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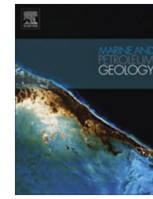

Fault system and thermal regime in the vicinity of site NGHP-01-10, Krishna–Godavari basin, Bay of Bengal

P. Dewangan [a,*], G. Sriram [a], T. Ramprasad [a], M.V. Ramana [a], P. Jaiswal [b]

[a] National Institute of Oceanography (Council of Scientific and Industrial Research), Goa, India
[b] Oklahoma State University, OK, USA

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ABSTRACT

Drilling/coring activities onboard JOIDES Resolution for hydrate resource estimation have confirmed gas hydrate in the continental slope of Krishna-Godavari (KG) basin, Bay of Bengal and the expedition recovered fracture filled gas hydrate at the site NGHP-01-10. In this paper we analyze high resolution multi-channel seismic (MCS), high resolution sparker (HRS), bathymetry, and sub-bottom profiler data in the vicinity of site NGHP-01-10 to understand the fault system and thermal regime. We interpreted the large-scale fault system (>5 km) predominantly oriented in NNW-SSE direction near NGHP-01-10 site, which plays an important role in gas hydrate formation and its distribution. The increase in interval velocity from the baseline velocity of 1600 m/s to 1750–1800 m/s within the gas hydrate stability zone (GHSZ) is considered as a proxy for the gas hydrate occurrence, whereas the drop in interval velocity to 1400 m/s suggest the presence of free gas below the GHSZ. The analysis of interval velocity suggests that the high concentration of gas hydrate occurs close to the large-scale fault system. We conclude that the gas hydrate concentration near site NGHP-01-10, and likely in the entire KG Basin, is controlled primarily by the faults and therefore has high spatial variability.

We also estimated the heat flow and geothermal gradient (GTG) in the vicinity of NGHP-01-10 site using depth and temperature of the seafloor and the BSR. We observed an abnormal GTG increase from 38 °C/km to 45 °C/km at the top of the mound, which remarkably agrees with the measured temperature gradient at the mound (NGHP-01-10) and away from the mound (NGHP-01-03). We analyze various geological scenarios such as topography, salinity, thermal non-equilibrium of BSR and fluid/gas advection along the fault system to explain the observed increase in GTG.. The geophysical data along with the coring results suggest that the fluid advection along the fault system is the primary mechanism that explains the increase in GTG. The approximate advective fluid flux estimated based on the thermal measurement is of the order of few tenths of mm/yr (0.37–0.6 mm/yr).

1. Introduction

Gas hydrate is an ice-like crystalline solid in which methane or other lighter hydrocarbon gases are trapped inside a cage of water molecules (Sloan, 1990). Gas hydrate is stable under high pressure–low temperature conditions and is formed when the methane gas dissolved in pore water exceeds its solubility limit. In marine sediment, gas hydrate occurs as vein filling, massive or nodular form or within the intergranular pore spaces (Helgerud et al., 1999). Under unstable conditions (high temperature–low pressure) gas hydrate dissociates and releases the trapped methane gas. This phase transition between the gas hydrate and free gas is known as the base of the gas hydrate stability zone (BGHSZ). The presence of gas hydrate within the sediments increases the velocity while free gas decreases the velocity thus creating a strong impedance contrast across the BHSZ. In seismics, the BHSZ is manifested as a seismic reflection commonly referred as the bottom simulating reflector (BSR; Hyndman and Spence, 1992; Singh et al., 1993; Helgerud et al., 1999). BSRs have been considered as one of the best proxy indicators for hydrate occurrence worldwide. Several gas hydrate related geophysical, geochemical and microbial proxies have been reported from the multidisciplinary investigations in the KG offshore (Ramana et al., 2006).

A collaboration program between Government of India and United States Geological Survey in 2006 for gas hydrate exploration led to multiple drilling/coring activities onboard R/V JOIDES

* Corresponding author.
E-mail address: pdewangan@nio.org (P. Dewangan).

