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Hydrocarbon Occurrences in Mahanadi Basin

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Summary

Generation of primary biogenic and mixed biogenic- thermogenic gas is analysed with the help of carbon isotope data and presence of associated non-hydrocarbon gases. Seismic interpretation of depositional elements is also carried out to decipher the occurrence of gases. Data are mainly restricted within the study area in Mahanadi Basin.

***Keywords**: Generation, accumulation, biodegradation, carbon isotope, mixed gas, associated non-hydrocarbon gases.*

Introduction

The exploration activity in Mahanadi Basin has been underway from the 1970s. Early exploration was mainly restricted to onland and upper shelfal part with no success in discovering Oil and Gas. In 2006 one well M-4 (Fig-1) was drilled beyond shelf edge towards basinal side (lower shelf) but failed to discover any hydrocarbon. First exploratory success in Mahanadi basin came in the year 2007 with the discovery of biogenic gas from channel sands in Channel Levee Complex type reservoir of Mio- Pliocene age. From then on Exploration was mainly targeted for Mio-Pliocene Channel Levee Complexes in addition to deeper prospects in Paleogene slope fans. In the process some more wells were drilled in different blocks in the basin and met with mixed results, some gas bearing and others dry. Recently an exploratory well M-9 was drilled with the success of discovering mixed biogenic and thermogenic gas at Paleogene level in the study area. The area under study (3D area) within this block (Fig-1) includes both gas bearing and dry wells. The gas producing/bearing wells have thin to very thin gas filled sand intervals in Mio-Pliocene and Paleogene levels. The big find is still awaiting and a relentless search is on to make this basin commercially viable for development.

The extensional tectonics played the major role in basin development. Stratigraphic succession started from Early Cretaceous Sediments with basaltic traps followed by Late Cretaceous through Paleogene and topped by Neogene sediments. All formation boundaries are marked by unconformity surfaces. Entrapments are all stratigraphic. Reservoirs are restricted to slope fan and canyon fill deposits in Paleogene, slope fan in Cretaceous and channel-levee-complexes in Mio-Pliocene sediments.

The discovered gas in shallow reservoirs is tested to be biogenic and in the deeper reservoir a mixture of both thermogenic and biogenic. The biogenic gas in the shallow reservoir may owe its origin either to diagenesis or to migration from deeper source after biodegradation of crude oil in the deep. Mixed gas in the deeper reservoir is thought to be accumulated by upward migration with biodegradation of higher HC component of oil and gas at deeper source.

The probable origin and accumulation of biogenic gas and mixed biogenic and thermogenic gases are attempted in this paper.

Geological Set up of Mahanadi basin

Mahanadi Basin is a peri-cratonic basin along the eastern continental margin of India which is separated from Krishna-Godavari basin by 850 E ridge. The main tectonic trends of Mahanadi Basin includes NE-SW trending Late Jurassic-Early Cretaceous “Main rift Phase” which is orthogonal to the older NW-SE trending Permo-Traissic Mahanadi-Gondwana trend. The main rift phase is characterised by a predominantly volcanic sequence with inter trappeans. The onset of drift phase is marked by regional basin-ward tilting and transgressive event also coincide with cessation of rift generated fault activity. From Late Cretaceous the initiation of shelf edge started with marine regressive phase at around 65 Ma where proto-

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Mahanadi, Devi, Brahamani etc. were the main channel system for transporting clastics to deltaic complex at the shelf edge. Late Cretaceous surface is an erosional unconformity indicating rate of sealevel fall faster than the rate of subsidence of the shelf. During end of Paleocene to Late Eocene there were marine transgressive and regressive phases. Indian plate was straddling past the Equator during this period indicating warm climatic condition conducive for carbonate development. Limestone with minor alteration of some clastic as well as some transported or reworked limestone can be expected in the deeper part of the basin. Rate of sealevel fall was faster than the rate of subsidence of the shelf during Paleocene and Late Eocene time. Late Eocene is absent in most of shelf part. Absence of Oligocene in the shelf and part of upper slope of the Mahanadi Basin, suggest regression in the Oligocene period. Rate of subsidence of Mahanadi shelf was faster than the rate of sealevel fall to produce Type-II unconformity (Posamentier et.al 1988) during Oligocene. With the onset of collision of Indian plate and Eurasian plate the major sedimentation activities prevailed during Post-Oligocene period till recent when channel activity was the major contributor of sediments in the deeper part of the basin. In the basal part of Miocene there was a major transgressive phase with small pulses of regression and the upper part of Miocene and Pliocene are mark progradation and numerous channel activities.

