Identification of Gas Hydrate reservoir facies from well data - A case history from KG-Deep Offshore.
Jagannath Nanda *, K M Shukla, M V Lall, U S Yadav and P Kumar
Gas Hydrate Research & Technology Centre, Panvel, ONGC, Navi Mumbai

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LWD, BSR, turbidite, channel and debris flow.

Summary
The present research work is an integrated approach to bring out the deep water reservoir facies, depositional environment and processes involved like deep water turbidite and debris flow in delineation of Gas hydrate reservoir. Well data correlated with seismic is being used for the interpretation of geological process responsible for Gas hydrate formation.

Introduction
The focus area of study for this paper is on Krishna-Godavari deep offshore basin. The Krishna-Godavari basin is a major intra-cratonic basin covering 145,000 km² in offshore. Our study area is located at the SW, central and NE part of the offshore basin (Fig. 1).

Fig. 1: Location Map in study area showing drilled wells

Based on the integrated log and laboratory studies, broadly two hydrate bearing zones are identified ranging in age from Early Pleistocene to Late Pleistocene (Kumar, P. and Shukla K. M. et. al. 2016) mainly consisting of very fine to fine grained sand, clay and at places gravel sized sediments.

General Geology and tectonic set up of the basin
Krishna Godavari Basin is a typical passive margin characterised by polycyclic evolution history which witnessed its first marine transgression during Albian-Aptian time. The eastward tectonic tilt of the basin facilitated onset of the primary fluvial pathways (Godavari and Krishna) and the two present day delta systems were established during early Miocene time. Structural pattern in the basin thus is typical of passive margin-with loading in shelfal area, related phases of growth and formation of frontal toe thrust. The normal/growth related listric faults in Pliocene have a general NNE-SSW trend and typically sole out in the shales below. The passive continental margins were a result of different rifting episodes during the breakup and dispersion of Gondwanaland to form the present Indian Ocean formed as the result of rifting between India and the rest of East Gondwanaland (Australia/Antarctica) in the Late Jurassic and Early Cretaceous. Plate reconstructions place the eastern Indian margin adjacent to Enderby Land in East Antarctica with the northern margin of “Greater India” along the western margin of Australia [Powell et al., 1988]. Rifting began in the Late Jurassic at about 160 Ma with breakup at about 130 Ma (magnetic Chron M10) [Powell et al., 1988].

Sediment input to the Bay of Bengal is dominated by the Ganges-Brahmaputra River system, which drains much of the Himalayas. The resulting sediment influx has built the Bengal Fan, the world’s largest extant sediment accumulation. The sediment thickness reaches a maximum of over 22 km on the Bangladesh shelf and over 2 km of fan sediments are found at 2°S [Curray et al., 1982], over 2500 km to the south.

Isopach maps show 8-10 km of sediment at the location of the Krishna- Godavari drill sites. The Late Jurassic rift structures along the eastern margin cut across older NW-SE trending Permian-Triassic Gondwana grabens and Pranhita- Godavari grabens [Sastri et al., 1981]. These structures served to delineate the fluvial drainage system throughout the evolution of the margin to the present and they now contain the Godavari Rivers. This river has a high sediment transport [Sastri et al., 1981; Biksham and Subrahmanyam, 1988] and the river has built substantial delts so that sedimentation at the prospective drill sites is dominated by the river input. As a result, seismic lines in the vicinity of the
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prospective drill sites show features typical of fans including cut and filled channels and abundant growth faulting. Thus the sediments to be drilled are likely clays with well-defined sand horizons.

In the Godavari offshore area, Eocene to lower Miocene sequence was deposited in a slope/deep basinal environment. The top of lower Miocene sequence is an erosional unconformity surface as evidenced by changes in dips and down lapping events. The middle Miocene sequence is dominated by marine transgression. The upper Miocene is another period of regression. The top of the Miocene shows extensive slumping and erosion as subsequent regression and faulting have scoured this surface. The Plio-Pleistocene is represented by deep marine dark grey claystone that forms the regional seal for basin. The sands are sourced from Godavari river system and deposited on the lower slope extending from one intra-slope basin to the other either through nick points or via right angle bends around the structure.

