Broadband Processing of Conventional 3D Seismic Survey for Better Reservoir Characterization of Gas Hydrate Deposits in KG Basin, India: A Case Study

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Keywords

Broadband, Gas Hydrate, KG Basin, BSR, AVO, PSDM

Summary

3D seismic survey acquired in KG deep water basin has been used for identification and mapping of Gas hydrate deposits and subsequently drilled under NGHP-2 successfully. Conventionally processed seismic data has limitations in reservoir descriptions far as thin bed resolution is concerned. In the present study, the legacy 3D seismic data in the study area was reprocessed in broadband sense by using state of art software for de-signature and de-ghosting (shot and receiver both). Broadband processed data are characterized by sharp and clean wavelets that deliver a significant increase in the frequency bandwidth. It provided significantly improved subsurface images, allowing much detailed interpretation. Broadband processed data has brought out small scale faults within reservoir and some faults are running up to seafloor clearly establishes the continuing melting of hydrates and escaping to the environments. AVO analysis of Pre-stack migrated seismic data demonstrates that bottom simulating reflector (BSR) is showing class III AVO anomaly. The BSR is working as top of the gas reservoir and might be so as solid hydrate and gas coexist near BSR. Horizon slice along BSR from AVO attribute volumes- Intercept, Gradient, Product (I*G) and Scaled Poisson's Ratio are showing spectacular images clearly depicting two disjoints accumulations of the gas hydrate with variable saturation. Anisotropic Pre-stack depth migration has also been carried out. The depth migration of the 3D data further enhanced the interpretability of the data and improved reservoir description. Deeper hydrate layer is observed for the first time on the PSDM section which was not observed in the PSTM data. The velocity model obtained after grid tomography (5 iterations) clearly show high velocity hydrate layer above BSR and patchy low velocity indicating free gas accumulations below the hydrate layer.

An attempt has also been made to estimate hydrate bound gas using resistivity log for hydrate saturation estimation. Accumulation-1 has shown very good reserve; ~2.8×10^{10} m^3 at STP which is equivalent to a conventional medium size gas field, though reservoir quality seems to be poor. However, accumulation-2 has shown smaller gas reserves due to poor saturation of hydrate, but reservoir quality seems better than those of accumulation-1.

Introduction

Gas hydrate exploration in India has gained momentum after coring the richest gas hydrate deposits of the World in deep waters of KG Basin in clay dominated reservoirs under NGHP-1 in 2006.(Collett et al.,2008). NGHP-1 has also established gas hydrate deposits in Andaman, and Mahanandi deep water basins. Seismic investigations for conventional hydrocarbon exploration in Andaman and Mahanadi deep water basin has proved wide spread accumulations of gas hydrates(Anand Prakash et al,2012) Further, NGHP-2 has confimed extensive accumulation of Gas hydrates in KG and Mahanadi deep waters in sand rich reservoirs (Collette et al., 2019). However, Mahanadi areas shows poor concentartion of hydarte possibly due to less gas supply from the source. Seismic data analysis has also estimated low saturation of gas hydrates in Mahanadi Basin(Anand Prakash et al.,2010)

3D Seismic data is the most powerful tool for identifying gas hydrate reservoir. The occurrence of highly-concentrated gas hydrate accumulations in sand-rich reservoir system significantly alters the physical properties of sediments, allowing these occurrences to be directly detected by conventional seismic data analysis and interpreation (Boswell et al.,2016). But conventional seismic data with limited bandwidth (10-60Hz) is detrimental to resolving thin reservoirs, and mapping of minor fault systems especially in hydrate reservoir which are less than 800 m below seafloor (MBSF). Recent advancement in seismic industry- Boradband Technology results in seismc data having frequency badwidth more than 4 octaves(4-120 Hz) would be very useful for hydrate reservoir description facilitating better understanding of petroleum systems of Gas hydrates.The lack of low freqencies in conventional seismic data put limimtaions to seismic inversion especially in areas of scanty well information (Michel L. et al.,2014) as well . Poor or no recovery of receiver and shot ghost notches in the frequency spectra of the conventionally processed seismic data limits its uses for thin reservoir description.