Seismic interpretation of the Area under study

Stratigraphic sequence is derived from the shelfal and deepwater wells penetrated deep into Trap or Basement. This provides the basic idea and understanding of general sedimentation and stratigraphy of the basin. On Precambrian basement, Early Cretaceous basaltic flow is overlain by Cretaceous clastic sediments. The Cretaceous sequence is unconformably overlain by Paleocene-Eocene sediments which are characterised by dominantly carbonates inter bedded with clastics related to a major transgressive and minor regressive cycles. A major regressive cycle is present at the onset of Late Eocene and continued till end of Oligocene causing absence of Late Eocene-Oligocene sediments in a vast area including the shelf and part of upper slope. In the deeper part of the basin Oligocene may be present. Mid Eocene is unconformably overlain by Mio-Pliocene clastic sediments. Rapid uplift of the Himalayas due to hard collision of Indian plate and Tibetan plate induced subsidence in Mahanadi Basin during Early Miocene. The onset of activity of Ganga-Brahamaputra feeder systems during Mid. Miocene along with older Mahanadi-Bramhani river system and the uplift in the west led to the huge influx of clastics into the basin and pro-grading deltaic sediments built out over Mio-Pliocene period. This progradation has continued till present day. The overall stratigraphy of the block area is summarized in Table-I.

Table-I

STRATIGRAPHY OF MAHANADI OFFSHORE BASIN

TIME	EVENTS	LITHOLOGY
Pliestocene to Recent	9. Progradation of clastic sediments with no subsidence.	Slope channels and canyons
Mio-Pliocene	8. Subsidence and progradation of clastic sediments	Slope channels,canyons and basin floor fans
Oligocene	7. Period of non-deposition or erosion	Absent on the shelf. Present in the deep basin.
Eocene	6. Developed shelf-slope break with further tilt towards east. 5. Collision of Indian plate with Asian plate.	Transgressive clastic starved sequence.
Paleocene	4. Drifting continued with basinal tilt and shelf-slope development.	Deltaic sedimentation through protoMahanadi
Late Cretaceous	3. Drifting continued with basinal tilt towards E with initiation of shelf-slope.	Sand in the upper and shale in lower part
Early Cretaceous-Late Jurassic	2. Rajmahal trap volcanism. 1. Rifting followed by drifting.	Rift fill sequence followed by volcanics
PreCambrian	Pre-rifting	Basement

The area under study was reviewed and the drilled well data of M-4, M-5, M-6, M-7, M-8, M-2, M-3 and M-9 were scrutinized. Seismic profiles have provided the data of stratigraphic and sedimentological importance (Fig-2, Fig-3). The shape, polarity and true amplitudes of seismic reflectors have been decoded to get valuable geological information. Seismic amplitudes within time windows and

Fig-1 Map showing the area under study (yellow part) with drilled wells(Black dots for dry, Red for gas wells)

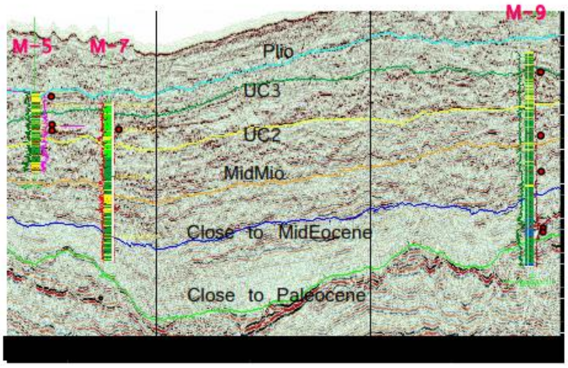

Fig-2 Stratigraphic interpretation with logs of wells with Gas zones in area under study

