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Facies Analysis, Depositional Environment and reservoir characteristics of deep water sediments: A case study from Godavari Clay Formation of Krishna-Godavari Basin, India

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Abstract

The Plio-Pleistocene Godavari Clay Formation of Krishna-Godavari Basin is traditionally reported as deep water deposits under continental slope abyssal plain set up. Present work documents four major facies associations, viz., (i) sandstone-rich facies association (FA-1) of sandy mass transport deposits (MTD), (ii) mudstone-rich facies association (FA-2) of muddy MTDs, (iii) Sandstone-mudstone heterolithic facies association (FA-3) of tidally affected reworked deposits and (iv)hemipelagic facies association (FA-4) of normal background deposits. FA-1 and FA-2 consisting of widespread clastic MTD in the KG Basin are delivered episodically into the deep water realm from western hinterland by proto-rivers. Frequent tropical cyclones, tsunamis, earthquakes, shelf-edge canyons with steep-gradients and seafloor fault scarps are considered to be favorable factors for triggering mass movements. Tidalites are well preserved in FA-3 and are represented by laterally accreted tidal bundles, tidal beddings and vertically accreted tidal rhythmites, described from drill core samples in this communication. Tidal beddings and tidal rhythmites in mud-dominated heterolithic units indicate reworking of sediments by tidally affected bottom currents in deep water realm. Petrographic, SEM and XRD study for the different facies belongs to FA-1 to FA-4 suggests that the sandy debrites exhibit high values of measured porosities, though often show evidences of early calcite cementation. Integration of reservoir characteristics with such process based facies analysis constitutes a powerful tool to geoscientist for prediction of the better reservoir quality.

Introduction

Our knowledge on deep water processes and their deposits have greatly enhanced during the 21st century and there is a definite paradigm shift for interpreting deep water processes from the simplistic submarine-fan models (emphasizing turbidite deposits) to more slope and gravity driven depositional processes and products, known as 'mass transport deposits' (MTD) (Shammugam, 2006; Shammugam et al., 1994, 2009; Shammugam and Moiola, 1995). As deep-water processes and their deposits (facies) are quite complex, seismic data cannot resolve the details (e.g., normal grading) of a specific process (e.g., turbidity current) due to poor vertical resolution of seismic data. Hence, facies models are the ultimate destination for deep water sedimentation mode.

So far, Plio-Pleistocene Godavari Clay, the topmost formation of KG Basin has been interpreted as being deposited in deep water regime on continental shelf-slope setting that incorporates different sandstone units at various stratigraphic levels. However, these studies were not substantiated with adequate supportive facies analysis and other traditional sedimentological attributes. Despite that, these lithounits have been explored and exploited as important hydrocarbon reservoir since decades by ONGC. Thus, a detailed and systematic analysis of Plio-Pleistocene Godavari Clay was felt necessary. This paper provides systematic documentation of the facies types to establish the depositional environment of the Godavari Clay, with particular emphasis on evidences of tidal sedimentation in a deep water perspective.

Geological background

The Krishna-Godavari Basin is composed of both onshore and offshore components. Present studies are confined to offshore part and restricted to Godavari Formation of Plio-Pleistocene age (Fig 1 & 2). Geographically the area lies to the south of Kakinada and Yanam towns, in the deep offshore part where the bathymetry ranges from 100 to 1200m.

The basic reservoir distribution of present-day shelfal domain is Mid-Late Miocene coastal plain to shore face sands and present day slope domain is Pliocene-Pleistocene slope-derived channel deposits and occasional incised slope channel sands. The primary targets for exploration in this part of the block are Miocene to Plio-Pleistocene submarine fan and channel-levee complexes.

The sands are sourced from Godavari river system and deposited on the lower slope extending from one intra-slope basin to the other. Vadaparru-Ravva-Godavari is the known and established petroleum system in offshore part of Krishna-Godavari Basin. The Plio-Pleistocene slope derived channel deposits and occasional incised slope channel sands form the reservoirs. The interbedded clays / shales of Plio-Pleistocene act as cap rock while the play is envisaged to be a strati-structural trap formed by updip pinchout.

