Evaluation of Petroleum Systems of Ariyalur-Pondicherry sub-basin (Bhuvangiri area) of Cauvery basin, India: A two dimensional (2-D) basin modeling study.

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ABSTRACT

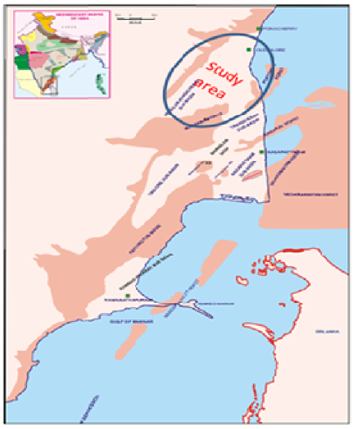
The Ariyalur-Pondicherry is one of the producing sub-basins of Cauvery basin mainly producing from Bhuvanagiri field having a moderate reserve base. About 6km of sedimentary thickness ranging in age from the Late Jurassic to Recent lies in the basin. The present study attempts to bring out a systematic evaluation of both active and speculative petroleum systems model for the basin using 1-D & 2-D modeling petromod software of M/S IES/Schlumberger. Geological and geochemical data of few drilled wells lying in the deeper as well as in the flank areas of the sub-basin are used in the present modeling. The identified principal petroleum system is the Andimadam-Bhuvanagiri wherein the Late Jurassic-Barremian shales are the main source and Turonian sands are the main reservoir. This petroleum system has attained the transformation ratio about ~85 % during Oligocene period. Besides, Cenomanian-Turonian and Paleocene (!) petroleum system also contributed towards hydrocarbon generation and accumulation having the transformation ratio of more than 50% for the Cenomanian shale during Recent time. The estimated reserve along the modeled profiles suggests that the basin has upside potential of reserve base. The study also identifies future prospective areas of exploration.

INTRODUCTION

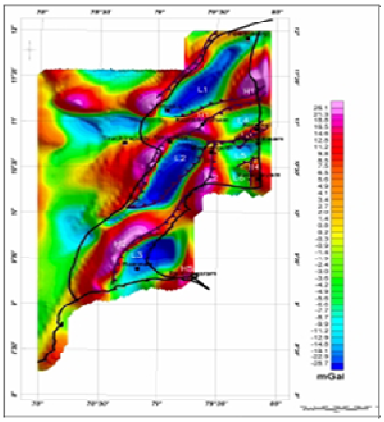
The Ariyalur-Pondicherry sub-basin is one of the major depressions of Cauvery basin. Cauvery basin extends along east coast of Indian peninsula bounded by $8^0$30’N & $12^0$30’N latitude and $78^0$30’E & $80^0$20’ E longitude. The first deep well for exploration was drilled in 1964. Cauvery Basin covers 1.5 lac Sq.km comprising 25000 Sq.km on land, 30000 sq.km shallow off shore. In addition there is about 95000sq.km of deep water offshore areas.

The Basin is a pericratonic rift basin (Shastri et al 1981, Biswas et al 1993), which came in to existence due to Gondwanaland fragmentation during drifting of India-Srilanka landmass system in Late Jurassic/Early Cretaceous. The basin exhibits a highly differentiated nature in to a number of parallel horsts & grabens trending in a general NE-SW direction, typical of rifting. The initial rifting caused the formation of NE_SW horst-graben feature, subsequent drifting and rotation caused the development of NE-SW cross faults. The Basin contains the following major tectonic elements.

The Ariyalur- Pondicherry (A-P) Sub basin, Tranqueber Sub basin, Nagapattinam Sub basin,Tanjore Sub basin, Ramnad-Palk bay Sub basin and Gulf of Mannar sub-basin. The basement high trends that separate these Cretaceous sub basins are: Kumbakonam-Madanam-Portonovo high, Pattukottai- Mannargudi-Vedaranyam-Karaikal high and Mandapam-Delft high.



Map showing the study area: Ariyalur-Pondicherry sub-basin



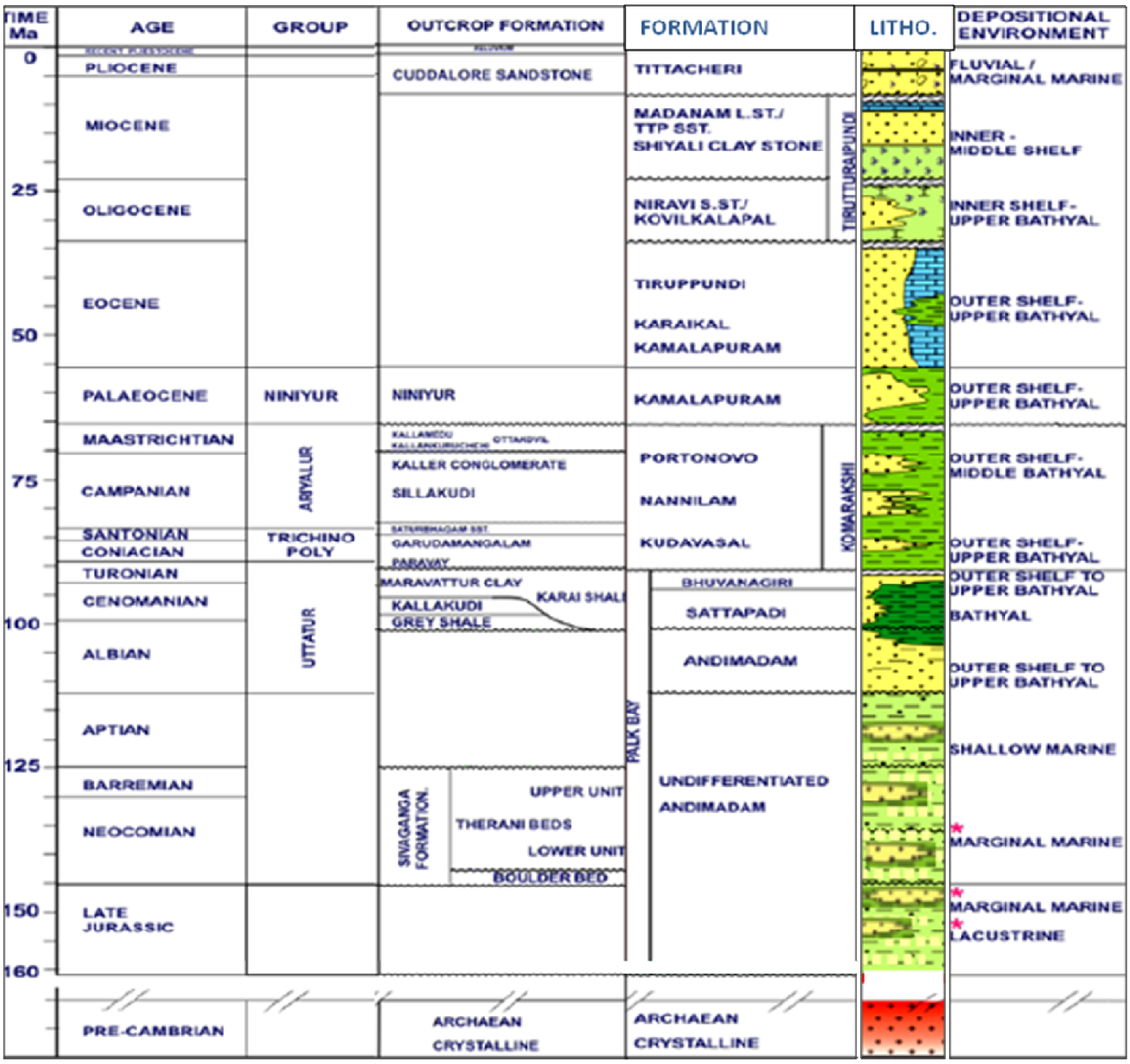
Bouguer Gravity anomaly Map showing: Ariyalur-Pondicherry sub-basin (Ram Babu et a .NGRI 2004)

This attempt presents the results of three one dimension (1D) and two regional (2D) basin modeling study of Ariyallur-Pondicherry sub basin. The main objective is to know the possible unexplored area of the basin by understanding the effect of burial history on timing of hydrocarbon generation and to identify main possible petroleum system, as the sub-basin is having number of source potential layers. The structural evolution/subsidence of the sub basin results significant control on hydrocarbon generation and distribution. The exploration in this sub basin has been less intensive and better understanding of hydrocarbon generation and charge in the basin will help to explore the remaining potential.