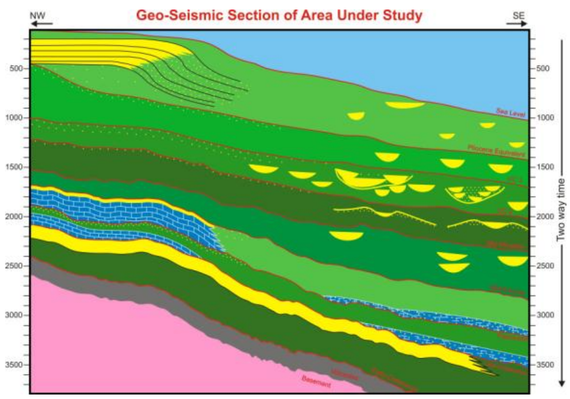

Fig-3 Seismo-Geological model showing Depositional Elements.

proportional slices are used in defining stratigraphic and geomorphic features. This reveals the change in lithology indicating the reservoir boundary or fluid changes suggesting the probable hydrocarbon accumulation.

The key depositional elements observed are Channel Levee Complex (Fig-4-1), channel mouth lobe, gravity flow canyon deposits(Fig-4-6), MTC (Fig.4-7) and slope fans (Fig-4-3). Out of all, the channel-levee complexes/slope channel-fan complexes are the most dominant depositional elements.

On the basis of large scale architecture the Mio-Pliocene channels are characterized by high sinuosity (Fig4-1), scrolling of point bars (Fig4-2), deep incision bound by overbank (Fig4-1), crevasse splay (Fig4-4) and expected high percentage of sand as observed in the well M-5, M-7 and M-9. Seismically these channels show high amplitude reflectors in seismic data and reversal in polarity of high amplitude reflectors in case of presence of gas. Low AI, SI and Vp/Vs are the other features of the gas bearing reflectors. Within Mio-Pliocene sequence channel-levee complexes/slope channels are present oriented orthogonally to the shelf-slope break. Attribute analysis and horizon slices indicate the sediment influx from the shelfal side i.e. from north to south. However, frequent lateral channel switching has resulted in heterogeneity in the form of isolated reservoirs. The wells M-5, M-6, M-7 and M-9 were gas bearing and the wells M-4 and M-8 are dry suggesting the heterogeneity or compartmentalisation of CLC type reservoir.

During Mid-Eocene, exposure of the platform and associated weathering resulted in channel erosion and incision. These incised channels transported calciclastic and siliciclastic material from the staging area down the slope, depositing them in slope fan complex(Fig-4-5). One of these slope fans on the eastern most corner of the area (Fig-4-3) has been tested by drilling a well M-9. Drilling results reveal the presence of a fan body filled with both calciclastic and siliciclastic sediments and a thin reservoir of mixed gas both biogenic and thermogenic.

Canyon/channel fan complex in Paleocene/Lower Paleogene (Fig-4-6) draw attention due to the fact that presence of sand has already been established in the drilled wells on the staging area in the interval of Paleocene and Late Cretaceous but without the charge.

Chrono-stratigraphically Late Cretaceous and Lower Paleogene sand in shelfal part may not match the sand in its lower slope part and will be separated by shale, clay or silt. Sand in down-dip will be changed to shale or clay with facies change. Recent results of mixed gas in the well M-9 evoke interest in searching oil and gas deep in the basin.

