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Gas hydrate and free gas saturations using rock physics modelling at site NGHP-01-05 and 07 in the Krishna–Godavari Basin, eastern Indian margin

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ABSTRACT

Several approaches exist for the estimation of gas hydrate and free gas depending on the nature and distribution of gas hydrate into the sediments. Here, we apply various rock physics models to the P-wave sonic velocity logs that were collected during the Indian National Gas Hydrate Program (NGHP) Expedition 01 at sites NGHP-01-05 and NGHP-01-07 for the resource estimate of gas hydrate. Using the weighted equation, it is found that maximum up to13% and 12% volumes of the pores of regional sediments above bottom simulating reflector (BSR) of sites NGHP-01-05 and NGHP-01-07 respectively are occupied by gas hydrates. Alternatively, gas hydrate saturations computed for these sites using effective medium models are found maximum up to 16% and 22%. We have further used the velocity porosity transforms to estimate the free gas saturations below the BSRs for both the sites. The saturation of free gas in the sediments at both the sites is found in the range of 0.5–2.2%.

1. Introduction

Gas hydrates have been inferred and recovered worldwide along the continental margins and permafrost regions. Gas hydrate is an ice like solid substance, composed of water and natural gas (mainly methane), which forms at low temperature and high pressure regime when methane concentration exceeds the solubility limit (Kvenvolden, 1998). Since 90s, high resolution multi-channel seismic (MCS) surveys and the three dimensional seismic surveys have been carried out for the exploration of gas hydrate along the continental margins of India. The bottom simulating reflectors (BSR), main marker for gas hydrate, have been identified in the Krishna–Godavari (KG), Mahanadi, and Andaman basins (Collett et al., 2008; Sain and Gupta, 2008; Shankar and Riedel, 2011; Sain and Gupta, 2012; Sain et al., 2012). In May–August 2006, the research drill ship JOIDES Resolution cored and drilled 39 holes at 21 sites (one site in the Kerala–Konkan basin; 15 sites in the KG basin, four sites in the Mahanadi basin and one site in Andaman regions) under the Indian National Gas Hydrate Program (NGHP) Expedition 01. Downhole wireline logs were acquired at most sites. Conventional wireline piston core and pressure cores were used to recover samples at selected sites. Some sites were not sampled because they were considered to contain little or no gas hydrate after the analysis of logging while drilling (LWD) data (Collett et al., 2008). It is observed that the saturation of gas hydrate is uniform in the pores of the sediments directly above the base of gas hydrate stability zone (Sain et al., 2011).

Presence of gas hydrate in the sediments significantly affects the bulk physical properties. The P and S wave velocities for gas hydrates are much high compared to the fluid occupying the pores (Stoll et al., 1971). On the contrary, P-wave velocity is reduced in free gas bearing sediments. Hence, the presence of gas hydrates in the sediments increases the velocities above the BSR and the free gas below the BSR reduces P-wave velocity. The extent of change in seismic velocities depends upon the saturation of gas hydrates and free gas in the sediments. P and S wave velocities can be obtained by many ways: multi-channel seismic data, wireline acoustic logs, vertical seismic profiling (VSP) and logging-while-drilling (LWD).

In past, many theories and methods have been proposed, which build a relation between the compressional velocity and gas hydrate saturation. Some of the popular theories are those of Wood et al. (1994) and Yuan et al. (1996) based on time average equation of Wyllie et al. (1958). Most of the methods can be termed as porosity–velocity relations applied to effective porosity reduction models (e.g. Hyndman et al., 1993; Yuan et al., 1996), time-averaging approaches (e.g. Pearson et al., 1983; Lee et al., 1993), and first principle based rock physics modelling approaches (e.g. Dvorkin and Nur, 1993; Helgerud et al., 1999; Carcione and Tinivella, 2000; Ojha and Sain, 2008).

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The Krishna–Godavari Basin is dominated by the clay stratigraphy and it was reported in the initial NGHP-01 report that gas hydrate occurs in facture at study sites NGHP-01-05 and 07. However, Cook and Goldberg (2008) demonstrated using Monte Carlo simulation that gas hydrate filled fracture at site NGHP-01-05 is not an extensive and continuous feature. Gas hydrate filled fracture planes at Site 5 likely only extend a few metres and are not continuous. The gas hydrate filled fractures appear almost exclusively in a hydrate-bearing interval and not connected to the base of the gas hydrate stability zone and they suggest the small planar fractures may be generated by gas formed locally by microbes. This proposed gas hydrate system may appear in many shallow clay-dominated marine sediments. In this study, we have estimated gas hydrate and free gas saturation from downhole log measurements of P-wave velocity at sites NGHP-01-05 and 07 of KG basin using different rock physics modelling approaches. We have assumed that gas hydrate can reside in the pore-spaces, replacing the fluid suspension, or can even form the part of cementation matrix. The models used for the estimation of gas hydrate and free gas are the Wood's model (1941), time average equation (Wyllie et al., 1958), weighted mean of multi- phase Wood and Wyllie equations (Pearson et al., 1983; Nobes et al., 1986) and models based on Biot–Gassmann theory (Dvorkin et al., 1999). The porosity at the study site is around 60–75% with critical porosity being 62–65% (Collett et al., 2008).

2. Data

During NGHP Expedition 01, a downhole logging programme was specially designed to study the gas hydrate saturations (Collett et al., 2008). Logging While Drilling (LWD) and wire-line logging data were acquired in sites NGHP-01-05 and NGHP-01-07 in the KG basin (Fig. 1). The P-wave sonic velocity and porosity logs at site NGHP-01-05 and 07 are used in this study. The LWD Sonic VISION data were used for velocity logs at the site. The tool records monopole acoustic waveforms (13 kHz) at four receiver locations above the source along the tool string (at 3.05, 3.25, 3.45, and 3.65 m distance). The drilling noise affects the measurements of the LWD sonic tool. Thus, at an average, eight consecutive waveforms are stacked to strengthen the signal.

