

MODELING OF THE PETROLEUM SYSTEM IN THE CAUVERY BASIN, SRI LANKA

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(Received 17th July 2020; accepted 03rd March 2021)

ABSTRACT

A part of the southeastern onshore area of India and the northwestern onshore area of Sri Lanka, and the Palk Strait come under the Cauvery Basin. The Indian side of the Cauvery Basin has proven hydrocarbon reserves, while the Sri Lankan sector remains relatively under-explored. Only six exploration wells drilled in the Sri Lankan sector from 1972 to 1981 was dry. Since little further exploration has taken place from 1981 to this date, the existence of an active petroleum system in the Sri Lanka sector of the basin is not known. The objective of this study was to simulate the petroleum system in the Sri Lankan sector of the Cauvery Basin on Petromod 1D software (v.12.2) using data from unpublished reports and data in the public domain. The model was validated using the measured vitrinite reflectance data. Results of the study showed that Albian and Late Cretaceous shale in the Pesalai area have relatively higher hydrocarbon source potential and that hydrocarbon exploration in the Sri Lankan sector of the Cauvery Basin should mainly target Cretaceous and Eocene clastic and carbonate reservoirs associated with faults and anticlinal traps. Hydrocarbon potential in the Pesalai area is relatively higher than that in the Palk-Bay area.

Keywords: *Cauvery Basin, petroleum system, hydrocarbons, Pesalai, Sri Lanka*

INTRODUCTION

The Cauvery Basin encompasses the southeastern onshore area of India, the northwestern onshore area of Sri Lanka, and the offshore area between the two countries (Fig. 1). Sri Lankan sector of the Cauvery Basin (Fig. 1) extends over 15,000 km², out of which its onshore area extends up to around ~20-30 km inland from the NW coastal line. The offshore areas of the basin lie in shallow water up to the 200 m isobath.

The Cauvery Basin is a pericretonic failed rift basin (Sastri et al., 1973; 1981), which has been evolved due to multiphase rifting between Indo-Lanka landmasses (Baillie et al., 2003). The onset of rifting that gave rise to the Palk Strait (see Fig. 1) was initiated around 132 Ma (Desa et al., 2018) and ceased around 90 Ma (Chakraborty and Sarkar, 2018; Raju et al., 2018; Chaudhuri et al., 2010). Paleomagnetic measurements from the Pesalai-1 well (Fig. 1) suggest that Sri Lanka had migrated around

2400 km from 16° S during the Paleogene to 8° N at present (Cantwell et al., 1978). The intervening NW-SE trending horsts/ basement ridges, which divide the Cauvery Basin into sub-basins/ depressions (Fig. 1), have been formed during the seafloor spreading between India and Antarctica in the early Cretaceous (Lal et al., 2009).

Stratigraphy, tectonic setting, and hydrocarbon prospectivity of the Indian side of the Cauvery Basin have been addressed in detail by Sastri et al. (1973; 1981); Chandra et al. (1991); Ramana et al. (1995); Murthy et al. (2008); Rana et al. (2008); Lal et al. (2009); Rao, et al. (2010); Chaudhuri et al. (2010); Chakraborty et al. (2018); Bastia and Radhakrishna, (2012), etc. Those facts on the Sri Lankan counterpart have been addressed by Cantwell et al., (1978); Premarathne, (2008, 2015, 2017, 2020); Bandara et al., 2020). Most of this information comes from gravity, magnetic and seismic data, and well reports gathered as a result of hydrocarbon exploration in the basin.

Six explorations wells were drilled in the Sri Lanka side of the basin during the 1972 -1981 period (see Fig. 1 for well locations). Though some gas shows were recorded in the Pesalai wells, none of them penetrated an economically feasible hydrocarbon deposit.

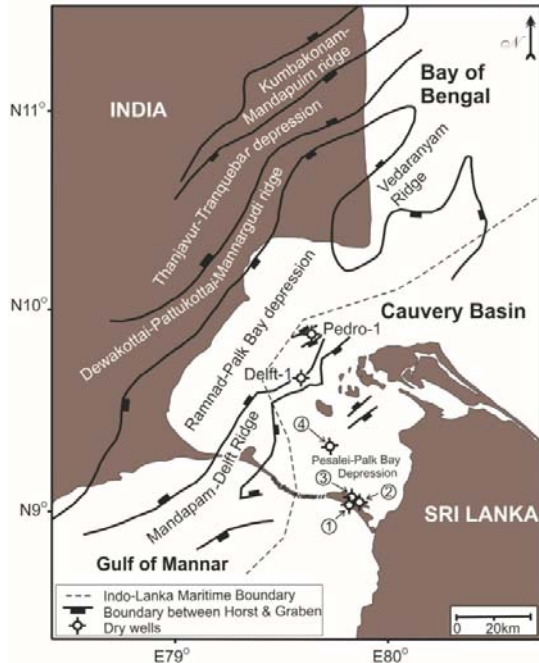


Fig.1. Sri Lankan side of the Cauvery Basin and hydrocarbon exploration wells drilled in it (modified after Premarathne et al., 2015) Encircled 1, 2, 3, and 4 in denotes Pesalai-1, 2, and 3 wells, and Palk Bay-1 well, respectively.

