

# BURIAL AND THERMAL HISTORY OF THE CAUVERY BASIN, SRI LANKA: A BASIN MODELING APPROACH

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## ABSTRACT

Cauvery Basin is located between the southeastern onshore areas of India and the northwestern onshore areas of Sri Lanka. The basin has evolved due to crustal extension between India and Sri Lanka as a result of the breakup of East Gondwana. The rifting began in the Hauterivian and continued until the Cenomanian. The Indian side of the basin accommodates commercially viable oil and natural gas deposits. Hydrocarbon exploration in the Sri Lankan sector of the basin commenced as early as 1957. Six exploration wells were drilled in Sri Lanka during 1972 to 1981. None of these wells encountered any economically viable hydrocarbon deposits. Little further exploration took place in the Cauvery Basin in Sri Lanka to this date. However, the Sri Lankan government has indicated its plan to resume hydrocarbon exploration in the Cauvery Basin after the discovery of natural gas deposits in the Mannar Basin in 2011. The Mannar Basin is considered to be the southern extension of the Cauvery Basin. Only a handful of studies is available on the Sri Lanka sector of the basin in the public domain, though plenty is available on the Indian counterpart. The objective of this study is to understand the burial and thermal history of the Sri Lankan part of the Cauvery Basin based on basin modeling techniques. Petromod 1D software (v. 12.2) was used to simulate the burial and thermal history of the Pesalai-1, Palk Bay-1, Delft-1 and Pedro-1 wells using data from unpublished well reports held at Petroleum Resources Development Secretariat in Sri Lanka. In addition, data available in the public domain were also used to derive some input data and boundary conditions. Results of the study show that southern part of the Cauvery Basin in Sri Lanka has experienced higher heat flows. The present-day geothermal gradient in Pesalai-1 and Palk Bay-1, Delft-1 and Pedro-1 wells are 25.5°C/km, 25.0°C/km, 21.3°C/km and 18.5°C/km, respectively. The present-day geothermal gradient of the basin increases from the north to the south. The highest bottom hole temperature (~90°C), was recorded in the Pesalai-1 well. The Pesalai area has experienced higher heat flows than the Palk Bay area. Current heat flows in Pesalai and Palk Bay areas are around 52 mW/m<sup>2</sup> and 48 mW/m<sup>2</sup>, respectively. The pre-rift heat flow in the Sri Lankan sector of the Cauvery Basin varied between 46 -40 mW/m<sup>2</sup>. Area where the Delft-1 and Pedro-1 well are located have undergone upliftment during the Albian to the end of the Eocene (around 100-34 Ma). The Sri Lankan Cauvery Basin has had a relatively a higher sediment influx after the Eocene. The sediment thickness decreases towards the north of the basin. Sediments penetrated by the Palk Bay-1, Delft-1 and Pedro-1 wells are thermally immature. However, Albian sediment penetrated by the Pesalai-1 well is marginally matured and has just entered the oil window.

**Keywords:** *Cauvery Basin, Heat flow, Pesalai, Palk Bay, Sri Lanka*

## INTRODUCTION

Cauvery Basin is located between the southeastern onshore areas of India and the northwestern onshore area of Sri Lanka. The Indian side of the Cauvery Basin extends over 62,500 Sq.km onshore and offshore up to 200 m isobath (Chaudhuri et al., 2010). The Sri

Lankan side of the basin lies over 15,000 Sq. km in northwest onshore and offshore areas up to 200 m isobaths. Both oil and natural gas is produced from onshore and offshore fields in the Indian side of the basin. Therefore, it is considered as a category one basin.

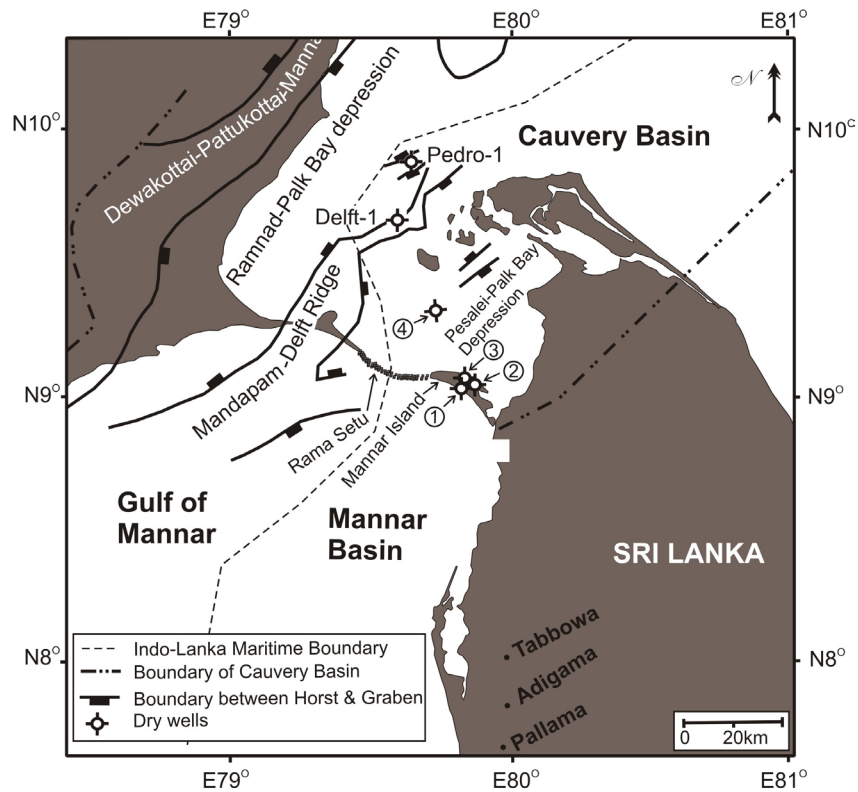


Fig.1. Sri Lankan side of the Cauvery Basin and hydrocarbon exploration wells drilled in it (modified after Premaratne et al., 2015) Encircled 1, 2, 3, and 4 in the Figure refer to Pesalai-1, 2 and 3 wells, and Palk Bay-1 well, respectively.