Petroleum system in Mahanadi Basin

The testing results of drilled wells confirm two petroleum systems (1) a shallow Mio-Pliocene biogenic gas system and (2) the non-biogenic which may be a gas-prone Late Cretaceous through Paleogene thermogenic system or a sub-volcanic oil-prone Early Cretaceous system. Discovery of mixed thermogenic and biogenic gas within Paleogene

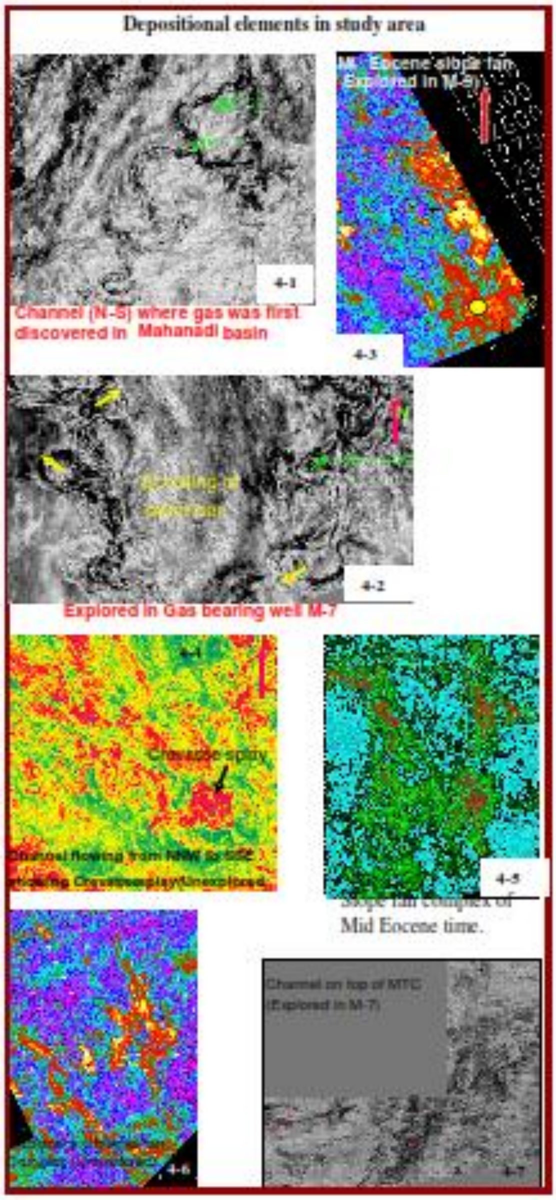

Fig.4. Depositional elements as observed on Mahanadi slope in the study area

slope fan in the well M-9 indicate thermogenic source and generation down-deep outside the block. Other drilled wells' results indicate the presence of a biogenic gas charge. Its adequacy to fill commercial-sized pools is partly proved from gas bearing wells. Biogenic Gas wherever present occupy a very small area thereby indicating less generation from the source pod. Absence of Oligocene in the land, shelfal part and in upper slope in Mahanadi basin indicate either the upliftment of the basin or the fall of sea-level during Oligocene time leaving exposed area to erosion and weathering. The intensity of weathering has been observed by the presence of earlier formed lineaments in NNW-SSE direction. Canyons, developed along those pre-existing lineament have left their marks by eroding the whole Eocene sequence at places. Owing to Himalayan orogeny, faults, lineaments or fractures already present might have opened up during Eocene thereby helping migration of hydrocarbon from the deep and intrusion of surface water deep down the formation. During Oligocene period of no deposition the fresh water intake might have aggravated and percolated deep down the formation only to help in altering the petroleum occurrence through biodegradation. Faults are not very prominent in the studied area of the basin thereby raising doubts about the migration path. With increase in depth, both pressure and temperature increases. So during Miocene time of basin sinking a good amount of overburden was created to help in thermal expansion of gaseous hydrocarbon which in turn fractured the roof of the reservoir and helped in migration.