Little further exploration has taken place in the Sri Lanka side of the basin since 1981. However, the Indian sector of the basin, which began hydrocarbon exploration almost the same time as the Sri Lankan sector, is now producing both oil and natural gas (Chandra et al., 1991). The Ramnad-Palk-Bay-Nagapattinam depression mainly under the Indian Jurisdiction (Fig. 1) is the most prolific petroliferous sub-basins (Murthy et al., 2008). Relatively a small part of this sub-basin comes under the Sri Lankan jurisdiction (see Fig. 1). PH-9-1 well, which has discovered oil, is located at the Indian side of the Ramnad-Palk Bay-Nagapattinam depression, just 21 km northwest of the Indo-Lanka maritime boundary (Ramana et al., 1995). It is the hydrocarbon discovery in the Indian side of Cauvery Basin located closest to Sri Lanka.

Resuming hydrocarbon exploration in the Sri Lankan side of the Cauvery Basin has been under consideration since the discovery of two

natural gas deposits in the Mannar Basin, which is located south of the Cauvery Basin. These discoveries in 2011 confirmed the occurrence of an active petroleum system in the Mannar Basin (Mohapatra et al., 2012; Premarathne et al., 2013). Both Cauvery and Mannar Basins share similar tectonic histories (Premarathne et al., 2016; Ratheesh-Kumara et al., 2020). Many researchers (e.g. Chandra et al., 1991; Chari et al., 1995; Baillie et al., 2003; Premarathne, 2008; Rana et al., 2008; Rao et al., 2010) consider the Mannar basin to be the southern extension of the Cauvery Basin. The petroleum geology of the Sri Lankan sector of the basin has been addressed by Cantwell et al. (1978) and Premarathne (2015, 2020). However, as to whether the Sri Lankan sector of the Cauvery Basin has an active petroleum system of its own or whether the petroleum system in the Indian side extends towards the Sri Lankan side still remains unknown due to the lack of well penetration and scarcity of data. The objective of this study was to simulate the hydrocarbon generation, expulsion, and the timing of hydrocarbon expulsion, and thereby to understand the possible petroleum system that may occur in the Sri Lankan sector of the Cauvery Basin.

METHODOLOGY

PetroMod 1D software (v. 12.2) was used to simulate the rate and the timing of hydrocarbon generation and the amount of hydrocarbon expulsion from potential source rocks penetrated by the Pesalai-1, Palk-Bay-1, Delft-1, and Pedro-1 wells. The four wells are located along a line that runs north-south direction over the Sri Lankan sector of the Cauvery Basin (see Fig. 1). Though the Pesalai-3 has been the deepest well (~2850 m) drilled at the basin in Sri Lanka, it and the Pesalai-2 well were excluded from this study due to the lack of availability of data, such as lithology, TOC, vitrinite reflectance, maceral composition, etc. Premarathne (2020) has modeled the burial, thermal and heat flow history of the study area on PetroMod 1D software using data from the Pesalai-1, Palk-Bay-1, Delft-1, and Pedro-1 wells. The same input data (lithology units and their depositional ages, degree of erosion and hiatus of unconformities) and boundary conditions (paleo water depths, the temperature at Sediment-Water Interface (SWI) and heat flows, etc.) were used for this study (Tables 1 & 2).

Table 1. Input data used in this study for Pesalai -1 and Palk Bay-1 wells (PSE = petroleum system events, Thick. = formation thickness, Depo. = deposition in Ma, Quat. = Quaternary, Plio = Pliocene, Mio. = Miocene, Turo. = Turonian, Alb. Albian, Apt, and Aptian. L., M., and E., stand for Late, Middle and, respectively). Erosion is in Ma. The unit of HI is mgHC/g TOC (data in the first 10 columns are from Premarathne, 2020).

Pesalai-1

Layer	Top	Base	Thick. (m)	Eroded (m)	Depo. from	Depo. to	Eroded from	Eroded to	lithology	PSE	TOC (%)	HI
Quaternary	0	50	50		2.6	0			Sandstone (qtz)	Overburden Rock		
Pliocene to L. Mio	50	333	283		11.6	2.6			Sandstone (qtz)	Overburden Rock		
M-E. Miocene	333	929	596		23	11.6			Marl	Overburden Rock		
Eocene	929	1287	358	176	56	33.9	33.9	23	Sandstone	Overburden Rock		
Paleocene	1287	1337	50		58	56			Shale (typical)	Seal Rock		
L.Cret._1	1337	2000	663	361	92	70	70	58	Shale (typical)	Source Rock	3	100
L.Cret._2	2000	2203	203		100	92			Sandstone (typical)	Reservoir Rock		
Albian_1	2203	2298	95	63	105	102	102	100	Sandstone (typical)	Reservoir Rock		
Albian-2	2298	2454	156		110	105			Shale (typical)	Source Rock	4.5	100
Albian 3	2454	2554	100		113	110			Conglomerate	Underburden Rock		