The LWD density log is used to generate the density derived porosity log for sites NGHP-01-05 and 07. The formation bulk density (ρ_b) of the medium, density of pore-water (ρ_w=1030 kg/m^3)

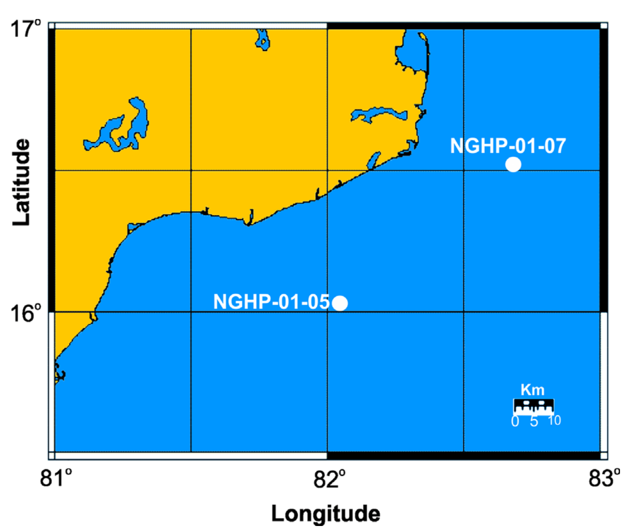

Fig. 1. The study area in the Krishna–Godavari Basin, eastern margin of India. NGHP-01-05 and NGHP-01-07 drill sites are shown with circles.

and the average grain density (ρ_g=2750 kg/m^3) measured in the core moisture and density (MAD) analysis are used to derive porosity:

$$\phi = \left(\frac{(\rho_g - \rho_b)}{(\rho_g - \rho_w)}\right) \quad (1)$$

Electrical resistivity appears to be the most strongly affected by the presence of gas hydrate in the marine sediment. Its inclusion in the pore space of marine sediments can significantly affect the bulk physical properties of the sediment. The measurement of such properties can therefore be used to estimate gas hydrate saturation (e.g. Yuan et al., 1996). Natural gas hydrate formation reduces the effective porosity and electric conduction, so that gas hydrate bearing sediment has high electrical resistivity. Downhole resistivity logs have been used extensively to estimate gas hydrate saturation using standard Archie's empirical relation (Collett et al., 2008; Shankar and Riedel, 2011; Shankar et al., 2012; Shankar and Riedel, 2013). Gas hydrate bearing sediments exhibit relatively high electrical resistivity values in comparison to water-saturated sediments. *In situ* pore fluid salinity measurements are utilised to determine appropriate values for the empirical parameters in the equations involved. Archie's law has established a relationship that the resistivity of a fully water saturated sediment (R_0) is proportional to the resistivity of the pore fluid or connate water (R_w) and can be written as using the equation: $R_0 = aR_w\phi^{-m}$. Where, a and m are the Archie constants, and ϕ is the porosity derived from the bulk density log, which is referred as density porosity. Archie's analysis is first undertaken using the log density porosity. It has been shown that the density porosity gives better estimates as compared to neutron porosity (Shankar and Riedel, 2011). Details of Archie's parameters analysis and gas saturation estimates procedures are described in detail (see paper by Shankar and Riedel (2011)).

3. Material and methods

3.1. Rock physics modelling

Many theories have been proposed for the estimation of gas hydrate depending on the way gas hydrates resides in the sediments and changes their micro-structure. Dai et al. (2008) have described six ways in which gas hydrate becomes the part of the sediments: (i) formation of gas hydrate at the grain contact, (ii) gas hydrate forms a coat over the grain, (iii) formation of gas hydrate within the grain, (iv) gas hydrate in fluid suspension, (v) gas hydrate forming a part of cementation matrix and (vi) gas hydrate occupying nodules, veins and fractures. The first five models are based on the concept of pore-filled morphology and are valid for homogeneous and isotropic medium (Dai et al., 2008; Holland et al., 2008). These models show a large variation in results and the empirical relations of rock physics models may not hold true for all cases (Helgerud et al., 1999; Ecker et al., 2000; Jakobsen et al., 2000; Xu et al., 2004; Yun et al., 2005; Dai et al., 2008; Ghosh et al., 2010). Rock physics models are used to study the change in elastic properties of rocks due to change in their mineral composition, fracturing or diagenesis (compaction, cementation, and dolomitization), change in characteristics of fluid, saturation and pore pressure, and finally any variation in the reservoir effective stress and temperature. These help in modelling the elastic parameters and developing a relation between porosity and velocity data. Thus, for a known lithology, a missing sonic or porosity log can be constructed from one another by choosing proper grain morphology and rock physics model. Rock physics models can indirectly be used for estimation of gas hydrate and free gas sediments in the gas hydrate bearing zones. These are used for estimating elastic parameters and velocity information for several values of gas hydrate saturation and the best fitting model gives the saturation of gas hydrate in the sediment pores.

We use some of these models and estimate the saturation of gas hydrate and free gas at sites NGHP-01-05 and NGHP-01-07. The first model used is Wood's (1941) model which is valid in only high porosity media. It is based on the assumption that hydrates form a part of the pore-space and are present in fluid suspension. Another model used here is the Wyllie model based on time average equation (Wyllie et al., 1958) which is valid for media with less porosity. It assumes that hydrates form the part of the rock matrix thereby effecting its composition. The velocities obtained from Wood model and Wyllie model are used as inputs for the three phase weighted equations (Lee et al., 1996). This model is more flexible and can be applied to medium of almost any porosity. Another approach attempted here is based on the effective medium theory (Dvorkin et al., 1999), which assumes that elastic moduli lie between the moduli of dry sediment at critical porosity. The outputs of all the models are compared to estimate the saturation of gas hydrate at sites NGHP-01-05 and NGHP-01-07.

3.1.1. *The Wood (1941) model*

The Wood (1941) method is one of the oldest approaches used to determine the *in situ* gas hydrate saturations. It is used for highly porous medium where gas hydrate forms a part of the fluid suspension. The model uses the equation defined as

$$\frac{1}{\rho V_p^2} = \frac{\phi}{\rho_w V_w^2} + \frac{1-\phi}{\rho_m V_m^2} \tag{2}$$

where V_p is the P-wave velocity of the hydrate-bearing sediment; V_w is the P-wave velocity of the fluid; V_m is the P-wave velocity of the matrix; and ϕ is the porosity (as a fraction).