Methodology

The study area is located off the east coast of India in the Krishna Godavari(KG) Basin which is a typical passive margin basin characterized by multiple episodes of sea level change(Figure 1).The area has been covered by 3D seismic data for deeper hydrocarbon exploration. The seismic section shows high amplitude discontinuous BSR. Under NGHP-2, several wells were drilled and cores were taken in the area. Gas hydrates in sand rich reservoirs with varying grain sizes from coarse silt to gravel (Collette et al., 2019) were encountered in the wells. The conventional seismic data shows poor temporal resolution in the target zone and it is severely masked by ghost energy precluding any reservoir level information to be gleaned. Minor fault systems at reservoir level are not discernible.

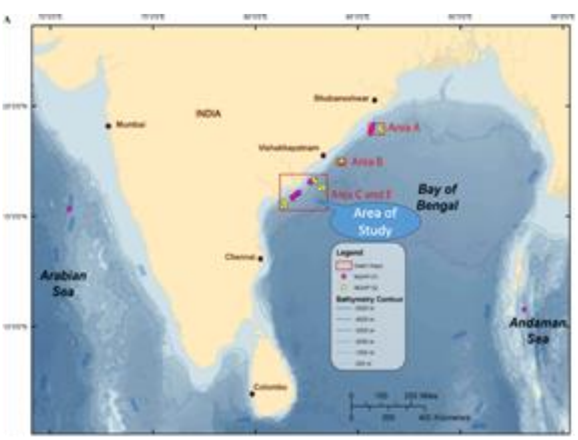

Figure 1. Area of Study falls within Area C and E. The area A, B ,C and E depicts investigation sites under NGHP-2 (Collette et at,2019)

In order to obtain high resolution seismic imaging and better reservoir description, the legacy 3D seismic data is reprocessed in broadband sense by de-ghosting process after de-signature (desired zero phase wavelet) and then Anisotropic KPSTM is done using RMS velocity and Eta fields . These fields were generated from target line PSTM in a grid 250x250m. Subsequently, 3D dataset is depth migrated (Anisotropic KPSDM) using interval velocity model derived after five iterations of grid tomography. The processing flow is shown in figure-2.

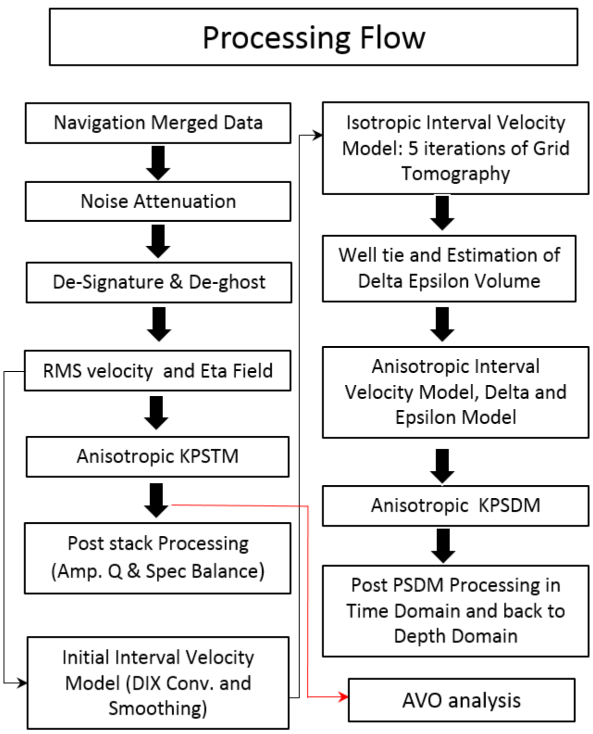

Figure 2. Processing flow used for Broadband processing and Depth Migration

An attempt is also made to carry out AVO study of broadband processed PSTM gathers. Various AVO attributes- Intercept (I), Gradient (G), Product (P*G) and scaled Poisson Ratio volumes are generated to characterize the hydrate layer in the area. We also generated horizon slices from AVO attribute volumes along BSR to study the hydrate saturation variation.

