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Configuration of the Indian Ocean and location of Sri Lanka

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ABSTRACT
The Indian Ocean is bounded by Iran, Pakistan, India, and Bangladesh to the north; the Malay Peninsula, the Sunda Islands of Indonesia, and Australia to the east; Antarctica to the south; and Africa and the Arabian Peninsula to the west. Island nations are located in the Indian Ocean, such as Comoros, Madagascar, Maldives, Mauritius, Seychelles, and Sri Lanka. Likewise, it is home to hundreds of islands. It has an area of about 73,440,000 square km. The Indian Ocean's average depth is 3,960 metres, and its deepest point, in the Sunda Deep of the Java Trench off the southern coast of the island of Java (Indonesia), is 7,450 metres. During the long span of time, since the Late Jurassic period (152myr) to present., the formation, evolution and present configuration of the Indian ocean obtained its inheritable characteristics, such as oceanic ridges and fracture zones, seamounts, ocean basins, trenches and continental rise, slope, and shelf. Besides, several well-defined coastal morphological features are found in the Indian Ocean: estuaries, deltas, salt marshes, mangrove swamps, cliffs, coral reefs, and complexes of barrier islands, lagoons, beaches, and coastal dunes which are highly significance for eco- and geo-tourism. With the development and evolution of these phenomena in the Indian Ocean, the island of Sri Lanka moves from Late Jurassic period to its present position. During the Upper Jurassic Period Sri Lanka was positioned within 65^{o}S-67^{o}S and 32^{o}E-36^{o}E in the Indian Ocean, and with the Sri Lanka detached from the southern supercontinent Gondwanaland, the Indian Ocean began to open up.

Keywords: Indian Ocean, Location, Sri Lanka, Island nations, Configuration

INTRODUCTION

The Indian Ocean is bounded by Iran, Pakistan, India, and Bangladesh to the north; the Malay Peninsula, the Sunda Islands of Indonesia, and Australia to the east; Antarctica to the south; and Africa and the Arabian Peninsula to the west. In the southwest it joins the Atlantic Ocean south of the southern tip of Africa, and to the east and southeast its waters mingle with those of the Pacific Ocean (Figure 1).

The Indian Ocean is the most complicated and least understood of the world's major oceans. Its evolution is of considerable geological importance, since the destruction of the ocean of Tethys along what is at present the Alpide belt has been accompanied by the production of Indian Ocean sea floor further south (McKenzie and Sclater 1971). Both authors mention that the Indian Ocean, which are still almost unexplored, and they believe that the observations available at present are sufficient to determine the major events in the history of this Ocean since the end of the Cretaceous. The history before the Upper

Cretaceous is less clear, but can probably be obtained by careful use of the available data. Several simple experiments are suggested to check this claim (McKenzie and Sclater 1971).

As a salt water body, the Indian Ocean covers approximately one-fifth of the total ocean area of the world. It is the smallest, geologically youngest, and physically most complex of the world's three major oceans. It stretches for more than 10,000 km between the southern tips of Africa and Australia and, without its marginal seas, and has an area of about 73,440,000 square km (Figure 1). The Indian Ocean's average depth is 3,960 meters, and its deepest point, in the Sunda Deep of the Java Trench off the southern coast of the island of Java (Indonesia), is 7,450 meters (Kanayev et al, Encyclopedia Britannia).

