Comparison of gas hydrate saturation estimated from isotropic and anisotropic modeling in the Mahanadi basin

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Keywords

Gas hydrate, Mahanadi basin, well logs, rock physics modeling, anisotropy.

Summary

Presence of gas hydrate established in the Mahanadi Basin after coring and drilling under National Gas Hydrate Programs (NGHP) of India. Gas hydrate saturation estimated from the basin to know the reservoir potential and its characteristics. Three sites have been drilled during NGHP Expedition-01 in the Mahanadi Basin used to estimate gas hydrate saturation. Logging-while-drilling (LWD) down hole log data recorded at two sites and at one site wireline log data acquired. Rock physics modeling applied to log data for the estimation of gas hydrate saturation. Gas hydrate saturation estimated from sonic log data by rock physics modeling assumes gas hydrate in the pore spaces of sediments. However, when gas hydrate is formed in marine sediments, the bulk physical properties of host sediments get change due to anisotropy and hence alter the estimated gas hydrate saturation. The estimated gas hydrate saturation at an example site NGHP-01-08 assuming anisotropic media reduces by a factor of two compared to the saturation estimation by assuming isotropic media. Gas hydrate saturation estimated from isotropic P-wave model varies up to more than 16%. The saturation estimated from anisotropic p-wave model shows variation up to 8-10% of the pore spaces.

Introduction

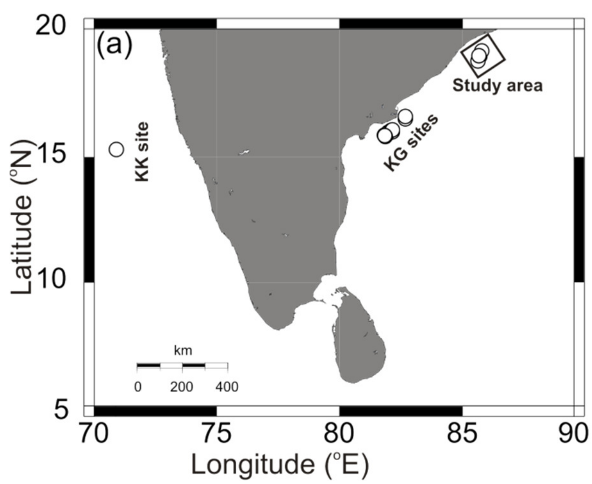
Gas hydrate is ice like crystalline solid substance, in which gas molecules (mainly methane) trapped by water molecules. Gas hydrate signatures has been identified from the analysis of high resolution multi-channel seismic (MCS) data (Mathur et al, 2008, Ramana et al., 2009, Prakash et al, 2010, Bastia et al., 2010a,b, Sain et al., 2012, Shankar and Riedel, 2014) in the Mahanadi basin and validated by drilling and coring (Collett et al., 2008).

The formation of gas hydrate in marine sediments usually changes the physical properties of the host sediment and creates anisotropy subsequently. In marine sediments, gas hydrate occurs in various morphologies such as: pore-filling, fracture-filling, small nodules, lenses and veins. In the simplest model, rising methane combines with the sediment pore fluid to form gas hydrate, partially replacing the pore fluid with little change to the sediment structure or volume. More complex models involve gas hydrate crystal growth by displacement of the ambient sediment, in case of veins, fracture-fill, small nodules, or lenses. The presence of gas hydrate in pore spaces of marine sediments can therefore significantly affect the bulk physical properties of the sediments. The gas hydrate-bearing sediments exhibit relatively higher seismic velocity than that of background (without gas hydrates). Seismic velocities are related to saturation of gas hydrates mostly through empirical porosity-velocity relationship based on effective porosity reduction model (Yuan et al., 1996), time-averaging approaches (Lee et al., 1993), and first-principles-based rock-physics modeling approaches (Dvorkin and Nur, 1993; Helgerud et al., 1999; Carcione and Tinivella, 2000).

The objective of this study is to predict the P-wave velocity for different amounts of gas hydrate saturation in the sediments using effective medium modeling approach and estimation of gas hydrate saturation from isotropic and anisotropic modeling at site NGHP-01-08. The site NGHP-01-08 is located at water depth of ~1689 m in the central part of the Mahanadi basin (Fig. 1). The Mahanadi basin was formed during rifting and break-up of the Gondwanaland during Jurassic period. The tectonics of the Mahanadi basin represents a rift zone trending to a NE-SW direction. The rift zone lies to the SE of the outcropping NW–SE-trending Gondwana Permian Triassic Mahanadi rift zone (Fuloria et al., 1992; Subrahmanyam et al. 2008). Its structural setting contains the NE–SW-striking Jurassic–Lower Cretaceous fault pattern that controls a system of depressions and highs.

