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Heat flow and gas hydrate saturation estimates from Andaman Sea, India

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ABSTRACT

Gas hydrate was recovered in the Andaman Sea along the eastern coast of the Andaman Islands during the India National Gas Hydrate Program (NGHP) Expedition-01 at Site NGHP-01-17. Coring confirmed gas hydrate occurs predominantly in discrete volcanic ash layers. Pore water chemistry, electrical resistivity and P-wave velocity logs are used to estimate gas hydrate saturations at Site NGHP-01-17. Gas hydrate saturation estimated from chloride concentrations shows values up to ~85% of the pore space for distinct ash layers from ~270 m below seafloor to the base of gas hydrate stability zone (BGHSZ). Gas hydrate saturations estimated from the electrical resistivity and acoustic velocity logs using standard empirical relations and modeling approaches are comparable to each other, but saturations are only ~20% of the pore space on average. This much lower gas hydrate saturation estimate from the log data is a result of overall reduced resolution of the logging tools relative to the typically 20–30 cm thick hydrate-bearing ash layers. Available 2D multi-channel seismic data were also analyzed and a bottom-simulating reflector (BSR) was imaged along several seismic profiles. The depth of the BSR is more than 600 m along the seismic line crossing Site NGHP-01-17, which makes this one of the deepest BSRs observed worldwide. To understand the unusual depth of the BSR, we mapped its depth and estimated heat flow from the BSR depth using a simple conductive model. BSR-derived heat flow values range from ~12 to ~41.5 mW/m^2 from the study area and follow the bathymetry trend of dominant North–South ridges and can be explained with the east-ward trending increase in heat-flow toward the current seafloor spreading center. We also modeled the BGHSZ to analyze the linkage between gas hydrate occurrences in the Andaman Sea and its relation to the tectonic activity. Our analysis suggests an extensively variable BGHSZ in the Andaman Sea controlled mainly by overall low geothermal gradients. Consistent local minor variations were observed with lower heat flow values over prominent topographic highs and higher values in valleys/troughs due to focusing and defocusing effects of the topography.

1. Introduction

Gas hydrates are ice-like crystalline solid compounds of water and natural low-molecular weight gas (mainly methane) that are formed at low temperature and high pressures (e.g. Kvenvolden, 1999). Temperature, pressure, methane concentration, pore fluid salinity, and nature of gas enclosed are the main factors that influence formation of gas hydrate (Sloan and Koh, 2008). Gas hydrates are inferred and recovered worldwide along continental margins and permafrost regions where the pressure and temperature are favorable for gas hydrate stability (e.g. Kvenvolden, 1998). The thickness of the gas hydrate stability zone (GHSZ) varies widely within oceanic regions depending on the factors mentioned above. Gas hydrate occurrences are often inferred from seismic data through observations of a bottom-simulating reflector (BSR) having characteristic reverse polarity with respect to the seafloor reflection (Taylor et al., 2000; Shankar and Riedel, 2010). Additionally, a BSR often cross-cuts sedimentary reflections and is sub-parallel to the seafloor reflection on a regional scale. The BSR marks the boundary between gas hydrate bearing sediments above and free-gas-bearing sediments below (Shipley et al., 1979).

Several previous geophysical investigations (Chopra, 1985; Sethi et al., 2004) in the Andaman Sea have been carried out to study gas hydrate occurrences including deep drilling by the India National

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Gas Hydrate Program (NGHP) Expedition-01 in 2006 (Collett et al., 2008). High resolution seismic data along the Andaman Sea show major geomorphic features such as faults, turbidity channels, sedimentary ridges, and slumps/slides (Scaife et al., 2011). Widespread BSRs on multi-channel seismic (MCS) data have also been identified and used to infer the presence of gas hydrate (Chopra, 1985; Sethi et al., 2004; Satyavani et al., 2008). Some mapping of BSRs was done on selected seismic sections in the water depths ranging from 850 to 2000 m by Sethi et al. (2004) and their detailed geophysical studies show also an indication of some free gas below the BSR. High reflection amplitude BSRs were observed to be parallel to the central half graben feature of the forearc basin. Flat spots identified in some structural prospects beneath the BSRs were also suggested to represent possible gas–water contacts. Other seismic attribute analyses were performed by Satyavani et al. (2008) showing the presence of gas hydrate and free gas along a seismic transect near to Site NGHP-01-17.

The India NGHP Expedition-01 was designed to conduct scientific ocean drilling, coring, logging, and geochemical studies to assess the regional geologic context and characteristics of gas hydrate occurrences along the continental margins of India (Collett et al., 2008). Drilling was performed with the *D/V* JOIDES Resolution. During the NGHP Expedition-01, fifteen sites were drilled. Out of these fifteen sites, Site NGHP-01-17 (Fig. 1) was located in the offshore of the Andaman Islands. Down-hole continuous coring and pressure cores were acquired to recover gas hydrate samples at this site. After the coring program was completed, wire-line logging was performed to acquire geophysical data for gas hydrate characterization.

In this study we present the first detailed gas hydrate characterization of the Andaman Sea region based on seismic and borehole geophysical data. Our two main objectives are: (1) define regional heat flow estimates from the BSR depth and combine those with 1D forward modeling of the base of gas hydrate satiability zone (BGHSZ) utilizing 2D MCS data and *in situ* measurements of thermal properties; (2) Gas hydrate saturation estimates utilizing borehole data from site NGHP-01-17 using Archie's (1942) relation, acoustic modeling methods, and core-derived pore water chemistry analyses.

