Sand Dispersal Pattern, Depositional Processes, Diagenesis and Hydrocarbon Prospectivity of Lower Cretaceous (Cenomanian-Turonian) Bhuvanagiri Sandstone of Ariyalur- Pondicherry Sub Basin, Cauvery Basin, India

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Summary

Ariyalur-Pondicherry sub basin of Cauvery Basin, located on the East Coast of India hosts more than 6000 m. sediments ranging in age from Early Cretaceous to Recent. Sandstone belonging to Bhuvanagiri Formation of Cenomanian-Turonian in age of Lower Cretaceous System has been proved to be oil/gas bearing. Based on lithological association and bio-stratgraphic data, Bhuvanagiri Formation has been divided into two sub units viz. Lower Bhuvanagiri (Cenomanian) and Upper Bhuvanagiri Formation (Turonian). Sandstone occurring in Lower Bhuvanagiri Formation is termed as Lower Bhuvanagiri sandstone and that of Upper Bhuvanagiri Formation is named as Upper Bhuvanagiri Sandstone. Bhuvanagiri sandstones having limited aerial extent are distributed in scattered fashion as discrete lobes. Mass transport gravity driven mechanisms, e.g., non-channelized debris flow and sandy slump have been identified as the principal depositional processes for Bhuvanagiri sandstone acting under bathymetry ranging from 150m. to 200m+. Sandstones located especially in the basinal part are highly altered by digenetic processes. However, sands towards the flank of the basin have the better porosity not only because of less overburden effect but also due to generation of secondary porosity by meteoric water flushing. Based on the integrated study, prospective areas have been delineated which could be the future exploration target in this sub-basin.

Introduction

The Lower Cretaceous (Cenomanian-Turonian) Bhuvanagiri Formation constitutes a prospective play in the Ariyalur-Pondicherry sub-basin of Cauvery basin, located on the east coast of India, due to its occurrence between potential source and seal units. Despite its favourable disposition with respect to these units, the exploration of Bhuvanagiri Formation has turned out to be non-commercial because the reservoir quality at depth of occurrence has been considered a major risk. As a component of the Research Project being carried out by K.D. Malaviya Institute of Petroleum Exploration of Oil and Natural Gas Corporation Limited, Dehradun, India, an integrated study was done on the sandstone of Bhuvanagiri Formation to bring out the distribution, geological processes which controlled the sedimentation vis-à-vis the depositional model, digenetic impact on the reservoirs and to predict the quality reservoirs for future exploration activities.

Regional geological setting and Stratigraphy

The Cauvery basin was evolved in Late Jurassic-Early Cretaceous time as a result of rift-drift phenomenon of the then Indian plate from East Gondwanaland. Evolution of this basin is genetically linked with the other simultaneously evolving extensional basins of East Coast of India, viz. Palar, Krishna-Godavari, Mahanadi and Bengal basins (Rangaraju et al, 1993). Early and Late Cretaceous sediments outcrop in the western margin of the basin. Based on gravity data, the Cauvery basin has been divided by the previous workers into three depressions each separated by intervening ridges as below:

1. Ariyalur-Pondicherry Depression
2. Tanjore Tranquebar Depression
3. Ramnad-Palk Bay Depression

Ariyalur-Pondicherry depression is the northernmost sub-basin of Cauvery basin and is partitioned by Kumbakonam-Madanam ridge from the adjacent Tanjore-Tranquebar depression. This sub basin, an asymmetric rift graben trending NE-SW, is flanked by outcropping Archaean granite gneisses in the west & northwest, Kumbakonam-Madanam ridge in the south/ southeast and east and extending to the present day offshore upto 200m. isobaths into Bay of Bengal towards northeast (fig.1) The area holds more than 6000m of sedimenmtary column ranging in age from Early Cretaceous to Recent (fig.2). It is mainly a Cretaceous basin with lesser Tertiary sediments. The total basin fill can be divided into nine depositional sequences viz. K0, K1, K2A, K2B, K3A, K3B, K3C, T1 and Younger (fig.3). Integrating with available bio-stratigraphic data, these sequences have been dated as Pre-Albian, Albian, Cenomanian, Turonian, Santonian, Campanian, Maastrichtian, Paleocene, and Younger (Post Paleocene) respectively. Each of the sequences identified above demonstrates different successive evolutionary phases of basin development (fig.4). The area has been affected by at least two phases of faulting (fig.5).

a) Basin forming normal extensional faults (red) trending NE-SW
b) NW-SW (blue) trending cross fault sets

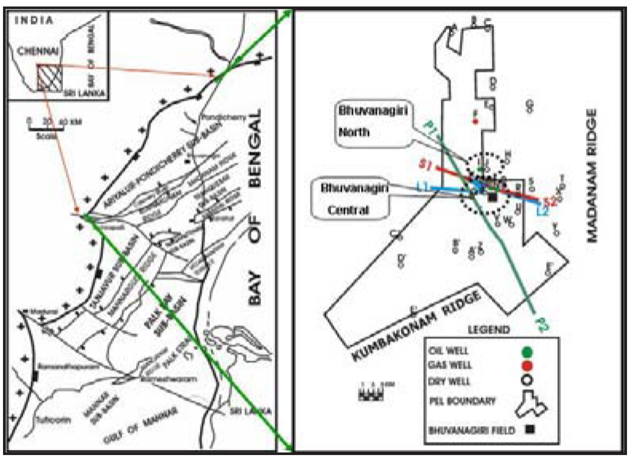

Fig.1: Index map showing study area.

