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**Fluid Expulsion Model for the Pre-Trappean Sediments of West Godavari Sub-Basin, Krishna Godavari Basin, India.**

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### Summary

Krishna Godavari Basin, located on the east coast of India, is a pericratonic passive margin basin comprising sediments ranging in age from Permian to Recent. In the West Godavari sub basin, hydrocarbon exploration is targeted to the pre-Trappean sediments i.e., Cretaceous and older, which were classified mainly into four units viz., (i) Rift fill/Gollapalli/Kanukollu of late Jurassic to Early Cretaceous, (ii) High Gamma High Resistivity (HG-HR) shale sequence of Lower Cretaceous, (iii) argillaceous section (Tirupati lower part) of Upper Cretaceous and (iv) arenaceous section (Tirupati upper part) of Upper Cretaceous ages. Presence of good source rocks with organic rich intervals is observed suggesting good hydrocarbon generation potential for this sub basin. Though oil and gas discoveries are made relatively in a large number of wells, the commercial scale finds are limited and are disproportionate to the expected potential. The present study, an effort to know the actual potential of the sub basin by integrating the geochemical data on a regional scale, is aimed at understanding the HC potential of the sub basin.

A fluid expulsion model based on Kinji Magara and Claypool has been attempted for all the four units. The major hydrocarbon (HC) expulsion centers of the former two units, viz. units (i) and (ii), appear to lie in the deeper parts enveloping the Kaikaluru high with the highest concentrations in Gudivada graben, NE plunge of Kaikaluru high and the NE part of Bantumilli graben. The third unit is observed to have three minor expulsion centers, one each in Gudivada, Bantumilli grabens and south of Tanuku High. Fourth unit has not shown any HC expulsion as it is mostly immature. Out of these four units the HG-HR unit appears to be the regional source rock and major contributor for the hydrocarbon accumulations in this subbasin. A composite hydrocarbon migration model has been brought out for identification of the possible accumulation locales.

### Introduction

More than 100 wells have been drilled in the West Godavari sub-basin out of which one third are proved to be hydrocarbon bearing. Majority of wells are clustered over the Kaikaluru High and large part of the sub-basin remained relatively unexplored. Presence of good source rocks in a number of wells suggests good HC generation potential. The established hydrocarbons so far seem to be disproportionate to the actual potential. In order to know the actual potential of the sub-basin, a fluid expulsion model has been attempted to understand the hydrocarbon potential of different units in the sub-basin and identification of possible accumulation locales.

Ganesh Kumar, et al., (1993) carried out fluid migration studies based on Kinji Magara (1978) for the East Godavari sub-basin. While carrying out the petroleum system analysis and fluid migration model for the West Godavari sub-basin, Murthy, et. al. (2005), further refined the nature and quantity of fluids expelled after maturation. ManMohan, et al. (2000) showed that HG-HR shale sequence of Lr. Cretaceous is relatively a good and matured source rock in West Godavari sub-basin. Prasad, et.al. (2006) carried out a comprehensive study on source to oil correlations in KG Basin.



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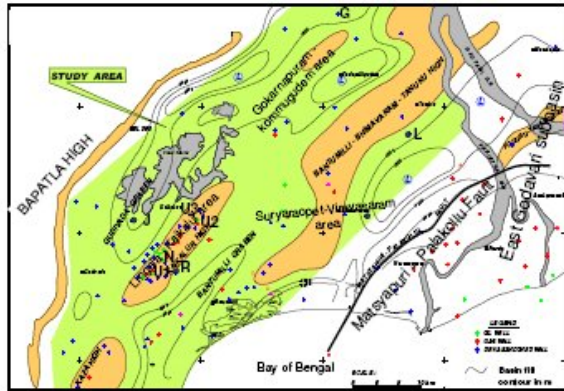


Figure 1 : Location map of West Godavari sub-basin, KG Basin.