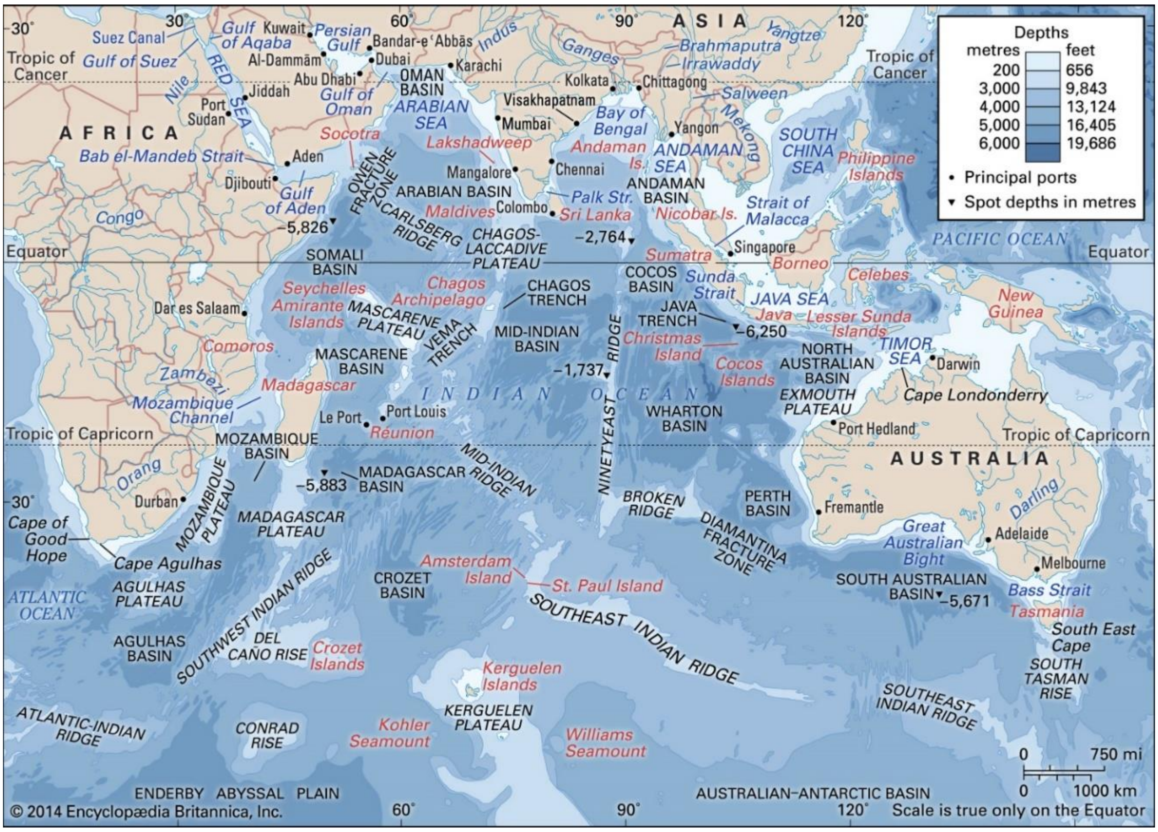

Figure 1. The Indian Ocean is bounded by Iran, Pakistan, India, and Bangladesh to the north; the Malay Peninsula, the Sunda Islands of Indonesia, and Australia to the east; Antarctica to the south; and Africa and the Arabian Peninsula to the west. Six island nations are located in the Indian Ocean, namely Comoros, Madagascar, Maldives, Mauritius, Seychelles, and Sri Lanka and it is home to hundreds of islands (ENCYCLOPÆDIA BRITANNICA).

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The origin and evolution of the Indian Ocean is the most complicated of the three major oceans. Its formation is a consequence of the breakup, which began about 180 Ma (million years ago), of the southern supercontinent Gondwanaland emerge by Late Jurassic, about 152 Ma ago (Figure 2). From 180 Ma to present drift of lands (forming continents, islands, island arcs etc.) and spreading of oceans and seas represent the inheritable configurations of the Indian ocean. In the Late Jurassic the Central Atlantic Ocean was a narrow ocean separating Africa from eastern North America. Eastern Gondwana had begun to separate from Western Gondwana. The Jurassic sediments in Sri Lanka designated as Tabbowa Beds (mostly arkosic sandstones) and Andigama-Pallama Beds (arkosic sandstones and carbonaceous shales with thin coal slivers) were formed locally onshore within fault-bounded basins (Ratnayake and Sampei, 2015). The result of this break-up was the spawning of the Atlantic Ocean. However, at this time, the Atlantic Ocean was relatively narrow and Indian Ocean was not developed.

At the beginning about 125 myr, Indian subcontinent in Barremian period was moved to the northeast. The Cretaceous is a geological period that lasted from about 145 to 66 myr, the new oceans were began to open (Figure 3). Due to plate tectonics, the India Plate split from