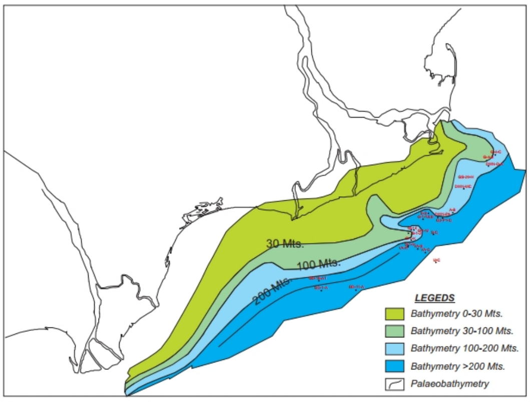

Fig. 1

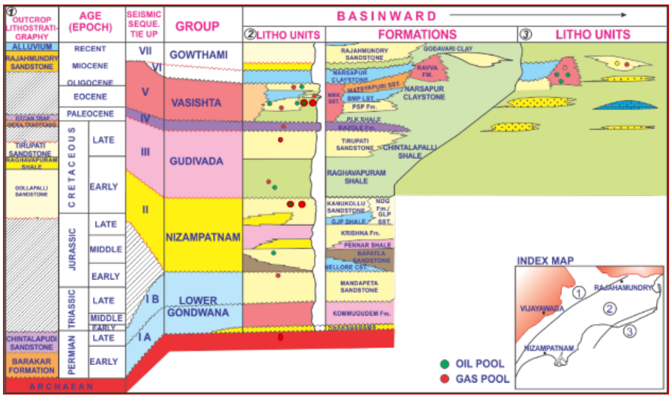

Fig. 2

Fig. 1: Paleo-bathymetry map with well location of the study area

Fig. 2: Generalised stratigraphy of KG Basin

This study on facies characteristics of the Plio-Pliestocene Godavari Clay is mainly based on available conventional cores from different units of the Formation. Across the oil fields of the KG Basin, sandstones within the Godavari Clay are some of the most prolific producing horizons and thereby extensive conventional cores have been taken since the field was discovered. More than 200m of cores (representing 34 cores from 26 wells) from different sandstone units of Godavari Clay formation (average thickness 2500m) are studied in detail at the Regional Geological Laboratory, ONGC, Rajahmundri. Scanning electron microscopic study of specific core samples are done to infer the reservoir characteristics. The facies characteristics calibrated with electrolog are used for interpreting depositional processes. By interpreting a specific depositional process (e.g. sandy slide, slump or sandy debris flow), one could infer the sand body geometry and reservoir property away from the well bore. (Fig. 3)

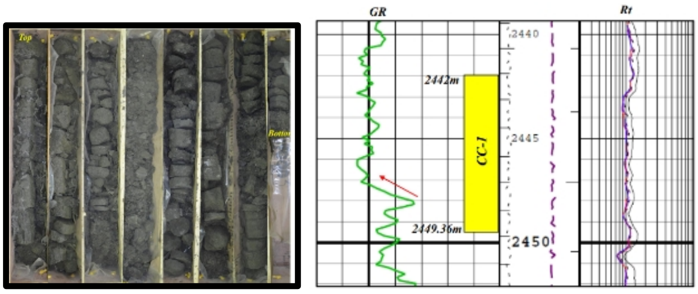

Fig 3. Representative whole core image with electrolog signature (Well GD-15-A, CC-1,2442-2451m, Rec-81.78%)

Sedimentology of the area

Godavari Clay consists of a number of sandstone units separated by intervening pelagic marine shales. The sandstone is mainly quartz wacke and/or arenitic in composition. As revealed from electrolog motif, the sandstone units have sharp and erosional base and also have sharp upper contact with the overlying mudstone units. The lithofacies and their association indicate sedimentation took place in a deep water realm under continental slope-abyssal plain set up and commonly identified in four major facies associations, viz. sandstone-rich facies association (FA-1), mudstone-rich facies association (FA-2), Sandstone-mudstone heterolithic facies association (FA-3) and pelagic-hemipelagic shale-dominated facies association (FA-4).These four facies associations with different facies types within the study area are described in the following section.

