

3D-Seismic prospecting of gas hydrate and its associated proxies in Gulf of Mannar offshore, Cauvery Basin: A case study

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Gas Hydrate, BSR, Mannar Offshore

Summary

Gas hydrate concentrated zones (GHCZs) have become targets for potential energy resources along continental margins worldwide. In 2006 and 2015, gas hydrate (GH) exploratory drilling in the east coast of India Krishna Godavari (KG) and Mahanadi Basins confirmed that GHCZs tens to hundreds of meters thick occur directly above bottom simulating reflections and/or intra gas hydrate stability zone (GHSZ) reflectors imaged in seismic data. First time, ONGC initiated to explore the Gulf of Mannar offshore, Cauvery basin for potential of gas hydrate prospects. This study uses conventional 3-dimensional (3D) seismic data, from the Gulf of Mannar offshore, Cauvery Basin East coast of India to identify analogous GHCZs. In this paper detailed analysis of the gas hydrate system within study area of the Gulf of Mannar sub Basin is provided, including: (1) the 3D spatial distribution of bottom simulating reflections; (2) a thickness map of potential GHCZs; and (3) a probabilistic volumetric gas initial-in-place estimate for these GHCZs using leads from our seismic data interpretations.

Introduction

India's energy requirements mainly depend on fossil fuels. Ever increasing demand for sustained industrial growth has forced an 80% import dependency leading to enhanced exploration for renewable and alternate energy resources such as coal bed methane, shale gas, and the gas hydrate found below ocean floor in form of ice-like substances. Natural gas hydrates do have the potential of becoming an alternate energy resource due to its huge deposits envisaged worldwide (Kvenvolden 1993). Gas hydrates are ice-like crystalline substances comprising of a methane molecule surrounded by a cage of water molecules. The gas hydrates are generally found in the permafrost and outer continental margins of the world. These are formed at

high pressure (8-30 MPa) and low temperature (10–20 °C) in shallow sediments, and are stable up to a few hundred meters below the sea floor. Methane trapped in hydrates and free gas below the hydrate bearing sediments is found in huge amount. An estimated reserve of 700000 TCF methane trapped in gas hydrates around the world (Kvenvolden,1993., Collett et al., 2009) has prompted a recent increase in hydrate researches worldwide. India has also began active research in establishing gas hydrate reserves in east and west coast by collecting geophysical, geological, geochemical and microbiological data under its National Gas Hydrate Programme (NGHP) initiated and governed by Ministry of Petroleum and Natural Gas, Government of India.

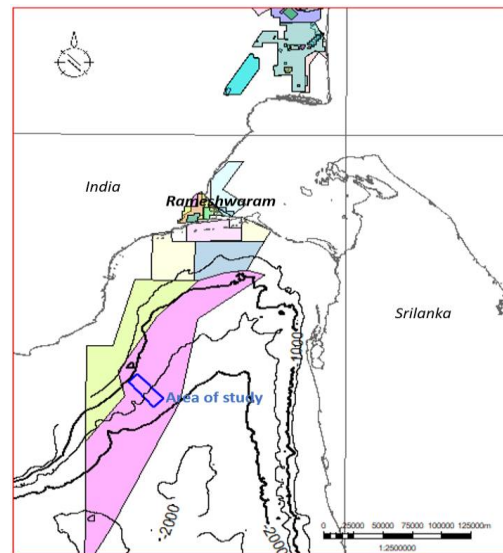


Figure 1: Location map of study area with bathymetry

NGHP-01 and 02 has established the presence of gas hydrate system in Mahanadi and Krishna-Godavari offshore basins, eastern continental margin of India; however, other promising petroliferous basins are relatively unexplored for gas hydrates. First time,

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ONGC initiated exploration efforts for gas hydrates in the Gulf of Mannar offshore Cauvery basin (fig-1). Conventional hydrocarbon acquired 3-dimensional (3D) seismic reflection data used in this study to: (1) identify and map potential gas hydrate concentrated zones (GHCZs) and its proxies; and (2) calculate a volumetric gas-in-place estimate for these newly mapped GHCZs using seismic data because of the absence of any gas hydrate well drilled in the study area.

