

STRATIGRAPHIC RESPONSES TO MAJOR DEPOSITIONAL EVENTS FROM THE LATE CRETACEOUS TO MIOCENE IN THE MANNAR BASIN, SRI LANKA

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ABSTRACT

The pericratonic Mannar Basin of Sri Lanka is characterized by sedimentary facies, sedimentation rates and a burial history from the Late Cretaceous to Miocene using two exploration wells. Basin modeling software was used to calculate standard burial history of the basin. The Late Cretaceous to Late Paleocene lithology of the Barracuda well recorded mud dominant sediments and interbedded sandstone with volcanogenic materials, and the Dorado North well recorded sand dominant sediments and interbedded mudstone. Therefore, the Dorado North well was subjected to relatively high-energy, and the Barracuda well was subjected to relatively low-energy depositional settings. The Late Maastrichtian sediments of the Barracuda well are marked by thick volcanogenic sediments. At the end of the Late Paleocene, sedimentary facies drastically changed from calcareous mudstone to argillaceous marl / marlstone in the both wells. These facies variations have an apparent relation with the sedimentation rates in the basin. Mud sedimentation rates were about double in the Barracuda well during the Campanian to Paleocene than in the Dorado North well and were approximately equal in the both wells during the Eocene, Oligocene and Miocene. This shift was interpreted as continuous subsidence of the basin and changes of an arid climate to warm and humid tropical condition. The highest sedimentation rate was due to igneous activities in the region near the Barracuda well during the Maastrichtian. The lowest sedimentation rate was recorded during the Eocene suggesting that the timing of collision between Indian and Asian plates. Burial history by 1D modeling indicated rapid subsidence from the Late Cretaceous to the Paleocene during the rift transition stage. Subsidence rate was decreased during the Eocene. The lithostratigraphic records in the basin were mainly influenced by tectonic settings and paleoclimate.

Keywords: *Lithostratigraphy, Sedimentation, Tectonics, Petroleum system, Paleoceanography*

INTRODUCTION

The Mannar Basin of Sri Lanka contains important sections of a thick Mesozoic and Cenozoic sediments of marine and continental

origins (Rao et al., 2010). The Petroleum Resources Development Secretariat of Sri Lanka (PRDS) recently carried out drilling program in the Mannar Basin using the deep water drill ship *Chikyu* and obtained numerous

rock cutting samples and observed several gas layers. Three offshore exploration wells were completed at the first stage of drilling program in 2011. The rock samples could indicate the nature of the basin system, geological characteristics and depositional environment of the basin. Data from the rock samples also can lead basin modeling. Sedimentary basin modeling using computer simulations is a geologically challenging task to reconstruct the basin system. Study of sedimentary basins considering the tectonic settings, paleoclimate and stratigraphic outlines provides fundamental evaluation of geological history and oil/gas systems (Rose et al., 2011). The USGS assessment on sedimentary basin with oil/gas potential was carried out in the South Asian region based on data provided by the Indian Directorate General of Hydrocarbons, published geologic information, commercial data from oil and gas wells and fields, and field production records (Klett et al., 2011). However, in this assessment, the Sri Lankan shelf was escaped due to paucity of data during that time. The purpose of this study is to identify the significance of the Mannar Basin in the context of the geological, sedimentological and tectonic history of the region.

LOCATION AND GEOMORPHOLOGY

The Mannar Basin is situated to the west to northwest of Sri Lanka (Figure 1). The continental shelf of Sri Lanka is narrow (~30 km) and depicts steep slopes beyond the 500 m isobaths (Desa et al., 2006; Sreejith et al., 2008). Bathymetry of the basin ranges from 20 m to in over of 4,000 m. The area of the basin under the Sri Lankan jurisdiction is about 45,000 km² (Jayawardena, 2013). The Mannar Basin is filled with 6 s (seismic two-way travel time) thick succession of sediments (Desa et al., 2006). NNW-SSE trending Comorin Ridge, between 2-6° N latitudes and 77-79° E longitude, marks a significant crustal boundary in the basin (Sreejith et al., 2008). The Comorin Ridge has a relief of about 1,000 m from the surrounding bathymetry of ~3,500 m (Desa et

al., 2006).

REGIONAL TECTONIC SETTING

The basement of the Mannar Basin consists of Precambrian metamorphic rocks and continental to transitional crust (Cooray, 1984; Desa et al., 2006). The Precambrian rocks of Sri Lanka show a similarity to rocks of southeast India (e.g., Cooray, 1984; Tsunogae et al., 2008).

Therefore, the basement can be divided into four areas based on the terrain age and composition. The gravity and magnetic

