Gas Hydrate Potential Along The Eastern Continental Margin of India

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Abstract

Bottom simulating reflector (BSR) is the main marker for the identification of gas hydrate in the subsurface sediments from seismic data. Based on BSRs mapped on the seismic sections, two national drilling, coring and logging programs were conducted in 2006 and 2015, respectively, which discovered a huge amount of gas hydrate along the Indian continental margin. The first Indian National Gas Hydrate Program Expedition 1 (NGHP-01) found gas hydrate as fracture-filled and pore-filled in fine-grained shallow sediments of Krishna-Godavari, Mahanadi and Andaman offshore basins. NGHP-02 was conducted in the deeper water parts of Krishna-Godavari and Mahanadi offshore basins to find gas hydrate deposits in the coarse-grained sediments. Well log and core data collected during the second expedition in 25 sites reveal a huge amount of gas hydrates distributed as pore-fill, fracture-fill and both pore- and fracture-fill (mixed) morphologies in sand and silt rich sediments. Rock physics modelling of sonic velocity and resistivity log shows that about 80-90% of the pore spaces are filled with gas hydrates at some depths, which are closely matching with available pressure core measurements. Lateral distributions of gas hydrate are delineated by integrating the well logs and seismic data. However, for the proper delineation and quantification of gas hydrate, characterisation of the reservoir is very important in terms of lithology, porosity, permeability, anisotropy and the morphology of gas hydrate distribution. Full waveform inversion of seismic data, advanced rock physics modelling and neural network technique, etc. are very useful for assessing the gas hydrate reservoirs. Based on certain assumptions, the estimated reserves in Indian offshore is about 1900 trillion cubic meters and 1% production can serve India's energy requirement for a few decades. However, the estimated reserves should be further refined incorporating more drilling and coring data.

Keywords: NGHP, Krishna-Godavari, Mahanadi, Andaman, Gas hydrate, Rock physics, Well log, Seismic.

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1. Introduction

Natural gas hydrates are solid, non-stoichiometric compounds of gas molecules (mainly methane) and water, formed under low temperature and high-pressure condition. Gas hydrates are found worldwide in shallow sediments of continental margins (where water depth exceeds 500 meters), beneath the permafrost, glaciers and some deep-water lakes (Sloan, 1998; Kastner et al., 1998; Kvenvolden, 1998). Solid gas hydrate holds a huge amount of energy in terms of gas; one-unit volume of gas hydrate can yield about 164-unit volume of methane gas at normal pressure and temperature. Below the gas hydrate stability zone, methane may be present as dissolved or free gas, but not as hydrate. Dissociation of hydrate releases methane (a greenhouse gas) into the atmosphere, which may cause global warming and reduce the sediment strength leading to the slope failure or seafloor instability (Sloan, 1998; Kvenvolden, 1998). Thus, Quantifications of natural gas hydrate and free-gas are essential in evaluating their resource potential and impacts on the environment. The rising demand for carbon emission-free alternate energy resources imposes research on the exploration and development of gas hydrate. Global reserves of gas trapped in gas hydrate are speculated to be 1-120 × 10^{15} m^3 (Ruppel and Kessler 2017; Makogon et al., 2007; Klauda and Sandler, 2005; Milkov, 2004; Ahlbrandt, 2002; Kvenvolden, 1998), however reliable estimates are yet to be made. This is almost 10 times of total reserves of conventional sources of natural gas (Ahlbrandt, 2002). Though, the volume of global gas that can be recovered technically is speculated to be ~$3\times10^{13}m^3$ (Boswell and Collett, 2011), which even is huge in a sense that only 15% of recovery can achieve the requirement of global energy for 200 years (Makogon et al., 2007).

Energy-craving countries like India are looking for an alternative energy source for their sustainable development. The Gas Authority of India Limited launched Gas hydrate exploration program in India in 1996 under the supervision of the Ministry of Petroleum & Natural Gas, Govt. of India. Later, The National Gas Hydrate Program (NGHP) was formulated under the Directorate General of Hydrocarbons (DGH), which engages industries like the Oil and Natural Gas Corporation (ONGC) Limited, Oil India Limited (OIL), Gas Authority of India Limited (GAIL), research institutes like the CSIR - National Geophysical Research Institute (CSIR-NGRI), CSIR - National Institute of Oceanography (CSIR-NIO), National Institute of Ocean Technology (NIOT) and various academic institutes. All these organizations belonging to different expertise initiated to work on geophysical, geological, geochemical and microbiological data to evaluate the resource potential of gas hydrates along the Indian shelf followed by the development of suitable technology for commercial production of gas from gas hydrates.

Geological conditions like seafloor temperature, geothermal gradient, bathymetry, sedimentation rate, the thickness of sediment, and total organic carbon (TOC) in sediments favour the formation of gas hydrate along the continental margins of India (Sain and Gupta, 2008). The presence of gas hydrate in sediments is generally mapped by identifying the BSR (bottom simulating reflector) in seismic sections or by direct evidence from drilling and coring. Analysis of acquired multichannel seismic (MCS) data shows prominent BSRs in the Mahanadi (MN), the Krishna-Godavari (KG) and the Andaman (AM) basins along the eastern continental margin of India. The drilling and coring programs during NGHP-01 and NGHP-02 confirm the presence of gas hydrate in the zones of Bay of Bengal, which was identified earlier from the surface seismic data. Studies on gas hydrate prospect forecast about 1900 trillion cubic meters of methane gas are being trapped in the form of gas-hydrates within the exclusive economic zone (EEZ) of India (Collett et al., 2008). Recovery of only 10% gas from the total gas hydrate reserve is equivalent to the energy demand of India for 100 years. This indeed is a very promising resource to overcome the ongoing energy crisis. However, to date, the exploitation of gas hydrate is not viable commercially worldwide due to lack of suitable technology. Identifying the potential zones of gas hydrate accumulation and quantification of the amount of gas hydrate from the acquired geophysical data are being carried out to aid the future production of gas hydrate. Figure 1 shows the drilling, coring and logging sites of two Indian National Gas Hydrate Programs along with the seismic data acquired by CSIR-NGRI for gas hydrate exploration (Collett et al., 2008, 2019; Sain et al., 2012). In 2006, NGHP-01 conducted drilling and coring off the continental margin of India, which identified gas hydrate predominantly as fracture-filled in clay-rich sediments along the eastern offshore (Collett et al., 2008; Ghosh et al., 2010a; Riedel et al., 2010). Total 39 wells were drilled at 21 sites and gas hydrate was identified at 13 sites (Collett et al., 2008). Logging data and infrared (IR) images of cores reveal the existence of massive gas hydrate deposits in the KG basin and a considerable amount of gas hydrate in the MN basin of the eastern Indian offshore. A lot of researches have been carried out to characterize and evaluate the gas hydrate reservoir using the data from the NGHP-01 expedition (Cook and Goldberg, 2008; Lee and Collett, 2009; Ghosh et al., 2010a; Ojha, 2012; Sain et al., 2012; Ojha and Sain, 2013; Wang et al., 2013; Sriram et al., 2014; Dewangan et al., 2014; Jaiswal et al., 2014; Ojha et al., 2016).

