Basin Inversion and Hydrocarbon Entrapment in Ramnad & Palk Bay Offshore of Cauvery Basin, India

Sushil Chandra*, N.D. Gideon, C. Chaturvedi, M.S. Rana et al
KDMIPE, ONGC, Dehra Dun

Summary

Hydrocarbon exploration in Ramnad and Palk bay offshore in the Cauvery basin has been continuing for over a decade to understand and decipher areas of hydrocarbon entrapment ever since the first strike was made in 1990. More than 40 wells have been drilled so far, out of which 5 structures have been proved to be hydrocarbon bearing. Three wells drilled in the Palk bay offshore to chase the well "AA" pool in to Palk bay offshore proved to be futile and gave a setback in the exploration effort. A comprehensive study carried out at KDMIPE on a regional scale throws a significant light on the hydrocarbon entrapment style and model in these areas. The integrated basement map reveals the depocenters, which hosts the source rock, forming kitchen for the basin. The areas bordering the depocenters are interpreted to have undergone inversion, forming paleotraps within Pre-Albian, which are still preserved. Double stage basin inversion is interpreted in this area, one being older initiated within Pre-Albian continued episodically up to Paleocene and another during Campanian – Maastrichtian time. The estimated Critical moment suggests that the time of expulsion of hydrocarbon is after the cessation of older basin inversion thus the structures formed by the inversion become favorable for hydrocarbon entrapment. The faults associated with the basin inversion acted as the conduits and the inversion is predicted as entrapment style in the Ramnad and Palk bay offshore. The inversion has been mapped regionally. The hydrocarbon prospectivity map demonstrates the entrapment model and has outlined areas falling in the same trend of discovered hydrocarbon fields that form prime target for future hydrocarbon exploration in the Ramnad and Palk bay offshore.

Introduction

Cauvery basin, a petroliferous basin forms the southwestern attenuated margin of Jurassic rift of the east coast of India. Taphrogenetic fragmentation of Archean basement as a result of rift-drift phenomena of Indian plate took place during late Jurassic-Early Cretaceous which resulted in formation of horst and graben aligned in NE – SW direction. The Bay of Bengal opened up around 125 Ma as India drifted apart. The Cauvery basin configuration was initiated in the NE-SW direction during rifting and different tectonic element took their shape by subsequent drifting. The maximum basin fill in the northern part is of the order of 6 Km. while it is around 5 Km. in the southern part.

The morphotectonic elements of the basin are defined by the deep– seated basement controlled fault systems with a series of depressions (sub-basins) and horst (ridges). These ridges are Kumbakonam-Madanam ridge, Karaikal ridge, Pattukottai Mannargudi ridge, Vedaraniyam high and Mandapam-Delft ridge. Grabens forming sub-basins are Ariyalur-Pondichery sub basin, Tranquebar sub basin, Tanjore sub basin, Nagapattinam sub basin, Ramnad sub basin - Palk-Bay offshore and Gulf of Mannar. The source rock facies are encountered in Andimadam Formation of Albian and Pre-Albian sediments. The hydrocarbon finds have been discovered in several reservoirs viz. Andimadam, Bhuvanagiri, Nannilam and Kamalapuram formation. The lithostratigraphic nomenclature of ONGC has been worked out by the Venkatarangan et.al. 1993.

Ramnad and Palk bay offshore areas constitute the southern part of Cauvery basin. The Palk bay offshore trending NE – SW is flanked by Mandapam Delft Ridge in the east, Pattukottai Mannargudi ridge in the west, Vedaranyam high in the north and on-land part of the Ramnad sub basin in the south. The Ramnad sub basin is flanked in the West, NW and SW by the Pattukottai Mannargudi ridge, Palk bay offshore to the North & North-east, Mandapam delft ridge to the east and Gulf of Mannar to the south. It covers an area of 400 sq.km. A number of wells have produced commercial hydrocarbon from Ramnad sub basin and one well at the border of Ramnad and Palk bay offshore produced commercial gas. However, three successive dry wells in the Palk bay offshore led to restudy the hydrocarbon potential of Palk bay offshore and to evaluate the hydrocarbon generation potential of Palk bay offshore.