Palk Bay-1

Layer	Top	Base	Thick. (m)	Eroded (m)	Depo. from	Depo. to	Eroded from	Eroded to	lithology	PSE	TOC (%)	HI
Quat. to L. Mio	37	258	221		9	0			Sandstone	Overburden Rock		
M-E. Mio	258	904	646		23	9			Marl	Overburden Rock		
Oligocene	904	1415	511		33.9	23			Shale (typical)	Seal Rock		
Eocene	1415	1641	226		56	33.9			Limestone (shaly)	Reservoir Rock		
Maastrichtian	1641	1850	209	310	72	67	67	56	Shale (typical)	Source Rock	0.6	120
Campanian	1850	1931	81		75	72			Shale (typical)	Source Rock	0.4	75
Campanian	1931	2012	81		78	75			Sandstone (typical)	Underburden Rock		

Table 2. Input data used in this study for Delft -1 and Pedro-1 wells. Abbreviations in the table are the same as those in Table 1 (data in the first 10 columns are from Premarathne, 2020).

Delft-1

Layer	Top	Base	Thick. (m)	Eroded (m)	Depo. from	Depo. to	Eroded from	Eroded to	lithology	PSE	TOC (%)	HI
Quat. to Pliocene	35	295	260		5.3	0			Sandstone (typical)	Overburden Rock		
Middle Miocene	295	571	276	216	16	10	10	5.3	Limestone	Overburden Rock		
Early Miocene	571	899	328		23	16			Shale (typical)	Overburden Rock		
L. Oligocene	899	1099	200		28	23			Shale (typical)	Seal Rock		
Early Oligocene	1099	1213	114		31.8	28			Limestone (shaly)	Reservoir Rock		
Early Oligocene	1213	1276	63		33.9	31.8			Sandstone (clay rich)	Reservoir Rock		
Albian	1276	1322	46	1650	101.6	100	100	33.9	Limestone	Reservoir Rock		
Albian	1322	1392	70		104	101.6			Sandstone (typical)	Reservoir Rock		
Albian	1392	1592	200		111	104			Conglomerate	Overburden Rock		
Albian -Aptian	1592	1734	142		116	111			Shale (typical)	Source Rock	2.1	32

Pedro-1

Layer	Top	Base	Thick. (m)	Eroded (m)	Depo. from	Depo. to	Eroded from	Eroded to	lithology	PSE	TOC (%)	HI
Quat.-Pliocene	37	279	242		5.3	0			Sandstone (typical)	Overburden Rock		
Miocene	279	660	381		14.8	5.3			Limestone	Overburden Rock		
Miocene	660	713	53		16.1	14.8			Shale (typical)	Seal Rock		
Miocene	713	991	278		23	16.1			Limestone (shaly)	Reservoir Rock		
Oligocene	991	1051	60		27.26	23			Shale (typical)	Seal Rock	0.7	45
Oligocene	1051	1081	30		29.39	27.26			Limestone	Reservoir Rock		
Oligocene	1081	1144	63		33.9	29.39			Shale (typical)	Seal Rock	0.71	45
Eocene	1144	1293	149		48	33.9			Sandstone (clay rich)	Reservoir Rock		
Albian	1293	1417	124	920	108	102	102	48	Shale (typical)	Source Rock	0.85	100

Sediment compaction during the progressive burial and the change in thermal conductivity, porosity, and permeability of sediments with increasing burial were simulated using default values available in the software database.

Premarathne (2015) has reported the Total Organic Carbon (TOC), Hydrogen Index (HI), and maceral composition of sediment samples from the four wells. Based on the hydrocarbon source character and lithology data available in Premarathne (2015), potential hydrocarbon source rocks and their average TOC and HI values were determined (see tables 1 and 2). Well data reported in Premarathne (2015) show that sediments from the four wells have a mixture of types II and III kerogen. However, the kinetic model TII (BP) proposed by Behar et al. (1997) was used to simulate the hydrocarbon generation upon thermal maturation of kerogen in potential source rocks.

The Petroleum System Elements (PSE) listed in tables 1 and 2 for each well is based on lithology data reported by Premarathne (2015) and unpublished well completion reports held at Petroleum Resources Development Secretariat (PRDS). When entering the PSE into PetroMod 1D software, there was a limitation, which prevented entering the same lithology unit to act as a source rock and a seal simultaneously. A generalized petroleum system event chart for the Sri Lankan sector of the Cauvery was prepared based on lithology information in Cantwell et al. (1978); Premarathne (2015) and unpublished reports, porosity and permeability data available in Shaw (2001) and simulations of hydrocarbon generation rates in this study. Model validation was carried out using the kerogen maturation profiles presented in Cantwell et al. (1978) for the four wells. The method used to validate the model is described in detail in Premarathne (2020).

