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RESEARCH ARTICLE

Marine Geology

Identification of depositional features in the Albian and Aptian sections over the hydrocarbon exploration block M2 on the Mannar Basin, Sri Lanka

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Abstract: The Mannar Basin extends over 45,000 km^2 off the western coast of Sri Lanka. It has evolved due to the multiphase rifting between Indo-Lanka landmasses during the Barremian-Paleocene time. The sediment thickness of the basin ranges from about 4 to 10 km. The northern part of the basin is a targeted area for hydrocarbon exploration in Sri Lanka. Though two natural gas discoveries were made in 2011, the basin remains a frontier due to lack of well penetration and 3D seismic coverage. As a result, the depositional features of sediment in the basin are little known. This study focuses on identifying paleo depositional features in the Albian and Aptian strata using 650 km^2 3D seismic data from the Mannar Basin. Root Mean Square (RMS) amplitude was used to characterize the depositional features in three-time windows on IHS Kingdom software (v.8.3). The results show the existence of a multi-level paleo submarine fan system in the Albian and Aptian strata. They are located relatively close to the western coastline compared to the fan system in the Eocene strata. The deposition of this paleo submarine fan system has taken place in a shelf marine environment and has been influenced by relatively high sea levels during the Albian and Aptian compared to the relatively low sea levels in the Paleocene and Eocene.

Keywords: Depositional features, Mannar Basin, RMS amplitude, seismic data, Sri Lanka.

INTRODUCTION

The Mannar Basin extends over 45,000 km^2 off the western coast of Sri Lanka. It lies in water depths ranging from 20 m in the northern part to more than 3,000 m towards the southern part of the basin. A major portion of the basin lies in deep-water (> 400 m) depths.

The Mannar Basin is a pericratonic failed rift basin (Curray, 1984). It has evolved due to the multiphase breakup of the Gondwana (Desa *et al*., 2006; Lal *et al*., 2009; Gibbons *et al*., 2013). The first phase of rifting began due to the extension between Africa and Antarctica in the Late Jurassic, while the second phase started with the breakup of East Gondwana in the Early Cretaceous (Baillie *et al*., 2002). The basin entered into a thermal sag phase in the early Paleocene and it remains as a passive margin ever since (Baillie *et al*., 2002; Premarathne, 2015; Premarathne *et al*., 2016). The formation and evolution of the basin have been addressed in detail by Baillie *et al*. (2002), Lal *et al*. (2009), Premarathne *et al*. (2016), Ratheesh-Kumar *et al*. (2020), Singh & Rao (2021), Premarathne and Ranaweera (2021).

The stratigraphic thickness of the basin varies roughly from 4 to 10 km. The oldest sediment overlain by the crystalline basement is thought to be Late Jurassic in age (Premarathne *et al*., 2016). Information on the basin's stratigraphy and tectonic history comes mainly from seismic data and hydrocarbon exploration wells. Since 1981, five exploration wells have been drilled in the Mannar Basin (well locations in Figure 1). Out of them, Dorado and Barracuda drilled in the M2 exploration block in the Mannar Basin in 2011, penetrated natural gas-bearing sandstones in Maastrichtian and Campanian strata, respectively (Figure 2B and 2C). This finding confirmed the occurrence of an active petroleum system in the basin. Campanian sandstone penetrated by the Dorado-North well, which was drilled 2.5 km north of Dorado, has higher porosity (~20%) indicating very good

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reservoir potential (Bandara & Premarathne, 2021). The last well, named Wallago drilled in the M2 block in 2013 ended up as a dry hole. The Petroleum system of the basin has been addressed in detail by Premarathne *et al*. (2015), and Galushkin & Dubinin (2020).

Albian and older sediment have not been penetrated by hydrocarbon exploration wells drilled so far in the Mannar Basin in Sri Lanka (Premarathne, 2015). However, some wells drilled in the Indian portion of the Mannar Basin and the Cauvery Basin, both on the Sri Lankan and Indian sides, have penetrated the Albian section (Rao *et al*., 2010; Premarathne, 2015). Recent to Late Cretaceous stratigraphy in the northern part of the Cauvery and Mannar Basins have been addressed in detail by Premarathne (2015), and Premarathne *et al*. (2016), respectively.

