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# The structure of methane gas hydrate bearing sediments from the Krishna–Godavari Basin as seen from Micro-CT scanning

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ABSTRACT

The Indian National Gas Hydrate Program (NGHP) Expedition 1, of 2006, cored through several methane gas hydrate deposits on the continental shelf around the coast of India. The pressure coring techniques utilized during the expedition (HYACINTH and PCS) enabled recovery of gas hydrate bearing, fine-grained, sediment cores to the surface. After initial characterization core sections were rapidly depressurized and submerged in liquid nitrogen, preserving the structure and form of the hydrate within the host sediment. Once on shore, high resolution X-ray CT scanning was employed to obtain detailed three-dimensional images of the internal structure of the gas hydrate. Using a resolution of 80 μm the detailed structure of the hydrate veins present in each core could be observed, and allowed for an in depth analysis of orientation, width and persistence of each vein. Hydrate saturation estimates could also be made and saturations of 20–30% were found to be the average across the core section with some portions showing highs of almost 60% saturation. The majority of hydrate veins in each core section were found to be orientated between 50 and 80° to the horizontal. Analysis of the strikes of the veins suggested a slight preferential orientation in individual sample sections, although correlation between individual sections was not possible due to the initial orientation of the sections being lost during the sampling stage. The preferred vein orientation within sample sections coupled with several geometric features identified in individual veins, suggest that hydraulic fracturing by upward advecting pore fluids is the main formation mechanism for the veined hydrate deposits in the K–G Basin.


## 1. Introduction

An abundant source of methane ($CH_4$) gas, in the form of gas hydrates, is stored within shallow permafrost regions, and deep ocean sediments on our continental margins. Gas hydrates exist as a crystalline ice-like solid within the pore space of these sediments under a restricted range of pressures and temperatures. If these conditions are sufficiently altered, dissociation will cause gas hydrate to revert back to its constituent parts of gas and water. Gas hydrates are of increasing worldwide interest because of their potential as a future energy resource (Dawe and Thomas, 2007; Makogon et al., 2007); a driver for global climate change (Dickens et al., 1995; Jahren et al., 2001); or their impact as a geotechnical hazard (Ashi, 1999; Paull et al., 2000).

Due to the remote and difficult environments in which subsea gas hydrates exist, geophysical techniques are used to help infer their distribution and volume within sediments (Pecher and Holbrook, 2000). To interpret the data from such surveys requires an understanding of the interaction between gas hydrate and sediment, which is usually based on assumed model parameters. The models therefore require information on the host sediment properties, which are ideally obtained through direct sampling at depth. Historically the recovery of gas hydrate bearing sediments from deep water marine environments has been problematic due to the thermobaric nature of gas hydrates (Dickens et al., 2000). The reduction in hydrostatic pressure during core recovery leads to dissociation of the hydrate which disturbs and alters the original state of the sediment (Kneafsey et al., 2011). In addition, methane solubility significantly reduces with declining pressure, leading to exsolution. Therefore obtaining samples of intact naturally occurring gas hydrate bearing sediments, and quantification of the hydrate present within the sediment, has not been possible using conventional coring techniques.

In order to address some of these sampling issues, pressure coring systems which enable gas hydrate bearing sediment

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samples to be recovered under in-situ pressures have been developed. Careful recovery and handling procedures can further reduce temperature induced gas hydrate instability during core recovery so that minimal disturbance occurs to the structure of the sediment. Several alternative pressure coring systems have been developed in recent years such as the IODP Pressure Core Sampler (PCS), the HYACINTH Fugro Pressure Corer (FPC) and the HYACE Fugro Rotary Pressure Corer (FRPC) (Schultheiss et al., 2008). Each system allows for recovery of a sediment core under hydrostatic pressure (PCS has a maximum hydrostatic pressure limit of 69 MPa, the HRC and FRPC are limited to 25 MPa), and all have been deployed on numerous drilling programs such as the Ocean Drilling Program (ODP) Leg 204 (Tréhu et al., 2003), International Ocean Drilling Program (IODP) Expedition 311 (Riedel et al., 2006), Indian National Gas Hydrate Program (NGHP) 01 Expedition (Collett et al., 2008) and the recent South Korean Ulleung Basin Gas Hydrate Expedition 1 (UBGH1) (Park et al., 2008).

The two most recently developed systems, the FPC and FRPC, have been designed so that once at the surface, the pressurized core barrel can be transferred under pressure into the Geotek Pressure Core Analysis and Transfer System (PCATS). Geophysical properties of the intact sediment under hydrostatic pressure, as well as the spatial variation of the hydrate within a sample, can then be determined using the MSCL–P (Multi Sensor Core Logger–Pressure) which is a component of the PCATS. The system therefore allows for information on gas hydrate host sediments to be collected whilst under pressure, and further applications to the PCATS are currently being developed to allow more detailed testing on such samples.

