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Estimation of gas-hydrates from seismic velocity-resistivity transformed data in the Krishna-Godavari basin, eastern Indian margin

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Summary

Gas-hydrates have been recovered in fracture shale at site 10 in the Krishna-Godavari basin, eastern Indian margin by Expedition-01 of Indian National Gas Hydrate Program. Higher values of resistivity and sonic logs indicate gas-hydrates between 30 to 150 m below sea floor, whereas the shallower and deeper sediments are brine-saturated. Direct application of simple Archie's formula to resistivity log results in overestimation of gas-hydrates compared to that measured by pressure cores at a few depths. This is because of its isotropic assumption for anisotropic media caused by fractures. Considering gas-hydrates as a part of matrix and brine in pores, we have established a relation between resistivity and velocity for sediments with and without gas-hydrates using the log data. We can estimate gas-hydrates from resistivity by employing the modified Archie's formula using saturation exponent that has been established by calibration with pressure core results. This saturation exponent incorporates the effect of fractures automatically. We have processed the high-resolution multi-channel seismic data at 6.25 m CMP interval with a view to build the best possible velocity models and improved seismic images along two lines passing through site 10. The velocity has been transformed into pseudo resistivity log at each CDP using the velocity-resistivity relation. The results of applying modified Archie's formula to the pseudo logs show gas-hydrates as varying both laterally and vertically up to 28% along the lines. The method is simple; does not require Archie's constants and porosity of sediments; and can be used in estimating gas-hydrates without any fracture modeling.

Keywords: *Gas-hydrates, saturation, Krishna-Godavari basin, velocity-resistivity relation, modified Archie's formula*

Introduction and Data

Gas-hydrates are a crystalline form of mainly methane and water, and are found in shallow sediments of outer continental margins and permafrost regions. They are formed in high pressure and low temperature regimes where the methane concentration exceeds the solubility limit **[Sloan, 1998; Kvenvolden, 1998]**. One volume of gas-hydrates releases 164 volumes of methane and 0.8 volume of fresh water at standard temperature and pressure (STP). Bottom simulating reflector (BSR), high resistivity, seismic blanking, high reflection strength and frequency shadow are the commonly used proxies for identifying gas hydrates **[Ojha and Sain, 2009; Satyavani et al., 2008]**. Seismic Attenuation or quality factor is also an important property to characterize the hydrate- and gas-bearing sediments **[Sain et al., 2009; Sain and Singh, 2011].**

BSRs, main marker for gas-hydrates, have been observed on seismic sections in the Krishna-Godavari (KG) basin **[Sain and Gupta, 2008; 2012; Sain et al., 2012]**. The logging and coring of Indian National Gas Hydrate Program (NGHP) under Expedition 01 have established gas-hydrates in the KG basin **[Collett et al., 2008]**. In addition to cores at (10B, 10D), well logs were also acquired via logging while drilling (LWD) and Wire-line logging (WLL).

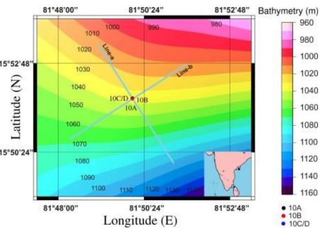

Fig.1: 2-D seismic lines around NGHP drilling site 10. Inset shows the study region (square) in the KG basin.

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Out of twelve (six in-line and six cross-line) high resolution MCS data around site 10 at deep water (1000 - 1200 m) in KG basin, we have taken up two perpendicular lines: Line-a (NW-SE) & Line-b (NE-SW), the location of which are shown in Fig.1. The site 10 is located near the cross point of seismic lines. The seismic data processing is performed using the Echoes and Geo-Depth commercial software (a Paradigm Product) with a view to produce improved shallow image (Fig.2) with the best possible velocity model (Fig.3).

The density porosity, resistivity, and P-wave velocity logs at site 10A and 10D are shown in Fig.4. High values in the resistivity and sonic velocity logs indicate gas-hydrates within 30 to 150 m below the sea floor. The gas-hydrate saturations estimated from the LWD resistivity log with isotropic model reach as high as 80% of the pore space, which is much higher than those measured by pressure cores (the maximum value is 26%) at specified depths. Here we present a new approach by considering a model in which gas-hydrates form a part of the matrix rather than remaining in pores filled with water for the estimation of lateral and vertical saturation of gas-hydrates along two perpendicular seismic lines around site 10 in the KG basin (Fig.1), where gas-hydrates have been found in fracture shale.