GEOLOGY OF THE ARIYALUR-PONDICHERRY SUB-BASIN

The Ariyalur-Pondicherry sub-basin is the northern most basement graben of Cauvery Basin and is separated from the southern Tranquebar sub-basin by the Kumbokanam – Madanam ridge. Virdhachalam low lies along the north western margin while the Chidambaram low grazes along the eastern flank of this sub-basin.

The two lows are separated by Andimadam –Neyveli ridge trending NESW and is running parallel to Virdhachalam low. The Bhuvanagiri field lies in central part of the sub-basin as a nosal feature. A series of longitudinal gravity step faults trending NE-SW are the main extensional faults associated with the syn-rift phase of basin formation and another orthogonal fault system trending NW-SE dissecting the older NE-SW trending faults have played a key role in hydrocarbon accumulation and migration. The Sands within Bhuvanagiri Formation are deposited as basin floor fans, which is hydrocarbon bearing. Andimadm Formation deposited from Jurassic to Albian period as Syn rift sequence and Sattapadi and other overlying Formations are defined as post rift sediments. Generalised litho-stratigraphy with depositional environment of the basin is as given below:



General Stratigraphy & Lithology of Cauvery Basin

MODEL BUILDING

Modeling in the sub-basin was carried out using three drilled wells. One well (CW) in the center of the sub-basin and two wells (FW & FW1) on the flank for 1D modeling. These models were calibrated & simulated for building of two 2D modeling along two regional seismic transects one across the sub-basin in NW-SE direction and another one is in NE-SW perpendicular to the earlier section passing through the common well (center of the graben) on which 1D model also generated.

MAP SHOWING THE 1-D WELL SECTIONS & 2-D TRANSECTS

INPUT PARAMETERS

Input data includes stratigraphy, age, depositional history and lithofacies characteristics. These data were obtained from the well completion reports of the wells along which three 1D models generated. The source rock parameters (TOC&VRo) and bottom hole temperatures are obtained from the lab reports and well logs. 2D modeling of the sub-basin were carried out using output of 1D well models, mainly of the central well (CW,center of the graben) as both the sections are passing through this well.

Input | Boundary Assignment | Output

	2 Name	3 Top [meter]	4 Base [meter]	5 Present Thickness [meter]	6 Eroded Thickness [meter]	7 Deposition Age from [Ma]	8 Deposition Age to [Ma]	9 Erosion Age from [Ma]	10 Erosion Age to [Ma]	13 Lithology	14 TOC [wt%]	Kinetics	15 HI [mg HC/g TOC]
1	Sediment Surface			0.00									
2	Recent	0.00	200.00	200.00		5.32	0.00			Sandstone (clay rich)	0.00	none	0.00
3	Middle Miocene	200.00	200.00	0.00	200.00	23.80	5.32	11.60	5.32	none	0.00	none	0.00
4	Oligocene	200.00	300.00	100.00		33.70	23.80			80Sst20Sh_1	0.00	none	0.00
5	Eocene	300.00	800.00	500.00		50.00	33.70			60Lst20Sh20Slt_1	0.00	none	0.00
6	Paleocene	800.00	1950.00	1150.00		65.50	50.00			90Sh10Sst_1	0.00	none	0.00
7	Maastrichtian	1950.00	2600.00	650.00		83.50	65.50			85Sh15Sst_1	0.00	none	0.00
8	Santonian	2600.00	3200.00	600.00		89.00	83.50			90Sh10Sst_1	0.00	none	0.00
9	Turonian	3200.00	3600.00	400.00		93.50	89.00			80Sst20Sh_1	0.00	none	0.00
10	Cenomanian	3600.00	4000.00	400.00		99.15	93.50			Shale (black)	2.00	Pepper&Corvi(1995)_TIIH(DE)	108.00
11	Late Albian	4000.00	4300.00	300.00		125.00	99.15			60Sst40Sh_1	0.00	none	0.00
12	Barremian	4300.00	4800.00	500.00		130.00	125.00			SHALE	2.38	Pepper&Corvi(1995)_TIIH(DE)	108.00
13	Valanginian	4800.00	4900.00	100.00		145.00	130.00			SHALE	2.38	Pepper&Corvi(1995)_TIIH(DE)	108.00
14	Jurassic	4900.00	5050.00	150.00		160.00	145.00			SHALE	2.38	Pepper&Corvi(1995)_TIIH(DE)	108.00
15	Basement	5050.00	5200.00	150.00		200.00	160.00			Granite (150 Ma old)	0.00	none	0.00
16		5200.00											
17													