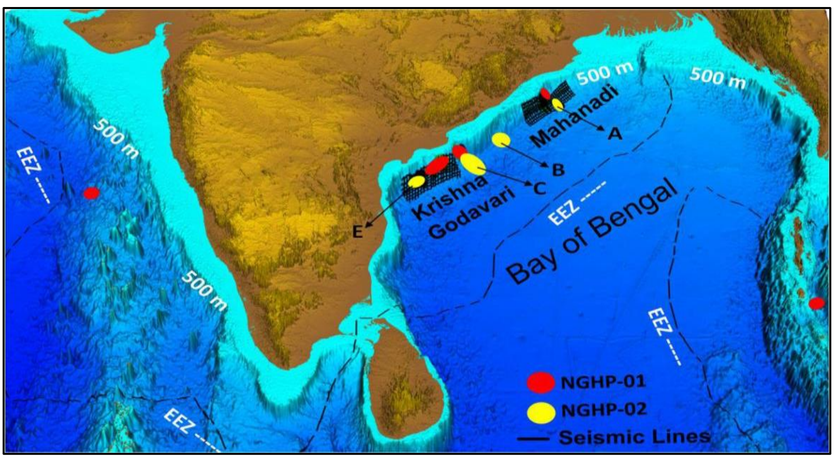

Figure 1. Location of drilling, coring and logging sites of Indian NGHP-01 and NGHP-02 expeditions along the eastern continental margin of India along with the 2D seismic data acquired by CSIR-NGRI (black grids).

During the expedition-02 in 2015, total 25 sites were drilled, cored and logged in Areas A, B, C, and E of the KG and Mn Basins to identify the zones of producible gas hydrate in coarse-grained sediments that can be accounted for pilot production test in future (Boswell et al., 2019; Collett et al., 2019; Holland et al., 2019; Hsiung et al., 2019; Saito et al., 2019). The amount of gas hydrate present in the sediments can be estimated from the acquired log data using rock physics theory, which can be further extended to the seismic data to know the lateral distribution of gas hydrate. Pure gas hydrate has a high sonic velocity of 3.7km/s compared to the water-saturated shallow marine sediment with a velocity of about 1.6-1.8 km/s and is electrically resistive. Therefore, the presence of gas hydrate elevates the seismic velocity and electrical resistivity of the host sediments, which can be translated in terms of the amount of gas hydrate present using the rock physics theory. Generally, gas hydrate saturation is overestimated by the resistivity log as the resistivity of clean water also increases nearby gas hydrate growth. Although estimation of gas hydrate from pressure cores are supposed to be ground truth, they are discrete. Therefore, the application of an advanced rock physics model, which accounts for the gas hydrate morphology and microstructure of sediment, is essential to estimate gas hydrate saturation continuously and accurately. A range of rock physics models (Gassmann, 1951; Lee and Collett, 2009; Dai et al., 2008; Dvorkin et al., 2003; Ecker et al., 1998; Helgerud et al., 1999; Jakobsen, 2000; Ghosh et al., 2010a, b) have been developed to interpret seismic velocity in terms of gas hydrate and free-gas concentrations. The research and development group of CSIR-NGRI, Hyderabad has been working for few decades on quantitative assessment of gas hydrate integrating seismic method or/and well log analysis with rock physics modelling in the continental margins of India and different parts of the world as well (Ojha and Ghosh 2021; Singh et al., 2020; Yadav et al., 2019; Jana et al., 2015. 2017, Ojha et al., 2010, 2016; Shankar and Riedel, 2014; Satyavani et al., 2013; Sain et al., 2012; Ghosh et al., 2010; Ojha 2012; Ojha and Sain, 2008, 2013; Subrahmanyam et al., 1998), Here, we present some recent works for evaluating gas hydrate potential and other related studies in the KG, MN and AM Basins. The thickness map of the gas hydrate stability zone along the Indian continental margin prepared by CSIR-NGRI (Sain et al., 2011) indicates the presence of a huge amount of gas hydrate (Figure2).

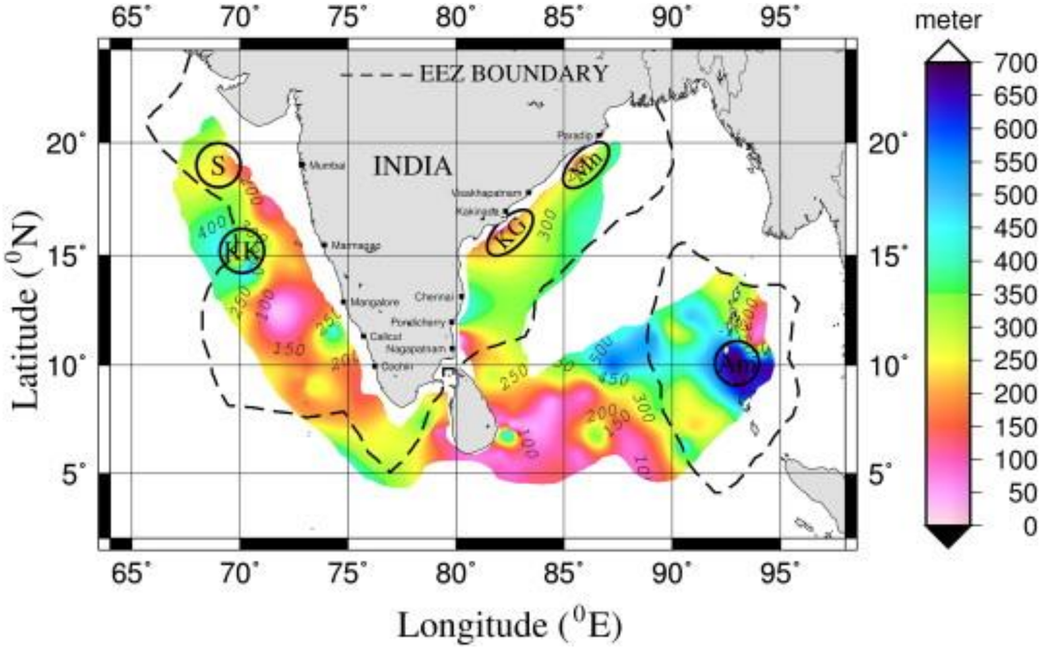

Figure 2. Probable gas hydrate thickness map along the Indian offshore prepared by CSIR-NGRI (Sain et al., 2011).

2. Gas hydrate potential in the Krishna-Godavari offshore Basin

Prominent BSR in the multi-channel seismic data, and well logs and core data from NGHP-01 have established that clay-rich marine sediment of the KG basin hosts one of the richest gas hydrate deposits in the world (Figure 3). Gas hydrate in clay-rich fine-grained sediment of the KG basin is distributed as disseminated, pore-filling, grain displacing as massive vein structures and the combined of both (Ghosh et al., 2010a). For the proper estimation of gas hydrate, an advanced rock physics theory like the combined self-consistent (SCA) and differential effective medium (DEM) theory is used to incorporate the fractures, anisotropy due to the orientation of clay platelets, ellipsoidal pores and the morphology of gas hydrate in the KG Basin. (Ghosh et al., 2010a, b). Figure 4 shows the predicted average gas hydrate saturations at NGHP-01-10 site for (i) pore filling, (ii) grain displacing, and (iii) a combination of grain displacing and pore-filling morphology are respectively 35–42%, 27–30%, and 33–41% of the total porosity within 60–140 m below the seafloor (mbsf). Gas hydrate saturation estimated from low-frequency seismic data assuming homogeneous and isotropic medium is often overestimated. Jana et al. (2015) have proposed a method to incorporate the heterogeneous microstructure of gas hydrate reservoir by generating a 2-D stochastic heterogeneous velocity and density fields using well log data (contains high frequency) in the KG Basin. These simulated fields comprise of all heterogeneities of the reservoir in the well log scale demonstrate that the predicted average gas hydrate saturation from seismic data is higher (~12%) than that attained from simulated 2-D heterogeneous velocity and density models (~9%) along a seismic line crossing the

NGHP-01-10 site (Figure 5). Similarly, the estimated gas hydrate saturation from the simulated 3-D heterogeneous resistivity and density model using corresponding logs and seismic data shows that the distribution of gas hydrate is rapidly decreasing away from the well NGHP-01-10 as shown in Figure 6 (Jana et al., 2017).