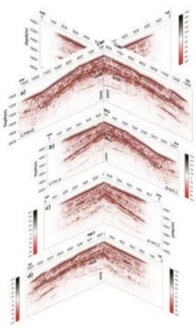

Fig.2: Fence diagram of seismic sections obtained by FX Wave equation PSDM along Line-a & b in a) SW-SE, b) NW-SW, c) NE-NW and d) SE-NE quadrants respectively

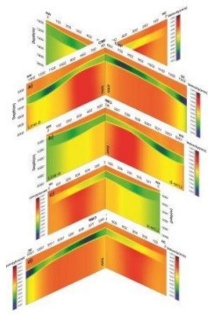

Fig.3: Fence diagram of seismic velocities derived by PSDM along Line-a & b in a) SW-SE, b) NW-SW, c) NE-NW and d) SE-NE quadrants respectively.

2. Methodology for Estimating Gas-hydrates

2.1. Quantification of Gas-hydrates using Archie's Law:

The saturation of gas-hydrates (S_h) can be estimated using the **Archie's law (1942)** in an isotropic medium as

$$S_h = 1 - \left[\frac{aR_w}{\phi^m R_t} \right]^{\frac{1}{n}} \qquad (1)$$

Where Rw is the water saturated formation resistivity determined by the ARP's formula; Rt is the true resistivity; ϕ is the porosity; a and m are Archie's constants; and n is the saturation exponent.

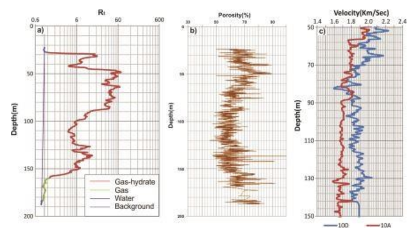

Fig. 4: a) Resistivity at site 10A, b) Porosity, and c) sonic velocities at site 10A and 10D.

Presence of fractures causes the medium anisotropy. Since Archie's law holds good in isotropic media only, the saturation estimated by Archie's equation shows much higher (80%) than that measured by the pressure cores (maximum 26%). **Ghosh et al. [2010]** used a crack inclusion model to estimate gas-hydrate saturation from sonic velocities at site 10D considering an anisotropic background in a fractured reservoir, which matches reasonably well with the pressure core. To deal with anisotropic behavior, **Lee and Collett [2009]** have made some corrections to the Archie's parameters (a=3, instead of a=3.2; m=2, instead of m=0.5; and n=3, instead of n=2) to minimize the difference between the pressure core value and the result obtained by the Archie's law (Fig.5). We see much improved result but still find some mismatches with the pressure core results. This may be due to not using accurate values of Archie's parameters required for an anisotropic medium.

2.2. Saturation from Formation Factor:

Archie's equations form the basis for resistivity log interpretation. They can be written as

$$F = \frac{R_0}{R_w} = a\phi^{-m} \qquad (2)$$

$$I = \frac{R_t}{R_0} = (S_w)^{-n} \qquad (3)$$

$$I = \frac{F_t}{F_0} \qquad (4)$$

Where F is the formation factor defined as the ratio of the resistivity (R_0) of fully brine saturated sediments to the resistivity (R_w) of the brine. I is resistivity index defined as the ratio of the (true) resistivity (R_t) of partially brine saturated sediments, to the resistivity (R_0) of fully brine saturated sediments. In the case of gas-hydrates bearing formation, we can say that the resistivity index is the ratio of formation factor of gas-hydrates bearing (partially brine saturated) sediments to the formation factor of non-hydrates or brine saturated sediments i.e.