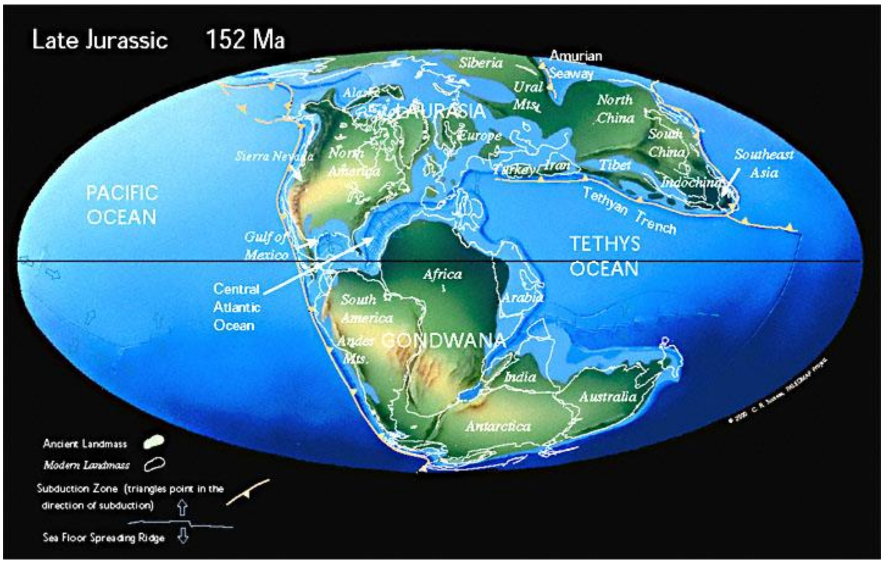


Figure 2. The supercontinent of Pangea began to break apart in the Middle Jurassic. [Plate tectonic maps and Continental drift animations by C. R. Scotese, PALEOMAP Project (www.scotese.com)].

Madagascar and collided (c. 55 Ma) with the Eurasian Plate, resulting in the formation of the Himalayas. By the western movement of Africa and separation of Australia from Antarctica some 53 Ma (Figures 3 & 4). By 36 Ma, the Indian Ocean had taken on its present configuration (Figure 5). Although, initially it first opened some 140 Ma ago, but almost all the Indian Ocean basin is less than 80 Ma (Barron. E., & Harrison, C. 1981; Kanayev, Morgan et al, Encyclopedia Britannia).

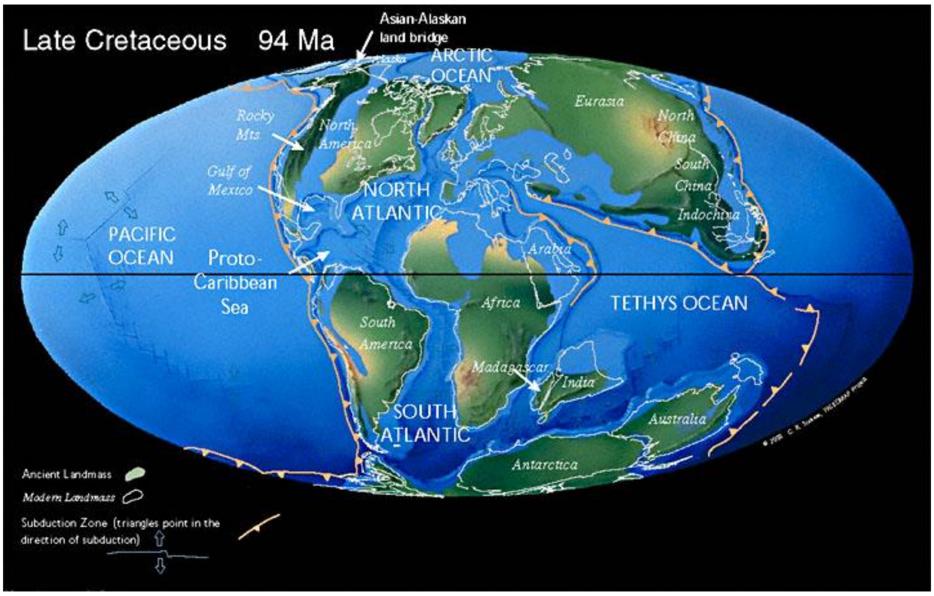


Figure 3. New Oceans Begin to Open [Plate tectonic maps and Continental drift animations by C. R. Scotese, PALEOMAP Project (www.scotese.com)].