RESULTS AND DISCUSSION

Timing of Hydrocarbon Generation and Expulsion

Albian shale penetrated by the Pesalai-1 well generating oil in two phases, the first phase from the Maastrichtian to Campanian and the second phase from the Early Miocene to Recent (Fig. 2).

In the first phase, hydrocarbon is generated at a maximum rate of 0.1 mgHC/gTOC/Ma around 70 Ma, while in the second phase at 0.2 mgHC/gTOC/Ma around 10 Ma (Fig 2). In other words, the maximum rate achieved in the second phase is twice the maximum rate observed in the first phase. The generation rate in the second phase continuously diminishes from 10 Ma to Recent (Fig. 2). This may be due to the exhaustion of the genetic potential of kerogen. Late Cretaceous sediments penetrated by the Pesalai-1 well also generate hydrocarbons at a maximum rate of 0.05 mgHC/gTOC/Ma during the second phase. However, hydrocarbons expelled from these stratigraphic intervals are less than 0.0005 metric tons (see Fig. 3). The rate of hydrocarbon generation in Cretaceous sediments penetrated by the Palk Bay-1, Delft-1, and Pedro-1 wells are less than 0.01 mgHC/gTOC/Ma (Figs. 4, 5 & 6). This is mainly due to the thermal immaturity of the potential source rocks penetrated by the three wells.

Hydrocarbon Source Rocks

According to Premarathne (2015), Albian claystone penetrated by the Pesalai-1 well has the TOC ranging from 6.9 to 2.9% and HI values around 100 mg HC/g TOC; Albian sediments recovered from the Delft-1 and Pedro-1 wells have average TOC values of 2.1% and 0.85%, respectively and HI values 98 and 32 mg HC/g TOC, respectively; Maastrichtian to Campanian claystone penetrated by the Palk Bay-1 well has TOC of 0.5% and HI values of 102 mg HC/g TOC.

Based on the above-mentioned TOC and HI values, the thermal maturity data and the hydrocarbon generation rates simulated in this study, it is obvious that Albian shale, particularly in the Pesalai area in the Sri Lankan sector, has relatively a higher hydrocarbon source potential. Coincidentally, Albian shale is considered to be the main source of oil and natural gas discovered in the Ramnad-Palk Bay-Nagapattinam depression under Indian Jurisdiction (Chandra et al., 1991; Murthy et al., 2008). Pre-Albian to Cenomanian sediment in the Indian sector, have relatively TOC and HI ranging 0.53-3.05% and 33-280 mg HC/g TOC, respectively, (Chandra et al., 1991).

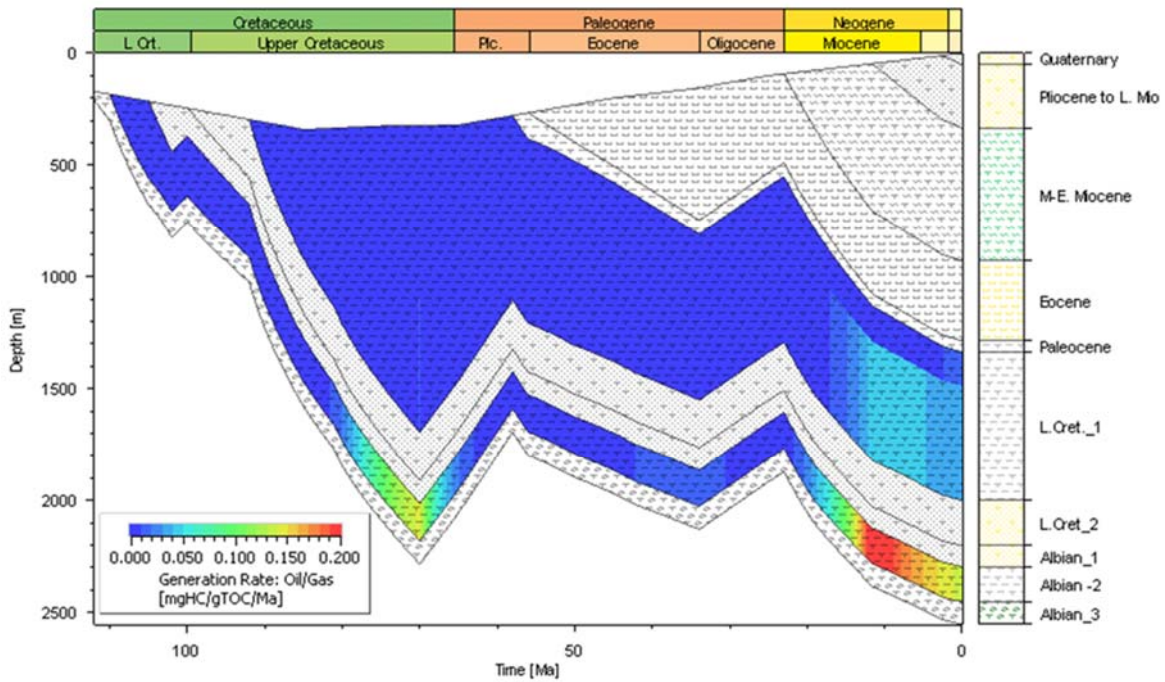


Fig. 2. Burial history plot for the Pesalai-1 well showing the rate of hydrocarbon generation in source rocks, which appear in blue.

