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Krishna-Godavari Continental Rift Basin: Shale Gas and Oil Play Systems

P K Padhy, Shishir Kumar Das and Arun Kumar*

Summary

Shale gas constitutes an important unconventional source of natural gas stored in organic rich, matured fine grained sedimentary rock. The organic rich source rock on deep burial with geological time, results in conversion of organic matter into oil and natural gas. A major part of the hydrocarbons is migrated and trapped in ideal locales constituting commercial accumulations. The appreciable quantities are retained in-situ and constitute the unconventional shale gas/oil plays. In case of shale oil/gas, shale acts as both source, reservoir as well as cap rocks. Based on the type of organic matter and maturation level (either oil or gas window), the unconventional hydrocarbons could be shale oil or shale gas or a combination of both. The gas in shale are held as free gas within natural fractures, pore spaces and some are stored as adsorbed gas on the organic matters. The shale is characterized by low matrix permeability, and it requires hydraulic fracturing for shale gas production.

A number of Indian sedimentary basins possess large volumes of source rock sediments, with wide spectrum of geological age ranging age from Proterozoic to Tertiary. The Krishna Godavari basin has evolved over the Eastern Ghat tectonic grain in consequence of Indo-Antarctica plate separation during late Jurassic-early Cretaceous period. The pericratonic Krishna Godavari basin, towards northeastern part, overlies orthogonally the southern extension of northwest-southeast trending intracratonic Pranhita- Godavari Gondwana graben and thus manifesting poly-basinal evolution with wide spectrum of tectono-sedimentary assemblages starting from Permian to Recent. Depositional environment, sedimentological and geochemical aspects of the envisaged Permian (Kommugudem Shale), the early Cretaceous (HG-HR Raghavapuram Shale) and Paleogene (Palakollu Shale, Vadaparru Shale and Bhimanapalli Limestone) Shale Gas/Oil Plays have been discussed. The scope of the offshore shale oil/gas can be worth reviewing after ascertaining the potential in the onland prospective areas.

Keywords*: Krishna-Godavari Basin, Permian, Early Cretaceous and Paleogene Shale Gas/ Oil plays*

Introduction

Shale is a fine-grained, fissile, detrital sedimentary rock formed by consolidation of clay (4 micron size) and silt-sized particles of other minerals, especially quartz and calcite into thin, relatively impermeable layers. The quality of shale reservoirs depends on their thickness and extent, organic content, thermal maturity, fluid saturation, permeability etc. Various clay types and volumes influence the quality of the shale reservoir from the petrophysical and geomechanical perspective (Atkins et. al., 2011). Shale stores large amounts of organic materials compared to other rock types and are deposited under marine, fluvial and lacustrine environments.

The organic components of the shale are algae-plants and marine organisms. During burial, these organic matters (the kerogen) cracks to form hydrocarbons.

