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Regionwide Geodynamic Analyses of the Cenozoic Carbonate Burial in Sri Lanka Related to Climate and Atmospheric CO_2

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Abstract: Asian tectonism and exhumation are critical components to develop modern icehouse climate. In this study, stratigraphic sections of eight wells in the Mannar and Cauvery basins were considered. The author demonstrated that this local system records a wealth of information to understated regional and global paleoclimatic trends over the Cenozoic era. The lithostratigraphic framework has been generally characterized by deposition of carbonate-rich sediments since the Middle Cenozoic. Geological provenance of carbonate sediments had probably related to local sources from Sri Lankan and Indian land masses. The main controlling factor of carbonate burial is rather questionable. However, this carbonate burial has indicated the possible link to the Middle to Late Cenozoic global climatic transition. This major climatic shift was characterized by long-term reduction of atmospheric carbon dioxide concentration over the Cenozoic era. Consequently, this geological trend (carbonate burial) has a straightforward teleconnection to the global cooling towards the glaciated earth followed by the development of polar ice sheets that persist today.

Keywords: Mannar Basin, Cauvery Basin, Sri Lanka, paleoclimate, carbonate burial, Cenozoic era.

Introduction

The Cenozoic era consists of three periods, i.e., the Paleogene (from 66.0 to 23.03Ma), Neogene (from 23.03 to 2.58Ma) and Quaternary (from 2.58 Ma to the Recent), and seven epochs from the Paleocene to Holocene based on the International Stratigraphy Chart (Cohen et al, 2013). The earth’s climate has undergone a significant and complex evolution during the Cenozoic era as a result of the topographic development of the oceanic Basins (e.g., passage opens), movement position of continents (e.g., plate reorganization/seafloor spreading and plate uplift) and earth’s orbital geometry (Kennett, 1977; Zachos et al., 2001; Tripati et al., 2009; Ratnayake, 2016a). The global climate has thus drastically fluctuated from greenhouse (Early Cenozoic) to icehouse (late Cenozoic) states during the past ~66 Ma and marked several glaciations (e.g., Oi-1 and Mi-1 events). Chemical/physical weathering and erosion of carbonate and silicate rocks due to tectonic activities can also potentially influence the reduction of atmospheric carbon dioxide concentration and surface temperature (Volk, 1989; Raymo and Ruddiman, 1992; Gaillardet and Galy, 2008). However, some researchers argued this widely accepted mechanism with new geochemical data of the dissolved oceanic beryllium ($^{10}Be/^{9}Be$) isotopic ratio as a paleo weathering proxy (Goddéris, 2010; Willenbring and Blanckenburg, 2010). Consequently, tectonically uplifted South Asia has still considerable implications on the understanding of source rock weathering to the long-term global climatic transitions with respect to plate motion and orogeny (Raymo and Ruddiman, 1992; France-Lanord and Derry, 1997; Willenbring and Blanckenburg, 2010). In contrast, several biogeochemical processes, such as precipitation of calcite by microorganism, corals and shelly animals control carbonate burial into the geological reservoirs. The cycle of carbonate burial also affects partial pressure of atmospheric carbon dioxide (pCO_2) over geological time (Ridgwell and Zeebe, 2005). Therefore, geological strata provide wealthy records of chemical and physical interactions in the geosphere and biosphere as well as in the hydrosphere (e.g., Quade et al., 1989; Prell and Kutzbach, 1992; Pagani et al., 1999; Guo et al., 2002; Jia et al., 2003; Ratnayake, 2016 b).

One of the best records of global Cenozoic climatic variations comes from the central Indian Ocean. Sri Lanka jurisdiction is characterized by several marginal marine Basins (e.g., the Mannar and Cauvery basins) in the central Indian Ocean. These localized sedimentary environments can also record global climatic signatures. This study discusses principal sedimentological changes and provenance of carbonate sediments in Sri Lanka. In this article, an attention has also been given to correlate sedimentary carbonate burial in Sri Lanka with respect to the major regional and global paleoclimatic changes

Table 1 Drilled well information of the Mannar and Cauvery Basins in Sri Lankan jurisdiction.