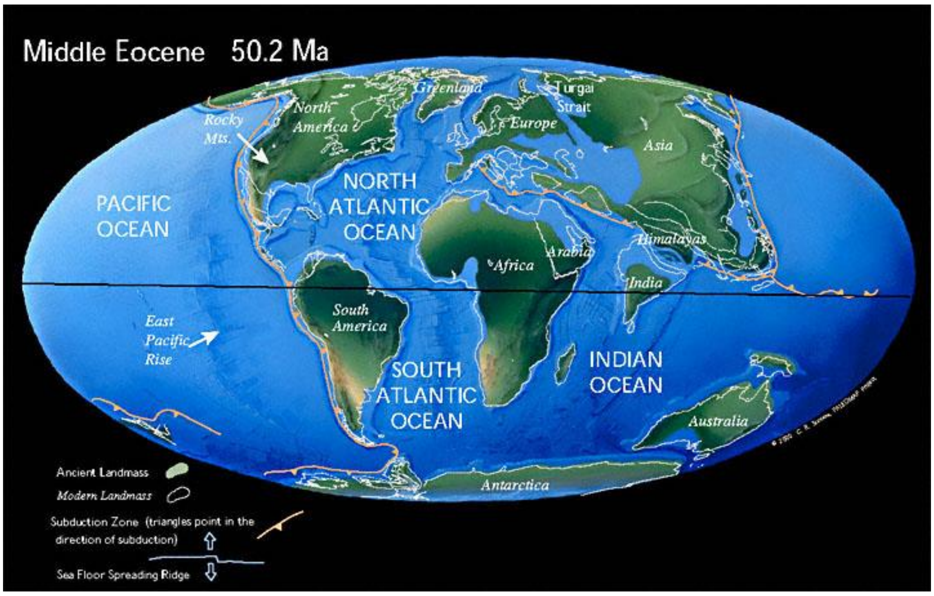


Figure 4. About 50 - 55 myr India began to collide with Asia forming the Tibetan plateau and Himalayas. Australia, which was attached to Antarctica, began to move rapidly northward [Plate tectonic maps and Continental drift animations by C. R. Scotese, PALEOMAP Project (www.scotese.com)]..

The Indian Ocean is well rich by submarine features such as oceanic ridges and fracture zones, seamounts, ocean basins, trenches and continental rise, slope, and shelf. The oceanic ridges consist of a rugged, seismically active mountain chain that is part of the worldwide oceanic ridge system and still contains centers of seafloor spreading in several places (Kanayev, Morgan et al; Encyclopedia Britanica). The Indian oceanic ridges form an inverted “ Y ” on the ocean floor, starting in the upper northwest with the Carlsberg Ridge in the Arabian Sea, turning due south past the Chagos-Laccadive Plateau, and becoming the Mid-Indian (or Central Indian) Ridge (Figures 1, 5 & 6). Seamounts in the Indian Ocean are extinct submarine volcanoes that are conically shaped and often flat-topped. They rise abruptly from the abyssal plain to heights at least 1,000 meter above the ocean floor. In the Indian Ocean, seamounts are particularly abundant between Réunion and Seychelles in the Central Indian Basin and the Vening Meinesz group near Wharton Basin. Bardin, Kohler, Nikitin, and Williams seamounts are the examples (Figure 1).

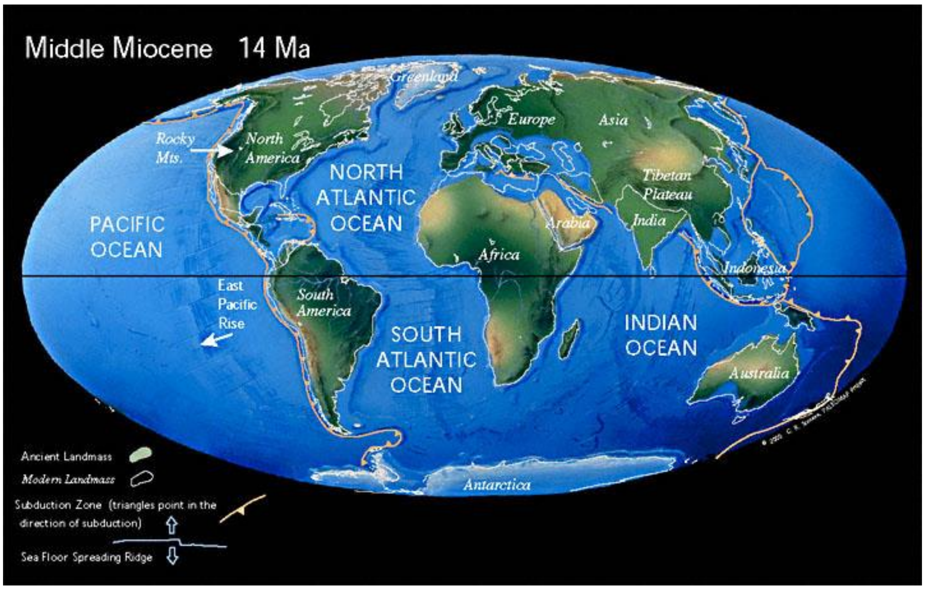


Figure 5. The World Assumes a Modern Configuration of the continents and the Indian Ocean. The drifting of India and Sri Lanka land block passed the northwards from the Equator [Plate tectonic maps and Continental drift animations by C. R. Scotese, PALEOMAP Project (www.scotese.com)]..

20 million years ago, Antarctica was covered by ice and the northern continents were cooling rapidly. The world has taken on a "modern" look, but notice that Florida and parts of Asia were flooded by the sea. When the Earth is in its "Ice House" climate mode, there is ice at the poles. The polar ice sheet expands and contacts, because of variations in the Earth's orbit (Milankovitch cycles). The last expansion of the polar ice sheets took place about 18,000 years ago. We are entering a new phase of continental collision that will ultimately result in the formation of a new Pangea supercontinent in the future. Global climate is

warming because we are leaving an Ice Age and because we are adding greenhouse gases to the atmosphere.