$$S_h = 1 - S_w = 1 - I^{-\frac{1}{n}}$$

$$S_h = 1 - \left(\frac{F_t}{F_0}\right)^{-\frac{1}{n}}$$

$$S_h = 1 - \left(\frac{F_0}{F_t}\right)^{n} \qquad (5)$$

For the estimation of gas-hydrates as per equation (5), we require the formation factors for gas-hydrates and non-gas-hydrate bearing sediments, and need not bother about the Archie's constant (a and m) and the porosity (ϕ) of the formation. However, we need the saturation exponent (n) quite accurately, which can incorporate the effect of fracture (anisotropy) or any other features. The formation factors can be derived from the resistivity log data, and the saturation exponent can be established by changing the value of n in equation (5) unless the estimated saturation matches with the pressure core results available at specified depths. Using n=8 we get better match (Fig.5) with the pressure core result than the saturation estimated by the modified Archie's equation **[Lee and Collett, 2009]** without depending on values of a, m and ϕ. Still, we have not obtained a perfect match with the pressure core. This may be due to the choice of inadequate background!

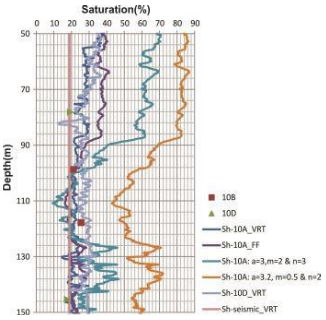

Fig.5: Saturations estimated by Archie's law (a=3.2, m=0.5, & n=2), modified Archie's equation (a=3, m=2, & n=3), present approach (FF) respectively from resistivity log data at site 10A. Saturations estimated by present approach through velocity-resistivity transform (VRT) of sonic log data at respective site 10A and 10D are also shown. The approach has been applied to large-wavelength seismic velocity at the drilling location. The triangles and squares represent saturations measured by pressure cores at 10D and 10B respectively.

2.3. Velocity Formation Factor Transform: Gulf of Mexico data

Now we are interested in estimating the saturations of gas-hydrates from seismic velocities derived along seismic lines. For this, we need to establish a relationship for transforming the seismic velocity to resistivity. A physical basis for the existence of such a relation is the dependence of these parameters on the total porosity. **Faust [1953]** tried to obtain the sonic curve by using the measured resistivity and gave a relation (Equation 6) between sonic velocity (V_P) at depth (Z) and formation factor (F). However, the Faust's equation acts well for stiff sediments only. Much later, **Hacikoylu [2006]** revisited Faust's equation and offered a new transform between the velocity and formation factor as (Equation 7)

$$V_p = 2.2888(ZF)^{\frac{1}{6}} \qquad (6)$$

$$\frac{1}{V_p} = \frac{0.9}{F} + C \qquad (7)$$

$$where \quad 0.27 \le C \le 0.32$$

This is based on a rock physics model appropriate for soft sand in the Gulf of Mexico (GOM). This resistivity-velocity transform equation is the best linear fit where the slope of the line is a constant and intercept (C) is variable between 0.27 and 0.32 that apparently bounds the available log data.

2.4. Velocity Formation Factor Transform: Krishna-Godavari data

With the motivation from above studies, we have plotted two best fit curves (Fig.6), one for the brine saturated i.e. non-hydrates bearing zone and the other for the gas-hydrates bearing zone to derive the velocity formation factor transform. For non-hydrates zone, we get a linear Equation (8) and for hydrates zone, it is a power function Equation (9).

$$\frac{1}{F_b} = 0.9759\left(\frac{1}{V_e}\right) - 0.3438 \qquad (8)$$

$$\frac{1}{F_t} = 39.929\left(\frac{1}{V_t}\right)^{13.596} \qquad (9)$$

We can see from Fig.6 that the formation factor (F_b) obtained by linear relation behaves like background to F_t obtained by power function. Now the question arises as to what velocity should we use to calculate the background formation factor for gas-hydrate bearing sediments? This is demonstrated in the next section.

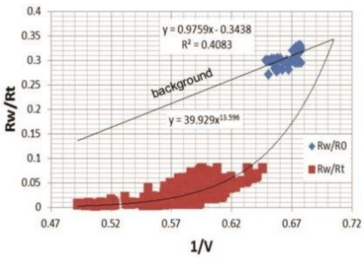

Fig.6: Relation between Rw/Rt and 1/Vp for hydrates bearing zone and non-hydrates bearing zone respectively, showing non-hydrates curve (sky blue) as back-ground to the hydrates bearing curve (rust).