Depositional sequences K2A and K2B corresponding to Lower and Upper Bhuvanagiri sandstone reservoirs are connected with Early Cretaceous source facies through deep-seated faults which act as conduits for hydrocarbon migration. In the central part of Ariyalur-Pondicherry depression two hydrocarbon bearing structures, for e.g. Bhuvanagiri central (producing from Lower Bhuvanagiri sandstone) and Bhuvanagiri north (producing from Upper Bhuvanagiri sandstone) have been discovered so far (ref.fig.1).

Age			Formation(m)	Thickness(m)
Recent to Mid.Miocene			Tittacherry Formation	300-500
Lower Miocene			Madanam Limestone	600-1200
			Vanjiyur Sandstone	
			Shiyali Claystone	
Oligocene			Kovilikalappal Formation	
			Niravi Sandstone	
Eocene			Tiruppundi Formation	200-400
Paleocene			Pandanallur Formation	200-600
			Karaikal Shale	
			Kamalapuram Formation	200-800
Cretaceous	Upper	Maastrichtian to Santonian	Portonovo Shale & Nannilam Formation	600-1500
		Santonian to Coniacian	Kudavasal Shale	
	Lower	Turonian to Cenomanian	Bhuvanagiri Formation	1000-1500
		Cenomanian to Albian	Sattapadi Shale	
		Albian to Pre-Albian	Andimadam Formation	
Archaean			Basement	

Fig.2 : Generalized stratigraphy of Ariyalur-Pondicherry sub-basin,Cauvery basin.

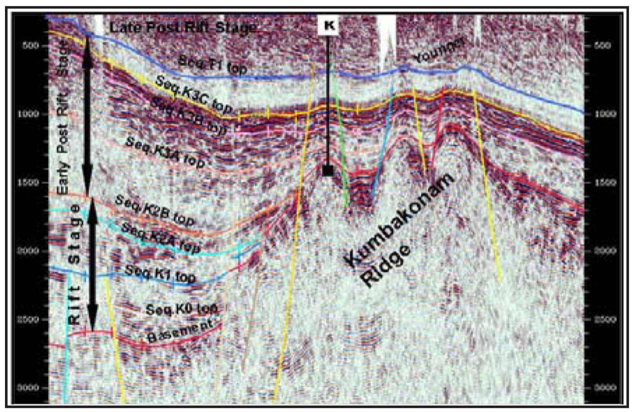

Fig.3 : Part of a seismic line S1-S2 (dip oriented) showing identified depositional sequences, different stages of basin evolution, basin architecture and various tectonic elements of Ariyalur-Pondicherry sub-basin,Cauvery basin

Data base

Over 3800 line-kilometers of two-dimensional (2-D) seismic data, Geo-scientific data of 30 wells including sedimentological, petrological, geochemical and petrophysical input and the available biostratigraphic data have been integrated in the present study.

Methodology

The methodology adopted for interpretation and integration is shown in figure 6.

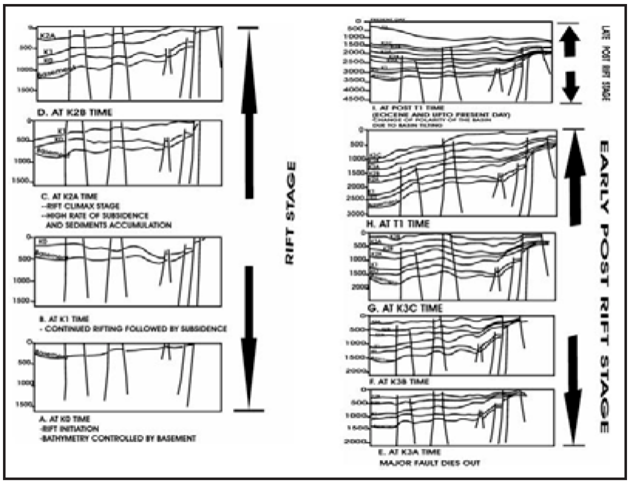

Fig. 4 : Paleotectonic analysis along seismic line P1-P2 showing successive stages of basin evolution of Ariyalur-Pondicherry sub basin,Cauvery basin

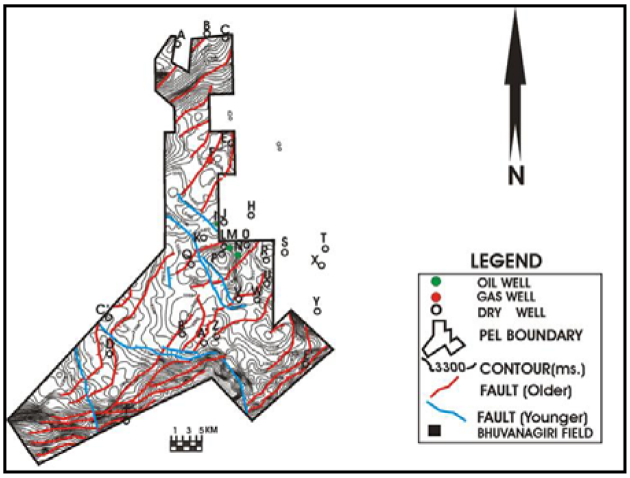

Fig.5 : Two way time structure map close to top of basement, Ariyalur-Pondicherry sub-basin,Cauvery basin