The Last Glacial Maximum (LGM) was during the Last Glacial Period that ice sheets were at their greatest extent. Vast ice sheets covered much of North America, Northern Europe, and Asia and profoundly affected Earth's climate by causing drought, desertification, and a large drop in sea levels; for e.g. Indian Ocean also. According to Clark et al. (2009), growth of ice sheets commenced 33,000 years ago and maximum coverage was between 26,500 years and 19–20,000 years ago (Figure 6), when deglaciation commenced in the Northern Hemisphere, causing an abrupt rise in sea level. Decline of the West Antarctica ice sheet occurred between 14,000 and 15,000 years ago, consistent with evidence for another abrupt rise in the sea level about 14,500 years ago. Although, Sri Lanka appear as landmass with Indian Peninsula, since late Jurassic period, the island of Sri Lanka emerged as separate by Late Cretaceous period (Figure 3). Thus, the block of Sri Lanka island obtained its present position by the Last Glacial Maximum (Figure 6; Katupotha 2020).

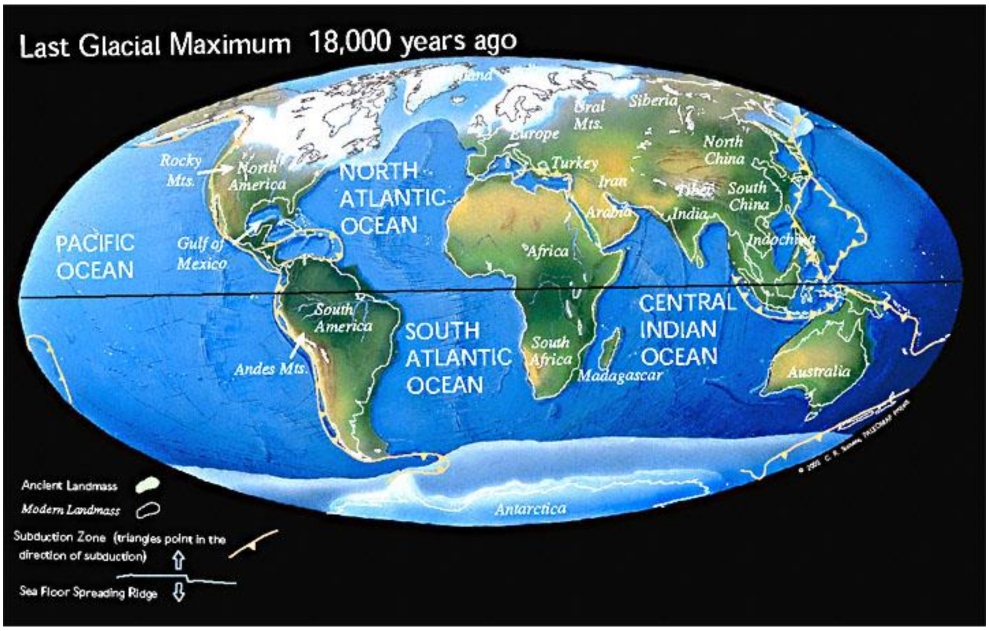


Figure 6. The Earth has been in an Ice House Climate for the last 30 million years [Plate tectonic maps and Continental drift animations by C. R. Scotese, PALEOMAP Project (www.scotese.com)].

All Fgures from 1 to 7 depict the formation, evolution and present configuration of the Indian ocean since Late Jurassic (152myr) to present. During this long span of time, with the opening and expansion of the Indian Ocean obtained its inheritable characteristics such as oceanic ridges and fracture zones, seamounts, ocean basins, trenches and continental rise, slope, and shelf. Besides, several well-defined coastal configurations are found in the Indian Ocean: estuaries, deltas, salt marshes, mangrove swamps, cliffs, coral reefs, and complexes of barrier islands, lagoons, beaches, and coastal dunes.