## Geologic Setting and Stratigraphic Units:

The study area (fig.1) covers the tectonic elements, Gudivada graben, Bantumilli graben, Kaza High, Kaikalur High, Bantumilli-Bhimavaram-Tanuku High of the basin. In the present study, the pre-Trappean sediments of West Godavari sub-basin have been classified mainly into four units viz., (i) Rift fill / Gollapalli / Kanukollu of late Jurassic to Early Cretaceous, (ii) High Gamma High Resistivity (HG-HR) shale sequence of Lower Cretaceous, (iii) argillaceous section (Tirupati lower part) of Upper Cretaceous and (iv) arenaceous section (Tirupati upper part) of Upper Cretaceous ages. The boundary separating the argillaceous and arenaceous units of U. Cretaceous is based on lithology whereas the other boundaries defining the lower units are based on the regional unconformities. Out of these four units, commercial HC occurrences have been so far encountered mainly at the top / bottom of HG- HR shale sequence. Scanty occurrences are within the U. Cretaceous argillaceous section and Rift fill/Gollapalli/Kanukollu Sst unit. Uppermost unit has not shown any indication of HC.

### (i) Rift fill / Gollapalli / Kanukollu of late Jurassic to Early Cretaceous:

This unit is dominantly arenaceous with minor shale alternations in the upper part and dominantly more argillaceous towards bottom in Lingala-Kaikaluru area. As a whole it becomes more argillaceous towards the northern part of Kaikaluru high. Except on the basement highs and Kommugudem-Gokarnapuram areas where Lower Gondwana sediments are encountered, this sequence has not been probed completely. In Suryaraopet and Viravasaram areas the wells were terminated within younger units only. This unit is bounded by a regional unconformity at its top and is overlain by HG-HR shale unit. It is underlain by basement in the western part of the basin (Suryaraopet, Kaikaluru and Lingala areas and to their west) and the Permo-Triassic to older (Lower Gondwanas) in the

eastern part (Gokarnapuram- Kommugudem area) where the subsurface extension of PG graben is seen. The lower argillaceous section and source rich shale alternations in the upper arenaceous section might serve as source for the hydrocarbon accumulations within the sequence. Oil and gas pools were discovered in this sequence in N and U2 wells.

### ii) High Gamma High Resistivity (HG-HR) shale sequence of Lower Cretaceous age:

Majority of the commercial HC occurrences in West Godavari sub-basin lie within this unit which is bounded by regional unconformities at its top and bottom. The pools in this unit mostly are located at the top (below the upper unconformity) and/or bottom (above the lower unconformity) in discrete lenticular sands. U1 is a unique well producing from a carbonate reservoir. The HG- HR (Raghavapuram) shale sequence was the resultant of post rift marine transgression into the NE plunging rift grabens (half grabens), forming a restricted and shallow water environment. The stagnant water conditions and slow rate of sedimentation led to the deposition of organic-rich Shale (Man Mohan and Rao, 1998). The HC entrapment mechanism for the reservoirs within this sequence is of strati-structural nature. Enough data input is available for the analysis, interpretation and final logical conclusions with considerable degree of confidence.

### Argillaceous section (Tirupati lower part) of Upper Cretaceous age:

HC were struck in this unit in Lingala\_Kaikaluru area apart from occasional HC shows. This unit also attains importance with the significant oil strike in U3 (others being gas wells). This unit was the resultant of post rift marine transgression on a basin-wide scale, mostly under open marine conditions, after the SE tilt of the basin. Pro-deltaic / inter deltaic shales constitute the major thickness of this unit interspersed with minor bar sands. Faults originating from the basement end within the lower part of this section and this unit is less disturbed tectonically. Similar to the underlying section, the entrapment mostly is strati-structural, as the sands in this unit are also discrete with limited extent.

### Arenaceous section (Tirupati upper part) of Upper Cretaceous age:

This dominantly arenaceous section is overlain by Palaeocene basalt flows and is the resultant of the progradation of the delta during Upper Cretaceous. In this unit so far no hydrocarbons have been reported in this sub-basin. The source rocks of this section appear to be mostly immature. This section with huge thickness of sands shows a monoclinial dip basinwards (SE/SW). The section seems to be undisturbed, except for having the simple basinal SE tilt and minor tectonic impact due to the Matsyapuri-Palakollu fault that caused a few very low amplitude



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anticlinal structures/nasal features in this sub-basin, (Kamaraju et al. 1998).