Hydrocarbon exploration in the Sri Lankan side of the Cauvery Basin began as early as 1957. The first exploration well in Sri Lanka was drilled in 1974 at the Pesalai area on Mannar island located in the northwest of Sri Lanka (Fig. 1). Later, five more exploration wells were drilled in the Sri Lankan side of the basin. However, all of these wells were abandoned as dry holes. Little further exploration took place in the Sri Lankan side of the Cauvery Basin to this date. PH-9-1 well in the Ramnad-Balk Bay-Nagapattinam depression in the Indian side of the Cauvery Basin is located around 21 km away from the Indo-Lanka maritime boundary (Ramana et al., 1995). It is the hydrocarbon discovery well in India located closest to Sri Lanka.

The Sri Lankan Government has indicated its interest to resume hydrocarbon exploration in the Cauvery Basin under its jurisdiction after the discovery of natural gas in the Mannar Basin in 2011. These discoveries confirmed the occurrence of an active petroleum system in the Mannar Basin (Mohapatra et al., 2012; Premaratne et al., 2013). The Mannar Basin in Sri Lanka, which is located immediately to

the south of the Cauvery Basin is considered to be a sub basin of the Cauvery Basin by some researches (eg. Murthy et al., 2008; Rana et al., 2008; Rao, et al., 2010). Though there have been many studies on geology, tectonic setting and hydrocarbon prospectivity of the Indian side of the Cauvery Basin (eg. 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., 2009; Bastia and Radhakrishna, 2012), only a handful of studies are available on the Sri Lankan side of the Cauvery Basin (eg. Cantwell et al., 1978; Premaratne, 2008; 2015; 2017). Cantwell et al., (1978) has addressed stratigraphy and source rock potential and thermal maturity of some potential source rocks penetrated by the exploration wells drilled in the Sri Lankan sector of the Cauvery Basin. Premaratne (2015; 2017), on the other hand, has addressed petroleum geology and present-day heat flows. The objective of this study is to understand the burial and thermal history of the Sri Lankan sector of the Cauvery Basin based on basin modeling techniques.

## TECTONIC SETTING

Cauvery Basin is a pericretonic failed rift basin (Sastri et al., 1973; 1981), which has been originated due to the fragmentation of East Gondwana (Katz, 1978; Sastri et al., 1981; Lal et al., 2009). Separation of Gondwana into east and west sections was initiated in the Middle Jurassic around 167 Ma (Reeves et al., 2002). The break up of the East Gondwana commenced in the Early Cretaceous around 130 Ma (Lal et al., 2009). This event was followed by the northward movement of the landmass comprised of India, Madagascar and Sri Lanka (Torsvik et al., 2002). Data from the Pesalai-1 well suggest that the Mannar island of Sri Lanka, which is currently located at 8° North latitude, was located 16° South latitude in the early Cretaceous (Cantwell et al., 1978). Rifting between Indo-Lanka landmasses has occurred as part of Sri Lanka's counter clockwise rotation around northern part of the island acting as a pivot (Yoshida, et al., 1992). This rotation has continued until about 96 Ma (Chari et al., 1995). The Syn-rift phase of the Cauvery Basin lasted from the late Jurassic to the Cenomanian epoch. (Chakraborty and Sarkar, 2018; Raju et al., 2018; Chaudhuri et al., 2010). Numerous down-to-basin extensional faulting took place in the Cauvery Basin due to rifting (Murthy et al., 2008). The basin is considered to have entered into a thermal sag phase after 96 Ma.

## BASIN MODELING SOFTWARE, INPUT DATA AND BOUNDARY CONDITIONS

### SOFTWARE

Petromod 1D software (version 12.2) was used to simulate the burial and thermal history of the Pesalai-1, Palk Bay-1, Delft-1 and Pedro-1 wells, which are located in northwestern onshore and offshore area of Sri Lanka (Fig. 1 for well locations).

### LITHOLOGY AND BIOSTRATIGRAPHY OF WELLS

Lithological descriptions in unpublished well reports held at Petroleum Resources

Development Secretariat (PRDS) in Sri Lanka and biostratigraphy data reported by Cantwell et al. (1978) for the wells were used in this study. The Cauvery Basin has erosional unconformities with greater hiatuses (Fig. 2). Erosional thicknesses were estimated based on average sedimentation rates of the formations immediately above and below each unconformity. Tables 1 and 2 summarize the main input data.

### HEAT FLOW

Parsons and Sclater (1977) proposed a typical heat flow pattern for rift basins. Accordingly, the heat flow of a rift basin gradually increases during the syn-rift period. It reaches a maximum value at the end of rifting and then declines exponentially during the post-rift period. As proposed by Chakraborty and Sarkar, (2018); Raju et al. (2018); Chaudhuri et al. (2010), the end of rifting period of the Cauvery Basin is considered to be 96 Ma. Premarathne (2017) has reported the present-day heat flows in the Pesalai-Palk Bay depression to be 39-50 mWm<sup>-2</sup>, while that in the Sri Lankan sector of the Ramnad-Palk Bay depression to be 37- 65 mWm<sup>-2</sup>. The pre-rift heat flow in the Cauvery Basin has not been fully understood. However, Premarathne et al. (2015) reported that the pre-rift heat flow in the adjacent Mannar Basin was 50.2 mW/m<sup>2</sup>. This is further supported by low vitrinite reflectance values reported for Late Jurassic sediments in a couple of small Grabens located at Tabbowa and Andigama (Fig. 1) in Sri Lanka by Ratnayake and Sampei (2015). Therefore, the pre rift heat flow in the Cauvery Basin could be around 50 mW/m<sup>2</sup>. Considering the above-mentioned factors (i.e. Present-day and pre rift heat flows, the time when the rifting was stopped and the typical heat flow pattern of a rift basin), different heat flow scenarios were modelled until the modelled kerogen maturation profiles for each well coincides with the measured kerogen maturation profiles of respective wells. Vitrinite reflectance data is not available for the Perdo-1 well. Therefore, the heat flow history at the Delft well was used for the Perdo-1 well, since the two wells are located close by.