Results and Discussion

Broadband processing of conventional seismic data mainly differs in de-ghosting processing and its effects on frequency spectra at the lower and higher ends. The recovery of lower frequency (4-10Hz) is beneficial for inversion of seismic data and fault plane imaging and higher frequencies beyond shot ghost notch is beneficial in resolving thin reservoir and better minor faults imaging (E. Kneller et al.,2013, L. Michel et al, 2014, Simon Baldock et al ,2013).

In the study area, the conventionally processed data shows very high amplitude continuous BSR but it is masked by ghost energy and thereby minor faults and thin reservoirs are not seen properly, although based on this data several wells were drilled successfully to confirm hydrate accumulations in the area (Shukla, et al., 2018). The de-ghost processing has shown improved temporal resolution and frequency bandwidth extension by removing frequency notches corresponding to the shot/receiver as well as improving lower frequency band (3-12Hz). Figure-3 demonstrate the effectiveness of de-ghost processing. Final broadband processed data are much superior to the conventional processed data (Figure 4) showing vertical fault systems and thin hydrate reservoir. Due to tuning effect of thin beds and ghost effect, the BSR looks continuous, high amplitude and masking the fault system (encircled in figure-4) in the conventionally processed data.

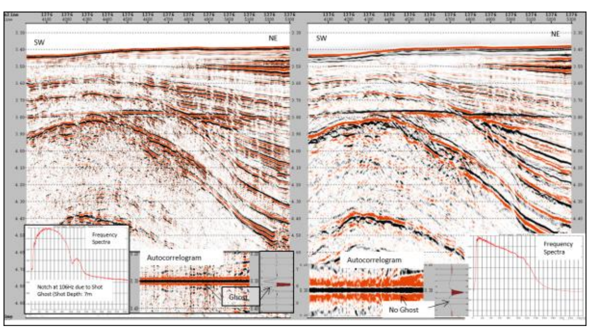

Figure 3. Seismic section before (a) and after de-ghost process (b) .Frequency Spectra and Autocorrelogram before and after De-ghost process are also seen in the inset

The broadband data clearly eliminated those effects and produced superior image for hydrate reservoir description. The RMS amplitude of BSR is extracted and the map is shown in figure-5, it depicts two separate hydrate accumulations in the study area. Minor faults at the reservoir level are observed clearly.

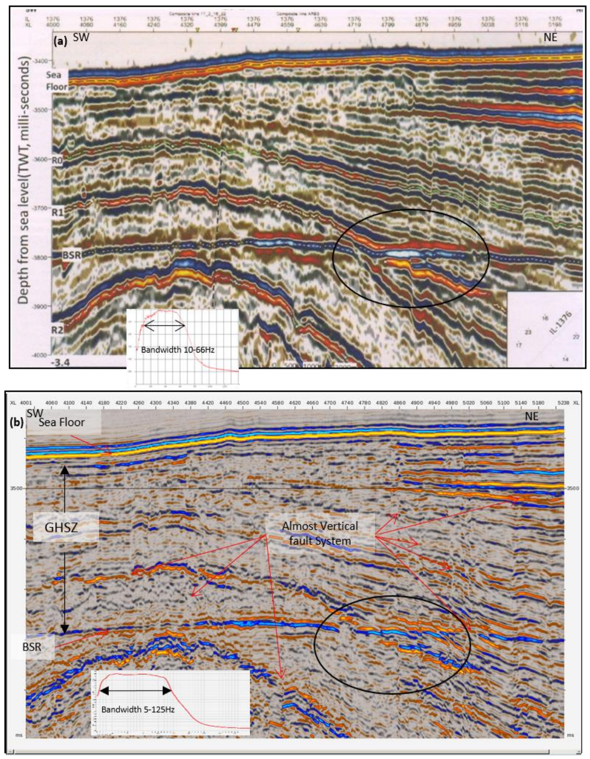

Figure 4. Conventional processed section (a) (from Shukla et al., 2018) has limited resolution, whereas the broadband processed section (b) clearly depicts vertical fault system and thin reservoirs. Minor faults in the reservoir zone are also seen clearly in the broadband processed section.