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Resolution around the continental margins of India. The expedition (NGHP-01), confirmed the presence of gas hydrate in Krishna–Godavari (KG) offshore basin (Collett et al., 2008). One of the sites, NGHP-01-10 shows ~128 m of elevated resistivity log response suggesting the presence of gas hydrates (Collett et al., 2008). The overall saturation of gas hydrate estimated based on the log and pressure core data is of the order of 25–30% (Lee and Collett, 2009; Lee, 2009). Sediment core recovered from NGHP-01-10 site show fracture-filling gas hydrate. Furthermore, the X-ray images of pressure cores collected in the gas hydrate bearing sediment show that the hydrate is preferentially accumulated in the fractures (Collett et al., 2008). In a later experiment (May, 2007), the geological and geochemical analysis of a short sediment core (~30 m) acquired close to NGHP-01-10 site onboard Marion Dufresne show evidences of paleo-expulsion of methane rich fluids through the fault system and the presence of chemosynthetic clams like *Calyptogena* spp. (Mazumdar et al., 2009).

Hydrate accumulation can be structurally or stratigraphically driven (Milkov and Sassen, 2002). In structural accumulation gases are transported to the GHSZ through features such as faults and mud volcanoes, e.g. northwestern Gulf of Mexico (Brooks et al., 1986; MacDonald et al., 1994; Milkov and Sassen, 2000, 2001; Sassen et al., 1999, 2001), Hydrate Ridge (Hovland et al., 1995; Suess et al., 1999, 2001; Trehu et al., 1999), and Haakon Mosby (Bogdanov et al., 1999; Ginsburg et al., 1999). In stratigraphic accumulation gases are transported along permeable horizons, e.g., Blake ridge (Xu and Ruppel, 1999; Dickens et al., 1997), Gulf of Mexico minibasins (Milkov and Sassen, 2001; Pflaum et al., 1986), Nankai trough (Matsumoto et al., 2001), and Mallik (Dallimore et al., 1999). A combination of both structural and stratigraphic transport and trapping mechanisms are also possible (Diaconescu and Knapp, 2000; Diaconescu et al., 2001). The understanding of structural and/or stratigraphic origin of hydrate formation is important to understand its genesis, accumulation, distribution of gas hydrate and also to estimate its economic potential. In the present study, we used the high resolution 2D multi-channel seismic data to study the subsurface structures close to the known gas hydrate site (NGHP-01-10). Other geophysical datasets used to interpret shallow subsurface structures include high resolution sparker, sub-bottom profiler and bathymetry.

In the continental margins the formation and distribution of gas hydrate appears to be closely related with the fluid/gas flow from deeper region into the base of the gas hydrate stability zone (BGHSZ) that can perturb the geothermal gradient (Ruppel and Kinoshita, 2000). In passive settings, anomalous flow occurs through permeable pathways in the zones with rapid sedimentation and compaction that prevents the fluids to be expelled during sedimentation (Judd and Hovland, 2007). In active margins the anomalous flow is mainly due to compression tectonics. Perturbations in BGHSZ have been linked to anomalous fluid flow in literature (Minshull and White, 1989; Davis et al., 1990; Zwart et al., 1996; Mann and Kukowski, 1999; Pecher et al., 2009). It is also a common practice to use BSR-derived heat flow to understand the thermal profile along the continental margins (Davis et al., 1990; Fisher and Hounslow, 1990; Hyndman and Davis, 1992; Ashi and Taira, 1993; Townend, 1997; Ganguly et al., 2000; Kaul et al., 2000). In this study, we estimate the geothermal gradient (GTG) from the BSR depth to understand the thermal regime around NGHP-01-10 site. We have identified zones of abnormal GTG and made an attempt to understand the origin of these observed abnormal GTG through the integrated interpretation of different geophysical datasets.

