey et al. 2007; Seol & Myshakin 2011). The reformation of secondary hydrates occurs because of the combined effect of several factors:

![Figure 4. Schematic mud-invasion model at SH 7 site of the GMG-1 project. Red arrows indicate the direction of drilling mud flow. The hole was drilled without the use of a riser. The drilling mud was directly discharged into sea water through the ‘open hole’. The dashed rectangle in the gas-hydrate-bearing layer represents a thin layer located in the centre of the hydrate-bearing layer, which was selected as research area and divided into 100 grid cells. Mud invasion in this thin layer was simplified as a 1-D radial displacement problem.](https://academic.oup.com/gji/article-abstract/193/3/1370/601509/100.grid.cells)
The squeezing effect of drilling mud invasion (i.e., increasing pore pressure due to mud invasion and flow resistance), endothermic cooling related to hydrate dissociation compounded by the Joule–Thompson effect (Moridis & Reagan 2007) and the lagged effect of heat transfer in sediments. Because of these factors, the local hydrate thermodynamic parameters fall below the phase equilibrium boundary. The relationship between mud invasion and hydrate reformation is, to some extent, similar to injecting the constituent components of hydrate (i.e., water and methane) for permeability measurements of GHBS in displacement experiments, which would likely lead to additional hydrate formation (Johnson et al. 2011). In addition, water from hydrate dissociation is displaced by mud invasion and dilutes the local salinity of pore water (Fig. 5d), further promoting the reformation of gas hydrate (Li et al. 2010; Seol & Myshakin 2011).

The occurrence of secondary hydrate, together with existing hydrate, means that the hydrate saturation is locally even higher than the original hydrate saturation (0.44). In the simulations, such a high-saturation hydrate ring formed, with a peak value of 0.4617 at a radial distance of 0.15 m from the borehole after about 12 h. The occurrence of this ring and free gas led to a decrease in local water saturation, forming ‘water troughs’ (Fig. 5c). The high-saturation hydrate ring may be attributed to the displacement effect of mud invasion and to permeability hysteresis related to secondary hydrates, which causes a reduction in permeability (Konno et al. 2008). Thus, the dissociated gas and water accumulate in this area and ultimately form the ring. The simulation results (Table 2) also show there occurs in situ hydrate dissociation following the high-saturation hydrate ring, although this is not apparent in Fig. 5c (this is further discussed in Section 4.1). For example, at 24 h, the hydrate saturation was 0.4612 at 0.17 m from the borehole, but just 0.4388 at 0.22 m from the borehole, which is lower than the original saturation of 0.44. Therefore, the high-saturation hydrate ring induced by secondary hydrates can serve to divide the whole hydrate dissociation area into two parts: from the borehole face to the position of the ring, and outward from the ring, with the degree of hydrate dissociation much less in the outward part. The aforementioned process of mud invasion accompanying with hydrate dissociation and high-saturation hydrate ring is described in Fig. 6 and was validated indirectly from the 20 and 24 h curves in Fig. 5d. The reformation of hydrate resulted in an increase in pore-water salinity while weak hydrate dissociation resulted in a salinity decrease (Fig. 5d). The mud invasion and heat transfer contribute to the development of the high-saturation hydrate ring and areas of hydrate dissociation migrate dynamically, radially from the borehole over time (see Table 2). This indicates that the secondary hydrates may dissociate again with ongoing heat transfer. Water and gas from the dissociation of original and secondary hydrate were squeezed closer to the surrounding sediment by the mud invasion and the secondary hydrates reformed again (Fig. 5c). With weakening of the mud invasion and heat transfer, the maximum saturation degree of the hydrate ring at 24 h fell below that at 12 h.

In summary, hydrate dissociation and reformation mainly occurred within 0.25 m of the borehole. Thereinto, hydrate dissociation mainly took place within 0.1 m and no hydrates existed within 0.05 m of borehole when mud invasion took place (after 24 h in this case). The degree of hydrate dissociation around the borehole was limited because the mud temperature crossed the hydrate stability phase boundary under the conditions of drilling mud pressure (13.54 MPa) and salinity (3.05 per cent). The mud invasion extended to about 1.0 m from the borehole after 24 h (Fig. 5d). These distances from the borehole (over which dissociation, reformation and mud invasion occurred) indicate the region in which we should evaluate the effect of mud invasion on borehole stability and well logging in the GMGS-1 hydraulic fracturing project.