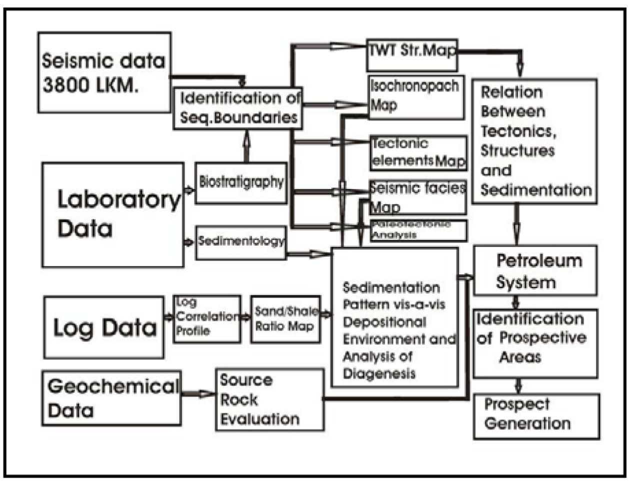

Fig.6 : Flowchart of methodology

Basin evolution

Sedimentation in Ariyalur-Pondicherry subbasin began in Late Jurassic/Early Cretaceous period with the first definite marine influence in the Albian (Narayanan et al. 1984). Cessation of riftng phase can be marked by the end of Turonian (SequenceK2B). Depositional geometries of identified sequences suggest mainly three episodes of basin evolution as below:

a) Extension Stage/Rift Stage (Late Jurassic-End of Turonian) ⇒development of syn-rift sequences over the Pre-Cambrian Basement during East Gondwana rifting (Seq. KO, K1 K2A & K2B)

b) Early Thermal Subsidence stage/Early Post Rift Stage (Late Cretaceous and Paleocene) ⇒Minor NE tilt of the basin and development of the sequences K3A, K3B, K3C and T1.

c) Late Thermal Subsidence stage/Late Post Rift stage ⇒Dominated by pronounced south-easterly tilt of the basin and development of Eocene and Younger sequences. Basin polarity got changed at this stage.

Paleotectonic analysis along seismic line A-A.' brings out the different successive stages of basin evolution as described earlier (refer.fig.4). Paleogeographic reconstructions made at different stratigraphic levels show the absence of regular shelf-slope system up to Santonian (Seq.K3A) level. Initiation of shelf-slope system is seen from Campanian (Seq.K3B) time. Existing positive areas (Kumbakonam-Madanam ridges) were fully peneplained at that stage (fig.7).

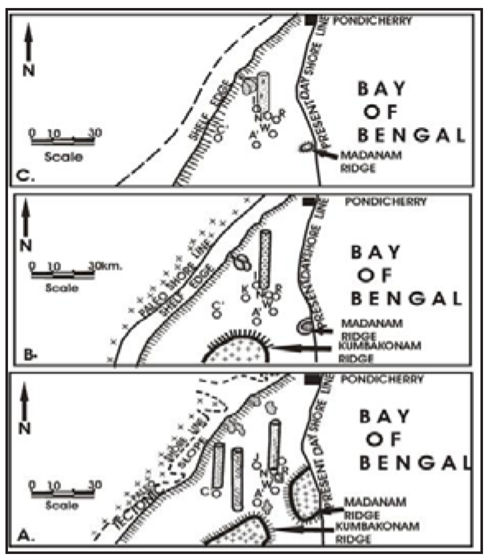

Fig.7 : Paleogeography(A)at the time of K2B,(B)at the time of K3A,(C) at the time of (K3B) of Ariyalur-Pondicherry sub-basin,Cauvery basin

Burial thermal history

Analysis of subsidence diagram of various wells brings out the asymmetry in burial history of Bhuvanagiri Formation in the basin. Fig.8 demonstrates primarily the two different rates of subsidence of Bhuvanagiri Formation. Initially the rate of basin subsidence was relatively faster till the time of 80 my. As a result considerable amount of clastics were accumulated during that span of time. Sandstone of Bhuvanagiri Formation got accumulated during Cenomanian-Turonian time (95-89 m.y.), after which basin got uplifted during the period in between 80-75 m.y.as shown an upward trend in the subsidence curve. Faster subsidence still continued upto 50 m.y. Beyond 50 m.y. rate of basin subsidence was much lesser as shown by the very much gentle slope of the subsidence curve.

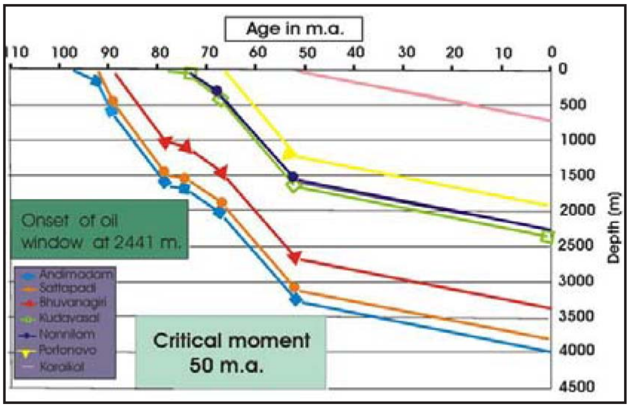

Fig.8 : Subsidence curve of well # N, Ariyalur-Pondicherry sub-basin,Cauvery basin

Burial temperatures in the Bhuvanagiri Formation, computed using thermal alteration index (TAI) shows about 90ºC at 2700m.,120ºC at 4000m., and about 190ºC at 4800m. This variation of burial temperatures is very significant from diagenetic impact on reservoirs.