Methodology

- Electro logs of all the wells were correlated with the help of biostratigraphy & lithologic data. The stratigraphic boundaries of the drilled wells were transferred to the representative seismic line using VSP data of the well.

- Eight reflectors corresponding to close to top of Basement, a reflector within Pre-Albian (K0-1), Albian (K1), Cenomanian (K2A), Turonian (K2B), Santonian(K3A), Cretaceous (K3C) , and Paleocene were identified.
- These reflectors were correlated regionally using seismic sequence stratigraphy method and relief map for the all correlated reflectors were generated for the entire study area.
- Isochronopach of sequence corresponding to sediments within Pre-Albian, Albian, Cenomanian, Turonian, Santonian, and Paleocene were prepared to decipher the depositional model.
- Regional seismogeological cross-sections have been prepared to elucidate basin configuration, regional stratigraphy and structure.
- Paleotectonic analysis was carried out to decipher the tectonic evolution of the sub-basin.
- Synthetic wells were generated and Geochemical studies revealed the hydrocarbon generation potential and the critical moment was estimated.
- Basin inversion has been interpreted in the study area and the inversion model explains its effect on Generation, Migration and Entrapment for hydrocarbon.
- Generation potential of the basin and hydrocarbon charge mechanism was studied and the hydrocarbon prospective areas have been delineated.

Basin inversion

Basin inversion can be defined as "a basin controlled by a fault system that has been subsequently compressed – transpressed producing uplift and partial extrusion of the basin fill (Copper et.al. 1989). Empirical evidence shows that where strike-slip component is dominant, relatively high angle normal faults can be reactivated and new structure need not be created. Where compression is dominant, parts of older normal faults may be rejuvenated, but more importantly, contractional structures are formed. (ref Basin inversion). The process of Basin inversion is dependent on its severity and its relationship to hydrocarbon generative phases, may have a positive or negative effect on the hydrocarbon systems of a rift basin. The Organic matter trapped within the sediments undergoes the process of maturation gradually with overburden pressure, Temperature and time where as in this case the sediments get over-pressured and early maturation / expulsion of hydrocarbon is initiated. Continued subsidence and hydrocarbon generation in surrounding kitchen is a critical factor, with migration often occurring synchronously with or shorter after, formation of inversion structure and traps. The typical inversion anticline is situated on the hanging block of the reverse faults. Hydrocarbon expelled from the underlying source rocks migrated upward along the adjacent faults. The oil gets trapped in conventional and fractured reservoirs in the core of the anticline. Areas of surviving paleotraps or traps near kitchens that may have been reactivated post inversion and if preserved are better areas where exploration effort should be concentrated.

Discussion

The drilled well "AA" has produced gas in the interval 2127-2122m and 2115-2110m from the Nannilam formation. The Santonian top corresponding to Nannilam formation is a chrono-stratigraphic boundary, which is represented by a high gamma break. The electro logs of wells "AA", "BB", "CC" & "DD" in NS direction was correlated and analyzed (Fig-2). The Sediments between Santonian to Turonian top host the main Nannilam formation, which corresponds to pay zone of well "AA" & fields of Ramnad sub basin. The Log profile was flattened at successive time boundaries. The higher thickness of Nannilam formation Well: "CC" being on present day high could only be explained by flattening at Santonian level (Fig-3). The lesser thickness of Maastrichtian sediment is explained with the model of basin inversion. The basin inversion exhumed the sediments upward, which subsequently underwent erosion accompanied by non-deposition thus explaining the less thickness in Maastrichtian w.r.t. other three wells. It is interpreted that older basin opening normal fault got reactivated subsequently in reverse direction, resulted in basin inversion. The well "DD" falls beyond the study limit hence is not being discussed.

