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INDIAN CONTINENTAL MARGIN GAS HYDRATE PROSPECTS: RESULTS OF THE INDIAN NATIONAL GAS HYDRATE PROGRAM (NGHP) EXPEDITION 01

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ABSTRACT

Studies of geologic and geophysical data from the offshore of India have revealed two geologically distinct areas with inferred gas hydrate occurrences: the passive continental margins of the Indian Peninsula and along the Andaman convergent margin. The Indian National Gas Hydrate Program (NGHP) Expedition 01 was designed to study the gas hydrate occurrences both spatially and temporally off the Indian Peninsula and along the Andaman convergent margin with special emphasis on understanding the geologic and geochemical controls on the occurrence of gas hydrate in these two diverse settings. During NGHP Expedition 01, dedicated gas hydrate coring, drilling, and logging operations were conducted from the 28th April, 2006 to the 19th August, 2006. NGHP Expedition 01 established the presence of gas hydrates in Krishna-Godavari, Mahanadi and Andaman basins. The expedition discovered one of the richest gas hydrate accumulations yet documented (Site 10 in the Krishna-Godavari basin), documented the thickest and deepest gas hydrate stability zone yet known (Site 17 in Andaman Sea), and established the existence of a fully-developed gas hydrate system in the Mahanadi basin (Site 19).

Keywords: NGHP, gas, gas hydrate, production, resources, drilling, coring, logging

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INTRODUCTION

The primary goal of the Indian National Gas Hydrate Program (NGHP) Expedition 01 was to conduct scientific ocean drilling/coring, logging, and analytical activities to assess the geologic occurrence, regional context, and characteristics of gas hydrate deposits along the continental margins of India in order to meet the long term goal of exploiting gas hydrates as a potential energy resource in a cost effective and safe manner.

NGHP Expedition 01 was planned and managed through a collaboration between the Directorate General of Hydrocarbons (DGH) under the Ministry of Petroleum and Natural Gas (India), the U.S. Geological Survey (USGS), and the Consortium for Scientific Methane Hydrate Investigations (CSMHI) led by Overseas Drilling Limited (ODL) and FUGRO McClelland Marine Geosciences (FUGRO). The platform for the drilling operation was the research drill ship *JOIDES Resolution (JR)*, operated by ODL. Much of the drilling/coring equipment used was provided by the Integrated Ocean Drilling Program (IODP) through a loan agreement with the US National Science Foundation (NSF). Wireline pressure coring systems and supporting laboratories were provided by IODP/Texas A&M University (TAMU), FUGRO, USGS, U.S. Department of Energy (USDOE) and HYACINTH/GeoTek. Downhole logging operational and technical support was provided by Lamont-Doherty Earth Observatory (LDEO) of Columbia University.

During its 113.5-day voyage (Figure 1, Table 1), the *JR* cored or drilled 39 holes at 21 sites (one site in Kerala-Konkan, 15 sites in Krishna-Godavari, four sites in Mahanadi and one site in Andaman deep offshore areas), penetrated more than 9,250 m of sedimentary section and recovered nearly 2,850 m of core. Twelve holes were logged with logging-while-drilling tools and an additional 13 holes were wireline logged. NGHP Expedition 01 was among the most complex and comprehensive methane hydrates field ventures yet conducted. The science team utilized extensive on-board lab facilities to examine and prepare preliminary reports on the physical properties, geochemistry, and sedimentology of all the data collected prior to the end of the expedition. All of the primary data collected during NGHP Expedition 01 are included in either the NGHP Expedition 01 Initial Reports [1] or the NGHP Expedition 01 Downhole Log Data Report [2]; which were prepared by the USGS and published by the DGH on behalf Ministry of Petroleum & Natural Gas (India).

EXPEDITION PLANNING AND EXECUTION

Pre-expedition geologic studies of available seismic and industry well data yielded a total of 12 proposed drill sites, exhibiting variable geologic conditions and seismic responses indicative of gas-hydrate-bearing sediments: one site in the Kerala-Konkan area on the west coast of India; eight sites on the east coast of India including six sites in the Krishna-Godawari Basin, and two sites in the Mahanadi area; and one drill site proposed for the convergent margin setting of the Andaman Islands.

For organizational purposes this project was divided into a series of three phases:

- Phase-I. Project Planning and Mobilization**:** This project started with the mobilization of the scientific ocean drilling vessel *JOIDES Resolution*, from Galveston, Texas to Mumbai, India; and the staffing of the science team and the development of a project prospectus.