Sandstone-rich facies association (FA-I)

The sandstone-rich facies association (FA-I) consists of different facies, viz. massive poorly sorted sandstone (I-1), sandstone beds showing primary glide plane between overlying sandstone and underlying deformed mudstone (I-2), isolated sandstone unit as injection structure from the main sand into underlying mudstone (I-3), deformed sandstone units with compressional folding and thrusting (I-4), sandstone with irregular and sharp contact (I-5), sandstone with steeply dipping clay filled layers (I-6), inverse grading of sandy matrix (I-7) and normally graded sandstone (I-8) (Fig. 4).This facies association, as a whole forms blocky and coarsening-up units and towards the distal part exhibits fining-up log motif.

Petrographically, the sandstone is represented by poorly sorted coarse grained quartz wacke and occasionally quartz arenites made up of sub-angular to sub-rounded, mainly mono-crystalline quartz grains with carbonaceous clay matrix and feldspar (Fig. 4A). Overall facies architecture with intimate association of these different facies types suggests deposition by sediment gravity flows and form MTD with different proportions of slides, slumps, debrites and to a lesser extent turbidites.

I-2

I-1

Fig 4. Sandstone rich facies association in Godavari Clay Formation.

Fig 4A. Petrographic attribute of sandstone rich facies association in Godavari Clay Formation.

Interpretation

FA-I has been interpreted as sandy mass transport deposits (SMTD), where grain concentration is more than 20% (Krynine, 1948). It denotes gravity driven downslope transport with high sediment concentration both as coherent solid mass (slide and slump) and as in coherent grain-fluid body (debris flow) whose basal surface is in constant contact with sea-floor. The presence of primary glide plane at base is the evidence for basal shearing. Broken-up mudstone chips may present above the shear plane and are derived from muddy sea-floor during bulldozing of sea-floor by translational slide movement. The different facies independently does not infer a particular type of SMTD, rather a particular group of facies of FA-1 represent a particular type of SMTD. On the contrary, a particular facies of FA-1 may indicate a combination of SMTDs (sandy debrites, slumps and slides). The deformed sands with slumped mudstone clasts can be classified as a separate depositional facies, namely sandy slumps (Fig.4). The massive sands can originally be emplaced as debrites and were subsequently remobilized as slides.

Mudstone-rich facies association (FA-II)

The mudstone rich facies association (FA-2) is composed of medium to dark gray, indurated mudstone with slump folds (II-1), mudstone with floating sandstone fragments (II-2), mudstone with internal shear planes (II-3), mudstone with boudins (II-4), mudstone with sand injections (II-5). Mudstone clasts range in diameter from 4-12cm. The thickness of this lithofacies is ~10m. (Fig. 5). Petrographic study reveals mainly lithic wacke microfacies having poorly sorted very fine to very coarse grained, sun-angular to sub-rounded quartz along with lithic fragment and feldspar embedded within argillaceous matrix.

G-1-K, CC-1

Fig 5. Mudstone rich facies association in Godavari Clay.

Interpretation

FA-II has been interpreted as muddy mass transport deposits (MMTD), where grain concentration is less than 20%. Mudstone intervals with slump folds and contorted layers are interpreted to be muddy slumps. The origin of chaotic fragments has been related to slumping. Slump folds commonly develop as a consequence of downslope mass movements. Floating mudstone clasts suggest deposition from laminar debris flows. Muddy matrix reflects the freezing deposition of cohesive debris flows.

Sandstone-mudstone heterolithic facies association (FA-3)

The heterolithic facies association consists of flaser, lenticular and wavy bedded heterolithic (III-1), quick rhythmic thick-thin sand-shale alternations, known as tidal bundles (III-2), tidal bundles with apparent bi-directional low angle foreset lamina (III-3), sandstone and mudstone with double mud layers (III-4), sandstone shale alternation with load cast and flame structure (III-5) and heterolothic facies with boudins (III-6) (Fig. 6). All the facies types show varied sand: mud ratio with systematic change from sand to mud and mud to sand in vertical successions. Petrographically, the sandstone is represented by quartz arenites, feldspathic arenite with bimodal grain size distribution (Fig. 6A).