**PALEO WATER DEPTH**

Biostratigraphy data available in well reports held at the PRDS, some bathymetry data of Cretaceous sediments from the Ramnad-Palk Bay depression reported by Chandra et al. (1991) and Eustatic Sea level changes reported by Pitman (1978) were used to estimate the depositional water depths of early Cretaceous

(~130 Ma) to Recent sediments penetrated by Pesalai-1, Palk Bay-1, Delft-1 and Pedro-1 wells. Relatively short-term (< 10 Ma) variations of depositional water depths caused by climate change and tectonic activities were not considered in this study.

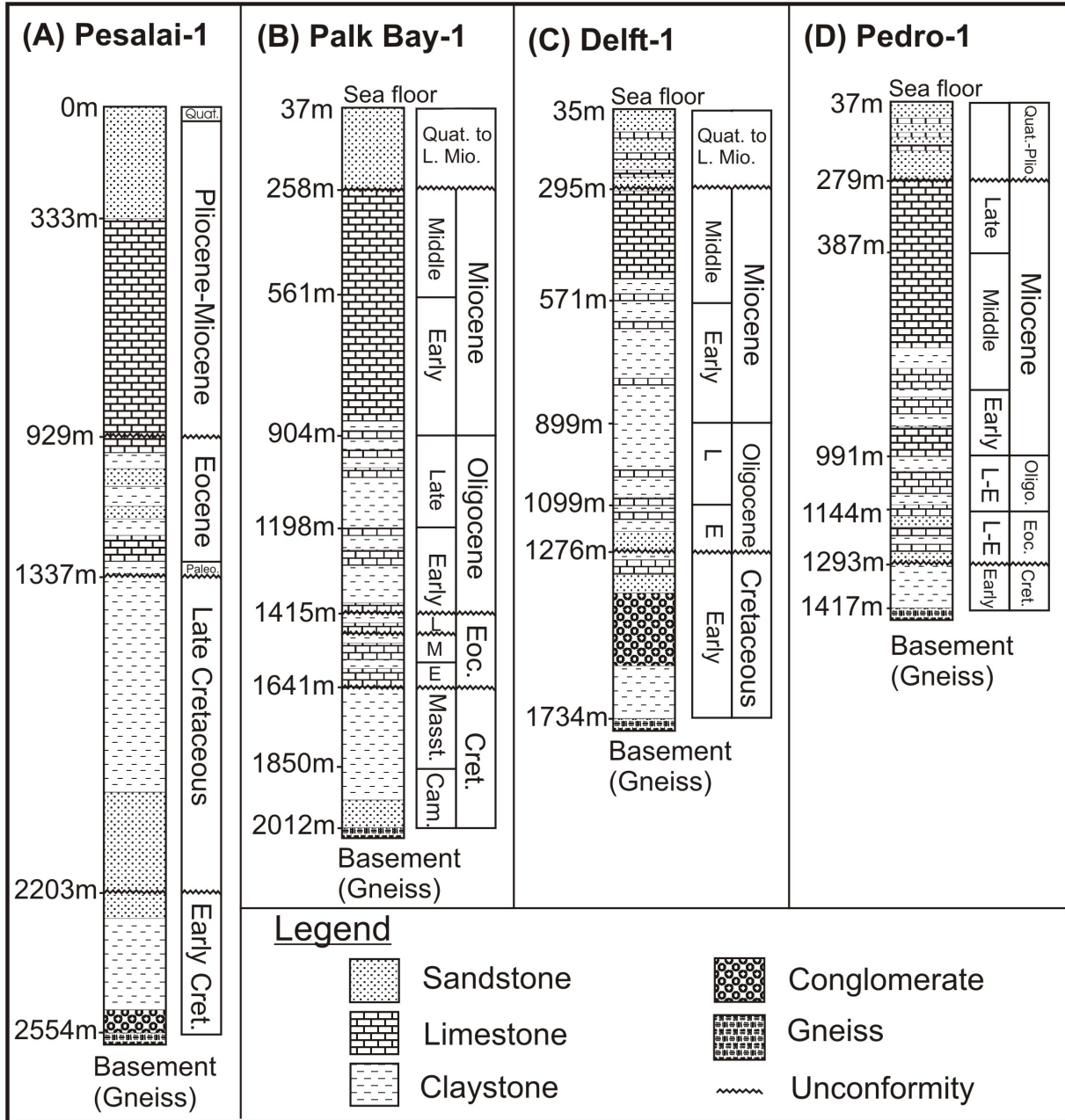


Fig. 2. Generalized stratigraphic sections of Pesalai-1, Palk Bay-1, Delft-1 and Pedro-1 wells (modified after Cantwell et al., 1978, and Sastri et al., 1981). Quat. = Quaternary; Plio = Pliocene; Mio. = Miocene; Eoc. = Eocene; Palio. = Pliocene; Cret. = Cretaceous; Masst. = Maastrichtian; Camp. = Campanian; E= Early; M = Middle; L = Late (after Premarathne, 2015).

Table 1. Input data used in this study for Pesalai -1 and Palk Bay-1 wells (Thick. = formation thickness, Depo. = deposition, Quat. = Quaternary, Plio = Pliocene, Mio. = Miocene, Turo. = Turonian, Alb. Albian, Apt and Aptian. L., M., and E., stand for Late, Middle and, respectively).