Description of Bhuvanagiri Formation

Based on lithologcal association and bio-stratgraphic data, the Bhuvanagiri Formation of Lower Cretaceous System (Cenomanian-Turonian), can further be divided into two sub units viz. Lower Bhuvanagiri and Upper Bhuvanagiri Formation (fig.9a & 9b). Lower and Upper Bhuvanagiri Formation correspond to the depositional sequence K2A (Cenomanian) and K2B (Turonian) respectively. Sandstones belonging to Lower Bhuvanagiri Formation and Upper Bhuvanagiri Formation have been termed as Lower Bhuvanagiri Sandstone and Upper Bhuvanagiri Sandstone respectively. In Bhuvanagiri area Lr.Bhuvanagiri Sandstone has produced oil/gas from two wells viz. **M** & **N** and Upper Bhuvanagiri Sandstone has produced oil/gas from the well **I**.

Lithology and mineralogical composition

Lithologically Lower Bhuvanagiri Formation is primarily sandy with minor intercalation of shales whereas, Upper Bhuvanagiri Formation comprises of sand and shale almost in equal proportion. Sandstones are medium to coarse grained, pebbly at places, dirty white to greenish, occasionally dark grey in colour. Composition of Upper Bhuvanagiri Sandstone varies from sub-arkosic calcarenite to arkosic wacke. Lower Bhuvanagiri sandstone varies from arkosic arenite to wacke and arkosic calc arenite to sub arkosic arenite. Matrix content varies between 10-25%. Mineralogical and textural immaturities of both the sands indicate very short transport of deposition.

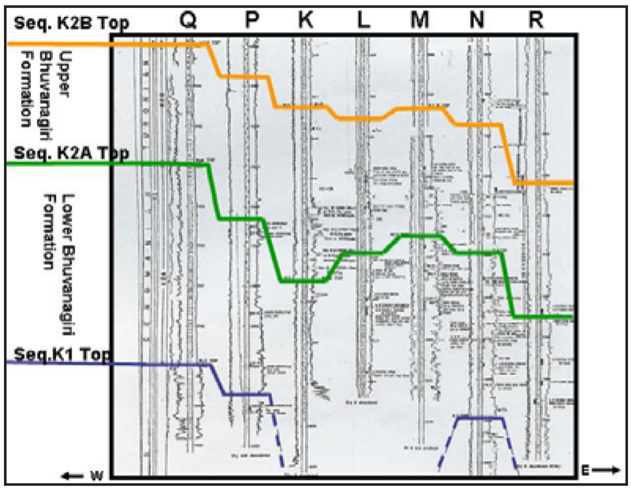

Fig. 9a : Electrolog correlation profile (L1-L2) across the wells Q,P,K,L,M,N & R showing the lateral and vertical distribution of Lower & Upper Bhuvanagiri Formations,Ariyalur-Pondicherry sub-basin.

Distribution

The sand dispersal pattern of Lower Bhuvanagiri sandstone is shown in fig.10. Discrete isolated lobes indicate different entry points, which have been shown in the map. Distribution pattern of Upper Bhuvanagiri sandstone is shown in fig.11. Major sand entry has been envisaged from western side with with minor input from eastern Madanam high. Paleogeographic map (refer fig.7) shows that during Cenomanian-Turonian time, the basin was surrounded by Kumbakonam-Madanam Ridge in South, East & South-Eastern sides The Eastern Ghat metamorphic complexes flanked western basin margin. Probable tectonic slope was much beyond west of the study area. Isochronopach maps (fig.12 & 13) indicate the depositional thick adjacent to the basin margin and near the flank of ridges as well. Electro log correlation profiles (ref.fig.9a) and seismogeological section along seismic line S1-S2 (fig. 14) demonstrate the vertical and spatial distribution of Bhuvanagiri sands. In seismic sections, sands are found to be mounded and having limited aerial extent (ref.fig.9b). Within K2A sequence (hosting Lr.Bhuvanagiri sandstone), seismic facies indicate

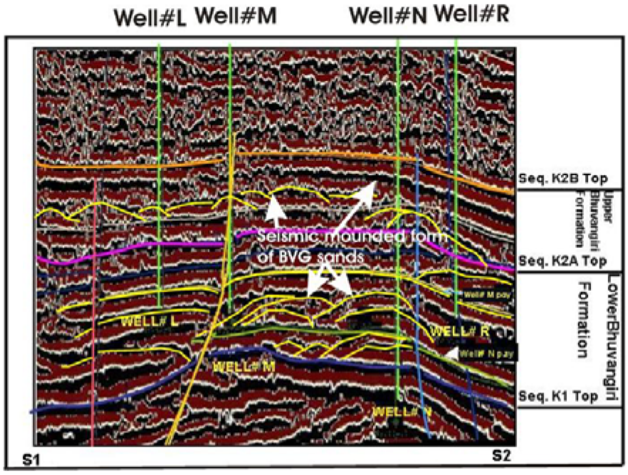

Fig. 9b : Part of seismic section along S1-S2 showing seismic mounded form of Bhuvanagiri sands.