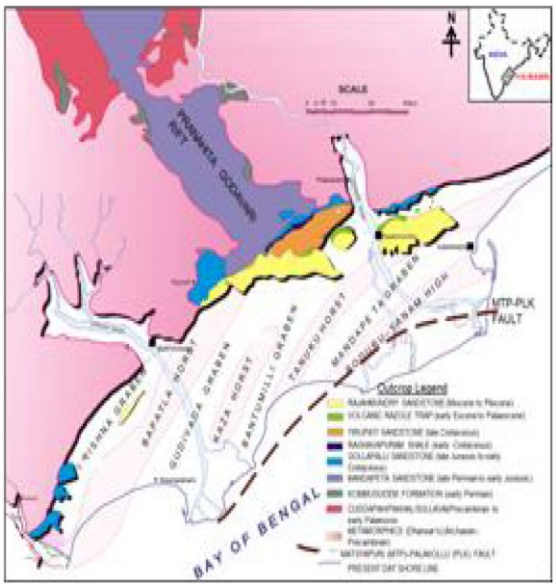


Fig.1. Geological map of Krishna-Godavari Basin

COD-Shale Gas, ONGC, VDODARA.
Email drpkpadhy@gmail.com

The thermal process causes the organic matter to mature and the level of maturity determines whether the shale contains oil, gas or both. The quantities of gas stored in the shale reservoir depends on specific source rock characteristics such as total organic carbon (TOC), thermal maturity, the type of kerogen present. Shale with high gamma (characteristics of rich organic matters), high resistivity, high TOC content (>2-3 wt %), high maturation value (Vro >1.0) is ideal for shale gas exploration. Source rock within low thermal maturity (oil window with Vro ranging from 0.6-1.0) would yield mainly shale oil. Natural fractures are more prevalent in silica-rich and carbonate-rich shales. The brittleness of the shale, with low clay content (<30%), is the key factor in carrying out successful hydrofracturing.

Shale Gas Plays of Potential Indian Basins

The concept of exploration of unconventional hydrocarbons in India had been pioneered way back in early nineties (Padhy, 1989, Padhy and Naik, 1991) and later Mishra, 2008, Rao, 2010, Kumar, 2013 and others. As per the US Energy Information Administration (EIA) study, 2011 four Indian basins namely Cambay, Krishna-Godavari, Cauvery and Damodar are estimated to hold 63 TCF (Table-1). It may be noted that depending on the thermal history of the basin, there is possibility of exploration of both shale oil and gas from the sedimentary basins of India.

Table-1: Perspective area if Indian Sedimentary basins and recoverable Shale gas reserves.

Basin	Area (sq miles)	Prospective Area (sq miles)	Risked Recoverable Reserves (TCF)
Cambay	20,000	940	20
Krishna-Godavari	7,800	4,340	27
Cauvery	9,100	1,005	9
Damodar	1,410	1,080	7

Paleogene Shale Gas play of Cambay, Assam and Assam Arakan; Cretaceous Shale Gas Play of Krishna Godavari and Cauvery, Permian Shale Gas Play of Krishna Godavari, Pranhita Godavari Damodar and Satpura; Neoproterozoic-Cambrian Shale Gas Play of Ganga and Proterozoic Play of Vindhyan basins hold promising. The pilot shale gas project of ONGC drilled four wells in Damodar valley. One well RNSG-1 flowed shale gas from the Barren Measure formation of Permian age.

Tectono-Stratigraphy of Krishna Godavari Basin

The Krishna-Godavari (KG) basin constitutes a typical rifted passive margin basin. The basin was evolved over the Eastern Ghat tectonic grain (Rao, 2001) in consequence of Indo-Antarctica plate separation and influence of oblique extension during late Jurassic period. The pericratonic Krishna Godavari basin, towards north eastern part, overlies orthogonally the southern extension of intracratonic Pranhita-Godavari (PG) paleo rift and thus manifests a dual rift province of basin evolution with typical tectono-sedimentary assemblages. The Krishna-Godavari pericratonic basin is characterized by northeast-southwest trending tectonic highs and lows, with intra-basinal ridge system (Fig.1) namely Bapatal, Kaza-Kaikular, Tanuku and Poduru-Yanam (from northwest to southeast). The subsurface geology depicted in NW-SE geological section (Fig.2) confirms the continuous of the PG graben across north eastern part of Gudivada and Mandapeta grabens. The KG Basin bears the testimony of tectono-sedimentation events from Permian to Recent (Fig. 3).

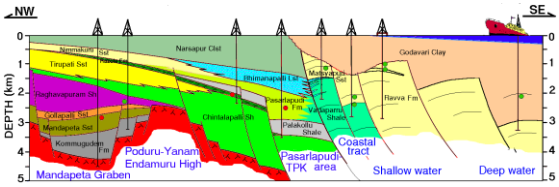
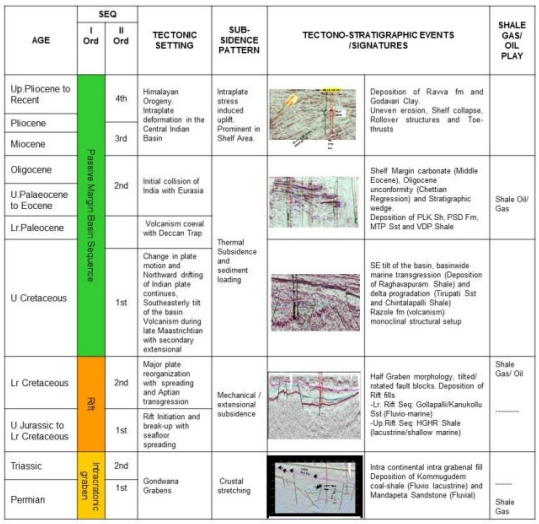