The stratigraphic boundaries, calibrated with the electrologs and biostratigraphy were transferred to key seismic sections using VSP. The direct evidence for the Precambrian basement in Ramnad, Gulf of Mannar and Palk bay offshore is very limited and the basement is drilled in few wells of Ramnad sub basin. The seismic data correlation of all the stratigraphic boundaries was carried out in the entire study area using seismic sequence stratigraphy technique. Relief maps close to top of Basement, a reflector within Pre-Albian (K0-1), Albian (K1), Cenomanian (K2A),

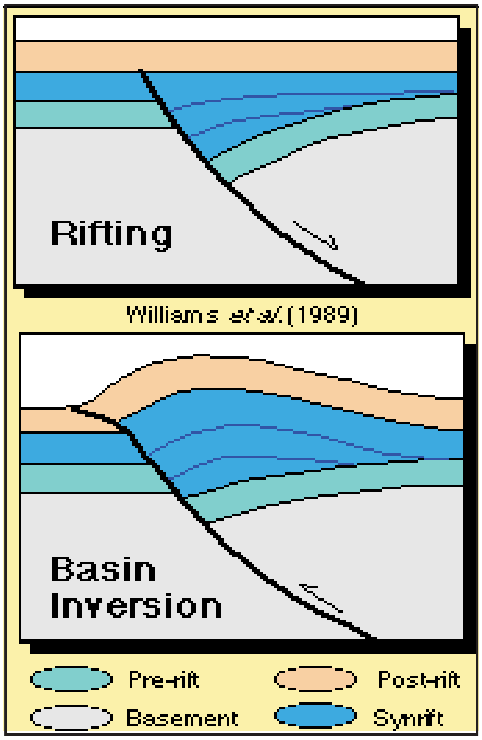

Fig.1.

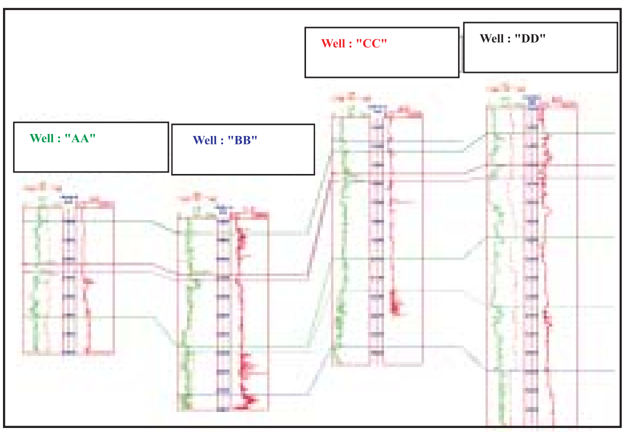

Fig-2 : Electro log correlation of well AA, BB, CC & DD showing the structural position in the present day time

Turonian (K2B), Santonian (K3A), Cretaceous (K3 C), and Paleocene were generated. Isochronopach maps for the sediments within Pre-Albian, Albian, Cenomanian, Turonian, Santonian, and Paleocene were prepared to decipher the depositional model.

The relief map close to top of basement (Fig-4) brings out the basin architecture which depicts a general trend of high and low aligned in NE – SW direction with the basin broadening in the central and south central part

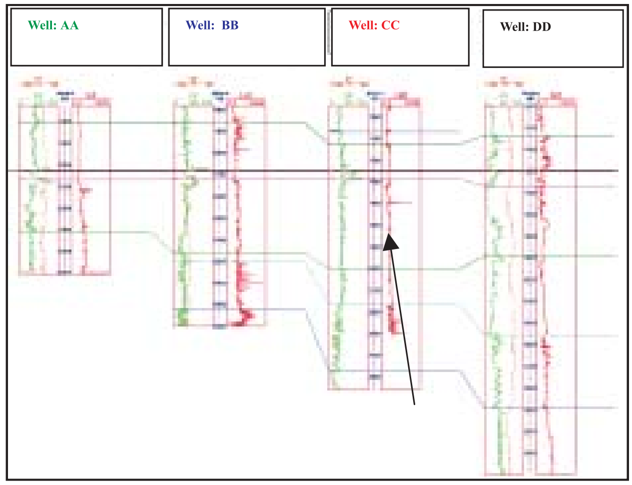

Fig-3: Same profile flattened at Santonian level showing the paleo structural position of formations older than Santonian.