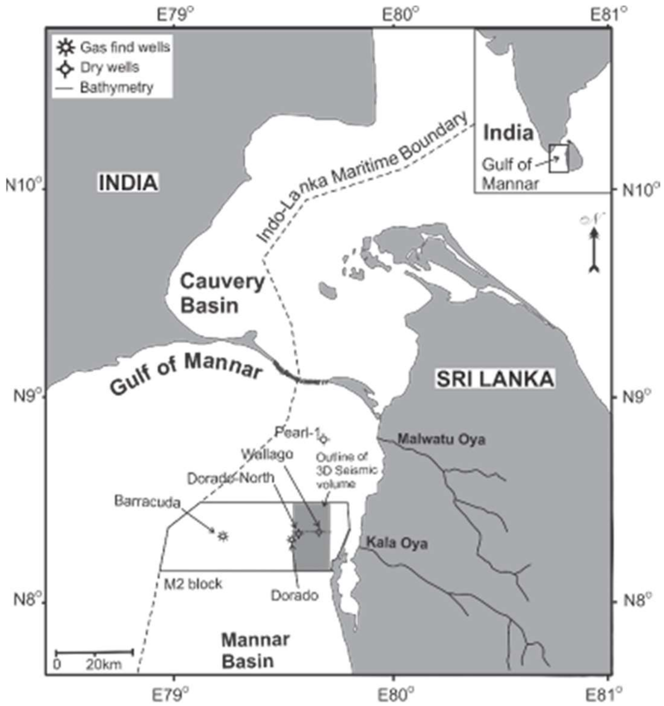

Figure 1: Locations of exploration wells and the 3D seismic coverage over the M2 block in the Mannar Basin (modified after Dushyendra *et al*., 2022). Dashed line across the 3D seismic coverage (gray color rectangle) shows the location of the seismic profile in Figure 3.

The formation of hydrocarbon reservoirs and seals in a shelf marine environment, among other factors, depends on sea-level changes (Bjørlykke, 2010; Miller *et al*., 2011). Ramkumar *et al*. (2011) discuss the Barremian–Danian sea level changes in the Indian portion of the Cauvery Basin. However, there is only a handful of studies on the relation between the relative sea level changes and depositional features in these stratigraphic intervals on the Sri Lankan side of the Cauvery and Mannar Basins due to the lack of well penetration and 3D seismic coverage. Among them, Dushyendra *el al.* (2022) discuss the depositional features in the Eocene and Paleocene sections in the M2 block (Figure 1) in the Mannar Basin, while Bandara *et al*. (2019) discuss that in sandstones intercalated with igneous rocks (Figure 2D) in the same block. Reuter *et al*. (2021) discuss the role of sea-level and climate changes in the assembly of Sri Lankan biodiversity using Miocene limestone in Sri Lanka. The objectives of this study were to identify the depositional features in the Albian and Aptian sections close to the coastal line under the M2 exploration block and then to compare them with the depositional features interpreted in the Paleocene and Eocene sediments in the M2 block by Dushyendra *et al*. (2022). This information will be useful to understand the change in the relative sea level and the deposition of reservoir facies in shelf marine environment in the Mannar Basin.