INPUT PARAMETER WITH TOC%, LITHOFACIES & KINETICS USED FOR MODELING

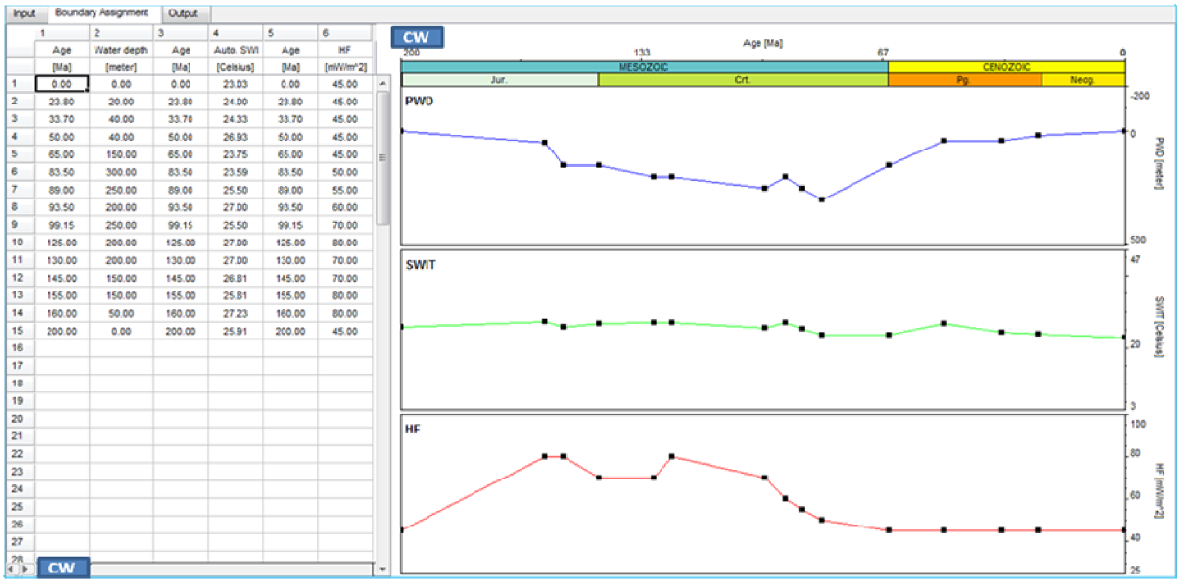
Facies Definition

	1 Name	2 Petroleum System Elements	3 Color	4 Lithology Value	5 TOC Model	6 TOC Value [%]	12 Kinetics	13 HI Value [mgHC/gTOC]	14 HI Map [mgHC/gTOC]	15 ID
1	Recent	Overburden Rock		Sandstone (clay rich)	Uniform	0.00	none	0.00	none	1
2	Middle Miocene	Overburden Rock		80Lst20Sh	Uniform	0.00	none	0.00	none	2
3	Oligocene	Overburden Rock		80Sst20Sh	Uniform	0.00	none	0.00	none	3
4	Eocene	Overburden Rock		60Lst20Sh20Slt	Uniform	0.00	none	0.00	none	4
5	Paleocene	Overburden Rock		90Sh10Sst	Uniform	0.00	none	0.00	none	5
6	Maastrichtian	Seal Rock		85Sh15Sst	Uniform	0.00	none	0.00	none	6
7	Santonian	Seal Rock		60Sh20Sst20Slt	Uniform	0.00	none	0.00	none	7
8	Turonian	Reservoir Rock		80Sst20Sh	Uniform	0.00	none	0.00	none	8
9	Cenomanian	Seal Rock		Shale (black)	Uniform	2.00	Pepper&Corvi(1995)_TIIH(DE)	108.00	none	9
10	Late Albian	Reservoir Rock		60Sst40Sh	Uniform	0.00	none	0.00	none	10
11	Barremian	Source Rock		SHALE	Uniform	2.38	Pepper&Corvi(1995)_TIIH(DE)	108.00	none	11
12	Valanginian	Source Rock		SHALE	Uniform	0.00	none	0.00	none	12
13	Jurassic_SR	Source Rock		SHALE	Uniform	2.38	Pepper&Corvi(1995)_TIIH(DE)	108.00	none	13
14	Jurassic	Source Rock		Shale (typical)	Uniform	2.38	Pepper&Corvi(1995)_TIIH(DE)	108.00	none	14
15	Basement	Underburden Rock		Granite (150 Ma old)	Uniform	0.00	none	0.00	none	15
16										

FACIES DEFINITION WITH PETROLEUM SYSTEM ELEMENTS AND KINETICS USED IN THE MODEL

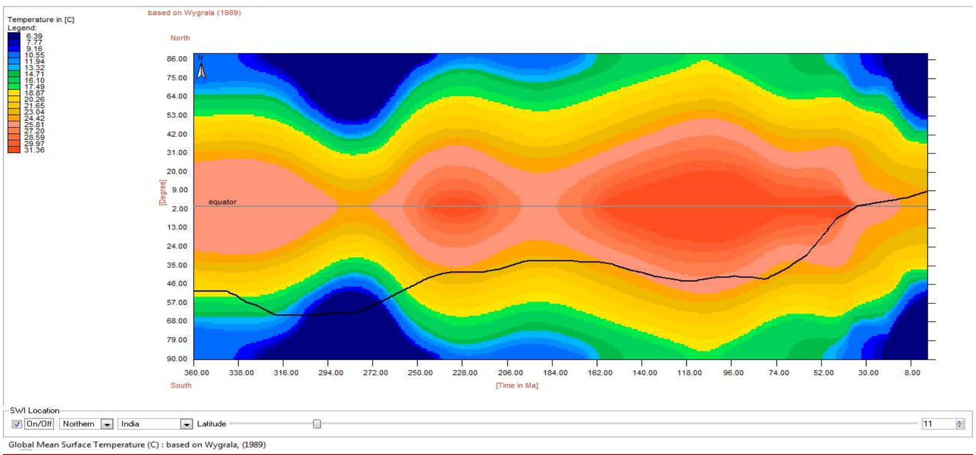
BOUNDARY CONDITIONS:

A. Paleowater depth (PWD): Paleobathymetry data are used in the reconstruction of the subsidence that occurred within the Ariyalur-Pondicherry sub basin. Paleobathymetry values used in the modeling were obtained from the available published lab reports and published literature.



PALEOWATER DEPTH, SWIT AND HF VALU WITH CURVE DURING DIFFERENT AGES

B. Sediment water interface temperature (SWIT): Surface temperature evolution was modeled in accordance with Global mean surface temperature as defined by Wyagrala (1989). Average surface temperature of 27^{0}C is observed during Late Jurrasic, which is onset of rift, which is decreased to 23^{0}C during Paleocene to Miocene period.



COMPUTED SWIT CURVE FOR THE SUB-BASIN

(GLOBAL MEAN SURFACE TEMPRATURE,WYGRALA(1989))

C. **Heat flow Value (HF):_** The heat flow model was developed on the basis of present day geothermal gradient, which was calculated using down hole temperature as obtained from the wells & on the basis of the knowledge of the tectonic history of the sub-basin, which was calibrated with the maturity data & corrected bottom hole temperature from wells.

Transient thermal effects related to rifting have not been incorporated in to the model because they are minute and likely to be overprinted by effect of crustal heterogeneity (Stein and Stein,1992) . In spite of this in our model heat flow value of 45mW/m2 assumed for pre-rift condition. Heat flow value of 80 mW/m2 assumed during onset of rifting, while heat flow value of 80 to 60mW/m2 during syn-rift sedimentation . 60 to 40mW/m2 value of heat flow for the post- rift sequences is considered, which is in agreement with the typical heat flow value of post-rift margins between 40 and 60 mW/m2 (allen and allen,1990) .

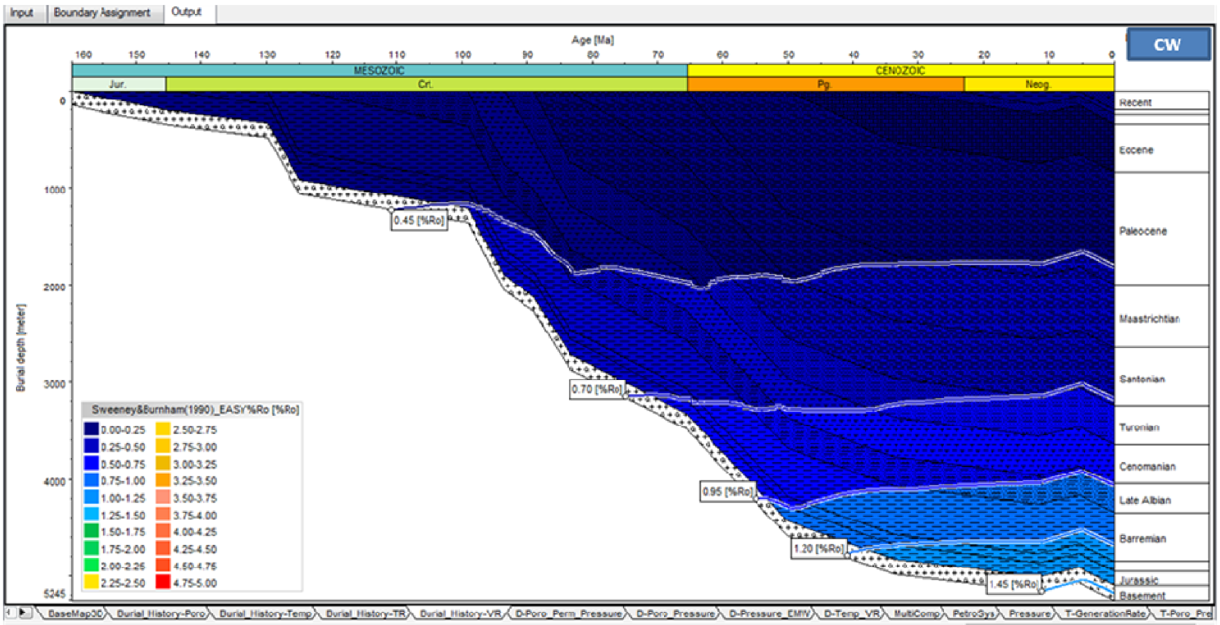
D. **Source rock parameter**: Obtained from an analysis of available well data/lab reports. The range of source rock parameters used in the 1-D and 2-D modeling are summarized in table of input parameter. The kerogen type and TOC content across the area were taken from available well completion reports and unpublished lab reports.