- Phase-II. Field Project Management, Operations and Research**:** The operational phase of NGHP Expedition 01 began with the arrival of the scientific crew in Mumbai, India on April 28, 2006 and ended 113.5 days later with the departure of ship from its final berth in Chennai on August 19, 2006. The expedition consisted of five separate "legs" as follows:

  - Leg 1 (April 28-May 16): Sailed southwest from Mumbai to a location in the Kerala-Konkan Basin, Arabian Sea; conducted drilling, logging, and coring operations; then sailed around the southern tip of India to port in Chennai.

  - Leg 2 (May 17-June 6): Conducted personnel and equipment transfers in Chennai, then sailed to ten sites in the Krishna-Godhawari and Mahandi basins;

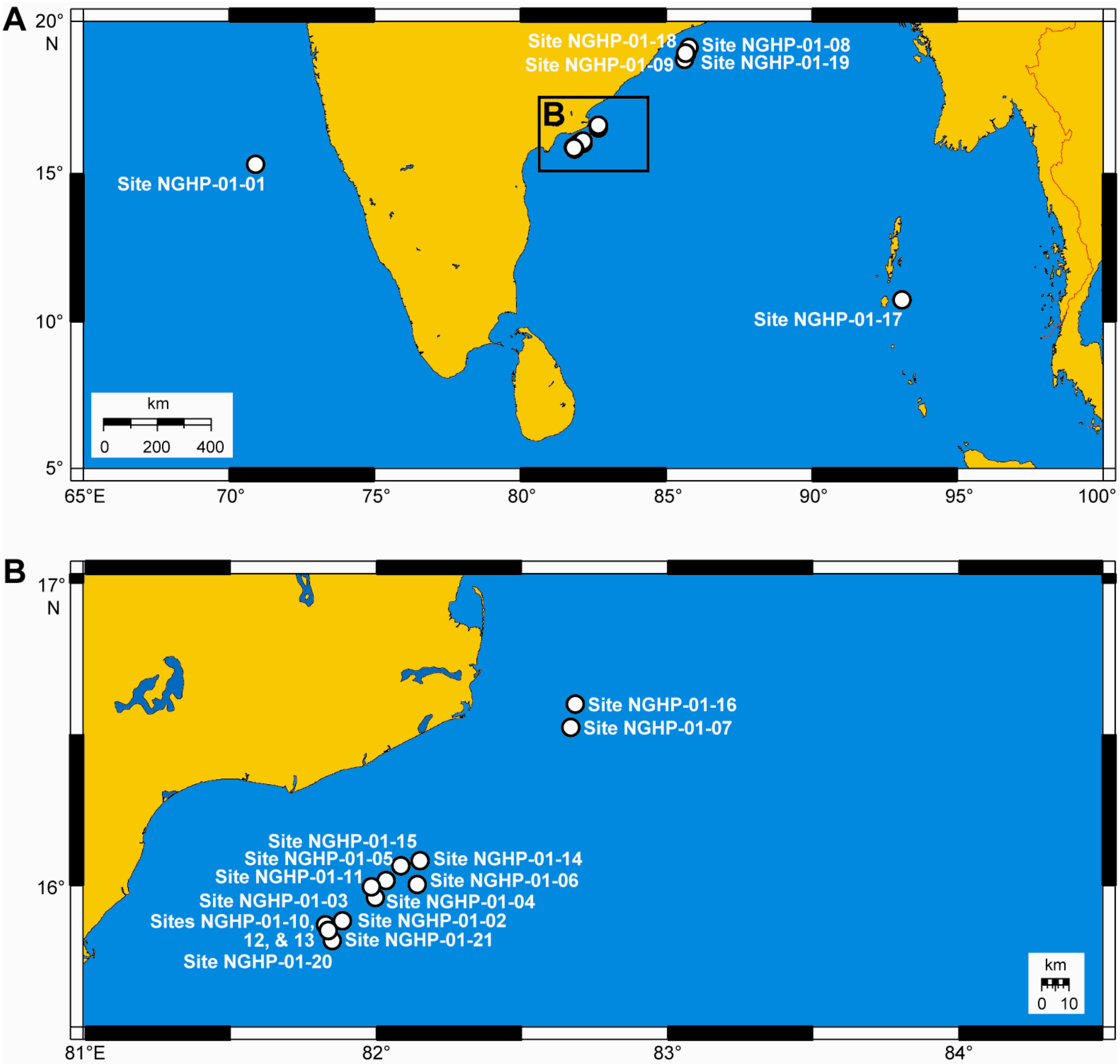

Figure 1. (A) NGHP Expedition 01 site map depicting the location of the 21 research drill sites established during the expedition. (B) Insert map of the drill sites in the Krishna-Godawari Basin [1].

conducted logging-while-drilling (LWD) operations; returned to Chennai.

