Gas hydrates characterization from seismic and well log data: Krishna-Godavari basin

*Anju K. Joshi, Laxmi Pandey, Arun K.P., Kalachand Sain
CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad-500007, India
anju841991@gmail.com

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BSR, model based inversion, three phase weighted equation, Archie's law.

Summary

We have identified the bottom simulating reflector (BSR) on a seismic section that passes through a well at site NGHP-01-11A in the Krishna-Godavari (KG) basin, and estimated the saturation of gas hydrates at the well location using the three phase weighted equation. To assess the results, we have compared with the values obtained using the Archie's law. The maximum amount of gas hydrates is found to be varying from ~5% to 12% in the sediment.

Introduction

Gas hydrates are ice-like crystalline solid in which gas molecules (mainly methane) are trapped inside the cages of water molecules, called the clathrates (Sloan, 1998; Kumar et al., 2009). The formation of gas hydrates depends on the optimum pressure and temperature conditions, supply of free gas and pore fluid chemistry. Gas hydrates contain immense amount of natural gas (Collett, 2002), which can meet the overwhelming energy requirement of the world in general, and of India in particular. They are found in ocean floor sediments at a shallow depth and in permafrost regions. The BSR is the main marker for gas hydrates, which shows several characteristics on seismic section like mimicking the shape of seafloor, cross cutting dipping sedimentary strata, and reversed polarity with reference to the seafloor reflection etc.

The Krishna-Godavari (KG) basin is a proven reserve of gas hydrates in which 15 sites have been drilled during the expedition NGHP-01 in 2006. The present study deals with the delineation of BSR along a 2D seismic line (Figure 1) in KG basin, which passes through the well at site NGHP-01-11A and estimation of gas hydrates saturation. The presence of gas hydrates in sediments alters the physical and mechanical properties of sediments and the changes can be clearly seen on the well log data. The BSR or the base of gas hydrates stability zone can be marked laterally by multi-channel seismic experiment using the model based acoustic impedance inversion.

In this paper, the properties like the resistivity and P-wave velocity are used to estimate gas hydrate saturation at the well location. The P-wave velocity of gas hydrates bearing sediments are modeled using Three-phase weighted equation and the estimated saturation is then assessed by comparing with the result obtained by using the resistivity log data.

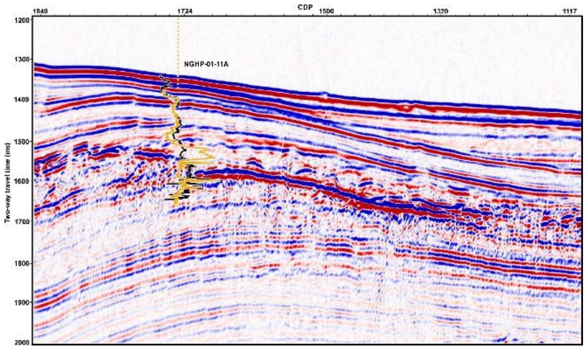

Figure 1: Post stack 2D seismic data superimposed with sonic (black) and resistivity (orange) logs.

Theory and method

The well log data gives the in-situ variations in physical properties throughout the depth of the well. The presence of gas hydrates alters the trend of compressional (P-) wave velocity and resistivity without much change in density. The P-wave velocity and resistivity values increase with the saturation of gas hydrates. A thorough analysis of sonic, resistivity and density logs provide information about the gas hydrates stability zone as well as the depth of BSR on seismic section.

Post stack impedance inversion

The post stack impedance inversion transforms the input seismic data into an inverted acoustic impedance section that provides layer information (Lee et al, 2013). The model based acoustic impedance inversion constrained with well data uses the density log, sonic log and interpreted horizons from seismic data as inputs. The method is based on the convolution of a source wavelet with the earth's reflectivity series (Lu and McMechan, 2002). The wavelet is extracted from seismic data using well logs. The P-wave reflectivity series is related to the acoustic impedance derived from the density and sonic logs. The seismic to well tie is performed using the synthetic trace generated by convolution of extracted wavelet with the reflectivity series. The initial low frequency model is constructed using the well logs and interpreted horizons. The inverted impedance section gives the clear boundary of gas hydrates and free gas, as high impedance above and low impedance below, and thus the BSR can be delineated from seismic data along a line.