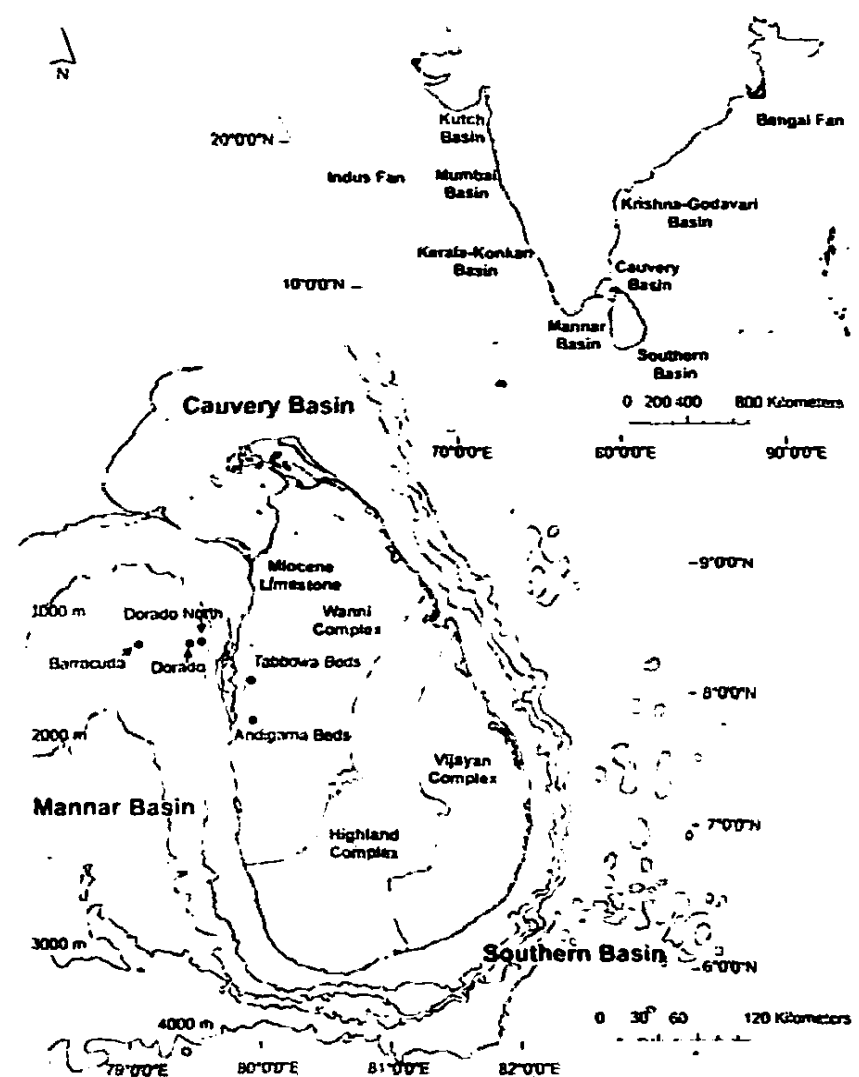


Fig. 1 Generalized regional map shows the Mannar Basin, Cauvery Basin, Southern Basin, Krishna-Godavari Basin, Kerala-Konkan Basin, Mumbai Basin, Kutch Basin, Bengal Fan and Indus Fan. Insert simplified geological map of Sri Lanka (after Cooray, 1994) shows all major litho-tectonic units and Miocene limestone beds, Andigama and Tabbowa Jurassic beds and locations of exploration wells.

anomalies of the southernmost part of the basin indicated highly attenuated and intruded continental to transitional crust (Ramana et al.,

2001; Sreejith et al., 2008). Consequently, continental to oceanic boundary of the basin lies about 250 km off southwest of Sri Lanka. Evolution of the N-S trending Mannar Basin consisted of four main phases, including a syn-rift phase, rift transition phase, thermal sag phase and a passive margin stage (Desa et al., 2006; Sreejith et al., 2008).

The Indian Ocean floor is characterized by a system of active spreading ridges that now separate into four major fragments of the former supercontinent, Gondwana: Africa, India, Australia and Antarctica (Molnar et al., 1988; Katz, 2000; Chatterjee et al., 2013). The breakup of Eastern Gondwanaland and the successive rifting, drifting, collision, and subduction in space and time are responsible for the present day configuration (Katz, 2000; Chatterjee et al., 2013). Gravity models have determined relatively thin (~21 km thick) continental crust on the western margin of the basin, which may have evolved due to the crustal stretching during the rift process (Sreejith et al., 2008). The oldest formations could deposit during the syn-rift phase. The 2D seismic data in the Mannar Basin shows evidence of the oldest sedimentary sequence below the Early Cretaceous (Rao et al., 2010). Also, the Late Jurassic sediments are documented in the drill core samples from the adjacent Cauvery Basin and outcrops in faulted basins (Tabbowa, Andigama and Pallama) within Wannu Complex of Sri Lanka (Figure 1).

Strong gravity and magnetic anomalies in the southern part of the Mannar Basin is interpreted as evidence of a lateral migrating tip of a seafloor spreading ridge flanked on either side by a highly attenuated crust. The seafloor created during the Early Cretaceous is estimated to have evolved with variable half-spreading rates (5.5 cm/yr-131 Ma, ~5.25 cm/yr-126.7 Ma and 1.53 cm/yr-121 Ma). Also, the Middle Cretaceous crust is evolved with comparability slower half spreading rate (0.6 cm/yr-84 Ma). Further, changes of fracture systems from the Early Cretaceous crust (~NNW-SSE) to the Tertiary crust (N-S)

indicate a change in the spreading direction of Sri Lanka (Desa et al., 2006). The stretching process was eventually led to continental splitting and it also contributed to the evolution of the rifted offshore sedimentary basins on western and eastern margin of the India (Sreejith et al., 2008).

The thermal sag phase of the Mannar Basin is affected by separation of Madagascar and Seychelles from India (Torsvik et al., 1998). PRDS data reveal that the youngest age of K^{40}/Ar^{40} whole rock dating of penetrated igneous layers in the Pearl-I exploration well is 76.8 Ma. Similarly, the mean Ar^{40}/Ar^{39} age determination of volcanic rocks and dikes (n=17) from the timing of hotspot related volcanism during the breakup of Madagascar and India recorded 87.6 ± 0.6 Ma (Storey et al., 1995).

The northward movement was drastically reduced after the subduction of Indian plate beneath the Asian Plate (ca. 50 Ma) and their continued convergence (Molnar and Tapponnier, 1975; Chatterjee et al., 2013). Erosions of the Himalaya and adjacent terrain have formed the world's two largest submarine sediment masses, the Indus and Bengal fans, around the Indian subcontinent (Davies et al., 1995; Métiévier et al., 1999; Clift, 2006). The Mannar Basin draws special regional and global interest because of its tectonic settings and relation to the Indus and Bengal submarine fans (Figure 1).

MATERIALS AND METHODS

The drill core cutting samples were taken at 10 m intervals from two exploration wells, namely CLPL-Dorado North 1- 82K/1 (referred to as Dorado North) and CLPL-Barracuda-1G/1 (referred to as Barracuda). The drilling recovered a continuous, ca. 1,420 m thick sedimentary sequences deposited in the Dorado North well and ca. 2,600 m thick sedimentary sequences deposited in the Barracuda well. The samples were contamina-

ted by drilling mud, rock sloughing from above, or may be due to lost circulation and pulverization. The Dorado North well was drilled in a water depth of 1,346.4 m and the total depth of the well was 3,622 m. The Barracuda well was drilled in a water depth of 1,509 m and the total depth of the well was

4,741 m (Figure 2). In this exploration well, natural gasses were predominantly discovered in totally 24 m thick of three hydrocarbon bearing sandstones between the depths of 4,067-4,206 m.