Table 1. Main properties and conditions of mud and hydrate deposits at Site SH7.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial temperature of GHBS</td>
<td>13.74°C</td>
<td>Grain density ($\rho_g$)</td>
<td>2600 kg m⁻³</td>
</tr>
<tr>
<td>Initial pressure of GHBS</td>
<td>13.2 MPa</td>
<td>Grain specific heat ($c_p$)</td>
<td>1000 J kg⁻¹°C⁻¹</td>
</tr>
<tr>
<td>Temperature at sea bottom</td>
<td>3.5°C</td>
<td>Geothermal gradient</td>
<td>0.0432°C m⁻¹</td>
</tr>
<tr>
<td>Pressure at the sea bottom</td>
<td>11.34 MPa</td>
<td>Wet thermal conductivity ($\lambda_w$)</td>
<td>3.1 W m⁻¹°C⁻¹</td>
</tr>
<tr>
<td>Initial water salinity (mass fraction)</td>
<td>3.05 per cent</td>
<td>Dry thermal conductivity ($\lambda_d$)</td>
<td>0.85 W m⁻¹°C⁻¹</td>
</tr>
<tr>
<td>Hydrate saturation in situ ($S_h$)</td>
<td>0.44</td>
<td>Thermal conductivity of hydrate ($\lambda_h$)</td>
<td>0.5 W m⁻¹°C⁻¹</td>
</tr>
<tr>
<td>Pore-water saturation in situ ($S_s$)</td>
<td>0.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mud temperature</td>
<td>15°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mud density ($\rho_m$)</td>
<td>1190 kg m⁻³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porosity ($\phi$)</td>
<td>0.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression coefficient</td>
<td>1.00 × 10⁻⁸ Pa⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite thermal conductivity model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capillary pressure model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative permeability model</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*a* Moridis et al. (2005, 2009a).

*b* van Genuchten (1980).


3.2 Effect of mud invasion on borehole stability in the GMGS-1 Project

The above simulation results indicate that mud invasion can cause the hydrate dissociation and further change the properties of GHBS, especially the distributions of hydrate saturation, pore pressure and pore-water salinity. As mentioned above, hydrate dissociation can result in a marked reduction in the mechanical strength of sediments (Winters et al. 1999a,b, 2007; Waite et al. 2008). In addition, mud invasion and hydrate dissociation result in increased water content and pore pressure around the borehole. The increased pore pressure is similar to ‘overpressure’ or ‘excess pore pressure’ (Xu & Germanovich 2006; Kwon et al. 2008; Rutqvist & Moridis...
Mud invasion in gas-hydrate-bearing sediments

2009; Kwon et al. 2010), defined as the gas pressure above the initial water pressure prior to dissociation (Holtzman & Juanes 2011). The increasing pore pressure results in reduced effective stress and may destabilize the sediment (Xu & Germanovich 2006; Waite et al. 2008) according to the theory of poromechanics (Biot 1941), resulting in instability of the borehole. Especially for soft, fine-grained, mud-dominated GHBS, such as at some sites on the Indian continental margin (Collett et al. 2008) and in the South China Sea (Zhang et al. 2007), gas invasion driven by overpressure (caused in turn by mud invasion and hydrate dissociation) may even lead to fracturing in the GHBS (Holtzman & Juanes 2010, 2011). Therefore, mud invasion coupled with hydrate dissociation poses a greater risk of borehole stability than in conventional oil/gas wells.

According to the simulation results in borehole SH7, hydrate dissociation mainly took place, and pore pressure and water saturation showed marked increases within 0.1 m of the borehole (Figs 5a and c). Consequently, this was the most unstable region in the area of the borehole. The next unstable region was that at the outside of the hydrate reformation area, that is, the second area of hydrate dissociation. The practical drilling results in the borehole SH7 of GMGS-1 project also showed that gas was released during the drilling operations. In addition, during open-hole logging with telemetry, orientation and a four-arm calliper string in GMGS1-SH7,
Table 2. Hydrate saturation near the borehole at 12, 20 and 24 h. The original hydrate saturation was 0.44. The data in grey cells are higher than original hydrate saturation. It can be found that hydrate dissociation take place both sides of the high saturation hydrate ring at the same time.

