Gas hydrate reservoir delineation and volumetric estimation in Krishna-Godavari Offshore: A case study

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Abstract

Gas hydrate will become targets for future potential energy resources along continental margins worldwide. Gas hydrates were found in nature at high pressure and lower temperature regime in continental margin and permafrost region. Gas hydrate bearing sediments reservoir has been discovered during NGHP R&D expedition in KG offshore. In this study, gas hydrate reservoir has been spatially delineated by seismic data and vertically by log data analysis. Seismic RMS amplitude and impedance values become high in gas hydrate zone due to high seismic velocity in gas hydrate bearing sediments compared to non-gas hydrate or free gas bearing zone. Sonic and resistivity values in log data are shows elevated values in gas hydrate zone with respect to non-hydrate bearing sediments. Spatial extension of gas hydrate bearing sediment is delineated by RMS amplitude attribute and impedance values. Gas hydrate bearing sediments thickness and saturation values are estimated by sonic and resistivity data. Three dimension reservoir porosity and gas hydrate saturation estimated by multi-attribute analysis of seismic and log derived values. Finally, an attempt made to estimate the volumetric resource of initial gas in-place in gas hydrate reservoir by Monte Carlo simulation in limited study area of lower reservoir.

Introduction

Global energy demand is continuing to be on the rise. India has recorded impressive rates of economic growth in recent years. A healthy rate of economic growth makes equal or more than the current rate of 8% per annum would require major provision of infrastructure and enhanced supply of energy. High economic growth would generate much higher demand for energy and this would present the country with a variety of choices in terms of supply possibilities. India’s energy demand is highly dependence on oil import. Import of oil is highly dependent of oil supply. Oil supply disruptions (emanating from external factors such as wars and political instability) is vulnerable to economy and adverse impacts of sudden oil price shocks. India needs to explore new source of alternate/ unconventional hydrocarbon to control the scarcity created by outer disturbance on energy supply by increasing the domestic production. Another major unconventional natural gas resource that has not yet been commercially exploited are natural gas hydrates (NGHs). Gas hydrate will be one of future option for country demand of energy when technology will upgrade with time.

General Geologic Setting of KG Basin

The Krishna-Godavari Basin is a proven petroliferous rift basin in middle part of eastern continental margin of India (ECMI). The KG offshore portion covers an area of at least 1,45,000 square km, however, onland portion of the basin covers an area of approximately 28,000 square km. The Krishna-Godavari Basin of ECMI was formed due to the breakup of India from the contiguous Australia-Antarctica in the Early Cretaceous, and subsequent dispersion of the continents in time and space. The main sediment input in the ECMI is dominated by the Ganges-Brahmaputra River system, which drains most from the Himalayas. The resulting sediment influx formed the Bengal Fan, the world’s largest sediment accumulation. Apart from that, additional and recent time sediment input in KG basin is from Krishna and Godavari Rivers. The shelf is very narrow at the mouth of river Krishna influencing sediment dispersal pattern over time. The Krishna delta is river dominated with more coarse grain (sand) sediments due to erosion of peninsular gneiss and Cuddapah basin, composed of metamorphic and meta sedimentary rocks of Archean and Proterozoic ages, respectively. However, Godavari River formed a Wave dominated delta over a wider shelf, draining the Deccan volcanics and Archean Eastern Ghats sediments with mixed clay and sand rich character. The huge sediment influx resulted in the development of growth fault activity in the shelf, capturing the shale load within the accommodation space created. Sedimentological analysis also reveals that the shallow sediments in the KG offshore are dominantly comprised of nanno fossil rich clays with occasional incursions of ~10-20 m thick foraminifera bearing clay zones and carbonate/pyrite bands with authigenic carbonates (Collett et al., 2008).

Host sediment of gas hydrate reservoirs in NGHP-02 area B are mainly composed of sand/ silt sediments deposited by turbidity channel (Nanda et al., 2019). Dome-shaped structure and its related synclinal structures defined by two folding systems has been observed based on seismic data analysis in the structural framework in large scale (Shukla et al., 2019; Saito et al., 2019). Gas hydrate bearing sediments in visual core consists predominantly of gray to dark olive-gray silty clay or clay and gray concaved fine sand lamination in clay. Lithofacies of the gas hydrate concentrated zone (GHCZ) is representing achromatic gray, thin sand lamination, high contents of mica (mostly biotite) both in clay and sand (Nanda et al., 2019) which gives high gamma value in LWD logs (Collett et al., 2019; Kumar et al., 2018). Study area is shown in figure 1.