### Pesalai -1

Layer	Top (m)	Base (m)	Thick. (m)	Eroded (m)	Depo. from (Ma)	Depo. to (Ma)	Eroded from (Ma)	Eroded to (Ma)	Lithology
Quaternary	0	50	50	-	2.6	0	-	-	Sandstone (quartzite, typical)
Plio. to L. Mio	50	333	283	-	11.6	2.6	-	-	Sandstone (quartzite, typical)
M. to E. Mio.	333	929	596	-	23	11.6	-	-	Marl
Eocene	929	1287	358	176	56	33.9	33.9	23	Sandstone (arkose, dolomite rich)
Paleocene	1287	1337	50	-	58	56	-	-	Shale (typical)
Camp. to Turo.	1337	2000	663	361	92	70	70	58	Shale (typical)
Cenomanian	2000	2203	203	-	100	92	-	-	Sandstone (typical)
Albian_1	2203	2298	95	63	105	102	102	100	Sandstone (typical)
Albian -2	2298	2454	156	-	110	105	-	-	Shale (typical)
Albian 3	2454	2554	100	-	113	110	-	-	Conglomerate (typical)

### Palk Bay -1

Layer	Top (m)	Base (m)	Thick. (m)	Eroded (m)	Depo. from (Ma)	Depo. to (Ma)	Eroded from (Ma)	Eroded to (Ma)	Lithology
Quat. to L. Mio.	37	258	221	-	9	0	-	-	Sandstone (quartzite, typical)
M. -E. Mio.	258	904	646	-	23	9	-	-	Marl
Oligocene	904	1415	511	-	33.9	23	-	-	Shale (typical)
Eocene	1415	1641	226	-	56	33.9	-	-	Limestone (shaly)
Maastrichtian	1641	1850	209	310	72	67	67	56	Shale (typical)
Campanian	1850	1931	81	-	75	72	-	-	Shale (typical)
Campanian	1931	2012	81	-	78	75	-	-	Sandstone (typical)

Table 2. Input data used in this study for Pesalai -1 and Palk Bay-1 wells (abbreviations are the same as that in Table 1)

**Delft -1**

Layer	Top (m)	Base (m)	Thick. (m)	Eroded (m)	Depo. from (Ma)	Depo. to (Ma)	Eroded from (Ma)	Eroded to (Ma)	Lithology
Quat. to Plio.	35	295	260	-	5.3	0	-	-	Sandstone (typical)
M. Mioene	295	571	276	216	16	10	10	5.3	Limestone (ooid grainstone)
E. Miocene	571	899	328	-	23	16	-	-	Shale (typical)
L. Oligocene	899	1099	200	-	28	23	-	-	Shale (typical)
E. Oligocene	1099	1213	114	-	31.8	28	-	-	Limestone (shaly)
E. Oligocene	1213	1276	63	-	33.9	31.8	-	-	Sandstone (clay rich)
Albian	1276	1322	46	1650	101.6	100	100	33.9	Limestone (ooid grainstone)
Albian	1322	1392	70	-	104	101.6	-	-	Sandstone (typical)
Albian	1392	1592	200	-	111	104	-	-	Conglomerate (typical)
Alb.-Apt.	1592	1734	142	-	116	111	-	-	Shale (typical)

**Pedro-1**

Layer	Top (m)	Base (m)	Thick. (m)	Eroded (m)	Depo. from (Ma)	Depo. to (Ma)	Eroded from (Ma)	Eroded to (Ma)	Lithology
Quat. - Plio.	37	279	242	-	5.3	0	-	-	Sandstone (typical)
Miocene	279	660	381	-	14.8	5.3	-	-	Limestone (Waulsortian mound)
Miocene	660	713	53	-	16.1	14.8	-	-	Shale (typical)
Miocene	713	991	278	-	23	16.1	-	-	Limestone (shaly)
Oligocene	991	1051	60	-	27.26	23	-	-	Shale (typical)
Oligocene	1051	1081	30	-	29.39	27.26	-	-	Limestone (ooid grainstone)
Oligocene	1081	1144	63	-	33.9	29.39	-	-	Shale (typical)
Eocene	1144	1293	149	-	48	33.9	-	-	Sandstone (clay rich)
Albian	1293	1417	124	920	108	102	102	48	Shale (typical)

## SURFACE TEMPERATURES

Zakharov et al. (2009) reported that the average surface temperatures in the Cauvery Basin and southern Indian near-bottom shelf water, during the Albian and Maastrichtian to be 17°C and 21°C, respectively. However, a data set for continuous variation of surface temperatures in the northwestern part of Sri Lanka from the early Cretaceous to the present is not available. Therefore, variations of surface temperatures in the study area for the last 130 Ma (Fig. 3) were generated using an algorithm proposed by Wygrala (1989). However, surface temperatures generated for the Albian and Maastrichtian time based on this algorithm show around 4°C over estimation for the Albian and 3°C under estimation for the Maastrichtian, compared to the surface temperatures reported by Zakharov et al. (2009) for the two-time periods, respectively. The current average surface temperature in the Pesalai area is around 28°C.

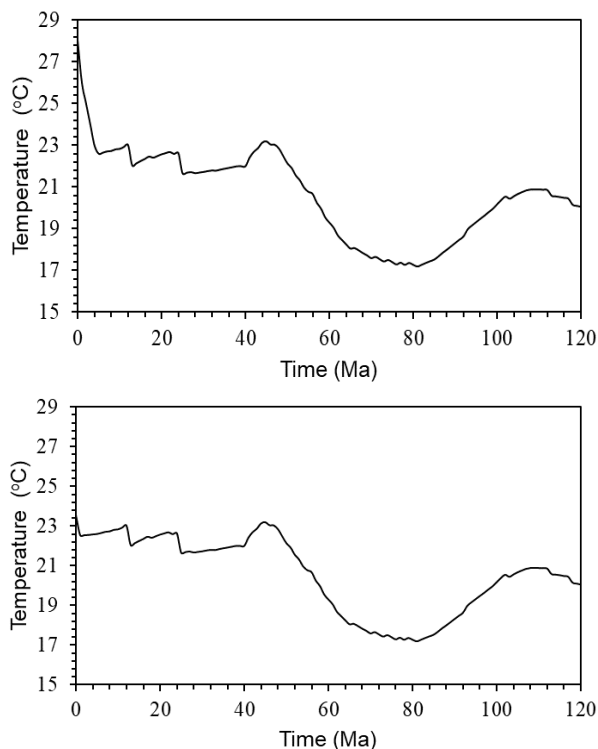


Fig. 3. Change in Surface Temperature and Ocean Bottom Temperatures of (A) Pesalai-1, (B) Palk Bay-1, Delft-1 and Pedro-1 Wells Used In This Study (After Wygrala, 1989).