During Late cretaceous to Paleocene time, along with the onset of passive margin set up, southeasterly tilt of the basin was developed resulting in major marine transgression and increase in depositional energy of the proto Krishna and Godavari Rivers, and vigorous passive margin progradation towards southeast (Fig.2).

Methodology
Electro logs are used for facies analysis establishing a relationship between seismic data, lithofacies associations and curve shapes. The calibration of LWD/wireline log shape by sedimentary sequence is always important for firmly establishing the log response and the identity of vertical sequences on these logs.

Case studies
Based on the seismic data (Shukla K. M. et. al. 2016) analysed during the expedition to identify suitable sand facies as reservoir for hydrates are correlated with the LWD/wireline logging and sediment data at GHRTC. The seismic data are nicely correlated with the well logs by identifying serrated, finning up and blocky signatures. Turbidite sand and debris flow were nicely brought out from the log and sediment studies. Post drill well data corroborated with the seismic observation as suggested identifies suitable sand facies hosting gas hydrate reservoirs. Based on lithofacies analysis of sediments encountered in the well and respective log signatures, depositional pattern have been identified and detail of each precesses is discussed area wise below.

AREA: E
The well undertaken for this study is located and marked as Area E (Fig. 1) and is located in the SW part of the basin. Two distinct lithounits are identified having age Late Pleistocene basing on LWD data analysed and correlated with seismic section showing evidence of slope failure, which is responsible for different geologic processes (Fig. 3). Unit-1 (200-250m) showing high resistivity and low gamma exhibiting serrated pattern. Unit-2 (250-300m) showing low resistivity and high gamma exhibits blocky pattern. Two representative lithologic types were also recognized in this succession coherent organic matter–rich silty clay and mass transport deposit (MTD) facies (Fig. 4). In many cores Mousse-like structures occur frequently. The major lithologic components of this section are MTDs and organic matter–rich silty clay. Core studies shows the sediments comprises the upper part of a muddy-matrix MTD and organic matter–rich silty clay. The boundary between the two lithologies is at 73.39 mbsf. Intercalation and patches of sand are common between 70.00 and 73.39 mbsf, 102.50 and 141.78 mbsf. The major lithologic component of this interval

Fig.2: Tectonic Map of KG Basin showing major tectonic activities.
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is organic matter–rich silty clay and mud and sandy matrix MTDs. The upper part of this interval is composed of organic matter–rich clay, silt, and intercalation and patches of sand. Burrows recognized are cut into chunks a few centimeters in size as a result of drilling disturbances. A poorly sorted interval occurs between 225.71 and 228.25 mbsf, the lower portion of which comprises an MTD. The 246.16–265.20 mbsf interval is characterized by mud matrix–supported MTD, whereas 265.20–268.0 mbsf is sandy matrix MTD (Fig. 4).

Depositional Process

The geologic process involved as interpreted from the log character and core is dominantly in the upper portion is turbidite deposit (200-250m) having Late Pleistocene age. The mechanism comprises of “Gravity-driven motions produced from turbulent suspensions are an important sediment-transport process in the modern ocean and the deposits that result from them constitute a significant portion of the sedimentary record”.

In this hydrate bearing section turbidites fine sand/silt sequences are deposited through turbulent suspensions in a gravity driven process. These sand turbidites are good hydrate reservoir.

The lower portion (250-300m) having age Late Pleistocene, interpreted as debris flows associated with MTD. These geological processes are associated with channels and levees emerging from the canyon mouth and sidewall failures and rotational slips have produced debris flows in all stages of development.