This suggests that thermogenic hydrocarbon was generated prior to Oligocene at a depth of 3 to 4 km within Cretaceous. Sediment thickness of minimum 3 to 4 km is required to reach the temperature range of 80 to 150^0 C with geothermal gradient of 25^0 C/km to 30^0 C/km for type-III kerogen (Fig-5a,b). Fig-6 shows 1D Petromod temperature modeling for the well M-4 with temperature measured from logs as input. This model suggests Heat flow of 60 mw/m2

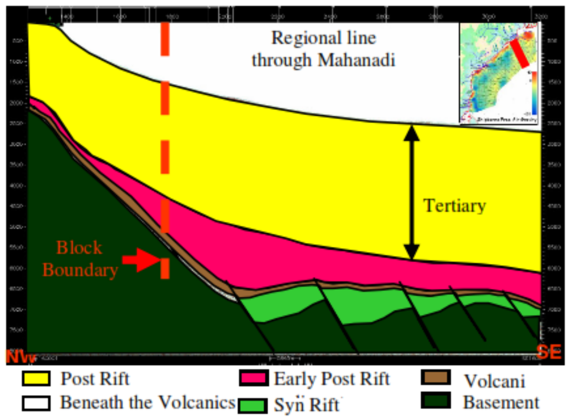

Fig-5a. Model section of Mahanadi Basin

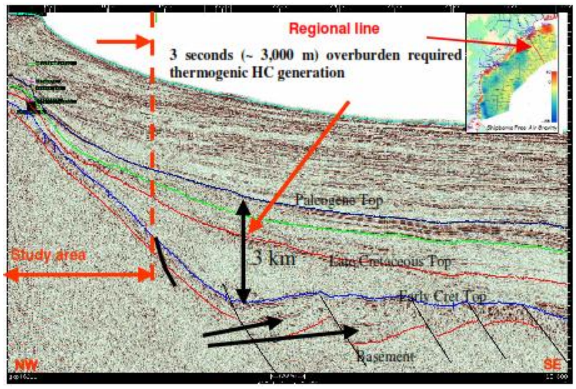

Fig-5b Regional Seismic Line showing Pre Cretaceous half grabens filled with rift sediments, possible source to generate sufficient hydrocarbons

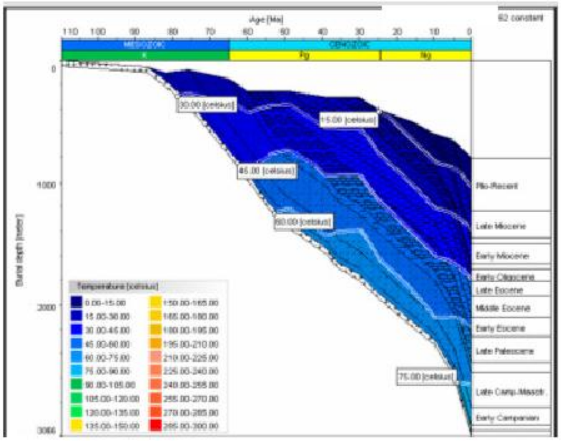

Fig-6 IES 1D Petromod- Heat flow calibration to well temperatures wrt M-4

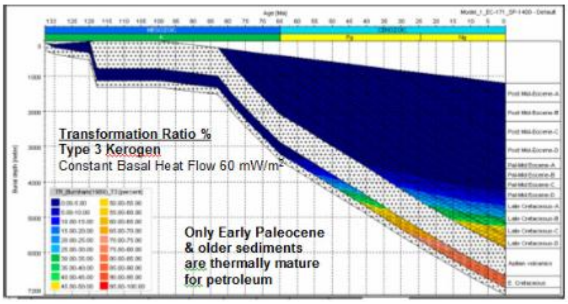

Fig.7 Source maturation modelling on line EC-171

can be taken as input in Mahanadi basin modeling studies. Different 3D Heat Flow maps along with the position of Indian plate are shown in the Fig-9. Maps indicate high heat flow @ 60mw/m2 from 112ma to 99ma. Afterwards this high heat flow gets diminished within Mahanadi Basin and shifted towards SE. The position of Indian plate in the inset in all the Heat flow maps shows plate-movement towards north thereby suggesting hotspots as the source of heat from the Earth's interior. The analysis of the basin modeling studies suggests this heat flow as enough to generate petroleum at Cretaceous level. The study along a 2D line connecting wells M-3 and M-5 and along GXT line shows hydrocarbon generation potential and geothermal