Sediment thickness in the Mahanadi deep water basin is more than 8 km of upper Cretaceous to Recent age. The bulk of these sediments were supplied from the Ganga-Brahmaputra deltaic system during the Mio-Pliocene times. During the Early Paleogene, the basin experienced passive margin carbonate and finer clastic sedimentation, while during the Neogene, it received major fan sediments from the Ganga-Brahmaputra system (Bharali et al., 1991).

The Mahanadi basin has the favorable temperature and pressure conditions for the formation of gas hydrates. The basin is characterized by geothermal gradients of 35-45 ºC/km and high sedimentation rate. The total organic carbon (TOC) content is estimated to be more than 1.5% (Collett et al., 2008) that favors the formation of gas hydrates in the basin.



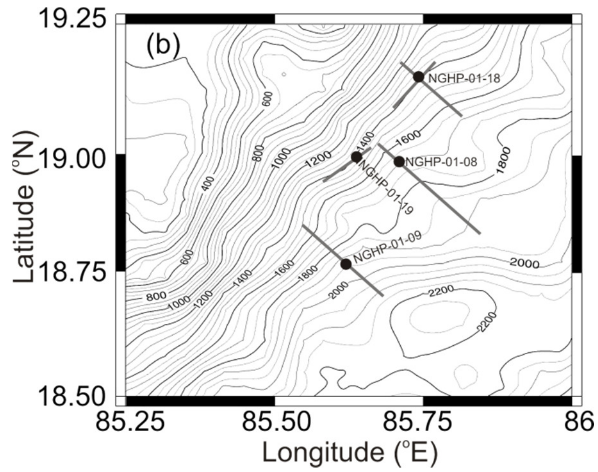


Figure 1: (a) Study area in the Mahanadi basin on the eastern margin of India. (b) Detail bathymetry of the basin with the location of drilling sites shown with black dots.

Method

For isotropic medium Helegrud's Model (1999) considers the effect of gas hydrate on sediment elastic moduli. The model requires knowledge of the porosity and the elastic moduli of the sediment grains pore water, and free gas. In modeling we considered hydrate as a component of the solid phase, modifying the elasticity of the frame. Background velocity is estimated using Dvorkin et al. (1999), which express the bulk and shear moduli of dry marine sediments. Effective saturated bulk modulus of sediment is calculated from the following relation given by (Dvorkin and Nur, 1998).

$$\frac{1}{K_{Sat}+\frac{4}{3}G_{Sat}}=\frac{S_W}{K_{SatW}+\frac{4}{3}G_{Sat}}+\frac{1-S_W}{K_{SatG}+\frac{4}{3}G_{Sat}}\ \ldots\ldots(1)$$

where, K_{SatW}, K_{SatG} are the bulk moduli of the sediment fully saturated with water and gas respectively and S_w is water saturation. These parameters are calculated using Gassmann's (1951) equation. Once the elastic wave parameters are known, the elastic waves are calculated as:

$$V_p=\frac{K_{Sat}+\frac{4}{3}G_{Sat}}{\rho_b}\ \ldots\ldots(2)$$

where, V_p is the background velocity and ρ_b is sediment bulk density.

Comparison of obtained velocity and background velocity estimates the saturation at each depth point. As, saturation values are iterated in background velocity computation, till measured and estimated velocity shows close correspondence. Thereby, saturation can be estimated at each depth point.

Here, anisotropy conditions are simulated by considering sedimentary unit to be composed of two distinct layers of fractures and host sediments (Lee and Collett, 2009). Each layer is considered to have physical properties of end members such that one of the end members correspond to gas hydrate filled anisotropic medium and other layer corresponds to host sediments saturated with water surrounding the anisotropic medium. Owing to different properties of two layers, different velocities are estimated corresponding to physical property of each layer. A sedimentary unit composed of two components is considered where first component has P-wave velocity (V_{P1}) and density (ρ_1), and the second component is characterized by P-wave velocity (V_{P2}) and density (ρ_2). The phase velocities of transverse isotropic media caused from anisotropy can be computed using the following equation (White, 1965).

$$A = \left\{\frac{4\mu(\lambda+\mu)}{(\lambda+2\mu)}\right\} + \left(\frac{1}{(\lambda+2\mu)}\right)^{-1}\left(\frac{\lambda}{(\lambda+2\mu)}\right)^{2} \quad (3)$$

$$C = \left(\frac{1}{(\lambda+2\mu)}\right)^{-1} \quad (4)$$

$$F = \left(\frac{1}{(\lambda+2\mu)}\right)^{-1}\left(\frac{\lambda}{(\lambda+2\mu)}\right) \quad (5)$$

$$L = \left(\frac{1}{(\mu)}\right)^{-1} \quad (6)$$

$$Q = \sqrt{[(A-L)\sin\theta^2-(C-L)\cos\theta^2]^2+4(F+L)^2\sin\theta^2\cos\theta^2} \quad (7)$$

$$V_p = \left(\frac{A\sin\theta^2+C\cos\theta^2+L+Q}{2\rho}\right)^{1/2} \quad (8)$$

where θ is the fracture angle, ρ is density and V_p is the background velocity.