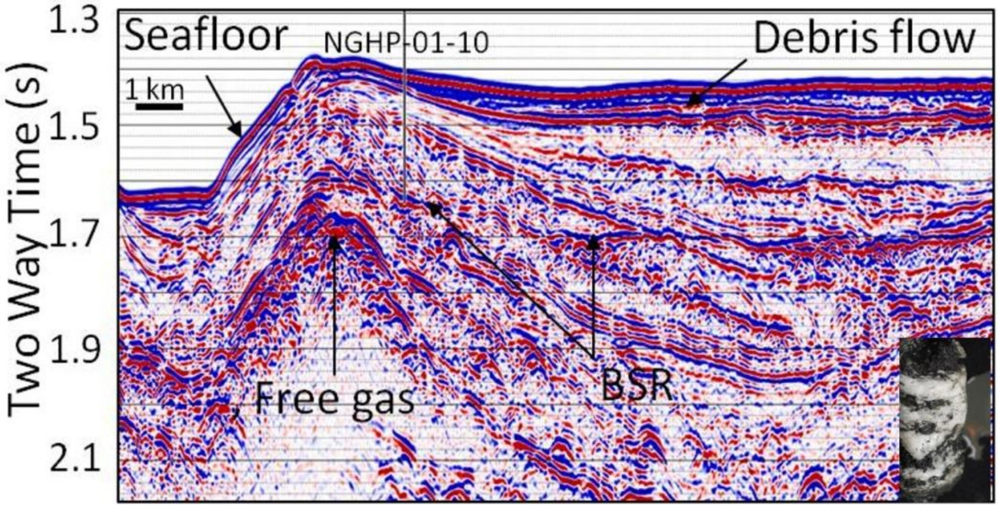

Figure 3. Multichannel seismic data shows the BSR and other features in the KG basin (Sain et al., 2012). The inset shows the massive gas hydrate samples recovered at well location NGHP-01-10.

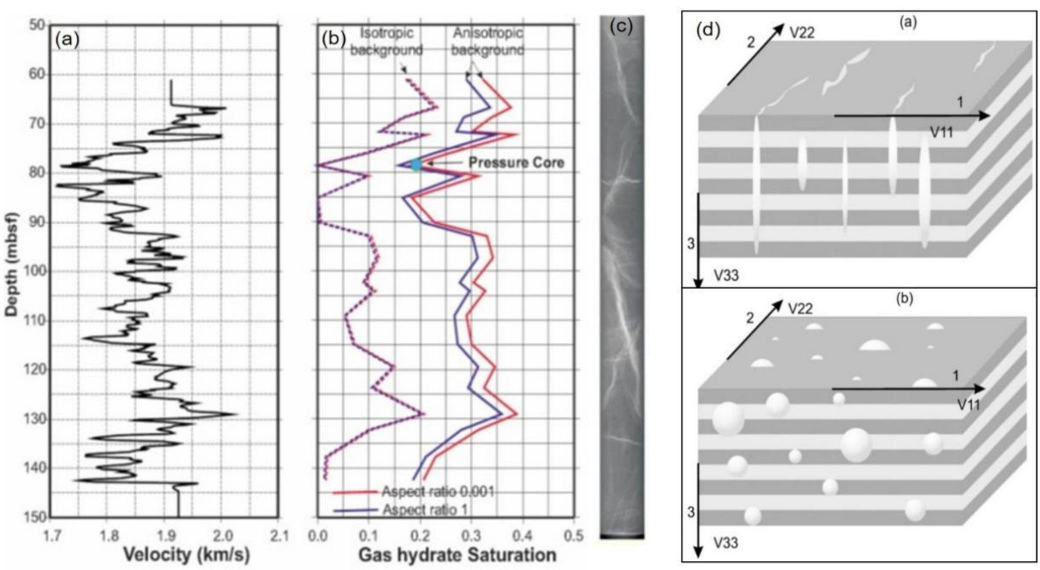

Figure 4. (a) Sonic velocity at NGHP-01-10D, (b) Estimated saturation of gas hydrates for isotropic and anisotropic background assuming fracture porosity of 5% with an

aspect ratio of fracture as 1 (blue curve) and 0.001 (red curve) respectively. The solid circle shows the estimation from the pressure core data, (c) X-ray image showing gas hydrate-infill near-vertical fractures and (d) Schematic diagrams of orthorhombic media caused by the vertical gas hydrate-filled fractures in a vertically transversely isotropic background. V11, V22 and V33 are compressional velocities along the three mutually perpendicular directions 1, 2, and 3, respectively. Fractures are considered as (a) ellipsoids (width = breadth, and width/length = aspect ratio) and (b) spheres (width = breadth = length), (Modified after Ghosh et al., 2010a).

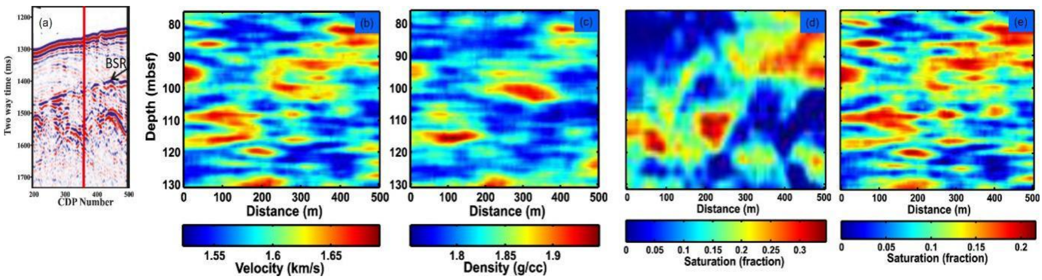

Figure 5. (a) Seismic section in KG Basin, (b) simulated *P*-wave velocity, (c) simulated density, (d) gas hydrate saturation estimated seismic impedance and (e) gas hydrate saturation estimated from 2-D simulated heterogeneous *P*-wave velocity and density models (modified after Jana et al., 2015).