In addition to the four units taken up for the study, the Lower Gondwanas viz., Mandapeta Sandstone Formation of Permo-Triassic age and the Kommugudem Fm. of Lr. Permian age are also present confining to the Gokarnapuram-Kommugudem area, where the subsurface extension of Pranahita-Godavari graben is seen. These Lower Gondwana sequences are in the late catagenetic to metagenetic stage and are excluded from the present study as better understanding of hydrocarbon generation potential of these sequences vis-à-vis organic matter quality needs integration of data with their counterparts in the eastern extension of the study area.

### Methodology:

#### Shale Compaction and Fluid Expulsion (Kinji Magara, 1978):

Transit time ( T ) values obtained from sonic logs for different wells are plotted against depth for shales for understanding the compaction history. These T values are generally sensitive to barium content in the mud, wherever mud weights are increased by adding barytes. As low density water is squeezed out by compaction, bulk rock density rises and this increase can be obtained from density logs. T values have been optimized by combining density log and sonic log data (Hegarty et al, 1988). Fluid expulsion volumes total, before maturation and after maturation are computed.

#### Hydrocarbon Generation and Expulsion (Claypool, 1996):

While the nature of fluid expelled before maturation is only aqueous (mainly water) phase, fluid expelled after maturation could be a mixture of aqueous and non-aqueous phases (water and hydrocarbons). In order to further refine the nature of fluid expelled after maturation and quantify the quantum of hydrocarbons that are generated and expelled, actual hydrocarbon generation and expulsion quantities are calculated for the source rich and contributing intervals of all the 4 units of study. Though computations are made for hydrocarbon generation and expulsion for the organic rich source intervals, the logical validity of data is verified with the after maturation fluid expulsion quantities and found to be satisfactory (where the whole sequence of a unit is source rich and contributing to hydrocarbon generation and expulsion).

Using the HCE values derived for the source rich intervals, HCE centers are identified for all the four units of study. To know the possible directions for migration of the generated/expelled hydrocarbons, it is very much essential to have the structural picture of the basin at that time and the subsequent changes it had undergone through ages. For this, it is also essential to have the HC generation timing. Representative wells covering different geological setup have been chosen for subsidence history/ Time Temperature Index (TTI) analysis of the different units and are calibrated /validated with maturity parameter, Tmax. Broad structural changes in the basin post hydrocarbon generation times have been obtained from paleo-structural analysis along select profiles.