In 2006, the Indian National Gas Hydrate Program (NGHP) embarked upon an expedition to investigate the methane hydrate resource on the continental shelf surrounding the Indian peninsula. In total, twenty-one Sites were drilled, with 13 Sites being identified as containing gas hydrates, where the hydrate resided in sands and fine grained sediments. The most significant accumulation was found in the Krishna–Godavari Basin, on the eastern margin of the Indian peninsula. Figure 1 shows the location of the accumulation at Site NGHP-1–10 in a water depth of 1049 m, where the hydrate was found to be in a deposit up to 130 m thick (Collett et al., 2008). Extensive sampling and pressure coring showed the hydrate to occur as discrete lenses and nodules that formed an interconnected vein or fracture network (Collett et al., 2008). There have since been a number of studies documenting the gas hydrate fracture system in an attempt to understand hydrate formation mechanisms (Cook and Goldberg, 2008; Daigle and Dugan, 2010; Riedel et al., 2010), and hydrate saturation estimates under such conditions (Cook et al., 2010; Ghosh et al., 2010; Lee and Collett, 2009).

The analysis by Cook and Goldberg (2008) utilized 360° resistivity data of the borehole wall during LWD to produce resistivity "images". These images highlight hydrate fractures as bright sinusoids when the borehole cylinder is unwrapped, and can therefore be used to identify the orientation and dip of fractures that cross cut the borehole (Cook and Goldberg, 2008). Riedel et al. (2010) utilized the same technique, but also obtained larger scale 3-D seismic data to analyze fault activity in the area. From both these analyses, Cook and Goldberg (2008) and Riedel et al. (2010) noted an abundance of high angle, sub vertical fractures with slight preferential orientation, but an overall widespread of strike directions in the region of Site NGHP-1–10.

Numerous pressure cores were taken at Site 10, and after initial characterization within the PCATS system, two cores were rapidly depressurised and sub-sectioned, wrapped in aluminium foil and placed in a canvas bag prior to being stored in liquid nitrogen. Core NGHP-01-10B-08Y was recovered using the FPC corer with a total length of 86 cm from a depth of 50.1 m below sea floor (from the top of core). This core was notionally sub-sectioned into four lengths of 6–26 cm, 26–46 cm, 46–66 cm and 66–86 cm. A further sample (core NGHP-01-21C-02E) was obtained from Site 21, located 20 m SE of Site 10 (see Fig. 1), which was drilled in an effort to further define the hydrate occurrence at Site 10, but also to obtain additional pressure cores for post cruise analysis. This core was recovered using the HRC corer with a total length of 110 cm being recovered from a depth of 56.5 m below sea floor (from the top of core). One section of the core from 23 to 46 cm was sectioned for characterisation. The sub-sectioned samples were under atmospheric pressure for a maximum period of 90 s before freezing, thus limiting the degree of dissociation.

This paper reports on the results of a detailed analysis into the 3-D structure and fabric of gas hydrates within fine grained sediments of the Krishna–Godavari Basin using high resolution X-ray computed tomography. From the resultant reconstructed images, estimates of

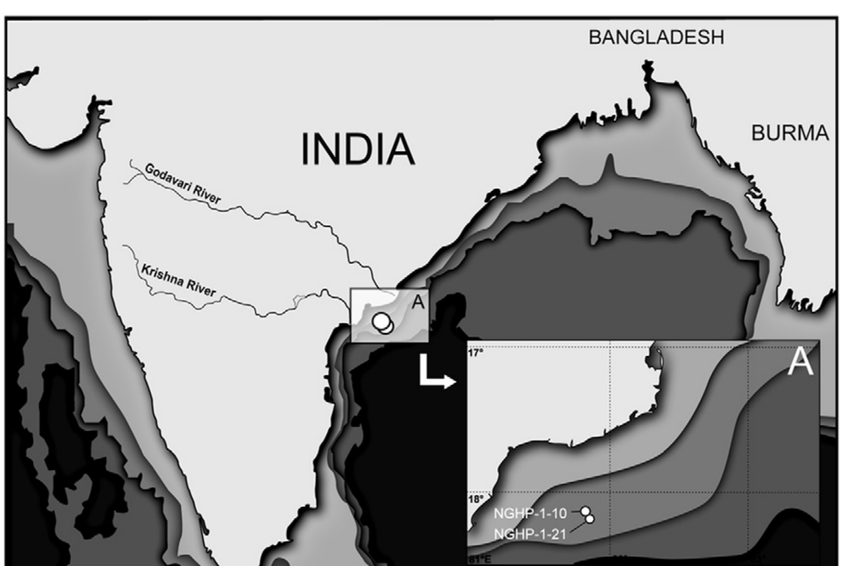


**Figure 1.** Site map of the NGHP-1 drill Sites 10 and 21.