Data base and methodology

This study emphasizes on the gas hydrate reservoir delineation based on 3D seismic data and logging while drilling (LWD) log data which are specially acquired for gas hydrate during NGHP R&D expedition 02 in KG offshore. Gas hydrate initially explored by mapping of bottom simulating reflectors in gas hydrate zone. Seismic velocity become high in gas hydrate zone. Sonic velocity in Gas hydrate bearing sediments becomes high due to solid nature of gas hydrate as compared to non-gas hydrate bearing sediments. Resistivity values are also high in gas hydrate bearing because gas hydrate formed by hydrogen bonding with pure water and act as an insulators. If gas hydrate saturation is very high then resistivity values becomes very high. We used modified Archie's equation to calculate gas hydrate saturation based on resistivity data.

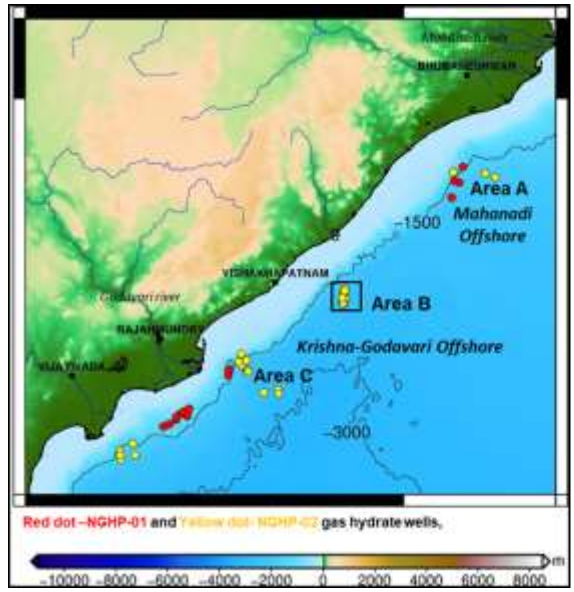

Figure 1: Study area location map shown by Black Square in Krishna-Godavari Offshore (Area B of NGHP-02).

The seismic inversion derived p-impedance was also used for multi attribute analysis for porosity and saturation estimation. In the multi-attribute regression analysis, a correlation between logs and seismic data is sought at the well location, and this correlation used to predict or estimate the volume of the log properties spatially across the seismic volume. Inversion data will also be used as an aid attribute for spreading data on a seismic map because impedance section across the reservoir successfully delineated water and hydrate bearing zone. This multi-attribute method can predict petrophysical parameters across the seismic line from the well data. The EMERGE module in Hampson Russell software package (Russell, 1998; Russell and Hampson, 1991; Hampson et al., 2005) is used for the multi-attribute regression method to predict reservoir porosity and gas hydrate saturation.

Gas-Initial-in-Place (GIIP) Estimate: At the exploration stage, it is important to develop systematic GH exploration methods that consider gas source, migration mechanisms into the hydrate stability field, zones of free gas, indicators of gas hydrate accumulation, and at least a first order volumetric gas-in-place estimate for zones of concentrated hydrates. We have adopted the volumetric gas-in-place estimation method used by the MH21 Research Consortium.

$$\mathbf{GIP = GRV * N/G * \Phi * GHSh * VR * CO}$$

whereby GIP represents the gas-in-place, GRV is the total rock volume extracted from our isopach maps of inferred zones of gas hydrate which is multiplication of area to thickness, N/G is the net to gross ratio, Φ is the porosity, GHSh is the gas hydrate saturation calculated from NGHP wells drilled for gas hydrate in eastern continental margin of India (the volumetric fraction of hydrates pore space occupancy), VR is the void ratio at standard temperature and pressure which value is 164, and CO is the hydrate cage occupancy which is defined as the ratio of hydrate cages occupied by a natural gas molecules to the total number of cages (Uchida et al., 1999).