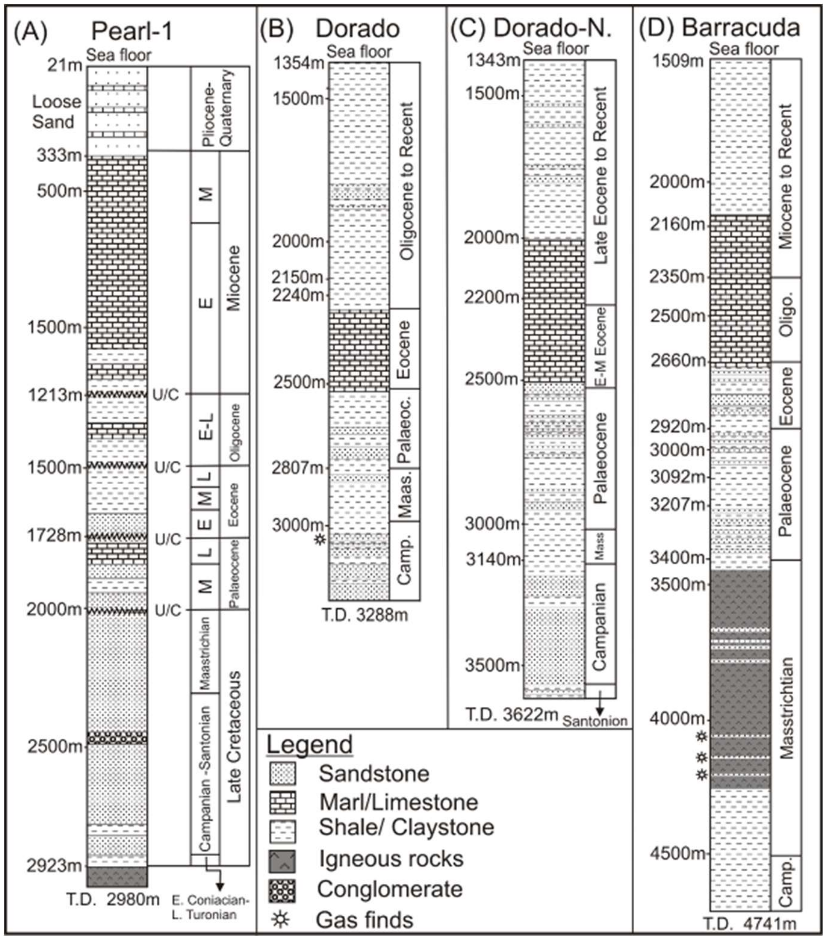

Figure 2: Generalised stratigraphic sections of the wells (a) Pearl-1; (b) Dorado; (c) Dorado-North and (d) Barracuda (modified after Premarathne *et al*., 2015). Oligo. = Oligocene; Palaeoc. = Palaeocene; Maas. = Maastrichtian; Camp. = Campanian; E = Early; M = Middle; L = Late; U/C = unconformity; T.D. = total depth

MATERIALS AND METHODS

Data, software and hardware

650 km^2 of post-stacked time migrated three dimensional (3D) seismic data, acquired over the M2 exploration block in the Mannar Basin (Figure 1) were obtained from the Petroleum Resources Development Secretariat of Sri Lanka (PRDS), the regulator of Sri Lanka's upstream petroleum industry. IHS Kingdom Suite (v. 8.3), on a workstation at the PRDS, was used for data analysis and interpretation. Some data from unpublished reports held at PRDS were also used for this study.

Because of the relatively thick (> 700 m) section of basalts interbedded with Maastrichtian sediments (Premarathne & Ranaweera, 2021) (Figure 2D), the quality of seismic data acquired and processed in 2012 was not clear below the Paleocene level. Therefore, the original data set has been broadband reprocessed in 2015. The reprocessing has significantly improved the seismic data compared to the previous data set due to the low frequency boost up and the reduction of high frequency random noise. This has improved the continuity of reflectors below basalts, offering better quality and greater interpretation confidence. Also, reprocessing helps in the identification of broad reservoir heterogeneities but has not improved the fault geometry significantly.

Data interpretation

In this study, three reflectors corresponding to the boundaries between the Early and Late Cretaceous (Albian Top), Albian and Aptian (Aptian top), and the crystalline basement (Basement) were interpreted using their seismic continuity and seismic to well correlation (Figure 3). Albian and Aptian top horizons were picked based on well correlation. In addition, three more horizons, one 60 ms below the Albian top horizon, and two, 120 ms and 450 ms below the Aptian top horizon were interpreted (seismic profiles in Figures 4, 5, 6 and 7). Lateral continuity and terminations of the reflectors were interpreted using on laps, down laps, top laps, and truncations.