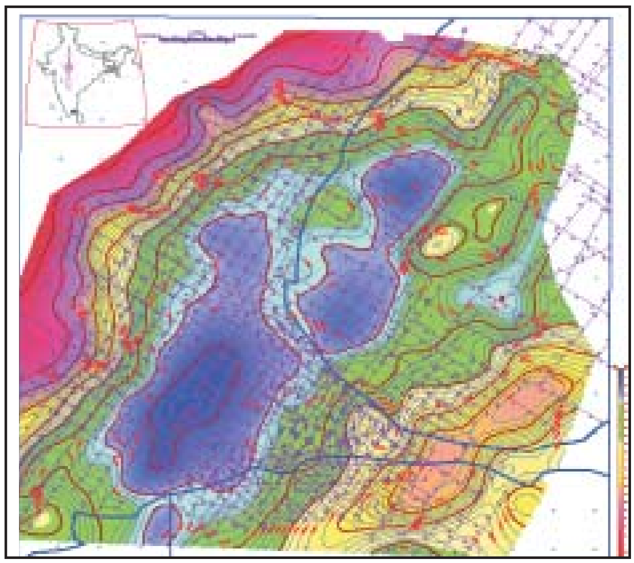

Fig 4 : Relif map close to top of Basement showing basin configuration and depocenters of the Ramnad & Palk bay offshore areas.

and tapering towards the northern part of mapped area. The NE-SW trending basin opening faults are responsible for formation of grabens. The deepest basinal low is seen in the Ramnad Sub Basin followed by the twin depocenters of little lesser magnitude in the western Palk bay offshore. As observed in the map, the basinal lows progressively deepen from North to South. The western side of Palk Bay low ranges in the order of 3800 – 3900 whereas the main Ramnad low is in the order of 4200ms in its central part.

The relief map on a reflector within Pre-Albian, K0-1 (Fig–5) brings out major change from the basement level due to massive inversion within Pre-Albian time. The bigger Ramnad low, which covered an areal extent of about 550 sq.

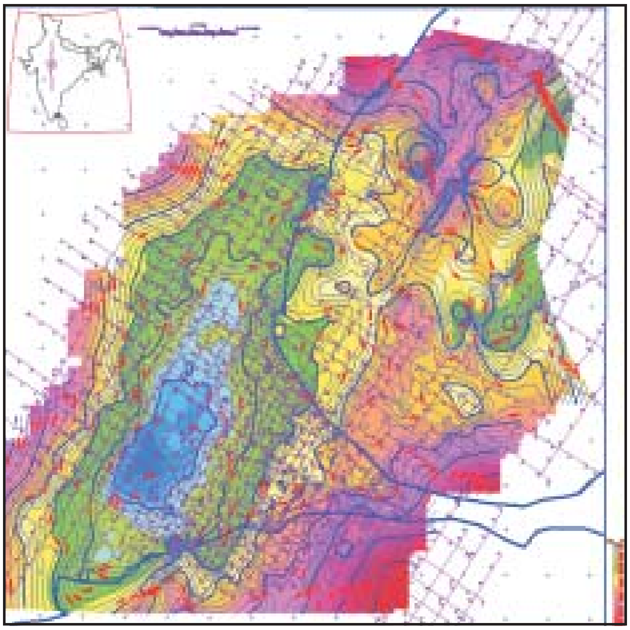

Fig.5: Relif map on a reflector within Pre-Albian (K0-1) showing the depocenter in the Ramnad on-land and the areas of basin inversion in the western Palk bay offshore areas.