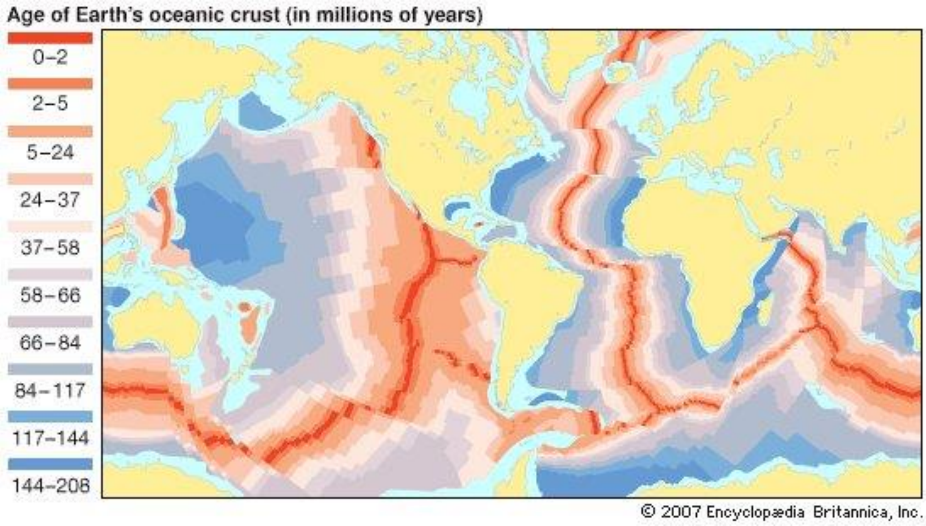


Figure 7. Evolution of the Ocean Basins through plate movements

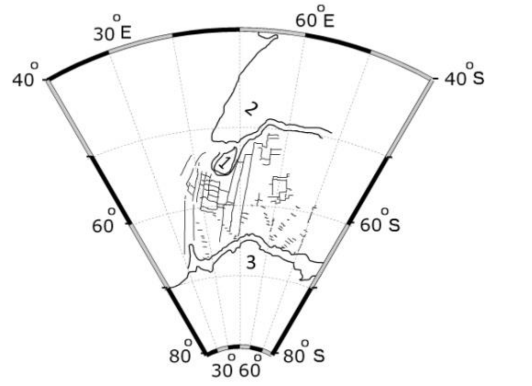
The huge load of suspended sediments from the rivers emptying into the Indian Ocean is the highest of the three oceans, and nearly half of it comes from the Indian subcontinent alone. Those terrigenous sediments occur mostly on the continental shelves, slopes, and rises, and they merge into abyssal plains (Encyclopedia Britannia). Cones of thicknesses of at least 1.6 km are found in the Bay of Bengal, the Arabian Sea, and the Somali and Mozambique basins. Wharton Basin off northern Australia has the oldest sediments. In the Ganges-Brahmaputra cone, sediments exceed 11 km in thickness and extend to latitude 10 S. Little sediment has accumulated along the southern Sunda Islands, probably because the Java Trench acts as a sediment trap; instead, silicic volcanic ash is found there. Brown and red clay sediments dominate in the deep sea between 10° N and 40 S away from islands and continents and are 300 meters thick. In the equatorial zone, an area of high oceanic productivity, calcareous and siliceous oozes are abundant. South of and beneath the Antarctic Convergence (roughly 50 S), another highly productive area, are diatomaceous algal oozes. Sediments are absent over a width of about 70 km on the oceanic ridge crests, and the flanks are only sparsely covered. The ocean floor is composed of basalt in various stages of alteration. The principal authigenic (ocean-formed) mineral deposits are phosphorites at depths of 40 to 400 meters), ferromanganese crusts at depths of (1,000 to 2,500 meters), ferromanganese nodules at depths greater than (3,000 meter), and hydrothermal metalliferous sediments at the crests of the Carlsberg and Central Indian ridges (Encyclopedia Britannica).

DISCUSSION

The Island of Sri Lanka in the Indian Ocean

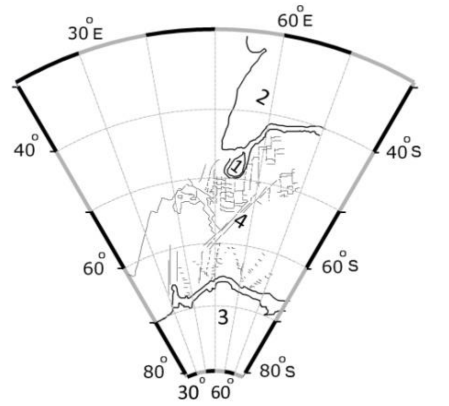
During the Jurassic period (201.3 ± 0.2 - 152.1 ± 0.9) many geological, biogeographical and ecological events occurred in the Earth. Accordingly, breakup of Pangaea into Gondwana and Laurasia, Sri Lanka emerged as a separate landmass (Dittus 2017, During the Upper Jurassic Period Sri Lanka was positioned within 65°S-67°S and 32°E-36°E in the Indian Ocean Figure 2). With the Sri Lanka detached from the southern supercontinent Gondwanaland, the Indian Ocean began to open up (Katupotha 2020).