Geological setup

Cauvery Basin bathymetry and geothermal data are favorable for gas hydrate presence. Cauvery Basin was also considered to be geologically favourable due to large quantity of potentially coarse-grained sediment input along with organic-rich sediments from the nearby river systems. Gulf of Mannar Sub-Basin constitutes the south eastern offshore part of Cauvery Basin, the southern most of the Mesozoic rift basins along the east coast of India. Late Jurassic fragmentation of eastern Gondwanaland into the Indian sub-continent, Antarctica, and Australia had initiated the formation of Mesozoic rift basins on the eastern continental margin of India including Cauvery Basin. Numerous deep extensional faults having NE-SW trends during rifting had initiated active subsidence that resulted in the formation of horst and graben blocks which subdivided the Cauvery Basin into many sub-basins including Gulf Of Mannar. Water depth ranges from 1100 m to 1900 m in study area (fig-2). Gulf of Mannar sub basin comprises of two cretaceous depocenters separated by the southward plunging NE-SW aligned Mandapam-Delft ridge.

Methodology

Seismic imaging is an important tool for identifying Gas Hydrate (GH) because both GH and free gas alter the physical properties of marine sediments, which will in turn affect the travel path and attenuation of the seismic wavelet. This results in a sharp contrast in mechanical properties at the phase boundary between GH saturated layers overlying a zone of free gas, water, and potentially pore filling hydrate occupy the pore space (Riedel 2013b). This contrast in physical properties is expressed in seismic data as bottom simulating reflections (BSRs), and BSRs remain our strongest remotely sensed indicator to infer the presence of GH. Study area is covered by

conventional marine streamer 3D seismic data (area shown in figure-1 & 2). The gas hydrate prospective area identification and delineation method primarily relies on recognizing the potential response of the reservoirs in 3-D seismic dataset and incorporates petroleum system concepts into the specific context of gas hydrate exploration (Boswell et al., 2016, Shukla et al., 2018). Mitigating the geologic risks inherent in such gas hydrate prospects through comprehensive evaluation of all relevant elements of the gas hydrate petroleum system, such as gas source, gas migration, and potential occurrence of suitable coarse-grained reservoirs (Collett et al., 2009). Gas hydrate prospect area delineation in this study further builds upon this approach, which includes four primary elements as described by Boswell et al., 2016 & Shukla et al. 2018 and presented in result and discussion section.

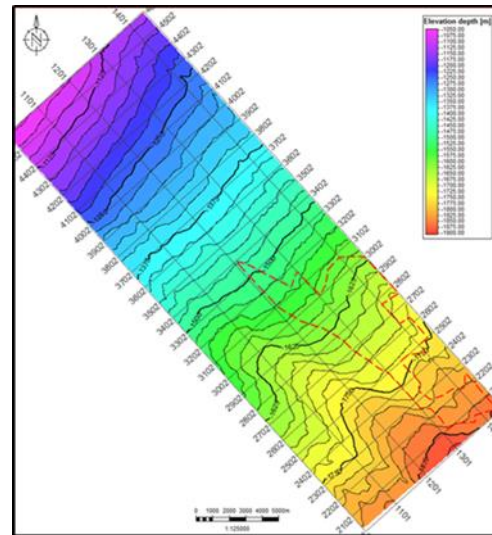


Figure 2: Seismic base map with sea floor relief map in meters.