The three phase Wood's equation for hydrate-bearing sediments (Lee et al., 1996) can be defined as

$$\frac{1}{\rho V_p^2} = \frac{\phi(1-S)}{\rho_w V_w^2} + \frac{\phi S}{\rho_h V_h^2} + \frac{1-\phi}{\rho_m V_m^2} \tag{3}$$

where V_h is the P-wave velocity of the pure hydrate; ρ_h is the density of pure hydrate; ρ is the bulk density of the medium; ρ_w is the density of pore water; ρ_m is the density of rock matrix; and S is the concentration of hydrate in the pore space (as a fraction);

To derive the bulk density of the sediment, we can use the weighted average of the constituent components using the following equation:

$$\rho = (1-\phi)\rho_m + (1-S)\phi\rho_w + S\phi\rho_h \tag{4}$$

When this equation is applied with a modified matrix velocity, it does not always accurately predict the observed velocity–porosity relations in marine sediments (Nobes et al., 1986). The velocities at different hydrate saturations obtained are matched with the sonic log and the model which best suits gives the estimated value of gas hydrate saturation.

3.1.2. *The Wyllie et al. (1958) model*

Wyllie et al. (1958) considered that the velocity inversion of a whole rock depends on the presence of fluid in the rock matrix in time average equation (Lee et al., 1996). Many theories have been proposed in the past which explain the behaviour of hydrate in the sediment pores and their effect on P-wave velocity. Timur (1968) first used the three phase time average equation to relate the porosity and ice saturation with the P-wave velocity at permafrost temperatures. Pearson et al. (1983) extended the work and applied the equation to hydrate-bearing rock and concluded that it qualitatively explains the known sonic properties of hydrate bearing sediments in consolidated medium. The three phase time average equation used by Timur (1968) and Pearson et al. (1983) is defined as follows:

$$\frac{1}{V_p} = \frac{\phi(1-S)}{V_w} + \frac{\phi S}{V_h} + \frac{1-\phi}{V_m} \tag{5}$$

where, V_p is the P-wave velocity of the hydrate bearing sediment, V_h is the P-wave velocity of the pure hydrate, V_w is the P-wave velocity of the fluid, V_m is the P-wave velocity of the sediment matrix, ϕ is the porosity and S is the hydrate concentration in the pore space.

Many of the past works show that the time-average equations are inconsistent, unless comparatively low matrix velocity is used (Hoyer et al., 1975). The time average equation assumes that the hydrate present in the pores forms part of the matrix. The estimated rock matrix velocity used for the NGHP-01-05 site is 3.77 km/s which is based on the assumption that the sediments of the region are composed of 90% clay and 10% quartz (Shankar and Riedel, 2011). For unconsolidated sediments, the velocity computed by the Wyllie model is found to be more as compared to actual value. The predicted velocity–porosity relationship for the time-average equation with a modified matrix velocity of 3.77 km/s (for the condition of no hydrate i.e. $S_h = 0$) forms an upper limit.

3.1.3. *Three phase weighted equation*

Nobes et al. (1986) observed that while the time average equation often overestimated the velocity value from porosity data, the Wood (1941) model often underestimated it. Based on these observations, Nobes et al. (1986) combined these two models using a single weighting factor. Lee et al. (1996) proposed a weighted combination of the Wood model and time average equation which can be used for estimation of gas hydrate saturation in marine sediments. In addition to the weighting factor of Nobes et al. (1986), Lee et al. (1996) introduced an exponential term on the saturation value of gas hydrate, thereby providing a flexible network that can allow this model to be applicable on the diverse set of conditions in which hydrate can occur in the marine sediments. The weighted mean of the Wood (1941) and time average equation is as follows:

$$\frac{1}{V_p} = \frac{W\phi(1-S)^n}{V_p^1} + \frac{1-W\phi(1-S)^n}{V_p^2} \tag{6}$$

where ${V_p}^1$ is the P-wave velocity calculated by the Wood equation, ${V_p}^2$ is the P-wave velocity obtained from the time-average equation, W is a weighting factor, and n is a constant simulating the rate of lithification with hydrate concentration.

For the case when the saturation of gas hydrate equals to zero ($S=0$), Eq. (6) becomes independent of the exponent n. Thus, for $S=0$, Eq. (6) resembles the equation of Nobes et al. (1986). As per Nobes et al. (1986), a value of $W>1$ favours the Wood equation and $W<1$ favours the time-average equation. Further, Lee et al. (1996) have shown that for hydrate bearing sediments, as n increases, the weighted equation approaches the time-average equation more rapidly, because $(1-S)$ is less than unity. Use of both, a weighting factor W and an exponential n provides flexibility in using the equation for several different conditions of formation of gas hydrate.

3.2. *Effective medium modelling*

Dvorkin et al. (1999) proposed an effective medium model for the modelling of elastic parameters of high porosity ocean bottom sediments. Helgerud et al. (1999) used the model of Dvorkin et al. (1999) and proposed a physics-based model which can be used to model the elastic-wave velocity of unconsolidated, high porosity, ocean bottom sediments containing gas hydrate.

3.2.1. Mathematical modelling for EMM

The baseline model used by Helgerud et al. (1999) is the Dvorkin et al. (1999) model, which relates the elastic properties of rocks by considering the model for dry rocks with low porosity (ϕ–ϕ_c), where ϕ is the porosity of the sediments and ϕ_c is the critical porosity lying between 62% and 65% for the KG Basin. At zero porosity, the bulk and shear moduli of the rock are K and G, respectively at ϕ_c, the effective bulk (K_{HM}) and shear (G_{HM}) moduli of this pack (dry) are given by the Hertz–Mindlin (Mindlin, 1949) contact theory:

$$K_{HM} = \left(\frac{n^2(1-\phi_c)^2G^2)}{18\pi^2(1-v)^2}P_{eff}\right)^{1/3} \quad (7)$$

$$G_{HM} = \left[\frac{5-4v}{5(2-v)}\right]\left[\frac{3n^2(1-\phi_c)^2G^2}{2\pi^2(1-v)^2}P_{eff}\right]^{1/3} \quad (8)$$