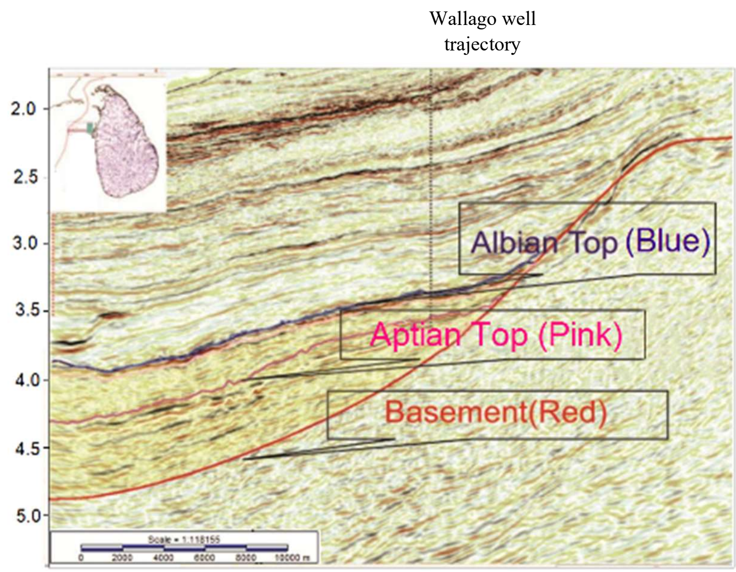

Figure 3: An E-W regional seismic profile (dashed line crossing the seismic coverage shown in Figure 1) showing the interpreted horizons.

Seismic attributes

The Root Mean Square (RMS) amplitude (Kenney & Keeping, 1962) (equation 1) was used in this study. It is a commonly used physical attribute calculated for a particular time window of stacked data. It demarcates the boundaries between different facies type and depositional environments. One of the weaknesses of the RMS amplitude attribute is that it is sensitive to noise as it squares every value within the time window. IHS Kingdom Suite was used to calculate the RMS amplitude.

$$xRMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \qquad \ldots(1)$$

Where, xRMS is Root Mean Square amplitude and n is number of amplitudes, $x_1, x_2, x_3 \ldots\ldots x_i$.

RMS amplitude was calculated for three time windows, a 60 ms window in the Albian section starting from the Albian top horizon and a 120 ms and 450 ms time windows in the stratigraphic interval below the Aptian top horizon (Figure 4). These intervals were denoted as +0.06 Albian Top (+0.06 ALT), +0.12 Aptian Top (+0.12 APT), and +0.45 Aptian Top (+0.45 APT), respectively. The positive (+) sign indicates that the time intervals are located below the Albian or Aptian top horizons.

RMS amplitude data from the three time windows were converted to RMS amplitude maps using the IHS Kingdom software. They were used to interpret depositional features in the time window. The same notation that refers to each time interval was used to refer to the RMS amplitude maps generated for the respective time intervals.

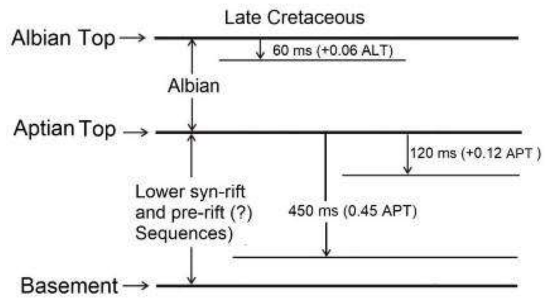

Figure 4: Relative positioning of the six (6) horizons interpreted and three time windows used to calculate RMS amplitude and create RMS amplitude maps (not to scale).

RESULTS AND DISCUSSION

Interpretation of horizons

Albian and Aptian top horizons appear as bright and continuous reflectors that could be easily mapped throughout the 3D seismic volume (Figure 3). They can be interpreted as a high amplitude, and acoustically hard (peak) events.