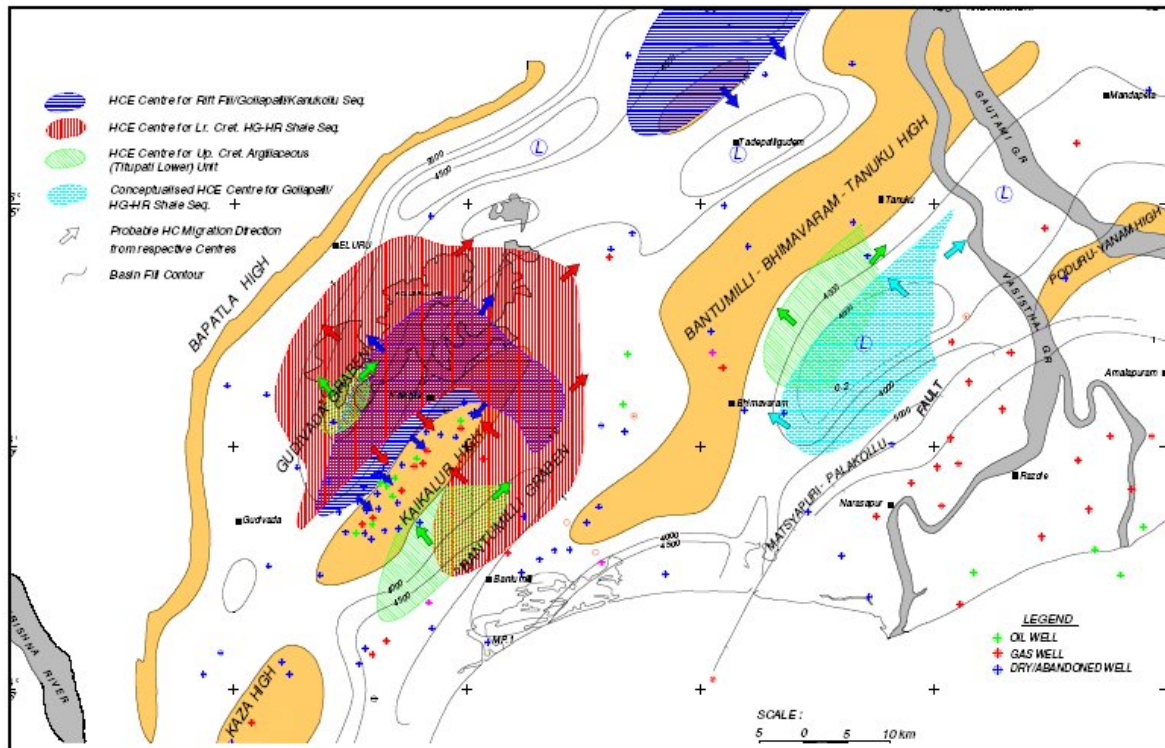


Figure 2: Composite HC Migration Model, WG Sub-basin



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**Some abbreviated terms:**

Fm = Formation, OM = Organic Matter, HC = Hydrocarbon (s), Tmax = Thermal Maturity Parameter, Unit is OC, HCE = Volume of hydrocarbons expelled as 350 API oil, Unit is m<sup>3</sup>/sq.m.

**Fluid Expulsion and Migration Model**

The onset of hydrocarbon generation from the oldest sequence was during the later stages of upper Cretaceous.

The broad structural picture of the basin, since then, did not change much except further increase in – (i) the pre- existing ‘sag’ in the Gudivada graben and (ii) SE/SW tilt’ of the sub-basin. A composite HC migration model of all the four sequences is pictorially depicted in fig.2.

**a) Late Jurassic to Early Cretaceous Rift fill/ Gollapalli/Kanukollu Sst. :**

**Fluid expulsion:** As the data in the partially penetrated section may not represent the whole sequence for different parameters used in the study, a conservative approximation has been made for such areas while extrapolating / interpolating from the known areas. Hence the actual fluid expulsion for the total unit could not be computed. However, based on the limited data and the thickness trends of the sequence, the fluid expulsion before and after maturation has been computed with certain degree of conceptualization.

Maximum fluid expulsion is envisaged in the Gudivada graben proportionate to the sediment thickness. The fluid expulsion trends before and after maturation are observed to be following the same trends as those of total fluid expulsion but for decreasing and different volumes. Actual HCE has brought out two expulsion centres - one in Gudivada-Bantumilli grabens enveloping the Kaikaluru Horst in a horse-shoe shaped pattern and the other one around G well (fig.3).

**Generation timing:** This unit entered ‘oil window’ in the late stages of Upper Cretaceous (~ 85 mya) in Gudivada graben (J); nearly at the end of the Cretaceous (~ 65 mya) in southern flanks of Kaikaluru and Tanuku Highs; and during Middle Eocene to Middle Oligocene (~ 30-50 mya) over the Kaikaluru and Tanuku Highs.

**Migration:** This deeply buried (3700 m in J) sequence in Gudivada graben raises to shallower depths in all the 4 directions i.e., NW towards Bapatla high, SE towards Kaikaluru high, northeast and southwest

The sequence holds rich contributing intervals in some of the wells on the NW flank of Kaikaluru high. The expelled HC from the area around these wells might have migrated laterally in SE towards the high and most

probably vertically into the overlying sequence until they got entrapped. Because of the NE plunge of Kaikaluru high, the HC expelled from the area around U2 also could have moved towards the higher parts of Kaikaluru high in SW direction. The established pools in N and U2 wells and the HC shows observed in this sequence may stand as evidence for its HC generation potential.

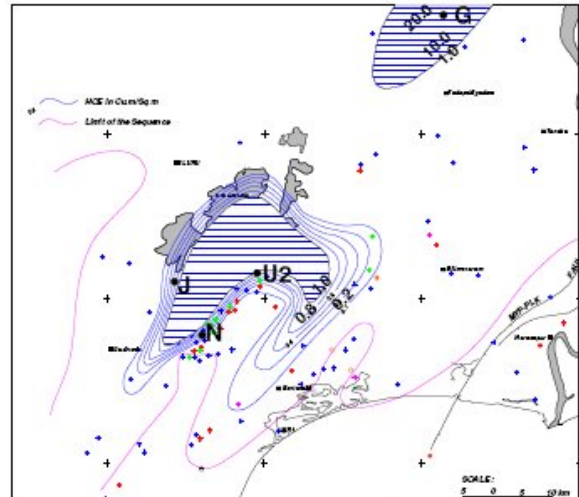


Figure 3 : HCE Map Rift fill/Gollapalli/Kanukollu Sequence

Kommugudem area shows a maximum HC expulsion of 25.5 m<sup>3</sup>/sq.m. These hydrocarbons appear to be gaseous in nature and from the structural point of view they might have moved in SE and ESE directions.