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>S</th>
<th>Position r (m)</th>
<th>0.12</th>
<th>0.15</th>
<th>0.17</th>
<th>0.20</th>
<th>0.23</th>
<th>0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td></td>
<td>0.08221</td>
<td>0.46169</td>
<td>0.43868</td>
<td>0.43860</td>
<td>0.43857</td>
<td>0.43857</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0</td>
<td>0.37095</td>
<td>0.4496</td>
<td>0.43881</td>
<td>0.43872</td>
<td>0.43868</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>0</td>
<td>0.28632</td>
<td>0.4612</td>
<td>0.44126</td>
<td>0.43888</td>
<td>0.43881</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. Schematic diagram of hydrate behaviour, along a radial direction from the borehole, during mud invasion in the case that the mud temperature is higher than the hydrate equilibrium temperature. (a) Initial stage of mud invasion, showing minimal dissociation of hydrates. (b) With ongoing mud invasion and heat transfer, a large amount of hydrate is dissociated and the resulting gas is displaced along the pore throat, finally accumulating at the position where flow resistance is greatest. (c) Hydrate reformation occurs in the gas accumulation region, effectively dividing the area of hydrate dissociation into two parts. The hydrate reformation reduces the permeability and increase the flow resistance of sediment, further promoting the accumulation of more gas and water which leads to the high-saturation hydrate ring formation in this area.

Spurious caliper 2 and 4 readings were observed in the GHBS. Upon return to the surface, it was found that caliper arms 2 and 4 were no longer attached to the calliper sub. The caliper-logging curves indicated that borehole shrinkage occurred from the depth of 162.5 mbsf (Fig. 7). At the simulation depth (166 mbsf), the value of borehole shrinkage is just approximately equal to the most unstable region which is within 0.1 m of borehole. Tension readings on the logging cable also indicated borehole collapse in the GHBS during logging with telemetry, full wave sonic and dual-density string. The borehole could not be logged below 170 mbsf because of these borehole stability issues (Nakai et al. 2007). While for SH1, SH6 and SH9 near by SH7 (Fig. 3), no gas hydrate occurrences were observed or indicated by any analyses such as core IR image, porewater freshening of cores and wireline logs. There have no caliper anomalies and wireline logging can be performed without borehole stability issues (Fig. 8). Therefore, we speculate that the borehole instability of Site SH7 was likely induced by mud invasion coupled with hydrate dissociation, which weaken the strength of clay-rich sediments and cause the creep shrinkage of clay layers because of water absorbing.

3.3 Effect of mud invasion on resistivity logging in the GMGS-1 Project

Another considerable effect of mud invasion is on well logging in the GHBS. Similarly to ice, hydrate is taken to have a non-conducting composition in the conduction model for resistivity well logging. The sediment resistivity increases when hydrates are present, which results in the high apparent resistivity in term of logging response characteristics (Winters et al. 2007; Gabitto & Barrufet 2009; Lee & Collett 2009a). When the mud salinity is equal to the pore-water salinity of in situ GHBS (e.g. the case of Site SH7 in GMGS-1 project) or lower than the salinity, a higher resistivity girdle around the borehole (compared with the original sediment resistivity) may form because of the formation of a high-saturation hydrate ring, the presence of dissociated free gas and the dilution of water salinity due to mud invasion and hydrate dissociation. The girdle would distort the well-logging data for example resistivity logging and probably result in a higher value of resistivity compared with the original level. Subsequently, a deviation is induced into the calculated hydrate saturation based on Archie’s formula (Archie 1942; we assume that this formula, used for conventional oil/gas reservoirs, is suitable for unconventional gas hydrate reservoirs. Most
natural gas hydrate deposits are still evaluated using this formula) and the Indonesian equation (Poupon & Leveaux 1971), as follows:

Archie’s formula: \[ S_H = 1 - \left( \frac{a R_w}{\Phi^m R_t} \right)^{1/n}, \] (2)

Indonesian equation: \[
\frac{1}{\sqrt{R_t}} = \left( \frac{V_{sh}^{1-V_{sh}/2}}{\sqrt{R_{sh}}} - \frac{\Phi^{m/2}}{\sqrt{a R_w}} \right) S_H^{n/2} \cdot S_H = 1 - S_w, \] (3)

where \( R_w \) is the resistivity of connate water, \( a \) and \( m \) are Archie constants and \( \Phi \) is the porosity. The parameter \( m \) is commonly called the cementation factor and both Archie constants \( a \) and \( m \) can be derived empirically (Lee & Collett 2009a). The parameter \( n \) is derived empirically and \( R_t \) is the formation resistivity in the presence of gas hydrate or other hydrocarbons (Archie 1942). \( V_{sh} \) is the shale content and \( R_{sh} \) is the shale resistivity. According to eqs (2) and (3), an increase in \( R_t \) will cause a corresponding decrease in \( S_H \); consequently, the calculated hydrate saturation is higher than that of actual hydrate-bearing sediments.

In practical logging operations in SH7, a dual-laterolog tool was used to measure both deep and shallow lateral resistivity plus spontaneous potential. The depth of investigation for deep and shallow lateral resistivity was 0.91 and 0.19 m, respectively (Nakai et al. 2007). The present simulation results show that the main area of distortion caused by mud invasion coupled with hydrate dissociation and reformation was within 1 m of the borehole (Figs 5c and d). Hydrate dissociation and reformation occurred mainly within 0.25 m of borehole (Fig. 5c). The higher resistivity girdle also likely developed in this region. Therefore, shallow lateral resistivity may be strongly distorted by the mud invasion, whereas deep lateral resistivity is only weakly affected.

To further clarify this point, eq. (2) can be rewritten as follows:

\[ R_t = \frac{a R_w}{(1 - S_w)^{n/2}} \] (4)

The difference value (\( \Delta R_t \)) between shallow lateral resistivity (\( R_{shal} \)) and deep lateral resistivity (\( R_{deep} \)) in GHBS is

\[ \Delta R_t = R_{shal} - R_{deep} = \frac{a}{\Phi^n} \left[ \frac{R_{shal}}{(1 - S_{shal})^n} - \frac{R_{deep}}{(1 - S_{deep})^n} \right], \] (5)
where \( R_{\text{shal}} \) and \( R_{\text{wdeep}} \) are the resistivities of pore water at a shallow investigation depth of 0.19 m and a deep investigation depth of 0.91 m, respectively. \( S_{\text{shal}} \) and \( S_{\text{wdeep}} \) are the corresponding hydrate saturations. \( R_{\text{shal}} \) and \( R_{\text{wdeep}} \) can be calculated by using Fofonoff’s equation \((\text{Fofonoff 1985})\). The calculation parameters in eq. (5), listed in Table 3, are obtained from the simulation results for borehole SH7 at 24 h (Fig. 5). The hydrate values in Table 3 show that there exist a strong hydrate reformation behaviour at shallow depth and weak hydrate dissociation at deep depth. In addition, values of \( a = 0.90 \), \( m = 1.12 \) (because it is unconsolidated clay-rich hydrate-bearing sediment in SH7 site) and \( n = 1.9386 \) are used for eq. (5) in this paper. The calculated values of \( R_{\text{shal}} \) and \( R_{\text{wdeep}} \) are 2.21 and 2.06 \( \Omega \) m, respectively, and \( \Delta R_e \) is 0.15 \( \Omega \) m. This result is consistent with logging data, which show that the shallow investigation resistivity is about 0.14 \( \Omega \) m larger than that at deep levels (i.e. at the simulation depth; Fig. 7; Nakai et al. 2007). However, for the Site SH1, SH6 and SH9 without hydrate occurrence, the deep resistivity is almost equal to or even larger than shallow one (Fig. 8). Hence, combining the caliper-logging curve and the dual-laterolog logging curves, we conclude that the behaviour of drilling mud invasion is linked to hydrate dissociation and reformation in GHBS of GMGS1-SH7. It would better adopt the deep resistivity log data to evaluate the hydrate reservoir in Site SH7.