Well	Sedimentary Basin	Classification	Water depth (m)	Total depth (m)	Drilled year
Pearl 1	Mannar Basin	Exploration well	21.03	3050.44	1981
Dorado	Mannar Basin	Exploration well	1383	3288	2011
Barracuda	Mannar Basin	Exploration well	1509	4741	2011
Dorado North	Mannar Basin	Exploration well	1346.4	3622	2011
Pesalai 1	Cauvery Basin	Stratigraphic well	N/A	2593	1974
Pesalai 2	Cauvery Basin	Stratigraphic well	N/A	2634.5	1975
Pesalai 3	Cauvery Basin	Stratigraphic well	N/A	2917	1976
Palkbay 1	Cauvery Basin	Exploration well	15.24	2386.28	1976
Delft 1	Cauvery Basin	Exploration well	12.8	1784.6	1976
Pedro 1	Cauvery Basin	Exploration well	12.8	2011.68	1981

during the Cenozoic era.

Study Area and Samples

Geological background

The offshore Mannar and Cauvery Basins are located between India and Sri Lanka (Fig. 1). These sedimentary Basins were probably developed as a result of the breakup of East-West Gondwana around 167 Ma (Molnar and Tapponnier, 1975). The rifting and subsequent drifting of continental fragments were associated with the opening of the Indian Ocean (McKenzie and Sclater , 1971; Norton and Sclater, 1979). In addition, intracontinental rifting formed graben structures on Indian and Sri Lankan margins (Shaw, 2002). The secondary openings of these offshore sedimentary basins began during the early Cretaceous of 137-124 Ma. It was followed by the northward movement of Indian plate as a single landmass before the sequential breakup of Sri Lanka, Laxmi ridge, Seychelles and Madagascar (Chatterjee et al., 2013). The igneous intrusions were recorded in the Mesozoic sediments. However, no volcanogenic sediments were observed in the Cenozoic sediments of offshore, Sri Lanka. The tectonic subsidence continued during the Cenozoic era and sediments were mainly deposited under shallow to deep marine stages. Thus, it led to deposition of thick pelagic clay, sandstone and carbonate shelf sediments under the influence of tectonic and climatic changes over the regional scale.

Materials and Methods

The drill core samples were considered from the offshore Mannar and Cauvery Basins (Fig. 1). In this study, sedimentary profiles of the Pearl-1, Dorado North, Dorado, Barracuda, Pesalai-1, Palk Bay-1, Delf-1 and Pedro-1 were examined based on data available from the literature and original sedimentological observations. These stratigraphic and exploration wells were drilled from 1974 to 2011 by different consortia. Sampling sites consist of wide range of water depths and drilling depths in the Mesozoic-Cenozoic sedimentary profiles (Table 1).

In detail, lithological compositions were determined based on mineralogy, color and cementing materials of cutting samples. The Dorado North and Barracuda cutting samples were extensively examined