km during basin opening time, has shrunk to around 275 sq. km during Pre-Albian time due to basin shrinkage resulting in inversion (Older inversion). However, the main Ramnad low has lengthened in the Northeastern direction and the two smaller lows of western Palk bay offshore during basement level (ref Fig 4) got obliterated. Two right lateral strike slip faults with reversal, in limited aerial extent has caused the changes in the basin configuration, consequently two small ridges thus created, are oriented in almost E – W direction (northern) and another NE – SW (southern). Seismic lines showing inversion are shown in the Fig-6 to Fig-8 and the sediments of this level wedge out on Pattukottai Mannargudi ridge in the north & west and on Mandapam delft ridge in NE and east direction. The wedge limit is shown on the map. This initial inversion during Pre-Albian is seen as "prominent" where as subsequent episodic inversion up to Paleocene is of smaller magnitude. The upwelling of sediments took place during Early Cretaceous time (older level) due to reactivation of basin opening fault in reverse direction along with strike slip component. The exhumed sediments of Pre-Albian thus created high which got buried due to subsequent sedimentation. The high rate of sedimentation from the north side coupled with non activity of basin opening fault (sedimentation rate > accommodation space) induced the transpressive force which resulted in selective reactivation and wrench faulting (strike slip with reverse fault).

The "older" basin inversion initiated within Pre-Albian time and continued episodically up to Paleocene in Palk bay offshore & Ramnad on-land holds good promises of hydrocarbon entrapment which has not been drilled so far. One representative seismic line each from Palk bay offshore and Ramnad offshore SL-PB & SL-RN shown below indicates the inversion initiated at the Pre-Albian and continued episodically up to Paleocene. Paleotectonic analysis carried out on this line confirms the inversion (Fig–9).

The reactivation of older normal fault in to reverse direction has taken all along the Ramnad on-land in almost NE–SW direction and the inverted corridor encircles the main Ramnad low in the east and southeast. The NE-SW corridor of inverted structure in Ramnad on-land part takes a swing in northern direction while entering in to Palk bay offshore. Thus the Ramnad low and western Palk bay low, which are the depocenters for hosting the source rock are bordered by inverted structures. This Paleo traps are still preserved and hence the first to receive and accumulate the expelled hydrocarbon. The relief map close to top of Pre-Albian (ref Fig 5) depicts the inversion corridor to be restricted within the contour values ranging from 2350 to 2900 ms.

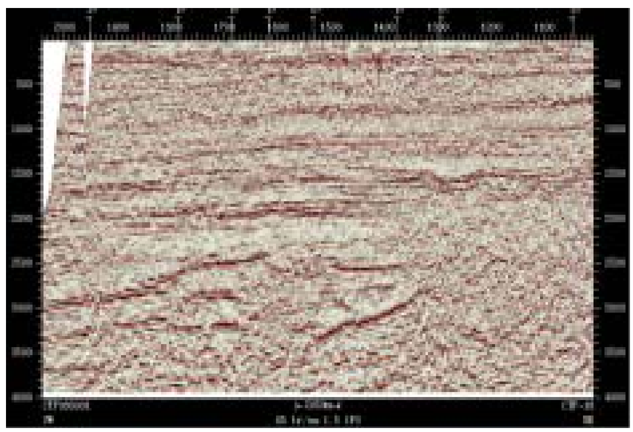

Fig.6: An uninterpreted Seismic section SL-PB showing the seismic signatures

Basin inversion and its effect on GME

Basin inversion has positive as well as negative effect on the Generation, Migration and Entrapment (GME) of hydrocarbon.

- Before Migration of Hydrocarbon : Sediments get over-pressured and early maturation / expulsion of hydrocarbon is initiated.
- During Expulsion / Migration of Hydrocarbon : The reactivated faults become conduit for migration and

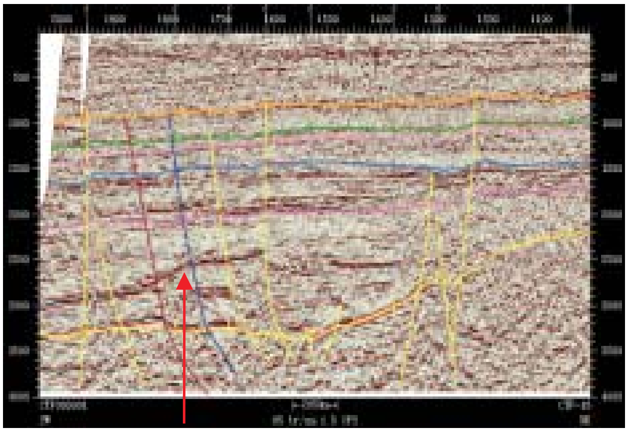

Fig.7 : Seismic line SL-PB (interpreted) showing the major inversion at Pre-Albian and episodically up to Paleocene.