## RESULTS AND DISCUSSION

### CALIBRATION OF HEAT FLOW HISTORY

Optimized heat flow histories for the Pesalai-1, Palk Bay-1, and Delft-1 wells are shown in Fig 4. Since modeled and observed kerogen maturation profiles (Fig. 5) for each well roughly agree, it could be inferred that the optimized heat flow trends shown in Fig. 4 are reasonably accurate. However, it should be noted that the accuracy of the optimized heat flow trends depends on the accuracy of assumed ocean bottom/surface temperatures (Table 1), the thermal conductivity of rocks, the sediment compaction models etc., for which default values in the software data base were used in this study.

The optimized heat flow histories showed that the Pesalai area on Mannar island (Fig. 1), where the Pesalai-1 well was located, had experienced relatively high heat flows compared to the Palk Bay-1 and Delft-1 well locations. The optimized present-day heat flows at the Pesalai-1, Palk Bay-1 and Delft-1 wells were around 44 mW/m<sup>2</sup>, 39 mW/m<sup>2</sup>, and 37 mW/m<sup>2</sup>, respectively. The optimized pre-rift heat flows at the Pesalai-1, Palk Bay-1 and Delft-1 well locations were 46, 42, and 40 mW/m<sup>2</sup>, respectively. The maximum heat follows reported at the Pesalai-1, Palk Bay-1 and Delft-1 wells at the end of the rifting period around 90 Ma were, 55, 47, 43 mW/m<sup>2</sup>, respectively.

Palaeo-heat flows of the Cauvery Basin increasing from the north to the south could be related to the crustal extension between Indo-Lanka Land masses that happened in an increasing manner towards south due to the counter-clockwise rotation of Sri Lanka during rifting from India. Increasing stratigraphic thickness from north to south of the Cauvery Basin in Sri Lanka supports this hypothesis. Similar observation was made in the adjacent Mannar Basin by Premarathne et al. (2016).

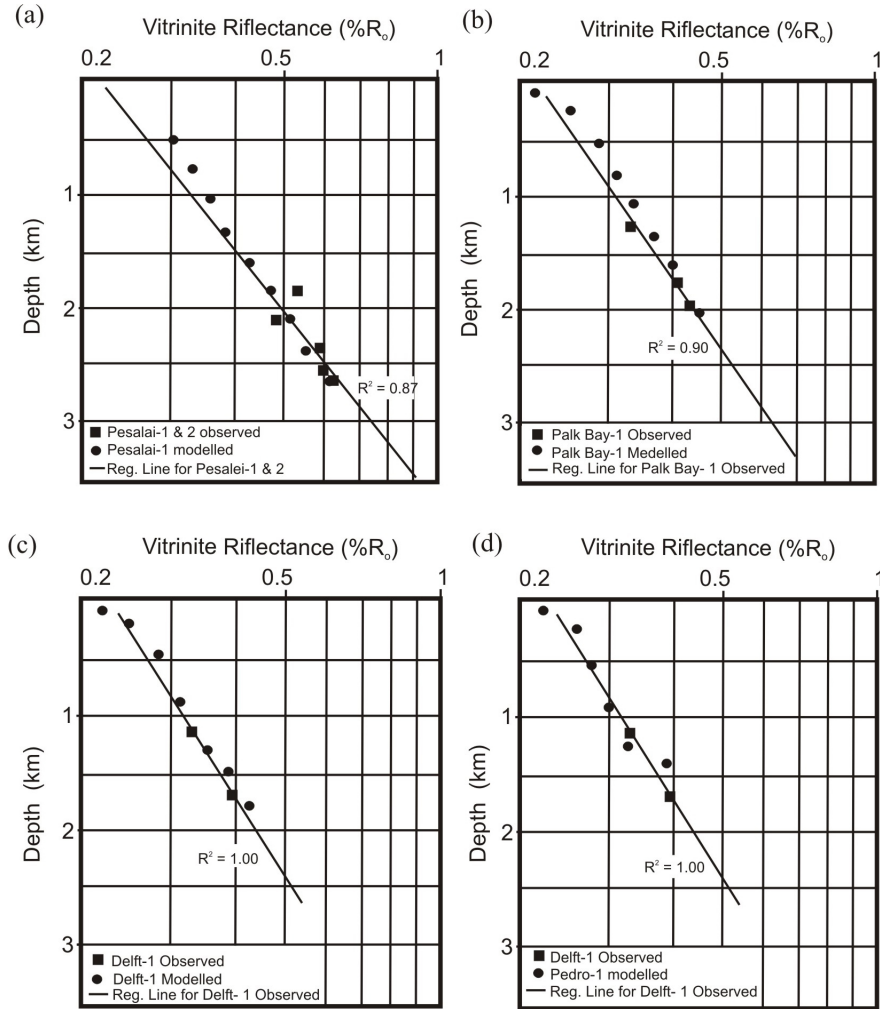


Fig. 4. Modeled and observed vitritine reflectance (VR) data for the (a) Pesalai-1 (b) Palk Bay-1, (c) Delft-1 and (d) Pedro-1 wells.

