9th Biennial International Conference
& Exposition on Petroleum Geophysics

"HYDERABAD 2012"

P-223

Gas hydrate stability zone modeling in the Krishna Godavari Basin, Eastern margin of India

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Summary

The Krishna Godavari (KG) basin is rich in gas hydrate and exhibits an area of wide range of gas hydrate stability zone (GHSZ). In this region, we modeled the base of the gas hydrate stability zone (BGHSZ) utilizing in situ temperature measurements acquired during national gas hydrate program (NGHP) Expedition-01. The bottom simulation reflector (BSR) closely approximates the BGHSZ, and due to the strong temperature influence on hydrate stability, the BSR is close to an isotherm. Thus BSR depth variations can be an indicator for local variations in heat flow, which in turn can be the result of fluid flow or faulting. We are trying to understand the linkage between fluid-flow and vertical fault system in the KG basin. Fluid flow showed a relation to fault systems where some of them are directly connected to gas hydrate bearing sedimentary formations. The influence of water bottom temperature, pore water salinity and geothermal gradient variation on GHSZ thickness is critically analyzed in relation to both geological formations and tectonics. Our analysis suggests a highly variable GHSZ in the KG basin controlled by local variations in the parameters of stability conditions. Recovery of gas-hydrate sample from the region and presence of gas hydrate above estimated BSR depths may indicate gas-hydrate in thermal equilibrium.

Keywords: *Gas hydrates, Seismic, bottom simulating reflectors, geothermal gradient.*

Introduction

Gas hydrates are inferred to occur worldwide along the continental margins and permafrost regions where the pressure and temperature are favourable for hydrate stability (Kvenvolden, 1998). The gas hydrate stability thickness varies widely within Arctic regions depending on factors such as ocean bottom water temperature, geothermal gradient, salinity of the formation water, composition of gas, etc. (Sloan, 1990). The continental margins show a shoaling of the hydrate stability zone, which often mark the region of slope instability and occurrence of gas venting features such as pockmarks (Hovland et al., 2002; Buenz et al., 2003, 2005; Buenz and Mienert, 2004). Gas hydrate occurrences are often inferred from the seismic data using a bottom simulating reflector (BSR), which is the boundary between hydrate-bearing sediments above and gassy sediments beneath (Shipley et al., 1979). Gas hydrates in the pore space of sediments, and pockmarks at the seabed are often related to the gas hydrate stability conditions prevalent at that location (Chand and Minshull, 2003; Fichler et al., 2005). In tectonically unstable regions, for example, due to compressional stresses and tectonics, gas hydrate stability is mainly controlled by the variation in geothermal gradient introduced by the stress induced fluid flow (Cooper and Hart, 2003; Ruppel et al., 2005). In such regions, the gas hydrate stability zone (GHSZ) could be varying very much laterally preventing the formation of any noticeable BSR. Hence, the factors affecting the stability zone have to be analysed critically, to locate the possible presence of gas hydrate in the sediments and its relation to fluid flow. Here, we analyse and model the GHSZ of the KG basin as a whole using stability parameters available from the region (bathymetry, geothermal gradient, bottom-water temperature, gas composition) using multichannel seismic data and drilling based information (geothermal gradient). The thickness of gas hydrate stability zone (GHSZ) varies widely within oceanic sediments by various parameters such as the ocean bottom water temperature, geothermal gradient, pressure (depth), salinity of formation water, and composition of gas (Sloan 1990). The continental margins show a shoaling of the BGHSZ, which often marks the region of slope instability, and gas venting through tectonic disturbances such as folding and faulting (Kvenvolden 1999; Hovland et al. 2002).

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The KG basin and other areas of the Indian continental margins are known for their large sediments influx from vast river system providing a large sediment load as well as organic carbon input into the deep sea environment. The KG basin is characterized by a zone of extensive toe-thrusts (Riedel et al. 2011), which significantly shape the seafloor morphology and can therefore affect the thermal regime and BGHSZ. If fluid-migration along such faults exists, the BGHSZ can be altered. Modeling the BGHSZ based on a purely conductive regime can therefore help assess the possible presence of fluid migration. This, in turn, provides implications on the overall fluid-circulation pattern of a basin. Hence, the high resolution multichannel seismic data are analyzed for the presence of gas and gas hydrate related anomalies in the Krishna-Godavari (KG) basin, off the eastern Indian margin (Fig. 1). The widespread BSRs, observed on seismic sections, indicate potential occurrences of gas-hydrates in the KG basin (Bastia 2006; Collett et al. 2008; Sain and Gupta 2008; Shankar and Riedel 2010). The BSRs are heterogeneous in character and are limited to local areas even though the gas hydrate is stable under prevalent thermo baric conditions at water depths between 800 to 1500 m. Factors such as the bathymetry, temperature, origin and composition of gaseous hydrocarbons and geological structures favor the formation of gas hydrates in most parts of the KG basin (Sain and Gupta 2008). However, the drilling and coring results show gas hydrates in massive lumps, and possibly in finely-distributed grain-displacing, fracture-fill, small nodules, or lenses (Collett et al. 2008).