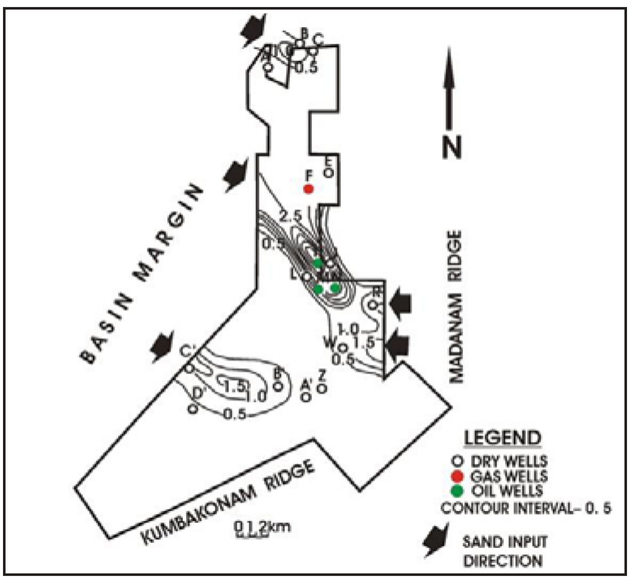

Fig.10: Sand/shale ratio map of Lower Bhuvanagiri Formation (Sequence K2A) of Ariyalur-Pondicherry sub-basin.

well-developed convex-upward external mounded forms down lapping on to K1 sequence boundary. Within K2B sequence (Upper Bhuvanagiri Formation), similar mounded

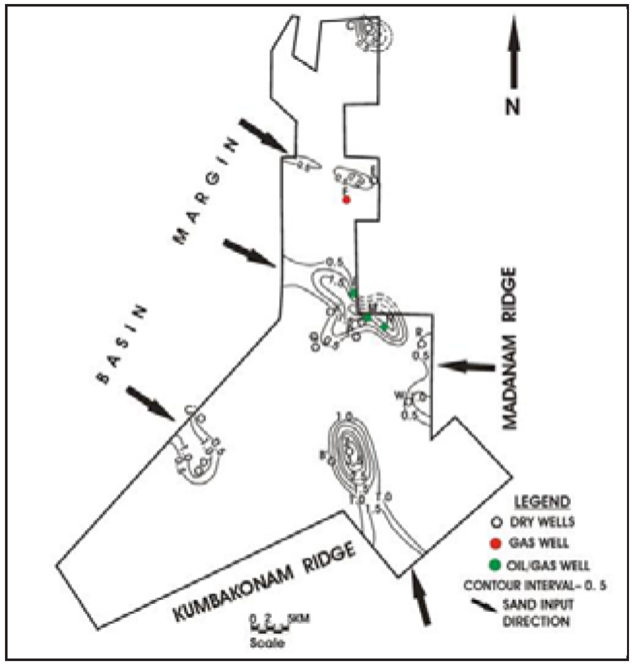

Fig. 11 : Sand/shale ratio map of Upper Bhuvanagiri Formation (Sequence K2B) of Ariyalur-Pondicherry sub-basin.

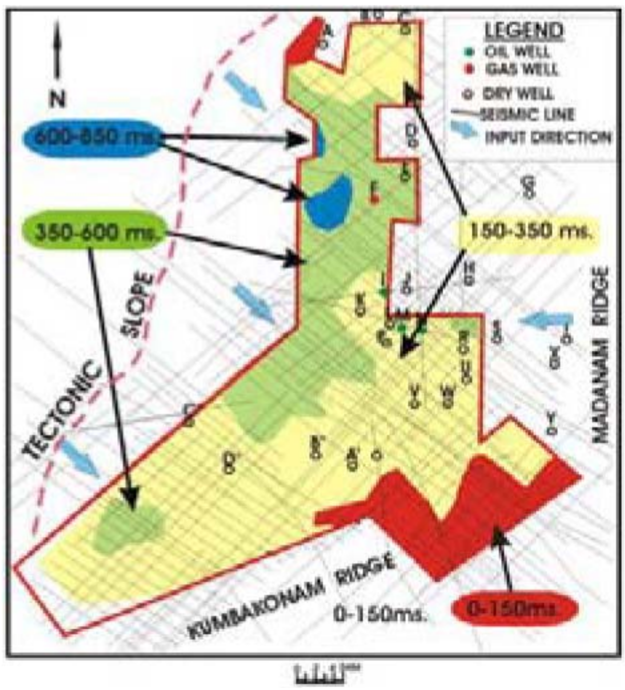

Fig.12 : Isochronopach map of Lower Bhuvanagiri Formation (Sequence K2A) of Ariyalur-Pondicherry sub-basin.

seismic facies down lapping on to K2A sequence are very well visible. It also exhibits blocky log motifs on wire line log. Limit of reservoir facies is characterized by loss of seismic amplitude.

Core sedimentology

About 420 m length of cores from a number of wells has been studied in this work. The study includes XRD, SEM, XRF and in section petrography. Some of the salient points of the study are outlined below:

a) Highly variable grain size reflects mass transport gravity/ slump deposits. In the slide/slump/debris/turbidite model, majority of sands were deposited as debris flow with subordinate amount of slumps & slides along with occasional reworked bottom current sediments.

