

## **Gas hydrate occurrence in the Krishna–Godavari Basin offshore, East coast of India**

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India is blessed with adequate reserves of coal and hydro resource whereas the conventional hydrocarbon (oil and gas) reserves so far estimated are inadequate to meet the growing demand of this country. Latest estimates indicate that India has around 0.4% of the world's proven reserves of crude oil and natural gas and against this the domestic consumption is estimated at 2.8% of the world's consumption. The balance of recoverable reserves, estimated at the beginning of 2001, is 733.70 million metric tonnes (MMT) of crude and 749.65 billion cubic metres (BCM) of natural gas. Crude oil demand is currently about 146 MMT against the domestic production of 34 MMT only. Similarly, the natural gas demand is currently about 179 million metric standard cubic meters per day (MMSCMD) against the domestic supply of about 80 MMSCMD. India's crude oil import dependency from the current level of 72% is likely to increase to 90% by 2025. India's domestic natural gas demand will show a breakaway growth with demand rising to 200 mm cubic meters per day (cmpd) from the present 70 mm cubic meters per day (cmpd). However, the additional gas production from the new finds, such as the one made by Reliance Industries in the Krishna-Godavari offshore, may still not be able to meet the entire requirement, since the power sector and fertilizer units likely consume >74% and the balance 26% of the projected demand by the other industries, transport and domestic use. This huge demand requires to be met either from the imports or increase in domestic production and switching over to other non conventional energy fuels. One such non-conventional fuel is methane gas stored in gas hydrate deposit. Significance of this gas hydrate is that its abundant availability in the shallow marine sediments of slope, and on dissociation 1 cubic meter of gas hydrate yields nearly 164 cubic meters of pure methane gas and about 0.8 cubic meters of fresh water. Ministry of Petroleum and Natural Gas (MoP&NG), Government of India initiated in 1996 with an ambitious plan of exploring gas hydrate deposits within the Indian continental margins to meet partly the projected demand-supply gap of fossil fuels. Continuous efforts of Indian scientific community and oil industry culminated at identification of most probable areas for detail exploration. One such promising area is the Krishna-Godavari offshore, eastern continental margin of India. Some results of this initiative under Indian National Gas Hydrate Program (NGHP) are presented in this report.

## Introduction

Gas hydrate has received global attention as a possible alternative non-conventional energy resource due to its tremendous holding capacity of pure form of methane under suitable low temperature and high pressure conditions in the permafrost and continental slope areas. Gas hydrate, or clathrate, is a crystalline molecular complex formed from mixtures of water and suitably sized gas molecules. Water crystallizes in the cubic crystallographic system, and forms a cage-like structure around a smaller 'guest molecule' such as methane, ethane, propane, isobutene, normal butane, nitrogen, carbon dioxide and hydrogen sulphide, of which methane is the most common<sup>1,2</sup>. The amount of natural gas estimated from the world's gas hydrate accumulations though are speculative ranges from at least 100,000 TCF<sup>3</sup>. In contrast, the conventional natural gas accumulations for the world are estimated at approximately 440 trillion cubic meters only. Gas hydrate fields world over have been initially recognised from the detection of anomalous acoustic reflections on the industry acquired conventional multichannel seismic (MCS) reflection data. This anomalous reflection was popularly known in the geoscientific community as the bottom simulating reflection or BSR. The likely occurrence of gas hydrate has been further constrained with: i) Gas Hydrate stability Zone (GHSZ) thickness map, ii) geochemical proxy indicators such as sulfate methane interface (SMI), chloride anomalies, and iii) methanotrophs and methanogenes and their dynamics at different depths in the gas hydrate bearing marine sediments.