Fig.2. Geological Cross section showing Tectonic and Stratigraphic Setup of Krishna-Godavari Basin.



AGE	SEQ I Ord	SEQ II Ord	TECTONIC SETTING	SUB-SIDENCE PATTERN	TECTONO-STRATIGRAPHIC EVENTS /SIGNATURES		SHALE GAS/ OIL PLAY
Up.Pliocene to Recent	Passive Margin Basin Sequence	4th	Himalayan Orogeny; Intraplate deformation in the Central Indian Basin	Intraplate stress induced uplift. Prominent in Shelf Area.		Deposition of Ravva fm and Godavari Clay. Uneven erosion, Shelf collapse, Rollover structures and Toe-thrusts	
Pliocene							
Miocene		3rd					
Oligocene		2nd	Initial collision of India with Eurasia	Thermal Subsidence and sediment loading		Shelf Margin carbonate (Middle Eocene), Oligocene unconformity (Chettian Regression) and Stratigraphic wedge. Deposition of PLK Sh, PSD Fm, MTP Sst and VDP Shale	Shale Oil/ Gas
U.Palaeocene to Eocene							
Lr.Paleocene			Volcanism coeval with Deccan Trap				
U Cretaceous		1st	Change in plate motion and Northward drifting of Indian plate continues, Southeasterly tilt of the basin. Volcanism during late Maastrichtian with secondary extensional			SE tilt of the basin, basinwide marine transgression (Deposition of Raghavapuram Shale) and delta progradation (Tirupati Sst and Chintalapalli Shale) Razole fm (volcanism) monoclinal structural setup	
Lr Cretaceous	Rifts	2nd	Major plate reorganization with spreading and Aptian transgression	Mechanical / extensional subsidence		Half Graben morphology, tilted/ rotated fault blocks. Deposition of Rift fills -Lr. Rift Seq: Gollapalli/Kanukollu Sst (Fluvio-marine) -Up.Rift Seq: HGHR Shale (lacustrine/shallow marine)	Shale Gas/ Oil
U Jurassic to Lr Cretaceous		1st	Rift Initiation and break-up with seafloor spreading				
Triassic	Intracratonic graben	2nd	Gondwana Grabens	Crustal stretching		Intra continental intra grabenal fill Deposition of Kommugudem coal-shale (Fluvio lacustrine) and Mandapeta Sandstone (Fluvial)	Shale Gas
Permian		1st					

Fig.3. Tectono-straigraphy of KG Basin-Major Tectonic setting and subsidence pattern (Padhy and Man Mohan, 2011).

The intracratonic tectono-sedimentation cycle of fluvio-lacustrine sediment (Kommuguden formation) of the Permian age and the dominant sandstone of Mandapeta formation of the Triassic age constitutes a southern extension of Gondwanic sedimentation (Pranhita-Godavari) in KG basin. The basin experienced a major hiatus (late Triassic to late Jurassic), corresponding to the Yanshanian Orogenic Moment-1 (Ravishankar et.al.,2005) prior to the breakup of the Indo-Australo-Antartica Gondwanaland.

The early synrift sediments (Gollapalli equivalents during Tithonian-Barremian) were deposited during early extensional subsidence accentuated by the earlier basement rifted fault systems. Differential basin subsidence continued along the basement bound fault system accommodating synrift sediments (upper Jurassic to early Cretaceous) of fluvio-marginal marine. With the basin tilt on account of early thermal cooling, the basin witnessed first marine transgression (restricted) during Aptian-Albian time depositing High Gamma – High Resistivity (HG-HR) Raghavapuram Shale. The basin tilt also facilitated on set of south-easterly principal fluvial systems and deposition of sediments (Fig.2).