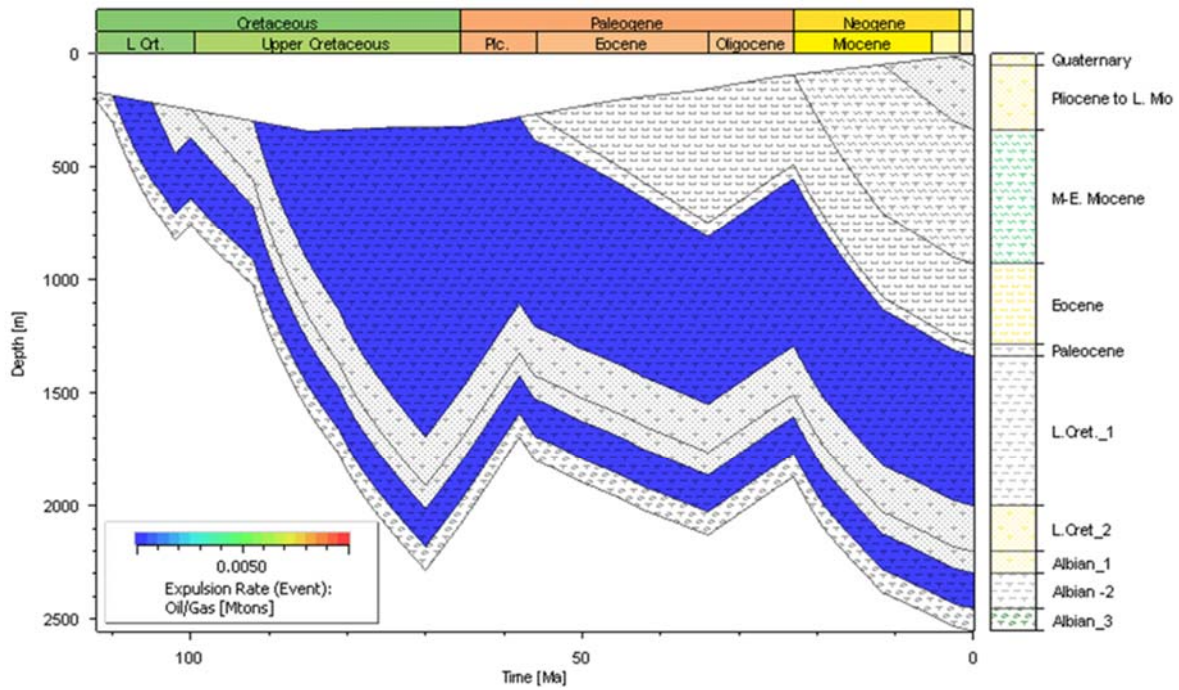


Fig. 3. Burial history plot for the Pesalai-1 well-showing amount of hydrocarbon expelled from potential source rocks.