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.

$$GIP = GRV * N/G * \Phi * GSh * VR * CO$$

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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 taken 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

4.1 Seismic Mapping and Interpretation

4.1.1 Bottom Simulating Reflections (BSRs)

This BSR appears as a continuous, crosscutting reflection to lithological strata that closely mirrors the seafloor and has opposite polarity to the seafloor (yellow horizon in figure 3 & 4). It reaches a minimum depth of ~1800ms in TWT and a maximum depth of ~2800ms in TWT from sea level (in figure 5a contours). The primary BSR predominantly exhibits a strong, high amplitude character, suggesting a continuous free gas zone present

beneath BSR (Figure 4, 5a & 6a). The continuous and generally high amplitude nature of the BSR is characteristic of a diffusive system supported by gas hydrate recycling processes. Selective increases in BSR amplitudes (patchy) indicates the important role of sand layers as a conduit for upward migration of gas-bearing fluids (Boswell 2016).

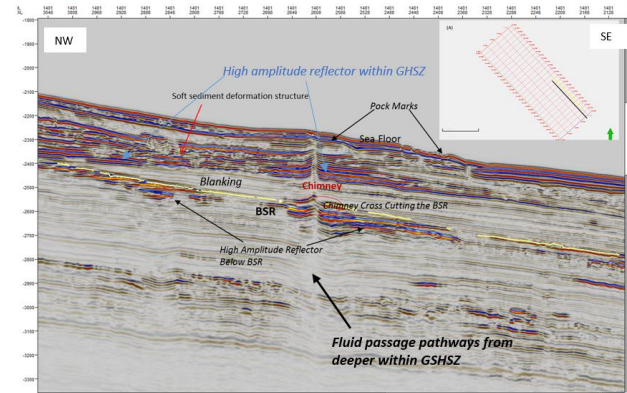


Figure 3. Seismic inline (NW-SE direction) which shows the Patchy BSR, gas hydrates proxies Chimney, Pockmarks etc. and High amplitude reflections (HARs) below BSR is observed.

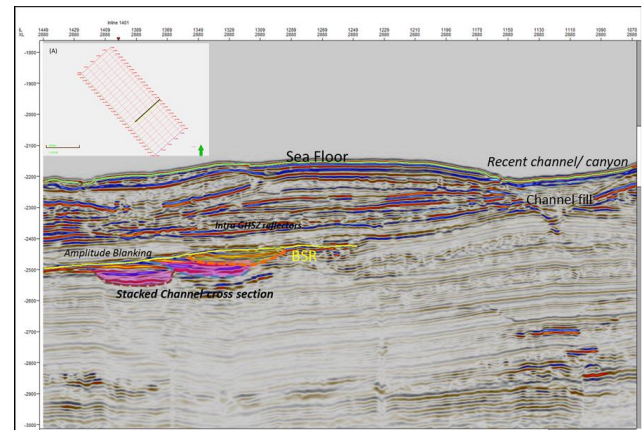


Figure 4. Seismic cross-line (NE-SW direction) which shows the BSR in yellow colour, GH proxies amplitude blanking, Intra GHSZ reflectors etc. and Stacked channel cross section across continental slope below the BSR.

4.1.2. Seismic Evidences for Gas Source and Migration Pathways into the GHCZs.

The 3D seismic volume reveals a complicated geologic environment including slope fan deposition with channels cut-fill structure. High amplitude reflections (HARs) correlating with gas charged sands are common beneath the BSR (Figures 4, 5, 6,

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&7). HARs are observed above the BSR nearly updip of zones where HARs are also below the BSR and these above HARs are likely to be gas hydrate reflectors (Figures 4, 5, 6 &7). The presence of gas appears in seismic data as reductions in acoustic impedance, which strengthens the reflectivity coefficient and results in HARs and polarity change. Blanking is observed in a thick sequence above the BSR in the lower southern part of the survey (Figure 6) is interpreted as significant low GH saturation.