In the Eqs. (7) and (8), P denotes the effective pressure. K, G and v are the bulk and shear moduli of the solid phase, and its Poisson's ratio respectively; and n is the average number of contacts per grain in the sphere pack (about 3–4 in the KG basin) which can be given by the following empirical relation (Avseth et al., 2005):

$$n = 20-34\phi + 14\phi^2 \quad (9)$$

and

$$v = \frac{3K-2G}{2(3K+G)} \quad (10)$$

Dvorkin et al. (1999) noticed that at porosity ϕ_c, the concentration of the pure solid phase in the rock is $(1-\phi/\phi_c)$ and that of the sphere-pack phase is (ϕ/ϕ_c). At this point, Dvorkin et al. (1999) expressed bulk (K_{dry}) and shear (G_{dry}) moduli of the frame as follows:

$$K_{dry} = \left[\frac{\phi/\phi_c}{K_{HM}+(4/3)G_{HM}} + \frac{1-(\phi/\phi_c)}{K+(4/3)G_{HM}}\right]^{-1} - \frac{4}{3}G_{HM} \quad (11)$$

$$G_{dry} = \left[\frac{\phi/\phi_c}{G_{HM}+Z} + \frac{1-(\phi/\phi_c)}{G+Z}\right]^{-1} - Z \quad (12)$$

$$Z = \frac{G_{HM}}{6((9K_{HM}+8G_{HM})/(K_{HM}+2G_{HM}))} \quad (13)$$

For the case of high porosities, where $\phi > \phi_c$, marine sediment is unlikely to look like a pack of identical spheres. At porosity $\phi > \phi_c$, the concentration of the void phase is $(\phi-\phi_c)/(1-\phi_c)$ and that of the sphere pack is $(1-\phi)/(1-\phi_c)$. Then the effective dry frame moduli are expressed as (Dvorkin et al., 1999)

$$K_{dry} = \left[(1-\phi)/(1-\phi_c)/\left(K_{HM}+\frac{4}{3}G_{HM}\right) + ((\phi-\phi_c)/(1-\phi_c))/\left(\frac{4}{3}G_{HM}\right)\right]^{-1} - \frac{4}{3}G_{HM} \quad (14)$$

$$G_{dry} = [((1-\phi)/(1-\phi_c))/(G_{HM}+Z) + ((\phi-\phi_c)/(1-\phi_c))/(Z)]^{-1} - Z \quad (15)$$

$$Z = \frac{G_{HM}}{6((9K_{HM}+8G_{HM})/(K_{HM}+2G_{HM}))} \quad (16)$$

For the saturated sediments, the bulk (K_{sat}) and shear (G_{sat}) moduli come from Gassmann's equation (1951):

$$G_{sat} = G_{dry} \quad (17)$$

$$K_{sat} = K\frac{\phi K_{dry}-(1-\phi)K_fK_{dry}/K + K_f}{(1-\phi)K_f + \phi K-(K_fK_{dry}/K)} \quad (18)$$

where K_f is the fluid bulk modulus. The elastic wave velocities are related to the elastic moduli and bulk density ρ_b.

$$V_p = \frac{\sqrt{(K_{sat}+(4/3)G_{sat})}}{\rho_b} \quad (19)$$

The elastic constants of the solid phase are calculated from those of the individual mineral constituents using Hill's (1952) average formula:

$$K = \frac{1}{2\left[\sum_{i=1}^{m} f_iK_i + \left(\sum_{i=1}^{m} f_i/K_i\right)^{-1}\right]} \quad (20)$$

$$G = \frac{1}{2\left[\sum_{i=1}^{m} f_iG_i + \left(\sum_{i=1}^{m} f_i/G_i\right)^{-1}\right]} \quad (21)$$

where m is the number of the constituents, f is the volumetric fraction of i-th constituent in the solid phase; and K_i and G_i are the bulk and shear moduli of i-th constituent, respectively. Effective pressure is the difference between the lithostatic and hydrostatic pressures: $P=(\rho_b-\rho_w)gD$, where ρ_b is the bulk density of the sediment, ρ_w is water density, g is the gravitational acceleration and D is the depth below seafloor.

4. Results

All the above mentioned rock physics models were used to estimate the gas hydrate and free gas saturation from the sonic P-wave velocity and porosity logs at sites NGHP-01-05 and NGHP-01-07. Various parameters required for developing these models are listed in Table 1 (taken from Helgerud et al. (1999)). The variation of velocity with gas hydrate saturation for both the sites was calculated for different values of porosities using Wood's model, Wylie's and the weighted mean equations independently (Fig. 2). For different hydrate saturations, the velocity computed by weighted equation is found to lie between the velocity values calculated by Wood's and Wyllie's equations. For proper modelling of the hydrate bearing sediments using weighted equation, the values of W and n need to be chosen efficiently. The weighted mean should be in such a way that if the porosity of the region is very low, the weighted equation approximates to Wyllie's model and tends towards Wood's model at high porosities (Fig. 3). Three curves have been plotted for the NGHP-01-05 site and it is found that the weighted mean curve shows a better agreement with the porosity log data (Fig. 3). The results presented in Fig. 4b indicate that the weighted equations (W=1.27) more accurately predict the P-wave velocity at the NGHP-01-05 site as compared to the time average or Wood's (1941) equations for the case when there is no hydrates. Similarly, Fig. 5b shows that weighted equations prove

Table 1
Elastic properties of sediment constituents (after Helgerud et al., 1999).

Sediment constituents	Bulk modulus (GPa)	Shear modulus (GPa)	Density (g/cm^3)	P wave velocity (km/s)
Clay	20.9	6.85	2.58	3.41
Quartz	36.6	45.0	2.65	6.04
Pore-water	2.4	0.0	1.03	1.5
Methane hydrate	8.7	3.5	0.92	3.8
Methane gas	0.1245	0.0	0.25	0.71