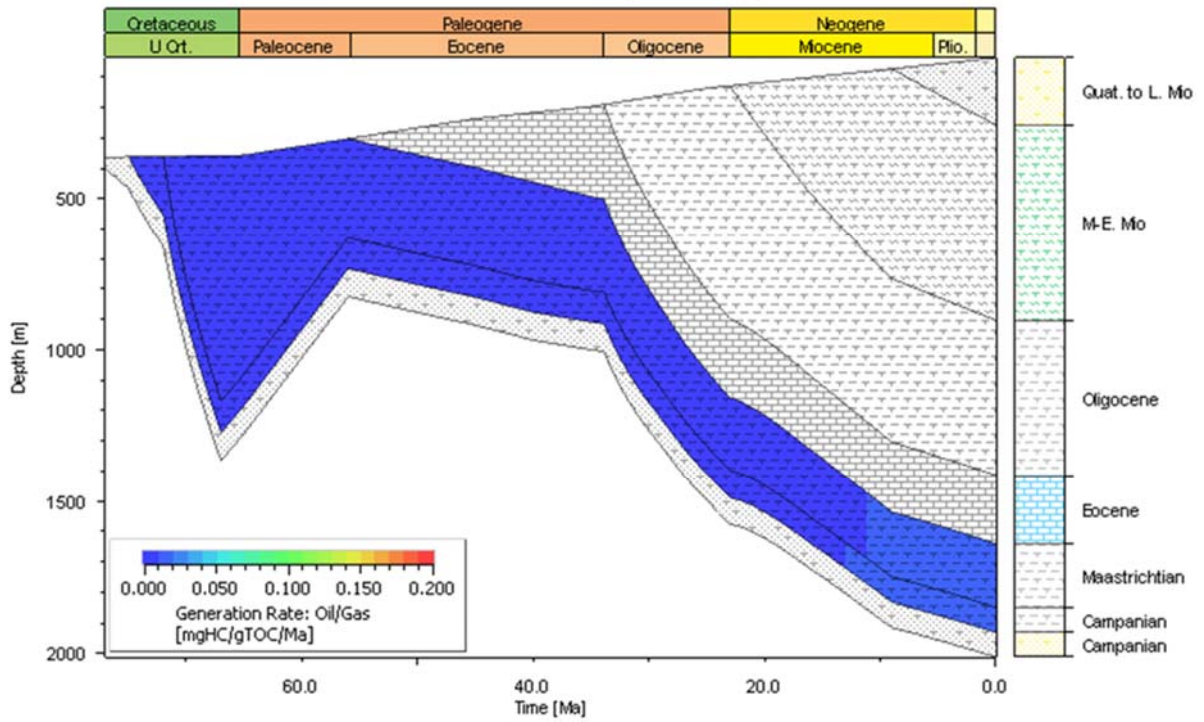


Fig. 4. Burial history plot showing the rate of hydrocarbon generation in source rocks penetrated by the Palk-Bay-1 well.

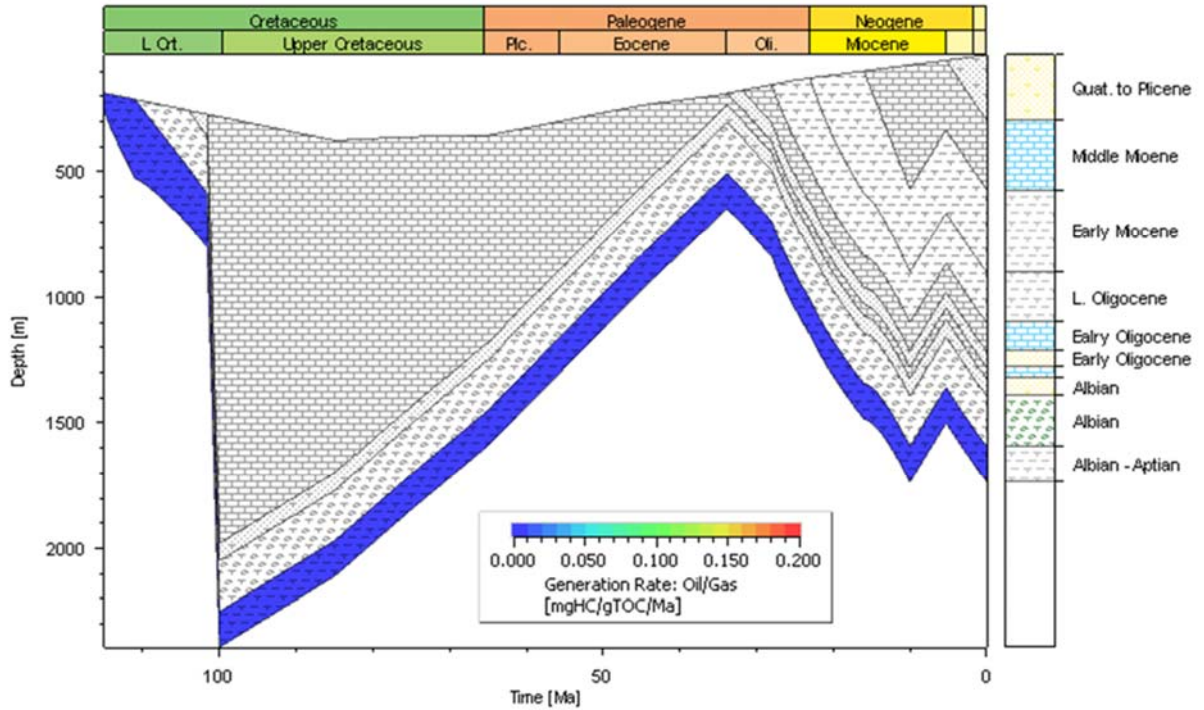


Fig. 5. Burial history plot showing the rate of hydrocarbon generation in source rocks penetrated by the Delft-1 well.