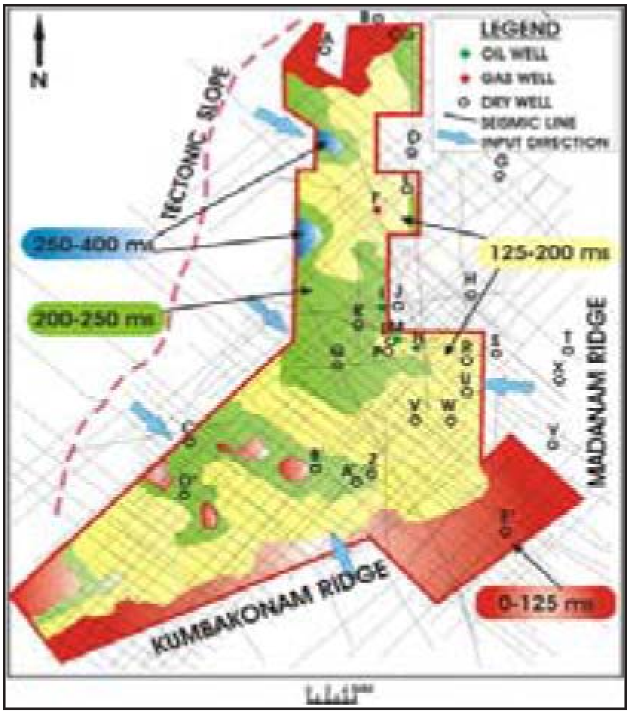

Fig.13: Isochronopach map of Upper Bhuvanagiri Formation (Sequence K2B) of Ariyalur-Pondicherry sub-basin.

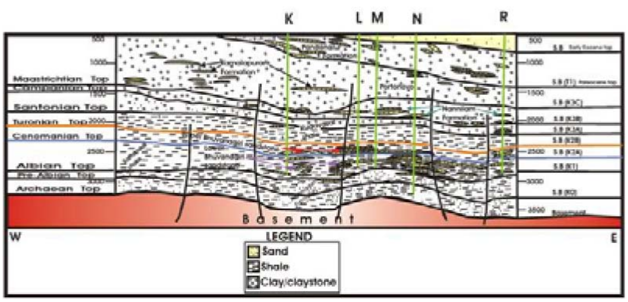

Fig 14 : Seismogeological section along seismic line S1-S2 depicting the spatial and vertical distribution of Upper and Lower Bhuvanagiri sandstones in Ariyalur-Pondicherry sub-basin.

a) The bathymetry for the deposited sediments ranges from 150-200 m+

b) Presence of large floating clay clasts (fig.15) indicate high viscosity of the transporting fluid which were mixed with sediments, increasing their overall gel. strength and carrying capacity.

c) It also indicates the presence of rapid supply of considerable volume of sediments being deposited on a narrow unstable shelf: this in turn was being carried downward as unstable sediment wedge.

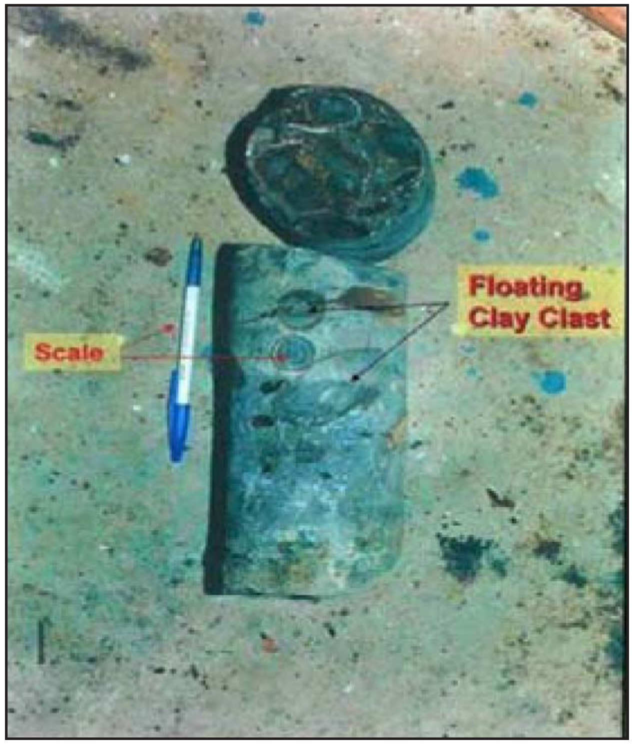

Fig 15 : Core photograph of Well # N U, CC-9 in the interval 3353.27-3362.27 of Upper Bhuvanagiri sandstones in Ariyalur-Pondicherry sub-basin.

Depositional environment

Based on cores, cuttings, and subsequent integration with electro logs and seismic data, attempt has been made to decipher the depositional model for Bhuvanagiri sands. Mass transport gravity driven processes, dominated by non-channelized sandy debris flow with slumps and slides, have been identified as principal depositional processes acting under bathymetry ranging from 150 to above 200m. Conceptualized depositional model for non-channelized sandy debris flow dominated mass transport system of Bhuvanagiri sands has been demonstrated in the fig.16. The sands in these deposits are apt to be more discontinuous and thus less predictable than those in the conventional submarine fan. This mass transport model thus has an important implication for reservoir geometry and correlation. Although there is no predictive model for debris flows yet, the current perception that debris flow sands do not form good reservoirs is not justified because debris flow can be thick, aerially extensive and excellent reservoirs (G. Shanmugam, 96).