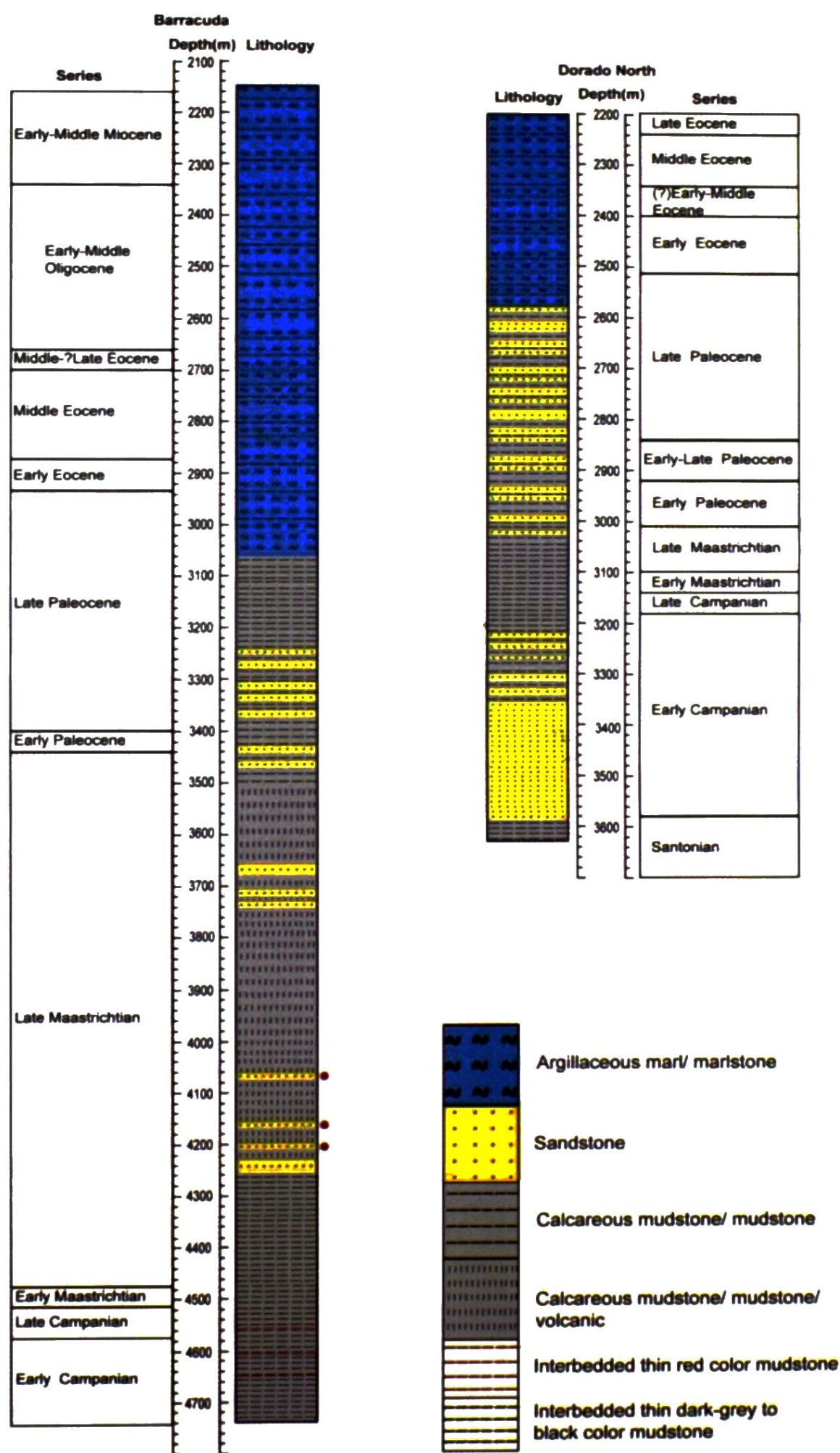


Fig. 2 Stratigraphic successions of the Dorado North and the Barracuda exploration wells. It was made based on original observation of cutting samples in the present study and the age profile from the PRDS report.

The 403 drill core cutting samples were taken, washed with dichloromethane: methanol 9:1 v/v solution using in manual and two times (30 min.) in ultrasonic cleaning methods at Shimane University, Japan. Samples were described to examine mineralogy, color, texture, rounding, sorting, grain size and cementing materials at constant sampling rates. Cutting samples are quite small about 0.5-3 cm, so large scale features such as fractures, bedding planes, and fossils often cannot be observed. Surface features of cutting samples were observed using the OLYMPUS CX 31-DP 21 magnifier.

Unpublished paleontological and geophysical reports from the PRDS allow dating the sedimentary columns. In particular, sequence boundaries were identified based on amplitude variations on seismic and correlating with corresponding biostratigraphic studies to get age profiles in the Mannar Basin. Age profiles in the unpublished final report of the exploration wells were obtained from PRDS with the special permission. Lithostratigraphic successions described in this paper were reconstructed using the fitting of sedimentological observations into the age profiles. Also, sedimentation rates of the Dorado North and the Barracuda wells were calculated using approximate

thickness of each mudstone beds.

Standard burial history of the Mannar Basin was modeled using petroleum system modeling software (BasinMod 1-D) based on the charter member of Platte River's Petroleum System Suit at Shimane University, Japan. Present thicknesses and the begin age of each facies were used for the model. Also, new lithologies such as argillaceous marl/marlstone, calcareous mudstone/ mudstone, and calcareous mudstone/ mudstone/ volcanic sediments were defined by mixing the percentages of the default lithologies. Minor hiatuses can be recorded close to the Late Maastrichtian, Late Paleocene, middle part of the Middle Eocene in the Dorado North and Barracuda wells and middle part of the Late Eocene, early part of the Middle Oligocene and early part of the Middle Miocene in the Barracuda well based on the previous interpretations of the Mannar Basin (Rao et al., 2010), Cauvery Basin (Shaw, 2002) and other rift-basins of the Indian subcontinent (e.g., Rao, 2001) and facies changes in the lithostratigraphic units of the exploration wells. Eroded thicknesses of each unconformity were unknown, but seemed small as discussed below. Therefore, around 10-20 m eroded thicknesses were used for the model. Consequently, uplifting was not described in the standard burial history model of the rifted Mannar Basin. Computer simulations automatically calculated initial lithological parameters of porosity, matrix density, matrix heat capacity, etc. The water and marine bottom depths were fixed throughout the sedimentary succession for the model.

RESULTS

Sedimentological observations and descriptions were performed for the lithostratigraphic succession of the two wells in the Mannar Basin (Figure 2). Stratigraphic units are summarized in Table 1. Also, magnifying observations of representative lithology are shown in Figure 3. Sedimentation

rates of the Dorado North and the Barracuda wells are shown in Figure 4. Computer simulations of the tectonic and total subsidence of the basin are shown in Figures 5 and 6. The total subsidence is defined as the sum of subsidence due to tectonics and subsidence due to sediment loading (load-induced subsidence).