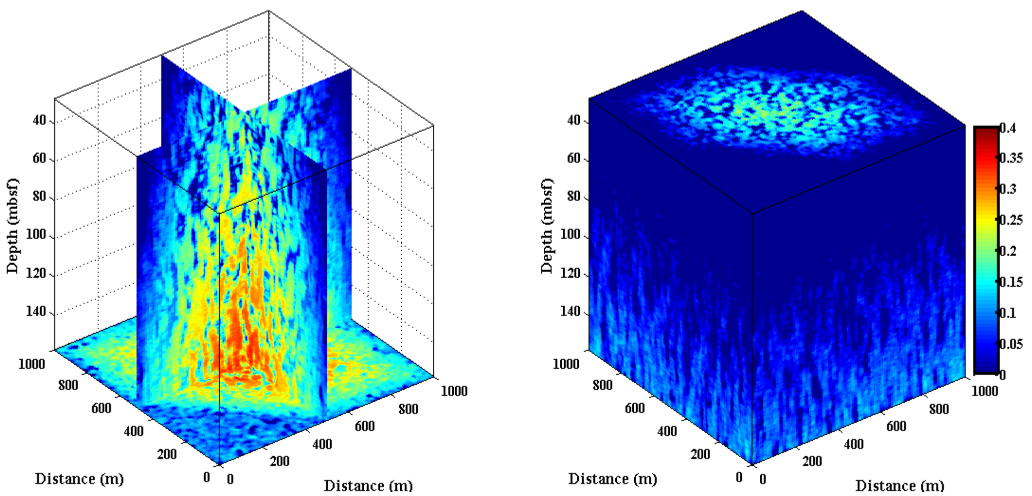

Figure 6. 3-D cross-sectional view of gas hydrate saturation calculated from simulated heterogeneous resistivity and density model using the resistivity log, density log and seismic data. A 3-D volumetric view (1000 m 1000 m x 131 m) of gas hydrate saturation model over gas hydrate-bearing zone around the borehole NGHP-01-10A (Jana et al., 2017).

Full waveform inversion is an advanced tool to invert seismic data to get details of the subsurface velocity structure, which is very useful for characterising gas hydrate reservoir as shown in Figure 7 (Ojha et al., 2016). Another very powerful tool in recent days is machine learning, which has been applied to find lithology using well log data and correlated nicely with seismic data (Figure 8).

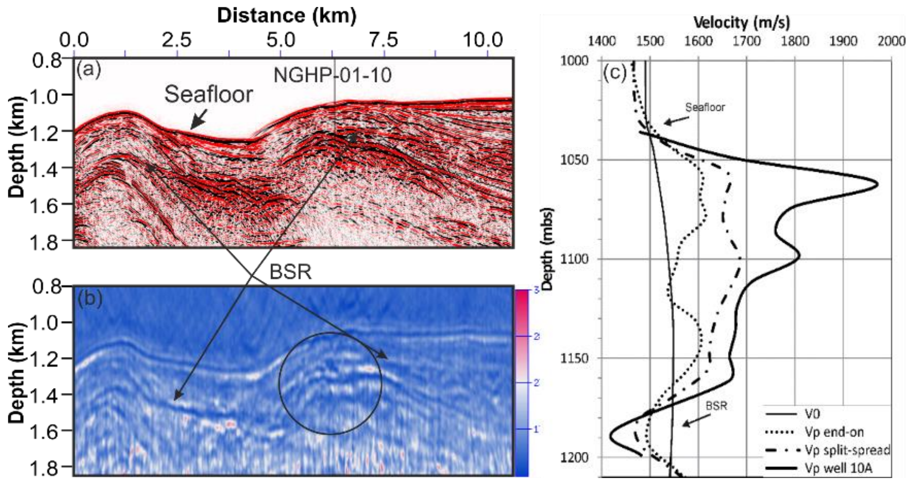

Figure 7. (a) Seismic section shows the BSR and seafloor in KG Basin, bottom, (b) inverted P-wave velocity using full waveform inversion in the frequency domain. The circle shows the resolved complex structures and (c) comparison of the results at well location NGHP-01-10 (modified after Ojha et al., 2016).

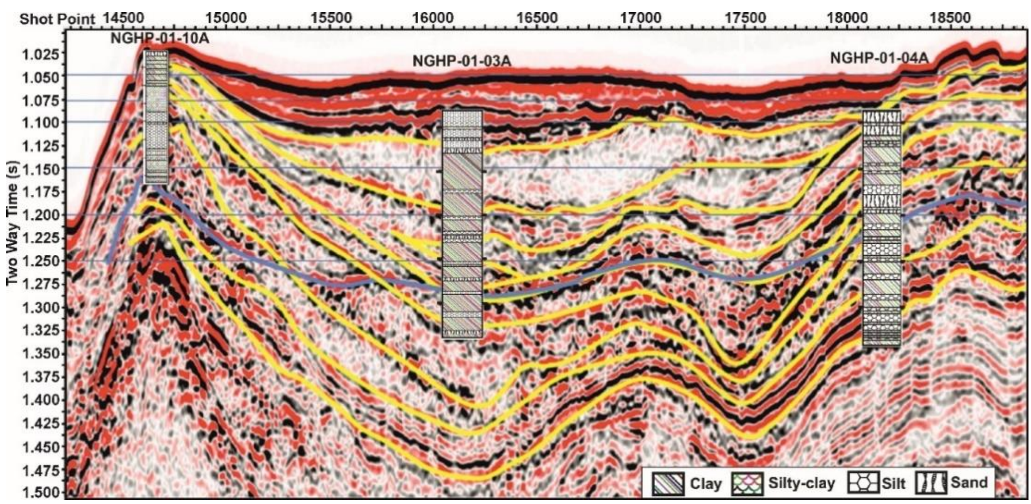

Figure 8. Predicted lithology with depth at three holes NGHP-01-10A, -03A and -04A are correlated various with lithology in the seismic section, where the BSR is marked with the dashed black line (Singh et al., 2020).

We show some works carried out in the Area-B of NGHP-02 Expedition, which was completely unexplored during the NGHP-01. Logging While Drilling (LWD) data were acquired at twelve sites in area B along Krishna Godavari (KG) offshore, where massive gas hydrate (up to 90% of the pore volume) are distributed as pore-fill, fracture-fill and mixed (both pore- and fracture-filled) morphology. The volume fraction of clay minerals is comparatively less in this deeper part of the KG basin than the shallow part explored during NGHP-01 Expedition. The mineralogy of layers varies from silty clay to clayey silt/sand to pure sand (100% quartz). Figure 9 shows that the rock physics modelling of the sonic and resistivity logs, and pressure core measurements suggest that the maximum gas hydrate concentration is about 85% of pore space at Sites NGHP-02-17, -19 and -22 (Yadav et al., 2019; Joshi et al. 2019; Pandey et al., 2019; Collett et al., 2019).