The thermal structure along a margin is generally assessed from heat flow studies carried out on the seafloor. The heat flow can be calculated from the thermal conductivity of near-surface material and geothermal gradient. The conductivity at a location can be measured either in situ or from materials recovered by gravity or piston coring from the seafloor. The temperature gradient is derived from a set of in situ temperature measurements. However, the direct measurement of heat flow is a very slow procedure and provides information only at discrete locations. We estimate the geothermal gradients and heat flows at various locations from the depths of BSRs identified on seismic sections.

Theory and /or Method

Base of the gas hydrate stability can be predicted if in situ temperature data, velocity of the sediment and pore water chemistry are known. Depth versus in situ temperature measurements plots shows straight line fit to the data (i.e. the gas hydrate in thermal equilibrium). BSR can reliably be used as a proxy for heat flow estimates if thermal conductivity and geothermal gradient are known. Geothermal gradient can be estimated if seafloor temperature, temperature at the BSR and BSR depth are known. Temperatures at the BSR depth can be estimated from the phase diagram of the gas hydrate or using the experimental thermobaric stability condition for the methane–seawater system.

$$G_{Surface} = \frac{(T_{BSR} - T_{water\_bottom})}{Z_{BSR}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where, $G_{Surface}$ is geothermal gradient at surface. T_{water_bottom}, T_{BSR} and Z_{BSR} are temperature at seafloor, temperature at BSR and depth of the BSR below seafloor (i.e. stability thickness) respectively. Since, the BSR closely approximates the base of gas hydrate stability zone, the BSR depths can be used to derive the local variations in heat flow due to tectonic disturbances and fluid flow through faults acting as migration pathways (Yamano et al. 1982; Townend 1997; Ganguly et al. 2000; Kaul et al. 2000; Shankar and Sain 2009; Horozal et al. 2009). This was done by assuming a linear temperature gradient and following simple conductive heat transport relationship:

$$HF = k \times G_{Surface} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where, HF is the heat flow in mW/m^2, k is the thermal conductivity in W/mK.

The GHSZ thickness is determined by water depth, pore pressure, seafloor temperature, thermal gradient, and gas and fluid composition. Using the BSR as the BGHSZ, we determine the potential gas hydrate stability thickness at site 15 of the NGHP-01, which is 126 meter below seafloor (mbsf) (Fig. 2). Simultaneously, we model the phase diagram using the depths of seafloor and BSR, water temperature profile and geothermal gradient observed during the NGHP-01 using the Brown et al. (1996) and the Sloan (1998) approaches, which is based on an empirical algorithm for the stability of methane hydrate in seawater with a variable salinity. The Brown et al. (1996) (red line) phase diagram is in good agreement with the Sloan (1998) (dotted blue line) phase diagram (Fig. 2). As the water depth increases, the temperature threshold for gas hydrate also increases. At a given water depth, the temperature thresholds for Sloan (1998) is little bit more than that of Brown et al (1996). Knowing the water depth and thermal gradient at a particular location, the GHSZ can be estimated by finding the seafloor temperature (black curve in Fig. 2) and drawing a straight line to the appropriate thermal gradient. The depth at which the thermal gradient line intersects the gas hydrate phase curve represents the lower boundary of gas hydrate stability zone. It is to be mentioned here that the temperature required for gas hydrate destabilization is higher when additional higher hydrocarbons are present in the gas phase, while a higher salinity has the opposite effect (Brown et al. 1996; Claypool et al. 1983; Dickens et al. 1994).