Three-phase weighted equation

Three-phase weighted equation is the weighted mean of the three-phase time average and Wood equation and it is applied to derive the relationship between the P-wave velocity and amount of gas hydrates filling the pore space (Lee et al., 1996).

Time average equation: In time average equation (Wyllie et al., 1958), the slowness is taken as the weighted sum of fluid and rock matrix. The three phase time average equation is given as:

$$\frac{1}{V_p} = \frac{\varphi(1-S)}{V_w} + \frac{\varphi S}{V_h} + \frac{1-\varphi}{V_m} \qquad (1)$$

where, V_p is the P- velocity of gas hydrates bearing sediment, V_h is the P-wave velocity of pure hydrate, V_w is the P-wave velocity of the fluid, V_m is the P-wave velocity of rock matrix, φ is the porosity as fraction and S is the gas hydrate saturation in pore space as fraction.

Wood Equation: *Wood* [1941] equation is approximately valid for particles in suspension and the three phase wood equation for gas hydrates bearing sediments is defined as:

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

Where, ρ is the bulk density of sediments, $\rho_w$is the fluid density, ρ_m is the density of matrix, ρ_h is the density of pure gas hydrates.

Three phase weighted equation: *Lee et al*, 1996 proposed that the interval velocity for gas hydrates bearing deep marine sediment can be estimated from a weighted mean (Pearson et al., 1983) three phase time average equation and the three phase wood equations, following the approach of *Nobes et al*. [1986] as:

$$\frac{1}{V_p} = \frac{W\varphi(1-S)^n}{V_{p1}} + \frac{1-W\varphi(1-S)^n}{V_{p2}} \qquad (3)$$

where, V_{p1} is the P-wave velocity by the wood equation, V_{p2} is the P-wave velocity by the time average equation, W is the weighting factor and n is a constant simulating the rate of lithification with gas hydrates saturation. The value of W is derived from regression analysis of V_p of sediments without gas hydrates. The gas hydrates saturation is estimated for which the modeled velocity best matches with the measured velocity. The volumetric fraction of gas hydrates in sediments which is called the concentration (Kumar et al., 2009) of gas hydrate,S_{hyd}, is calculated as:

$$S_{hyd} = \varphi S \qquad (4)$$

Archie’s law

The electrical resistivity of water saturated sediments R_0 is expressed using the Archie equation (Archie,1942) as

$$R_0 = \frac{aR_w}{\varphi^m} \qquad (5)$$

Where, R_w is the resistivity of connate water, ‘a’ and ‘m’ are the Archie's constants and φ is the porosity. R_w is calculated using the equation of state of seawater (Fofonoff, 1985). Using the calculated R_w and measured resistivity from well log (R_t), the formation factor (F) is calculated. The Archie's constants are determined from a cross plot between the formation factor and density porosity (Lee and Collett, 2009). The parameter n varies between 1.715 (unconsolidated sediments) and 2.1661 (sandstone) (Pearson et al.,1983). In the present study, we use n=2. The gas hydrates saturation is thus estimated using the formula

$$S_h = 1 - \left(\frac{aR_w}{\varphi^m R_t}\right)^{\frac{1}{n}} \qquad (6)$$

The concentration of gas hydrates is calculated using the equation 4.

Results and Discussion

The gas hydrates bearing sediments show high P-wave and resistivity without much change in density. The decrease in porosity can be inferred as the presence of gas hydrates. By thorough analysis of well log, the depth of BSR is determined at 150 meters below sea floor (mbsf), and the gas hydrates stability zone on seismic section varies between 113 to 150 mbsf. Figure 2 shows the level of BSR marked from the well logs.