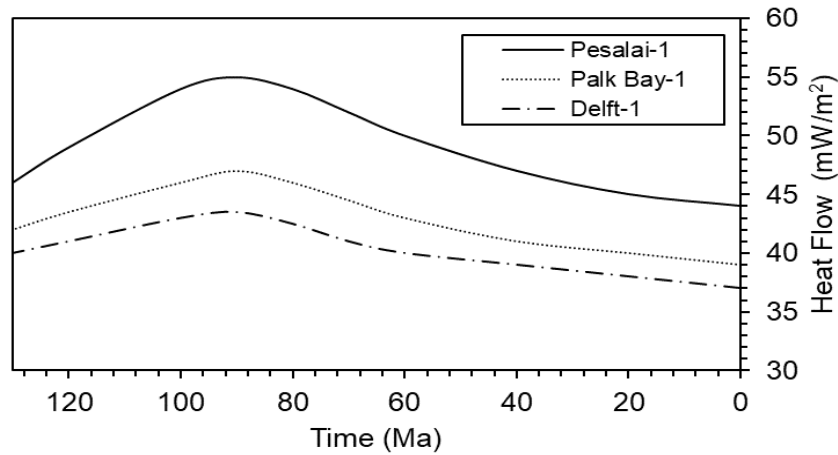


Fig.5. Optimised heat flow histories at the Pesalai-1, Palk Bay-1 and Delft-1 well locations.



## THERMAL HISTORY

Modeled present-day geothermal gradient in the Pesalai-1 and Palk Bay-1, Delft-1 and Pedro-1 wells were 25.5°C/km, 25.0°C/km, 21.3 °C/km and 18.5°C/km, respectively. The current geothermal gradients computed using the Bottom Hole Temperatures (BHT) data by Premarathne et al. (2018) for the Pesalai-1 and Palk Bay-1, Delft-1 well locations are 26.29°C/km, 24.31°C/km, and 22.7°C/km, respectively. The measured values were closer in

agreement with the values simulated in this study. This indicates that optimized present-day heat flow values used for this study are to be reasonably accurate. Change in formation temperatures through geological time are shown on burial history plots for the four wells (Figs. 6 and 7). According to the modelled thermal history, the maximum formation temperature of 90°C was recorded in the Pesalai-1 well (Fig. 6A).

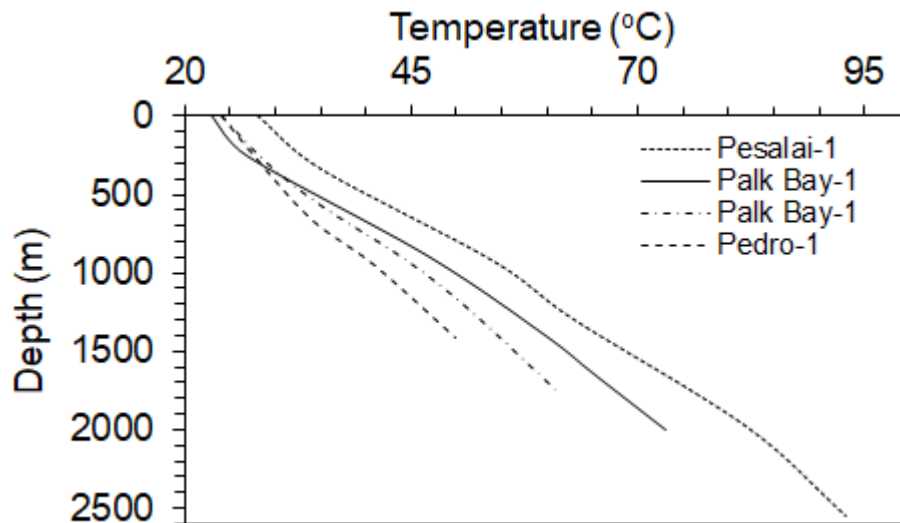


Fig. 6. Modelled present-day geothermal gradients for (a) Pesalai-1, (b) Palk Bay-1, (c) Delft-1 and (d) Pedro-1 wells.

## BURIAL HISTORY

Burial history plots for the Pesalai-1 and Delft-1 wells (Figs. 6A and 7) show that there was an erosional unconformity probably due to upliftment during the Albian Epoch. In addition, two more erosional unconformities, could be seen in Pesalai-1 from the Maastrichtian to the Middle Paleocene and in the Oligocene. In the Palk Bay-1 well (Fig. 6B), an erosional unconformity could be seen during the Maastrichtian to the end of the Paleocene. In the Delft-1 well, an unconformity occurred from the early Cenomanian to the end of the Eocene. This unconformity in the Pedro-1 well, occurred from the early Cenomanian up to the middle Eocene. Burial history plots for all the four wells indicate a rapid deposition from the Oligocene to present. Specially, Palk Bay-1 well (Fig. 6B), indicates

that the accumulation of 2/3 of its stratigraphic thickness took place during the last 45 Ma.

Albian unconformity in the Pesalai-1 and Delft-1 wells (Fig. 2A and 2C), marks the end of the rifting period in the Cauvery Basin. The unconformity in Delft-1 and Pedro-1 from the early Cenomanian to the end of Eocene could be due to the upliftment associated with the buoyancy created by Reunion hotspot and intraplate deformation after the collision of the Indian plate with the Eurasian plate in the early Eocene. This collision gave rise to a rapid upliftment and erosion, which supplied a massive amount of terrigenous sediments into depocenters of the Cauvery Basin, both in the Indian side as well as in the Sri Lankan side. This is attributable to the rapid accumulation of sediments from the Oligocene to present.