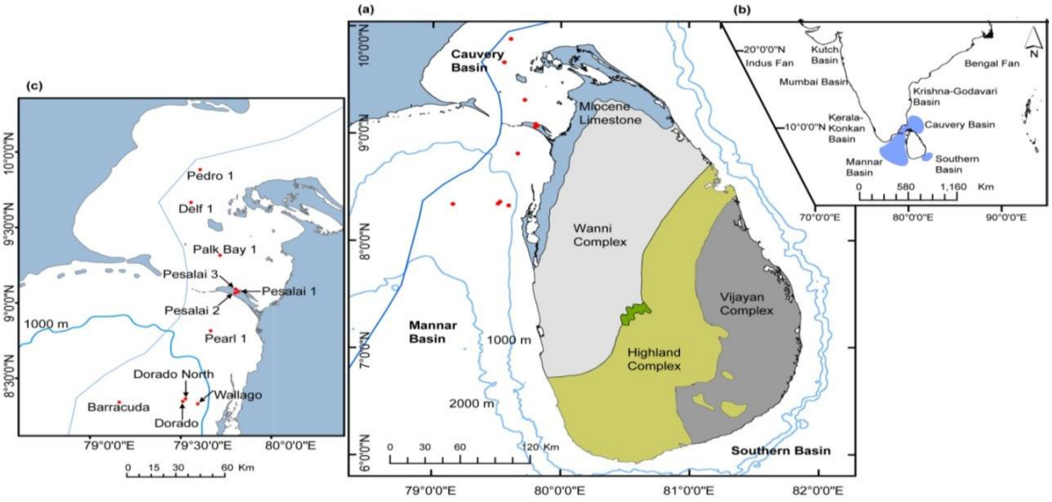

Fig. 1 (a) Simplified geological map of Sri Lanka shows the Mannar basin, Cauvery basin and Southern basin, (b) inserted regional map shows surrounding oceanic Basins on the Indian subcontinent and (c) onshore and offshore stratigraphic and exploration wells in the Mannar and Cauvery basins (modified after Ratnayake et al., 2014, Ratnayake and Sampei, 2015 b) .

at Shimane University, Japan. Moreover, remaining and available cutting samples were stored at Petroleum Resources Development Secretariat (PRDS) sample room Colombo, Sri Lanka. The lithostratigraphic columns were reconstructed using fitting of lithological compositions into available unpublished age profiles based on paleontological and geophysical reports of the Petroleum Resources Development Secretariat. Variations of principal lithological boundaries were finally identified on the basis of compositions, following core observations and the efforts of several workers (Ratnayake et al., 2014; Kularathna et al., 2015; Premarathne, 2015; Ratnayake and Sampei, 2015 b; Premarathne et al., 2016).

Results and Discussion

Figures 2, 3 illustrate the distribution of main lithological units in the representative wells of the Mannar and Cauvery Basins. Stratigraphic relation-ships among each facies are quite complicated due to lateral facies variations, both from east to west and from north to south under a wide variety of depths ranging from the onshore/basin margin to center deposits. Hiatuses and erosional unconformities also complicated the correlation of each facies in these sedimentary successions. However, the Cenozoic stratigraphy can be divided into two major depositional sequences based on broad-scale facies analysis. The lower sedimentary sequence mainly composed of mudstone and sandstones intercalations (Figs. 2, 3). These siliciclastic sediments were probably deposited in a marginal marine environment (Ratnayake et al., 2014). It is overlain by carbonate-rich sediments of argillaceous marl/marlstone to limestone (Figs. 2, 3), and probably associated with relative high sea-level/water depths. This sequence stratigraphic boundary is clear in all stratigraphic and exploration wells of the Mannar and Cauvery basins (Figs. 2, 3). However, their facies variations/basin fill processes have shown a complicated time intervals followed by local topography (bathymetry) of the basins. In detail, carbonate-rich facies were dominantly recorded in the deepwater basin-centers (e.g., Barracuda, Dorado and Dorado North wells) since the late Paleocene/Eocene epochs (Fig. 2). The present water depths are greater

