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New evidences for dating, paleoenvironmental settings, source potential and geo events of Cretaceous sequences from petroleum perspective in Krishna-Godavari Basin, India

Abstract:

Globally Mid Cretaceous holds more than 50% of the world's known petroleum reserves. More reserves are being discovered in Rift basins worldwide.

Rao (2013), Karuppuswamy (2013) and Syam Mohan (2013) brought to light the recent success stories of oil/ gas particularly in Krishna- Godavari Basin. Break through discoveries in mid-Cretaceous, KG-Basin are G-4-F (offshore), YS-5-AA (Yanam offshore), Malleswaram-C, Vanadurru South-A and Kottalanka-B. The lithostratigraphic units like Gollapalli Sandstone, Nandigama Formation, Kanukollu Formation, High Gamma- High Resistivity unit, Raghavapuram Shale and Tirupati Sandstone are bearers of oil/ gas. These oil and gas bearing strata in terms of geologic time span are within Aptian to Coniacian. The global events during this period include six Ocean Anoxic Events (OAE 1a, 1b, 1c, 1d and OAE2 and OAE3). Although lithostratigraphic units are basic fundamental but most of the litho units when perceived on basin scale are diachronous in nature. Global tectonic events during this interval, or close by, include final breakup of India-Antarctica (140Ma) Rajmahal volcanism and separation of Madagascar (89Ma/ 90Ma) and Deccan Volcanism (66-65.5 Ma).

Microfossils played a major role in correlation of deep exploratory wells in petroleum industry ever since, these are first used by Gryzbosky 120 years ago. Micropaleontologists used to be part of core team in petroleum industry nevertheless with advent of seismic stratigraphy; biostratigraphic information has become less critical. Hydrocarbon exploration demands predictive power. Geoscientists learn lessons from existing oil and gas fields- their geologic evolution, source, reservoir and cap rocks and project imagination to new or partially discovered basins through correlation and comparison; thus demands a geologic time frame to pigeonhole all stratigraphic information- lithofacies, biofacies, geochemical and depositional setting across the globe.

Geologists utilize various tools in determining the age of rock record. For dating subsurface sedimentary sequences across the globe, foraminifera are the only low cost and high precision tools utilized. Besides nannoplankton, dinoflagellate cysts, spore-pollen, silicic flagellates, diatoms, acritarchs and others play a role in deciphering the order of superposition and irreversible evolutionary history of any sedimentary basin for successful exploration.

Any geologic rock record is discontinuous, interspersed bybreaks in sedimentation. The duration of hiatus is best determined by foraminifera and other microfossils. In biostratigraphy, chronostratigraphy and / or any other stratigraphy, accuracy in prediction of time is very critical and be closer to true values; thus enhances predictive capability in turn increases success probability.

Discussion and Results:

Limits and Contents of Formations:

Nellore Claystone, Bapatla Sandstone, and Pennar Formation: were dated Tithonian to Aptian based on dinocyst assemblages (Bijai Prasad, 1995).

Krishna Formation is given Valanginian to Hautervian age by Bijai Prasad, (1995) based on dinocysts. As shown in Table-1 palynologists giving older ages based on dinocysts when compared to standard planktic foraminiferal biochronology.

Gollapalli Formation: Neocomian age was suggested for outcrops. Rare planktic foraminifera were found in claystone layers in upper part of this formation in few wells suggestive of Aptian/Albian age.

Nandigama Formation: Currently, only arenaceous unit is considered as Nandigama. In type section *Hedbergella* suggestive of probable Albian age. In Vanadurru South-A, planktic foram suggestive of latest Aptian to Early Albian.This is equivalent to type section Raghavapuram Shale. In Bantumilli South-A,

Nandigama Formation ranges in age from Late Cenomanian to Turonian.The time limits of Nandigama Formation are different at different localities.

Raghavapuram Shale: On basin scale, the Raghavapuram Shale ranges in age from Late Aptian to Campanian spanning about 42 My. Three subdivisions are possible:

A) Raghavapuram Shale (sensostricto) = Lower Raghavapuram Shale: It spans from Middle -Late Aptian to Early/ Middle Albian. Bijai Prasad's finding of *Ammonites,Acanthohoplites* of Late Aptian to Early Albian age from type section of Raghavapuram Shale is very significant. Age equivalent in subsurface is represented by moderately deep marine sediments with planktic foraminifera like *Ticinella bejaouensis, Hedbergella trochoidea, H.gorbachikae, Microhedbergella miniglobularis* and others. It is of interest that Reddy et al, (2014) found *H.trochoidea* and broken ammonites of Late Aptian to Early Albian from the upper part of Terani beds in Cauvery Basin representing earliest marine transgression. This event is usually taken to represent top of synrift in Cauvery Basin. Late Aptian- Early Albian transgressive event represents a maximum flooding surface (MFS) in both Cauveryand Krishna- Godavari basins.