The research activity in the field of gas hydrate has been intensified primarily to: i) assess the amount of pure methane present in the gas hydrate, ii) understand the geohazard caused by the sudden release of gas from gas hydrate when are affected either by changes in pressure and temperatures or any tectonic disturbance, and, iii) address its impact on climate due to mixing of methane gas with atmosphere as well as the ecology of environment below the water and subsurface as well. Recent gas hydrate expeditions (Hydrate Ridge, Oregon Margin, Cascadian Margin, Gulf of Mexico, Arabian Sea, Bay of Bengal and Andaman Sea, South China Sea, East Sea) aboard JOIDES Resolution (JR) have similar goals like characterisation, mapping of spatial and temporal extent, quantification, concentration estimation and composition, and measurement of gas hydrate morphology within the sediment and the *in situ* properties of the matrix. The BSR, one of the primary proxy indicators in gas hydrate detection in general can be recognised on the MCS records as a pseudo reflector that mimics the seafloor topography with a polarity reversal, crosscuts different lithological boundaries, and associates with amplitude blanking above and below it. Further, the BSR also indicates a depth below which the hydrate destabilises. Some of the best known world major oilfields (for example the Gulf of Mexico, the Norwegian Sea, and along the

northern Cascadian margin) are long known not only for their conventional hydrocarbon reserves but also for their gas hydrate potential.

India has several onshore and offshore proven petroliferous basins, and the Krishna-Godavari offshore is the best examples in the eastern continental margin of India (*Figure.1*). The theoretical gas hydrate stability zone (GHSZ) thickness map<sup>4</sup> generated for the Indian offshore shows in general a good thicknesses surrounding the Indian peninsula, and in particular depict >300m thickness in the KG offshore. Further, the industry acquired conventional MCS data depict several BSR like signatures. The National Institute of Oceanography (NIO) in collaboration with Oil and Natural Gas Corporation Limited (ONGC) and Gas Authority India Limited (GAIL) undertook for the first time multidisciplinary scientific investigations of the shallow sediments in Goa and KG offshore along western and eastern continental margins respectively under the aegis of Directorate General of Hydrocarbons (DGH), an extended arm of MoP&NG. These investigations though preliminary in nature have shown the cursory indications of shallow gas escape features in the BSR prone areas. Analyses of sediment samples indicate that clays dominate in the KG offshore and provided prior knowledge of pore water chemistry (sulfate and chloride distribution along core depth). Further, the microbiological studies (mainly enumeration of heterotrophs, sulfate and nitrate reducing bacteria and nitrifiers) indicate the sediments are conducive for growth of different bacteria. The good concentration of TOC (<1.0->1.5%) in the short cores (~6m) strongly indicate the suitability of KG offshore for gas hydrate exploration, and the deep drilling aboard JOIDES Resolution (2006)<sup>5</sup> confirmed the presence of world thickest gas hydrate deposit the KG offshore. We present some interesting findings in the KG offshore pertinent to Indian gas hydrate research activity.

### Geological setting of KG Basin

The KG basin occupies an onshore area of about 28,000 sq. km and extends offshore beyond mid-slope, encompassing an area of 145,000 sq. km. This basin is an integral component of the eastern continental margin of India (ECMI), which has evolved as a consequence of rifting and subsequent drifting of India from the contiguous Antarctica–Australia<sup>6</sup>. The KG basin is characterised by three distinct successive tensional tectonic regimes viz., early rift, main rift and drift phases<sup>7</sup>. The early rift phase i.e., the Gondwana rift phase commenced in late Paleozoic through block faulting. The Late Jurassic rift structures along the eastern margin cut across older NW-SE trending Permian-Triassic Gondwana grabens including the Mahanadi and Pranhita-Godavari grabens<sup>8</sup> and the cross trend of Pranhita-Godavari extends to coastal plains of the KG basin. The third phase attains significance with the development of offshore extension of the onshore basin and its structural style in time and space since early Cretaceous. Marine sediments comprised of clastic and carbonates were deposited over the rift filled sediments, and variable thicknesses shale-silt-clay and sand beds of

Upper Cretaceous to Recent age<sup>9-11</sup> characterise this basin. The continued eastward tilting of the continental blocks resulted in a Tertiary deltaic system with south-eastward prograding shelf edge evolved<sup>11</sup>. The KG basin thus developed has upper Paleozoic to lower Mesozoic non marine graben fill sequence onshore and an upper Mesozoic to Holocene sequence of marine sediments in the offshore.