The geological history of Sri Lanka is closely tied to that of India; both were linked at the heart of the ancient supercontinent of Pangea during the Mesozoic when Sri Lanka was geologically connected to Madagascar, Africa, southern India and Antarctica (Dissanayake and Chandrajith, 1999). During the Lower Cretaceous, Sri Lanka has somewhat rotated anticlockwise from ENE-WSW to NE-SW; i.e. from 64°S-66°S to 33°E-38°E (Figure 6 & 7, Katupotha 2020). Several structural features of land around the Cauvery Basin and its sub-basins, including Ramnad sub-basin experienced marine conditions during Lower Cretaceous (145.5-113.0 Ma). Also, during the Cretaceous period (145.5-72.1 Ma) more than 850m thick sandstones were deposited in the Mannar Basin. The Mannar Basin between Sri Lanka and India was more than 200 km wide at that time. Likewise, the Mannar Basin and surroundings hold 4.0 km of sediments, nearly half of which may be of Cretaceous age and the rest of the Tertiary age sequence (Ramana et al. 1995). By Lower Cretaceous, Sri Lanka was located within 45°S - 50°S and 53°E - 56°E (Figure 7) 121 Ma ago as mentioned by Desa et al. (2006). It is clear that this figure indicates the initial signs of Indian Oceanic ridges, basins and volcanic basements of present islands were formed due to sea floor spreading (Segev 2002).



1 Sri Lanka
2 Indian Peninsula
3 Antarctica. By 121 Ma initial ridges, basins and bays were formed.

Figure 8



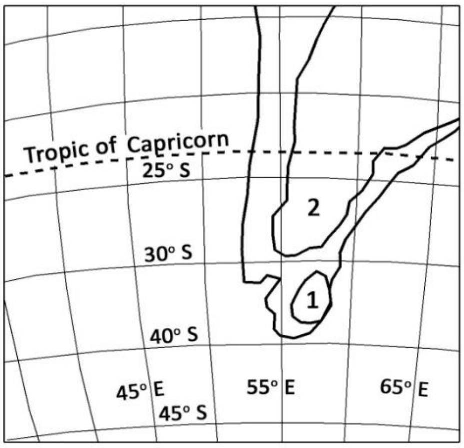
1 Sri Lanka
2 Indian Peninsula
3 Antarctica
4 Formation of Ninety East Ridge and other Mid Indian Ocean ridges, basins as well as bays formed by 84 Ma.

Figure 9

Figures 8 and 9. Locations of Sri Lanka in Lower Cretaceous Period, 121 Ma ago and Sri Lanka in Upper Cretaceous Period, 84 Ma ago (Desa et al. 2006).

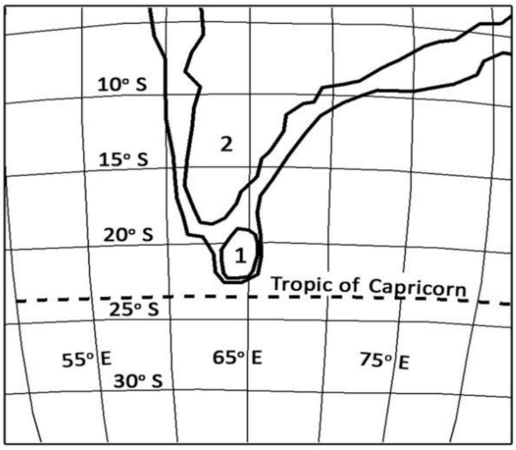
Findings of the vegetation development and paleoecology ages of the strata on the central Kerguelen Plateau, Southern Indian Ocean, conducted by Barbara et al (2002) also useful to confirm the cyclic events and seafloor spreading as well as northern drift of Sri Lanka. Furthermore, during the Santonian (85.8 Ma) and Campanian (83.5 Ma) stages of Upper Cretaceous, Sri Lanka moved further north and east (45°S - 50°S and 53°E - 56°E) rotating to the north (Figures 8 and 9, Desa et al. 2006; Figure 9-Segev 2002). The Figure 9 emphasizes that a linear, age-progressive seamount chain for e.g. the Ninety East Ridge and other structural features gradually formed by Upper Cretaceous (No. 4 on Figure 9 is not Ninetyeast Ridge but Kerguelen FZ-86°E FZ). Thus, the evolution of the Indian Ocean, sea floor spreading and sea level rise indicate that Sri Lanka has moved northwards from 65°S – 67°S and 33°E - 42°E to 35°S - 38°S and 54°E - 57°E during the Maastrichtian Stage (70.6 Ma) of the Cretaceous Period. Beside the above, during the Paleocene (65.5 - 58.7 Ma and Lower Eocene Epochs (around 55.8 Ma) the Indian subcontinent collided with Asia and the Himalayan Orogeny began between 52 and 48 Ma (Figure 4). At those times, locations of Sri Lanka are shown in Figures 4, 10 and 11. All those igneous and tectonic activities, formation of mantle plume heads, volcanism, rifting and development of spreading centers were clearly responsible for the evolution and drifting of Sri Lanka northwards (Segev 2002; Desa et al 2006).