In the absence of data from this sequence south of Tanuku High, HCE could not be attempted. Any probable source development, its maturation and HC expulsion, if any, in this area would have favored the migration towards the Bhimavaram and Tanuku high and its SE flanks

**b) Lower Cretaceous (Aptian-Albian) HG-HR (Raghavapuram) shale sequence:**

**Fluid expulsion:** Larger parts of fluid expelled from this sequence appear to have occurred before maturation itself. The HC expulsion map (fig.4) shows an expulsion centre enveloping the Kaikaluru horst with a maxima lying in the Gudivada graben /Kolleru Lake (10.89 m<sup>3</sup>/sq.m in well J). This area appears to have expelled oil along with gaseous hydrocarbons. The area outside the center shown, i.e., HCE <1.0 m<sup>3</sup>/sq.m, also appears to have expelled gaseous hydrocarbons but to a minor extent.

**Generation timing:** This sequence entered ‘oil window’ towards the end of Upper Cretaceous in Gudivada graben (~67 mya in J) and on southern flanks of Kaikaluru (~ 57 mya) and Tanuku Highs (~ 62 mya); and during upper Eocene to Oligocene (~26-41 mya) on over the Kaikaluru and Tanuku Highs.



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**Migration:** Palaeo-structural analyses (Manmohan & Rao 1998) suggest...(1) SE/SW tilt of the basin occurred post HG-HR times (2) Gudivada graben experienced further sag Post HG-HR times and (3) Reactivation of basement highs occurred post-Trappean times also. These observations help in understanding the migration model for the HCE in the HG-HR sequence and Upper Cretaceous argillaceous unit.

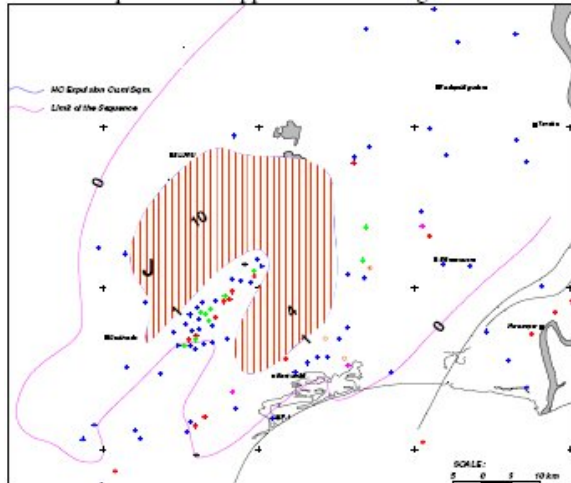


Figure 4: HCE Map, Lr.Cret. HG-HR Shale Sequence

The stratal pattern of the sequence shows dips in SE/SW directions and hence the generated HC might have laterally migrated principally in NW and NE directions from the expulsion centre in the Gudivada graben. The migration in SW in Gudivada graben/Kaikaluru high may be minimal. Migration in SE direction from the graben towards Kaikaluru high is evidenced by the HC pools observed in

this sequence in Lingala and Kaikaluru prospects (fig.5). Bedding planes, unconformities at the top and bottom of the sequence might have served as conduits for lateral updip migration in NE, NW and SE directions. The faults near Kaikaluru horst might have contributed for vertical migration into the younger sequences in Upper Cretaceous argillaceous section (TPT Lower). The horse-shoe shaped expulsion centre covers part of Bantumilli graben south of Kaikaluru High (3.59 m<sup>3</sup>/sq.m) and the generated and expelled HC might have moved in NW/NE direction towards the NE part of the Kaikaluru high.