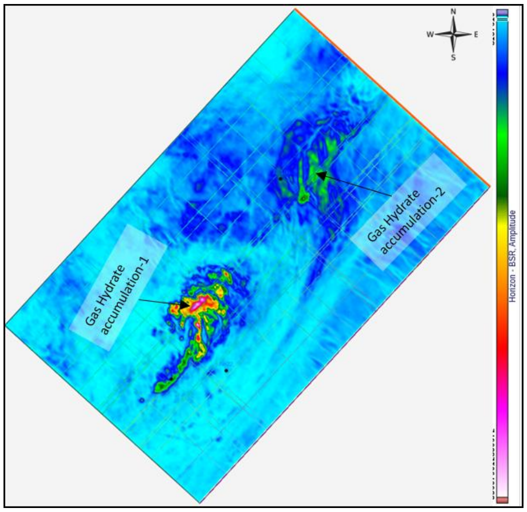

Figure 5. RMS amplitude map along BSR indicates two separate gas hydrate pools in the area and the amplitude variation indicates the varying concentration of gas hydrate.

AVO analysis

AVO analysis of PSTM gathers at various locations (Figure-6a) shows that amplitude of BSR increase with offset though the increase in amplitude is of varying degrees. Free gas and hydrate coexist around BSR therefore BSR may be working as a top of gas reservoir, hence it depicts classical AVO anomaly. Figure- 6b shows a sample common image gather and AVO curve of BSR and a reflector below it. Three term AVO curves of BSR shows classical AVO anomaly of class III (Rutherford, et at., 1976). Similar results were also reported in Gas hydrate accumulations in Mahanadi and Andaman deep water basins by Anand Prakash et al.2010, 2012, 2017 .

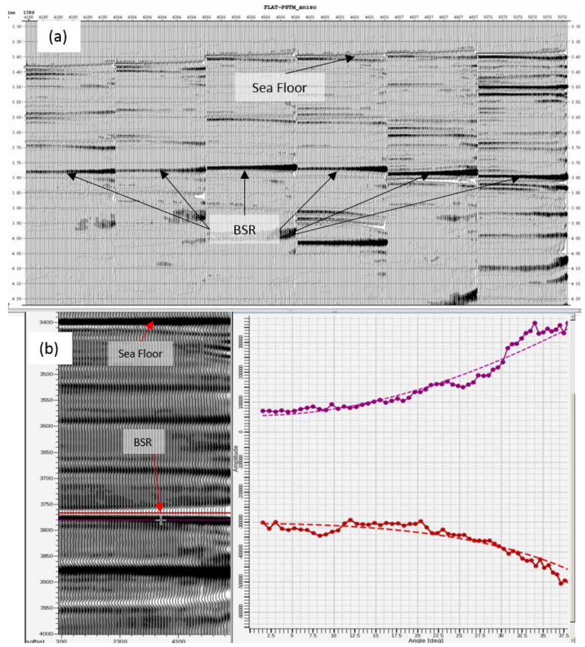

Figure 6. AVO Feasibility Study; (a) CIGs at various locations showing BSR amplitude increase with offset of varying degrees indicating variable concentration of Gas hydrates;(BSR is showing positive amplitude whereas Seafloor is showing negative amplitude)
(b) The AVO Curve of BSR is showing classical class III AVO anomaly; SEG positive convention followed)