The hard collision between the Indian and Eurasian plates during the drifting phase resulted in the mountain building of Himalayas, and the subsequent monsoon activity promoted the rejuvenation of Ganges, Brahmaputra, Mahanadi, Krishna, Godavari and Cauvery and other minor tributaries thereby facilitating major transportation of huge sediment influx into the Bay of Bengal<sup>12</sup>. This sediment flow has manifested in the form of deltas and delta-fronts. The Mahanadi, Krishna–Godavari and Cauvery delta fronts on the inner shelf and beyond are some typical examples of this sort. The shelf is incised by head-ward-eroding point-source canyons which are now abandoned and filled with clay and reworked sediments. Several V-shaped canyons flanked by steep faults characterize the upper to middle slope regions, while turbidity channels and levee wedges traverse the shelf and slope<sup>13</sup>. The high terrestrial input is a rich source of organic carbon, and its quick burial resulted in methane generation both at shallow and deeper levels. An extensive marine transgression took place in the early drift phase with south-easterly tilt in late Cretaceous which led to the deposition of Ragavapuram shale<sup>7</sup>. The Tertiary period is marked by several cycles of transgression and regression, and rapid seaward progradation of deltaic domains. This process led to narrowing of shelf and the deposition of sediments associated with growth faults and fan deltas. Geochemical parameters reveal greater terrestrial input in Paleocene, which resulted in occurrences of Tertiary oils in the offshore. The drilling results confirm the presence of hydrocarbons in the Permo-Triassic to Pliocene. More specifically the middle/upper Miocene to mid Pliocene is the promising hydrocarbon prospect off Godavari<sup>11,7</sup>. Pliocene sands either in the combination of sand-silt-clay or sand/silt/shale sequence has proved as the best payoff zones of either crude oil or gas. Occasionally, the sand in a stratigraphic channel fan complex of lower Cretaceous age show the presence of hydrocarbon prospects. From the drilling results it appears that most of the hydrocarbon occurrences in the onshore are from Permo-Triassic, whereas in the offshore, lower Cretaceous to Pliocene are potential zones. Abnormal pressures due to advection of gases are observed especially in the Palaeogene deposits, these being the prospecting zones in the KG Basin<sup>8</sup>. Since hydrocarbon generation is taking place in the KG offshore, the upward migration of natural gases can play a vital role in occurrence and formation of gas hydrate deposits at shallower levels, where the required pressure-temperature conditions prevail.

## Materials and methods

Four multidisciplinary cruises onboard the research vessels *ORV Sagar Kanya* and *AA Sidorenko* were undertaken during 2002–'03 by NIO and acquired geophysical, geological, geochemical and microbial data in the KG offshore. Some important results from the JR cruise are also incorporated towards better understanding and evaluation of the subsurface geological conditions. The geoscientific data comprised of geological sampling and underway geophysical data. The geological samples were used to determine the textural characteristics of sediments, and the pore water chemistry to infer sulfate and chloride anomalies which are also proxy indicators. The geophysical data was used to generate seafloor mosaic and to infer subsurface geological environment and gas escape features. The seafloor mosaic generated from the swath bathymetry data obtained from Hydrosweep system (M/s Atlas Elektronik GmbH, Germany) is used as a base map. A Geo Acoustics Deep Tow system (Model 2000 Geo Acoustics, UK, comprised of chirp sonar, side scan sonar and altitude sensor) was deployed to record simultaneously the seafloor images and higher resolution subsurface information. The processed MCS data provided by oil industry were re-examined to confirm BSRs. Aliquots of core material were analyzed for i) fermenters, ii) sulphate reducing, iii) nitrate-reducing, and, iv) nitrifying bacterium.