Nevertheless, weak hydrate dissociation occurs at the depth of deep resistivity logging (Table 3), the calculated hydrate saturation at this depth by using the equation of state of sea water by Fofonoff \((\text{Fofonoff 1985})\) and Archie’s formula is still a little higher than that without considering mud invasion and hydrate dissociation. This difference is also validated by the pore-water freshening test. The hydrate saturation determined by the test was commonly lower than those from resistivity logging. The maximum value of hydrate saturation from pore-water freshening test is 43 per cent while the peaking value from resistivity logging is about 48 per cent (Fig. 9; Nakai et al. 2007; Lu et al. 2008). Lee & Collett (2011) concluded that values of gas hydrate saturation derived from resistivity would be overestimated for anisotropic GHBS (e.g. containing vertical fractures) if isotropic GHBS were wrongly assumed. However, gas hydrates at Site SH7 are disseminated throughout the sediment, in which no fractures occur. Therefore, the overestimation of hydrate saturation in the GMGS-1 project was most likely due to drilling mud invasion coupled with hydrate dissociation.

The same phenomenon was observed in the Indian National Gas Hydrate Program Expedition 01 (NGHP-01): gas hydrate saturations \((\geq 50 \text{ per cent})\) calculated by conventional Archie analysis using logging data were much higher than those \((\geq 26 \text{ per cent})\) estimated from pressure cores from nearby wells in the Krishna–Godavari Basin (Lee & Collett 2009a). In addition to the anisotropic nature of the reservoir and the values of selected parameters (such as \( m \) and \( n \)) in Archie’s formula, it is also possible that the distortion caused by mud invasion coupled with hydrate dissociation contributed to the saturation difference. In JIP Leg I, values of gas hydrate saturation derived from seismic data were systematically lower than those estimated from downhole logs (Dai et al. 2008).

<table>
<thead>
<tr>
<th>Logging position (m)</th>
<th>Pressure (MPa)</th>
<th>Temperature (°C)</th>
<th>NaCl concentration (per cent)</th>
<th>Hydrate saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19 (shallow)</td>
<td>13.5068</td>
<td>14.0846</td>
<td>2.9250</td>
<td>0.4485</td>
</tr>
<tr>
<td>0.91 (deep)</td>
<td>13.3512</td>
<td>13.7346</td>
<td>3.0497</td>
<td>0.4396</td>
</tr>
</tbody>
</table>

Table 3. Calculation parameters for eq. (5), obtained from simulation results at 24 h (Fig. 5). The hydrate saturation of 0.4485 at a shallow logging depth is higher than the original value of 0.44, while the hydrate saturation of 0.4396 at a deep logging depth is close to the original value. The former implies hydrate reformation and the development of a high-saturation hydrate ring, while the later implies very weak hydrate dissociation at this depth.

In addition to thin layer effect on hydrate saturation estimation \((\text{Dai et al. 2008})\), mud invasion may also have contributed to this discrepancy. Therefore, appropriate correction for the distortion of well-logging results by mud invasion should be considered in further research, in order to correctly identify and assess hydrate resources. At the same time, the drilling conditions should be identify and limited to reduce the risk of mud invasion and hydrate dissociation during drilling operations in GHBS, especially in Shenhua hydrate area of China South Sea.

4 DISCUSSION

During mud invasion, secondary hydrates tend to form in areas of hydrate dissociation. The secondary hydrates, together with the original hydrate deposits, may result in the total hydrate saturation exceeding that of the \(\text{in situ}\) GHBS. Therefore, compared with conventional oil/gas-bearing sediments, hydrate dissociation and reformation are the main characteristics of mud invasion in GHBS when the invasion conditions are in the unstable region of gas hydrates. The characteristics of drilling mud invasion in conventional oil and gas reservoirs are influenced by many factors. For example, invasion depth and range are controlled by the properties of the mud and the reservoir. In order to identify the influence factors of mud invasion in GHBS and limit the suitable drilling conditions for borehole stability and good logging interpretation, we further discuss the effects of drilling mud properties on mud invasion in GHBS, based on Site SH7 of the GMGS-1 hydrate drilling project.