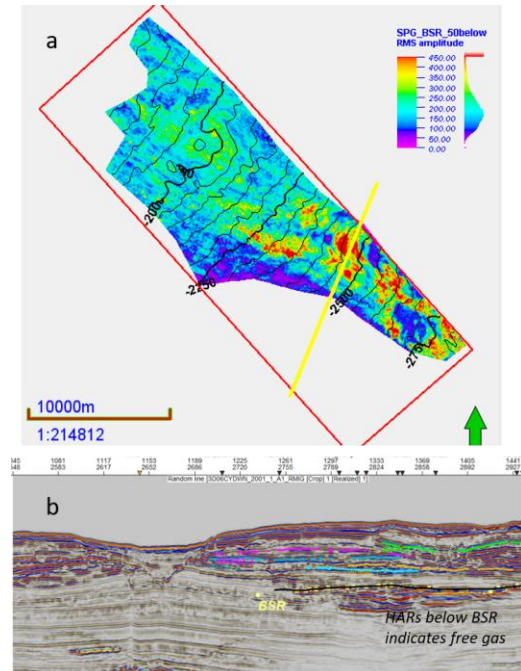


Figure 5: a) RMS amplitude below BSR in 50 ms window and b) random seismic line in strike direction showing HARs below BSR. Contours show the BSR relief in TWT.

High RMS amplitude in 50 ms window below BSR in figure 5a may indicate the free gas possibility. HARs appear frequently at and well beneath the BSR throughout the seismic data suggesting gas is sourced from deeper sediments also. Gas migration in marine sediments can proceed as a short-range and/or long range process. In the Gulf of Mannar, we observe geophysical evidence for both short and long range migration. Gas proxies identified in the 3D seismic data, indicate a likelihood that gas migrates into the GHSZ by means of two mechanisms: (1) diffuse flow along permeable stacked channel filled by HARs below BSR (Figures 4, 6 and 7); (2) episodically as

focused fluid flow through deep reflector via fluid expulsion passage or chimney structure as shown in seismic section (Figure 3, 4, 6 & 7).

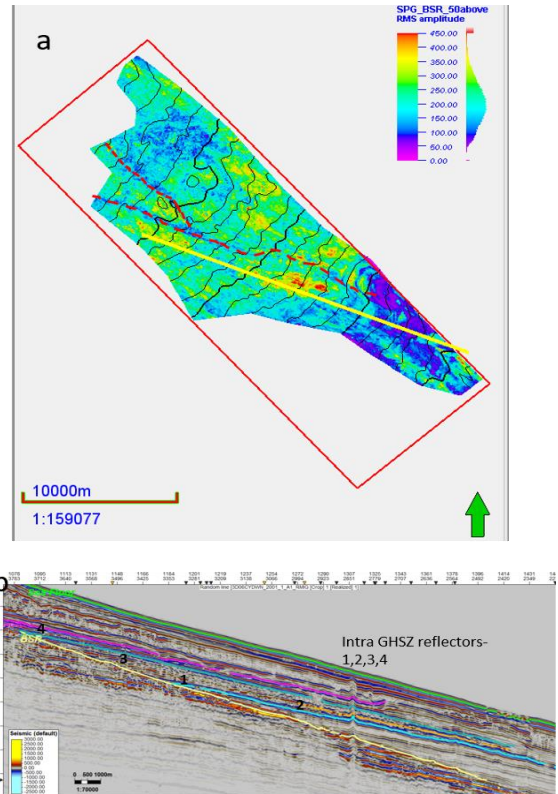


Figure 6: a) RMS amplitude above BSR in 50 ms window and b) random seismic line in dip direction (in fig a shown by yellow line) showing within GHSZ reflectors 1, 2, 3 and 4.

4.1.3. Direct indication of gas hydrate presence within the GHSZ:

Gas hydrate presence within sand-rich reservoirs is the key aspect in gas hydrate prospective area identification. This can be inferred from the following seismic evidence:

High amplitudes within the GHSZ: Strong amplitudes above the BSR are viewed as potential direct indicators of GH, particularly when the amplitude is the same polarity as the sea-floor and occurs in sediment packages that have seismic character suggestive of sand-prone depositional systems. High amplitude interpretation to distinguish between wet sand and gas hydrate is difficult. However if polarity reversal at base of the GHSZ or BSR occurs, there is a possibility that high amplitudes that occur above BSR are related to gas hydrate.