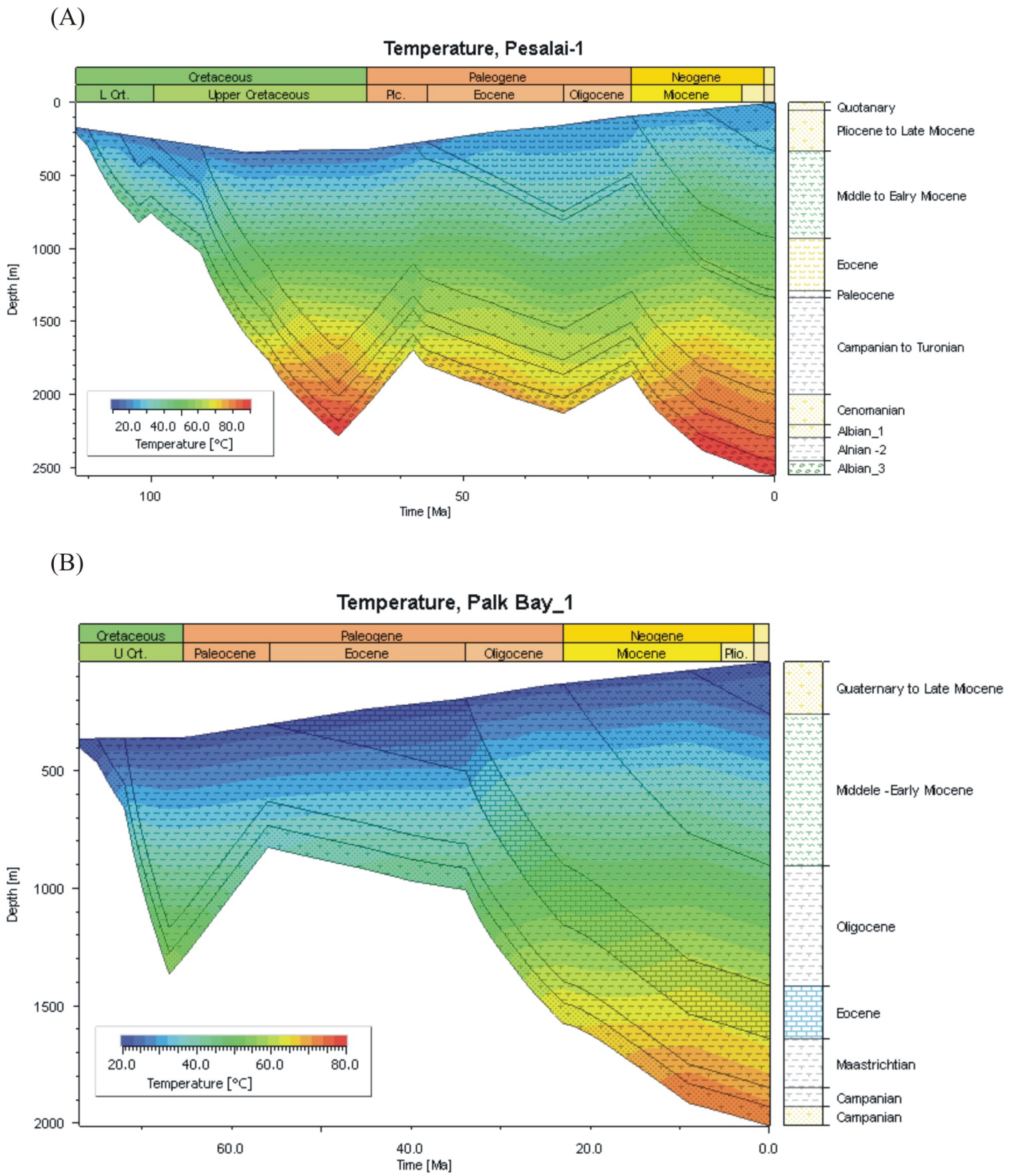
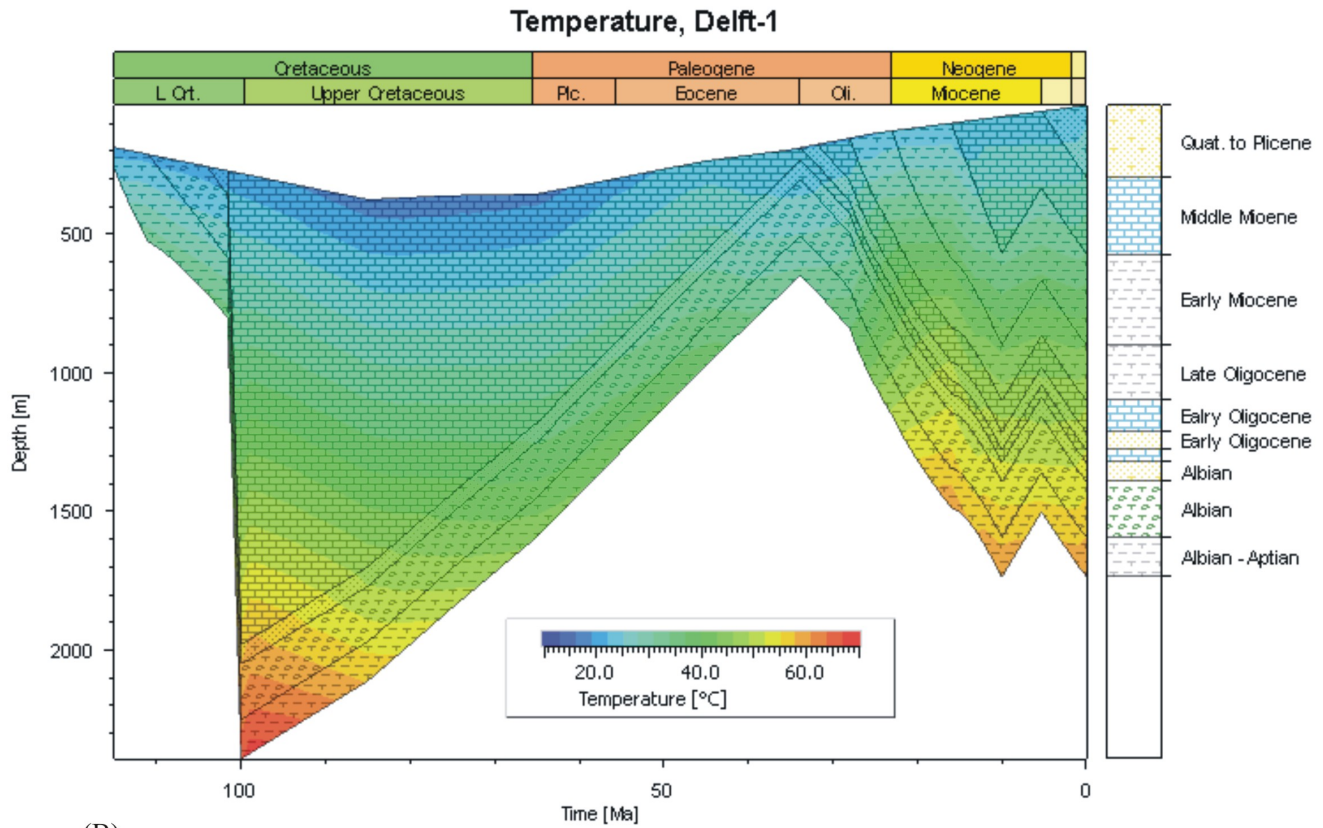


Fig. 7. Burial and thermal history plots for (A) Pesalai-1 well (B) Palk Bay 1 well.