Depositional marine environments can be classified as shoreface/nearshore, shelf, and slope environments with increasing inferred paleo-water depths (Sahoo *et al*., 2014). In seismic data, shelfal sandstones are characterized by moderate to high amplitude and continuous reflectors (Sahoo *et al*., 2014). Accordingly, it can be thought that the top part of the Albian and Aptian stratigraphic sections have been deposited in a shelfal marine environment and they could be rich in sandstone. Albian sediments penetrated by most exploration wells drilled on the Sri Lankan side of the Cauvery Basin is bounded on top by an unconformity (Premarathne *et al*., 2015). However, such information is not available for the Albian strata in the Sri Lankan portion of the Mannar Basin since no well has reached this stratigraphic interval.

Below the Albian section exist the bottom-most syn-rift sediment and probably pre-rift sediment overlain by the crystalline basement. Premarathne *et al*. (2016) think that the oldest sediment overlain by the crystalline basement could be Late Jurassic in age. The maximum thickness of the stratigraphic section below the Aptian top in the study areas is around 550 ms (Figure 3).

The crystalline basement (below the red line in Figure 3), is composed of metamorphic rocks. It is characterized by variable amplitude reflections, with poor to low continuity. The interpreted sedimentary sequence wedges towards the east and abuts against the basement creating a three- way closure (Figure 3).

Interpretation of RMS amplitude maps

Relatively high amplitudes areas (bright spots) on seismic profiles appear in red and yellow colours in RMS amplitude maps, while relatively low amplitude areas appear in green and blue colours (+0.06 ALT, +0.12 APT, and +0.45 APT in Figures 5, 6, and 7, respectively). Note that the three RMS amplitude maps are not colour-normalized because each map required different colour intensities to highlight the depositional features appearing in them. The dark/ black coloured areas on the right in each RMS amplitude map indicate that respective reflectors do not extend to that area. The interface between coloured and dark coloured areas indicates the margin where each reflector terminates (truncations) against the crystalline basement.

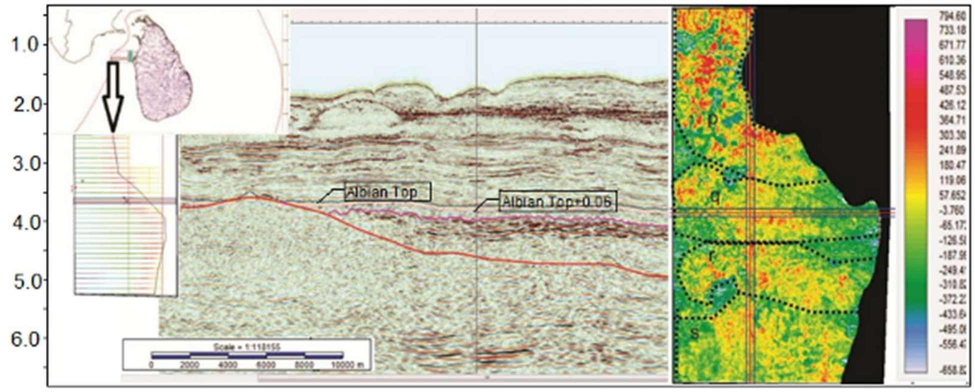

Figure 5: +0.06 ALT RMS amplitude map. p, q, r, and v, indicate the paleo submarine fan system. The seismic profile on the left side indicates the interpreted Albian top and +0.06 ALT horizons in peach and pink colours, respectively.