Fig. 6

Fig. 6A

Fig 6. Heterolithic facies association in Godavari Clay Formation.

Fig 6A. Petrographic attribute of heterolithic facies association in Godavari Clay Formation

Interpretation

Rhythmic bedding and double mud layers are diagnostic products of tidal processes. Visser (1980) originally explained the origin of double mud layers by alternating ebb and flood tidal currents with extreme time–velocity asymmetry in modern shallow-water subtidal settings. Similarly, deep-water tidal deposits with double mud layers have been documented in modern and ancient submarine canyons (Shanmugam 2003). The units of mudstone with double mud layers are interpreted as muddy tidalites. Silt/sand laminae can be explained by bottom-current reworking (e.g., deep-marine tidal currents). Sandy and muddy tidalites together constitute ~20% of the cored interval and is encountered in

Pelagic-hemipelagic shale-dominated facies association (FA-4)

FA-4 is represented by grey, soft, carbonaceous claystone (IV-1), claystone with sand/silt lenticles (IV-2), red claystone (IV-3) shale with iron concretion and red band (IV-4), shale with shell fragments (IV-5), claystone with glide plane (IV-6) and limestone(IV-7) (Fig 7). Diagenetic features like glauconite pellets and biotite altering in to Fe-oxide are also noticed. Red claystone is light brown, soft and calcareous and having silt grade quartz, dark colour mineral embedded in matrix. Red bed exhibiting abundant hematitic pigment mixed with clay matrix and cherty claystone interspersed with dark gray clay ground mass. XRD analysis indicates that montmorillonite, kaolinite and illite are present in order of abundance (Fig.7A). Limestone occur as thin inter-beds within claystone is mainly pelloidal foraminiferal packstone containing pelloids, milliolids and bioclastic fragments (Fig.7B). These sediments were deposited in inner to middle shelf regime as shallow marine carbonates with minor transport.

Interpretation

FA-4 is interpreted to deposit by the process of suspension settling as hemipelagic deposits (hemipelagite) in outer shelf to upper bathyal environment. The lithofacies and their association indicate sedimentation took place in a deep water environment much below the wave-base. Red bed exhibiting abundant hematitic pigment mixed with clay matrix and cherty claystone interspersed with dark gray clay ground mass. The bottom currents, infusing oxygenated water might have been responsible for the occurrence of the red beds in the area.

IV-5

IV-4

IV-7

Fig 7B. Petrographic attribute of limestone in Godavari Clay

Fig 7. Hemipelagic facies association in Godavari Clay Formation

Evidences of tidal influence-In this paper we studied and documented direct evidences of tidal sedimentation in deep water, as observed in core samples, having average thickness of 2-8m each. Spatial and temporal variations in different flow types in the tidal environments have produced distinct sedimentary structures in the studied rock succession. The most conclusive of these structures are (a) tidal bundles with mud drapes on sand foresets (often double mud drapes) (b) tidal beddings (like flaser, lenticular and wavy beddings) and (c) horizontally laminated tidal rhythmites.

Tidal Bundles-Tidal bundles are characterized by a sand-mud couplet with varying thickness, commonly considered as depositional unit corresponding to one tidal cycle. The tidal bundles are separated into four components: (i) a sandstone lamina deposited during the dominant current stage; (ii) a mud drape formed during the subsequent slack-water stage; (iii) another sandstone lamina deposited during the subordinate current stage, commonly thinner than the previous sand deposited, and (iv) a second mud-drape formed during the slack water stage following the subordinate current stage (Fig. 6).

Mud drapes-In certain tidal bundles, it is common to find very fine mudstone closely interlaminated with very clean, well sorted sandstone. These two contrasting lithologies occur clearly and discretely with no mixing of materials. Where mud dominates, the sand occurs as thin laminae and lenses, whereas with a domination of sand the mud occurs as continuous or discontinuous laminae (Fig. 6).