AREA: C

The well undertaken is located and marked as Area C (Fig. 1) in the central part of the basin. Based on the analysis of LWD and wireline logging data, three logging units are identified. Unit 1 (0–181.6 meters below seafloor is defined as relatively homogeneous (clay dominant), logging Unit 2 (181.6–327.9 mbsf) is defined by variable log responses (sandrich channel-levee system), and logging Unit 3 (327.9 – 374.0 mbsf) is defined as another homogeneous interval. A channel system identified at 248–271
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mbsf is characterized by low natural gamma radiation (Fig.- 5). Based on lithologic characteristics, recovered sediment can be divided into lithostratigraphic having age Early Pleistocene to Late Pleistocene, Units I (0–251.23 mbsf) and II (251.23–337.03 mbsf). Unit I is composed mainly of carbonate grain–bearing terrigenous organic matter–rich olive-black silty clay and muddy-matrix mass transport deposit (MTD). Unit II consists predominantly of coarse-grained sediment such as gravel, coarse to fine sand, gravelly mud/sand, and silty clay.

Two lithostratigraphic units, I (0–251.23m) and II (251.23–337.07m), were recognized in the cores from this site (Fig. 5). Unit I is divided into three subunits (IA–IC), and Unit II is divided two subunits (IIA and IIB). The unit boundaries are based on significant changes in sediment components and sedimentary structures, verified by comparing X-ray computed tomography (XCT) images, physical properties, and interpretations of LWD and seismic results.

Subunit IA (0–73.50m) is characterized by an abundance of muddy-matrix MTD representing poorly stratified chaotic facies such as irregularly folded sand layers and bedding and inclined bedding planes (Fig. 5). Additionally, irregularly shaped and sized clasts composed of soft silty clay can be commonly observed as lighter coloured mottling in the olive-black silty clay matrixes. Yellowish brown calcareous sandy patches/nodules/gravels scattered in silty clay matrixes were commonly found in the middle and lower part of this subunit.

This subunit (73.50-190.17m) is composed mainly of olive-black silty clay with fine sand to sandy silt layers, lenses, and patches. Sandy layers commonly have sharp and undular/erosive bases that are upward grading and interlaminated with clay characterized as typical turbidite sequences (Fig. 6). Bioturbation and burrows were also observed as sandy discontinuous layers or lenses and patches contained in silty clay matrixes. The major components of the silty clay of this subunit are quartz, lithic fragments, detrital carbonates, and terrigenous organic matter.

Subunit IC (190.17–251.23m) is characterized by gray to olive-black clayey silt with wavy or lenticular fine sand laminations (Fig. 5). The major components of Subunit IC are quartz, lithic fragments, carbonate grains, and terrigenous organic matter. Sediment with soupy texture was rarely observed in the middle part of this subunit. Mousse-like sediment texture was commonly found throughout the subunit.
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The major lithologic components of Subunit IIA (251.23–303.61 m) are gravel, gravelly mud and sand, and fine to coarse sand, which are intercalated by olive-black to black silty clay (Fig. 5 & 6). Gravel is poorly sorted and includes subrounded granule- to pebble-sized quartz, chert, sandstone, shale, and limestone. Calcareous lithoclasts (granule to pebble sized) are predominantly scattered in the lower half of the silty clay in this subunit. The sedimentary succession of Subunit IIA seems to repeat the fining-upward succession in several to dozen meters scale. The fining-upward successions suggest that Subunit IIA is stacked channel deposits of a channel-levee system in a deepwater slope fan system. The major components of this subunit are quartz, lithic fragments, detrital carbonates, and terrigenous organic matter.

The major lithology of Subunit IIB (303.61–337.07 m) is characterized by mainly massive black silty clay with scattered gravel- and sand-sized grains (Fig. 7). Light yellowish brown calcareous layers and nodules/gravel were abundantly observed throughout the subunit. Sandy lamination and normal grading from gravelly silty clay to sandy clay were occasionally observed. Major components of Subunit IIB are quartz, lithic fragments, detrital carbonate, and terrigenous organic matter.