2. Geological setting

The Andaman Sea is situated at the eastern edge of the Bay of Bengal. The Andaman Sea is a complex, extensional active backarc basin, bounded by Myanmar on the north, Thailand and Malaysia on the east and the Andaman and Nicobar Islands on the west (Fig. 1). The convergent-oblique movement of the Indian plate as it subducts underneath the Burma plate, causes compressive north–south wrench tectonics (Alam et al., 2003). The backarc system developed when the overriding plate was stretched and rifted, causing the creation of two distinct plates, the Sunda plate and the Burma plate with an intervening spreading center. Backarc spreading began in the early Miocene, approximately 25 Ma. Current plate boundaries were defined about 3 Ma (Curray, 1991). The plates are currently separating at a rate of 3.76 cm/yr (Kamesh Raju et al., 2004). The Andaman Basin is believed to have been formed by the spreading activity in the Central Andaman Trough (Kamesh Raju et al., 2004). Subduction of the Indo-Australian plate beneath the Southeast Asian plate occurs along the entire Sunda arc (Whittaker et al., 2007), resulting in oblique convergence in the Andaman-Nicobar sector. The effects of this oblique subduction include strike-slip faulting parallel to the trench axis and formation of the backarc extension and basin (Eguchi et al., 1979).

The accumulation of a thick column of sediment during accretion in the subduction zone resulted in the development of folding, faulting, and overall deformation of the sediments allowing the formation of anticline and syncline structures. The tectonic stresses induced by the oceanic lithospheric subduction and the sediment accretion progressively typically remove the original bedding in the subduction complex and sediments with potentially high organic content are transported to greater depths beneath the forearc through sediment accretion. These sediments could account for the generation of biogenic gases and methane produced under reducing environments (Chopra, 1985). The tectonic deformation creates possible migration pathways for free gas through the pervasively fractured rocks of the subduction complex. The released gas can subsequently form gas hydrates upon entering the GHSZ. However, there was no notable faulting allowing such deep-rooted fluid migration near Site NGHP-01-17. Analyses of the recovered core rather suggest *in situ* degradation of organic material as major mechanism for methane generation and gas hydrate formation. This type of *in situ* production of methane for local highly concentrated gas hydrate accumulations within the coarser fraction of the sediment column formed by sandy turbidites was also suggested for the accretionary complex off Vancouver Island by Malinverno (2010) as discussed further below.

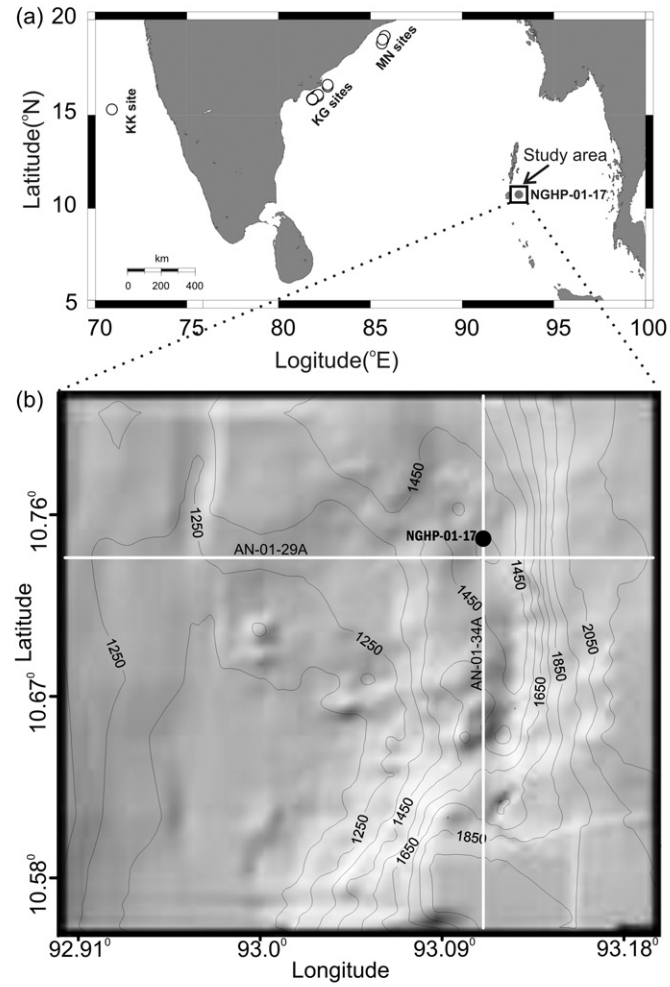

Figure 1. (a) Map of study area showing the location of the drilling transect across the Andaman Sea drilling site NGHP-01-17 targeted during NGHP Expedition-01. (b) Detail bathymetry derived from multi-channel seismic (MCS) data superimposed on shaded relief map with drill site location (black filled circle) of Site NGHP-01-17. The solid lines marks the transect MCS line AN-01-34A, which across the drilling site and an adjacent cross line AN-01-29A are shown. The water depth at Site NGHP-01-17 is ∼1344 m.

The overall sediment flux that is received in the Indian offshore is large, between 1 and 2 billion tons of sediments exported each