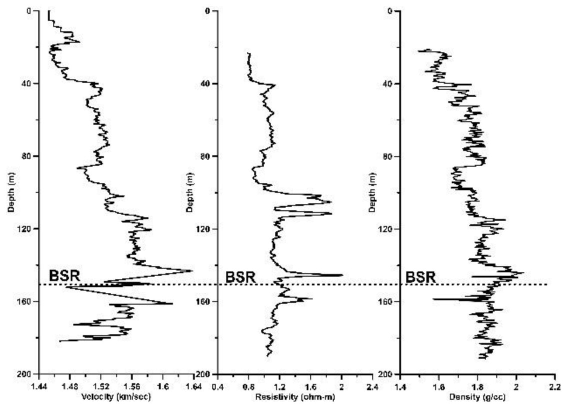

Figure 2: Well log data at NGHP-01-11A

The model based acoustic impedance inversion yields an inverted impedance (Figure 3) from which the lateral extent of BSR, which is a boundary between high impedance above and low impedance below, can be delineated. The BSR on inverted seismic section matches quite accurately with that marked by well logs.

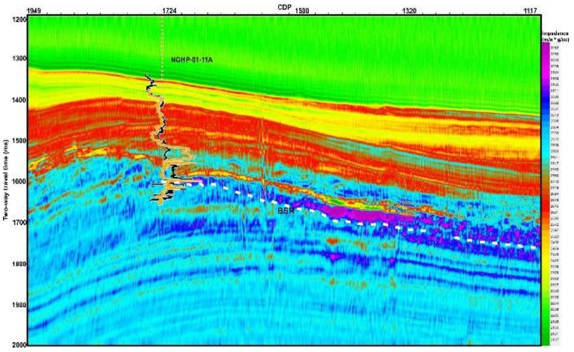

Figure 3: Inverted acoustic impedance section superimposed with velocity (black) and resistivity (orange) logs.

Gas hydrate concentration from velocity

As BSR is confirmed along the seismic section, the three-phase weighted equation is used to model the compressional velocity at the well site NGHP-01-11A for the estimation of gas hydrates. The weighting factor W is determined by the regression analysis of P-wave velocity of sediments without gas hydrates and is fixed at W=1.5. Figure 4 gives the similarity between computed P-wave velocity and the measured P-wave velocity for NGHP-01-11A. The saturation is estimated within the minimum error between the modeled and measured velocities. The saturation of gas hydrates is then converted into concentration, which is found to have a maximum value of ~5% at 137mbsf.

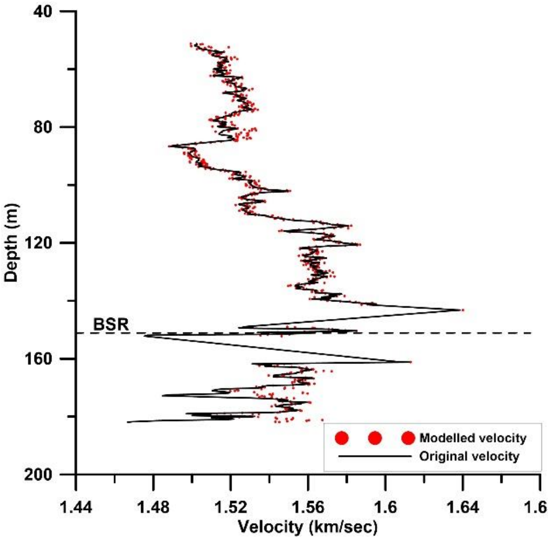

Figure 4: Modeled and measured velocities of NGHP-01-11A using three phase weighted equation.

Gas hydrate concentration from resistivity

The saturation of gas hydrates is estimated using the relation between resistivity of gas hydrates bearing sediments and water saturated sediments. The high resolution LWD resistivity log data is used for this purpose with a view to assess the results. The formation factor (F) is calculated using the formula,

$$F = \frac{R_t}{R_w} \qquad (7)$$

The value of Archie parameters, tortuosity factor a =1.3952 and cementation factor m=1.68 are determined from a cross plot between formation factor and density porosity of water saturated sediments. Figure 5 shows the difference between the water saturated resistivity R_0 and the measured in situ resistivity R_t and we can see that R_0 is close enough with R_t for water saturated sediments.