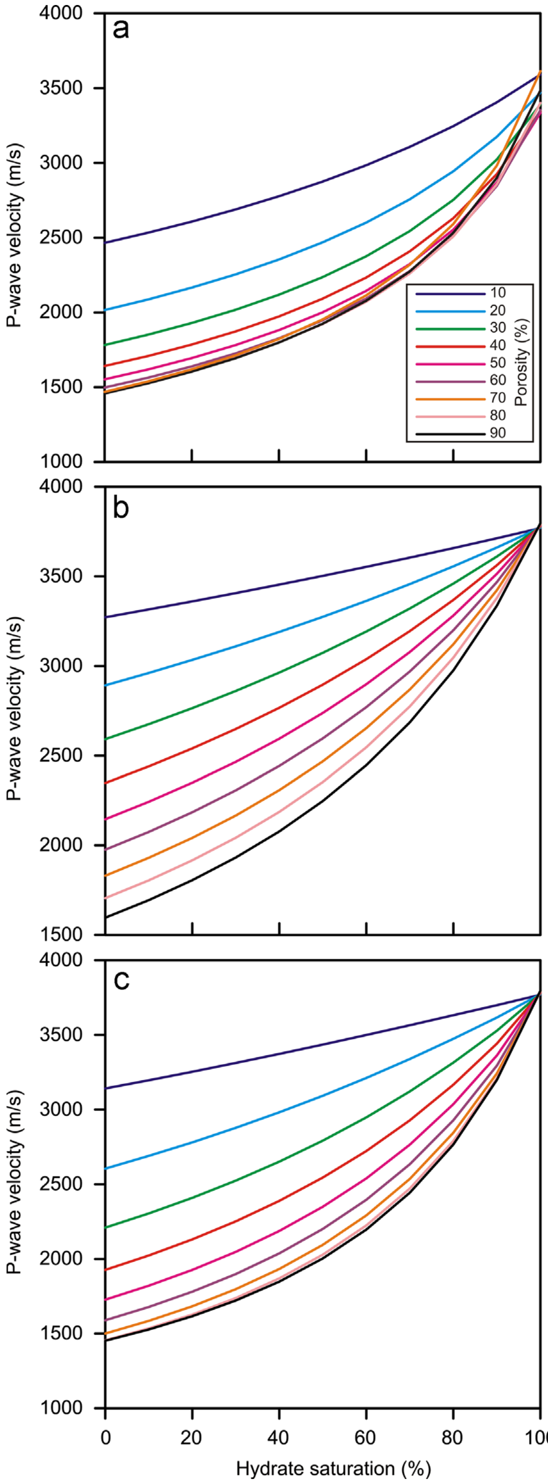

Fig. 2. P-wave velocity versus hydrate saturation trend at different porosity values for (a) Wood's (1941) model, (b) Wyllie's time average model and (c) weighted mean (W=1.27) of the Wood and Wyllie models.

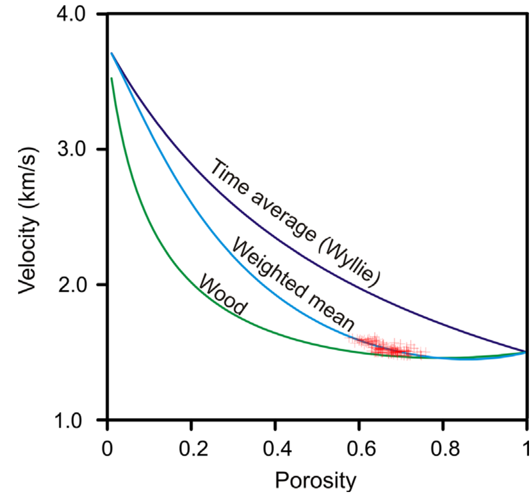

Fig. 3. The porosity–velocity values at the NGHP-01-05 site in KG basin obtained for Wood's model, Wyllie's time average equation and the three phase weighted equations.

to be better approach for the estimation of gas hydrate and free saturations at the site NGHP-01-07.

The sediments in the study sites of KG basin exhibit porosity values between 55% and 65%. For such range of porosity values and unconsolidated media, Wood's model should work to some extent. However, Wood's model assumes the constituents are in suspension, the predicted velocities values by this method for the sites NGHP-01-05 and NGHP-01-07 are found to be lower than the actual values. Thus, the velocities estimated by this method do not match the zones where there are no-hydrates (Figs. 4a and 5a). Due to this problem, the Wood model cannot be used for the estimation of gas hydrate at these sites.

The three phase weighted mean equation was used to generate the curves for different saturations of gas hydrate and free gas for sites NGHP-01-05 and NGHP-01-07, and the resultant curves were matched with the sonic log data (Figs. 4b and 5b). The weighted curve for zero saturation of gas-hydrate is found to overlap with the part of the sonic log curve devoid of hydrates. This observation allows us to infer that the assumed weighted mean is correct for this site. By this method, it is found that the pores at site NGHP-01-05 are saturated with about ~11–13% gas hydrates and ~0.5–0.7% of free gas. Similarly, for the site NGHP-01-07, the maximum saturations of gas hydrates and free gas are estimated up to 10% and 1.5% respectively. The BSR depth was observed ~125 m and ~188 m at site NGHP-01-05 and 07 respectively from the sea bottom (Collett et al., 2008). Based on the above observations, we further estimated the gas hydrate and free gas saturations variations with depth for both the sites using the weighted equation (Figs. 6a and 7a). It is found that the gas hydrate saturation varies maximum up to ~13% and free gas saturation up to ~0.7% at site NGHP-01-05 (Fig. 6a). Similarly, maximum saturations of ~12% and ~2.2% for gas hydrate and free gas respectively are noted at site NGHP-01-07 (Fig. 7a).

Figs. 4c and 5c show the results obtained from the non-contact effective medium model (EMM) formulated by Dvorkin et al. (1999) and further applied over gas hydrate by Helgerud et al. (1999). The P-wave velocity data are obtained using EMM for sites NGHP-01-05 and NGHP-01-07 for several different saturations of gas hydrates and free gas. These data are further superimposed over the sonic P-wave velocity and the saturations of gas hydrate and free gas are predicted (Figs. 4c and 5c). We have used EMM (Dvorkin et al., 1999; Helgerud et al., 1999) to generate the gas hydrate and free gas saturation log for both the sites (NGHP-01-05 and NGHP-01-07) (Figs. 6b, c and 7b, c). Fig. 6b shows the gas hydrate and free gas saturation variation with depth at site NGHP-01-05 obtained using the non-contact model. Results show that the gas hydrate saturation varies maximum up to 16% at 101 m below the sea floor (mbsf) and free gas saturation maximum up to 1.2% at around 142 mbsf for non-contact model (Fig. 6b). Fig. 6c