Flaser, lenticular and wavy bedding-Alternate sand-dominant and mud-dominant units manifest spring-neap tidal cyclicity, with systematic development of flaser, wavy and lenticular beddings (identified as ‘tidal beddings’) in an overall fining-up succession. The flaser beddings are characterized by simple, bifurcated and wavy flasers. Within the sandstone-dominated intervals, flaser bedding with discontinuous mud streaks is common.

Interpretations of tidalites-Tidal bundles with double mud drapes correspond to the sedimentation during dominant ebb and flood tide event interrupted by two still stand phases corresponding to two mud drapes, respectively Arrangement of successive mud–sand–mud laminae within sand-dominated units are conclusive evidence of subtidal environment. The difference in the thickness and number of sandy foresets enclosed between the two bounding mud layers is attributed to the sequential change in the strength of tidal current. The thickness of the bounding drape is controlled by the amount of mud in the system during the slack phase.

Plio-Pleistocene depositional model and sediment dispersal pattern

The different facies of FA-1 with an overall coarsening-up to blocky serrated log motif suggest deposition by mass transport process. The finer pelagic-hemipelagic shale of FA-3 with profound evidences of bioturbation indicate background indigenous sedimentation in a deep water realm with a very low rate of sedimentation. The heterolithic sandstone-mudstone with abundance of tidal signatures and traction dominated sedimentary structures much below the wave-base as described in different facies of FA-3 suggest deposition by a tide-affected bottom currents in deep water environment. Therefore, three different depositional processes interacted with each other and left their signatures in different litho-units of Godavari Clay.Pliocene environments are interpreted to be comparable to the modern upper continental slope with widespread mass-transport deposits and submarine canyons in the Krishna–Godavari Basin. Frequent tropical cyclones, tsunamis, earthquakes, shelf-edge canyons with steep-gradient walls of more than 30u, and seafloor fault scarps are considered to be favorable factors for triggering mass movements. Sandy debrites occur as sinuous canyon-fill massive sands, intercanyon sheet sands and canyon-mouth slope-confined lobate sands. Canyon-fill facies are characterized by the close association of sandy debrites and tidalites.

Reservoir quality

Petrographic study for the different facies has been studied. The best reservoir is composed mostly of sandy debrites This facies exhibits high values of measured porosities (~30%) (Fig.8). Sandy tidalites and related bottom-current reworked (BCR) facies exhibit moderate porosity (15–20%) and permeability. Muddy tidalites are poor reservoirs. Muddy slumps and debrites and hemipelagites are considered to be non-reservoirs. Post-depositional sandy injectites, closely associated with FA-1, also exhibit high values of porosity and permeability. Sandy debrites on the upper-slope settings develop not only sheet-like geometries but also exhibit high porosities and permeabilities because of low mud matrix.

Conclusions

Fig. 8: Representative image of sandy debrite (Well GS-29-H, CC-1, 2182.47-2191.67m, Rec.-100%) A) Whole core image, B) Zoomed photograpph of sandy debrite (from box 2 top), C) Petrographic study reveals feldspathic wacke microfacies D) Scanning electron micrograph image showing isolated intergranular micropores.

Significant findings from this core based documentation of deep water sediments are –

i) four depositional facies have been identified and interpreted: (1) sandy mass transport deposits consists of sandy debrite, sandy slump, sandy slide and occasionally turbidites, (2) muddy mass transport deposits mainly with slump and debrite, (3) sandy and muddy tidalites and tidally affected bottom currents and (4) pelagite-hemipelagite normal background finer low energy deep sea deposits.
ii) Facies succession bearing various tidalites (tidal bundles, tidal beddings and tidal rhythmites) signifies deep water subtidal depositional system with tidally affected bottom currents and with rapid fluctuation in depositional conditions.
iii) Facies architecture reveals predominance of MTDs derived from the land prodeltaic sediments.
iv) The best reservoir is composed of the facies that represents sandy debrites with approximately 30% porosity.

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