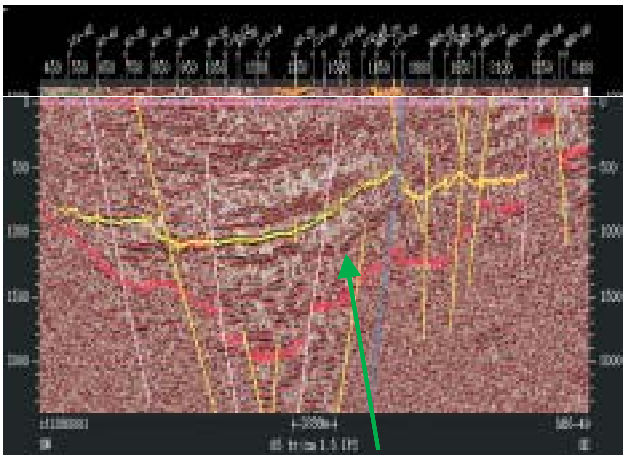

Fig.8 : Seismic section SL-RN from Ramnad sub basin flattened at Albian top indicates the inversion.

structurization due to inversion provide the entrapment.

- After Migration of Hydrocarbon : The reactivation of faults during Basin inversion causes leakage in the structure and releases accumulated hydrocarbon. Breaking down of Liquid hydrocarbon in to Gases due to basin inversion and associated shrinkage, is another significant negative effect.

Relationship between critical moment & inversion

Two synthetic wells "Ramnad_low" & "PBS_west" were generated for which the stratigraphy was taken from the regional correlation and the ideologies were generated with the help of nearby drilled wells and conceptualized model.Geochemical studies and 1D Genetic modeling carried out by the KDMIPE estimated the critical moment (ref unpublished report of ONGC) for these synthetic wells which is as follows.

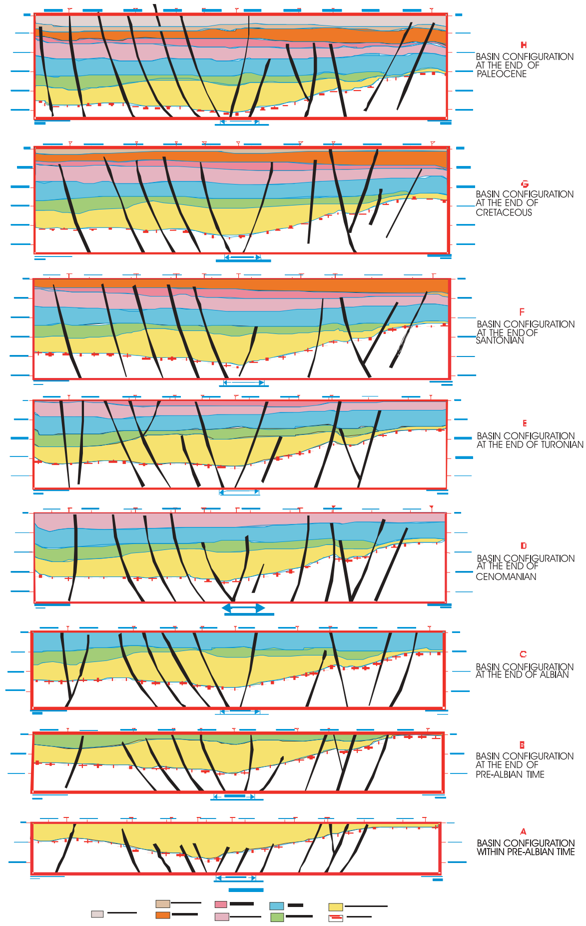

Fig.9 : Paleotectonic analysis carried out on seismic line SL-PB shows the massive inversion at Pre-Albian level, followed by upwelling of sediment resulting in part erosion of exhumed sediment. Subsequent inversion are found to be episodic in nature up to Paleocene.