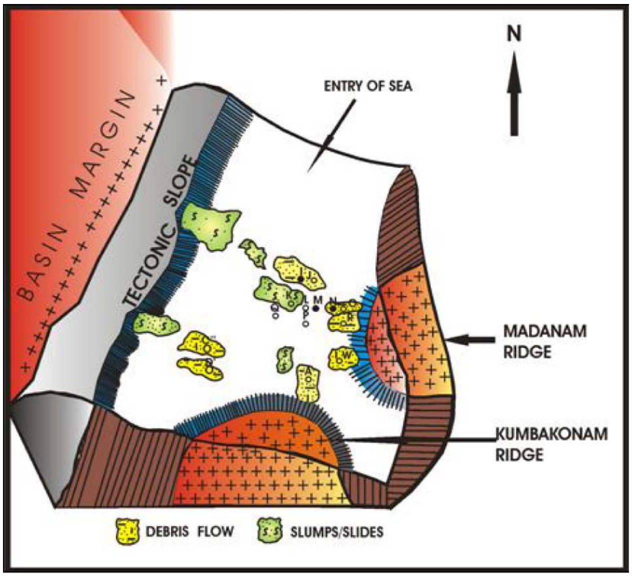

Fig 16: Cartoon diagram depicting depositional model for non-channelised debris flow dominated Bhuvanagiri sandstones in Ariyalur-Pondicherry sub-basin.

Diagenesis

1) Authigenic minerals

Authigenic phases in the Bhuvanagiri sandstone reservoirs are mainly carbonate, quartz and clays, and include bitumen/pyrite. Carbonate is mainly calcite and occurs as a patchy, coarsely crystalline/poikilotopic pore-filling cement and grain/clay replacement. Cement percentage normally varies between 25% to 5%. Authigenic quartz occurs as overgrowths (fig. 17 a & b), the abundance of which increases with depth i.e. with increasing thermal maturity. Authigenic clay is mainly kaolinite and chlorite with rare smectite.

Kaolinitic clay occurs in the intergranular space and chloritic clay occurs as thin rims around the grains, as pore filling and lining of primary and secondary pores.

2) Grain compact dissolution and physical compaction

The figure below demonstrates an example of closed permeability pathway due to point contact. Micro porosity

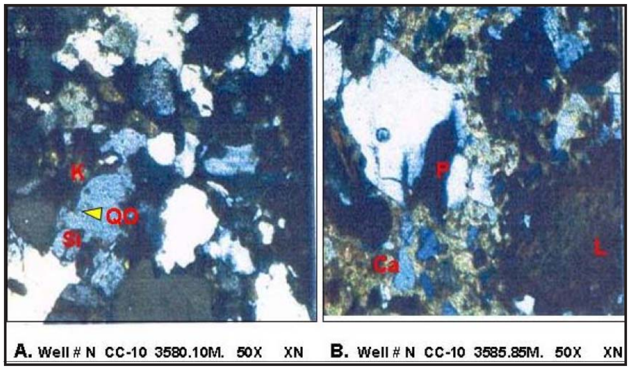

Fig 17(a) :Thin section micrograph shows abundant quartz overgrowth (QO) with silica cement (SI) destroying the porosity.Small pores are filled up with Kaolinitic clay(K); (b) Subsequent to quartz overgrowth,calcite cement(Ca) filled the pores (P).Calcite cement shows minor leaching (L) with generated microporosity. .

is being hosted on either sides of the point contact, but may never be effective (Pendkar et al., 2002). Thick sediments accumulation, particularly in the basinal part may have resulted in higher compaction and associated diagenetic changes.

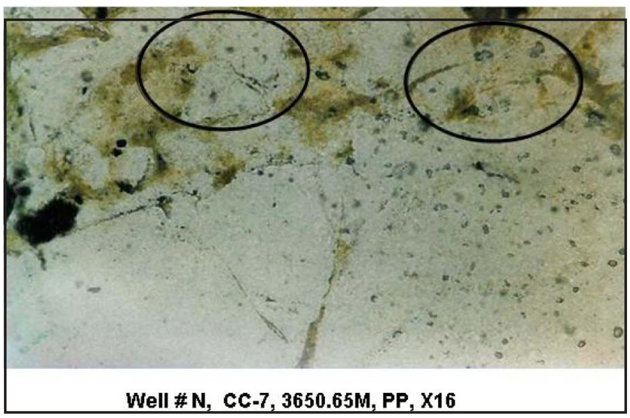

Fig 18 : Thin section micrograph representing Lower Bhuvanagiri sandstone shows the example of closed permeability pathway due to point contact.

3) Secondary porosity

Sesondary porosity was generated by partial to complete dissolution of liable grains, particularly feldspar and calcite cement because of meteoric water flushing during Turonian regression. Meteoric influence is also well supported by stable isotopic studies (ref.annexure-I). Maximum meteoric water flushing vis-à-vis generation of secondary porosities is envisaged in the areas where entry of meteoric water took place and temperature below 90ºC which retards quartz precipitation (Prabhakaran et. al., 2004). Therefore, reservoirs with secondary porosities are anticipated along the basin margins and also near the flanks of the exposed ridges,.

Hydrocarbon migration

Critcal moment of hydrocarbon in Ariyalur-Pondicherry sub basin has been worked out as 50ma (Thomas et al., 2000). This data provides the basis for the time of the onset of generation, migration and accumulation of hydrocarbon Thus, beginning of Eocene time corresponds to 50ma.

Reservoir quality prediction

Based on the above studies, conceptualized composite diagenetic map prepared for both Lower & Upper Bhuvanagiri sandstone reservoirs (Sequence K2A & K2B respectively) are given in figures. 19 & 20 respectively Both the figures show three diagentically distinct zones. **(Zone-I):** In the central basinal part along the axis of Ariyalur-Pondicherry depression, ***porosity reduction zone*** prevails. Marine diagensis with secondary chlorite and abundant quartz over growth might have reduced the primary porosity of the formation. **(Zone-II):** Towards northwest, southwest and the southeastern part mixed layer (Chlorite/ Kaolinite) dominant digenetic field shows the ***partly preserved porosity zone*** due to calcite leaching and feldspar dissolution. **(Zone-III):** The third zone, predicted as *the* ***area*** *of least diagenetic effect* occupying mainly the flank part of the basin, shows ***porosity generation area*** where meteoric water flushing has generated the secondary porosity.