CALIBRATION & RESULTS:

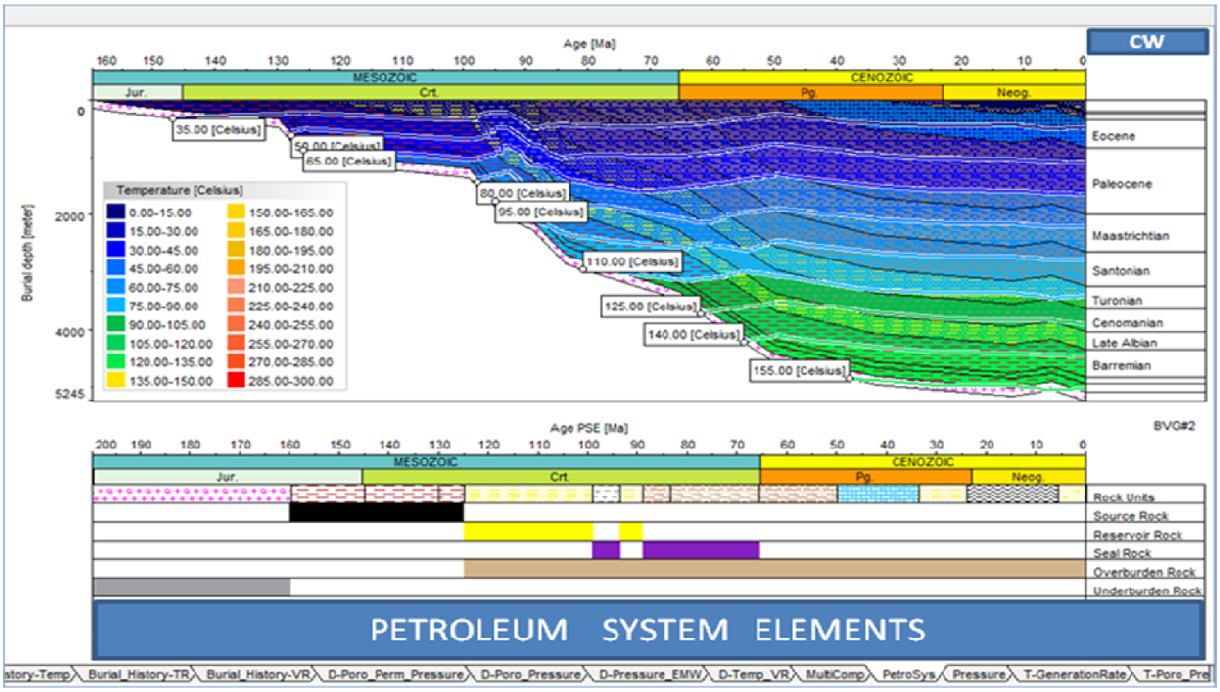
Three (1-D) Burial history models were generated ,one along a well at the central part of the graben to understand the history of syn-rift sequences and two along the wells on the SE flank of the sub-basin ,which is covered mainly by post- rift sequences. Back striping and sediments unfolding procedure analyzed on the generated **2-D** models along two seismic transects across the sub-basin, enabled us for better understanding of the burial history and other elements of petroleum system. Maximum burial observed over the central part of the basin due to deposition of thick sediments of pre Albian age followed by rapid subsidence during Late Cretaceous. The possible cause for this could be the upliftment of western Indian peninsula during Early Eocene or the Neogene upliftment and resultant erosion of Middle Miocene sediments .

Paleo-structure analysis suggests the differentiation of syn -rift and post -rift sequences of thick sedimentary fill, which was punctuated by several tectono-eustatic events and is highly varied and ranges from 200m to 6 km in thickness . Onset of rifting observed around 160Ma and continued till the 101.5Ma (end of rifting). this is in agreement with the assumption that the time of initiation of rift between India & Srilanka is also around 132.5Ma ,which is close to value assumed by others (130Ma by Katz 1978 and 126Ma by Lawver et al 1985,1992). During this period (Jurassic to Early Cretaceous) slope of the basin was towards NNW and thick syn-rift sediments deposited. A major unconformity separates the upper cretaceous sequence from the Paleocene after which there was a south-eastward tilt of the basin observed. This tilting is probably related to the uplifting of western peninsular India during the passage of India over the reunion hotspots concomitant with the magmatic out pouring of the Deccan basalt (shastri et al). This changed the basinal slope from NNW to SSE direction during late Paleocene/Early Eocene. Due to this the western marginal part acted as provenance, which is responsible for the thick pile of post- rift sediments or for the rapid subsidence of the basin over the period (Late Cretaceous to Recent). This changed the diagenetic conditions & compactions leading to the change in the petrophysical properties and finally affected the maturity of the syn-rift sediments.

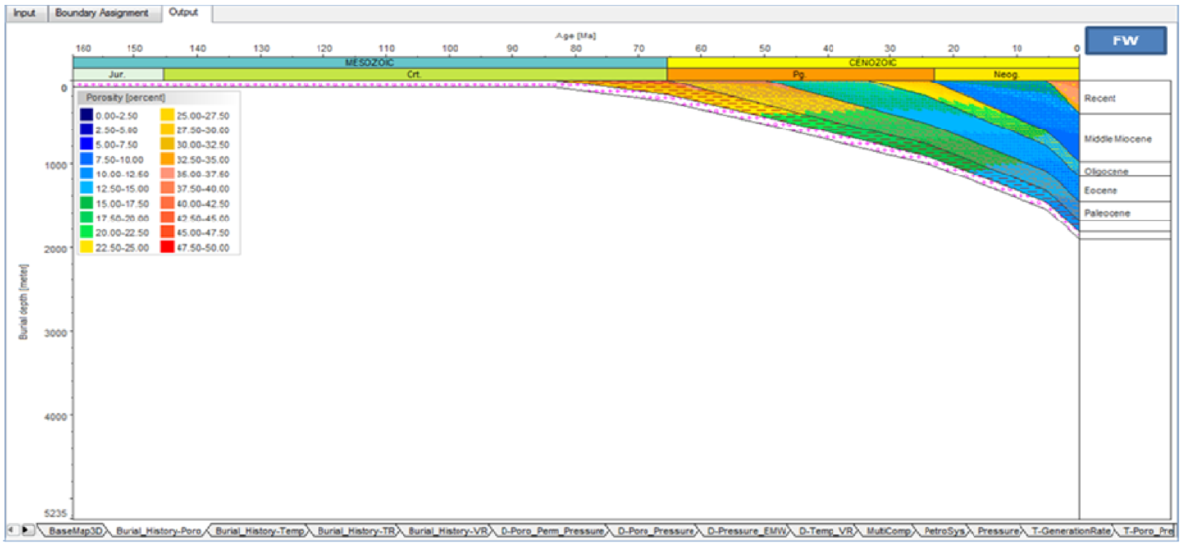
Vetrinite reflectance (VRo): The vitrinite reflectance data is a vital input for present day maturity & thermal history calibration s in 1-D & 2-D petroleum modeling. Vitrinite reflectance results of the model after Sweeney and Burnham (1990) are in accordance with the measured value. A value of 0.45% VRo is observed during Middle Paleocene to Santonian period. There is a moderate increase in VRo value up to 0.70% till Late Albian. Thereafter an increasing trend is observed from Albian top to Middle of Barremian, where it reaches to 0.90%. A sharp increase in VRo up to 1.20% in the shales of Lower Barremian (from 4100m) to Jurassic period is observed. Maturity as indicated by vitrinite reflectance is highest in the sediments of Barremian to Jurassic age. VRo is mostly affected by upliftment followed by erosion. Erosional events are also expressed by marked decrease in VRo value in well section and bend in 1-D model curve. This is the most prominent for the middle Miocene period.