On resistivity log, an anomalous increase in resistivity is found at 95 to 115 mbsf without any significant increase in P-wave velocity. Hence, the saturation estimated from the resistivity log at this depth interval cannot be attributed to gas hydrates. The maximum saturation derived from the resistivity method is ~12% at 146 mbsf.

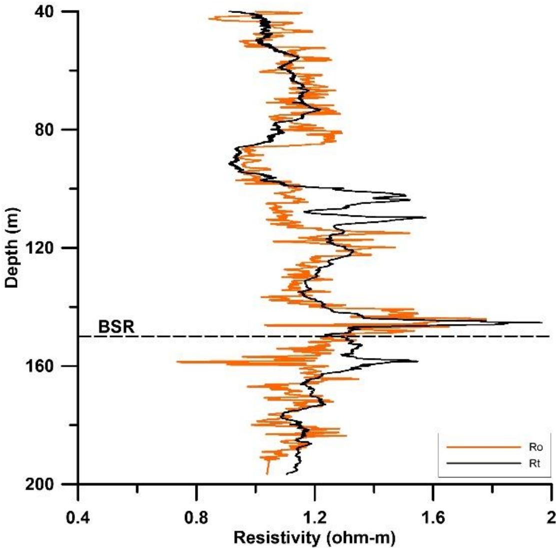

Figure 5: Measured LWD resistivity R_t and calculated water saturated resistivity R_0 determined from Archie's analysis.

The gas hydrate concentrations estimated using above two methods are shown in Figure 6.

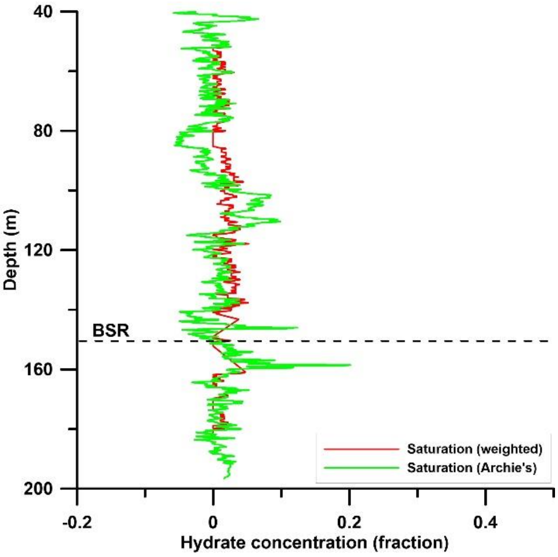

Figure 6: Concentration of gas hydrate estimated from velocity log (red) and resistivity log (green) at site NGHP-01-11A.

At a depth range of 144-147mbsf, the velocity values are not available in the LWD log data and hence cannot validate the amount of gas hydrates at this depth interval. The concentration of gas hydrates estimated from both the velocity and resistivity logs are close enough at the depth interval between 113 to 150 mbsf. However, the results from the velocity modeling show comparatively lower S_{hyd} values. Since, pressure core is not available within the entire depth of the well at this site, further validation is not possible. The overall maximum gas hydrates concentration at site NGHP-01-11A is found out to be within a range of 5% to 12%.

Conclusions

The model based acoustic impedance inversion constrained with well data at site NGHP-01-11A has been performed for the delineation of lateral extent of BSR along the 2D seismic line in the KG basin. The BSR has been identified as a clear boundary between the high impedance above and low impedance below and is confirmed by superposing the well logs on the impedance section. The gas hydrates have been estimated from both the P wave-velocity log using three phase weighted equation and the resistivity log using Archie's equation. The maximum amount of gas hydrates is found to be varying from ~5% to 12% in the sediment.

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