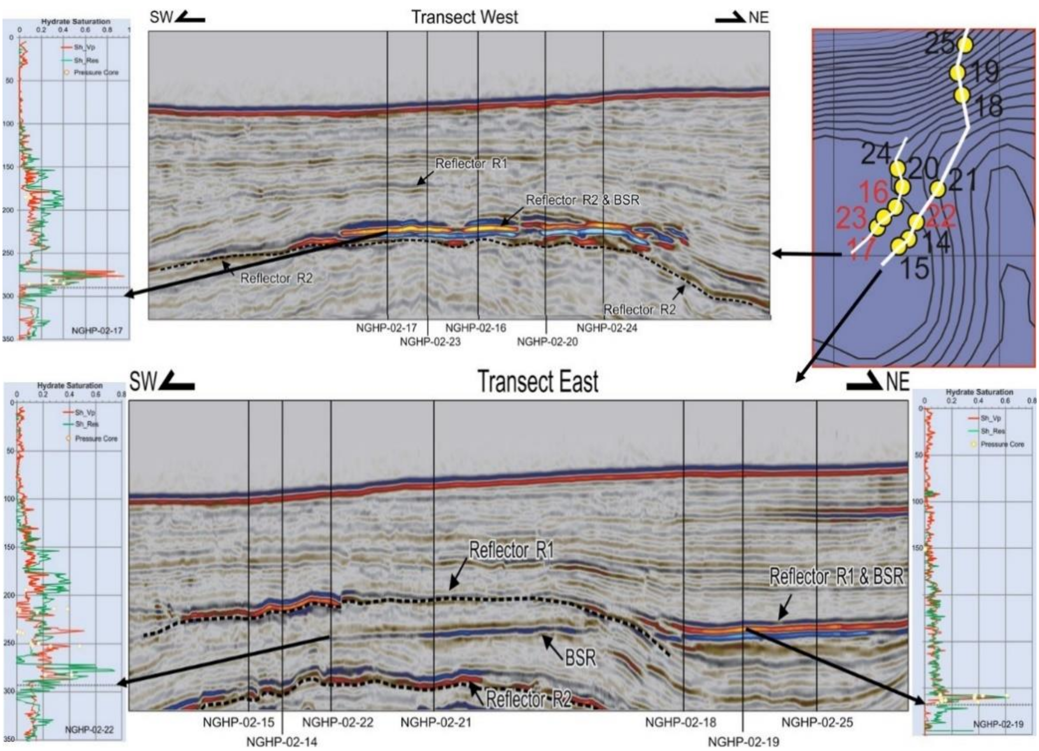

Figure 9. Gas hydrate saturations estimated Sites NGHP-02-17, -19 and -22 using sonic velocity (red curves), resistivity log (green curves) and pressure core data (yellow dots). Seismic sections show very strong BSR due to the interference between the BSR and another reflector termed as R1 (bottom) and R2 (top), (modified after Collett et al., 2019 and Yadav et al., 2019).

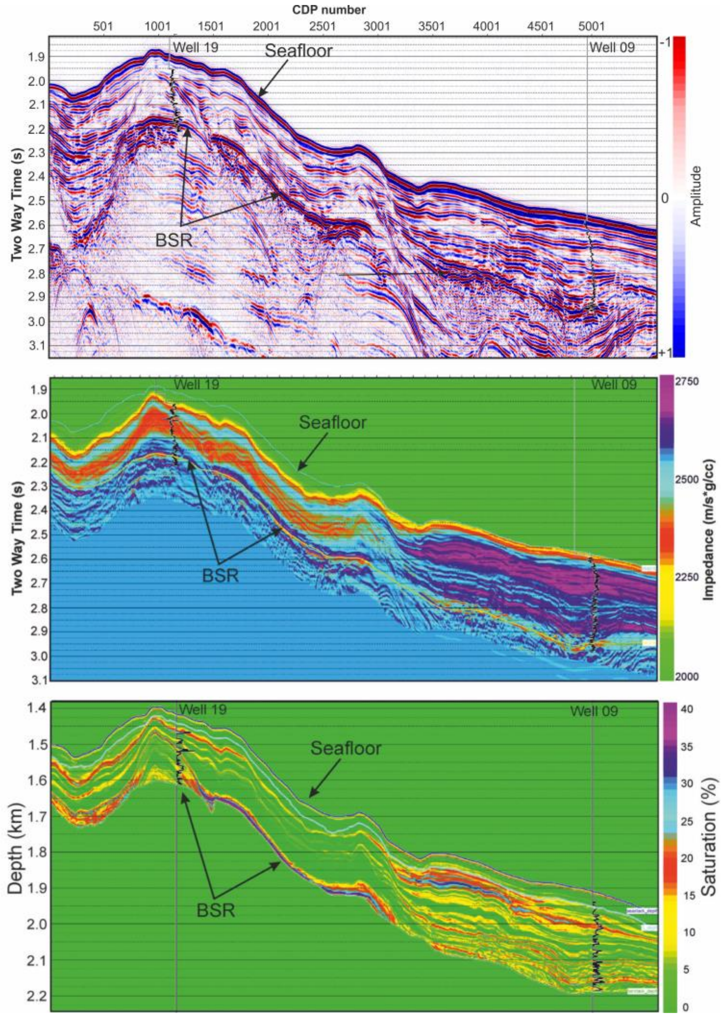

Figure 10: (top) Seismic data acquired by CSIR-NGRI shows strong and continuous BSR, (middle) acoustic impedance obtained using a model-based post-stack seismic inversion and (bottom) gas hydrate saturation obtained from the inverted impedance using rock physics modelling. Sonic logs at well NGHP-01-19B and -9A (black curves) are superimposed on the seismic and impedance section, where the saturation estimated using the sonic log is superimposed on the saturation section (modified after Ojha and Ghosh, 2021).

3. Gas hydrate potential in the Mahanadi offshore Basin

Compared to the KG Basin, very less work has been carried out at the MN Basin as wells drilled, cores and logged at this Basin show less amount of gas hydrate concentration in the pore space. Analysis of well logs, pressure core measurements and Infra-Red (IR) anomalies of the NGHP-01 expedition show that gas hydrate exists as disseminated within the fine-grained sediment, in contrast to the massive gas hydrate deposits in the KG basin. 2D multi-channel seismic data were also analysed for lateral extension of the gas hydrate distribution by identifying the BSR, the depth of which varies from ~200-300 mbsf depending on the depth of water in the MN Basin (Figure 11). Gas hydrate is mainly observed in the deep-water channel and the levee complexes as interpreted from the regional seismic data. Analysis of seismic data, sonic velocity and resistivity log shows that the maximum gas hydrate is about 30% of the pore space (Ojha and Ghosh 2021; Arun et al., 2020; Shankar and Riedel, 2014). Out of three sites, the sonic and resistivity logs collected at Hole NGHP-01-9A and -19B have been analysed by integrating the seismic data to characterise the reservoir (Figure 12).

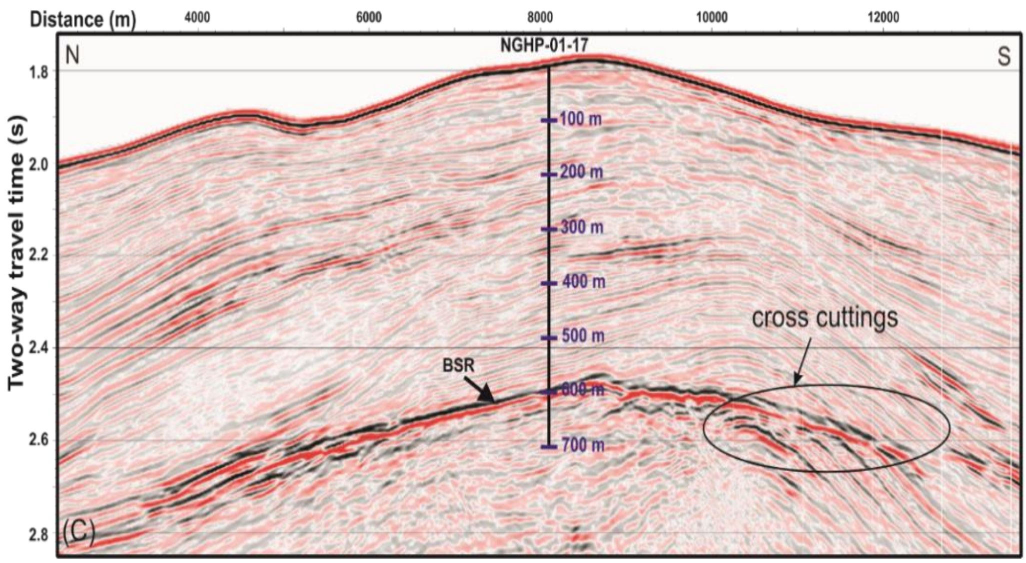

Figure 11. Seismic section showing one of the deepest BSR and very clear cross-cutting in the Andaman offshore Basin (Kumar et al., 2014).