During passive margin phase, the basin experienced widespread extrusion of volcanic basalt (Keller et al, 2008) during Late Maastrichtian (C29r) to Early Paleocene (C29n) during the northward drifting of the Indian plate over the Reunion hot spot (Curray and Munasinghe, 1991). The drainage reorganization (southe-easterly flowing complex) has fed enormous sediment inputs resulting in further outbuilding of delta progradation further south-east into coastal and offshore area accompanied with fast synsedimentation. During Late Oligocene the basin witnessed a higher magnitude of sea level drop (Raju et.al., 1994, 2005) exhibiting hiatus of the order of 7.5ma.

Another major sea-level fall is prominently observed during Late Miocene and the magnitude of hiatus from Mio-Pliocene ranges from 5 ma to 18 ma. The hiatuses related Late Oligocene and Late Miocene are attributed to uplift of the Indian peninsula (Raju et al, 1994, 2005).

Shale Gas Play System

In KG basin prime source rocks are distributed within Permian, early Cretaceous and Paleogene sections. These source facies could be potential for shale gas/oil exploration (Fig.2). Detailed depositional environment and source rock geology of the important plays are enumerated below:

Permian Shale Gas Play (Kommugudem Shale):
This sequence of Permian age (Asselian-Sakmarian-Tatarian) comprises of shale-coal with minor sandstone and it is underlain by the Basement and overlain by Mandapeta Sandstone of Triassic age.

Depositional Environment and Sedimentological Characteristics: The cyclothemic sequences of carbonaceous shale, coal and sandstone have been deposited under fluvio-lacustrine environment. The core data indicates presence of glauconite. The core logs infer presence of shale with minor reworked thin ripple sandstone of tidal influence (Prabhakaran et al; 2004). Shales are dark grey to black hard compact, silty and occasionally carbonaceous. The inter-bedded sandstones in coal-shale are dirty white, medium to coarse grained, feldspathic. Glauconite and pyrites are often found.

Kaolinite clays are dominant along with chlorite, smectite and illite (Prabhakaran et al; 2004). The increasing accommodation to sediment influx further enhanced for preservation of organic contents and the coal-shale developed within the sequence acts as a good gaseous source facies. At the end the fall in base level resulted in a sub-aerial unconformity. Around 900-1000m thickness of Kommugudem Shale is deposited.

Log Characteristics: The GR log shows alternations of high and low (spiky nature) due to the presence of carbonaceous shale and feldspathic sandstone. The coal and carbonaceous shale show high resistivity. The log characteristics around Kommugudem-Madhavaram-Mandapeta West-Mandapeta-Ramachandrapuram area are mentioned in Table-2.

Table-2: Log characteristics of shales of different formations in KG basin.

Shale in Formation	Gamma (API)	Resistivity (Ohm-m)	Neutron Porosity (%)	Density
Permian-Kommugudem (Kommugudem – Mandapeta west-Mandapeta area)	80-160	10-400	20-48	2.2-2.7
Early Cretaceous -HG-HR Raghavapuram Shale (Penugonda-South Mahadevpatnam area)	65-100	3-8	18-30	2.3-2.6
Early Cretaceous -HG-HR Raghavapuram Shale (Gajulpadu-Lellapudi-Lingala area)	90-130	5-20 (at places upto 100)	24-30	2.3-2.5

Source Rock Characteristics: The Kommugudem Shale is characterized by alternating sequences of carbonaceous shale, sandstone and coal. It is principally gas prone source facies. Source rock and geochemical characteristics of Kommugudem Permian age (Fig.4) imply encouraging scenario for shale gas exploration.