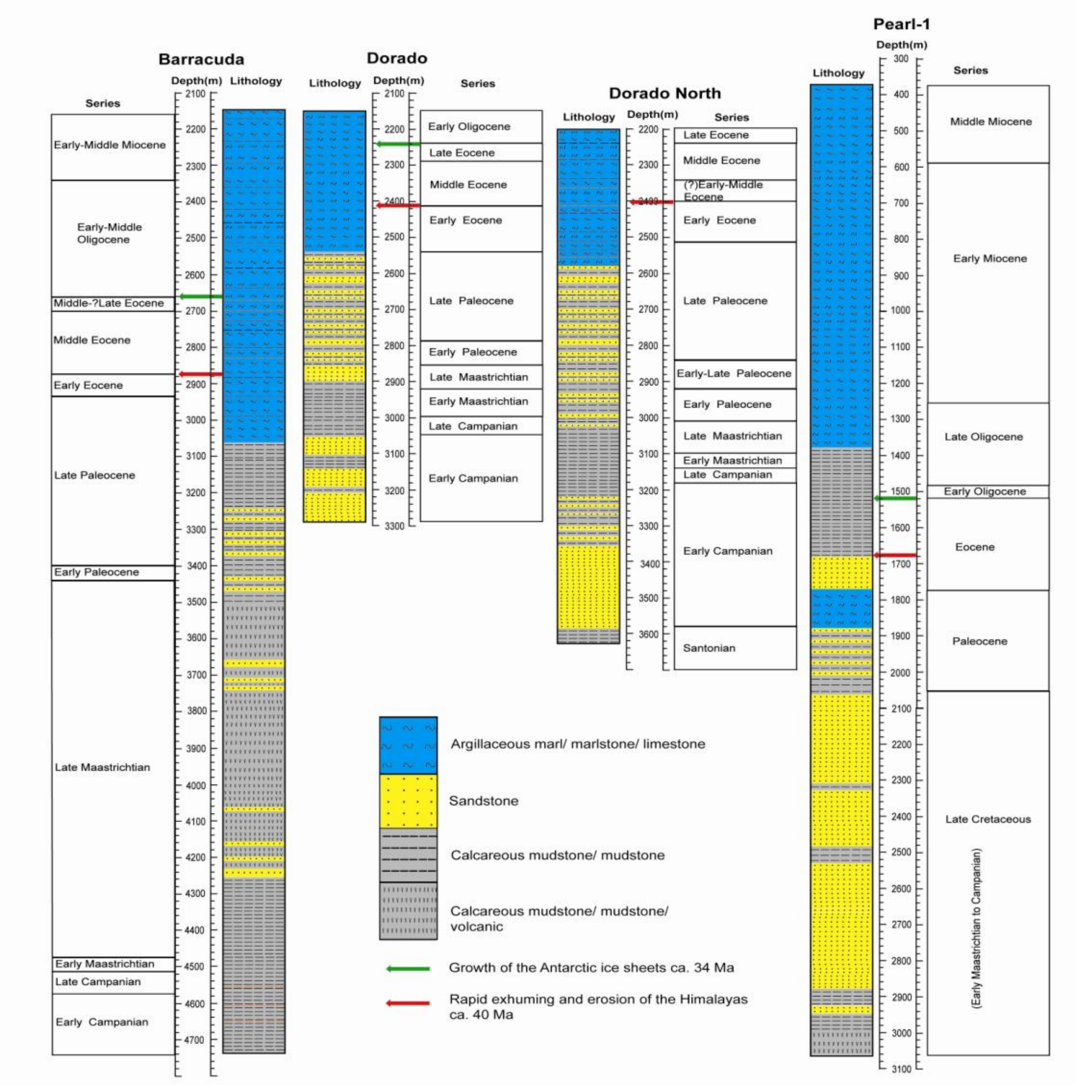

Fig. 2 Simplified stratigraphic columns of the Mannar Basin. (Note: Stratigraphic columns of the Dorado North, Dorado and Barracuda wells were illustrated considering depths to the present sea-level. However, stratigraphic column of the Pearl-1was illustrated without considering depth to the present sea-level).

than 1300 m in these deepwater exploration wells (Table 1). Similarly, carbonate burial was permanently developed in the shallow water basin-margins (e.g., Pearl-1, Pesalai-1, Palk Bay-1, Delf-1 and Pedro-1 wells) since the Oligocene/Miocene epochs (Fig. 3). The present water depths are less than 25 m in the shallow water stratigraphic and exploration wells (Table 1). This trend suggests that the extensive carbonate burial was predominantly developed with limited clastic input and isolated bathymetric highs (relatively high sea-level). Consequently, this major facies change can be probably controlled by oceanic chemistry during the Cenozoic era (Fig. 3).