The T_{water_bottom} is estimated using the linear regression from in situ temperature measurements by the NGHP-01 which is comparable with the CTD measurements by Mazumdar et al. (2007): $T_{water\_bottom} = 13.09 - 0.0062 \times z$, where z is water depth in meter (Shankar et al, 2010). The T_{BSR} is estimated using the experimental thermobaric stability condition for the methane–seawater system (Bouriak et al. 2000), which is based on pure methane and standard seawater (34 ppt). The thermal conductivity (k) is a function of depth below the seafloor, and is taken from the NGHP-01 at all sites cored in the KG area (Collett et al. 2008). The ZBSR is determined from velocity function deduced from the sonic logs (Collett et al. 2008; Shankar et al. 2010). We further assumed a hydrostatic pressure regime and calculated the pressure using a constant water density of 1030 kg/m3. BSR depth is estimated assuming a uniform velocity 1580 m/s within the hydrate stability zone.

Examples

Analysis of multi-channel seismic data from the KG basin reveals a verity of seismic indicators of gas hydrates. The BSR is generally of low amplitude and poor to moderate continuity in the shallow part of the seismic section (Fig. 3b). The BSR is follow the geothermal and seen to cross-cut stratigraphy in regions where the sediment bedding in the dipping through the BGHSZ. Continuity of the reflectors is disturbed by faults. Enhance reflections below the BSR are also seen and prominent when the overall amplitude of the BSR is high. In general, they are laterally extensive in the deeper part of the basin.

In order to map the distribution of BGHSZ, and to understand the changes in BSR occurrences, and amplitude characters across the 2D seismic profiles, we use 1D thermal modeling to predict the BGHSZ as described by Shankar et al. (2010). We assume a hydrostatic pressure regime, uniform thermal conductivity (based on little variation observed during the measurements of NGHP-01), and a uniform P-wave velocity structure with a gradual increase from seafloor to BSR. We use the gas hydrate (structure I) stability curve calculation by Bouriak et al. (2000), based on pure methane and on average standard seawater salinity (34 ppt), which is in good agreement with the geochemical pore-water and void gas measurements made at various sites of NGHP-01. The seafloor temperatures and thermal gradients are allowed to change according to water depth variation across the 2D data using the database of thermal measurements established during the NGHP-01.

The BSR depth predicted from this phase diagram matches reasonably well with the depth of BSR observed on seismic section. However, small differences in phase boundary temperature are observed at grater depths due to fluid composition (Dickens and Quinby-Hunt 1994). The seafloor temperature measured in situ at site 15 and fitted to water temperature CTD measurements (Mazumdar et al. 2007) is utilized in this study. The depths of seafloor and BSR are marked from the stack section in Fig. 2. Geothermal gradient for the upper sedimentary layer is calculated from the in situ measurement and its linear extrapolation, shown with black dash line in Fig. 3a.

The geothermal modeling is performed to predict the theoretical BGHSZ. The modeled BGHSZ (black dotted line on seismic sections displayed in Fig. 3b correspond well to the observed BSRs. The fluctuations of the predicted BGHSZ from the observed BSRs are likely due to errors arising from picking the seafloor, variability of seafloor temperature and geothermal gradient, which is function of water depth (Shankar et al. 2010).

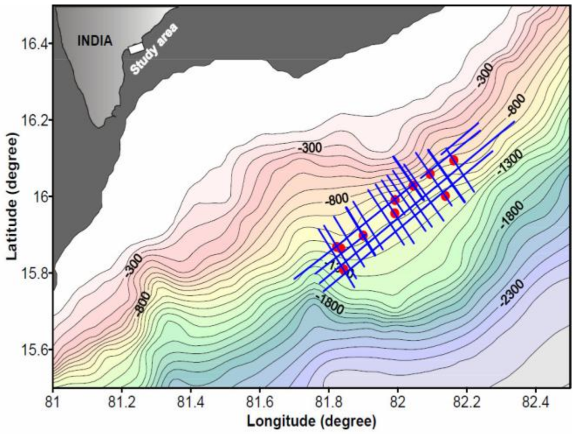

Figure 1: Bathymetry map of the Krishna-Godavari (KG) basin, off the eastern Indian margin. Location of drill sites by the NGHP-01 are shown with red circles. Solid blue lines are the 2D high resolution MCS lines. Bold red lines with corresponding figure numbers represent the lines used in this study. The color bar represents the water depth in meter below seafloor. Contours are also shown to indicate water depth directly. Inset shows location of the KG Basin on the east coast off India.