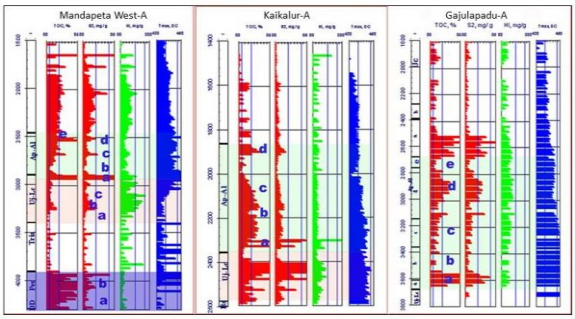


Fig.4. Source Rock logs of wells in Mandapeta West, Kaikalur, and Gajulapadu areas. Good source rock development is seen in Permian (outlined with a deep blue tinted box), Upper Jurassic to Lower Cretaceous (outlined with a pink tinted box) and Aptian Albian (outlined with a light blue tinted box) sequences. Based on the SR facies and lithology variations the Permian, the Upper Jurassic to Lower Cretaceous and the Aptian-Albian sequences have been subdivided into 2 (marked a and b), 3 (marked a to c) and 5 (marked a to e) homogeneous units respectively. The log columns represent TOC (%), S2 (mg HC/gm rock), HI (mg HC/g TOC, and Tmax (centigrade).Source: PS Cube, 2007

The play maps of the average TOC and Vro of the Kommugudem section show prospective area around Kommugudem-West Mandapeta-Mandapeta area (Figs.5 and 6). Source rock characteristics are given in Table-3.

Table-3: Source rock characteristics of shales of different formations in KG basin.

Formation	Thickness (m)	TOC (wt %)	VRo (%)	Tmax (°C)	Type
Permian-Kommugudem	900-1100	2-8 (Max.12)	0.8-1.5	440-580	III
Early Cretaceous - HG-HR Raghavapuram Shale	2000m (Max)	1.0-4.7 (Max. 8.0)	09-1.0	430-450	II/III

Early Cretaceous Shale Gas Play (HG-HR Raghavapuram Shale):

The HG-HR sequence, which unconformably overlies the early rift fill sequence (Gollapalli Sandstone), marks the marine transgression during early Cretaceous (Aptian-Albian). The lithofacies above HG-HR is characterized by high gamma-low resistivity shale of late Cretaceous age.

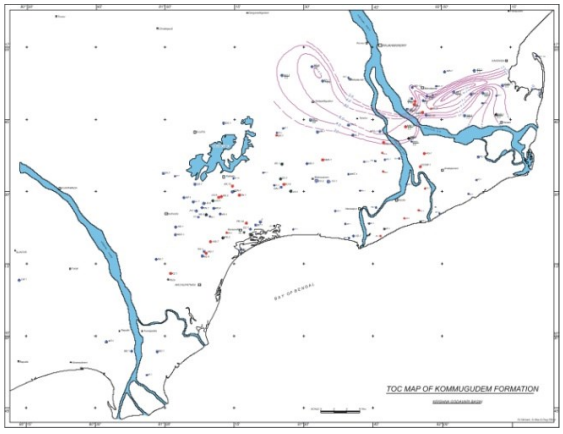


Fig.5. TOC map of Kommugudam Formation

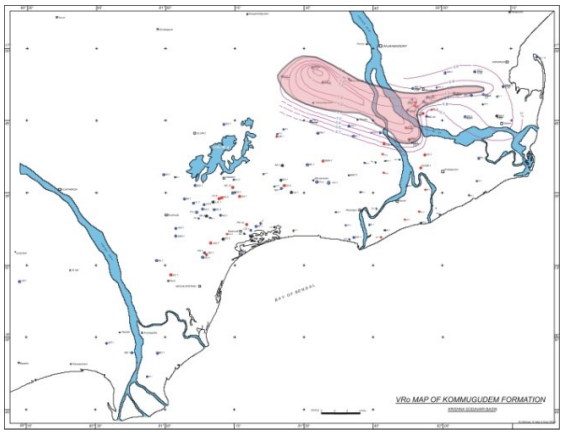


Fig.6. VRo map of Kommugudam Formation. The pink shade shows the area of interest around Kommugudem,Mandapeta-west-Mandapeta.