Depositional Process

The Upper Unit seems to be deposited as derived from the log and sediment signatures is dominantly turbidity current in a channel-levee system. Turbulent suspensions are an important transportation mechanism, which operated during the depositional process. The Lower Unit is deposited as suggested by the electrologs and sediments in a repeated fining-upward succession in several to dozen meters scale. The fining-upward successions suggest that Subunit IIA is stacked channel deposits of a channel-levee system in a deepwater slope fan system.

The Lower most part of the Unit-II is consists of scattered gravel- and sand-sized grains as suggestive of a debris flow process in channel-levee system. This is often followed by confined channelization down slope and then the cycle ends with unconfined fill that probably represents flushed shallow shelf gravelly and coarse grained sediments.

AREA: B

The well undertaken is located and marked as Area B (Fig. 1) is located in the NE part of the basin. Four distinct units are identified basing on the analysis of LWD data. Logging Unit 1 (0–187.9 mbsf) is characterized by variable natural gamma radiation (NGR) values. Logging Unit 2 (187.9–272.5 mbsf) is characterized by variable changes in NGR lower average values. Logging Unit R2 (272.5 – 296.8 mbsf) is characterized by high NGR, high density, and high resistivity values. Logging Unit 3 (296.8 – 360.0 mbsf) is characterized by low NGR values.

Fig.7: Core photograph showing typical turbidite sequence sand/silt and clay alternations (A). Organic matter and very fine sand/silt (B & C)
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Unit 1 is clay dominated with occasional appearance of thin sand/silt laminations. Log motif shows serrated pattern suggesting clayey turbidite sequence. Unit 2 is comparatively more sand/silt dominated having diatoms, with trace amounts of calcareous nannofossils. Siltsized quartz and carbonate fragments are the siliciclastic components, together making up ~10% of the sediment. Unit R2 is the main reservoir facies consisting of gray silty clay, gray carbonate- and quartz-bearing silty clay, and gray carbonate-bearing quartz silty sand. Sand often exhibits grading that fines upward (Fig.- 8). The Unit 3 comprises of sand/silt alternations with clay.

Depositional Process
As from the log signature and lithofacies encountered it clearly indicates that these deposits are turbidite channel sand deposits. The depositional process involves the mechanism in which the sediment moves under gravity as cohesionless flows that are transformed basinward into fluids moving under gravity in the form of high-density turbidity currents. These fine turbidite sands can act as a good reservoir for the hydrates.

CONCLUSIONS:
Based on the integrated studies two well-developed Gas Hydrate system has been identified in deep offshore and hydrates are distributed in sand dominated facies. The seismic data analysed during the expedition to identify suitable sand facies as reservoir for hydrates are correlated with the LWD/wireline logging and sediment data. The seismic is well correlated with the well logs by identifying serrated, finning up and blocky patterns. Turbidite sand and debris flow were nicely brought out from the log and sediment studies. This studies further strengthens the fact that electrolog signatures and sediment studies, identifies that broadly two geological processes turbidity current and debris flow are mainly responsible for the deposition of gas hydrate bearing reservoirs in the Indian Offshore.

The lithofacies in the SW part of the study area is sand-silt-clay sequences, like massive graded very fine sand, laminated sand/silt-clay indicates as fine-grained turbidities and bottom current re-working of these sediments. The fine grained sand in this turbidite sequence can act as a good hydrate reservoir.

The hydrate bearing sediments in middle part of study area is mainly debris flow dominated. It consists of scattered gravel- and sand/silt-sized grains in a channel-levee system. Due to the presence of polymodal grains it may not act as a good hydrate reservoir.

In the NE part of the study area excellent reservoir facies sediments are encountered. The sediments are very fine sand/silt sediments deposited by turbidite channel.

Way forward: In the deep water system more channel-levee sand bearing hydrate reservoir facies as in the NE part of the study area should be targeted as a promising reservoir rock.

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REFERENCES