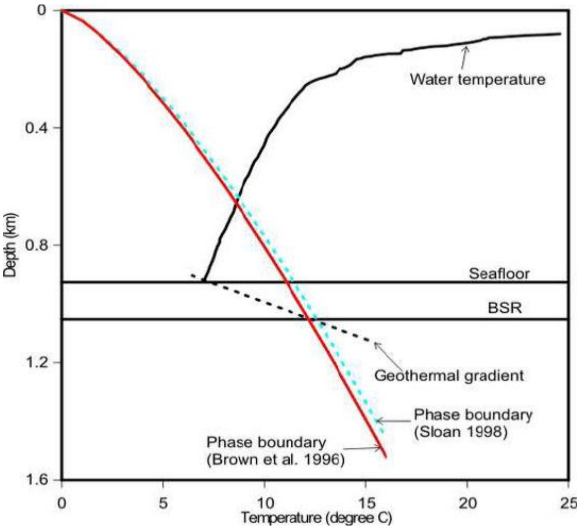

Figure 2: Methane hydrates stability curve of Brown et al. (1996) and Sloan (1998) for site 15 of NGHP-01 in the KG basin. Geothermal gradient interpolated from the in situ temperature measurements. Water temperature profile of CTD measurements is taken from Mazumdar et al. (2007).

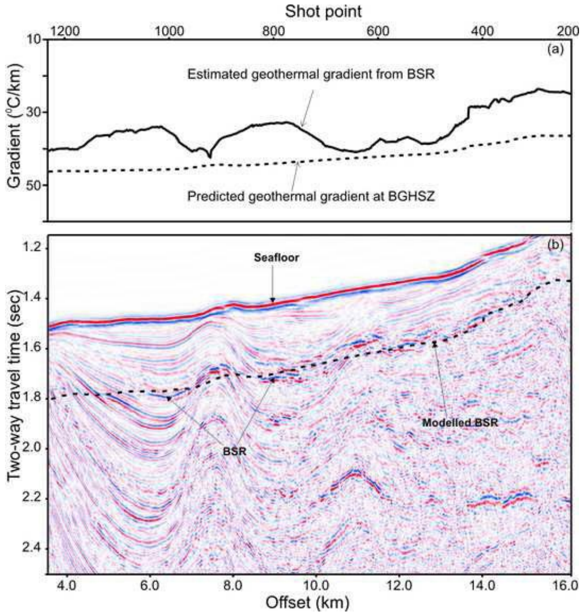

Figure 3: (a) Estimated geothermal gradient (shown with solid curve) from the position of the BSR and the predicted geothermal gradient (dotted curve) at BGHSZ. (b) 2D MCS profile with low amplitude BSR is observed. Modeled BGHSZ (or BSR) is shown with dotted black line.

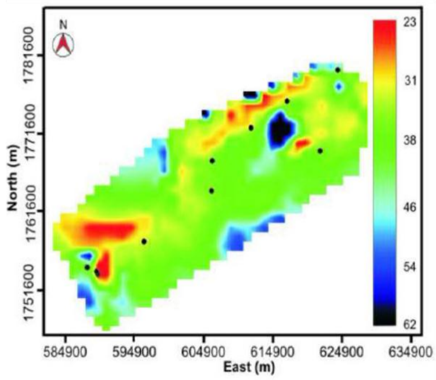

Figure 4: Regional heat flow map derived from the observed BSR depth on 2D seismic section. The color bar represents the heat flow values in mW/m^2.

Conclusions

High resolution 2D MCS data in the KG basin shows widespread occurrences of BSRs and hence gas hydrates.

The structural elements like the faults or fractures and seafloor morphology are important, which control the distribution of BSRs. The BSR-derived heat flows (23–62 mW/m2) (Fig.4) are quite favourable to the formation of gas hydrate in the KG Basin. Over all, the heat flow trends follow the seafloor bathymetry of the basin and systematic increase of heat flow is observed except local variations at few places. The BSR-derived heat flow across the major topographic features corresponds well with the expected trend (low heat flow values at high topography and vice versa) due to focusing and defocusing effect of the topography. There are currently no probe measurements available from the study area, however in situ geothermal gradient measurements from NGHP-01 are comparable with the estimated values.

The thermal modeling of BGHSZ shows close correspondence between the observed and modeled BSR depths on seismic section (Fig. 3b). This modeling approach is very useful for providing the continuity of the BGHSZ especially where a BSR can not easily identified or scanty or is disturbed by local tectonic activity, or masked by other sedimentation patterns parallel to seafloor.

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Acknowledgements

We thank the Director NGRI for his kind permission to present this work. We would like to acknowledge DGH, ONGC and the scientists and crew-members of Expedition 01 Indian NGHP, who acquired the log and core data.