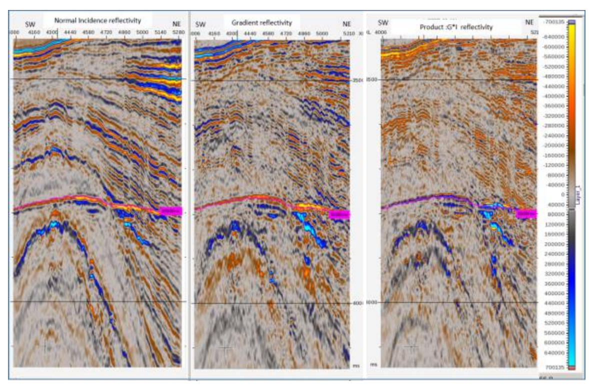

Figure 7. AVO attribute sections- Intercept, Gradient and Product (G*I) depict negative values for intercept and gradient but positive values for product (P*G) with respect to the BSR. The BSR shows AVO anomaly of class III

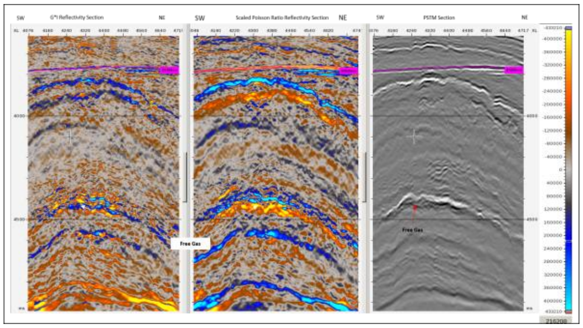

Figure 8. The Product (G*I) reflectivity section and Poisson Ratio section show favourable anomaly indicative of deeper gas. The seismic section shows amplitude anomaly as well at that level.

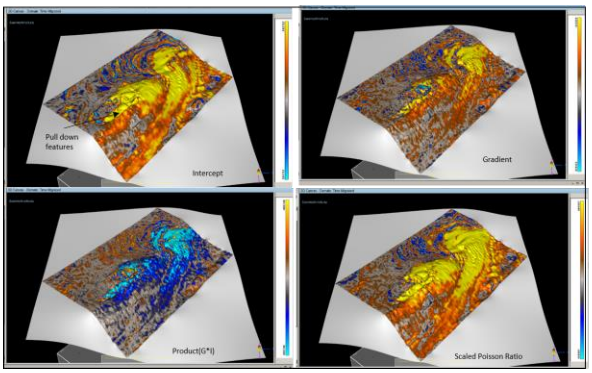

Figure 9. Horizon slices taken from AVO attributes (I, G ,G*I and Poisson Ratio) along BSR shows two distinct anomaly not connected to each other. The amplitudes of the attributes clearly indicate the spatially varying concentration of gas hydrate accumulations.

Figure-7 shows a representative Intercept, Gradient and Product (I*G) sections. The BSR depicts the AVO anomaly very clearly; both intercept and gradient show negative reflectivity but the product is positive. Some very interesting AVO anomaly is also observed at deeper level indicating gas accumulation. Product (I*G) section is positive and scaled Poisson Ratio is showing negative reflectivity in figure -8. Horizon slice (along BSR) from AVO attribute reflectivity volumes show some spectacular images (Figure-9) showing gas hydrate distribution in the reservoir concentrating at the structural highs. The intensity of the anomaly is directly associated with the concentration of hydrate in the reservoir. Pull down features due to some gas above the hydrate layer and faulted BSR are observed very significantly. These sections also confirms two distinct hydrate accumulations without any interconnection.

Pre-stack Depth Migration

Anisotropic Kirchhoff's pre-stack depth migration with 4 Km aperture and best possible interval velocity field obtained by several iterations of grid tomography produced significantly improved seismic image. Figure-10a shows a representative PSDM section across hydrate accumulation-1 showing minor and major faults cutting the BSRs and running upto seafloor. The deeper BSR is observed first time in the PSDM section which were not seen in the PSTM processed data (Figure 10b). The log motifs of density and resistivity indicate very good saturation but poor quality reservoir as the density is low and further lowers in the hydrate zone. Variation of density in hydrate zone coupled with amplitude variation of BSR indicate heterogeneous reservoir. Figure-11 shows a PSDM section across hydrate accumulation-2. Log motifs indicate good quality reservoir as the density is relatively higher and stable in the hydrate zone than that of accumulation -1 but poor saturation of hydrate is expected since the resistivity is quite low.