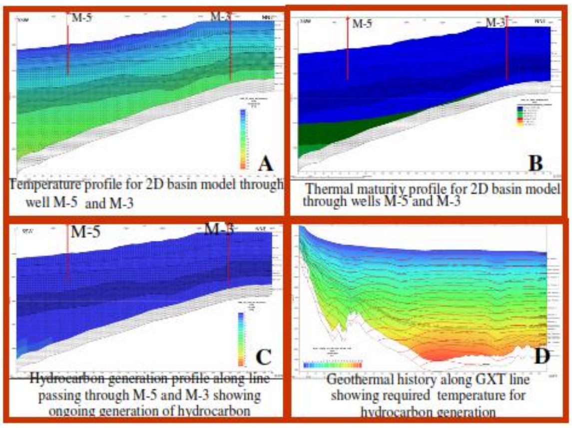

Fig-8 A, B, C showing potential for hydrocarbon generation within the study area and slide D represent geothermal history close to study area.

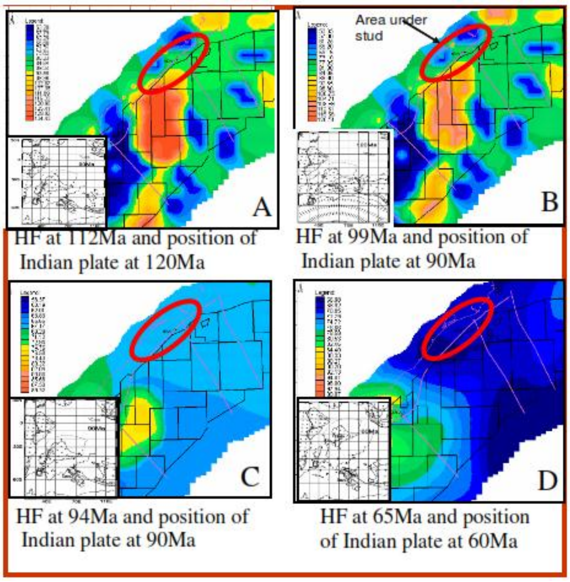

Fig-9 A,B,C,D representing HF scenario with time.

history respectively(Fig-8). Drilled well data in Mahanadi offshore indicate thick shale at the base topped by moderately thick sand layer within Late Cretaceous. This shale as passive margin rift-drift deposits from Gondwana continents can be considered as source rock.. The other most likely source rock belongs to syn-rift sediments of Early Cretaceous age as observed from the GXT line in the Fig-5b. Maturity maps in Fig-10 also suggest presence of maturity at Albian – Cenomanian time. Therefore, basin modeling study suggests generation, migration and accumulation of hydrocarbon in the basin.

Hydrocarbon accumulation in the area under study

Presence of Biogenic gas is confirmed in wells M-5, M-6, M-7 and M-9 at Mio-Pliocene level and mixed biogenic and thermogenic Gas at Paleogene level in the well M-9. The ∂^{13}C isotope values range from -64.3 to -67.5 as reported from the Mio-Pliocene gas analysis results of wells M-5, M-6, M-7 and M-9. The ∂^{13}C isotope values range from -64.3 to -67.5 as reported from the Mio-Pliocene gas analysis results of wells M-5, M-6, M-7 and M-9. The ∂^{13}C isotope value of M-9. The ∂^{13}C isotope value