## Salient findings

The seafloor mosaic (*Figure.2*) shown between the water depths of <400 and >2000 m exhibits different geomorphic features such as: i) a delta front incised with valleys within the water depths of <400–600 m, ii) a deep water fan beyond 1200m water depth, and iii) an approximately WNW–ESE-trending sedimentary ridge in the south-western part of the study area. The fan-like feature gently deepens offshore and is bounded by an approx. NNW–SSE and E–W trending scarp/steep fault-like structural elements in the north and west respectively. A NE-SW trending toe-thrust fault is interpreted from swath bathymetry mosaic under seismic constraints, and this toe-thrust fault grazes the ~1400 m depth contour, and this fault appears to be abutting with the NNW-SSE trending boundary fault of the fan like feature. The offshore area up to 1600m water depth is seen with several mudflows caused by either slumping or sliding. Effect of slumping/sliding is seen in the form of sediment flows and sediment build-up in the mid-slope region. The sedimentary ridge, with an overall basal width of about 10 km, rises to <950 m above the seafloor at a water depth of 1,400 m. West of this ridge, there are linear turbidity channels bounded by steep scarps. These geomorphic features have significantly contributed in deposition of clays and sands and detrital flux.

Some segments of the seabed over the BSR prone zone in the study area are seen with pockmarks of variable dimensions (30-40m diameter), while the shallow subsurface sedimentary strata

associate with gas chimneys, gas masking/saturation, acoustic pipes<sup>14</sup>. These features are the manifestation of the upward migration of high pressure gas below the seafloor and subsurface strata. Faulting in the subsurface layers with a throw of about 5–20 m and presence of mud diapirs with a relief of 20–100 m are common features particularly seen in the BSR prone areas (*Figure 3*). The BSRs are continuous to discrete in character, and cross cutting of lithology could be seen only in a few coast perpendicular (dip) tracks. Study of occurrence of gas hydrate deposits world over indicates various geological setups that hold these deposits. For example, in Gulf of Mexico it occurs in muds; Green Canyon: in rubble; Blake Ridge: in muds; Niger delta: in clay; McKenzie delta: in sand and gravel; Black Sea: in clayey silt; Caspian Sea: in clayey silt; Lake Baikal: in sand silt; Costa Rica: mud and muddy sands and microfractures; Middle American Trench (Mexico): ash and mud; Oregon: silt; Hydrate Ridge: carbonate crust; Okhotsk Sea Ooze and silt; Japan Sea: sand with clay; Makran coast: sands<sup>15</sup>.

The wide spread host sediments vary from mud /clay to sand and gravel. One important factor to be considered apart from the shallow geological environment is the continuous supply of methane gas or its generation due to microbial mediation. The predicted GHSZ thickness below the seafloor is around 300m and most of the inferred BSRs occur within <200-300m in the KG offshore. Since gas hydrate occurs at shallow levels within the slope sediments of Quaternary age, the knowledge of the shallow geological environment therefore is an important factor in understanding the occurrence and genesis of gas hydrate. The shallow sediments comprised of nannofossil bearing to nannofossil-rich clay, clay, and silty clay that ranges in color from dark brown to dark grey near the top of the core to very dark gray to greenish black to black. Major sediment components include non-biogenic grains comprised of clay minerals, quartz, feldspar, mica, pyrite, authigenic carbonates, and heavy minerals, and biogenic grains of calcareous nannofossils, foraminifera, mollusk shell fragments, and sponge spicules. Few locales are filled with sand rich sediments. The analyses of short cores (~5m) and the long cores (>200m) show that the sediments comprised of nannofossil bearing silty clay, clay with thin beds of sand. At few locations, mollusk shells (primarily bivalves) and visible foraminifera tests occur sporadically throughout the sediment. Possible fossil chemosynthetic communities composed of a variety of mollusk shells with some encrusted by carbonatic worm tubes were also recovered during NGHP Expedition 01. Recent investigations onboard *M/V Marion Dufresne* have shown the presence of chemosynthetic clams directly indicating the presence of cold seeps at subsurface levels. Concentrations of authigenic carbonate nodules of varying size (a few millimetres to over 5 cm) are also observed near these fossil assemblages. In addition to these concentrated zones, authigenic carbonates are observed in all holes below 15-20 mbsf and occur as both small (1-3 cm) and large (7-8 cm) nodules and thin (2-3 cm) fine-grained horizontal bands. However at few locations variety of nannofossil bearing clay, volcanic glass bearing clay, pyrite bearing clay and authigenic bearing clay encountered. In the KG offshore most