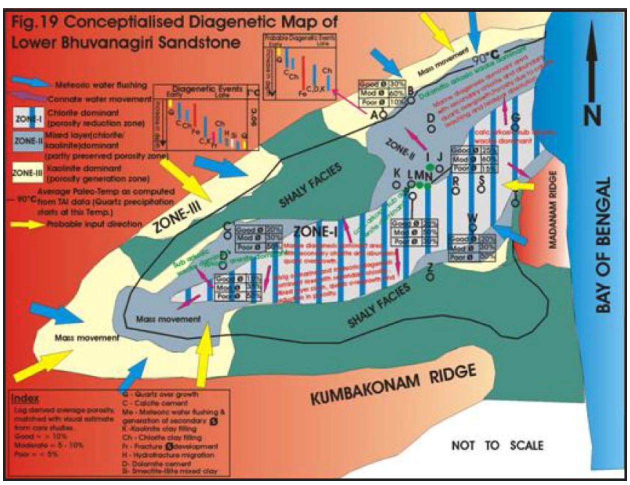

Fig 19 : Conceptualised diagenetic map of Lower Bhuvanagiri sandstones, Ariyalur-Pondicherry sub-basin.

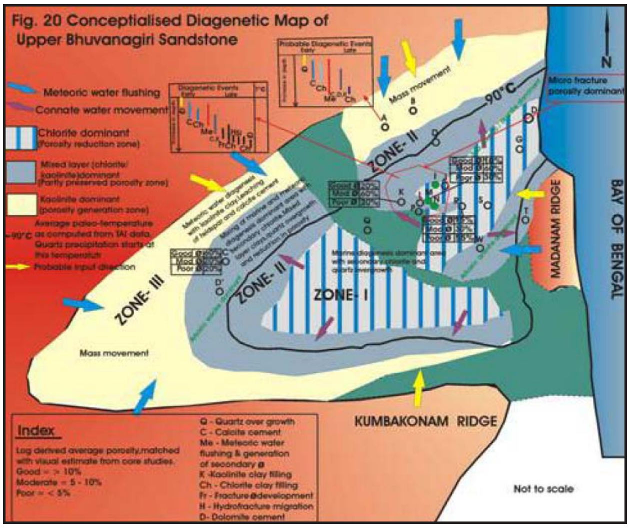

Fig 20 : Conceptualised diagenetic map of Uower Bhuvanagiri sandstones, Ariyalur-Pondicherry sub-basin.

Hydrocarbon prospectivity

Based on the present study quality reservoirs are found mainly near to basinal flank and slope of the ridges where generation of micro porosities are envisaged. In addition to that ***partly preserved porosity zone*** (Zone-II of fig.19 &20) is also anticipated the prospective areas from hydrocarbon point of view.

Conclusion

Lower Cretaceous (Cenomanian-Turonian) Bhuvangiri Sandstones (both Lower and Upper) having limited aerial extent are distributed in scattered fashion as discrete lobes. Sand distribution pattern suggests more than one entry point. Major entry was from the western-northwestern part of the basin with minor entry from the southern and eastern Kumbakonam ridge and Madanam ridge respectively.Nnon-channelized sandy debris flow dominated mass transport gravity driven processes viz., debris flow, slumps have been interpreted as the principal depositional processes for Bhuvanagiri, sandstone acting under bathymetry ranging from 150m. to 200m+. Diagenetic processes alter both Lower and Upper Bhuvanagiri Sandstones. As such there is no significant difference between Lower and Upper Bhuvanagiri Sandstone from diagenetic point of view.Studies reveal that calcite and quartz diagenesis is the most dominant processes which affect the reservoirs in early diagenetic phases.Secondary porosities generated by meteoric water flushing during the end of Turonian have been subsequently reduced by marine diagenesis.Critcal moment of hydrocarbon in Ariyalur-

Pondicherry sub basin has been worked out as 50ma. This data provides the basis for the times of the onset of generation, migration and accumulation of hydrocarbon taking place in the beginning of Eocene time which corresponds to 50ma.Prior to hydrocarbon expulsion, most of the porosities were already reduced due to quartz overgrowth, chlorite filling and calcite cementation Diagenetic map brings out the quality reservoirs which are mainly near to basinal flank and slope of the ridges.Based on the present study, prospective areas from hydrocarbon point of view have been delineated.

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Views expressed in this paper are that of the author(s) only and may not necessarily be of ONGC.

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Annexure-I
Stable isotope studies

Stable isotope analysis was carried out for thirteen selected samples of Lower Cretaceous Sandstone of wells of Bhuvanagiri and adjacent structures. The isotopic values for both **d**18O and **d**13C were computed. The samples were identified to be carbonate bearing based on both petrographic and XRD studies. The value for delta carbon has an average value of –5.25 and fluctuates between –12.9 to –2.2 with a standard deviation of 2.97. The value for delta oxygen has an average value of –12.58 and fluctuates between –16.3 to –9.8 with a standard deviation of 2.2. The depleted value with respect to PDB (Peedee Belemnite) for oxygen indicates a strong meteoric influence.