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In this study, a Root Mean Square (RMS) seismic amplitude strength attribute method is used to delineate gas hydrate accumulations and to infer the GHCZs (Shukla et al., 2018). The RMS value is an important measure to infer the energy in a waveform over a certain length of time window. In figure a high RMS amplitude value in most part of area above BSR in 50 ms window indicates the presence of GHCZs. South east part of study area RMS amplitude is low due the acoustic blanking as inferred at seismic line (in fig 3, 6 & 7) indicated low saturation of GH and below probable free gas zone. Free gas zone in this part indicates by HARs below BSR. The anomalous peak value in instantaneous amplitude values gets averaged over the selected time window (often one waveform) therefore amplitude distributions from trace to trace are most likely smooth and minimize the effect of noises. This leads to better prediction of amplitude strength changes that are most likely related to lithological and elastic rock properties of gas hydrate bearing sediment. Channel axes are also shown in the red dotted line in figure 6a. Intra GHSZ reflectors with same polarity of sea floor mapped in the area and marked in seismic line by 1, 2, 3 and 4 (figure 6b). These reflectors are the GHCZs. BSR is crosscutting these reflectors at base and polarity of these reflectors become reverse at base of GHSZ. These reflectors amplitude occur in the packages of the sediment which are thinning down slope indicating the slope fan with channel cut-full deposition.

4.1.4. Seismo-geological evidences of sand reservoir facies within the GHSZ

Gas hydrate prospect in sand reservoirs are considered to be more suitable for gas production than gas hydrate in a shale or mud reservoir with existing technology. In our study area, sand bearing reservoirs to host gas hydrate formation and accumulation are present; the important evidence for the presence of sand bearing gas hydrate include the following:

Seismic facies of sedimentary sections characterized by monotonous and laterally consistent seismic reflectors within intervals of laterally consistent thickness are thought to be less prospective for sand occurrence. In contrast, zones of strong lateral thickness variation, including potential cut-and-fill, or zones with generally more poorly organized internal reflections, are considered to have greater

potential for sand occurrence (Riedel et al., 2013b). In the dip direction in seismic section in figure 6 and 7 intra GHSZ reflectors shows the variation in thickness.

The expression of the BSR is controlled by many factors, both geological and related to the nature of the seismic data. However, BSRs, particularly where expressed not as a trough-leading reflector, but as an alignment of anomalous seismic responses or discontinuous/ patchy as shown in figure 7, is suggestive of a sedimentary section of variable permeability that is potentially more sand-prone (Boswell et al., 2016).

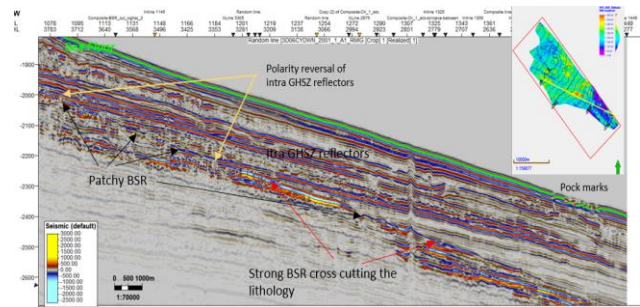


Figure 7: Seismic section across dip direction showing Patchy BSR left side in updip and strong BSR at down dip side where HARs below BSR. Polarity reversal of intra GHSZ reflectors observe at BSR crosscutting marked by yellow arrow.