4. Gas hydrate potential in the Andaman offshore Basin

One of the deepest BSR observed at 610 m depth in the seismic section (Kumar et al., 2014) was validated by drilling, coring and logging at one site below 1344 m water depth in the AM basin during the NGHP-01 expedition, where gas hydrate is found distributed in volcanic ash layer (Collett et al., 2008). Figure 12 shows, though the average gas hydrate saturation in the AM basin is only 5% of pore volume, the total amount of gas trapped in the form of gas hydrate within 308 m thick sedimentary column above the BSR is about 1570.8 cubic meter. Average free gas saturation is predicted as ~ 1.4% of the pore space within 80 m thick sediment column below the BSR (Ojha and Sain, 2013; Shankar and Riedel, 2013; Satyavani et al., 2008).

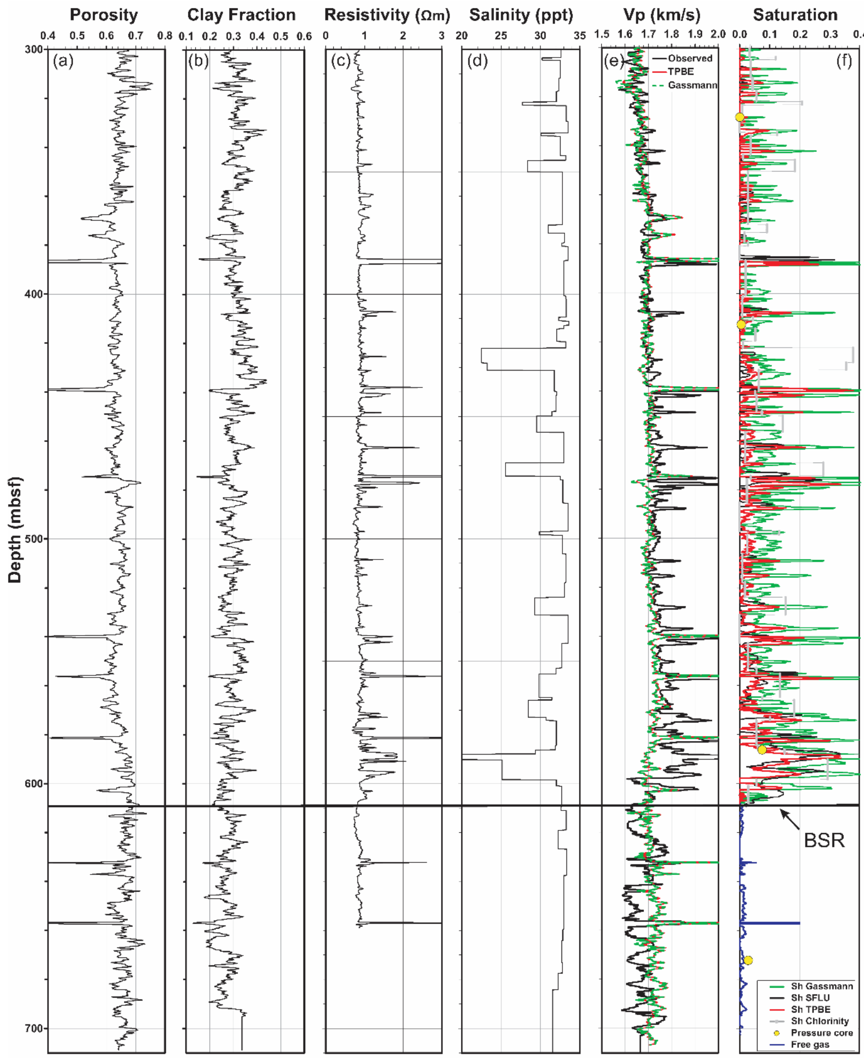

Figure 12. (a) Density porosity, (b) Clay fraction from the gamma-ray log, (c) SFLU resistivity, (d) Salinity of porewater, (e) sonic P-wave velocity (black line), the theoretical velocity of water-saturated sediments using the Biot (red line) and Gassmann's (dotted green) equation and (f) Hydrate saturation estimated using SFLU resistivity (black line), Biot equation (red line), Gassmann's equation (green), pressure cores (yellow dots) and free gas saturation using Gassmann's equation (blue line) at Site NGHP-01-17.

5. Exploitation scenario of gas hydrate

Gas hydrates are not stable like conventional hydrocarbons or minerals, as they dissociate at normal pressure and temperature (STP) conditions. Besides, gas hydrate exists in water depth more than 500 m and shallow soft sediments. Therefore, present technologies for hydrocarbon exploration are not suitable for the production or validation of gas hydrate. Drilling from a ship to recognize and evaluate the lateral extent of the resource is also very expensive.

We are hopeful about the initiative of NIOT, Chennai, India for researching the development of appropriate technology to address the issues of gas hydrate exploitation. However, methane gas trapped underneath the gas hydrate zone can probably be exploited economically in near future. Therefore, identification of spots having domes extending from below towards the seafloor, seafloor hills and dipping strata intersecting the seafloor are necessary to detect gas traps in hydrate-seals (Kvenvolden, 1998). To produce methane gas from gas hydrate three methods such as the (i) thermal stimulation, (ii) depressurization and (iii) inhibitor injection are proposed (Holder et al., 1984). However, none of the methods is economical with available technology. The application of any production method is dependent on the host rock, the morphology of gas hydrate and the geological/tectonic environment. Laboratory experiments on depressurization and/or thermal stimulation provide important information on gas production (Kwon et al., 2008; Yun et al., 2011). India participated in a consortium of onshore test production at Mackenzie delta in the Arctic region, where a small volume of methane gas has been produced from gas hydrates for few days (Dallimore and Collett, 2005; Hancock et al., 2005; Takahisa, 2005; Kurihara et al., 2008). The depressurization method among all other methods seems to be economically viable as it dissociates a substantial volume of gas hydrates relatively rapidly with less energy expenditure. Test drilling in marine sands of the Nankai Trough, Japan (http://www.mh21japan.gr. jp/english/; Tsuji et al., 2009) shows that the depressurization method is suitable in coarse-grained host sediments. Japan claims to be the first country to establish methane production from marine deep-water gas hydrate deposits after conducting more test productions through the national methane hydrates program (MH21) in near future. In case of India, oil and gas industries and R&D institutes with international collaboration may adopt production strategy as CO_2-sequestration, since a large number of coal plants (~90 GW total capacity) may provide an economic incentive for gas hydrate production as well as reducing greenhouse gas by developing Carbon Capture & Storage (CCS) technology.