The controls on GH occurrence and stability are affected by the geothermal gradient, sediment thermal conductivity, pore pressure, porosity, permeability, pore water salinity, the amount of total organic carbon (TOC), flux of natural gas from depth, in situ gas production, gas solubility with depth, ambient pore water gas saturation, pore water availability, host sediment grain size and mineralogy, effective stress, and potentially even the morphology of the hydrate itself. Thus, it is important to keep in mind that results may arrive at large estimation variations. Variations or uncertainty in input parameters are calculated by Monte Carlo. Monte Carlo simulation is a technique that helps to reduce the uncertainty involved in estimating outcomes. It can be applied to complex, non-linear models or used to evaluate the accuracy and performance of other models. It is a technique that converts uncertainties in input variables of a model into probability distributions. By combining the distributions and randomly selecting values from them, it recalculates the simulated model many times and brings out the probability of the output.

Results and Discussion

Gas hydrate reservoir in study area is located in geological anticline and syncline structures. Figure 2 is showing all the twelve gas hydrate wells drilled in study area along with a seismic reflector surface close to BSR and lower reservoir of gas hydrate. This clearly indicating the wells from A1 to A5 are located at the crest part of anticline, A6 to A9 at interface and A10 to A12 in syncline part. It indicates left side dome type anticline structure and right side the doubly plunged basinal syncline structure. BSR is a seismic reflector which mimics the sea floor in reverse polarity and cross cutting the geological structure. Bottom simulating reflector (BSRs) level mapped reflectors surface along with RMS amplitude attribute in 50 ms window is shown in figure 3. High RMS amplitude observed at the wells A1, A2, A3, A4 and A5. Low RMS amplitude is observed in wells A6 to A9. Moderate values of RMS amplitude were observed in wells A1 `0 to A12. Lead from these observations, two wells (one from anticline well A1 and another from syncline A11) gas hydrate facies and saturation has been estimated and shown in figure 4 and 5 respectively.

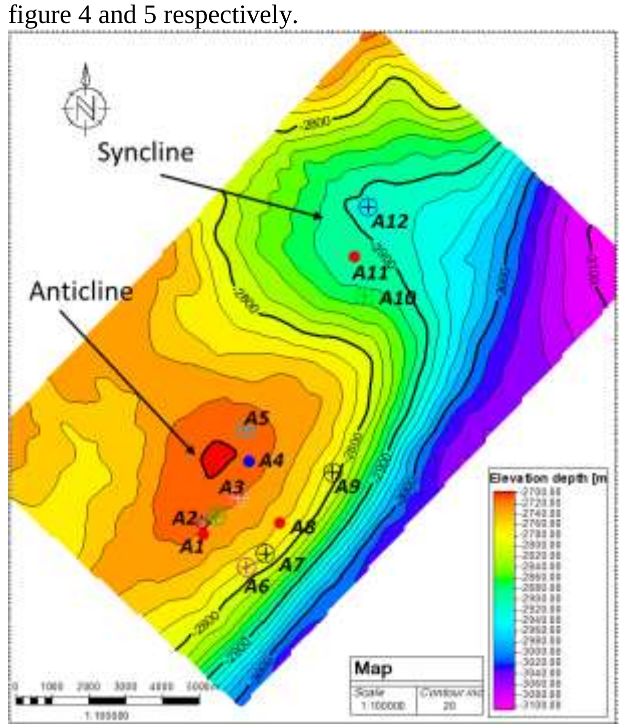

Figure 2: Surface map at seismic reflecor related to gas hydrate reservoir at Miocene level with gas hydrate wells.

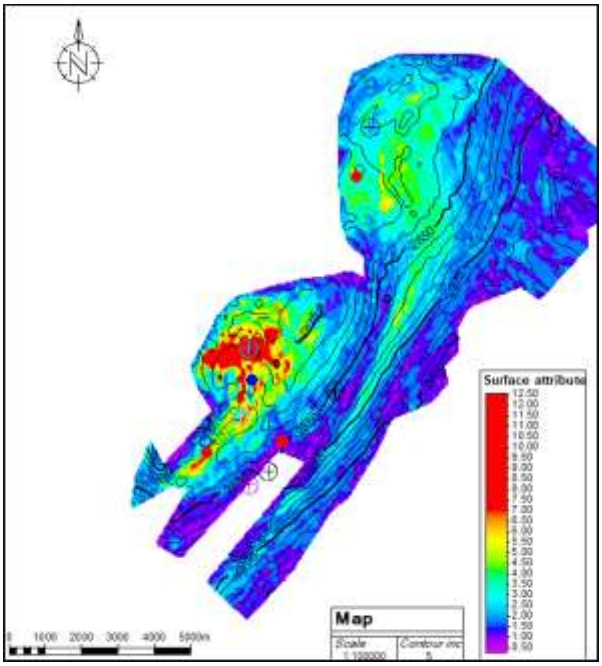

Figure.3. RMS amplitude in 50 ms window across the mapped BSR.