Briefly, the early Cenozoic was characterized by noticeably higher concentrations of greenhouse gasses and a much warmer global temperature as well as poles with little or free ice in contrast to the present day (Pearson and Palmer, 2000; Zachos et al., 2001, 2008; Moran et al., 2006). For example, the earth experienced short-term and extreme global warming events such as the Late Paleocene Thermal Maximum (LPTM) and the early Eocene Climatic Optimum (EECO) during the early Cenozoic. The LPTM and EECO periods are characterized by a 5 to 6°C rise in deep-sea temperature and a long-term maximum in atmospheric carbon dioxide level respectively (Fricke et al., 1998; Bains et al., 1999; Lourens et al., 2005; Zachos et al., 2005, 2008; Weijers et al., 2007). However, the middle to late Cenozoic climate can be generally considered as global cooling era due to a sharp decline in atmospheric carbon dioxide level of more than 2000 ppm to below 500 ppm (Pearson and Palmer, 2000; Kent and Muttoni, 2008; Edwards et al., 2010). This drawdown of atmospheric CO_2 concentration caused the growth of large continental ice sheets in the Antarctica (ca. 34 Ma) and the Arctic Oceans (ca. 3 Ma) over the Middle to Late Cenozoic (Molnar and England, 1990; Raymo and Ruddiman, 1992; Pearson and Palmer, 2000; Pälike et al., 2006; Tripati et al., 2009).

Geochemical and isotopic data also support the hypothesis of climatic transition from greenhouse to icehouse states. The marine $^{87}Sr/^{86}Sr$ isotope composition can be used as a proxy for chemical weathering rates (Hess et al., 1986; Richter et al., 1992). The measured $^{87}Sr/^{86}Sr$ ratio in foraminifera from the Indian foreland basin and Bengal basin suggested uplift and erosion of the Himalayas starting