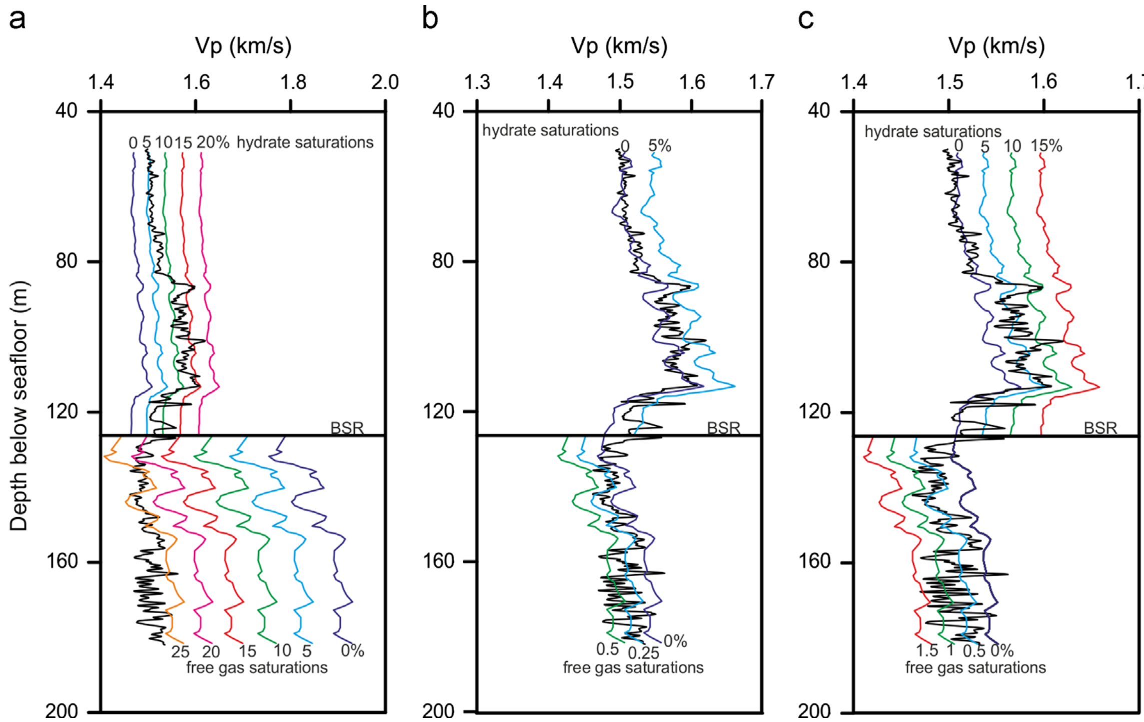

Fig. 4. Prediction of gas hydrate (above BSR) and free gas (below BSR) saturations at site NGHP-01-05 in the KG basin from (a) Wood's model, (b) three phase weighted mean curves ($W=1.27$ and $n=0.5$) and (c) non-contact model results obtained by elastic medium modelling (EMM) is superimposed on sonic P-wave velocity log (black line).

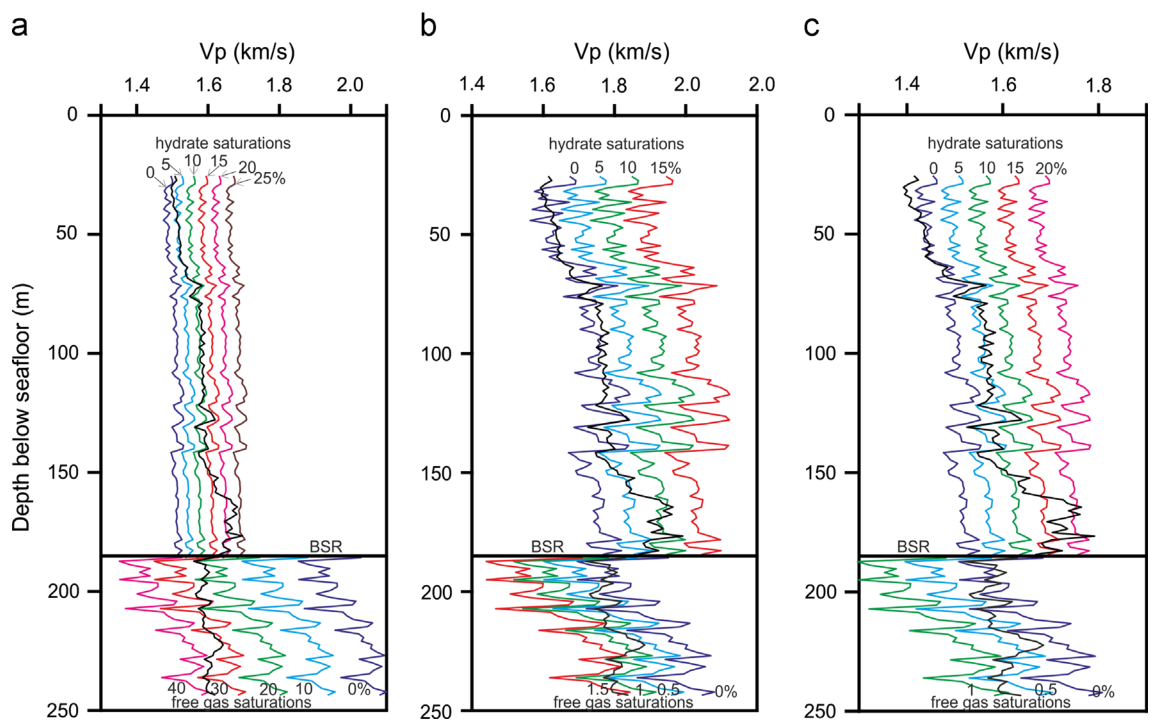

Fig. 5. Prediction of gas hydrate (above BSR) and free gas (below BSR) saturations at site NGHP-01-07 in the KG basin from (a) Wood's model, (b) three phase weighted mean curves ($W=1.27$ and $n=0.5$) and (c) non-contact model results obtained by elastic medium modelling (EMM) is superimposed on sonic P-wave velocity log (black line).

shows the gas hydrate saturation maximum up to 14% at 101 mbsf for contact model. Fig. 7b and c show the saturation results from site NGHP-01-07 obtained using EMM for non-contact model and contact model respectively. We have used the gas hydrate and free gas saturation values obtained at several depths from the pressure core data at sites NGHP-01-05 comparison.