SANDSTONES

The overall sandstone units of the two wells from the Mannar Basin are mainly wacke, with detrital quartz and feldspar. Subangular to subrounded quartz grains are poorly to moderately sorted in an authigenic matrix. Also rigid rock fragments, heavy minerals and marine bioclasts are recorded in minor quantities. No significant mineralogical differences were observed throughout sandstone sedimentary successions. Sandstones are texturally and mineralogically immature. The detrital mineralogy of the Dorado North well is dominated by quartz, with abundant feldspar. The detrital mineralogy of the Barracuda well is dominated by feldspar, with abundant quartz. The average authigenic cement and clay percentages of the Dorado North well are ~5% and ~15% respectively. In the Barracuda well, the average authigenic cement and clay percentages are ~10% and ~20%, respectively.

INTERBEDDED RED MUDSTONES AND BLACK MUDSTONES

Well log analysis indicates the existence of thin red color centimeter scale mudstone layers in the Early to Late Campanian and Late Paleocene to Eocene sediments of the Mannar Basin (Table 1 and Figure 2). A little or no remaining amorphous organic matter contains in red color mudstones (Figure 3b).

The uppermost Early Campanian sediments of the both wells predominantly contain black color mudstone in different thicknesses (Figure 2). Mudstone thicknesses are prominent in the Barracuda well (Table 1). Black mudstones comprise a large proportion of mixed a-type

and b-types amorphous organic matter (Figure 3e).

VOLCANOGENIC SEDIMENTS

The Late Maastrichtian sediments of the

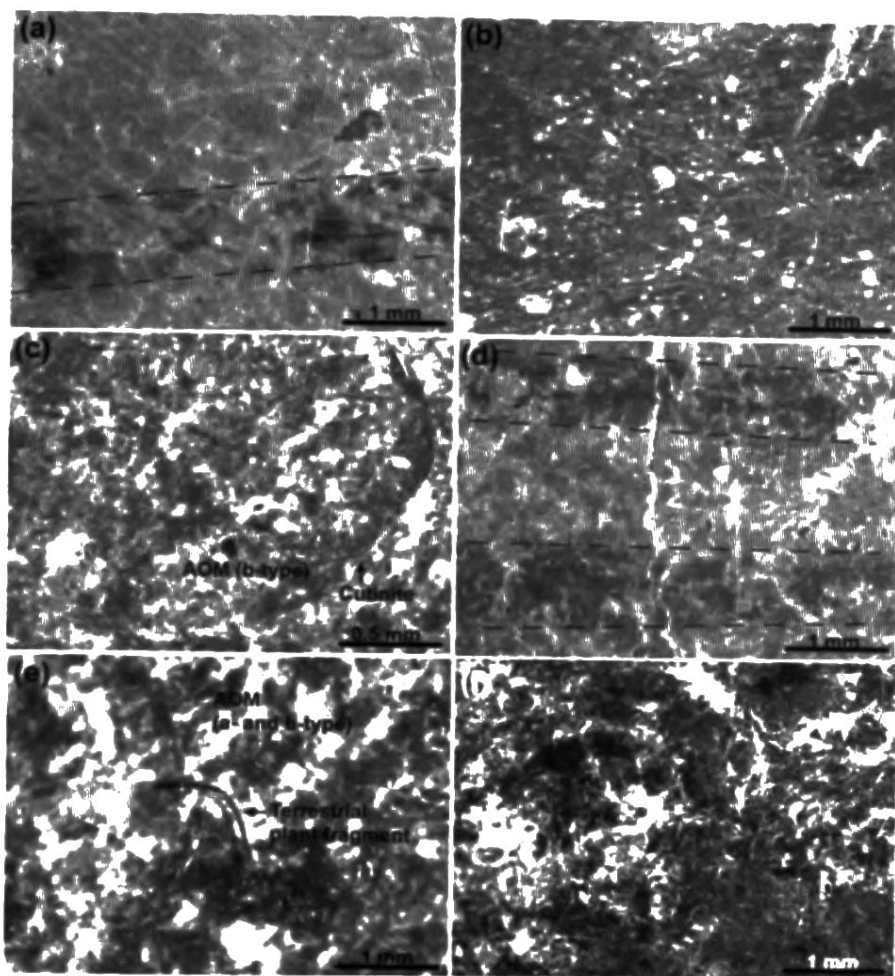


Fig. 3 Representative photomicrographs show surface mineral and maceral (organic) components in the Mannar Basin. Images (a) and (b) were taken from the Dorado North well, (a) the Late Eocene marlstone (2230-2230 m), (b) the Early Eocene red color mudstone (2400-2410 m). Images (c) to (f) were taken from the Barracuda well, (c) the Middle Oligocene marlstone (2370-2380 m), (d) the Early Oligocene marlstone (2550-2560 m), (e) the Late Paleocene interbedded black color mudstone (3170-3180 m), and (f) the Late Maastrichtian volcanic (3870-3880 m).

Barracuda well consist of medium gray to brownish black color volcanogenic tuffaceous sediments and interbedded mudstone/sandstone (Table 1 and Figure 2). Photomicrograph confirms the variation in grain size in color in volcanic rocks (Figure 3f). Olivine and plagioclase are typical phenocryst phase possibly suggesting of basaltic composition.

CALCAREOUS MUDSTONE ARGILLACEOUS MARLSTONE BOUNDARY

Although both well samples show carbonate accumulation throughout the whole sedimentary successions, a clear boundary between calcareous mudstones/ mudstones/ interbedded sandstone in the lower portion of the wells and argillaceous marl/ marlstone in the upper portion of the wells is recognized at 2580 m in the Dorado North well and at 3060 m in the Barracuda well, respectively (Figure 2).

DISCUSSION

SANDSTONES

The lowermost Early Campanian sediments of the Dorado North well consist of thick sandstone and alternating thin mudstone layers (Figure 2). These sandstone beds formed under the influence of fluvial activities as increasing river runoff can carry clastics to the structurally higher flank of the basin. Therefore, the Dorado North well may probably indicate somewhat shallower environments in the basin. Interbedded sandstones of the Late Maastrichtian porous volcanogenic sediments of the Barracuda well could represent petroleum reservoir quality lithology.

Sandstones of the Early to Late Paleocene ranged from poor to moderate sorting and fine- to medium-grained sands. After the Late Paleocene, the relative percentages of sand in the argillaceous marl / marlstone are remarkably low, suggesting that poor reservoir quality lithology (Figures 2 and 3a, c, d).