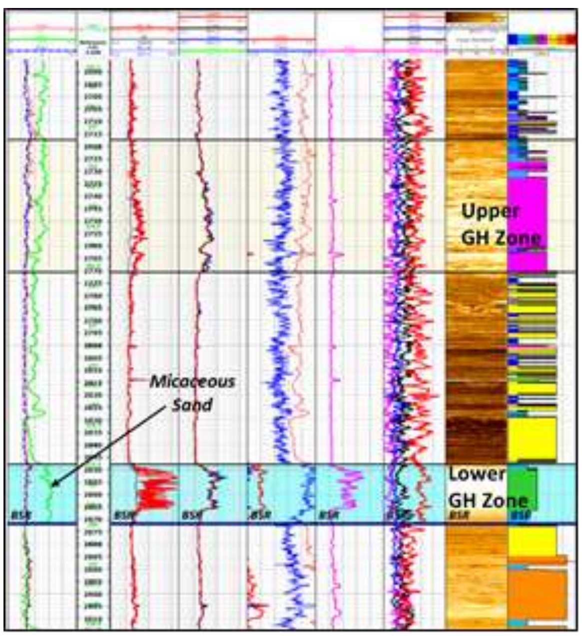

Figure 4: Facies model of gas hyrate wells A1 of anticline structure, and upper and lower gas hydrate zone has been demarcated for net gas hydrate zone calculation.

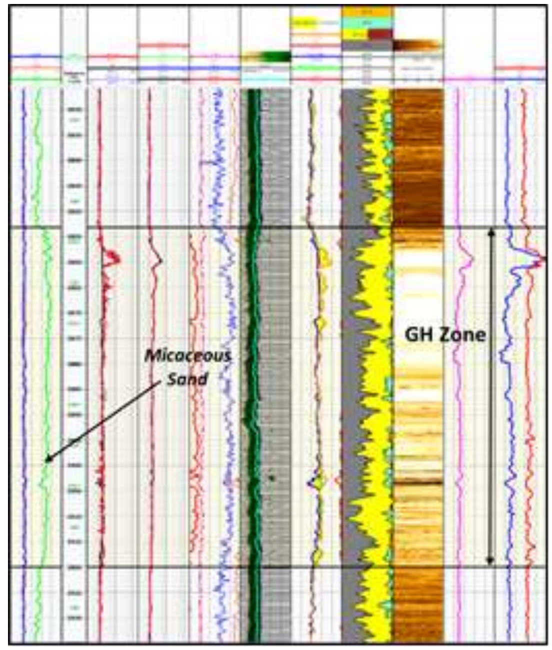

Figure 5: Facies model of gas hyrate wells A11 in syncline part and only upper gas hydrate zone has been observed for net gas hydrate zone calculation.

In well A1 at anticline showing the two gas hydrate upper and lower reservoirs as shown in figure 4. Upper gas hydrate reservoir is fractured with low saturation as compred to lower GH zone. Lower gas hydrate zone is highly saturated with pore filling gas hydrate morphology. In well A11 in syncline part showing only upper gas hydrate zone with higher thickness and low saturation. Lower gas hydrate zone of highly saturated gas hydrate reservoir is observed only limited area of anticline part as shown in figure 2. Five gas hydrate wells (A1-A5) falls in this anticline lower gas hydrate reservoir. Gas hydrate reservoir porosity and gas hydrate saturation estimated in this area and spatilly populated using seismic data (10 sqkm 3D seismic data) . Gas hydrate saturation is estimated by resistivity and sonic log data at these wells.