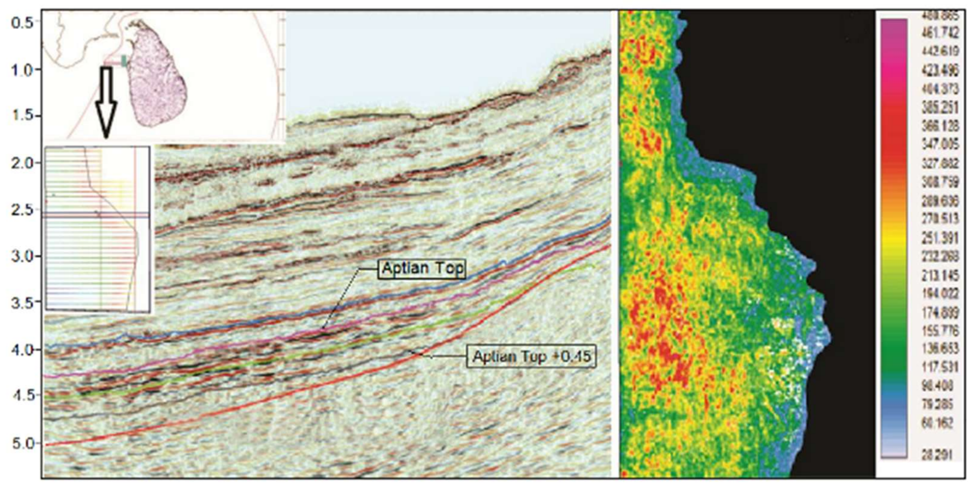

Figure 6: +0.12 APT RMS amplitude map. t, u, and v, indicate the paleo submarine fan system. The seismic profile on the left side indicates the interpreted Aptian top and +0.12 APT horizons in pink and peach colours, respectively.

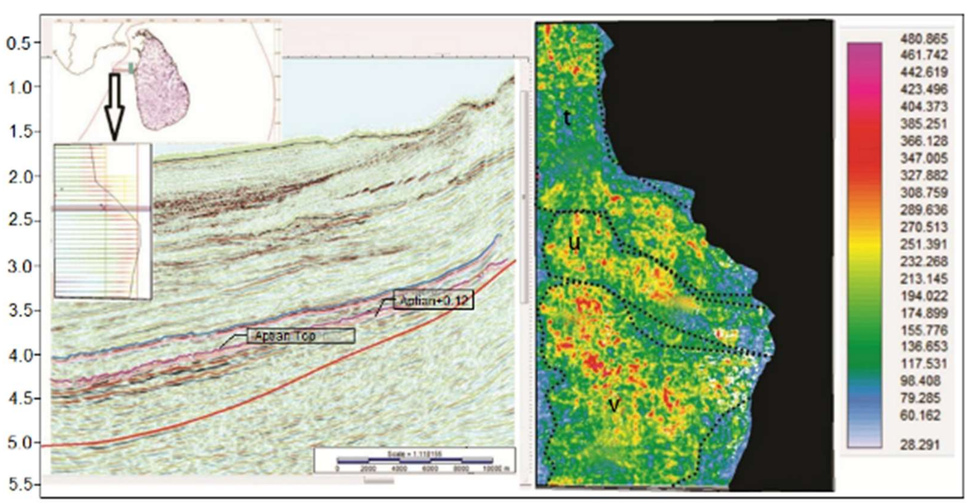

Figure 7: +0.45 APT RMS Amplitude map. The seismic profile on the left side indicates the interpreted Aptian top (pink) and +0.45 APT horizons in pink and gray colours, respectively.

However, such a distinct depositional feature cannot be related to the +0.45 APT RMS amplitude map, though it has a relatively high amplitude areas at its center. The time interval used to calculate the RMS amplitude in the +0.45 APT map is much larger compared to the other two time windows. This interval has considered the amplitude data in a 450 ms time window where the maximum thickness of the sediment package between the Aptian top horizon and the crystalline basement is about 550 ms (see Figure 3). Therefore, the +0.45 APT RMS amplitude map includes RMS amplitude data from almost the entire stratigraphic section.

John *et al*. (2010) think that the relatively high amplitude zones in RMS amplitude maps could be due to higher acoustic impedance contrast generated by the intercalation of sand and clay/silt. However, a higher acoustic impedance contrast can be generated by the intercalation of other lithologies and their pore fluids.