B) Middle Raghavapuram Shale= HG-HR unit: It spans from Middle/Late Albian to Turonian rarely up to Coniacian. Planktic foraminiferal markers include *Ticinella raynaudi, T. primula, Rotalipora subticinensis* suggestive of Middle-Late Albian in the lower part of HG-HR unit, *Rotalipora reicheli, R. cushmani* indicative of Cenomanian in the middle part and *Helvetoglobotruncana helvetica, H. praehelvetica, Praeglobotruncana stephani* in the upper part. The paleobathymetry is in general deeper than 100m reaching below foraminiferallysocline (FL) in few wells like G-4-F, KL-B. In general, the uppermost part represents hiatus matching with global sea level drop. In Cauvery Basin, the top of Karai Shale (top of Middle Turonian) is unconformable with overlying formation. It is recognizable physically and by foraminiferal data too. The Albian to Turonian succession represents a complete cycle with paleobathymetry reaching deeper than 150m. These events match well with KG Basin. Main difference is preservation of calcareous forams and very high percentage of agglutinated forams in KG Basin which appear to be due to high temperature and effusion of volcanic gases.

C) Upper Raghavapuram Shale, usually LG-LR Shale: It spans from Coniacian to Middle Campanian age. Planktic markers include species of *Marginotruncana*, *Dicarinella concavata*, *D.asymetrica* and *Globotruncana ventricosa* (in a few wells). In many wells, the upper part represents shallowing of the sea level.

Kanukollu Sandstone: Ranges in age from Albian to Coniacian in type section;paleobathymetry reached slightly greater than 70m.It is a package equivalent to middle Raghavapuram Shale

Vanadurru Shale: This litho unit was introduced by Robertson Group (1987) and assigned Aptian-Albian; paleobathymetry up to 200m or more reached during Turonian to Santonian at Vanadurru-A.

Gajulapadu Shale: Planktic forams suggest Albian age. Recent analysis hasshownthat palynologists are giving older ages based on dinocysts ascompared tostandard planktic forams. A few case examples are illustrated in tables-1, 1a, 1b. These differences /discrepancies in dating are due to our failure to calibrate and/or integrate time span and ranges of dinocysts(vs) forams valid for Indian basins

Chintalapalli Shale: Planktics suggest Santonian to Maastrichtian age.

Tirupati Sandstone: It has been assigned an age of Santonian/Campanian to Maastrichtian based on some microfossil control and stratigraphic superposition.

Redbed:A distinct and unique sedimentary sequence encountered in several wells for example RP-1, it is of Albian to Coniacian; earlier dated to be Oxfordian to Valanginian (Aswalet al, 2002)

Top of Synrift: Dating and Timing of Transgressive events

a) **Early Permian:** Incursion of shallow sea; this event was dated based on palynofossils. (Bijai Prasad). This event took place after prolonged erosion or non-deposition with the duration of hiatus 240 My.
b) **Triassic**: Two incursions of shallow sea. This event was dated based on dinoflagellate cysts (Aswal and Mehrotra 2002) But doubts prevail whether normal marine conditions existed in KG basin during Triassic
c) **Oxfordian/ Tithonian Trangressive Event**: This event was dated based on nannofossils from SMA-A by Q.A.Ali and dinoflagellate cysts
d) **Berriasian Transgressive Event**: This event was dated based on dinoflagellate cysts and spore-pollen and needs further study. In areas like KS-3-A and Nellore-A; transgressive shales and claystone (onlap) covers basement. (the formations- Nellore Claystone - Pennar Shale)
e) **Mid/ Late Aptian Transgressive Event:** Lakshminarasimhapuram well-A, Tanuku-A, YS-8-A, Vanadurru South-A and south Velpur-A. This event was dated on the basis of planktic forams.
f) **Albian** sea-level rise event recorded in several areas. In recent wells, it was found that sediments dated as Oxfordian age or Valanghinian age (based on dinocysts) are found to be Albian, in terms of planktonic foraminifera
g) **Cenomanian Transgressive Event**: In Bantumilli-B, this event was dated on the basis of planktonic foraminifera. At this location, Cenomanian marine transgression onto the Archean basement.
h) **Turonian Transgressive Event**: In NAC-1A (offshore), Aibhimavaram-A, this event was dated on the basis of foraminifera. Here Turonian marine sediments directly overlie weathered basement which in turn overlie basement in KG Basin Middle Turonian event represents a MFS.
i) **Santonian Transgressive Event**: In Kaikalur-A, this event was dated on the basis of foraminifera, nannoplankton and dinoflagellate cysts. On Kaikalur high, marine Santonian sediments directly overlie Archean Basement.
j) **Campanian Transgressive Event**: In KRI-1-A (Offshore), this event was dated on the basis of planktic foraminifera.
k) **Middle Paleocene Transgressive Event**: In UD-2 (near 820 East Ridge), this event was dated on the basis of planktic foraminifera; due to subsidence of basement during different times at different parts of the basin.