Based on the above study we have chosen the lower R2 gas hydrate reservoir for gas hydrate saturation and NMR porosity estimation. Lower pore filling gas hydrate reservoir formation is only available in 5 wells (from A1 to A5) at anticline structure and beyond this structure lower reservoirs deeps down below BSR. Therefore, five gas hydrate drilled wells (A1-A5) were considered for the saturation and porosity map generation. Modeled saturation through multi attribute regression analysis in red curve versus actual porosity in black curve along the 5 gas hydrate is shown in figure 6. Cross-plot of predicted saturation versus actual saturation shows the cross correlation of 81% (figure 7). Modeled vs actual porosity and saturation correlation more than 80% is considered to be good. Further, this process is applied to full seismic data. Porosity and saturation volume has been generated. Estimated saturation along eaterern and western transect is shown in figure 8 A&B. Gas hydrate saturation is high at the geological anticline structure of area B as compared syncline areas gas hydrate wells. Gas hydrate saturation is also predicted by multi attribute analysis throughout the seismic volume along gas hydrate. Predicted saturation profile along the wells A1 to A5 is shown in figure 9. Gas hydrate is absent in well A4 and thin layer of low saturation hydrate layer is observed in well A5. Similar pattern top and bottom layer of the gas hydrate reflectors were mapped and surface map generated. Saturation map has been generated and shown in figure 10. Similar pattern total neutron porosity maps has generated and shown in figure 11.

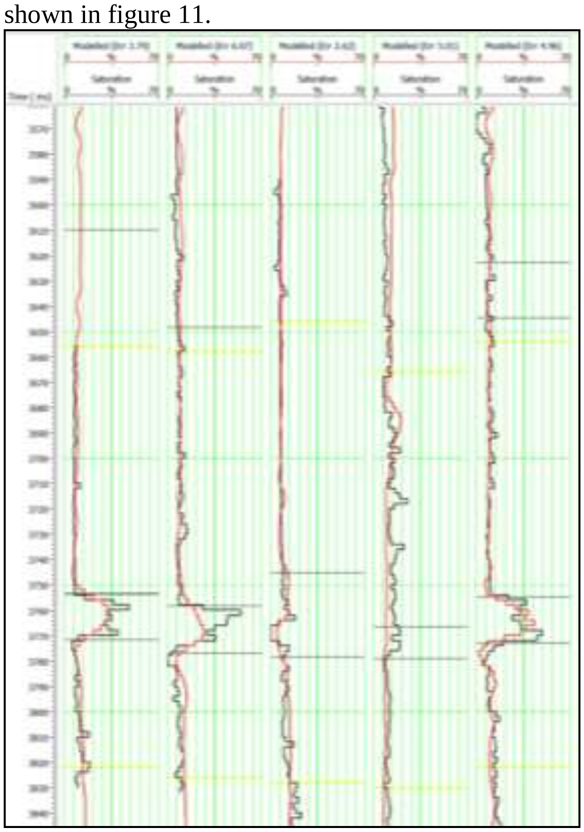

Figure 6. Actual and predicted gas hydrate saturation with depth at well locations (from left to right A1, A3, A4, A5 and A2) using multi-attribute analysis.

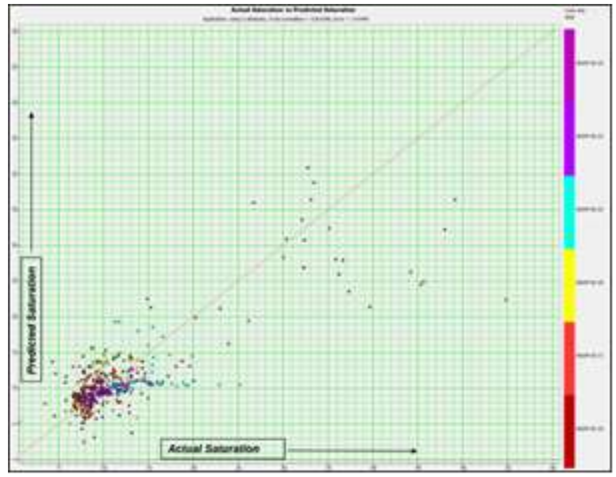

Figure 7. Cross-plot of actual versus predictedgas hydrate saturation at well locations using multi-attribute analysis.