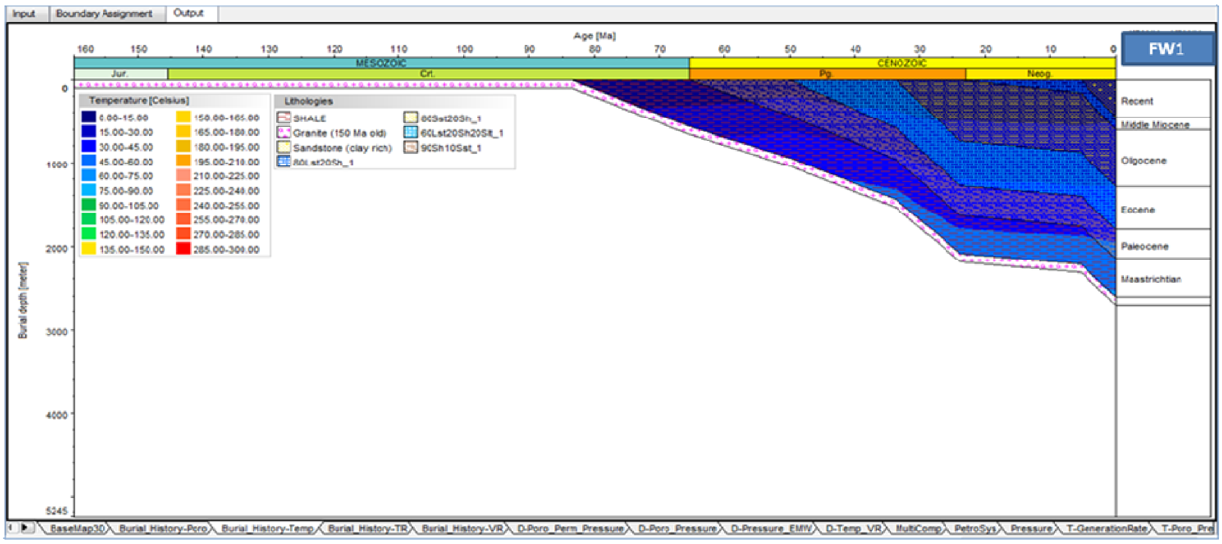
ISO-VRO LINES SHOWN ON BURIAL HISTORY CURVE OF WELL CW



ISO-TEMPRATURE LINES AND PETROLEUM SYSTEM ELEMENTS: BURIAL HISTORY CURVE OF WELL CW

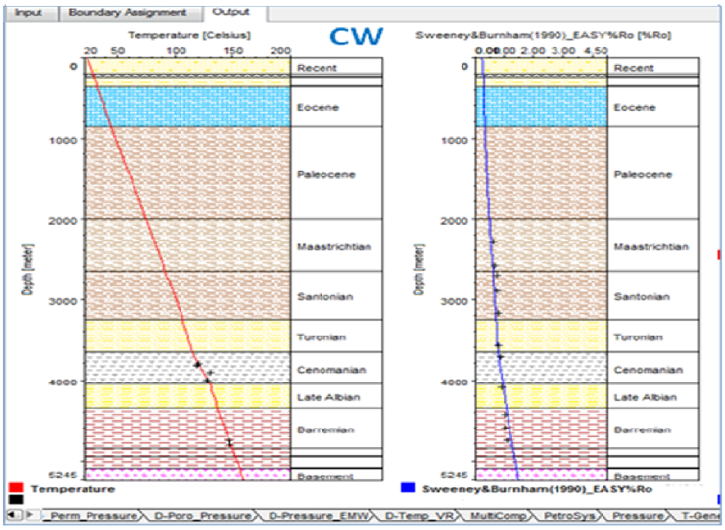


BURIAL HISTORY CURVE OF WELL FW



BURIAL HISTORY CURVE (WITH TEMPERATURE) OF WELL FW1

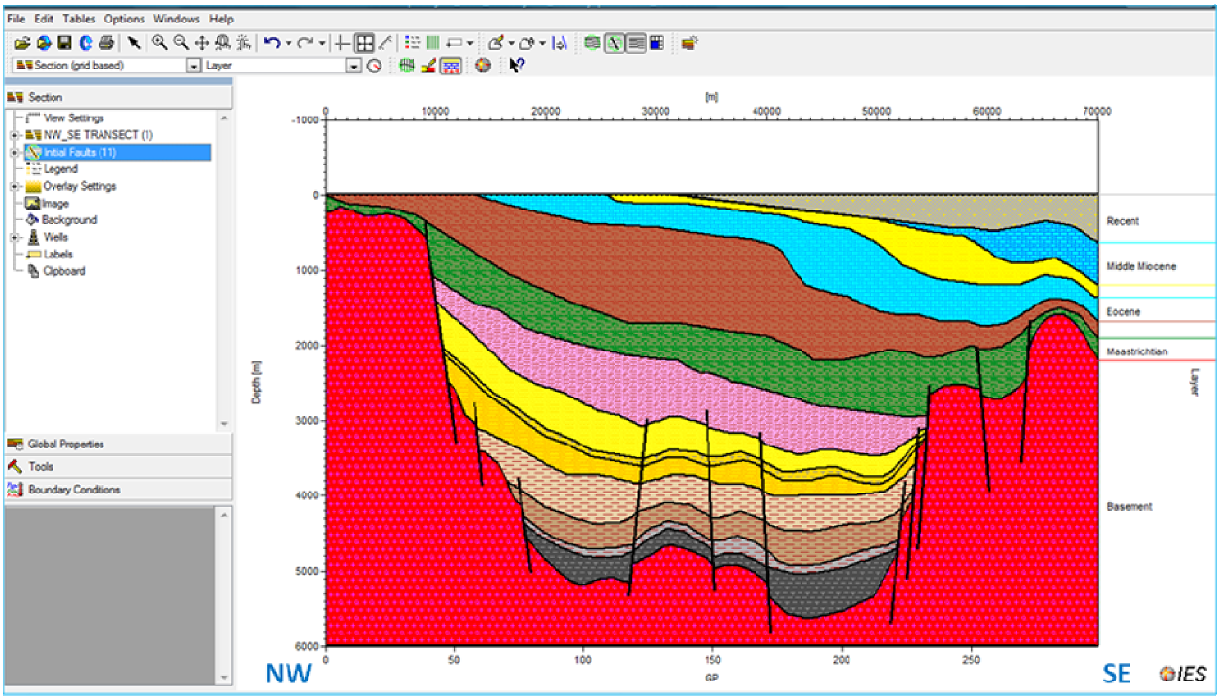
Temperature & Maturity: Model predictions of temperature at given depths are almost uniform except in the Cenomanian ,where it is deviating from temperature measured in the well. The average temperature gradient is 3.2^0C/100m and it is constant up to 4000m or up to Late Albian top. After this there is an increase in the gradient & temperature reaches to 155^0C in the sediments of Jurassic age . Syn-rift sediments i.e sediments of Jurassic to Late Albian age showing the temperature range from 155^0C to 120^0C . This may be due to higher heat flow value as compared to post- rift sediments, which are having low value of heat flow. This high value of vitrinite reflectance and temperature increased the hydrocarbon generation potential of the sediments below the Late Albian Formation. It suggests the oil window is below ~3000m of depth.



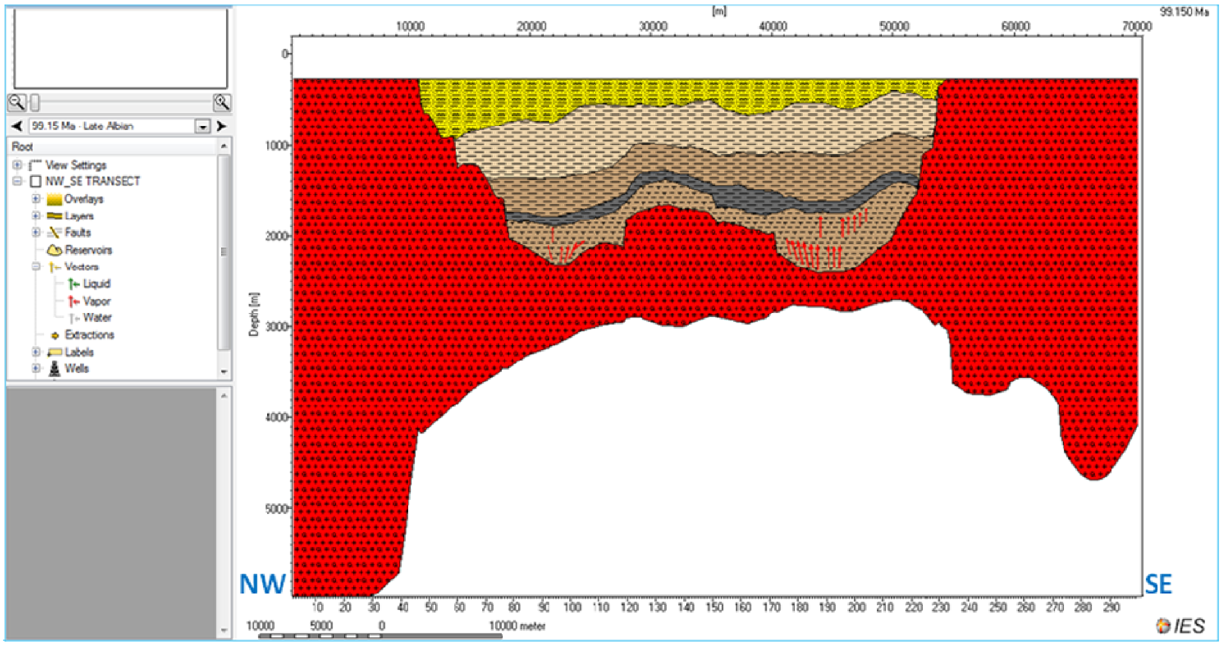
VRO % AND TEMPERATURE CALIBRATION (WELL CW)