Synthetic well : "Ramnad_low" (Ramnad sub basin)

- The critical moment for onset of hydrocarbon generation (0.7% VRO) is estimated at 82 my (Lower Campanian) for Pre-Albian sediments.
- The critical moment for wet gas & condensate i.e. VRo 1.3 % is estimated at 20 m.a. (early Miocene time) for Pre-Albian sediments.

Synthetic well : "PBS_west" (Palk bay offshore)

- Critical moment for Pre-Albian sediments of western Palk bay offshore has been estimated at 59 m.a. (Selandian – Middle Paleocene).

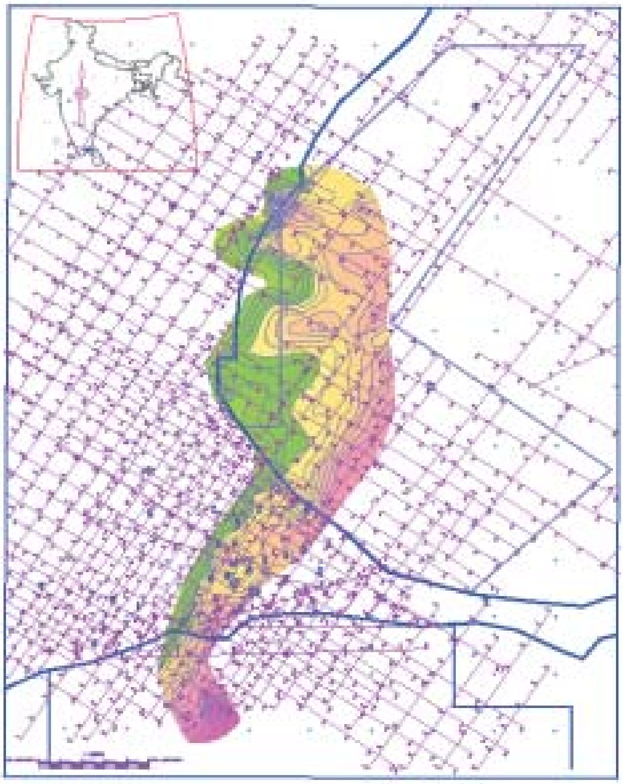

Fig.10 : The prospective areas identified based on the inversion style

Entrapment model

The hydrocarbon charged areas of Ramnad sub basin, which is aligned in NE – SW corridor takes a swing in northern direction in Palk bay offshore. This NE-SW corridor is formed due to inversion initiated during Pre-Albian continued episodically up to Paleocene and the faults responsible for inversion are interpreted to be "conduits". Thus, the entrapment style is interpreted to be "inverted structures ". These inverted areas bordering the kitchen of Ramnad low and western Palk bay low will be the first to be charged with the migrating hydrocarbon. The highly prospective areas are delineated based on the older inversion model (Fig-10), which provides the exploratory lead.

Conclusions

- Eight horizons calibrated with biostratigraphy and log data were correlated regionally and integrated maps of different stratigraphic levels of Ramnad and Palk bay have been prepared.
- The depocenters at the time of Basement, Pre-Albian and Albian time have been mapped which reveals the distribution of source rock facies.
- Pre-Albian sediments are interpreted to host source rock facies in western Palk bay offshore. Andimadam formation & lower part of Sattapadi formation has source rock facies in Ramnad sub basin.
- Source rock facies of Ramnad low and western Palk bay offshore is derived from Pattukottai Mannargudie ridge & Gulf of Mannar through south-western corner of Ramnad low.
- The cutting samples of drilled wells indicate only type – III & type – IV Kerogen, however finer clastics of undrilled section of the basinal low may contain type II Kerogen.
- Ramnad sub basin and Palk bay offshore have undergone basin inversion at different stratigraphic levels due to reactivation of older normal fault in to reverse direction along with strike slip component. The present study has brought out the implications of inversion on Generation, Migration and Entrapment (GME).
- The prospectivity map brings out the NE–SW main hydrocarbon fairway in the Ramnad sub basin which swings towards North in to western Palk bay offshore.

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