6. Conclusion

Identification and delineation of gas hydrates from the seismic surveys have established that the KG, MN and AM regions in the Bay of Bengal are the most prospective zones of gas hydrate, which have been validated by two national drilling and coring programs, namely NGHP-01 and -02. Assessment of gas hydrate potential is essential to aid research in the safe commercial exploitation of gas from gas hydrate. Several approaches integrating seismic, well logging and rock physics modelling have been established indigenously for quantitative assessment of gas hydrate in the prospective zones of the Indian shelf. We cite examples of KG, MN and AM Basins in the Bay of Bengal, where we develop methods to quantify the amount of gas hydrate from the available data. We predict massive gas hydrate deposits in the KG basin (20-90% of pore space), moderate deposits (10-15% of pore space) in the shallow part of the MN basin and 5% of pore space in the thickest gas hydrate reservoir in the AM basin. Kerala-Konkan (KK) and Saurashtra basins in the Arabian Sea along the western margin of India are found by the surface geoscientific studies as the next targets for gas hydrate exploration. Numerous geophysical and geological attributes designate that the Cauvery basin in the eastern margin and the KK basin in the western margin of India are the potential gas hydrate-bearing zones. Initially, the existence of gas hydrate in the continental selves of India was inferred by identifying BSRs in the seismic sections, which were acquired for the conventional oil and gas explorations. Recently, CSIR-NGRI, Hyderabad, India has acquired seismic data with parameters required exclusively for gas hydrate exploration in the KG and MN basins, and a similar plan is going to be executed to acquire new data in the AM, KK and Cauvery basins. These data would certainly help in carrying out further investigations on gas hydrate identification, delineation and assessment to prescribe prospective sites for test production with a view of predicting commercial exploitation of gas from gas hydrates in the future. Systematic research on the development of production technology to tap gas from gas hydrate is of utmost priority. Since gas hydrate is a pack of enormous energy and India hosts a huge amount of marine gas hydrate, it could emerge as the most important energy resource in India if exploited commercially.

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7. References

Ahlbrandt, T. S., 2002. Future petroleum energy resources of the world. International Geological Review, 44, 1092–1104.

Arun, K. P., Sain, K. and Kumar, J, 2019. Application of constrained AVO inversion: 2-D modelling of gas hydrates and free gas in Mahanadi basin, India. JNGSE 78, 103287.

Boswell, R. and Collett, T. S., 2011. Current perspectives on gas hydrate resources. Energy Environmental Science 4, 1206–1215.

Boswell, R., Yoneda, J. and Waite, W. F., 2019. India National Gas Hydrate Program Expedition 02 summary of scientific results: evaluation of natural gas-hydrate-bearing pressure cores. Mar. Pet. Geol. 108, 143–153.

Collett, T. S., et al., 2008. NGHP Expedition 01, 2006. Initial Reports, Directorate General of Hydrocarbons, Noida and Ministry of Petroleum & Natural Gas, India.

Collett, T. S., et al., 2019. India National Gas Hydrate Program Expedition 02 summary of scientific results: gas hydrate systems along the eastern continental margin of India. Mar. Pet. Geol. 108, 39–142.

Cook, A. E. and Goldberg, D., 2008. Extent of gas hydrate filled fracture planes: Implication for in situ methanogenesis and resource potential, Geophys. Res. Lett. 35, L15302.

Dai, J., Snyder, F., Gillespie, D., Koesoemadinata, A. and Dutta, N., 2008. Exploration for gas hydrate in the deepwater, northern Gulf of Mexico: Part I. A seismic approach based on geologic model, inversion, and rock physics principles. Mar. Petro. Geol. 25, 830-844.

Dallimore, S. R. and Collett, T. S., 2005. Scientific results from the Mallik 2002 gas hydrate production research well program, Mackenzie delta, Northwest Territories, Canada. Geological Survey of Canada Bulletin 585, 36.

Dewangan, P., Mandal, R., Jaiswal, P., Ramprasad, T. and Sriram G., 2014. Estimation of seismic attenuation of gas hydrate bearing sediments from multi-channel seismic data: A case study from Krishna-Godavari offshore basin, J. Mar. Pet. Geol. 58, 356-367.

Dvorkin, J., Nur, A., Uden, R. and Taner, T., 2003. Rock physics of gas hydrate reservoirs. Leading Edge 22, 842-846.

Ecker, C., Dvorkin, J. and Nur, A., 1998. Sediments with gas hydrate: Internal structure from seismic AVO. Geophysics 63, 1659-1669.

Gassman, F., 1951. Elasticity of porous media: Uber der Elastizitat poroser Media. Vierteljahrsschrift der Naturforschenden Gesell-schaft 96, 1-23.

Ghosh, R., Sain, K. and Ojha, M., 2010. Effective medium modeling of gas hydrate-filled fractures using sonic log in the Krishna–Godavari basin, offshore eastern India. J. Geophys. Res. 115, B06101.

Ghosh, R., Sain, K. and Ojha, M., 2010. Estimating the amount of gas hydrate using effective medium theory: a case study in the Blake Ridge. Mar. Geophys. Res. 31, 29-37.

Hancock, S., Collett, T. S., Dallimore, S.R., Satoh, T., Huenges, E. and Henninges, J., 2005. Overview of thermal stimulation production test results for the Japex/JNOC/GSC Mallik 5L-38 Gas Hydrate Research Well. In: Dallimore, S. R., Collett, T. S. (Eds.), Scientific results from Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada. Geological Survey of Canada Bulletin, 585.

Helgerud, M., Dvorkin, J., Nur, A., Sakai, A. and Collett, T. S., 1999. Elastic wave velocity in marine sediments with gas hydrates: effective medium modelling. Geophys. Res. Lett. 26, 2021-2024.

Holder, G. D., Kamath, V. A. and Godbole, S. P., 1984. The potential of natural gas hydrates as an energy source. Annual Review of Energy 9, 427-445.

Holland, M. E., Schultheiss, P. J. and Roberts, J. A., 2019. Gas hydrate saturation and morphology from analysis of pressure cores acquired in the Bay of Bengal during expedition NGHP-02, offshore India. Mar. Pet. Geol. 108, 407–423.

Hsiung, K. H., Saito, S., Kanamatsu, T., Sanada, Y., Yamada, Y. and NGHP Expedition 02 JAMSTEC Science Team, 2019. Regional stratigraphic framework and gas hydrate occurrence offshore eastern India: core-log-seismic integration of National Gas Hydrate Program Expedition 02 (NGHP-02) Area-B drill sites. Mar. Pet. Geol.108, 206–215.

Jaiswal, P., AI-Bulushi, S. and Dewangan, P., 2014. Logging-while-drilling and wireline velocities: Site NGHP-01-10, Krishna-Godavari Basin, India. J. Mar. Petrol. Geol. 58, 331-338.

Jakobsen, M., Hudson, J. A., Minshull, T. A. and Singh, S. C., 2000. Elastic properties of hydrate-bearing sediments using effective medium theory, Geophys. Res. 105, 561–577.

Jana, S., Ojha, M. and Sain, K., 2015. Gas hydrate saturation from heterogeneous model constructed from well log in Krishna–Godavari Basin, Eastern Indian Offshore. Geophys. J. Int. 203, 184–194.

Jana, S., Ojha, M., Sain, K. and Srivastava, S., 2017. An approach to estimate gas hydrate saturation from 3-D heterogeneous resistivity model: A study from Krishna-Godavari basin, Eastern Indian offshore. Mar. Petrol. Geol. 79, 99-107.

Joshi, A. K., Sain, K. and Pandey, L., 2019. Gas hydrate saturation and reservoir characterization at sites NGHP-02-17 and NGHP-02-19, Krishna Godavari Basin, eastern margin of India. Mar. Pet. Geol. 108, 595-608.

Kastner, M., Kvenvolden, K. A. and Lorenson, T. D., 1998. Chemistry, isotopic composition and origin of a methane-hydrogen sulfide hydrate at the Cascadia subduction zone. Earth planet. Sci. Lett. 156, 173-183.

Klauda, J. B. Sandler, S. I., 2005. Global distribution of methane hydrate in ocean sediment. Energy & Fuels 19, 459–470.