INTERBEDDED RED MUDSTONES

The depth and extend of the red color thin mudstone layers cannot be precisely determined using the cutting samples (Table 1 and Figure 2). However, biostratigraphic and

Table 1a Schematic stratigraphy of the Dorado North

Series	Depth/ m	Thickness/ m	Lithology	Special features
Late Paleocene to Eocene	2200-2580	380	Light gray to medium light gray color calcareous mudstone/ fine to medium grained, light gray to medium light gray	Red color mudstones (2350 m to 2580 m), black fine-scaled laminations (2200 m to 2370 m and 2430 m to 2580 m)
Early Paleocene to Late Paleocene	2580-3010	430	Fine to coarse grained, light gray to medium light gray color calcareous mudstone and interbedded sandstone layers	
Late Campanian to Maastrichtian	3010-3210	200	Fine grained, olive gray to brownish black color mudstone	Black color mudstone (3180 m to 3210 m)
Early Campanian	3210-3350	140	Interbedded fine to medium grained, light gray to olive gray color calcareous mudstone/ sandstone layers	Red color mudstones (3230 m to 3270 m), black color mudstone (3270 m to 3300 m)
Early Campanian	3350-3580	230	Medium to coarse grained, light gray color sandstone	

Table 1b Schematic stratigraphy of the Barracuda exploration wells.

Series	Depth/ m	Thickness/ m	Lithology	Special features
Late Paleocene to Early-Middle Miocene	2139-3060	920	Fine to medium grained, light gray to medium dark gray color marls / calcareous mudstone	Red color mudstones (2660 m to 2720 m), black fine-scaled laminations (2440 m to 2660 m and 2750 m to 3060 m)
Early Paleocene to Late Paleocene	3060-3440	380	Fine to medium grained, very light gray to medium light gray color calcareous mudstone and interbedded sandstone	Black fine-scaled laminations (3060 m to 3200 m)
Late Maastrichtian	3440-4260	820	Medium to coarse grained, medium gray to brownish black color volcanogenic sediments / interbedded mudstone / sandstone	
Early Campanian to Late Maastrichtian	4260-4741	480	Fine to medium grained, greenish black to brownish black color mudstone	Red color mudstones (4550 m to 4660 m), black color mudstone (4510 m to 4550 m and 4660 m to 4741 m)

sedimentological studies of the Upper Cretaceous oceanic red beds have been widely reported in paleoceanographic reconstruction elsewhere (e.g., Hu et al., 2005; Wang et al., 2011). Amorphous organic matter poor red color mudstones appear to be diagnostic of oxic pelagic sediments (Figure 3b). Therefore, red mudstone of the basin can probably represent (1) intercalation of little productive marine sediments under oxic conditions in the aftermath of organic-rich mudstones, or (2) reworked continental red beds by erosion and then transported to marine environments. Hu et al. (2005) observed that at least hemi-global distribution of oceanic red mudstones predominant of the Cretaceous, although some are as younger as Early Cenozoic.

BLACK MUDSTONES

The uppermost Early Campanian black mudstones of the both wells (in different thickness) show deposition of organic rich sediments during the rift transition stage of the basin (Figure 2). The predominant thicknesses in the Barracuda well reveal that deeper part of the basin was subjected to low-energy, reducing condition, whereas the structural higher flank of the basin (the Dorado North well) was subjected to high-energy conditions during the Late Cretaceous (Table 1). This depositional trend can be observed up to Late Paleocene sedimentary succession of the basin. According to optical data, the relatively high intensity of the mixed amorphous organic matter indicates preservation of planktonic remains and plant resins under the reducing environments (Figure 3e). Also, black fine-scaled laminations (ca. 1-5 mm in thickness gray/black color banding) are dominant in typical form the Late Paleocene sedimentary sequences of the both wells (Table 1 and Figures 3 a, d). These laminations can probably represent cyclic changes in supplies of organic matter under oxygen-poor to anoxic conditions (e.g., Valdés et al., 2004). The Middle Oligocene to Middle Miocene sediments sometimes contain black carbon particles about 0.1-0.3 mm in diameter, possibly suggesting seasonal forest / terrestrial fire events of the

watershed area (e.g., Jia et al., 2003; Harris, 2006). Also, lithostratigraphic interpretations of the two wells indicate somewhat discontinuous and changeable depositional sequences across the basin.

VOLCANOGENIC SEDIMENTS

The Barracuda well penetrated thick volcanogenic fine tuffaceous sediments, suggesting that several periods of volcanism during the Late Maastrichtian due to the breakup of Madagascar/ Seychelles from India (Storey et al., 1995; Torsvik et al., 1998). In this marine basin, mafic to intermediate low viscosity lava could probably spread in a wider area. Also Keller et al. (2008) and Tantawy et al. (2009) described the effects of the Late Maastrichtian volcanism of the Indian Ocean, at Ninety east Ridge Deep Sea Drilling Project Sites 216 and 217, Wharton Basin Site 212 and Krishna-Godavari Basin. Activated local tectonics sometimes could be accompanied by volcanic activities of the area. Vonhof and Smit (1997) data suggest that a rapid outflow of more than $1 \times 10^6 \text{ km}^3$ of basaltic lava of the Indian region. Also, thermal history of the area indicates that significant heat flows during the Late Cretaceous to underlie Early Cretaceous synrift sediments.

CALCAREOUS MUDSTONE ARGILLACEOUS MARLSTONE BOUNDARY

Calcareous mudstone probably indicates deposition of calcite by coccolithophores and foraminifera in the marine sediments (Ridgwell and Zeebe, 2005). In contrast, tectonic movement, Cenozoic orogeny and development of shallow marine carbonate platform over the Asian paleoceanic basins have been widely discussed (e.g., France-Lanord and Derry, 1997; Zachos et al., 2001). The Mannar Basin is characterized by development of marlstone from the Late Paleocene and also this facies change probably correlated with the onshore Tertiary limestone beds of Sri Lanka (Figure 1). Further, development of the carbonate platform is primarily related to movement of Indian Plate into warmer northern latitudes. However, the

increment of carbonate accumulation can be caused by weathering of broad uplifted regional mountain plateau (France-Lanord and Derry, 1997; Zachos et al., 2001). Based on the burial history model as discussed below, the Mannar Basin underwent continuous subsidence and Eocene to Miocene argillaceous marl/ marlstone can probably deposit under deepwater marine conditions.