5. Discussions

In this paper, we have estimated the saturations of gas hydrate and free gas at sites NGHP-01-05 and NGHP-01-07 in the KG basin using rock physics. Using the various rock physics models, the P-wave velocity logs are generated for both sites for several

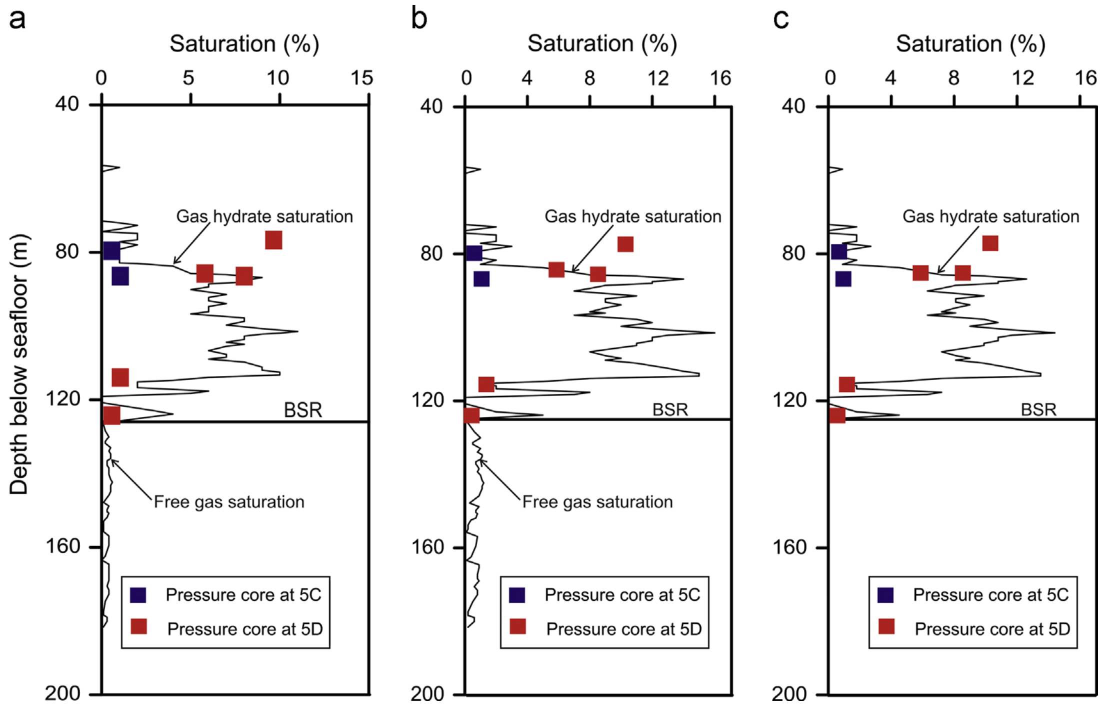

Fig. 6. Variation of gas hydrate and free gas saturation with depth at site NGHP-01-05 in the KG basin obtained from (a) three phase weighted modelling ($W=1.27$ and $n=0.5$), (b) non-contact model and (c) contact model approach. Pressure core values are also shown for comparison.

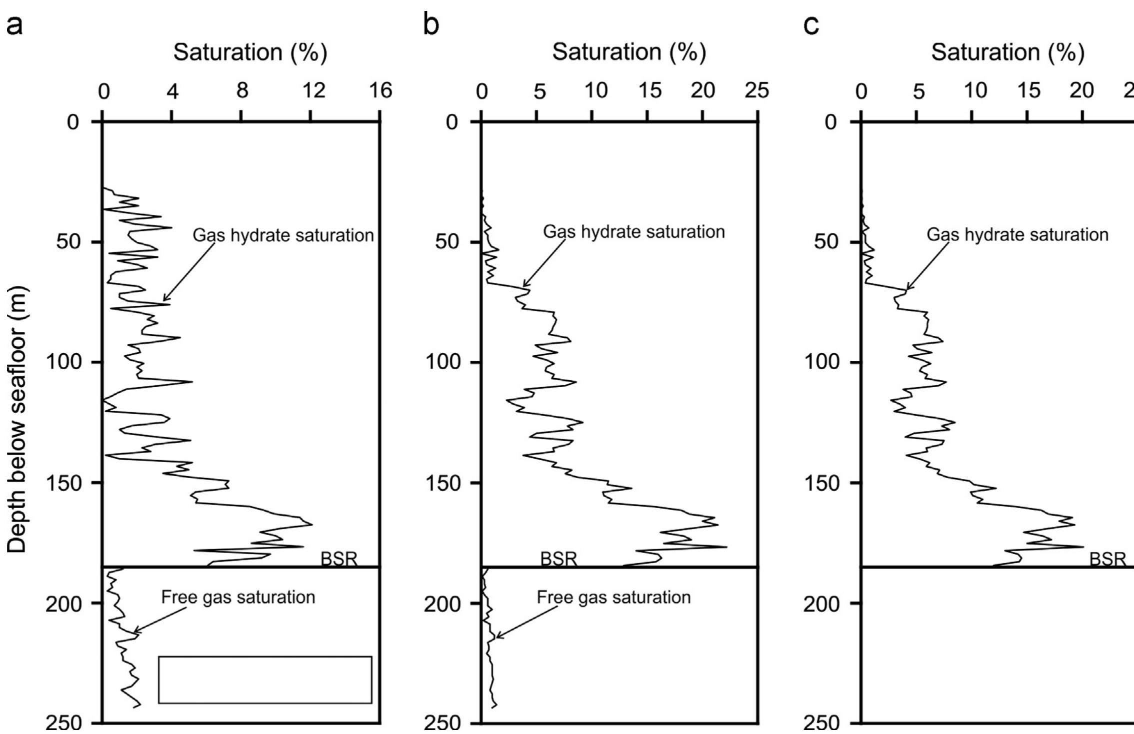

Fig. 7. Variation of gas hydrate and free gas saturation with depth at site NGHP-01-07 in the KG basin obtained from (a) three phase weighted modelling ($W=1.27$ and $n=0.5$), (b) non-contact model and (c) contact model approach.

different values of gas hydrate and free gas saturations. These results are further matched with the actual sonic velocity logs and data showing best match gives the estimate of gas hydrate and free gas saturations at the study sites (Figs. 4a–c and 5a–c). Tables 2 and 3 show the gas hydrate and free gas saturations obtained from various rock physics models. The results are found to differ from each other and a proper conclusion cannot be drawn directly based on the observations listed in Tables 2 and 3 for site NGHP-01-05 and 07 respectively. While Wood's equation overestimates the hydrate saturation, the Wyllie equation estimates large saturation values (Figs. 4a and 5a). As per theories, Wood's model is valid for region having high porosity and hydrate present in suspension form and time average equations of Wyllie hold true for low porosity and highly consolidated media. When studying a rock matrix combined with pores partially saturated with fluid or gas hydrate, the media can neither be considered a tight and

Table 2
Gas hydrate and free gas saturations obtained using different approaches at site NGHP-01-05.