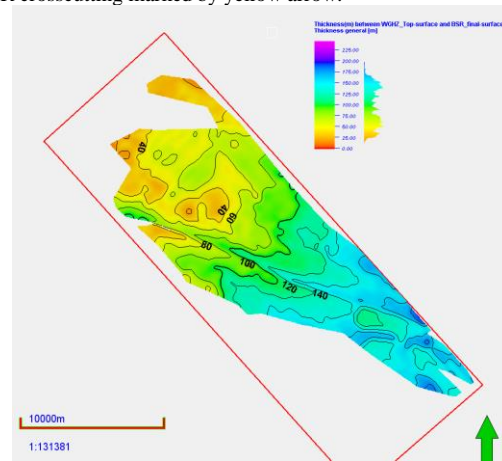


Figure 8 Isopach map of GHCZs reflectors with BSR

4.1.5 Isopach map of GHCZs reflectors with BSR

The upper boundary of GHCZs is defined by Upper high amplitude stratigraphic reflector within GHSZ with same polarity as sea floor. Total four reflector have been mapped within gas hydrate zones 1, 2 3 and 4 as shown seismic (figure 6b). Due to local

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nature of some reflector we have taken the envelope of surfaces of upper most layer of intra GHSZ reflectors. Isopach map is created between envelope surface of GHCZs reflectors and BSR surface (figure 8). Sediment velocity is taken as 1700 m/s for shallow sediment. GHCZs thickness varies from 20 to 180 m.

4.2. Volumetric Gas initial in-Place Estimate

This resource estimate provides a first-order gas-in-place estimate for the GHCZs. Assumptions of input parameters for Monte Carlo simulations explain the uncertainty in the inputs. Area is taken as 190 sq km and GHCZs thickness ranges between 20 to 180m 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. N/G value may be considered from 0.0 to 0.6. The porosity and GHSh are based on NGHP sites measurements for a sand rich interval in east coast of India. The preferred porosity value is 40% (appropriate for the unconsolidated shallow marine sediment) but NGHP data shows that it could range from 30–50%. GHSh value ranges from 5 to 50 % and likeliest value is 25%. 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. There could be large errors with extrapolating the GHSh from NGHP sites of KG and Mahanadi Basin to Gulf of Mannar offshore in eastern continental margin of India without drilling confirmation.

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 10,000 trial runs, 10,000 estimations of resource and summary statistics of the output were derived and shown in figure 9. Mean value is 86.39 BCM. P10, P50 and P90 value of the GIIP are 25.70, 72.89 and 165.11 BCM respectively methane is locked up in the GHCZs imaged in our seismic data.

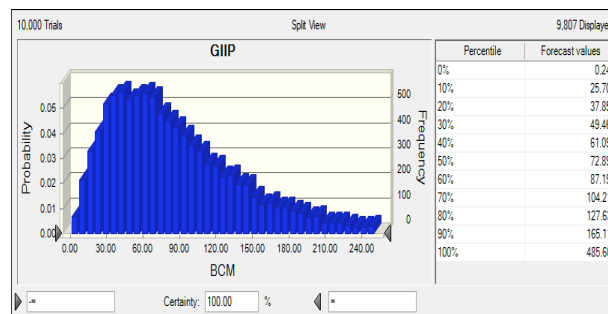


Figure 9. Outcome of monte carlo simulation of gas initial in-place in GHCZs

Conclusions

3D seismic volume was interpreted for identification of gas hydrates prospective area. BSR (as proxy of gas hydrate) and intra gas hydrate reflector above BSR was observed and mapped. Total 190 sqKM of BSR area was mapped in this study. Gas hydrate proxies like chimney, pockmarks and amplitude blanking above BSR and HARs below BSR are observed and interpreted in seismic data. This indicates possible presence of gas hydrates in the area. Isopach map of the GHCZs prepared and its thickness varies from 20 to 180m.

Prognosticated gas initial in-place (GIIP) in gas hydrate resource in study area is 72.89 BCM (P50 value) by Monte Carlo simulation. This value is based on several assumptions. Confirmation of this resource is only possible by drilling and testing the gas hydrate prospects in Gulf of Mannar offshore.

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