- Leg 3A (June 7-June 25): Informed with the LWD results, the crew sailed to a total of four selected sites within Krishna-Godhawari basin for drilling, coring, and logging operations, before returning to Chennai for personnel and equipment transfers.

- Leg 3B (June 26-July 17): Conducted additional drilling, coring, and logging operations at five additional sites within the Krishna-Godhawari region.

- Leg 4: (July 18-August 19): After personnel transfers via helicopter, the team sailed east and cored and logged a site east of Little Andaman Island, then traveled northwest to two sites within the Mahanadi Basin, then moved southwest to further explore two additional sites within the Krishna-Godhawari Basin, before finally sailing to Chennai. Drilling, coring, and logging operations were conducted at each site during Leg 4.

• Phase-III. Demobilization and Collaborative Post-Field Project Analysis of Geologic Data and Samples (ongoing): The project included a wide range of collaborative post-field analysis of samples collected during the expedition and reporting of the geologic results of this effort. Phase-III also provided for the publication of the NGHP Expedition 01 Initial Results volume [1].

The pre-expedition site review and selection process first focused on the occurrence of seismic identified bottom-simulating reflectors (BSRs) which were inferred to indicate the occurrence of gas hydrate. In addition, the sedimentary section above the BSR was further examined for evidence of potential gas hydrate occurrences. Recent studies of 2D and 3D seismic data and drilling results from northern Alaska and Canada have led to the development of viable methods for identifying concentrated gas hydrate occurrences in sand reservoirs. In general, it has been shown that high amplitude seismic events within the expected gas hydrate stability zone can reveal the occurrence of relatively thick, highly saturated gas hydrate reservoirs. Thus, in the NGHP Expedition 01 site review process, special attention was given to identifying high amplitude stratigraphic and/or structurally controlled features within the available 2D seismic database. The site review process also incorporated conventional oil and gas seismic-stratigraphic exploration concepts. One of the primary gas hydrate reservoir targets were considered to be the prominent fan cut-and-fill channel features along the eastern margin of India. Within this expedition, several apparent large shelf margin canyon fill depositional sequences were targeted.

EXPEDITION SCIENTIFIC RESULTS

One of the specific sets of objectives of this expedition was to test gas hydrate formation models and constrain model parameters, especially those that account for the formation of concentrated gas hydrate occurrences. During the 113.5 days of NGHP Expedition 01, 39 holes were cored/drilled at 21 sites (Figures 1 and 2, Table 1). The necessary data for characterizing the occurrence of in-situ gas hydrate such as interstitial water chlorinities, core-derived gas chemistry, core physical properties, IR thermal images of the recovered core, and downhole measured logging data (LWD-MWD and/or conventional wireline log data) were obtained from most of the research sites established during NGHP Expedition 01. Most all of the sites established during NGHP Expedition 01, except for Site NGHP-01-01, yielded some evidence for the occurrence of gas hydrate. However, the inferred in-situ concentration of gas hydrate varied significantly from site-to-site.

In recent years significant progress has been made in addressing key issues on the formation, occurrence, and stability of gas hydrate in nature. The concept of a “gas hydrate petroleum system” is gaining acceptance. In a “gas hydrate petroleum system”, the individual factors that contribute to the formation of gas hydrate occurrences, such as (1) gas hydrate pressure-temperature stability conditions, (2) gas source, (3) gas and water migration efficiencies, and (4) growth of the gas hydrate in suitable host sediment or “reservoir”, are identified and quantified. In the following technical summary, these geologic controls on the stability and formation of gas hydrates will be