Rock physics models	Hydrate saturation (%)	Free gas saturation (%)	Remarks
Wood (1941)	–	–	Highly over estimated
Wyllie et al. (1958)	–	–	Highly under estimated
Weighted mean ($W=1.27$ and $n=0.5$)	11–13	0.5–0.7	–
EMM (non-contact)	14–16	1–1.2	–
EMM (contact)	12–14	–	No gas for contact model

Table 3
Gas hydrate and free gas saturations obtained using different approaches at site NGHP-01-07.

Rock physics models	Hydrate saturation (%)	Free gas saturation (%)	Remarks
Wood (1941)	–	–	Highly over estimated
Wyllie et al. (1958)	–	–	Highly under estimated
Weighted mean ($W=1.27$ and $n=0.5$)	8–12	0.5–2.2	–
EMM (non-contact)	20–22	1.2–1.4	–
EMM (contact)	18–20	–	No gas for contact model

perfectly consolidated matrix, nor can it be considered as a suspension. Thus the computed values of P-wave velocity will be lying in between the results of these two models. Due to these problems, these two models have become outdated and are not generally used in most modern seismic and log studies of gas hydrates.

We have also used the weighted equations for the estimation of gas hydrates and free gas saturations in the sediments of the two sites using Lee et al.'s (1996) equation. For zero saturation of gas hydrate, this equation is independent of the exponent n and thus resembles the equation of Nobes et al. (1986). In order to use this equation for estimation of gas hydrates, we assume that there is no gas hydrate and generate P-wave velocity log for several different values of W. The log that best fits the observed sonic velocity log gives the required value of W. For the case of KG basin data, it is found that for $W=1.27$, weighted equation for zero hydrate saturation shows a good fit with the observed data. For $W=1$, the weight of Wood as well as Wyllie equations in the three phase weighted equations are equal. Nobes et al. (1986) have shown that for $W>1$, the equation favours the Wood equation and for $W<1$, the equation favours time average equation. The saturation exponent n introduced by Lee et al. (1996) provides flexibility by allowing the weighted equation to be applicable over diverse conditions of formation of gas hydrate in marine sediments. Similar to the weighting factor W, the exponent n is calculated by fitting the equation over a set of data relating velocities versus hydrate concentrations in the pore spaces of the sediments. Larger values of n simulate the behaviour of consolidated and cemented matrix, but the accuracy of saturation estimates for hydrate and free gas is reduced. For the case where hydrate is disseminated throughout the pore space, the lower value of n such as $n=1$ may be better suited for the velocity computation (Lee et al., 1996). On the other hand, if the hydrates are layered or selectively cement grains at low concentrations, then a larger value of n fits better.

In addition to the velocity–porosity transforms based on empirical relations, we have used the effective medium model formulated by Dvorkin et al. (1999). Helgerud et al. (1999) used it as the baseline model for modelling the elastic parameters of hydrate bearing sediments. The porosity of the regional sediments is found to lie very close to the critical porosity. It is neither very low nor too high as compared to the critical porosity value for the region. Critical porosity is the porosity value above which the modulus-porosity trend abruptly changes (Dvorkin and Nur, 2000). For porosity values less than critical porosity, the stiffness of the sediment is determined by the framework of contacting grains and for porosity values greater than critical porosity, it is determined by the pore fluid. Due to porosity values for sites NGHP-01-05 and NGHP-01-07 being close to critical porosity value, it cannot be assured whether the hydrates form a part of the fluid suspension or the cementation matrix. Hence, we have analysed the data using both the cases and estimated gas hydrate saturations for both contact as well as non-contact models. For contact and non-contact models, free gas will form part of the pore fluid.

The results estimated using the effective medium models are expected to be more accurate because the physical properties of the medium are taken into consideration. The other models are empirical velocity–porosity transforms and will hold true only for a limited range of porosity values. The results obtained by the contact and non-contact model are also found to differ. In the case of the contact model, the hydrates are present in more consolidated form and hence the volume concentration of the hydrates reduces. The saturation estimates for the EMM depend upon the value of the coordination number n. For the KG basin, the clay content is approximated to be around 90% and the sediment exists in highly unconsolidated form. Based on the porosity values, the average number of contacts per grain for sites NGHP-01-05 and NGHP-01-07 is around 3–4 (as per Avseth et al. (2005)).

6. Conclusions

We have estimated the gas hydrates and free gas at the sites NGHP-01-05 and NGHP-01-07 in the KG basin using various rock physics modelling approaches. The Wood model and the Wyllie model are found to fail on the KG basin data. Weighted equation is found to predict the gas hydrates and free gas saturations to good. However, this method requires the tuning of parameters such as W and n, we need additional data such as core samples in order to use this method. Using the weighted equation, we have estimated the saturation of gas hydrates as ~11–13% and free gas as ~0.5–0.7% at the site NGHP-01-05 and ~8–12% and ~0.5–2.2% gas hydrates and free gas respectively at site NGHP-01-07. Both sites have also been studied using the effective medium models and gas hydrates are estimated as ~14–16% and ~12–14% for the non-contact model and contact models respectively for the site NGHP-01-05. As per the non-contact model, the pore spaces of this site are found to be saturated with around ~1–1.2% of free gas.

Similarly, for site NGHP-01-07, the gas hydrate and free gas saturations obtained by using non-contact model are up to maximum ∼22% and ∼1.4% respectively and the gas hydrate saturation up to maximum ∼20% using the contact model. Due to consideration of the rock physical properties no requirement of parameter tuning, effective medium model is independent of the condition in which the hydrates lie within the sediment. Thus the results of this model are more accurate as compared to the effective models. Also we have compared the results at site NGHP-01-05 with the available pressure core data and the effective medium model proves to be a superior method over the empirical transforms.

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