TURBIDITES

The Paleocene sediments of the Dorado North well consist of mainly arenaceous sediments compared to the Barracuda well (Figure 2). The Paleocene mudstone and interbedded sandstone can probably represent increased clastics from land and development of deepwater turbidites systems due to sea-level changes or sediment gravity flows. The adjacent Cauvery Basin suggests regional uplift, which changes the depositional environments from upper bathyal and neritic conditions in the Late Cretaceous to sub-littoral and sub-areal conditions in the Paleocene (Shaw, 2002). The Paleocene to Early Eocene sediments of the shallow water Mannar Basin were abundance of foraminiferas such as *Subbotina triloculinoidea*, *S.wilcoxensis*, *Planorotalites compressa*, *Morozovella aragonensis*, *M.formosa* and *Acarinina pentacamerata* suggesting that upper to lower bathyal conditions (Rao et al., 2010).

HISTORY OF SEDIMENTATION RATE

The history of sedimentation rates was evaluated using the present mudstone thicknesses of the sedimentary columns (Figure 4). Sedimentation rates in term of mud components respond to major controlling factors in paleogeography (tectonics), paleoceanography and paleoclimate.

Mud sedimentation rates of the Dorado North well during the Campanian, Maastrichtian and Paleocene are 8 m/Ma, 22 m/Ma and 9 m/Ma, and the Barracuda well recorded values are 18 m/Ma, 49 m/Ma and 27 m/Ma respectively (Figure 4). Sand dominant facies over the structurally higher flank (the Dorado North well) of the basin reflected the prominent fluvial

influence during the Campanian to Paleocene. In this period, mud dominant facies over the structurally lower flank (the Barracuda well) of the basin reflected the prominent marine influence (Figure 2). However, igneous activities may have caused significantly to increase the Maastrichtian sedimentation rate in the Barracuda well mainly be due to location in close to igneous source in the region (Figure 4). Also, rapid subsidence can act as an acceleration proxy for sinks of sediments in the Barracuda well during the Maastrichtian. Further, overall accumulation rates show somewhat a bell curve distribution from Campanian to Paleocene (Figure 4).

Sedimentation rates were lowest in the Eocene (13 m/Ma) during timing of the collision between Indian and Asian plates. The Barracuda well recorded relatively higher sedimentation

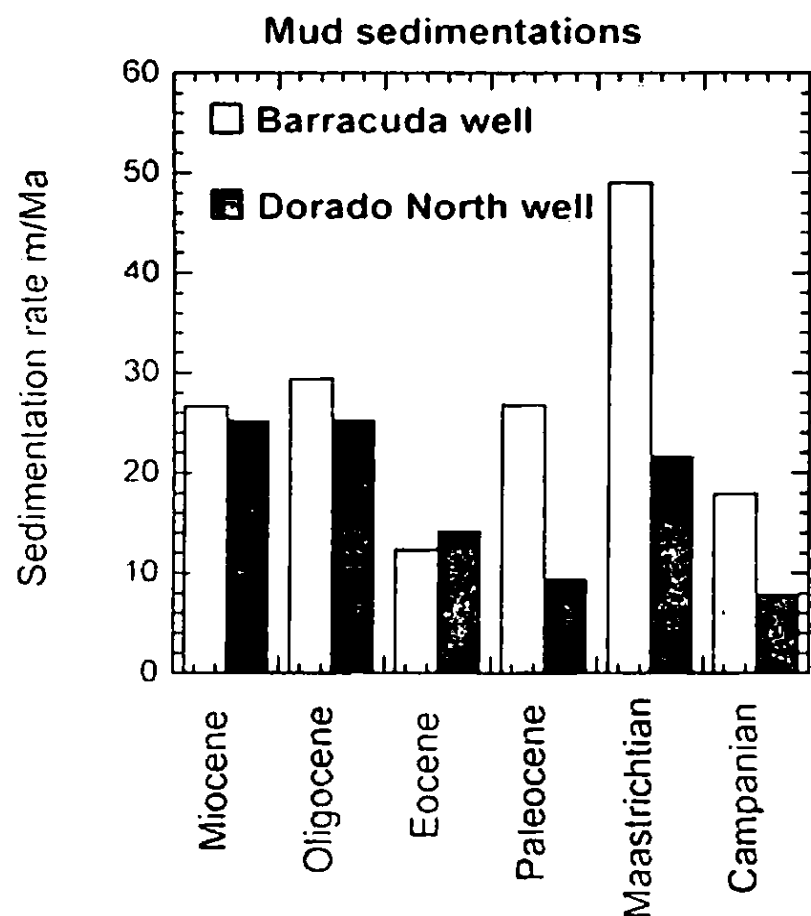


Fig. 4 Mud sedimentation rates of the Dorado North and the Barracuda exploration wells in m/Ma.

rates than the Dorado North well throughout the whole sedimentary succession except for the Eocene (Figure 4). Similarly, the lowest sedimentation rates over the basins of the Indian subcontinent were recorded during the Eocene due to the collision between Indian and Asian plates (ca. 50 Ma) and/ or weak ocean circulation (Davies et al., 1995; Goldner et al., 2014).

Sedimentation rates were increased during the Oligocene (average = 27 m/Ma) and Miocene (average = 26 m/Ma). These changes can be probably correlated with accumulation of weathered soils and sediments from newly uplifted mountain and/or changes of oceanic circulation / upwelling of the region (Davies et al., 1995; Métivier et al., 1999; Goldner et al., 2014). In contrast, Rao et al. (2010) identified hiatuses and / or erosional unconformities using biostratigraphic studies in the shallow water Mannar Basin. The major boundaries were recorded close to Early Eocene, Middle Eocene, Late Eocene, Early Oligocene and Middle Miocene. Consequently, real mass accumulation rates may be somewhat higher than the calculated values of the Oligocene and Miocene (Figure 4). Similarly, rising of clastic / terrestrial sedimentation rates of surrounding basins probably started from the Oligocene (Métivier et al., 1999) or Neogene (Davies et al., 1995; Harris, 2006).