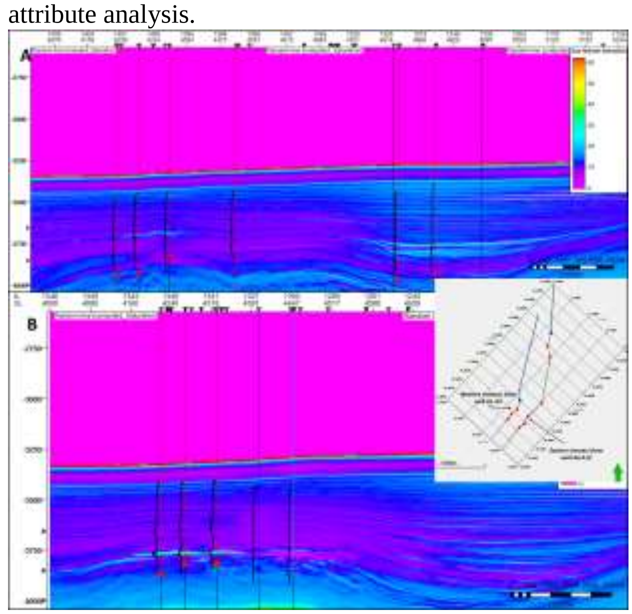

Figure 8: Inset map showing 3D seismic base map with eastern and western transect. Twelve wells consider for study. **(A)** Saturation profile along eastern transect from well A6 to A12 (from left to right). A12 wells resistivity data not projected. **(B)** Saturation profile along western transect from well A1 to A5 (from left to right). Black curve indicates the resistivity curve.

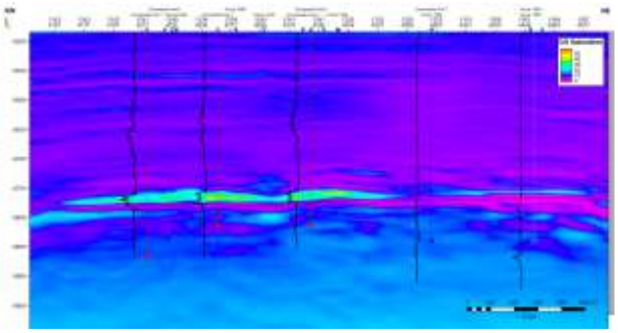

Figure 9: Saturation profile along western transect from well A1 to A5 (from left to right) at anticline in. Black curve indicates the resistivity curve.

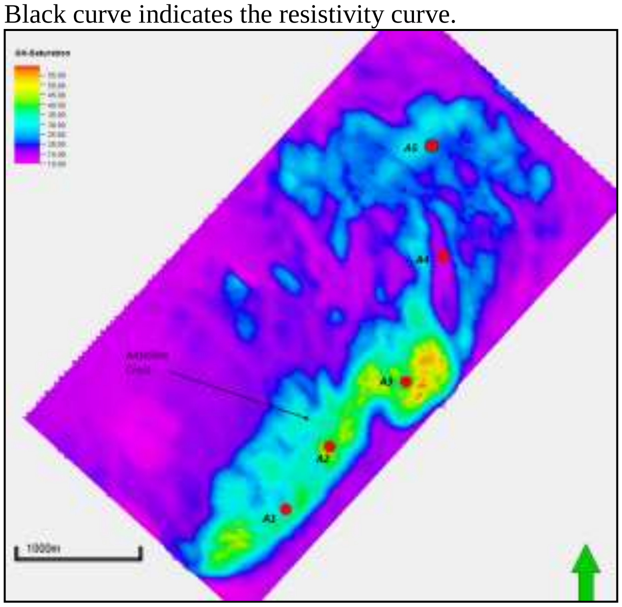

Figure 10: Saturation map estimated by multi-attribute regression analysis of seismic and log data of lower gas hydrate reservoir.

4.2. Volumetric Gas initial in-Place Estimate

This resource estimate provides a first-order gas-in-place estimate for the gas hydrate bearing sediemts. Assumptions of input parameters for Monte Carlo simulations explain the uncertainty in the inputs. Here we have selected a very limited area of 12 sqkm seismic data at the anticline structure. Five wells A1 to A5 falls in this area and. Gas hydrate saturation is very high estimated in wells A1, A2 and A3. However gas hydrate is very low and absent in well A5 and A4 respectively at the gas hydrate reservoir close to BSR at anticline geological structure. We have consider only 5 log data and within boundary of these area an attempt made to calculate the resource of gas in place in gas hydrate reservoir. Maximum area of gas hydrate is 8 sqkm and minimum area is 3 sqkm which is calculated from gas hydrate saturation