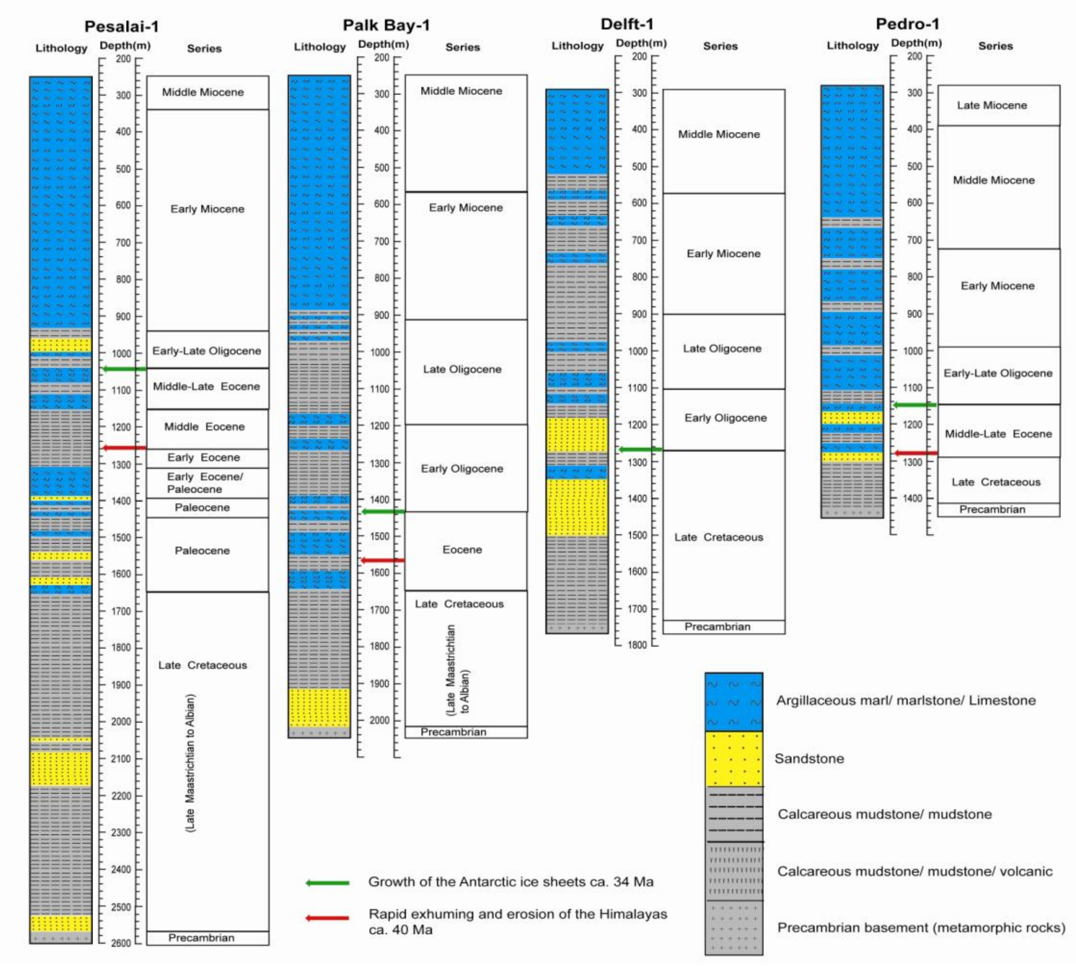

Fig. 3 Simplified stratigraphic columns of the Pesalai-1, Palk Bay-1, Delf-1 and Pedro-1 wells in the Cauvery basin.

ca. 40 Ma ago (Najman et al., 2000, 2008). Similarly, the changes of benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ values can reflect changes of ice-volume and temperature (Zachos et al., 2001; Pearson et al., 2009; Licht et al., 2014). For example, the relatively high $\delta^{18}O$ values (>2.5‰) can probably suggest the development of permanent ice sheets according to the global deep-sea isotope records from over 40 sites in Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) (Zachos et al., 2001). The compiling of above literature suggests that plate motion and orogeny in Asia is critical to understand global climatic changes during the Cenozoic era. Therefore, in this study, the author's main aim is to correlate sedimentological evidence in marine sedimentary cores of Sri Lanka in relation to the timing of well-known climatic shift from greenhouse to icehouse states.

Development of the middle Cenozoic carbonate platform of Sri Lanka was generally initiated due to the movement of Indian plate into northwards warmer latitudes (Ratnayake et al., 2014). Similarly, developments of the middle to late Cenozoic (Eocene-Miocene) carbonate platforms are widely recorded in the surrounding oceanic Basins along the margin of Indian subcontinent (Whiting et al., 1994; Davies et al., 1995; Métivier et al., 1999). For example, the carbonate growth in the western continental margin of India began during the late Oligocene and resulted in the vertical aggradation up to 3000 m, and lateral progradation of 100 km thick carbonate sediments (Whiting et al., 1994). Moreover, the Cenozoic carbonate burial in Southeast Asia was controlled by the clastic influx, tectonics and oceanography/climatic fluctuations, as succinctly reviewed by Wilson (2002). In general, Himalayan rocks have been suggested as the main cause for the development of carbonate platform in the Bay of Bengal and Indus Fan sediments. Specifically, weathering of newly and continues uplifted Himalayan rocks caused to accumulate carbonate sediments in last ca. 40 Ma, which may be due to combined rapid physical denudation with chemical weathering and fast transportation of sediments to the Indian Ocean (Molnar and England, 1990). Moreover, the erosion of sediments also plays a fundamental role in a burial of organic carbon along with carbonate carbon in the surrounding oceanic Basins (Beck et al., 1995; France-Lanord and Derry, 1997). However, here the author's unresolved question is the main controlling factor to precipitate carbonate sediments in the deepwater Mannar and shallow water Cauvery Basins. Because carbonate deposition in these sedimentary successions can be mainly controlled by several factors such as an increase in weathering and erosion of silicate rocks, apparent increase in precipitation of calcite by coccolithophores and foraminifera, results in higher $p\text{CO}_2$ at the surface, and/or a combination of these processes. It is still difficult to identify exact phenomena using only sedimentary profiles and it leaves as an unresolved question for future studies.