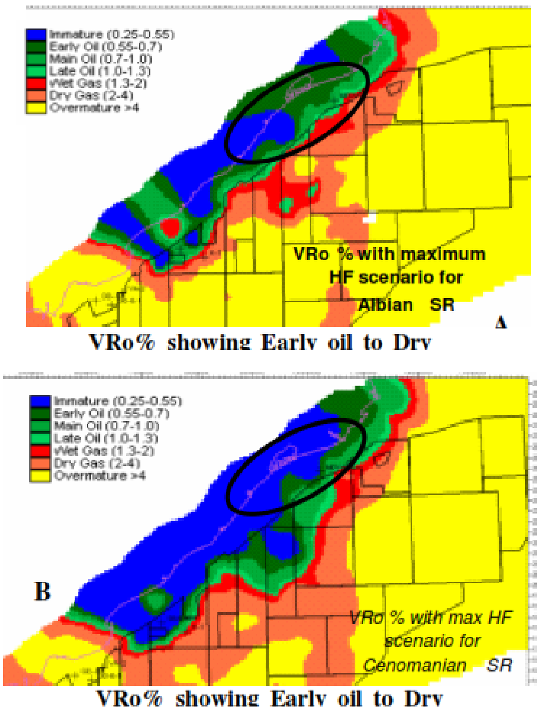

Fig-10 Slides A,B indicating maturity in 3D basin modeling study carried out by ONGC-IES team.

of -54 for the gas from deeper level in the well M-9, indicate the presence of mixed biogenic and thermogenic gas under sediment thickness of 2100m in Paleogene level (Fig-11). The other associated gases besides methane are N_2 and CO_2 in the well M-7 in Mio-Pliocene and CO_2 in M-9 in Mio-Pliocene and Paleogene. Presence of O_2 is observed in wells M-5 and M- 6 in Mio-Pliocene level. Gas analysis report of M-7 shows CO_2 % in the range of 0.08 to 0.23 under the 650m of sediment cover. The report of M-9 indicates CO_2% in the range of 0.51 to 0.37 under sediment cover of more than 1200m and 2100m respectively. C-isotope fractionation or difference in dry gas generation process may play a role in the variation in CO_2% with depth. The increase in pressure and temperature with depth makes the proposition of diagenesis difficult at deeper level. In the well M-9 mixed biogenic and thermogenic gas is present at deeper level and only biogenic at shallow level. In this well, CO_2 % (0.51) in biogenic gas at shallow is more than CO_2 % (0.37) in mixed thermogenic and biogenic gas at deeper level. C- isotope values of CO_2 are not available in the analysis to say anything on C-isotope fractionation effect. The generation of dry methane gas by diagenesis at shallow and by biodegradation at deep may be a probable explanation for different CO_2% at different depths in different wells.

The gas analysis of the well M-7 reports the presence of 0.91% to 3.7% N_2 along with dry methane gas in Mio-Pliocene. But the gas analysis of M-9 does not report the presence of N2 with dry methane gas in Mio-Pliocene and Paleogene. Presence of N2 with biogenic gas probably indicates the presence of aerobic bacteria which oxidizes Ammonia into N_2. This can happen during early generation of gas immediately following the deposition of sediments through diagenesis (Tisso and Welte, 1984). Late generation of hydrocarbon when a lot of overburden is present reduces the chance of presence of aerobic bacteria thereby reducing the chance of producing N_2. But this can also happen by oxidation, water flushing and aerobic degradation of crude oil at deeper depth. Invasion of fresh or meteoric water in shallow or deeper level help in supplying oxygen for the oxidation of Ammonia to N_2. So process of generation of biogenic gas either by diagenesis or by biodegradation of crude oil at deeper depth may not be ascertained by presence of N_2. Prinzhofer and Pernaton, (Gas isotope tracing by Prinzhofer and A.Battani, Oil and Gas science and Technology, vol-58(2003)) showed experimental results of methane migration through shale,