Prospectus Designation	Leg	Site Number	Water Depth (m)	Dpeth to base of Methane hydrate Stability Zone (mbsf)	BSR Depth (mbsf)	Dominent Sedieement Type	Gas Hydrate Reservoir Type	Gas Source
KKGH01	1	NGHP-01-01	2663	360	no BSR	Carbonate oozes	None	None
KGGH03-A	2	NGHP-01-02	1058	NA	170	Clay/silt	Combination	Microbial
GDGH05-A	2	NGHP-01-03	1076	203	209	Clay with silt/sand beds	Silt/Sand	Microbial
KGGH01	2	NGHP-01-04	1081	NA	182	Clay/silt	Combination	Microbial
KGGH02-A	2	NGHP-01-05	945	130	~125	Clay with silt/sand beds	Combination	Microbial
KGGH04	2	NGHP-01-06	1160	NA	210	Clay/silt	Combination	Microbial
KGGH06-A	2	NGHP-01-07	1285	198	188	Clay with silt/sand beds	Combination	Microbial
MNGH01-1-A	2	NGHP-01-08	1689	NA	257	Clay/silt	Combination	Microbial
MNGH-01-2	2	NGHP-01-09	1935	NA	~290	Clay/silt	Combination	Microbial
KGGH03-A	2	NGHP-01-10	1038	160	~160	Clay/silt	Fracture	Microbial
GDGH12-A	2	NGHP-01-11	1007	NA	150	Clay/silt	Combination	Microbial
KGGH03-A	3A	NGHP-01-12	1038	NA	~160	Clay/silt	Fracture	Microbial
KGGH03-A	3A	NGHP-01-13	1038	NA	~160	Clay/silt	Fracture	Microbial
GDGH14-A	3B	NGHP-01-14	895	150	109	Clay with silt/sand beds	Silt/Sand	Microbial
GDGH11	3B	NGHP-01-15	926	126	126	Clay with silt/sand beds	Silt/Sand	Microbial
Stepout	3B	NGHP-01-16	1253	178	170	Clay with silt/sand beds	Silt/Sand	Microbial
ANGH01	4	NGHP-01-17	1344	620	~608	Clay/silt with volcanic ash beds	Silt/Ash	Micro/Thermo
MNGH-REL 5	4	NGHP-01-18	1374	210	~210	Clay/silt	Clay/silt?	Micro/Thermo
MNGH-Gap	4	NGHP-01-19	1422	220	205	Clay with silt/sand beds	Silt/Sand	Micro/Thermo
KGGH05	4	NGHP-01-20	1146	NA	~220	Clay with silt/sand beds	Silt/Sand	Microbial
KGGH03-A	4	NGHP-01-21	1049	NA	~160	Clay/silt	Fracture	Microbial

Table 1. NGHP Expedition 01 site summary data, including listing of pre-expedition prospectus site designation, leg number, site number, water depth as determined by drilling or coring, depth to the base of methane hydrate stability zone, depth of the seismic identified bottom simulating reflector (BSR), dominant sediment type at each site as determined by coring or inferred from downhole log data, gas hydrate reservoir type as determined from various data sources, and predicted gas source. Combination = silt/sand and fracture reservoirs [1].

reviewed and assessed for the drill sites established during NGHP Expedition 01.

Gas hydrate stability conditions

NGHP Expedition 01 featured 76 temperature tool deployments in an attempt to characterize the thermal regime of the sites occupied during the expedition (Table 1). Two standard IODP temperature tools were deployed during the expedition, including the APCT (eight times) and the DVTP (44 times). We also deployed the new APCT-3 tool 24 times.

The downhole temperature data collected during the expedition was used to calculate the depth to the base of the gas hydrate stability zone (GHSZ) at most of the sites that were continuously cored. Gas hydrate exists under a limited range of temperature and pressure conditions such that the depth and thickness of the zone of the GHSZ can be calculated. Most gas hydrate stability studies assume that the pore pressure gradient is hydrostatic (9.795 kPa/m). However, the seafloor temperature and geothermal gradient for any given site can be highly variable. The temperature data acquired during this expedition have been used to make a preliminary estimate of the depth to the base of the GHSZ at each site. In this study a pure methane hydrate was assumed and a porewater salinity of 35 ppt were used to estimate the depth to the base of the GHSZ at a total of 11 sites established during NGHP Expedition 01 and reported in Table 1. For the most part, the calculated depth to the base of the GHSZ for each site falls near the estimated depth of the BSR as inferred from seismic data. In the case of Site NGHP-01-14, however, it appears that the estimated depth of the BSR is much less than what would be expected from the gas hydrate stability calculations.