Depositional Environment and Sedimentological Characteristics: The restricted marine environment, shallow bathymetry, very slow rate of sedimentation and the nearness to the provenance resulted in the deposition of High Gamma-High Resistivity Shale (HG-HR) sequence (Man Mohan and Rao, 1998, 2002). The sequence is carbonaceous, organic rich, silty and with high thorium and potassium content. The HG-HR sequence is dominantly argillaceous and the lower part is more carbonaceous. The intervening sandstones are dirty white, light grey to grey friable to hard and compact, medium to very fine grained, occasionally coarse and pebbly, calcareous, moderately to well sorted. Siltstone is dirty white, light, moderately hard, compact and calcareous.

Since this was in the transitional stage of the reversal of the basin slope, the slope gradient was not enough to facilitate a major fluvial system. Thus this sequence lacks huge reservoir facies except for transgressive bar type sands

along the palaeo-shore (Man Mohan and Rao, 2002). Core studies of Lingala area suggests sand lying over the lower unconformity is fine to medium grained, well sorted sand with flaser and wavy bedding, thin alternations of silty claystone, abundant plant material, bioturbation, burrows, claystone lenses and load structures indicating a near shore environment. The shales are found to be rich in clay with quartz, siderite, glauconite, orthoclase and pyrite. Hydrocarbons are mainly entrapped within reservoirs deposited during transgressive and regressive phases, close to the unconformities (Fig.7). This sequence, in onland part, wedges out towards south-west in Gudivada Graben. At places near the basin margin, the entire sequence is represented by arenaceous facies.

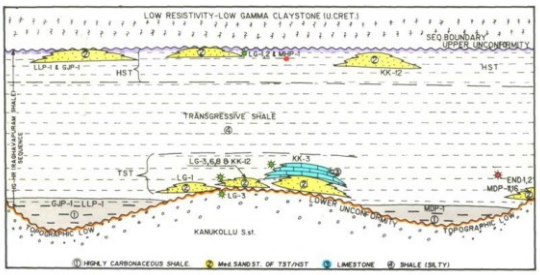


Fig.7. Schematic diagram showing types of litho facies and HC habitat within HG-HR. The lenticular sands are deposited during both the transgressive and regressive phases and are observed to be found just above the lower unconformity and below the upper unconformity. Isolated limestone reservoir found in Kaikalur-3 is the sole carbonate hydrocarbon reservoir in the basin (Man Mohan and Rao,1998)

Log Characteristics: The sequence exhibits relatively higher gamma and resistivity as compared to the overlying and underlying ones. Natural Gamma Ray Spectrometry (NGS) logs display that the High Gamma-High resistivity Shale intervals have a considerably higher Thorium and Potassium contents.

The upper member of Raghavapuram argillaceous section (High Gamma-Low Resistivity) unconformably overlies on the HG-HR and is underlain by Tirupati Sandstone. The Thorium value against this sequence show low compared to the underlying sequence.

The lower part of HG-HR in some of the wells shows high Gamma with abnormal high resistivity (around 100 ohm-m, at places even 200 ohm-m, Table-2). The log expression towards the lower part of the HG-HR section in Malleswaram area is characterized by high resistivity (8-30 ohm. m), high porosity (around 40%) and low density (2.3-2.4).

Source Rock Characteristics: HG-HR Shale is the principle source facies having kerogen Type II and III (Figs.4 and 8). It may be noted that maximum of 1.0 vitrinite value is observed around Penugonda-South Mahadevpatnam-Kavitam-Vygreswaram areas with TOC of 2.0 wt% (Figs. 9 and 10).

