Marine and Petroleum Geology 58 (2014) 368–381

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Effect of thermal non-equilibrium, seafloor topography and fluid advection on BSR-derived geothermal gradient

R. Mandal [a], P. Dewangan [a,*], T. Ramprasad [a], B.J.P. Kumar [b], K. Vishwanath [b]

[a] CSIR-National Institute of Oceanography, Goa 403004, India
[b] Directorate General of Hydrocarbons, Noida, U.P 201301, India

A R T I C L E I N F O

Article history:
Received 22 November 2013
Received in revised form
8 April 2014
Accepted 9 April 2014
Available online 18 April 2014

Keywords:
Gas hydrate
BSR
Geothermal gradient
MTDs
Shale tectonics

A B S T R A C T

The seafloor and bottom simulating reflectors (BSRs) are interpreted from the 3D seismic data acquired in Krishna–Godavari (KG) offshore basin in the vicinity of sites drilled/cored during National Gas Hydrate Program (NGHP) Expedition-01. The shallow structures such as inner toe-thrust fault system, regional and local linear fault systems and mass transport deposits are inferred from attributes of seafloor time structure as well as from the seismic profiles. The geothermal gradient is estimated from the depths and temperatures of the seafloor and the BSR. The temperature at the BSR depth is estimated from the methane hydrate and seawater salinity phase boundary assuming that the BSR represents the base of the gas hydrate stability zone.

The spatial variations in geothermal gradient (GTG) show a strong correlation with seafloor topography in the KG basin. The GTG decreases by ~13–30% over the topographic mounds formed due to inner toe-thrust faults and recent mass transport deposits. The GTG decreases by only 5–10% over the mounds, likely due to defocusing of heat flux based on one-dimensional topographic modeling. Hence, the GTG perturbation due to topography alone cannot explain the observed GTG anomaly. The temperature profile beneath these mounds may not be in equilibrium with the surroundings either due to the recent upliftment of sediments along the inner toe-thrust faults or rapid deposition of sediments due to slumping/sliding. In contrast, an increase in GTG by 10–15% is observed in the vicinity of major fault systems. We presume that the likely mechanism for the increase in GTG is fluid advection from a deeper part of the basin. A detailed thermal modeling involving the effect of surface topography, high sedimentation rates, fluid advection and sediment thickening due to tectonics is required to understand the thermal profile in KG offshore basin.

1. Introduction

Gas-hydrate is an ice-like, crystalline solid in which methane and other lighter hydrocarbon molecules are trapped inside the cages of water molecules and stable under high pressures and low temperatures in Polar Regions (onshore and offshore permafrost) and sediments of continental margins (Kvenvolden et al., 1993; Sloan, 1990). Globally, it occurs as massive, nodular, laminar and disseminated form within the inter-granular pore spaces (Brooks et al., 1986). Enormous amount of methane or other lighter hydrocarbon gases are stored as gas hydrate within the gas hydrate stability zone (GHSZ); free gas may exists below the GHSZ which adds to the global storage of hydrocarbon gases. This potentiality of hydrocarbon gas prompted scientific community to study the natural gas hydrates as an alternative energy resource. It is also believed to be an important factor for global climate change, marine geohazard (Kvenvolden, 1993), and drilling hazard for deepwaters hydrocarbon exploration (Nimblett et al., 2005).

In seismic sections, gas hydrate is identified by an anomalous reflector known as Bottom Simulating Reflector (BSR) which mimics with the seafloor, crosscuts geological layers and its polarity is reversed with respect to that of seafloor. BSR acts as a boundary between the overlying gas hydrate bearing sediments and underlying free gas bearing sediments (Hyndman and Spence, 1992; Shipley et al., 1979). The presence of gas hydrate increases the seismic velocity while free gas decreases the velocity thereby creating a strong negative impedance contrast across the GHSZ (Helgerud et al., 1999). In addition to BSR, other geological structures such as pockmarks, gas chimneys and mud mounds are considered as good indicators for the presence of methane in the

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

http://dx.doi.org/10.1016/j.marpetgeo.2014.04.002
0264-8172/

subsurface sediments (Holbrook et al., 1996; Ramana et al., 2006; Riedel et al., 2006).

The thickness of GHSZ depends on geothermal gradient (GTG), pressure, salinity and phase curve of methane and seawater (Kvenvolden, 1993). The theoretical GHSZ thickness maps of the Indian continental margins (NIO, 1997; Sain et al., 2011) have shown Mahanadi, Krishna–Godavari (KG), Kerala-Konkan (KK), Cauvery and Saurashtra basins to have potential for the occurrence of gas hydrate. The Indian National Gas Hydrate Program (NGHP) Expedition-01 confirmed the presence of gas hydrate in KG offshore, Mahanadi and Andaman basins (Collett et al., 2008). The thickness of GHSZ can also be estimated from the seismic data, and it can be used to understand the regional variation in GTG assuming negligible effect of the variations in pressure, salinity and composition of hydrocarbon gases. The primary factors which can affect the GTG are seafloor topography (Lachenbruch, 1968), migrating of deeper, warmer fluid through the existing faults/fractures network (Cooper and Hart, 2002; Dewangan et al., 2011; Minshull and White, 1989; Ruppel and Kinoshita, 2000; Ruppel et al., 2005) and sediment thickening due to local tectonics (Wang et al., 1993). The BSR-derived GTG has been studied in KG offshore basin primarily from sparsely spaced 2D seismic data, and the effect of seafloor topography (Shankar and Riedel, 2010) and fluid advection in the vicinity of Site NGHP-01-10 (Dewangan et al., 2011) have been reported. However, a systematic study of the variation in GTG and its relationship with shallow depositional environment has not been established. In the present study, we re-processed and interpreted the 3D seismic data covering the drilling/coring sites of NGHP-Expedition-01 and established the shallow depositional environment in KG offshore basin. This is the first report of 3D seismic data from a well studied gas hydrate rich margin. The regional variation in GTG is estimated from the depths of seafloor and BSR obtained from the three-dimensional seismic data. We attempt to understand the observed variations in GTG based on the shallow depositional environment in KG offshore basin.