In addition, the permanent carbonate accumulation in the deeply buried (present water depth > 1300 m) sediments occurred before the middle Eocene (ca. 40 Ma ago). Therefore, these observations clearly suggested that neither Himalayan erosion nor chemical weathering has been directly influenced in an initiation of carbonate platform in the deeply buried offshore sediments in Sri Lanka. Furthermore, geological strata indicate carbonate accumulation after the Eocene-Oligocene climate transition (ca. 34 Ma) in the relatively shallow buried (present water depth < 25 m) sediments (Figs. 2, 3). This period is characterized by a sharp decline in atmospheric CO_2 concentration, as demonstrated by paleoclimatic proxy studies and model simulations across the globe (Raymo and Ruddiman, 1992; Zachos et al., 2001, 2008; Edwards et al., 2010). Although the main controlling factor of carbonate precipitation is unknown. Well-preserved and permanent $CaCO_3$ deposition in these sedimentary basins had a close teleconnection with the Cenozoic global cooling towards the present glaciated earth after the late Eocene/early Oligocene climatic transition (Pearson and Palmer, 2000; Pearson et al., 2009; Licht et al., 2014).

To know the provenance of carbonate rocks in the offshore sedimentary basins in Sri Lanka is an essential point to understand the local system in Sri Lanka. It is determined that ODP sites 717, 718 and 719 of the far south of Sri Lanka (~800 km) represent the most distal regions of Himalayas sediments during the Quaternary (Clift, 2006). The Quaternary sediments in the Indian Ocean show the highest sedimentation rates after the intensification of modern monsoon precipitation in South Asia (Harris, 2006). Consequently, it is suggested that proto-/Himalayan topographic elevations during the Eocene to Miocene epochs were not sufficient to provide enough suspended and dissolved sediment loads in Sri Lanka jurisdictions of the Mannar and Cauvery Basins, based on mainly ODP Leg 116 evidence in sites 717, 718 and 719. The ODP Leg 166 was designed to investigate the history of the tectonic uplift in Asia, erosion of the Himalayas, and sediment transport and deposition mechanisms of the distal Bengal fan (Cochran et al., 1987). In addition, this interpretation is highly dependable on multi-stages elevation history of the Himalayan region in the literature (Harrison et al., 1992; Prell and Kutzbach, 1992; Raymo, 1994; Garzione, 2008; Wang et al., 2008). Therefore, the uplifted rocks in Sri Lankan and Indian landmasses (Eastern Ghats) can be suggested as possible sources for the carbonate burial in these sedimentary profiles under the tropical climate.

Another scenario could be that the uplifting of larger mountain plateaus in the Indian subcontinent provides a source of heating in the lower atmosphere during the summer, which creates a vast, low-pressure system over the subcontinent. A broad uplifted mountains act as a barrier and changing the Asian monsoon precipitation (Ramstein et al., 1997; Harris, 2006; Dupont-Nivet et al., 2007). There is no direct method to measure the past monsoon precipitation in these sedimentary basins based on stratigraphic and sedimentological features. In addition, the timing of intensification of the South Asian summer monsoon has been questioned. Because it depends on catchment area, sampling resolution, sedimentation rate/ distribution and analytical methods (Ratnayake et al., 2017). In what follows, the Northern Hemisphere summer monsoon probably intensified in South Asia and decreased precipitation (aridification) in North/ Central Asia since them middle to late Miocene (Pagani et al., 1999; Dettman et al., 2001; Zhisheng et al., 2001; Gupta et al., 2004; Dupont-Nivet et al., 2007). Although the author never expects Himalayan sediments in the Mannar or Cauvery Basins during the Miocene, the carbonate-rich offshore (Figs. 2, 3), and onshore rocks in the Miocene (Ratnayake and Sampei, 2015a) could probably be deposited under the initiated present Asian monsoon seasonality, according to an observed paleoclimatic/ sedimentological teleconnection with the regional scale.

Conclusion

Geological evidence indicates that carbonate-rich sediments were mainly deposited since the Late Paleocene in the deep water Mannar Basin and started after the Eocene-Oligocene climatic transition in the shallow water areas of the Mannar and Cauvery Basins. In a broad sense, the trend of carbonate deposition in the offshore area of Sri Lanka had a relationship with long-term (million-year scale) gradual reduction of atmospheric carbon dioxide concentration, and formation of Antarctic continental ice-sheets towards the present glaciated Earth. The geological provenances of pelagic carbonate sediments in Sri Lanka could be probably related to local sources rather than proto-/Himalayan sources. It has also been proposed that the Miocene geological strata could probably deposit under the influence of present summer monsoon seasonality in South Asia.

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