Gas source

The availability of large quantities of hydrocarbon gas from either microbial or thermogenic sources or both is an important factor controlling the formation and distribution of natural gas hydrate. Stable carbon isotope analyses indicate that the methane in most oceanic gas hydrate is derived from microbial sources; which appears to be also true for most of the gas hydrate occurrences discovered on NGHP Expedition 01 based on preliminary analyses of gas molecular and isotopic compositions (Table 1). However, shipboard compositional gas analyses may indicate a thermal origin for a portion of the gas in the gas hydrate occurrences in the Mahanadi Basin (Sites NGHP-01-18 and NGHP-01-19) and in the Andaman deep offshore area (Site NGHP-01-17).

Gas and water migration efficiencies

Geologic controls on fluid migration limit the availability of gas and water for the formation of gas hydrate. If migration pathways are not available, it is unlikely that a significant volume of gas hydrate would accumulate. Therefore, geologic parameters such as water and gas chemistry, as well as sediment permeability and the nature of sediment faulting must be evaluated to determine if the required gas and water can be delivered to the sedimentary section potentially hosting gas hydrate.

At a regional scale, especially in the Krishna-Godawari Basin, the occurrence of gas hydrate appears to be closely associated with large scale structural features. For example, the fractured controlled gas hydrate accumulation at Site NGHP-01-10 is found at the crest of a relatively large, tightly folded, ridge structure and the occurrence of gas hydrate appears to be controlled by gas flux through the local fracture system generated by the regional stress regime.

At a macroscopic to microscopic scale, the analysis of IR images of conventional cores, X-ray images of pressure cores, downhole LWD derived resistivity images and visual observations of cores upon recovery reveal the occurrence of gas hydrate in the offshore of India in a wide range of conditions. In general, most of the recovered gas hydrate was characterized as either pore-filling grains or particles disseminated in coarser grain sediments or as a fracture-filling material in clay dominated sediments. These observations further indicate the apparent need for effective migration conduits, such a fractures and stratigraphically controlled carrier beds, to deliver and concentrate the gas required for the formation of the observed gas hydrate occurrences.

Yet to be completed (post-expedition) detailed analysis of gas and interstitial water samples will give us additional important insight into fluid and gas sources and their migration within the offshore sediment of India.