2.5. Background Formation Factor:

The background formation factor means the formation factor when gas-hydrates are absent, and replaced by matrix. For a fracture-filling model, we can calculate the true velocity (V_t) using the time average equation (10). We assume that before the formation of gas-hydrates, the matrix was soft; and after formation of gas-hydrates, the matrix became stiff due to crystalline solid nature of gas-hydrates. To calculate the background formation factor, we use the effective velocity (V_e), which is the velocity of the medium when gas-hydrates are replaced by matrix material. This velocity can be obtained simply by replacing V_h (velocity of pure hydrates) with V_m (velocity of matrix) in Equation (10) as shown in Equation (11).

$$\frac{1}{V_t} = \frac{\phi(1-S_h)}{(1-\phi S_h)V_w} + \frac{\phi S_h(1-\phi)}{V_h(1-\phi S_h)} + \frac{1-\phi}{V_m} \qquad (10)$$

$$\frac{1}{V_e} = \frac{\phi(1-S_h)}{(1-\phi S_h)V_w} + \frac{\phi S_h(1-\phi)}{V_m(1-\phi S_h)} + \frac{1-\phi}{V_m} \qquad (11)$$

$$\text{where} \quad \frac{1}{V_m} = \frac{1-C}{V_q} + \frac{C}{V_c}$$

$$\frac{\phi(1-S_h)}{1-\phi S_h} \quad \textit{is water filled porosity}$$

$$\frac{\phi S_h(1-\phi)}{(1-\phi S_h)} \quad \textit{is hydrate filled porosity}$$

Where C is the clay part and (1-C) is quartz part in matrix; V_w, V_q and V_c are the velocities of water, quartz and clay respectively. ϕ is the porosity.

The elastic constants K, μ and ρ for various elements are taken from **Lee [2012]** as

$$K_q = 38\ ,\ \mu_q = 44\ ,\ \rho_q = 2.65$$

$$K_c = 20.9\ ,\ \mu_c = 6.6\ ,\ \rho_c = 2.58$$

$$K_h = 8.41\ ,\ \mu_h = 3.54\ ,\ \rho_h = 0.925$$

The analysis of sediment cores at site 10 shows 0-20% quartz and 80-100% clay for the sediments in the KG basin **[Collett et al., 2008]**. We have taken 90% clay and 10% quartz as average mineralogical composition to calculate the effective velocity from the true velocity (V_t). We have calculated V_t and V_e using equations (10) and (11) for the entire range of porosity and the said mineralogical composition, and cross plotted them in Fig.7a, which shows a linear trend (Equation 12). We have also cross-plotted the V_e and V_t by varying the mineralogical compositions (Fig. 7b and c), and observe that the linear relationship between V_e and V_t exists for all porosities and any mineralogical constituents. Using this relation, we can calculate the background velocity

(V_e) from the velocity (V_t) of gas-hydrates bearing sediments as.

$$V_e = 0.9944 V_t + 0.003 \qquad (12)$$

2.6. Saturation from sonic and seismic velocities using new approach

Using equation 12, now we calculate the background velocity (V_e) from the true velocity (V_t) of sonic log (Fig.4) at site 10A; and the true (F_t) and background (F_b) formation factors (Fig.8) using equations (8) and (9); and the saturation of gas-hydrates (Fig.5) using equation (5) with saturation exponent n=8. The saturation estimated by this new approach through velocity-resistivity transform shows further improvement over the previous result obtained from the resistivity data alone using equation 5 with n=8.We have also applied this new approach to the WWL velocity log (Fig.4) at site 10D, and the result (Fig.5) also matches reasonably with the pressure core. For translating the large-wavelength seismic velocities (derived along the cross lines based on PSDM) in terms of saturation of gas-hydrates, we pick up the seismic velocity-depth function at each CDP, and estimate the saturation (Fig.9) using the present approach as described above. This shows that the saturation of gas-hydrates varies both laterally and vertically up to 28% along the lines. The saturation of gas-hydrates at the cross point (CDP 550) along Line-a is displayed in Fig.5 to show how well it matches with the pressure core results. The saturations estimated by present and earlier methods from the sonic and seismic velocities at sites 10A and 10D are compared in Fig.10 to demonstrate the effectiveness of the present approach, which is very simple and applicable to any geological set up including fractured shale.