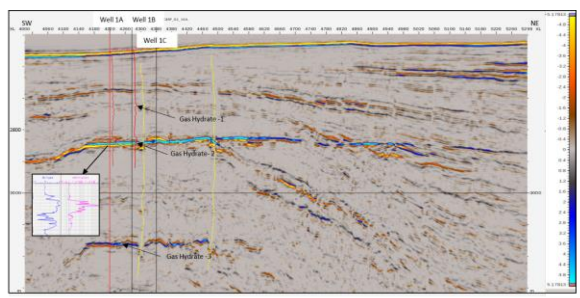

Figure 10a. Depth section shows additional BSR at deeper level brought out by PSDM processing. The low density ~1.9gm/cc and variable in the hydrate zone indicates poor quality reservoir in accumulation 1. Amplitude variation of BSR and faults are some significant features of PSDM processing. Depth of hydrate layer encountered in the well is matching with BSR in depth section

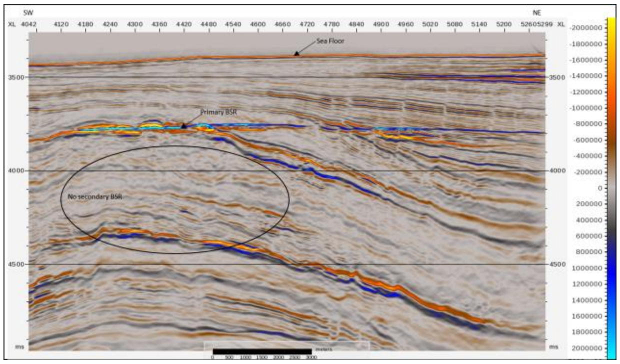

Figure 10b. PSTM section shows primary BSR at shallow level but no BSR at Deeper level

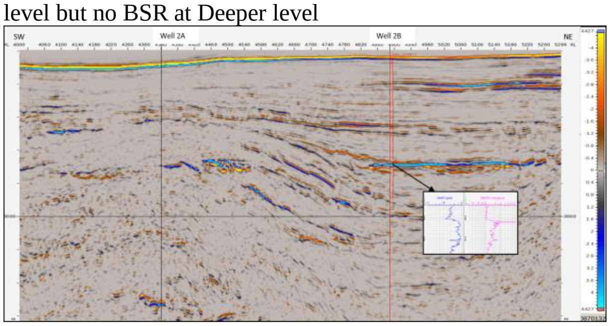

Figure 11. PSDM section showing BSR at accumulation-2; density and resistivity log motifs of hydrate layer are seen in inset. The uniform high density ~2.2 gm/cc of the hydrate layer indicates good quality reservoir but limited pool having less saturation as the resistivity in hydrate layer is quite low. Amplitude variation of BSR and faults are some significant features of PSDM processing as

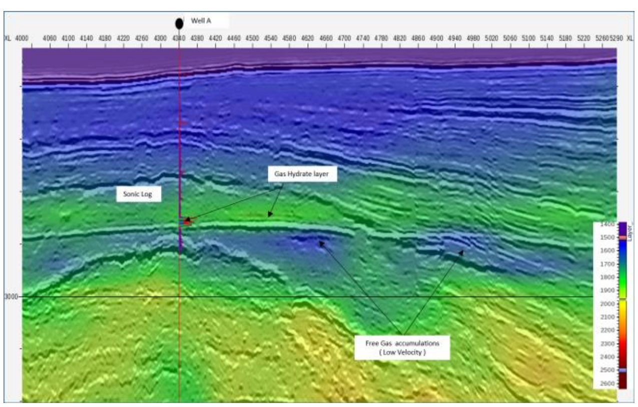

Figure 12. PSDM section overlain by interval velocity and sonic log matches with the high velocity hydrate layer with BSR at depth ~2865 m. The low interval velocity below BSR indicates some free gas accumulations.