4.1 Effect of mud density on mud invasion in GHBS

In some cases, mud density needs to be increased for drilling safety, such as to prevent wellbore instability and well kick. A typical example is well WR313-G, which was drilled during the GOM JIP Leg II. In this case, it was found to be difficult to use sea water with intermittent sweeps of 10.5 lbm gal\(^{-1}\) (about 1258 kg m\(^{-3}\)) drilling mud to maintain borehole stability and to remove drill cuttings from the hole below 503 mbsf. Multiple backreams per stand had to be used to prevent the drill string from occasional pack-off. After adopting a protocol of continuously pumping 10.5 lbm gal\(^{-1}\) of weighted drilling fluid, the rest of the hole was drilled incident free (Collett et al. 2012). This protocol actually increased the equivalent circulation density of drilling mud; therefore, higher mud density results in enhanced borehole stability. However, it may also influence the behaviour of mud invasion in GHBS.

Under the same mud temperature (15°C) and salinity (3.05 per cent) as above, the behaviours of mud invasion into GHBS were simulated under different pressure scenarios. The scenarios considered are densities of drilling fluid of 1190, 1250 and 2000 kg m\(^{-3}\), equal to pressures of 13.54, 13.64 and 15 MPa at the invasion spot, respectively. The simulation results revealed that no gas hydrate dissociation or reformation took place for a density of 2000 kg m\(^{-3}\), because hydrates remained stable under this condition, for which the equilibrium temperature is about 15.7°C at a pressure of 15 MPa, and the NaCl concentration is 3.05 per cent.
Mud invasion in gas-hydrate-bearing sediments

No free gas or regenerated hydrates formed around the borehole (Fig. 10a).

However, if the mud temperature remains higher than the hydrate stability condition under higher pressures (e.g. 1250 kg m$^{-3}$ at 15°C or even 2000 kg m$^{-3}$ at 20°C), the mud invasion shows some interesting characteristics. Higher pressures led to deeper invasion (see the NaCl concentration plot in Fig. 10b). If the difference between mud temperature and hydrate equilibrium temperature is very small, there is a low degree of gas hydrate dissociation. The higher pressure acted to retard the hydrate dissociation and led to a smaller amount of free gas content in the formation (see the gas saturation plot in Fig. 10b), which caused a lower degree of hydrate reformation. The maximum hydrate saturation in the case of 1190 kg m$^{-3}$ at 15°C was about 0.4496, and the value at the same temperature for 1250 kg m$^{-3}$ was about 0.4468 (see the hydrate saturation plot of Fig. 10b). However, in the case of a larger difference between the mud temperature and the hydrate equilibrium temperature, higher pressure led to deeper invasion, increased the speed and depth of heat transfer and extended the range of hydrate dissociation (see Fig. 10b for the case of 2000 kg m$^{-3}$ at 20°C).

Of relevance to the simulation results is the fact that gas is compressible and its occurrence results in an increase in multiphase flow resistance. For the case of 2000 kg m$^{-3}$ at 20°C, the larger amount of free gas that dissociated from hydrates might be more easily accumulated and detained in certain small regions of the hydrate dissociation area during mud invasion, compared with the case of a smaller amount of gas (Fig. 6). In addition, the higher pressure resulted in pressure propagation over a greater distance. These factors led to the rapid formation of secondary hydrates with higher saturation and greater range. The ‘hydrate crest’ had a saturation of about 0.634 at 0.27 m from the borehole. The position of hydrate crest corresponded to an ‘aqueous and gas saturation trough’ and a ‘NaCl concentration crest’. The exothermic reaction of hydrate reformation would also result in enhanced hydrate dissociation at sites behind the area of hydrate reformation, resulting in the formation of a deeper ‘hydrate trough’ (see the discussion in Section 3.1 and Fig. 6) and a corresponding ‘aqueous and gas saturation crest’ and a ‘NaCl concentration trough’ (Fig. 10b).