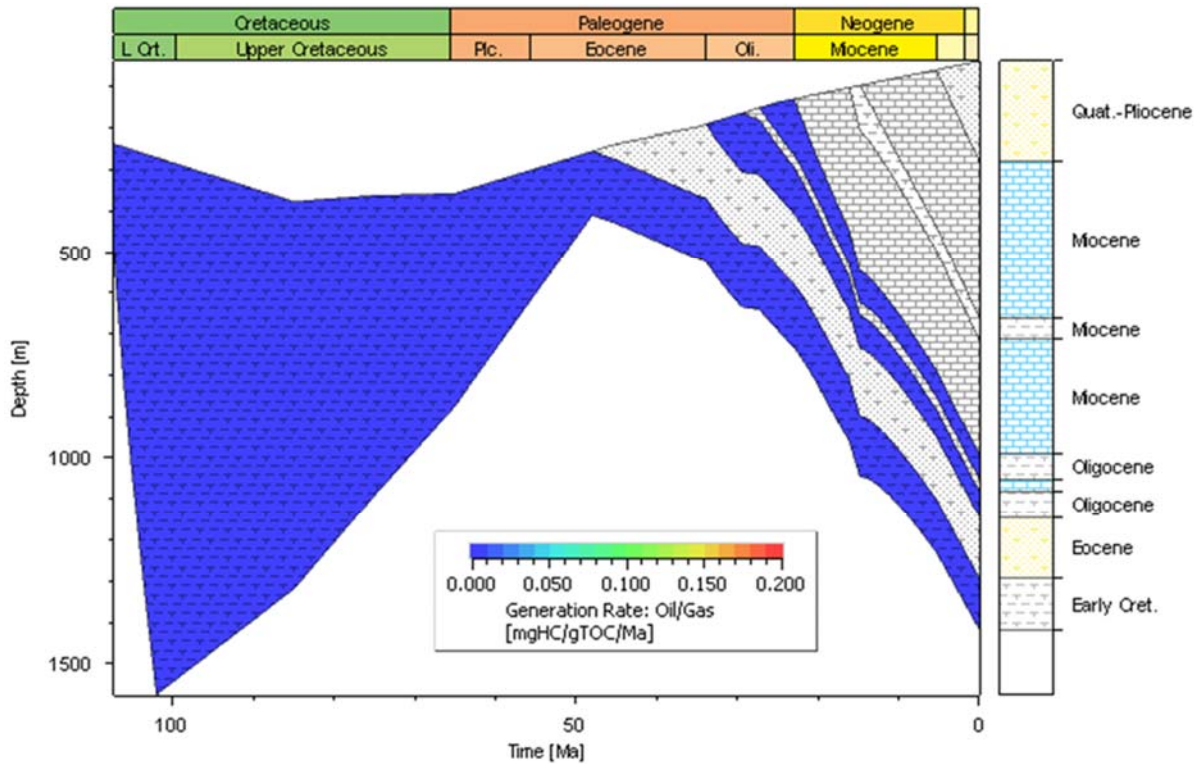


Fig. 6. Burial history plot showing the rate of hydrocarbon generation in source rocks penetrated by the Pedro-1 well.

The presence of both types II and III kerogens in sediments (Premarathne, 2015) indicates that the Cauvery Basin in Sri Lanka has the potential to produce both oil and natural gas upon thermal maturity. But, the kerogen maturation profiles and generalized stratigraphic columns appear in Figs. 2, 4, 5, & 6 show that the potential source rocks penetrated by the four wells have never been buried to sufficient depths for them to reach the gas window throughout the depositional history of the basin.

Hydrocarbon Traps and Seals

A wide variety of trapping mechanisms in the Sri Lankan sector of the Cauvery Basin are evident in the seismic coverage over the basin (Cantwell et al., 1978; Shaw, 2001). They include rotated fault blocks formed during the syn-rift period (130-90 Ma) of the basin (Shaw, 2001), anticlinal closures formed due to basin inversion continued through the Oligocene (Premarathne et al., 2016) and stratigraphic pinchouts and channel fills (Cantwell et al., 1978).

Stratigraphic sections of the wells (Figs. 4, 5 & 6) indicate that the potential reservoirs, in the Cretaceous, Eocene, Oligocene, and Miocene stratigraphic sections, are underlain by sufficiently thick fine-grained sediments that could act as potential hydrocarbon seals.

Potential Reservoirs

Figs. 4, 5 & 6 indicate that Albian and Late Cretaceous source rocks are underlain by clastic and carbonates potential reservoirs in the Cretaceous, Eocene, Oligocene, and Miocene sections. The Cretaceous section has sandstone reservoirs, the Eocene and Oligocene sections have both carbonate and sandstone reservoirs and the Miocene section has carbonate reservoirs. Shaw, (2001), based on the interpretation of wireline logs run on the wells drilled in the Sri Lankan sector of the Cauvery Basin, concludes that sandstone and limestone deposited in the above mentioned stratigraphic intervals have good porosity and permeability. When considering the stratigraphic thinness and the timing of deposition of the potential reservoir rocks and the timing of the formation of structural traps, it is apparent that Albian and

Late Cretaceous sandstones could be the most potential hydrocarbon reservoirs in the Sri Lankan sector of the Cauvery Basin. Coincidentally, oil and natural gas deposits already discovered in the Indian side of the Ramnad-Palk-Bay-Nagapattinam depression have been accumulated in Albian sandstones (Chandra et al., 1991).