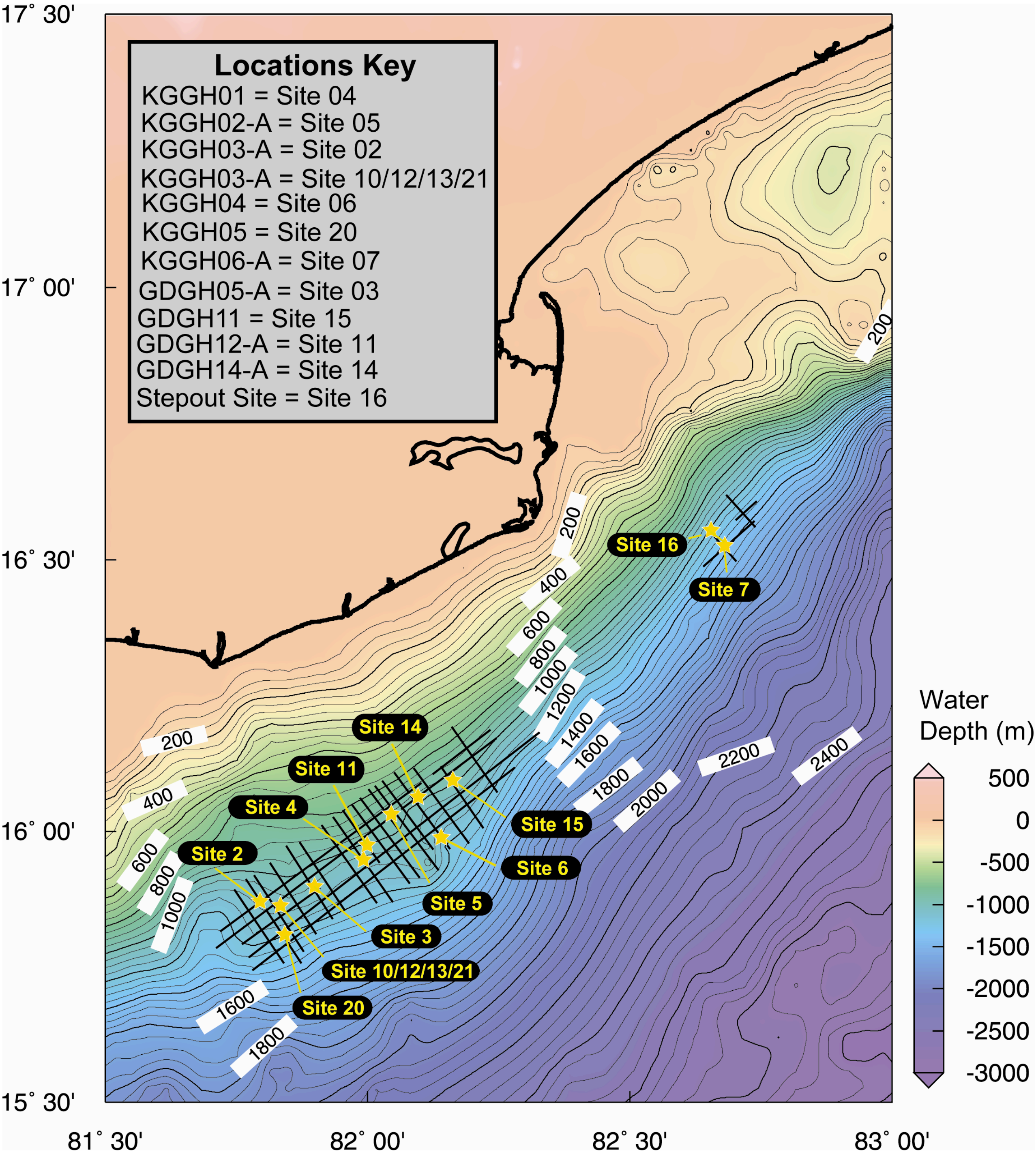

Figure 2. NGHP Expedition 01 site map depicting the location of the research drill sites established in the Krishna-Godawari Basin [1].

Gas hydrate “reservoir”

For the most part, the interpretation of downhole logging data and linked IR imaging, interstitial water analyses, and pressure core imaging from the sites drilled during NGHP Expedition 01 indicate that the occurrence of concentrated gas hydrate is mostly controlled by the presence of fractures and/or coarser grained (mostly sand-rich) sediments.

As reviewed in Table 1, the occurrence of highly concentrated gas hydrate accumulations at Sites NGHP-01-3, -5, -7, -14, -15, -16, -17, -19, and -20 are partially controlled by the presence of suitable host (reservoir) sands. Gas hydrates in reservoir-quality sands are best known from the Arctic. However, there are also documented cases of marine sands with high gas hydrate saturations. Examples include the Nankai Trough gas hydrate discoveries, and hydrate occurrences at the Ocean Drilling Program (ODP) Leg 204 and Integrated Ocean Drilling Program (IODP) Expedition 311 sites off the Pacific coast of North America. These results suggest that one of the primary controls on the degree of gas hydrate saturation is reservoir lithology.

In the case of Sites NGHP-01-10, -12, -13, and -21, however, the recovered gas hydrate occurs as fracture filling material. The majority of marine gas hydrate systems that have been studied to date are fine-grained, clay-dominated and are associated with surficial gas seeps. The discovery of the 130-m-thick fracture controlled gas hydrate accumulation at Site NGHP-01-10 also appears to occur within a fractured clay-dominated system in which gas hydrate is concentrated in vertical and subvertical gas conduits that at one time was connected to a seafloor seep.

Further analysis of the downhole acquired borehole resistivity images from other sites (Sites NGHP-01-2, -4, -5, -6, -7, -8, -9, and -11) indicate that many of the individual, apparent stratigraphically controlled disseminated gas hydrate occurrences, actually occur in “combination reservoirs” consisting of horizontal or subhorizontal coarse grained permeable sediment beds (sands for the most part) and apparent vertical to subvertical fractures that provide the conduits for gas migration.

In a recent review article by Boswell et al [3], four different marine gas hydrate play types were identified: (1) sand-dominated reservoirs; (2) clay-dominated fractured reservoirs, (3) massive gas hydrate formations exposed on the seafloor; and (4) low-concentration disseminated deposits encased in largely impermeable clays. The first two of these play types, which also occur in the offshore of India, we described as worthy of further exploration “as both provide the bulk permeability necessary for the high gas hydrate concentrations”. Boswell et al [3] also notes that these two play types are often closely related and found in combination, which is again similar to the results of the NGHP Expedition 01 effort.