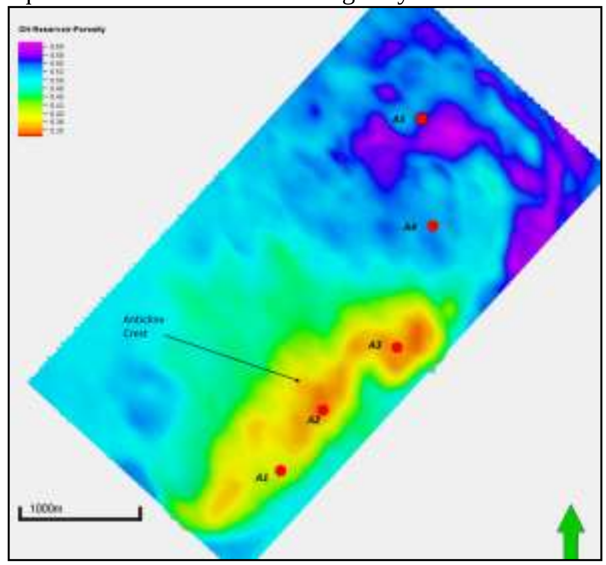

Figure 11: Gas hydrate reservoir formation porosity map estimated by multi-attribute regression analysis of seismic and log data of lower gas hydrate reservoir.

Parameters	Minimum	Most Likely	Maximum
Area (sqkm)	3	5	8
Thickness(m)	18	24	55
N/G	0.3	0.5	0.7
Porosity(%)	40	45	50
Saturation (%)	30	40	50
Cage occupancy	0.90	0.94	0.99

Table 1: Input parameters for initial gas in-place in gas hydrate reservoir by Monte Carlo simulation.

distribution map. Gas hydrate concentrated thickness ranges between 18 to 55 m as per the isopach map. Net-to-Gross (N/G) ratio depends on sand to clay ratio and values. The most commonly practiced methods is assigning a value of 0 for non-reservoir rocks and assigning a value of 1 to reservoir rocks. This is principally based on depositional facies model. So the big assumption here is the depositional facies/architectural elements in the model being directly related to pay. Net to gross (N/G) value may be considered from 0.3 to 0.7(values are based on the core and log data). The porosity and GHSh are based on NGHP sites measurements for a sand rich interval in east coast of India. Gas hydrate saturation values varies from 30 to 50 % in pore filling reservoir of gas hydrate. The preferred or most likely porosity value is 45% (appropriate for the unconsolidated shallow marine sediment) but NGHP data shows that it could range from 40–50%. GHSh value ranges from 30 to 50 % and likeliest value is 40%. The VR (164) also assumes a pore-filling hydrate model. CO is set at a mode of 0.94 based on observations from recovered natural gas hydrates collected in cores around the world but could range from 0.90–0.99. These values are derived from log data which were acquired during NGHP R&D expedition 02. Input parameters for resource estimation and Monte Carlo simulation run is shown in figure table.

The next step is to start the Monte Carlo simulation-a value from each distribution is randomly picked and resource is recalculated many times, each time using a different combination of values for the GHCZs thickness, porosity, CO and Gas Hydrate saturation. After 5,000 trial runs, 5,000 estimations of resource and summary statistics of the output were derived. Mean value is 97.259 BCF. P10, P50 and P90 value of the GIIP are 157.148, 89.723 and 46.894 BCF respectively methane is locked up in the GHCZs imaged in our seismic data and log data at anticline gas hydrate reservoir.

Conclusions

Gas hydrate reservoir porosity and saturation map have been generated based on multi-attribute regression analysis. High gas hydrate saturation are observed on the crest part of anticline structure. Gas hydrate saturation map has been estimated across the highly concentrated zone. Effective porosity volume is also generated of the gas hydrate lower reservoir. Low porosity value are observed in the gas hydrate reservoir as compared to water bearing sediment at same level. Low porosity in gas hydrate bearing sediments are observed due to solid nature of gas hydrate in pore spaces of the host reservoir. Predicted gas hydrate saturation map helps to better positioning of gas hydrate well for pilot production testing in future. Initial gas in-place in lower gas hydrate reservoir has been calculated by the Monte Carlo simulation. Mean value of placed initial gas resource in lower gas hydrate reservoir is 97.259 BCF.

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