Examples

Elastic properties of effective media containing various amounts of gas hydrate or free gas can then be calculated according to different assumptions concerning their formation mechanisms (Helgerud et al., 1999). Gas hydrate is modeled either as part of the pore fluid, or as part of the load-bearing sediment matrix. The gas hydrate in-pore model assumes that the gas hydrate occurs in the sediment pore space, without adding stiffness to the sediment frame. As a consequence, the sediment S-wave velocity is nearly unaffected by the occurrence of gas hydrate. For the gas hydrate in-frame model, elastic properties of the sediment frame are recalculated, with grains of gas hydrate included as part of the sediment frame. Under this mode of occurrence, gas hydrate adds some stiffness to the sediment frame, and the sediment S-wave velocity is slightly increased by gas hydrate but much less so than for a model in which gas hydrate cements the grain contacts (Dvorkin and Nur, 1993). Both the gas hydrate in-pore and in-frame models predict an increase in P-wave velocity with increased gas hydrate saturation (slightly more for the gas hydrate in-frame model).

A reference velocity-depth profile is calculated from the Helgerud (2001) rock-physics model to match the observations in the measured LWD/wireline velocity log at well site. Measured neutron porosity is used for site NGHP-01-08 in our calculation. Two porosity trends are adopted: one is the smoothed linear fit and the other a 3m running average porosity-depth profile. The average mineralogy is taken to be 90% clay and 10% quartz, with the elastic parameters of the sediment constituents summarized in Table 1. To estimate gas hydrate saturation, P-wave velocity versus depth profiles for various gas hydrate saturations are computed, using the gas hydrate in-frame model. These constant gas hydrate saturation profiles are plotted with measured P-wave velocity data to provide an estimate of gas hydrate saturation.

Figure 2 shows gas hydrate saturation estimates from P-wave velocity data at site NGHP-01-08 in the Mahanadi basin. The P-wave sonic velocity data at site NGHP-01-08 predicts gas hydrate saturation of maximum up to 16% (Fig. 2c). Anisotropic modeling at this site shows 8% gas hydrate saturation which is just half of the estimated saturation compared to isotropic modeling (Fig. 2c).

Material	Bulk Modulus (GPa)	Shear Modulus (Gpa)	Density (g/cm^3)	P (km/s)	S (km/s)
Clay	20.9	6.85	2.58	3.41	1.63
Quartz	36.6	45.0	2.65	6.04	4.12
Pore Water	2.4	0.0	1.03	1.5	0.0
Methane Hydrate	8.7	3.5	0.92	3.8	2.0
Methane gas	0.1245	0.0	0.25	0.71	0.0

Table 1: Elastic properties of sediment constituents (After Helgerud, 2001).

The main source of uncertainty in gas hydrate saturation estimates from the rock-physics modeling approach is related to the choice of the mineral assemblage used to build the model, and the elastic properties of those mineral components. Our choices for mineral constituents based on the sedimentological descriptions of the recovered core. The fact that our baseline of zero-percent gas hydrate follows closely the measured P-wave velocity in the intervals where no gas hydrate was encountered (especially when using a three meter running average porosity) increases our confidence in the derived gas hydrate concentration estimates from this technique.

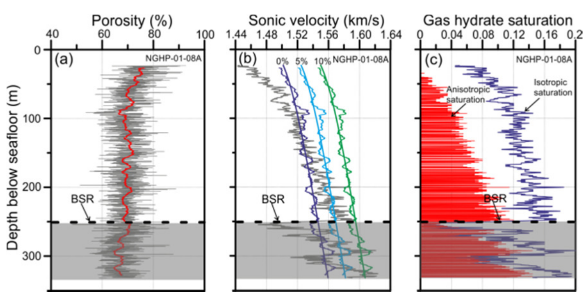


Figure 2: (a) Porosity versus depth LWD measurements at site NGHP-01-08A. Red bold curve shows the three meter running average. (b) P-wave velocity measurements from sonic log and predicted velocities for gas-hydrate-bearing sediments using the gas hydrate in-frame rock physics model for varying gas hydrate saturation. Straight lines are based on linear porosity trends, whereas a three meter running average was also used in the prediction to achieve high resolution. (c) Gas hydrate saturation estimated from isotropic and anisotropic modeling.

Conclusions

Gas hydrate saturations were estimated from P-wave velocity using an effective medium isotropic and anisotropic modeling approach, defining average mineral assemblages based on sedimentological core descriptions. Saturation obtained from anisotropic and isotropic model shows wide differences with anisotropic model providing results closer to pressure core measurements. It is evident that in presence of anisotropy, conventional models lead to over estimation of gas hydrates. Therefore, anisotropy needs to be incorporated to obtain appropriate gas hydrate saturation estimates.

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Acknowledgement

The authors wish to express sincere thanks to DGH and ONGC for the log data set which is used extended studies on gas hydrate in the Mahanadi basin.