Sand, fractured clay, and combination reservoirs are the primary emerging economic targets for gas hydrate production. Because conventional marine exploration and production technologies favor the sand-dominated gas hydrate reservoirs, investigation of sand reservoirs will likely have a higher near-term priority in the NGHP program. It is perceived that the NGHP effort will likely include future drilling, coring, and field production testing. It has been concluded that Site 10 represents a world class shale dominated fracture gas hydrate reservoir, worthy of further investigation. NGHP Expedition 01 also discovered significant sand and silt dominated gas hydrate reservoirs. It has been proposed that in a 2009-2010 time-frame, NGHP Expedition 02 may be constituted to drill and log several of the most promising sand dominated gas hydrate prospects.

Summary

The operational highlights of NGHP Expedition 01 included the following:

- 113.5 days of operation without any reportable injury or incident.
- Only 1% of total operation time was down time due to equipment malfunction or weather.
- Examination of 9,250 m of sedimentary section at 39 locations within 21 sites located in four geologically-distinct settings.
  - Collected LWD log data in 12 holes at 10 sites.
  - Collected wireline log data at 13 sites.
  - Collected vertical seismic profile data at six sites.

- Collected 494 conventional cores, encompassing 2,850 m of sediment, from 21 holes (78% overall recovery).
  - Collected detailed shallow geochemical profiles at 13 locations.
  - Established temperature gradients at 11 locations.
- Extensive sample collection to support a wide range of post-cruise analyses, including:
  - Collected about 6,800 whole round core samples for examination of interstitial water geochemistry, microbiology, and other information.
  - Collected more than 12,500 core subsamples for paleomagnetic, mineralogical, paleontological, and other analyses.
  - Collected about 140 gas-hydrate-bearing sediment samples for storage in liquid nitrogen.
  - Collected five one-meter-long gas-hydrate-bearing pressure cores for analysis of the physical and mechanical properties of gas-hydrate-bearing sediment.
  - Collected 21 re-pressurized cores (nine representing sub-samples from gas-hydrate-bearing pressure cores).
- Conducted 97 deployments of advanced pressure coring devices, resulting in the collection of 49 cores that contain virtually undisturbed gas hydrate in host sediments at near *in situ* pressures.

The key scientific highlights of NGHP Expedition 01 included the following:

- Conducted comprehensive analyses of gas-hydrate-bearing marine sediments in both passive continental margin and marine accretionary wedge settings.
- The calculated depth to the base of the methane hydrate stability zone, as derived from downhole temperature measurements, closely matches the depth of the seismic identified bottom simulating reflectors (BSRs) at most of the sites established during this expedition.
- Discovered gas hydrate in numerous complex geologic settings and collected an unprecedented number of gas hydrate cores.
- Most of the recovered gas hydrate was characterized as either pore-filling grains or particles disseminated in coarser grain sediments or as a fracture-filling material in clay dominated sediments.
- The occurrence of concentrated gas hydrate is mostly controlled by the presence of fractures and/or coarser grained (mostly sand-rich) sediments.
- Gas hydrate were found occurring in “combination reservoirs” consisting of horizontal or subhorizontal coarse grained permeable sediments (sands for the most part) and apparent vertical to subvertical fractures that provide the conduits for gas migration.
- Delineated and sampled one of the richest marine gas hydrate accumulations yet discovered (Site NGHP-01-10 in the Krishna-Godovari Basin).
- Discovered one of the thickest and deepest gas hydrate occurrences yet known (offshore of the Andaman Islands, Site NGHP-01-17) which revealed gas-hydrate-bearing volcanic ash layers as deep as 600 meters below the seafloor.
- Established the existence of a fully developed gas hydrate system in the Mahanadi basin of the Bay of Bengal.
- Most of the gas hydrate occurrences discovered during this expedition appear to contain mostly methane which was generated by microbial processes. However, there is also evidence of a thermal origin for a portion of the gas within the hydrates of the Mahanadi Basin and the Andaman offshore area.
- Gas hydrate in the Krishna-Godawari Basin appears to be closely associated with large scale structural features, in which the flux of gas through local fracture systems, generated by the regional stress regime, controls the occurrence of gas hydrate.

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