Transformation Ratio: Transformation ratio were calculated using published type –III kinetics of Pepper and Corvi (1995)_TIIIH (DE), although the presence of type –II (~10%) is also evident by lab reports but for the modeling kinetics for type-III is applied as the kerogen of type –III is dominant (~90%). Results indicate that transformation observed in the layers of Jurassic, Barremian and Cenomanian age. The first transformation occur in syn- rift sediments of Jurassic age during Cenomanian (~90 Ma) period and maximum transformation occur during Oligocene period. Transformation ratio significantly decreases in the sediments of Cenomanian age. The Maturity is indicated to be higher in the south eastern part of the model to that of north-western part, this affects the potential of the Barremain and underlying Jurassic sediments as in this part they have been buried deep enough and indicated the first transformation.

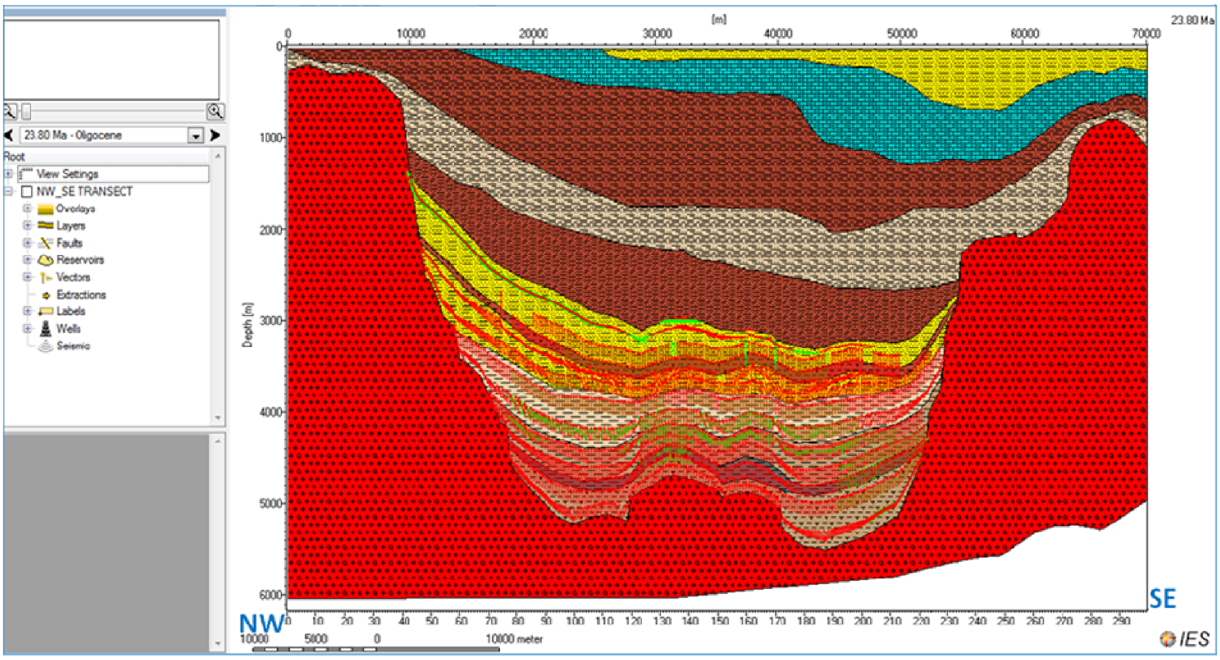
Analysis of transformation with time indicates that most of the organic material is already transformed till late Eocene /Early Oligocene time. Maximum transformation is 80-85 % as indicated by model in the shales of Jurassic age and 20-15% is still available for the transformation. In the Barremian and Cenomanian layers the transformation ratio is 40 -60%. The critical moment as indicated by the model is Cenomanian (~65.5Ma). The simulated models indicated that total reserve along the modeled profiles is in a order to approx. ~15 MMTOE and ~11MMm3 of gas. This suggests that the basin has upside potential of reserve base. The study also identifies future prospective areas of exploration.