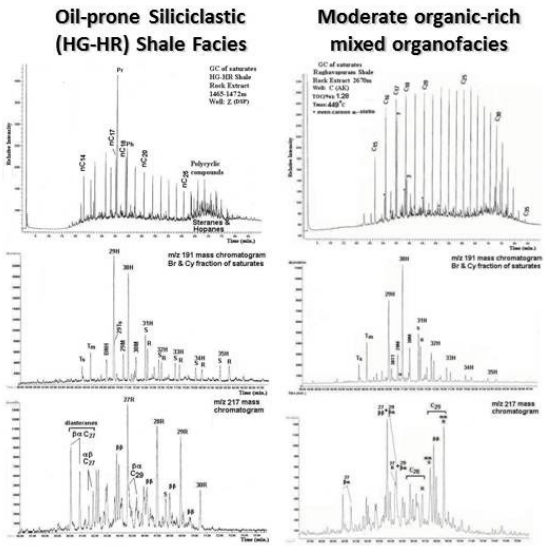


Fig.8. Geochemical Characteristics of the source rocks of Raghavapuram Shale. Decreasing abundance of long chain (C_{25}+) n-paraffins, High abundance of hopanes and algal- derived ($C_{27} > C_{29}$) steranes infer oil-prone source facies. High abundance of C_{20}+, Low abundance of steranes ($C_{27} << C_{29}$) indicate dominant terrestrial input (Prasad et.al.,2005)

In west Godavari sub-basin maximum vitrinite of 0.8-0.9 is observed in around Gajulapadu-Lellapudi-Lingala and towards south east around Malleswaram-Bantulilli vitrinite value of 0.9 is seen over a limited area where as high TOC has been found in and around Gudiveda graben in Gajulapadu-Lellapudi, Gokarnapuram-Mahadevpatnam, Akhividu area (3.0 -3.5 wt%), Kaikalur-Lingala area (average 2.0 wt %). The expulsion efficiency is calculated to be of 60-70%.

Paleogene Shale Gas/Oil Play

Huge thickness of Tertiary sequence is deposited in the coastal island and off shore area. Pallakollu Shale and Vadaparru Shale, deposited under marine condition, constitute important source facies (Fig.11). The organic matter is of terrestrial in nature (Type III kerogen). Pallakullu Shale constitutes fair to good mature source rock unit in East Godavari Sub basin. The average TOC content varies from 0.5-2% in the western part (Narsapur-

Chintalaplli area) to 4.4% in the Amalapuram-Vetlapalem with Tmax values in the range of 453-470°C.

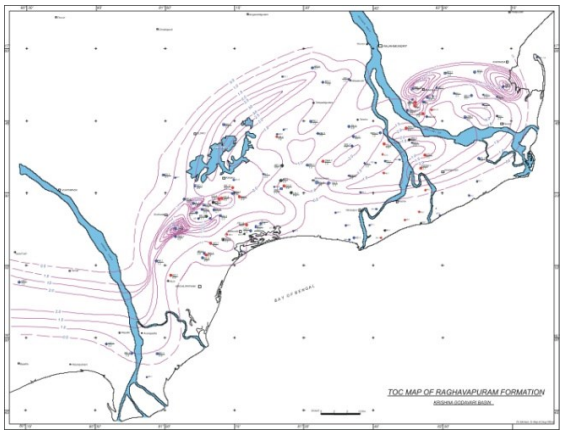


Fig. 9. TOC map of Raghavapuram Formation

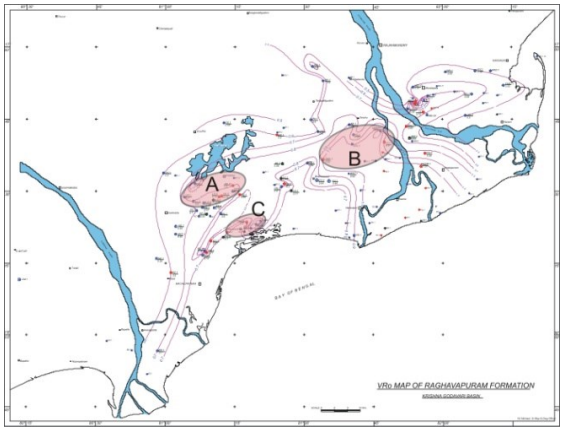


Fig.10. VRo map of Raghavapuram Formation.The pink shade shows areas of interest for shale gas/oil. (A) Gajulapadu-Lellapudi-Lingala (B) South Mahadevpatnam (C) Malleswaram-Bantumilli .