Hydrocarbon Migration

Lack of lateral reservoir continuity could be expected due to the division of the basin into sub-basins/ depressions by basement ridges. The occurrence of potential reservoirs approximately 1000 to 1500 m vertically above the oil window invokes substantial vertical hydrocarbon migration. The burial history modeling in Premaratne (2020) demonstrates the

importance of deep syn-rift faulting as a means of providing vertical conduits into potential reservoir units located above the oil window.

Chances of Occurring an Active Petroleum System

The most probable petroleum system that could encounter in the Sri Lanka sector of the Cauvery Basin is summarised in the Petroleum System Event (PSE) chart given in Fig. 7. It was prepared based on the data and modelling result of only 4 wells located mainly in the north-western part of the onshore and offshore areas under the Sri Lankan jurisdiction. Delft-1 and Pedro-1 wells were drilled on structural highs (Fig. 1). This could be the reason for their relatively thin stratigraphic columns.

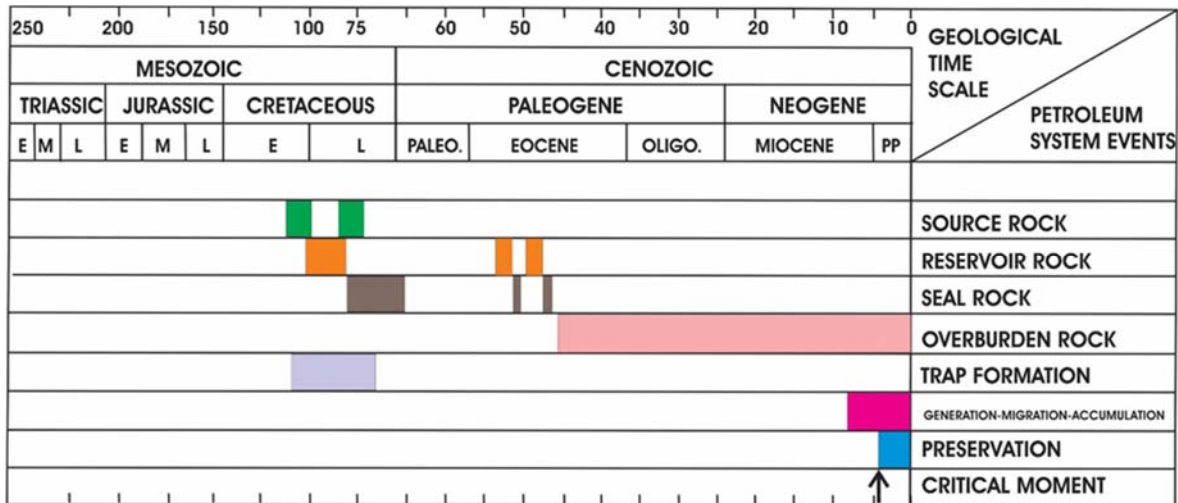


Fig. 7. Petroleum system events chart for the most probable petroleum system in the Sri Lankan sector of the Cauvery Basin. Paleo. = Paleocene, Oligo. = Oligocene, PP = Pliocene and Pleistocene, E = Early, M = middle and L = Late

A basement depth isopach map of the Sri Lankan sector of the Cauvery Basin, generated using seismic data, shows that the stratigraphic thickness at some places in the Pesalai-Palk-Bay depression reaches 3000 m (Cantwell et al., 1978). In line with this observation, the Pesalai-3 well researched a total depth of 2850 m. Kerogen maturation Profiles available in Premaratne (2020) show that the thermal maturity of sediments currently buried at 2800 m depth has reached the vitrinite reflectance value of around 0.7%R_o. Therefore, it is possible that Cretaceous potential source rocks at that depths had generated and expelled a significant quantity of hydrocarbons. A large part of the north and north-eastern offshore area of Sri

Lanka remains underexplored. As a result, the petroleum geology of this area is relatively unknown. There is a possibility that the petroleum system in the Indian side of the Ramnad-Palk Bay-Nagapattinam depression extends towards the north and north-eastern parts of Sri Lanka. One of the main barriers to lateral extension of the petroleum systems is the Mandapam-Delft ridge (Fig 1). However, whether the ridge continues to extend towards the north-east direction is not known clearly due to the lack of data availability. More exploration wells and high-resolution seismic coverage are required to fully understand and to prove the existence of an active petroleum system in the Sri Lankan sector of the Cauvery Basin

CONCLUSIONS

Albian and Late Cretaceous sediments are the most potential hydrocarbon source rocks occur in the Sri Lankan sector of the Cauvery Basin. Hydrocarbon potential in the Pesalai area is relatively higher than that in the Palk-Bay area. Hydrocarbon exploration in the Sri Lankan sector of the Cauvery Basin should mainly target Cretaceous and Eocene clastic and carbonate reservoirs in faults and anticlinal traps.

ACKNOWLEDGEMENTS

The author is thankful to the Director-General of Petroleum Resources Development Secretariat (PRDS), for providing data and granting permission to publish this work; to Preeni Vithanage, Chaminda Kularathne, and Damsith Weerasinghe at PRDS for their myriad support.

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