2. Geological setting

The study area is located in the continental slope of KG basin, Eastern Continental Margin of India (ECMI). The evolution of ECMI initiated ~130 Ma when India separated from its conjugate Australia/Antarctica, eastern Gondwanaland (Johnson et al., 1980; Powell et al., 1988). The KG basin and its adjacent two basins, namely Mahanadi and Cauvery basins also evolved in ECMI as a consequence of rifting and drifting. KG basin is one of the most promising petroliferous basin in India, which occupies an area of 28,000 km^2 onland and 145,000 km^2 offshore (Bastia and Nayak, 2006; Rao, 2001). The sediment thickness of KG basin varies from 3 to 5 km in the onshore region and ~8 km in the offshore region (Prabhakar and Zutshi, 1993). Krishna and Godavari river systems discharge bulk of sediment load in KG offshore basin. The basin contains thick sequences of sediments with several cycles of deposition ranging in age from Late Carboniferous to Holocene (Rao, 2001). It has been noticed that during Neogene period, sedimentation rate increased drastically after the upliftment and erosion of Himalayas (Subrahmanyam and Chand, 2006). The KG basin geomorphology is very divergent and contain different kind of geological structures such as channel-levee system, sliding/slumping, diapirs, mass transport deposits, gas chimney, bathymetric mounds (Ramana et al., 2009; Dewangan et al., 2010; Ramprasad et al., 2011; Riedel et al., 2011).

One of the characteristic features of KG basin is shale tectonism. Due to the huge load of sediments deposited by Krishna and Godavari rivers, KG basin shows deformation structures such as Paleogene and Neogene extensional growth faults in the continental shelf and upper slope regions and toe-thrust in deep offshore regions similar to those observed in gravity-driven shale tectonism (Bastia, 2006; Damuth, 1994; Gupta, 2006; Rao and Mani, 1993; Rao, 1993). The shale tectonism occurs due to the movement of overpressured Miocene and Pliocene shale strata (Basu, 1990; Rao and Mani, 1993; Rao, 1993) and leads to the formation of prominent topographic features and fault/fracture network. These faults/fracture network acts as the most favorable pathways for fluid migration (Dewangan et al., 2010) which may reposition the BSR and sometimes obliterate the same. The fluids carrying hydrothermal pore fluids, brines and free gas or warm water upon reaching the seafloor may results in the formation of pockmarks, craters or mud mounds (Hovland and Judd, 1988). Several pockmarks, gas chimneys and mud mounds have been reported in KG offshore basin based on the interpretation of high resolution geophysical data (Ramana et al., 2006). Geological and geochemical analysis of a short core (~30 m) acquired onboard RV *Marion Dufresne* in the vicinity of NGHP-01-10 showed a paleo-expulsion event confirming the expulsion of methane rich fluids through fault system (Mazumdar et al., 2009). The expulsion of the fluids beyond the GHSZ may destabilize the upper slope sediment, and initiate slumping/sliding which leads to mass transport deposits in offshore regions (Bugge et al., 1987; Ramprasad et al., 2011).

3. Data and processing

The map of the available geophysical data such as multibeam bathymetry (Ramana et al., 2009) and the sites drilled/cored during NGHP-Expedition-01 (Collett et al., 2008) in KG offshore basin is shown in Figure 1. In the present study, 3D multi-channel seismics (MCS) data acquired by Oil and Natural Gas Commission Ltd. (ONGC) in KG offshore basin (Fig. 1) have been re-processed and interpreted to understand the shallow depositional environment and estimate the regional variation in GTG. The seismic data were acquired in 2002 onboard M/V Western Monarch using five receiver cables and dual source air-gun. A 2750 cu. in. air gun was fired every 50 m and five 5-km long cables (each 200 channels with 25 m group interval) were deployed to record the seismic data. The separation between the cables is ~200 m. The 3D seismic volume covers an area of 1940 km^2 in the KG offshore basin (Fig. 1). The 3D seismic data is binned along the inline and crossline directions and their spacing are 50 m and 12.5 m, respectively. The Root-Mean Squared (RMS) velocities are obtained at a grid of 500 m × 500 m using conventional semblance analysis. In order to account for conflicting dips between the geological layers and BSR, common-offset F-K Dip-Move out (DMO) was incorporated during seismic data processing, and refined velocities have been estimated after DMO correction (Liner, 1990). A brute stack seismic section was obtained by stacking the seismic data after applying normal-moveout (NMO) correction. A Stolt 3D migration scheme was adopted for post-stack time migration (PSTM) (Stolt, 1978). The processing of raw 3D seismic data was performed using ProMAX 3D software on HP Z800 workstation.

The seafloor and BSR reflections were identified and picked in the processed 3D PSTM volume using SeisWorks software on HP Z800 workstation. The BSRs were picked mainly along inlines, but were cross checked in the crosslines seismic section for continuity, and BSR have been observed on an area of ~700 km^2. The seismic data exhibits a variety of geological structures such as faults, bathymetric mounds, toe-thrust, slope basin and slumping/sliding. The picking of BSR as maximum positive amplitude (seafloor amplitude is negative in the present study) was challenging in the seismic section due to dipping reflectors, slope basin and mounds. Therefore, we choose to pick the BSR as zero-amplitude transition