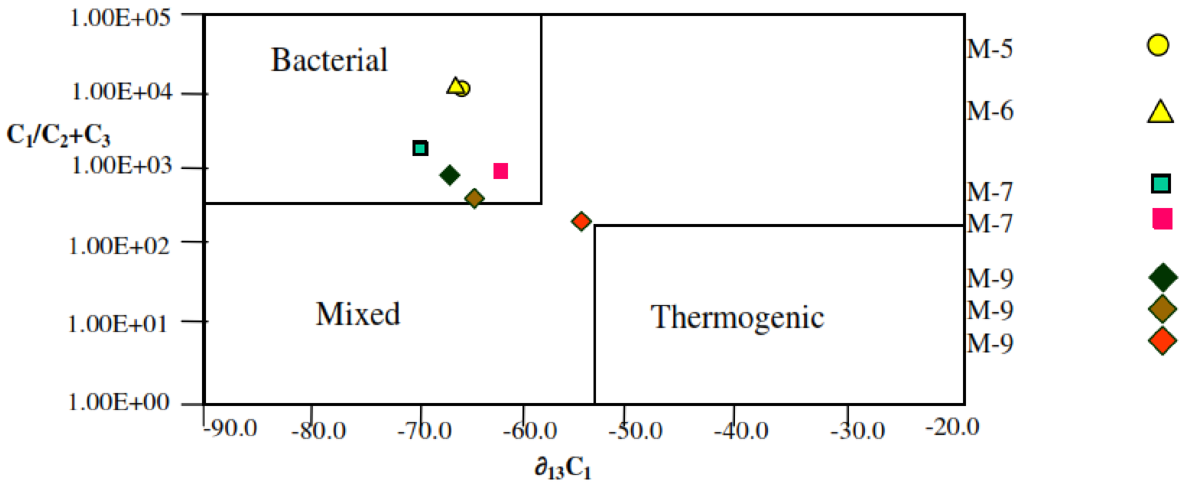

Fig-11 Mahanadi Basin Gas plots in Bernard's Diagram

saturated or not with water. According to him the migration occurs by water solubilisation/diffusion and the ranges of genetic signatures corresponding to bacterial and thermogenic methane are also represented, showing that a purely thermogenic methane may present a bacterial signature (or a mixed one), due to its migration through a porous rock.

Conclusion

The combined effects of tectonic, atmospheric, oceanic and biological processes generated petroleum in Mahanadi basin by the end of Late Eocene within the compartments in thick late Cretaceous shale or in the Early Cretaceous syn-rift sediments. Sediment-thickness of 3 to 4 km was deposited by the end of Eocene with average heat flow @60 mw/sq.km. This condition was conducive for generation of hydrocarbon as suggested by Basin modeling study. Primary Biogenic gas is restricted within Mio- Pliocene sediments. Mixed gases in the deeper reservoir (Paleogene) suggest two alternatives for their origin. The first alternative suggests opening up of old faults, lineaments or fractures during Eocene owing to Himalayan orogeny, thereby helping migration of hydrocarbon upwards from the deep and intrusion of surface water downwards. During Oligocene period of no deposition the fresh water intake might have aggravated and percolated deep down the formation only to help in altering the petroleum occurrence through biodegradation. The second probable explanation of presence of mixed thermogenic and biogenic gases in Paleogene is thermal expansion of pore fluids which eventually caused fracturing of the top compartment seal during Miocene time of basin sinking. Hydrocarbons and other pore fluids originated in Cretaceous then moved vertically into the overlying lower pressured sediments and accumulated in the nearest stratigraphic traps in Paleogene level. However, these two alternatives are hypothetical as the area studied is less explored. $\partial_{13}\mathbf{C_1}$ values of gases clearly demarcate the biogenic from mixed biogenic-thermogenic with the help of Bernard's diagram. Among non-hydrocarbon gases the variation in CO_2% in different wells at different depths suggest different generation processes of dry methane gas at deep and shallow. In general it is observed CO_2% increases with depth. No relation between CO_2% and N_2 can be established from the scanty data. N2 is reported in all the wells except M-9.

Exsolution of gas from the water solution could result from reduction of hydrostatic pressure due to upliftment or erosion or fall of sea level. In marine environments, produced biogenic methane is retained in solution at different pressure temperature gradient. So availability of methane in free gas state is essential for any commercial accumulation.

Due to paucity of wells the data remains very scanty to come to any definite conclusion. Attempts are made to analyse these data of few wells to make a meaningful contribution.

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