Figure-12 shows a representative PSDM section overlain by interval velocity. Higher velocity above BSR indicates gas hydrate accumulations. The low interval velocity below BSR indicates free gas just below the hydrate layer. The depth matching of hydrate layer in the well with PSDM section is a testimony of very good velocity field. High velocity variation across BSR was not picked up by grid tomographic process due to its limitations. Full wave form inversion (FWI) will be attempted in our next study to obtain most accurate velocity model for further insight into the reservoir.

Reserve Estimation

Several wells with logging measurements obtained while drilling (LWD) were drilled to probe the two hydrate accumulations in the study area. Resistivity log superimposed on the depth migrated seismic section clearly indicates a hydrate layer of ~30m thick at depth of 2865 m and its extension above BSR. Gas hydrate, like ice acts as an electrical insulator, so presence of gas hydrate (or free gas) increases the resistivity of the host rock, and therefore gas hydrate saturation can be estimated by using Archie’s (1942) equation, as proposed by Mr. Lu and Mc Mechan (2002)

$S=1-(Ro/Rt)^{1/n}$ ------------------(1)

Where Ro is resistivity of the formation fully saturated with water which can be estimated as the background resistivity which is ~1.5 Ωm, Rt is the measured resistivity in the hydrate zone which is ~18Ωm. For hydrate clastic sediments, n=1.9386 (Pearson et al., 1983). The hydrate saturation is estimated ~ 70% using the above parameters. The exponent “n” in the above equation (1) is empirical and can introduce error in hydrate concentration estimates. The well encountered mainly claystone and siltstone, so average porosity of hydrated sediments in the area is assumed ~30% without any loss of generality. For the purpose of this study, the gas hydrate yield is taken 150 m^3 of hydrocarbon gases. The total volume of hydrate-bound gas (V) in accumulation -1 is estimated of the order of 2.8 x 10^{10} m^3 at standard temperature and pressure (STP). This gas hydrate resource is comparable (by volume) with the reserves of a major conventional gas fields.

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However, accumulation-2 in the area has saturation of approximately 30% as the resistivity increase is from 1.1 Ωm to 2.2 Ωm in the hydrate zone. Though accumulation-2 is smaller in size as compared to accumulation-1 but the reservoir quality might be better as the density of the host rock is higher 2.2 gm/cc than 1.9 gm/cc in accumulation-1

Conclusions:

Broadband processed seismic data are of higher bandwidth more than four octaves (4-120 Hz) helped in deciphering hydrate reservoir in a better way depicting minor reservoir level faults. AVO attributes on broadband data show two separate gas hydrate accumulations with variable saturation. The BSR depicts AVO anomaly of class III. The depth migrated seismic data shows some additional hydrate layer below the primary layer drilled and confirmed under NGHP-2. The amplitude variations of BSR and faults (almost vertical) clearly indicates ongoing melting of hydrates and escaping to the environments. The velocity field obtained by several iterations of fine grid tomography shows high velocity hydrate layer above BSR and some free gas accumulations below BSR showing very low velocity. It corroborate pretty well with the sonic log. RMS amplitude of mapped BSR horizon clearly indicates two separate deposits of gas hydrate in the area. The reserve estimation of hydrate bound gas is of the order of 2.8 x 10^{10} m3 at STP in accumulation-1. The gas reserve is comparable (by volume) with the reserve of a major conventional gas fields
Pre-stack inversion and FWI studies are being attempted to further enhance our understanding about the hydrate reservoir in the area.

Note: This paper represents views of the authors. Organization to which authors belong to may have different opinion.

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Acknowledgements

The authors are thankful to Mr. R.K. Srivastava Director (Exploration), ONGC Ltd. for his kind permission to present this work. We express our sincere thanks to Mr. K. Vasudevan, GGM-Basin Manager, WOB, and Mr S.K.Sharma, GGM-HGS, Mumbai for their kind support and guidance.
We express our sincere thanks to Mr. M. K. Jain, CGM-GP, SPIC, WOB, Mumbai for technical support.