The formation of secondary hydrate with high saturation also had a strong influence on the mud invasion in GHBS. When the density of mud increased to 2000 kg m$^{-3}$ at 20°C, the pore pressure at the hydrate crest (about 0.27 m from the borehole) showed a sharp decrease (Fig. 10c), indicating that the gas content showed a marked decrease and that fluid flow was blocked by high-saturation hydrate. The results of both experiments and numerical simulations indicate that the permeability of sediments is reduced by hydrate formation (Liu & Flemings 2007; Garg et al. 2008; Kneafsey et al. 2011).

The above results show that an increase in mud density inhibits hydrate dissociation and enhances borehole stability under conditions of a low degree of hydrate dissociation. Therefore, the mud density to prevent borehole instability in Site SH7 should be larger than 1190 kg m$^{-3}$, perhaps 1250 kg m$^{-3}$ is suitable, as its results in
Figure 10. Properties of sediment around the borehole for various mud densities. (a) Distribution of gas saturation around the borehole at same temperature 24 h. (b) Distributions of hydrate saturation, aqueous saturation, gas saturation and NaCl concentration around the borehole at 20 h. (c) Distribution of pore pressure around the borehole at 20 h. The red curve indicates that the pore pressure spread was retarded by high-saturation hydrate, which reduced the permeability of GHBS.

borehole WR313-G of JIP II project. However, if the mud temperature greatly exceeds the hydrate equilibrium temperature, a higher mud density would enhance the degree of hydrate dissociation, reformation and mud invasion, which would cause problems for borehole stability and well logging interpretation. Furthermore, an excessively high mud density (e.g. 2000 kg m\(^{-3}\)) would give rise to other drilling problems, such as mud loss, given the narrow window of safe mud density in offshore drilling operations. Oceanic hydrates commonly occur in shallow and underconsolidated sediments, resulting in a high risk of formation fracture. Hence, it is noteworthy that the mud density of 2000 kg m\(^{-3}\) discussed here is rarely adopted in oceanic hydrate drilling operations. However, the present case shows that control of drilling mud temperature is an important issue for safe drilling in gas hydrate and for accurate well logging. Next, we discuss the effect of mud temperature on mud invasion into GHBS.

4.2 Effect of mud temperature on mud invasion in GHBS

During conventional oil and gas drilling, the invasion of drilling mud into sediment is governed by differences in hydraulic and osmotic pressure, and the effect of temperature on mud invasion is neglected (Zhang et al. 1999), meaning that the mud invasion is treated as an isothermal process (Bilardo et al. 1996). This isothermal case is invalid when the mud invasion takes place under the condition of mud temperature higher than the hydrate equilibrium temperature in the drilling of GHBS. Figs 11a and b show that the higher the temperature of drilling mud, the larger the degree of hydrate disso-
Mud invasion in gas-hydrate-bearing sediments

4.3 Effect of mud salinity on mud invasion in GHBS

In deep-water oil or gas drilling, hydrate inhibitors (e.g. NaCl and KCl) are usually added to the mud to enhance its performance and to prevent gas hydrate formation and aggregation in the well (Ebeltoft et al. 1997). Here we simulated the effect of mud salinity on mud invasion into GHBS. Higher mud salinity results in greater hydrate dissociation during mud invasion under a given mud density (1190 kg m$^{-3}$) and temperature (15°C; Fig. 12a). This behaviour can be explained as follows: (1) salt, as a thermodynamic inhibitor, can cause the phase equilibrium curve to shift toward destabilization, which enhances dissociation and (2) increasing salinity results in enhanced heat transfer because of the higher heat conductivity of salts compared with surrounding sedimentary rocks (Nagihara et al. 2002). A high-saturation hydrate ring and corresponding low-saturation water ring form around the borehole with the invasion of high-salinity mud (Fig. 12a). There is greater hydrate dissociation and more secondary hydrates, in the case of mud with a salinity of 10 per cent compared with a salinity of 6 per cent. The temperature of sediments near the wellbore showed a marked drop due to the endothermic reaction associated with hydrate dissociation (Masuda et al. 1999, Nazridoust & Ahmadi 2007) and due to the higher thermal conductivity of mud with higher salinity (Fig. 12b). The dropped temperature keeps the hydrates which occur outside of the high-saturation hydrate ring stable. Therefore, no hydrate trough was observed in Fig. 12a. The temperature increased again due to the exothermic reaction of secondary hydrate formation (Fig. 12b). For a mud salinity of 10 per cent, pressure propagation was delayed by secondary hydrate formation during mud invasion (Fig. 12b), thereby blocking further mud invasion. The higher the mud salinity, the more pronounced this trend.