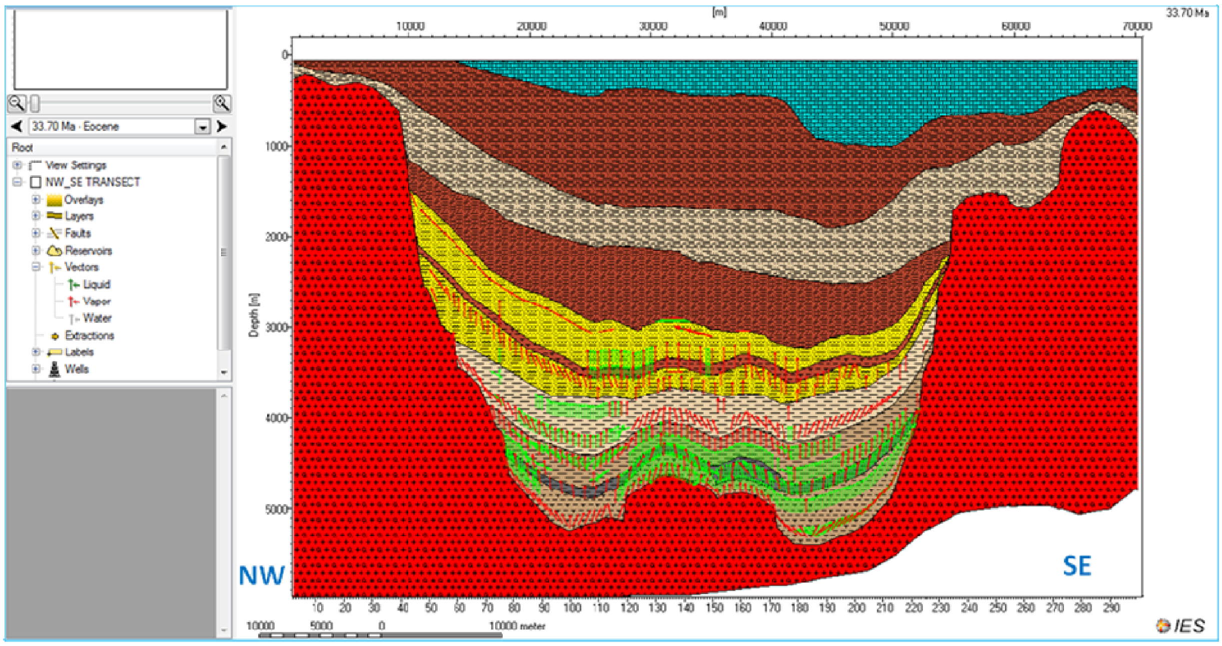
DEGITISED HORIZONS & FAULTS ALONG NW-SE SECTION WITH DEFINED LITHOFACIES



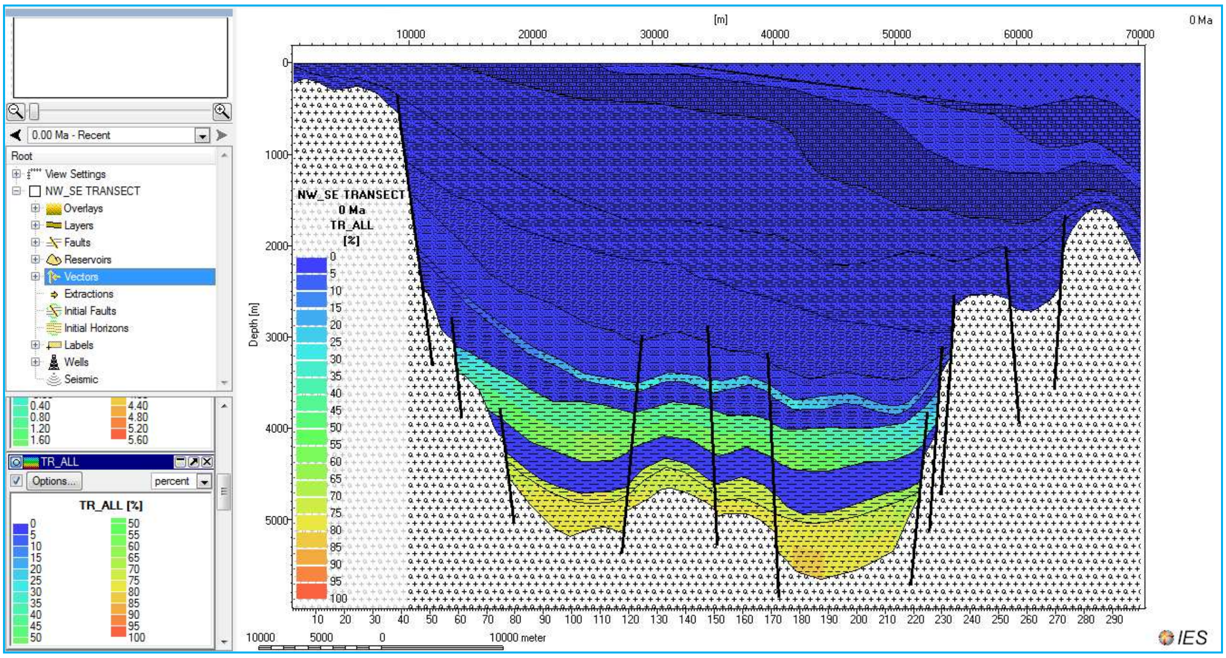
FIRST TRANSFORMATION TO HYDROCARBON: NW-SE TRANSECT WITH BASIN SLOPE IN NW DIRECTION



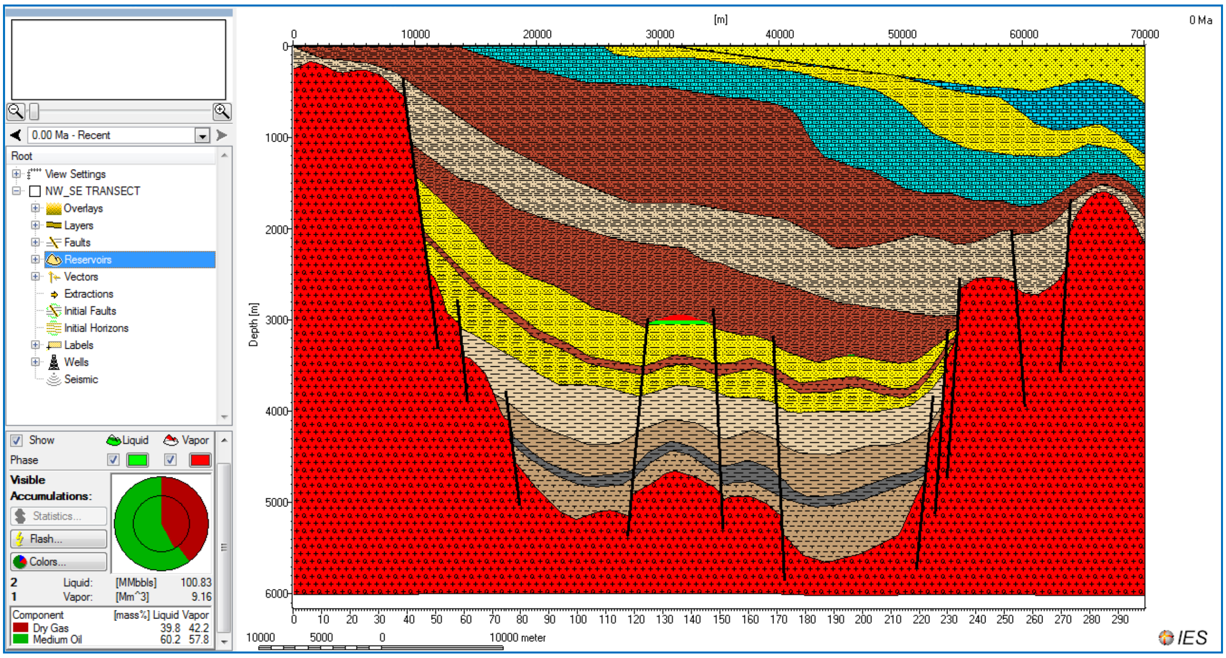
MAXIMUM TRANSFORMATION TO HYDROCARBON OBSERVED DURING LATE EOCENE OR EARLY OLIGOCENE



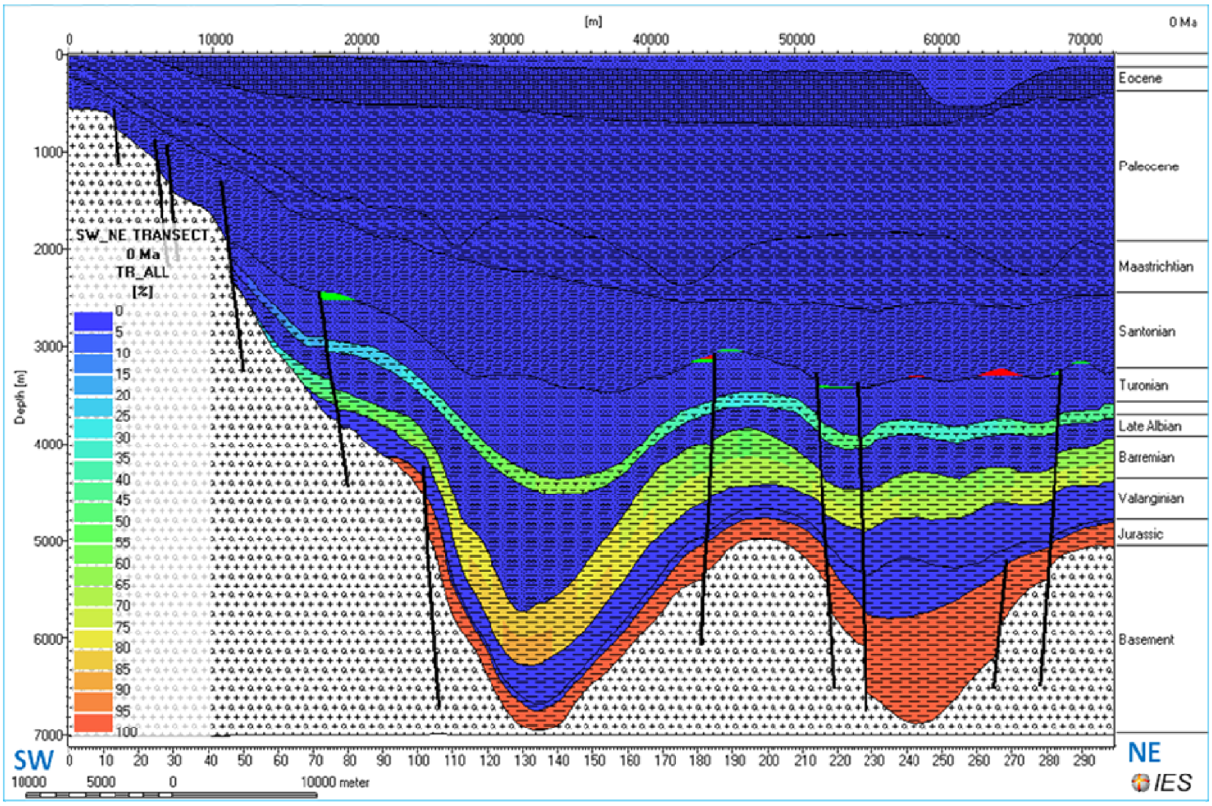
SLOPE OF BASIN CHANGED FROM NW TO SE DIRECTION DUE TO TILTING: OBSERVED IN EOCENE