Interpretation with previous work

Dushyendra *et al*. (2022) have interpreted the depositional features in the Eocene and Paleocene sections in the M2 block using the same seismic attribute used in this study, but on a much larger seismic coverage (1850 km^2). Their study has unraveled the existence of a multi-level Eocene and Paleocene submarine fan system emerging from the west coast of Sri Lankan and a northeast-southwest trending deep water channel system in the Eocene section (Figures 8 and 9). The Eocene fan systems are located relatively distant (~18 km) from the coastline (Figure 8), while the Albian and Aptian fan systems interpreted in this study occur relatively closer to the coastline (Figures 5, 6, and 9). Such a distinct fan system is not visible in the Paleocene (Figure 9).

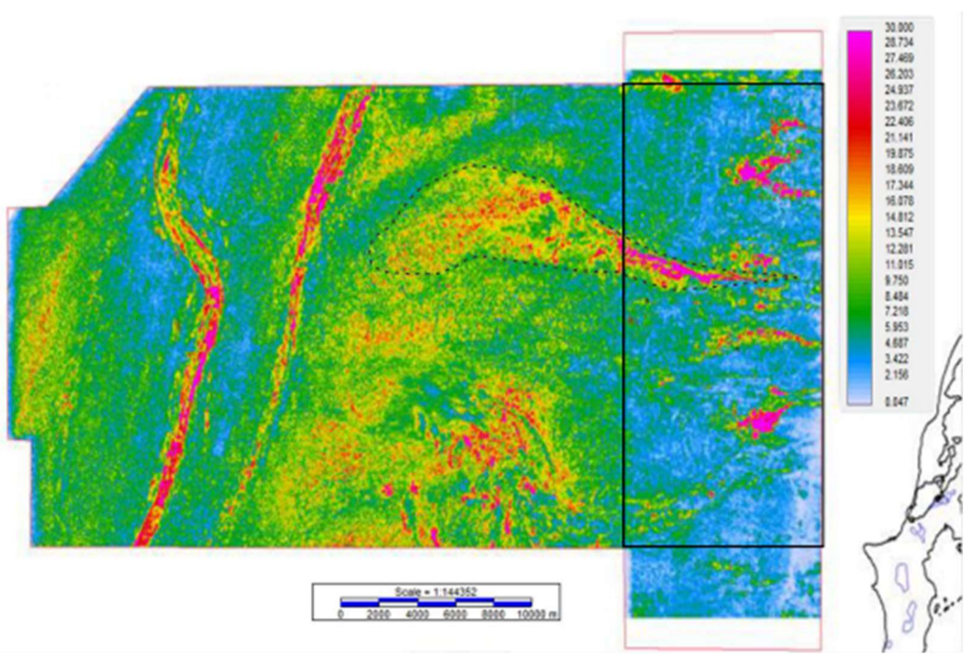

Figure 8: RMS Amplitude map showing submarine fan and channel systems in the Eocene section. RMS Amplitude has been calculated for a 50 millisecond time interval between the Paleocene-Eocene reflector and a horizon 50 milliseconds above it (after Dushyendra *et al*., 2022). The rectangle indicates the seismic data coverage of this study.

The rate of sedimentation on continents and their margins are controlled by the relative sea level, which results from the combined effect of eustatic sea-level and tectonic subsidence or upliftment (Miller *et al*., 2011). Eustatic sea levels in the Cretaceous are relatively higher compared to that in the Paleocene and Eocene (Vail *et al*., 1977; Haq *et al*., 1987; Kominz *et al*., 2008). The Collison of the Indian and Eurasian tectonic plates in the Early Eocene created regional upliftment and the Himalayan orogeny (Torsvik *et al*., 2002). As a result, an erosional unconformity in the Eocene section can be observed in many of the hydrocarbon exploration wells drilled in the Cauvery and Mannar Basin (Sasthri *et al*., 1981; Premarathne, 2015; Premarathne *et al*., 2016). Based on these observations, it could be thought that there had been high relative sea levels in the Mannar Basin in the Albian and Aptian compared to that during the Eocene, which agrees well with the Paleo submarine fan system located distant to the coastline in the Eocene compared to the Albian and Aptian.