In summary, however, all epoch sediments from Santonian to Miocene are recognized in the exploration wells, and changing patterns in sedimentation rates with age are similar in the both wells. Therefore, in this study, influence of unconformity/hiatus can be negligible for general discussion in the sedimentation rates for the rifted basin. Mud sedimentation rate is about double in the Barracuda well than in the Dorado North well during the Campanian to Paleocene

(Figure 4). However, mud accumulation is approximately equal both in the Barracuda and the Dorado North wells during the Eocene (14 m/Ma and 12 m/Ma), Oligocene (25 m/Ma and 29 m/Ma) and Miocene (25 m/Ma and 27 m/Ma), respectively. It suggests that mud sedimentation rates of the Dorado North well show considerable accretion from the Eocene (Figure 4). Sedimentary facies as described above and sedimentation rates seem to change apparently from the Eocene. These shifts have been interpreted as a sign of climatic change and continuous subsidence of the basin as shown in standard burial history model (Figure 5). Ali and Aitchison (2008) and Chatterjee et al. (2013) suggest that Sri Lanka and Southern India was subjected to an arid climate during the Late Cretaceous and Paleocene whereas; the Eocene recorded tropical conditions. The enhanced source weathering under a warm and humid climate in tropical marine basins may have been sensitive to argillaceous sediments, burial of organic matter and to consume of atmospheric CO₂ (France-Lanord and Derry, 1997; Ridgwell and Zeebe, 2005).

BURIAL HISTORY

The different types of sedimentary basins have varying tectonic subsidence and uplift curves. Rift-type basins tend to have concave-up curve with the subsidence fast early on/after rifting and then slow later on (Watts et al., 1982; Watts

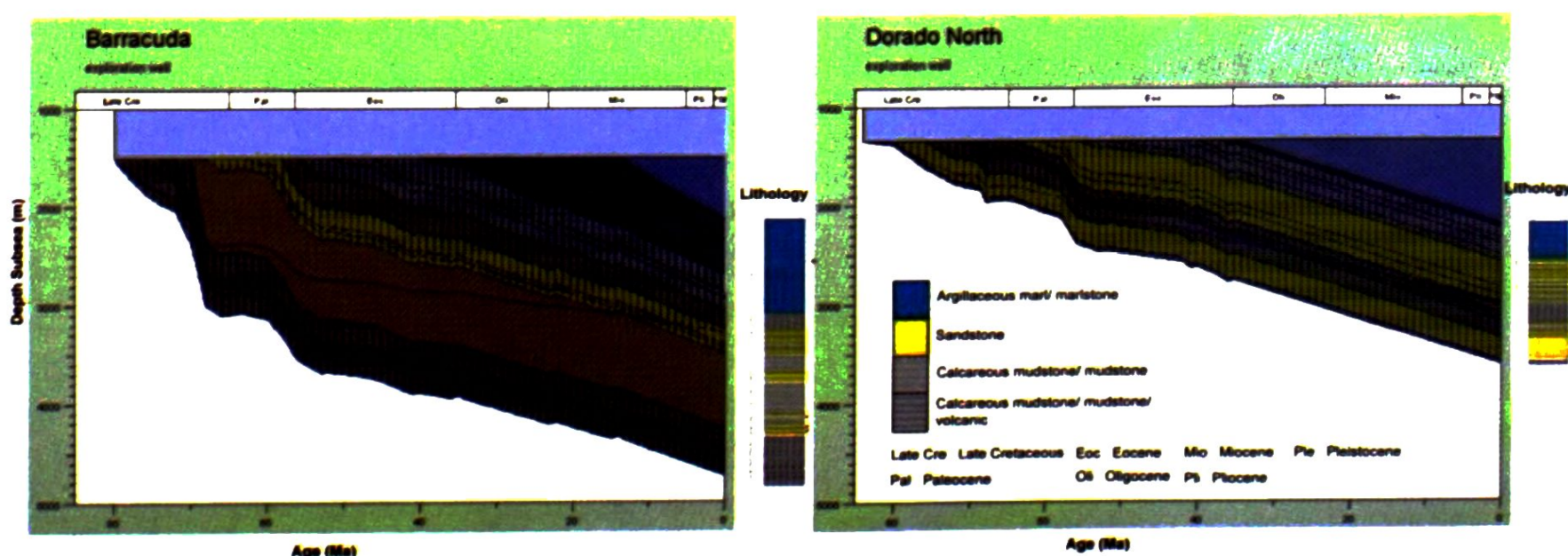


Fig. 5 Simplified standard burial history models of the Dorado North and the Barracuda exploration wells and stratigraphic correlations. Blue color line shows the general trend of tectonic subsidence. The thicknesses of the eroded sections are unknown. Therefore, the flat interval indicates no subsidence or some minor uplifting.

and Thorne, 1984). The burial history curve of standard tectonic subsidence always records the lowest value in subsidence of any sedimentary basins (Figure 5). In this study, thicknesses of erosional unconformities and/or hiatuses cannot be estimated using only sedimentary facies. However, the influence of uplifted height and an eroded thickness could be smaller as discussed above on sedimentation rates. The positions of minor hiatus were correlated as stated above based on mainly the previous interpretations (e.g., Rao, 2001; Shaw, 2002; Rao et al., 2010).

In this burial model, concave-up curve represent rapid tectonic subsidence at the rift transition stage from the Late Cretaceous (average = 41 m/Ma) to Paleocene (average = 25 m/Ma). In particular, the rifting and drifting of Madagascar / Seychelles from India may cause drastically to increase the Late Cretaceous subsidence rates of the Barracuda well. Also, model reveals that tectonic subsidence rate is more prominent in deeper part (the Barracuda well) of the basin (Figure 6). This rapid subsidence was gradually decreased during the Eocene (average = 16 m/Ma) probably due to collision between Indian and Asian plates. The average subsidence rates of Oligocene and Miocene are 17 and 19 m/Ma, respectively (Figure 6). Therefore, the changes in subsidence rates from Eocene to Miocene can be reflected a passive margin deposition. In contrast, tectonic subsidence curves of the adjacent Cauvery Basin show similarity to our interpretation (Chari et al., 1995). However, detail models of thermal history and timing of petroleum / natural gas generation based on data of biomarker and vitrinite reflectance will be published elsewhere.

CONCLUSION

Tectonic activities have been accounted for many of the variables that control sedimentary environment, lithostratigraphy, sedimentation rates and evolutions of the basin as follows.