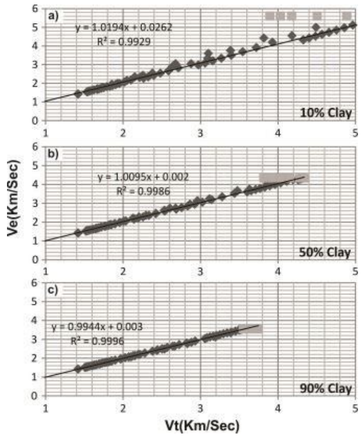

Fig.7: V_e Versus V_t plot for different mineralogical composition for a) 10% clay; 90% quartz, b) 50% clay; 50% quartz and c) 90% clay; and 10% quartz.

3. Discussion and Conclusions

We have applied the GeoDepth special processing to MCS data and imaged shallow sections along Lines-a and b around the site 10 in the KG basin, where gas-hydrates have been recovered in fractured shale. The BSRs have been clearly brought out on seismic sections. However, the amplitudes of BSRs are not very high. The tectonic activity in the region influences the distribution of gas-hydrates as faults might have disrupted the BSRs. As a by-product, we have obtained seismic velocities along the lines, where the velocities match well at the cross point. Presence of gas-hydrates in the sediments is indicated by high velocity anomaly Fig.3.

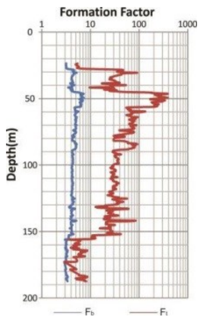

Fig. 8: True (F_t) and background (F_b) formation factors derived from sonic velocity at site 10A.

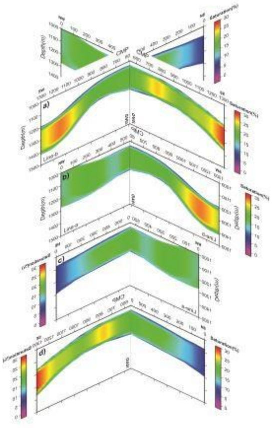

Fig.9: Fence diagram for saturation of gas-hydrates, derived by present approach, along Line-a & b (in SW-SE, NW-SW, NE-NW and SE-NE quadrants).

We have established the relation between normalized resistivity (formation factor) and velocity for both hydrate- and non-hydrate- (water saturated) bearing formations in the KG basin, which can be used for velocity-resistivity transformation and vice versa for many geophysical application. We have also established the relation between the true velocity and effective velocity i.e. the velocity of the medium if gas-hydrates are replaced by matrix materials. Using these relations, we have calculated the true formation factor and the background (without gas-hydrates) formation factor respectively. The application of present approach to the sonic velocity at sites 10 provides better estimation than previous results **[Lee and Collett, 2009; Ghosh et al., 2010]**. The seismic velocities along two lines have been translated into saturation of gas-hydrates that vary both laterally and vertically (5-28%) along the lines. The advantage of this new approach is that we need not use the Archie's constants (a & m) and porosity (ϕ) of the formation, which are automatically incorporated while calculating the formation factors. We need to know only the saturation exponent (n) that has been established by calibrating with the pressure core values at specified depths. The method is simple and can be used for quick estimation of lateral/vertical variation of gas-hydrates in any medium including fractures.

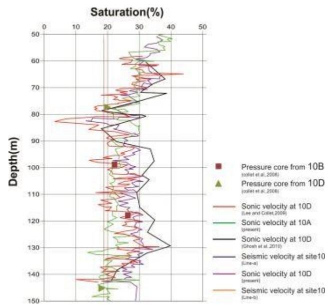

Fig.10: Saturations estimated at 10A and 10D by different methods using sonic log data. Saturations estimated by present method at the drilling location from seismic velocities along Line-a and b. and seismic velocities. The triangles and squares represent saturations measured by pressure cores at 10D and 10B respectively.

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