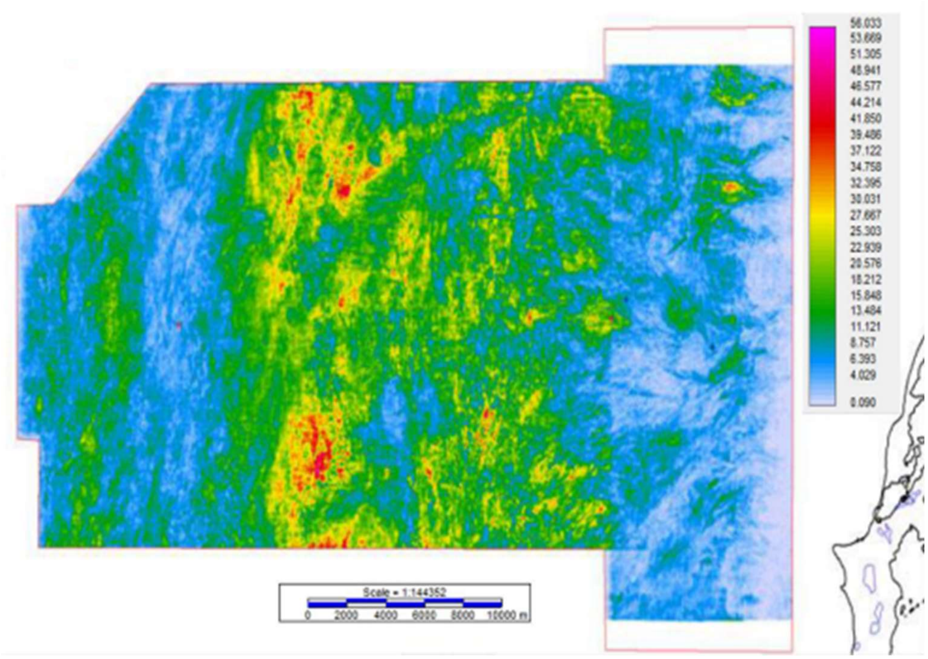

Figure 9: RMS Amplitude map showing submarine fan and channel systems in the Paleocene section. RMS Amplitude has been calculated for a 100 millisecond time interval between the Cretaceous-Paleocene reflector and a horizon 100 milliseconds above it (after Dushyendra *et al*., 2022).

The absence of a fans system in the Paleocene could be related to the low sea levels, sediment starvation or the presence of an erosional unconformity. Around 500 m thick Paleocene stratigraphic section in the Dorado-North and Barracuda wells (Figures 2C and 2D) rules out the notion of sediment starvation. However, the relatively thin Paleocene stratigraphic interval bounded on top by an unconformity (Paleocene Eocene boundary) is seen in the stratigraphic section of the Pearl-1 well (Figure 2A). Baillie *et al*. (2002) are of the opinion that the rifting between indo-Lanka landmasses, which ceased at the end of the Cretaceous period, created regional upliftment. This is enunciated as an unconformity in some regional wells (e.g. Figure 2A). On the other hand, the relative sea level curve that Ramkumar *et al*. (2004) developed for the Barremian-Danian strata of the Cauvery Basin indicates relatively high sea levels in the Albian and Aptian compared to that in the Danian. Hence the absence of Paleocene submarine fan system could be related to the non-deposition and/or erosion due to low relative sea levels.

CONCLUSIONS

A distinct paleo submarine fan system and a distributary channel system in between the fans occur in the Albian and Aptian close to the western coastline under the M2 exploration block in the Mannar Basin, Sri Lanka. They have been deposited in a shelf marine environment. The formation of these fans has been influenced by the sea level, which was relatively high during the Albian and Aptian compared to the Paleocene and Eocene.

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