Kumar, P., et al., 2014. Geologic implications of gas hydrates in the offshore of India: Krishna–Godavari Basin, Mahanadi Basin, Andaman Sea, Kerala–Konkan Basin. Mar. Petrol. Geol. 58, Part A, 29-98.

Kurihara, M., Funatsu, K., Ouchi, H., Masuda, Y., Yasuda, M., Yamamoto, K., Numasawa, M., Fujii, T., Narita, H., Dallimore, S. and Wright, F., 2008. Analysis of the JOGMEC/ NRCAN/Aurora Mallik gas hydrate production test through numerical simulation. Proc. 6th Int. Conf. Gas Hydrates, Vancouver.

Kvenvolden, K. A., 1998. Methane hydrate—A major reservoir of carbon in the shallow geosphere?. Chem. Geol. 71, 41–51.

Kwon, T. H., Cho, G. C. and Santamarina, J. C., 2008. Gas hydrate dissociation in sediments: pressure-temperature evolution. Geochemistry, Geophysics, Geosystems 9 (Q03019).

Lee, M. W. and Collett, T. S., 2009. Gas hydrate saturations estimated from fractured reservoir at site NGHP-01-10, Krishna-Godavari Basin, India. J. Geophys. Res. 114, 1–13 B07102.

Makogon, Y. F., Holditch, S. A. and Makogon, T. Y., 2007. Natural gas hydrates — a potential energy source for the 21st Century. JPSE 56, 14–31.

Milkov, A.V., 2004. Global estimates of hydrate-bound gas in marine sediments: how much is really out there? Earth Science Review 66, 183–197.

Ojha, M. and Ghosh, R., 2021. Assessment of gas hydrate using pre-stack 1 seismic inversion in Mahanadi Basin, offshore eastern India. Interpretation 9 (2), 1-42.

Ojha, M., 2012. Quantitative Assessment of Gas Hydrate from Seismic Data. Lambert Academic Publishing.

Ojha, M., and Sain, K., 2008. Appraisal of gas hydrate/free-gas from VP/VS ratio in the Makran accretionary prism. Mar. Pet. Geol. 25, 637–644.

Ojha, M., and Sain, K., 2013. Quantification of gas hydrate and free gas in the Andaman offshore from downhole data: Current Science 105, 512–516.

Ojha, M., Sain, K. and Minshull, T. A., 2010. Assessment of gas hydrate saturations in Makran accretionary prism using the offset dependence of seismic amplitudes: Geophysics 75, C1–C6.

Ojha, M., Sen, M. K. and Sain, K., 2016. Use of split spread configuration of marine multichannel seismic data in full waveform inversion, Krishna-Godavari basin, India. J. Seis. Expl 25, 359-373.

Pandey, L., Sain, K. and Joshi, A. K., 2019. Estimate of gas hydrate saturations in the Krishna-Godavari basin, eastern continental margin of India, results of expedition NGHP-02. Mar. Pet. Geol. 108, 581-594.

Riedel, M., Collett, T. S., Kumar, P., Sathe, A. V. and Cook, A., 2010. Seismic imaging of a fractured gas hydrate system in the Krishna–Godavari Basin offshore India. Mar. Pet. Geol. 27, 1476–1493.

Sain, K. and Gupta, H. K., 2008. Gas hydrates: Indian scenario. J. Geol. Soc. Ind. 72, 299–311.

Sain, K., Ojha, M., Satyavani, N., Ramadass, G. A., Ramprasad, T., Das, S. K. and Gupta, H. K., 2012. Gas-hydrates in Krishna-Godavari and Mahanadi basins: New data, J. Geol. Soc. Ind. 79(6), 553-556.

Sain, K., Rajesh, V., Satyavani, N. Subbarao, K. V. and Subrahmanyam, C., 2011. Gas-hydrate stability thickness map along the Indian continental margin. Mar. Petrol. Geol. 28 (10), 1779-1786.

Saito, S., Hsiung, K. H., Sanada, Y., Moe, K., Hamada, Y., Nakamura, Y., Wu, H. Y., Shinmoto, Y., Yamada, Y. and NGHP Expedition 02 JAMSTEC Science Team, 2019. Gas hydrate occurrence and distribution controlled by regional geological structure off eastern India: estimates from logging-while-drilling in Area-B, National Gas Hydrate Program Expedition 02 (NGHP-02). Mar. Pet. Geol. 108, 216–225.

Satyavani, N., Sen, M. K., Ojha, M. and Sain, K., 2013. Azimuthal anisotropy from OBS observations in Mahanadi offshore, India. Interpretation, 1, T187–T198.

Shankar, U. and Riedel, M., 2013. Heat flow and gas hydrate saturation estimates from Andaman Sea, India. Mar. Petrol. Geol. 43, 434-449.

Shankar, U., Riedel, M., 2014. Assessment of gas hydrate saturation in marine sediments from resistivity and compressional-wave velocity log measurements in the Mahanadi Basin, India. Mar. Petro. Geol. 58,265-277.

Singh, A., Ojha, M. and Sain, K., 2020. Predicting lithology using neural networks from downhole data of a gas hydrate reservoir in the Krishna–Godavari basin, eastern Indian offshore. Geophys. J. Int. 220, 1813–1837.

Sloan, E. D., 1998.Clathrate Hydrate of Natural Gases. Marcel Dekker, New York.

Sriram, G., Dewangan, P. and Ramprasad, T., 2014. Modified effective medium model for gas hydrate bearing, clay-dominated sediments in the Krishna–Godavari Basin. Mar. Pet. Geol. 58, 321-330.

Subrahmanyam, C., Reddi, S. I., Thakur, N. K., Rao, T. G. and Sain, K., 1998. Gas-hydrates-a synoptic view. Journal of the Geological Society of India 52 (5), 497-512.Satyavani, N., Sain, K., Lall, M. and Kumar, B. J. P., 2008. Seismic attribute study for gas hydrates in the Andaman Offshore India. Mar. Geophys. Res. 29 (3), 167-175.

Takahisa, I., 2005. Overview of production test results for the Mallik 2002 gas hydrate production research well program. J. Jpn. Inst. Energy 84, 106–111.

Tsuji, Y., et al., 2009. Methane-hydrate occurrence and distribution in the Eastern Nankai Trough, Japan: findings of the Tokai-oki to Kumano-nada methane-hydrate drilling program. In: Collett, T.S., Johnson, A., Knapp, C., Boswell, R. (Eds.), Natural Gas Hydrates — Energy Resource Potential and Associated Geologic Hazards: AAPG Memoir 89, 228–249.

Wang X., Sain, K., Satyavani, N., Wang, J., Ojha, M. and Wu, M. S., 2013. Gas hydrates saturation using geostatistical inversion in a fractured reservoir in the Krishna-Godavari basin, offshore eastern India. Mar. Pet. Geol., 45, 224-235.

Yadav, U. S., Shukla, K. M., Ojha, M, Kumar, P. and Shankar, U., 2019. Assessment of gas hydrate accumulations using velocities derived from vertical seismic profiles and acoustic log data in Krishna-Godavari Basin, India. Mar. Pet. Geol., 108, 551–56.

Yun, T. S., Lee, C., Lee, J. S., Bahk, J. J., Santamarina, J. C., 2011. A pressure core-based characterization of hydrate-bearing sediments in the Ulleung Basin, Sea of Japan (East Sea). J. Geophys. Res. 116, B02204.