The organic facies representing Palakollu Shale differs from the overlying Vadaparru Shale, by virtue of higher Gammacerane and C_{28} sterane contents in Palakollu Shale extracts suggesting contribution from dominantly marine source precursors in comparison to Vadaparru Shale (Prasad et.al.,2005).

Vadaparru Shale formation of Eocene age, a dominantly argillaceous unit with minor limestone and sandstone intercalations is rich in organic matter (av. range of TOC 0.8-7.2%) . Higher bitumen yields varying from 1500-8700ppm suggests better oil-prone source facies. Distribution of organic matter and remaining generation potential show increasing richness from the onland to present coast line and further offshore area. Vadaparru Shale unit with good to very good source rock characteristics (TOC in the range of 4.2 to 26.3%, and S2: 3.3- 45.6mg HC/g rock) in off shore wells also. It may be noted that the Paleogene section experiences high pressure.

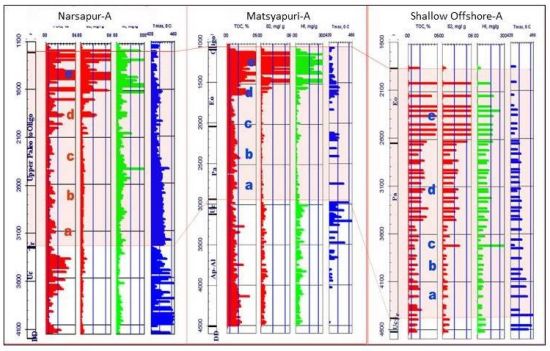


Fig.11. Source Rock logs in Narsapur, Matsyapuri and Shallow offshore wells show source rock development in Upper Paleocene to Oligocene sequence. Based on the SR facies and lithology variations the sequence has been subdivided into 5 (marked a to e) homogeneous units. The log columns represent TOC (%), S2 (mg HC/gm rock), HI (mg HC/g TOC, and Tmax (deg. centigrade). Source : PS Cube, 2007

The Bhimanpalli limestone also exhibits presence of source facies at places (Prasad et.al., 2005). Lithologically Bhimanapalli formation (middle Eocene) consists of highly fossiliferous limestone with thin sand and shale beds at places. The abundance of organic matter varies from poor to very good (TOC: 0.3 to 14.6%). The source rock characteristics are remarkably improved towards southwest around Narsapur area with better organic richness (av.TOC: 3%; max. TOC: 14.6%) and the generation potential (av. S2: 7.5 and max. S2: 37). The Bhimanapalli sediment is also adequately mature for generation of hydrocarbons around Mori and West Mori areas with av. TOC values greater than 2% (max. TOC: 10%) and good remaining generation potential (av. S2: 4 and max. S2: 10) with moderate level of maturity at Tmax: 440°C (Prasad et.al., 2005).

Some of the Mio-Pliocene reservoirs of Krishna-Godavari basin are characterized by dominance of biogenic methane and mixed gas (thermogenic and biogenic) with carbon isotopic values ranging from -50 to -67 per mil. The coastal area and in shallow offshore area presence of biogenic gas has been established in Neogene sequence. Possible unconventional gas can be explored from the biogenic source rock.

Conclusions

Shale gas play could be one of the important resources for fossil fuel energy of India. Indian sedimentary basins have thick organic rich source sequences deposited over wide geological age. Based on geology and detailed subsurface geochemical data, prevalence of three Shale Gas Play Systems of Permian, early Cretaceous and Paleogene age have been envisaged in Krishna-Godavari basin. The Permian sediments with high thermal maturity could yield gas where as the early Cretaceoous and Paleogene appear to be more of shale gas/oil. Permian shale gas play appears to be prospective around Kommugudem-West Mandapeta –Mandapeta area. The prospective areas for early Cretaceous shale gas/oil play is around South Mahadevpatnam-Kavitam-Penugonda, Kaikalur-Lingala-Gajulapadu.

The Paleogene shale oil/gas play including Bhimanapalli Limestone (thermogenic as well as biogenic gas) appears promising in island and shallow off-shore area.

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