If mud salinity is much higher than the salinity of the original sediment, mud invasion would still increase the sediment salinity and appear as a ‘low-resistivity invasion’ even though the water from hydrate dissociation would dilute the salinity of pore water (Fig. 12b). However, the high-saturation hydrate ring and gas from
hydrate dissociation would act to increase the sediment resistivity. Therefore, the dynamic response characteristics of resistivity well logging, in the case of mud invasion in the GHBS, are more complicated than those in conventional sediment. Appropriate correction for the distortion of well-logging results by mud invasion should be considered in further research, in order to correctly identify and assess hydrate resources. Nevertheless, a general principle is to adopt lower (like sea water) or no salts in the drilling mud for the hydrate drilling.

5 CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

In this study, the characteristics of drilling mud invasion and the effect of mud properties on mud invasion into GHBS was investigated by numerical simulations under the conditions of mud temperature over hydrate equilibrium temperature and overbalanced drilling, considering the case of the GMGS-1 project in China. The primary results are as follows:

(1) The radial formation of secondary hydrate at a certain depth in sediments adjacent to a borehole is attributed to the increased pore pressure caused by mud invasion and flow resistance, to the endothermic cooling that accompanies hydrate dissociation compounded by the Joule–Thompson effect, and to the lagged effect of heat transfer in sediments. The hydrate saturation of secondary hydrates and existing in situ hydrates could be higher than that of the original sediment, resulting in the formation of a high-saturation hydrate ring around the borehole.

(2) In the case of the borehole SH7 of GMGS-1 project, the simulation results, practical drilling and logging data indicated the influence of mud invasion coupled with hydrate dissociation and reformation on well logging and borehole stability was confined to within 1 m of the borehole. The likely occurrence of a high-saturation hydrate ring, the presence of dissociated free gas and the dilution of water salinity associated with hydrate dissociation could affect the well-logging data and cause an erroneously high value of shallow laterolog compared with greater depths. Subsequently, the hydrate saturation calculated from resistivity logging would be higher than that of actual hydrate-bearing sediments. Therefore, suitable correction for the distortion of well-logging results by mud invasion should be considered when identifying and refining ocean hydrate resources.

(3) Mud density, temperature and salinity are the important factors affecting hydrate stability and secondary hydrate formation during mud invasion, among which temperature and salinity play primarily roles. It is necessary to control the temperature, density, salinity and filtration loss of mud and to prevent hydrate dissociation to ensure borehole stability, drilling safety and well-logging accuracy when drilling in GHBS. Managed pressure drilling (MPD) operation can be employed to ensure a small pressure difference.
between mud and sediments. In addition, it would be preferential to adopt a low-salinity mud system containing suitable temporary plugging additives for drilling. The simulation results also show that, under some conditions, even the LWD method may not be applicable to GHBS because mud invasion and hydrate dissociation occur extremely rapidly. This problem may be addressed by developing a novel deep lateral logging method.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. George Moridis and Wen Yue Xu for valuable suggestions regarding our models and theoretical analysis. We also sincerely thank Dr. Timothy S. Collett and M.W. Lee for kind and valuable discussions at the 7th ICGH. We also thank two anonymous reviewers for their constructive suggestions and Mrs. Valerie Dennis and Dr. Bruce Buffett as editors. This work was supported by the National Natural Science Foundation of China (Nos 50704028, 40974071, U0933004), the Guangzhou Center for Gas Hydrate Research, Chinese Academy of Sciences (No. o807s2) and Fundamental Research Funds for Central Universities (No. CUGL100410 & 120112).

REFERENCES