**c) Upper Cretaceous argillaceous (Tirupati Lower) unit:**

**Fluid expulsion:** In the areas around Kaza-Kaikaluru High and Kommugudem the total fluid was expelled before maturation itself. The HCE map (fig.6) shows three principal expulsion centers; one in Gudivada graben (0.24 m<sup>3</sup>/sq.m in J), Bantumilli graben (0.38 m<sup>3</sup>/sq.m) and south of Tanuku High (0.93 m<sup>3</sup>/sq.m) respectively.

**Generation timing:** This unit entered 'oil window' during Middle Eocene (~47-43 mya) over the southern flanks of Kaikaluru and Tanuku Highs; during Upper Oligocene to lower Miocene in Gudivada graben and (~28 mya in J) and SW part of Kaikaluru High (~ 22 mya); and during Middle Miocene times in NE part of Kaikaluru High and Tanuku High areas (~ 14-10 mya). Only the lower part of this unit entered 'oil window' in Gudivada graben and NE part of Kaikaluru High.

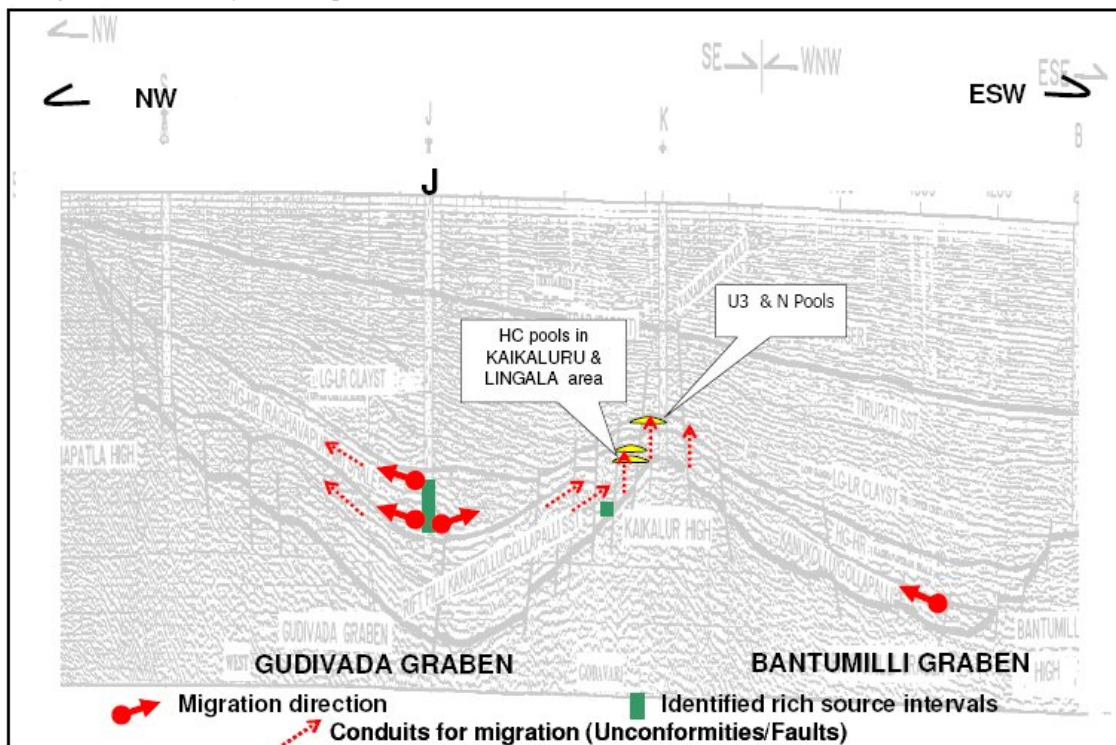


Figure 5: Schematic HC Migration Model Gudivada – Lingala- Kaikaluru – Bantumilli graben.