of the conventional hydrocarbon gases from deeper horizons are of microbial origin, and the stable isotope studies of hydrate core samples recovered under NGHP expedition 01 also indicate that the methane gas present in the hydrate samples is derived from microbial sources, and the estimated gas hydrate saturation as high as 50 of the pore space at NGHP-01 site 10. The generation of huge quantities of hydrocarbon gases at the deeper horizons and their migration is important factor in controlling the formation and distribution of natural gas hydrate at the shallower depths. Therefore prior knowledge of the fluid migration pathways apart from the geology is required to assess the gas hydrate potential of this area. The terrestrial organic matter occurs in trace from 3 to 5% in both smear slides and rarely in coarse fraction<sup>14</sup>.

The seismic sections show the faults of different dimensions. This situation prevails more or less in the KG offshore indicating the presence of pathways for migration of methane gas either from the deeper horizons or from the shallow ones. It is well established that the most discoveries of hydrocarbons in the KG offshore have been within the sands deposited by turbidity flows<sup>16,11,17</sup>. The Pliocene sandstone reservoir contains evidence of major Neogene growth faults related to the petroleum system in the upper slope region at 260–460 m water depths<sup>18</sup>. Since gas reservoir are surmised to be below the BSR prone areas, it is reasonable to propose that the shallow sediments are getting continuously enriched with the free gas. The observed sedimentary ridge (*Figure.2*) is a manifestation of shale tectonics in the KG offshore, and the seismic line AD-94-11 (*Figure 3*) crosses the northern flank of this sedimentary ridge. A low-relief anticline structure occurs below the BSR, and this horizon is characterized by several faults. The upper strata above the BSR are devoid of continuous reflections, indicating that the sediment pore space could saturate either with gas, contain gas hydrate, or that the sediments are of homogeneous clay/silty clay. The discovery of the 130-m-thick fracture controlled gas hydrate accumulation at Site NGHP-01-10 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, where a BSR occurs above a fault controlled structural high (*Figures 4 & 5*), there by supporting the predicted GHSZ thickness as well as aided in confirmation of inferred BSRs on conventional seismic records as the most probable locales for gas hydrate harvesting. Further, the occurrence of gas hydrate appears to be controlled by gas flux through the local fracture system generated by the regional stress regime, which facilitated in upward migration of the microbially generated methane to upper sedimentary sequence<sup>5</sup>. With mankind's increasing interest in the deeper offshore areas (search for oil and gas), the stability of the seafloor becomes increasingly important for any engineering structure. Dissociation of gas hydrate will result in increased fluid pressure, dilation of the soils and developing of gas bubbles, all of which substantially weaken the soils. Due to the destabilization of gas hydrate zones, fluid expulsions can take place and result in development of pock marks and loose sediments. These disruptions affect manmade structures if they are located or planned for installation in future.

## **Conclusions**

High resolution swath bathymetry mosaic depicted several geomorphic units, formed during the development of eastern continental margin. The delta fronts, sedimentary ridge and turbidity channels are important features both in controlling the terrestrial influx and settlement of sediments. The deep tow acoustic system depicts significant proxy indicators such as clusters of pockmarks and different varieties of gas escape features including gas vents and chimneys, blanking zones, gas saturated sediments, mud diapirs. Some BSRs particularly in the vicinity of subsurface structural features have a direct bearing in mapping gas hydrate zones, and this has been demonstrated during the gas hydrate drilling program under NGHP. Analyses of the cores indicate that the gas hydrate bearing sediments are mostly silty clays (~80%), and occasionally inter bedded with sand bodies, and the TOC up to 3%. The sulfate methane interface in general found to vary between 9 and 36 mbsf. However, at majority of drill locations the SMI is in between 20 and 25 mbsf. The gas hydrate occurrence in KG offshore is associated with fractured clay. This emphasises the need of exploring such fracture/fault network systems within the sediments. The abundant occurrence of authigenic carbonates amply indicate oxidation of methane gas emanating from the deeper layers. The chloride anomalies vary between 663 and 206 mm, and this anomalous behaviour could be seen wherever the gas hydrate encountered in the core or in the sediments where hydrate dissociated. In several core gas hydrates are observed either in the form of a massive lump or in fragments/ traces/ disseminated form. All the investigations so far conducted in the KG offshore have proved its potential for gas hydrate harvesting, however, the geology needs to be understood due its heterogeneity nature. Since the deep drilling either aboard JR or its equivalent ship is an expensive affair, we therefore strongly believe that a systematic mapping using high frequency seismic source (200-1200 Hz) of the shallow subsurface geology in the KG offshore as a primary requirement followed by study of intermediate length cores (40-60m) to assess SMI, and other chemical parameters since these proxy indicators serve as best possible precursors for the likely occurrence of gas hydrate deposits. We also suggest for detail environmental studies to assess the impact of release of methane gas through the water column and its effect on the ecology and atmosphere.