2. Study area

Krishna–Godavari (KG) basin is one of the petroliferous basins located in the middle of eastern continental margins of India (ECMI) extending from Vishakhapatnam in the north to Ongole in south (Fig. 1). The ECMI evolved due to the separation of India from East Antarctica around 132 Ma, and subsequently resulted in the formation of three prominent basins namely Cauvery, KG, and Mahanadi (Powell et al., 1988; Scotese et al., 1988; Ramana et al., 1994). The KG basin is predominantly drained by rivers Krishna and Godavari that deposit the bulk of detrital sediment. The sediment thickness in the basin has found to exceed 8 km in some of the offshore depocenters (Prabhakar and Zutshi, 1993). The stratigraphy of the KG basin comprises Cretaceous to Recent sediments (Rao, 1993, 2001). The sedimentation rate varied throughout the geological time, but increased dramatically after the upliftment and erosion of Himalayas during the Neogene period (Subrahmanyam and Chand, 2006).

A characteristic feature of the KG basin is shale tectonism (Vijayalakshmi, 1988; Rao and Mani, 1993; Rao, 1993; Bastia, 2006; Gupta, 2006), a gravity-driven tectonic activity induced by movement of thick sediment mass over deeply buried mobile/overpressure shale strata (Damuth, 1994; Wu and Bally, 2000). The mobile/overpressured shale strata are known to exist in KG basin in

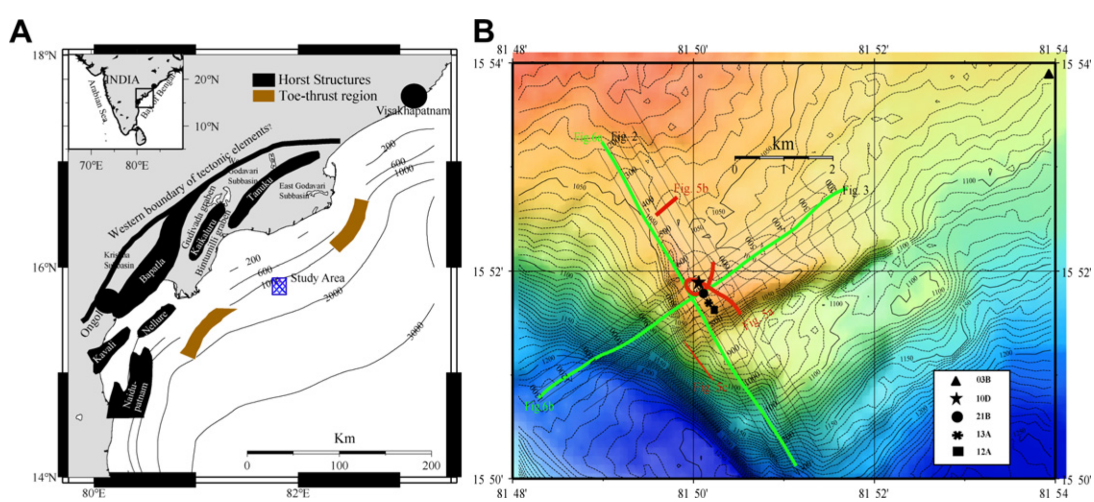

Figure 1. Location map of the study area in KG offshore basin along with the regional tectonics setting showing the horst and graben structures (Rao, 2001; Bastia, 2006) onshore KG basin, Bay of Bengal. The zoom out of the study area with multibeam bathymetry is shown in Figure 1B. The illustrated seismic lines, sub-bottom profiler, and high resolution sparker data are illustrated in the bathymetry map. The illustrated seismic lines are annotated with CDP numbers and the NGHP sites drilled onboard JOIDES Resolution (NGHP-01-10/21/12/13/03) are highlighted on the map. The location of NGHP-01-03 site where no significant presence of gas hydrate is observed is also shown in the map.