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### Migration:

i) The migration model for the center around J (Gudivada graben): The generated and expelled hydrocarbons around J area appear to be gaseous and liquid in nature and might have migrated updip laterally in NW/NE directions as the beds of this sequence dip in SE/SW. Fig.5 shows the beds downlapping in the SE direction. This sequence becomes sandy near basin margins. Migration in SE/SW (opposite to the dip of the sequence) might be minimal.

ii) The migration model for the center around R (Bantumilli graben): Keeping in view the palaeo-structural configuration post HC generation times, the HC expelled from this center appear to have preferred the NW/NE directions towards the Kaikaluru high. These hydrocarbons appear to be gaseous in nature.

iii) The migration model for the center around L (south of Tanuku High): This center appears to have generated and expelled gas with subordinate liquid HC. Keeping in view the structural set up and the basin tilt, it can be envisaged that the expelled HC might have migrated in NW/NE directions towards Tanuku high and its SE flank. d) Upper Cretaceous arenaceous (Tirupati Upper) unit: Fluid expulsion: Fluid expulsion after maturation for this unit is minimal (except south of Tanuku High). Hence the fluid expulsion before maturation itself was the total fluid expelled from this unit.

Generation timing: Lower part of this unit appears to have entered the 'oil window' during upper Miocene over Tanuku High (~ 6 mya) and it is immature in the remaining area.

Migration: This unit is inferred as non source rock and as such no considerable generation and expulsion of hydrocarbons took place in this.

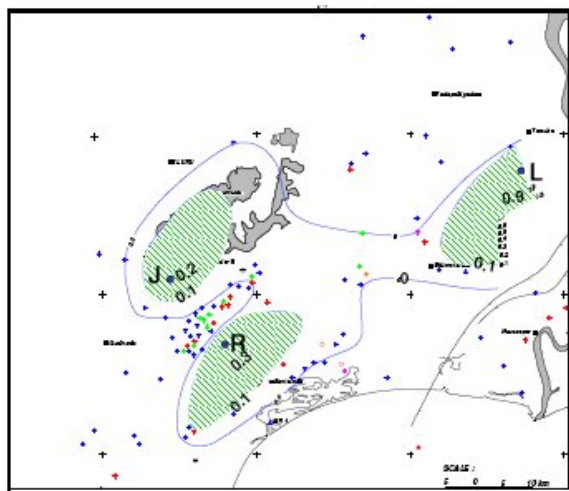


Figure 6: HCE Map, Up. Cret. Argillaceous (TPT Lr.) Unit

### Conclusions:

Fluid expulsion studies have been carried out in the West Godavari sub-basin for the four units of pre-Trappean sediments, viz. (i) Rift fill / Gollapalli / Kanukollu of late Jurassic to Early Cretaceous, (ii) High Gamma High Resistivity (HG-HR) shale sequence of Lower Cretaceous, (iii) argillaceous section (Tirupati lower part) of Upper Cretaceous and (iv) arenaceous section (Tirupati upper part) of Upper Cretaceous ages.

Rift fill/GLP/KNK Sst sequence unit entered 'oil window' in the late stages of upper Cretaceous in grabenal areas and during Middle Eocene to Middle Oligocene over the Basement Highs.

The Lower Cretaceous HG-HR Shale sequence appears to be the regional source rock and principal contributor for the HC accumulations in WG sub-basin. This unit entered 'oil window' towards the end of Upper Cretaceous in grabenal areas and during Upper Eocene to Oligocene over the Basement Highs.

The Upper Cretaceous argillaceous (TPT Lower) unit entered 'oil window' during Middle Eocene over the southern flanks of Kaikaluru and Tanuku Highs; during Upper Oligocene to lower Miocene in Gudivada graben and SW part of Kaikaluru High; and during Middle Miocene times in NE part of Kaikaluru High and Tanuku High areas.

The Upper Cretaceous arenaceous (Tirupati upper) unit has entered 'oil window' during Upper Miocene over Tanuku High and is immature in the remaining area.

The major Hydrocarbon Expulsion Centers of the first two units viz., Rift fill/GLP/KNK Sst sequence and HG-HR Shale sequence, appear to lie in the deeper parts enveloping the Kaikaluru high with the highest concentrations in Gudivada graben, NE plunge of Kaikaluru high and the NE part of Bantumilli graben. The third unit, i.e., Upper Cretaceous argillaceous (Tirupati Lower) unit is observed to have three minor expulsion centers, one each in Gudivada & Bantumilli grabens and south of Tanuku High. Fourth unit, i.e., Upper Cretaceous arenaceous (Tirupati upper) unit has not shown any HC expulsion as it is mostly immature till now.

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