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*Figure Captions:*

*Figure.1* Study area with **the structural and** tectonic trends

*Figure. 2.* A) Detailed bathymetry of the study area (50-m contour interval). B Seafloor mosaic derived from swath bathymetry data. The major geomorphic features identified are a delta front (DF) with valleys and canyons, a toe thrust fault (TTF, dashed line), turbidity channels (TC), a sedimentary ridge (SR), a fan, slumps/slides (SL) and scars (SC). White patch at top Data gap resulting from this area being occupied by drilling rigs and locations of NGHP drill wells

*Figure. 3 (a &b).* Typical multichannel seismic sections depicting BSRs and several faults of varied dimensions. These faults are surmised to be as the fluid migration pathways

*Figure.4* Seismic line GDSW-16(orientation is NW-SE) crossing drill site NGHP-01-21. Note the occurrence of deep seated high amplitude reflectors inferring the occurrence of free gas as well as potential shallow debris flow. Also the seismic section where NGHP-01-10 well drilled is shown along GD9W-45 (Refer fig 2 for locations).

*Figure.5.* Massive and disseminated form of gas hydrate recovered from KG offshore during NGHP expedition

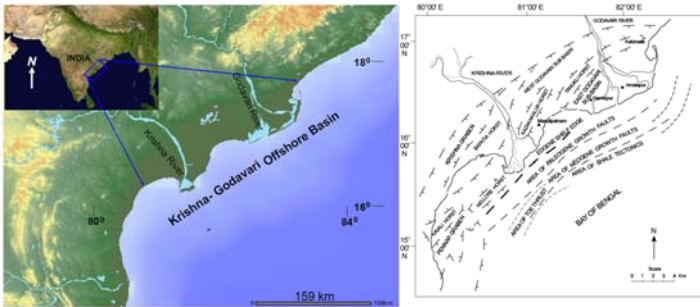


Fig.1

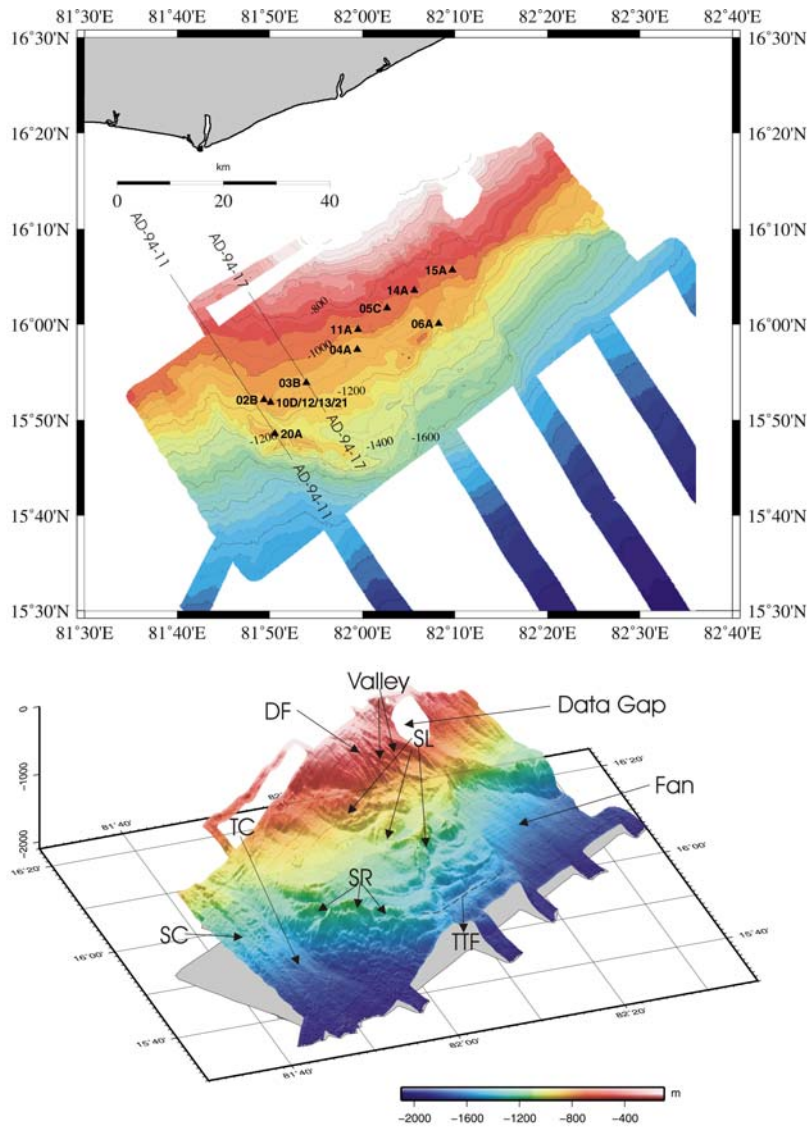


Fig.2

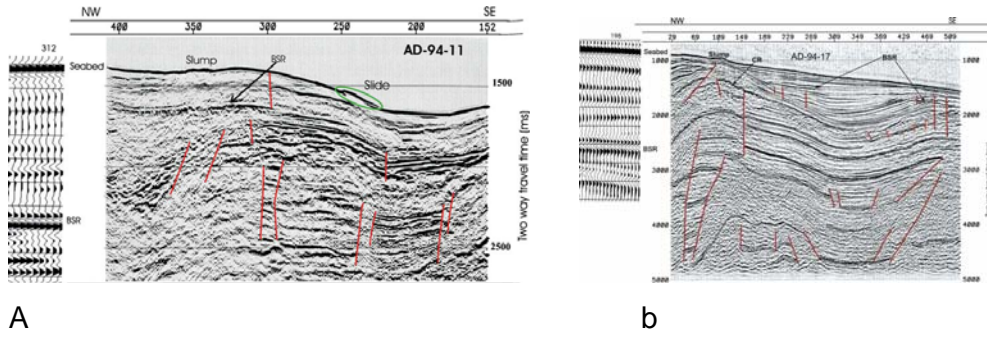


Fig.3

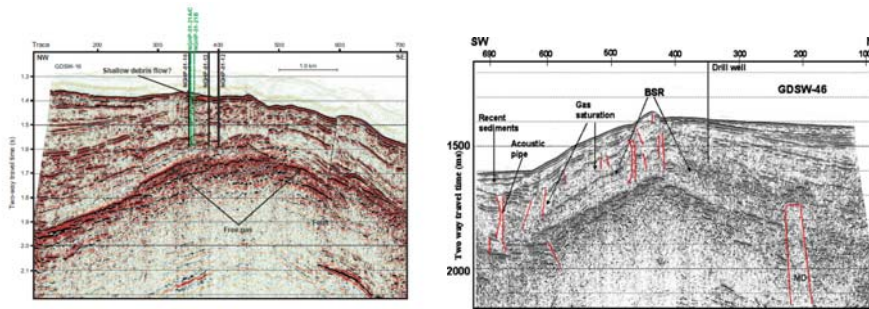


Fig.4



Fig.5