Geochemical data:

Generalization for KG Basin by previous workers were that HG-HR Shale unit is primarily at peak oil maturity stage with deeper sections approaching peak maturity to late maturity stage. The organic matter is primarily of Type III, with some organic rich, oil and gas prone streaks having a mixture of Type III- Type II OM.In the presently investigated wells HG-HR unit and lower part of upper Raghavapuram Shale are in oil window during Albian, Cenomanian, Turonian rarely in Coniacian at one locality.

Conclusions:

a. The HG-HR sequence is not of Aptian-Albian age as followed by Lal et al. (2007) and other specialists. Major part is of Albian-Cenomanian-Turonian age. In a few cases like LN-A, SVL-A, the lower limit of the HG-HR is in Late Aptian. The upper limit in RP-A extends to Coniacian.
b. The deposition of sediments of HG-HR unit is not of shallow marine as published by many authors On the other hand the succession of HG-HR unit in the studied wells was deposited in a complete mega cycle with paleobathymetry reaching upper bathyal/ up to outer neritic.
c. A nearly complete KG Basin T-R cycle is related to mid-Cretaceous events – black/dark grey shales, anoxic conditions, high % of TOC, possible oceanic acidity resulting in dissolution of calcareous foraminifera and presence of very high % of agglutinated foraminifera (AF) at some levels with deep marine smooth walled AF accounting up to 98% of the foraminiferal assemblages. At some locations the Cenomanian-Turonian sediments appear to have deposited below local Foraminifera Lysocline (FL). At some levels foraminifera are also black to very dark in colour suggesting probable high temperatures. In modern oceans the FL is below 2500m. But during mid-Cretaceous rift basins, local FL could be upper-middle bathyal.

1. The percentage of TOC is relatively high in the interval of HG-HR sequence. The richness of OM appears to be closely related to ocean anoxic events. OAE 1 a (Early Aptian), Jacob OAE 1b (Late

Aptian) Urbino OAE 1b (Early Albian), OAE 1c (lower part of Late Albian), OAE 1d (Late Albian), OAE 2 (latest Cenomanian- earliest Turonian) and OAE 3 (Coniacian-Santonian).

a. Manmohan et al., (2003) arrived at the conclusion that HG-HR shales were the result of post rift marine transgression.
b. In LN-A, YS-8-A, VNS-A and SVL-A the first major transgression of open sea is within Mid-Late Aptian.

2. Recent finding of Aptian volcanism in offshore well G-18-A in Kakinada graben is significant.(Raju et al., 2013)
3. According to Manmohan et al., that HG-HR sequence represents the particular transition stage in geological history of the basin when the paleo-slope of the basin was changing from towards NW to SE.
4. The Gollapalli Sandstone are with a paleo-current direction of 10-20o to the northwest (VasudevaRao and Krishna Rao, 1977 see in G.N.Rao, 2001). Tirupati Sandstone has a paleo-current direction of 5-10o dip towards the southeast the change in paleo-slope is later to Gollapalli Formation.
5. Present data suggests the tilt/ paleo-slope towards SE was probably created already by Middle Aptian.
6. In the Cretaceous period, one of the most significant events is the unconformity or drop in sea level during middle/ late Turonian. There is other unconformities- example: a) Within the Cenomanian b) Within the Turonian c) Close to upper part of Turonian d) Close to base of Campanian are recognized in KL-B.

References

1. D.S.N.Raju, “A final report on project-Foraminiferal Biostratigraphy and Paleoenvironmental studies on six wells: GS-29-6, GS-KW-4, GD-7-1, KG-DWN-98/4-NAC-1A, VGSW-1 and LN-1, Krishna-Godavari Basin”, Jan. 2011

2. D.S.N.Raju, “A final report on project-Foraminiferal Biostratigraphy and Paleoenvironmental analyses on selected wells of KG-PG Basin, India”, May. 2012

.Table-1: Well SMA-A

Depth (m)	Foraminifera		Dinoflagellate cysts	
	Age	**Paleobathymetry**	**Age**	**Paleoenvironment**
	Turonian	>100m	Turonian	Inner shelf
2535-2540	Probably Turonian	>100m	Albian	Inner- outer shelf
3095-3100	Cenomanian	>100m	Earliest Barremian	Sub tidal, inner shelf
3300-3305	Albian	Bathyal	Upper Valanginian	Sub tidal ,inner shelf
3460-3465	Not older than Late Aptian	>50m	Lower Valanginian	Sub tidal, inner shelf

1(b) Well RP-A

1(c) Well BTS-A

Depth m	Foraminifera	Dinoflagellate cysts
	Age	**Age**
(4090-4095) (4100-4105)	Turonian	Barremian-Hautervian

Depth m	Foraminifera	Dinoflagellate cysts
	Age	Age
2160-2165	Coniacian/Santoni	Aptian
2231 (Core)	Coniacian	Barremian Cuttings (2225-2255)
2360-2365	Coniacian	Late Valanginian
2967	Albian	Valanginian/ Oxfordian
(4195-4200) (4217-4218)	Not older than late Cenomanian	Barremian Hautervian