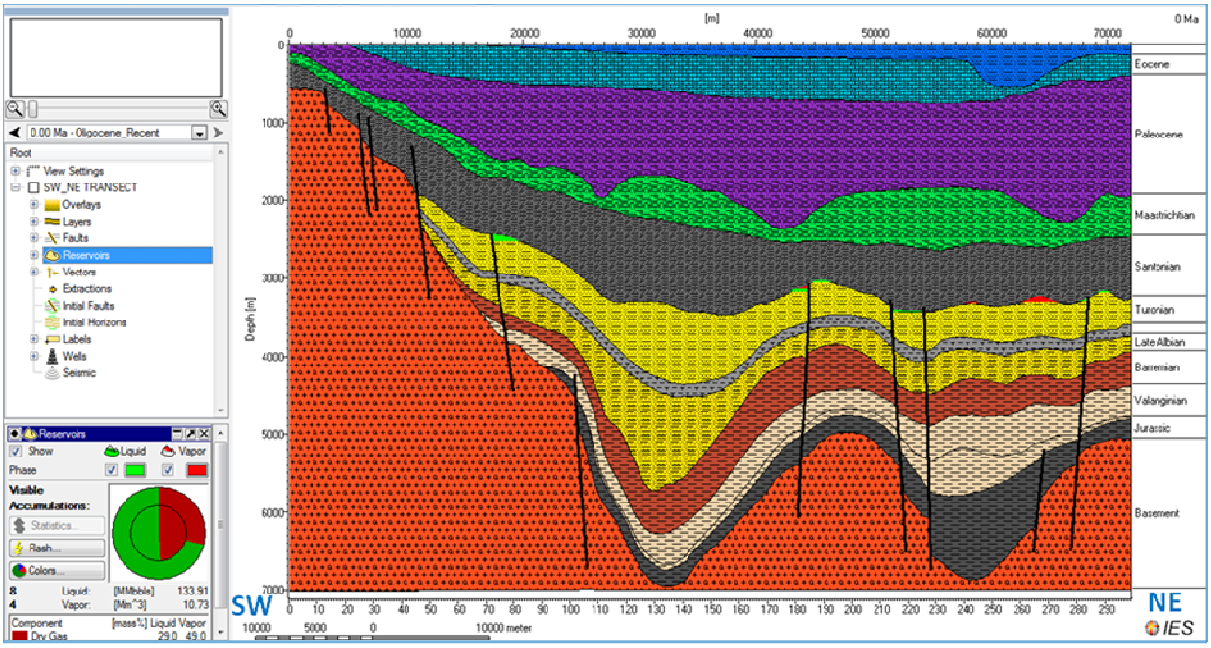
TRANSFORMATION RATIO (%) IN DIFFERENT LAYERS: AS ON TODAY IN NW-SE SECTION



HYDROCARBON ACCUMULATIONS: NW-SE PROFILE



HYDROCARBON TRANSFORMATION (%) IN DIFFERENT SOURCE LAYERS ALONG SW-NE TRANSECT



DISTRIBUTION OF HYDROCARBON ACCUMULATIONS ALONG SW-NE SECTION

PETROLEUM SYSTEM, HYDROCARBON GENERATION, MIGRATION AND ENTRAPMENT IN THE ARIYALUR-PONDICHERRY SUB-BASIN

Numerous source rock potential layers within Andimadam and Sattapadi Formations of Late Jurrasic-Albian to Cenomanian age respectively are present in Ariyalur-Pondichery sub-basin.. Samanta et al (1998) and Sinha et al(1998) made a relative evaluation of both the formations and concluded that Andimadam has better source rock charactrestics . Based on the source rock analysis and correlation studies (Chandra et al.,1993, Pande et al. 1995, Janardhanan et al 2002,Banajee et al 2003)

-the Andimadam-Bhuvangiri **(.)** petroleum system is envisaged in the Ariyalur-Pondicherry sub-basin. (Note (.) indicates speculative nature of petroleum system)

In the study shales of Late Jurassic, Barremian (Andimadam Formation) and Cenomanian (Sattapadi Formation) are considered as source potential with the average TOC value 2.38 % (as per the lab report),HI value 108mgHC/g (as per the lab report) . Although the these formations contain mainly type –III with low % of type –II organic matter, the Kinetics as defined by Pepper & Corvi(1995)_TIIIH(DE) for type –III is used for the modeling.

The sediments of Late Albian and Turonian age (Bhuvangiri S.St) are considered as reservoir rocks and the layers of Cennomanian Santonian, and Mastrichtian age are considered as seals.

Both (2-D) simulated models were tested by comparing the results with the distribution of known hydrocarbon accumulations (HC bearing wells) in the Ariyalur-pondicherry sub-basin. The main accumulation is observed within the layer of Turonian /U.Cretaceus age (Bhuvan giri sand stone), confined in the top part of the layer. In the wells, accumulations found in the middle or bottom middle of the same layer (Turonian age). It is because splitting of the reservoir layer (Turonian age) is not attempted during modeling due to change in lithofacies ,which is observed in the layer as per the drilled wells.

Number of source potential layers shown in the previous works but as per the outcome of the study layers of Jurassic, Late Jurassic and Barremain age are observed as main source for hydrocarbon generation in the sub-basin.. The Bhuvangiri sand stone (Turonian/Up.Cretaceous age) is observed as the main reservoir rock. This is in accordance with the actual well data. This also certains that Petroleum system in the basin is -The **Andimadam-Bhuvangiri (!)** petroleum system is existing in the Ariyalur-Pondicherry sub-basin. (Note (!) indicates certainty nature of the petroleum system. Besides, Cenomanian-Turonian and Paleocene (!) petroleum system also contributed towards hydrocarbon generation and accumulation having the transformation ratio of more than 50% for the Cenomanian shale during Recent time.

SUMMARY

Structural evolution & subsidence played a major role for the generation, migration and accumulation of hydrocarbon which is mainly of medium oil and dry gas in the sub basin. Observed vitrinite reflectance value increases at equivalent depth moving southeastward across the NW-SE section, indicating that this part of the subbasin has higher overall source rock maturity. The critical moment is observed around 65.5Ma with oil window below ~3000m of depth and maximum transformation ratio observed during Late Eocene/ Early Oligocene period. This model suggests a petroleum system- Andimadam-Bhuvangiri with certainty with late Jurassic-Barremian as major source rock and Turonian as main reservoir. Besides, Cenomanian-Turonian and Paleocene (!) petroleum system also contributed towards hydrocarbon generation and accumulation having the transformation ratio of more than 50% for the Cenomanian shale during Recent time. The simulated models indicated that total reserve along the modeled profiles is in a order to approx. ~15 MMTOE and ~11MMm3 of gas. This suggests that the basin has upside potential of reserve base. The study also identifies future prospective areas of exploration. Two dimensional models are limited to simulating migration along a single line of section, however, migration is a three dimensional process which is influenced by the petrophysical properties of the formations hence to come to a definite conclusion better understanding of diagenetic changes along with fault seal analysis is essential.

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