- (1) Lithostratigraphic columns marked thick sequences of sediments with several cycles of depositions. The Late Cretaceous to Late Paleocene lithology of the Barracuda well

recorded mud dominant sediments and interbedded sandstone and volcanogenic materials whereas, the Dorado North well recorded sand dominant sediments and interbedded mudstone. It indicates that the Dorado North well was subjected to relatively high-energy, fluviomarine dominant and the Barracuda well was subjected to relatively low-energy, marine dominant depositional settings. These facies can probably represent increased clastics from land and development of deepwater

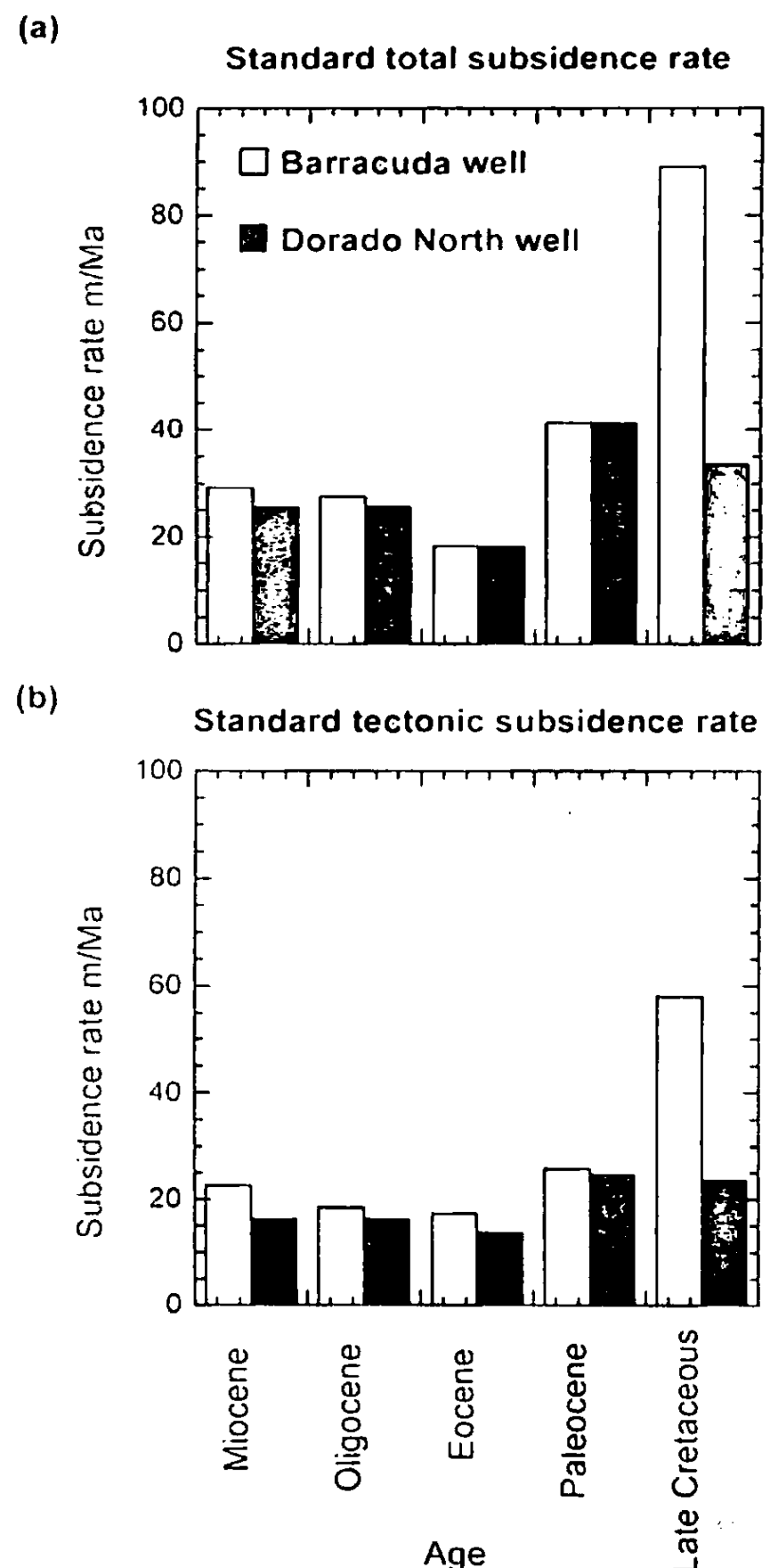


Fig. 6 Standard burial rates of the Dorado North and Barracuda exploration wells in m/Ma (a) total subsidence, (b) tectonic subsidence.

turbidites systems may be due to sea-level changes or sediment gravity flows.

- (2) The Late Maastrichtian sediments of the Barracuda well are marked by thick volcanogenic sediments (ca. 820 m) overlain by calcareous mudstones (ca. 480 m).
- (3) After the Late Paleocene, sedimentary facies were drastically changed from calcareous mudstone to argillaceous marl / marlstone in the both wells. These sedimentary successions were recorded minor to trace amount of sand.
- (4) The whole sedimentary successions can be divided into two chronozones based on sedimentation rates that are (1) the Campanian to Paleocene and (2) the Eocene to Miocene. The mud sedimentation rates of the Dorado North well during the Campanian, Maastrichtian and Paleocene are 8 m/Ma, 22 m/Ma and 9 m/Ma, and also in the Barracuda well recorded values are 18 m/Ma, 49 m/Ma and 27 m/Ma, respectively (Figure 4). Consequently, significant mud accumulations (more than double) were observed in the Barracuda well during the Campanian to Paleocene. However, mud accumulation is approximately equal in the Dorado North and Barracuda exploration wells during the Eocene (14 m/Ma and 12 m/Ma), Oligocene (25 m/Ma and 29 m/Ma) and Miocene (25 m/Ma and 27 m/Ma) respectively (Figure 4). This considerable shift has been possibly interpreted as changes of arid climate (during the Late Cretaceous and Paleocene) into warm and humid tropical climate (from the Eocene to Miocene) and/ or continuous subsidence of the basin. Therefore, the structural higher flank of the basin (the Dorado North well) could be more sensitive to regional terrestrial climatic changes and the basin subsidence during the first chronozone. However, in this period, deeper part of the basin (the Barracuda well) is more sensitive to regional marine changes and tectonic process such as igneous activity.
- (5) The highest sedimentation rate of the Mannar Basin recorded in the Barracuda well during the Maastrichtian. It may be

associated with igneous activities of the region. The lowest sedimentation rates of the Barracuda well indicate timing of the collision between Indian and Asian plates during the Eocene.

- (6) Sedimentation rates were increased after uplifting of the region during the Oligocene and Miocene. However, unconformities may somewhat decrease the absolute sedimentation rates of the basin.
- (7) Burial history by 1D modeling of the Mannar Basin indicates that rapid subsidence from the Late Cretaceous to the Paleocene during the rift transition stage. Subsidence rate decreased during the Eocene followed by collision between Indian and Asian plates.

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