(A)



(B)

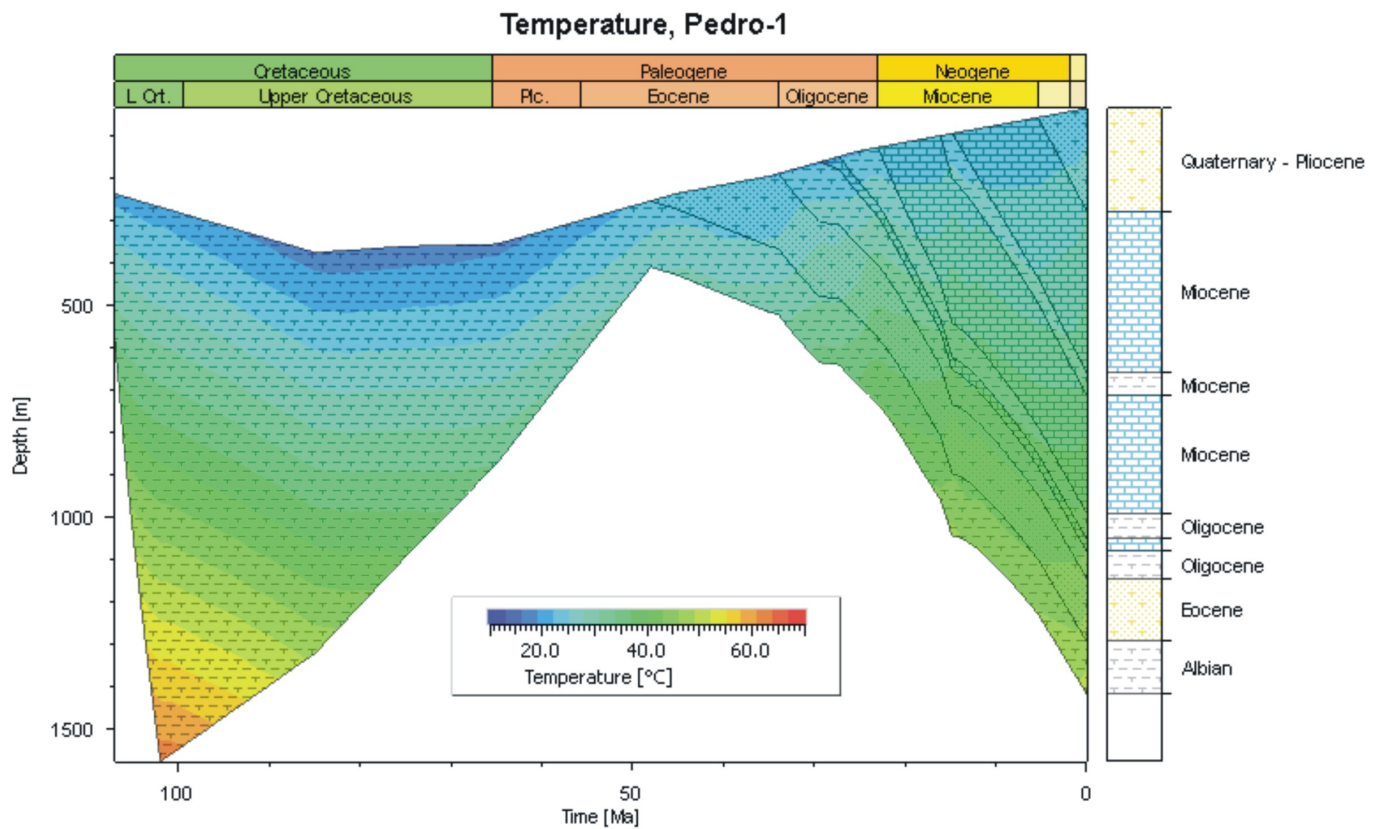


Fig. 8. Burial and thermal history plots for (A) Delft -1 well (B) Pedro-1 well.

## CONCLUSIONS

Southern part of the Cauvery Basin in Sri Lanka experienced higher heat flows than the northern part. The present-day geothermal gradients in the Pesalai-1 and Palk Bay-1, Delft-1 and Pedro-1 wells are 25.5°C/km, 25.0°C/km, 21.3°C/km and 18.5°C/km, respectively. The present-day geothermal gradient in the basin increases from the north to south. The highest formations temperature of around 90°C was recorded in Albian sediments penetrated by the Pesalai-1 well. The Pesalai area has experienced higher heat flows than the Palk Bay area. The current heat flows in the Pesalai and Palk Bay areas are around 52 mW/m<sup>2</sup> and 48 mW/m<sup>2</sup>, respectively. The pre-rift heat flow in the Sri Lankan sector of the Cauvery Basin varies between 46 - 40 mW/m<sup>2</sup>. Pre-rift heat flow in the Sri Lankan Cauvery Basin is slightly lower than that in the northern part of the Mannar Basin. Delft-1 and Pedro-1 well locations have undergone upliftment during the Albian to the end of the Eocene (around 100 -34 Ma). The Sri Lankan part of the Cauvery Basin has experienced relatively a higher sediment influx after the Eocene. The sediment thickness decreases towards the northern part of the basin. Sediments penetrated by the Palk Bay-1, Delft-1 and Pedro-1 wells are thermally immature. However, the Albian sediment penetrated by the Pesalai-1 well is marginally matured and has just entered the oil window.

## ACKNOWLEDGEMENTS

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