Plate reconstruction models of Desa et al (2009) depicting the paleo positions of India, Antarctica and Australia. The reconstructions of these landmasses are made using the rotation parameters; fracture zones and magnetic anomalies; Paleo positions from the Deep-Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) LEGS 22 AND 26 AND ODP LEG 121 (Saunders et al 1991). Similarly location of the Kerguelen mantle plume; probable western extent of the Australia-Antarctica spreading center; Early Cretaceous magnetic anomalies and fracture zones in the Bay of Bengal, Northeastern Indian Ocean and Enderby Basin, East Antarctica, Kerguelen Fracture Zone very significant to the study of drifting Sri Lanka from the Antarctic Circle to present position located in the northern hemisphere (Saunders et al 1991; Ramana et al. 2001; Segev 2002; Desa et al. 2006 and 2009).



1. Sri Lanka
2. Indian Peninsula

Figure 10



1. Sri Lanka
2. Indian Peninsula

Figure 11

Figures 10 and 11. Location of Sri Lanka during Paleocene Period, 65.5 - 58.7 Ma ago and Location of Sri Lanka during Lower Eocene Period, 56.0-38.0 Ma ago.

During the Bartonian Stage (40.4 Ma) in Eocene Mid-Tertiary Period and Priabonian Stage in Upper Oligocene the island of Sri Lanka resided within 5°S - 10°S, 73°E - 74°E. During the Oligocene Epoch (33.9 - 28.1 Ma) the continents continued to drift toward their present positions and Antarctica continued to become more isolated and finally developed a permanent ice cap. mountain building in western North America continued, and the Alps started to rise in Europe as the African plate continued to push north into the Eurasian plate, isolating the remnants of the Tethys Sea. This activity of the plates was crucial for Sri Lanka to reach the Equator, because sea floor spreading. Accordingly, plate movements studies, palaeo anomaly and palaeo climatic studies are very important to attain this situation. Subsequently, by Oligocene (33.9 - 28.1), Eocene (28.4 myr) and Miocene (23.03 Ma) Periods, the boundary of the northern part of Sri Lanka was very close to the Equator (Figures 12 and 13), and Miocene fauna and modern plants thrived in the Mannar Basin area. Due to climatic and ocean level changes, the Miocene limestone belt, about 800m thick was formed (see, Katupotha 2013. Table 1 and Katupotha 2019, Table 1).

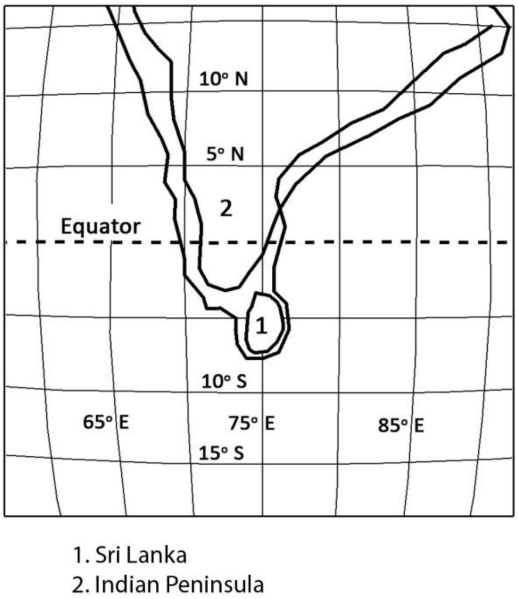


Figure 12

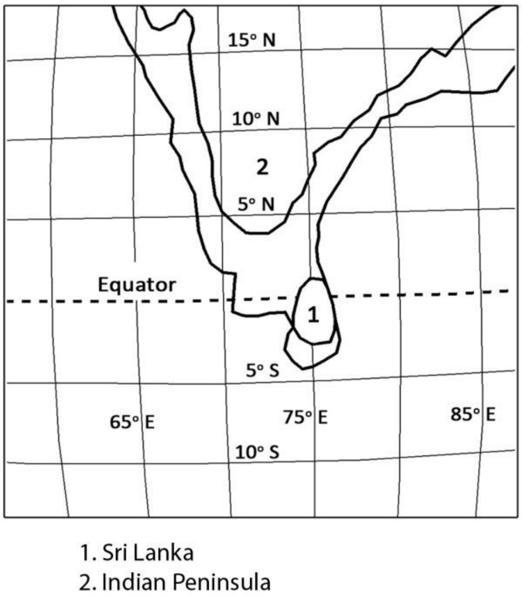
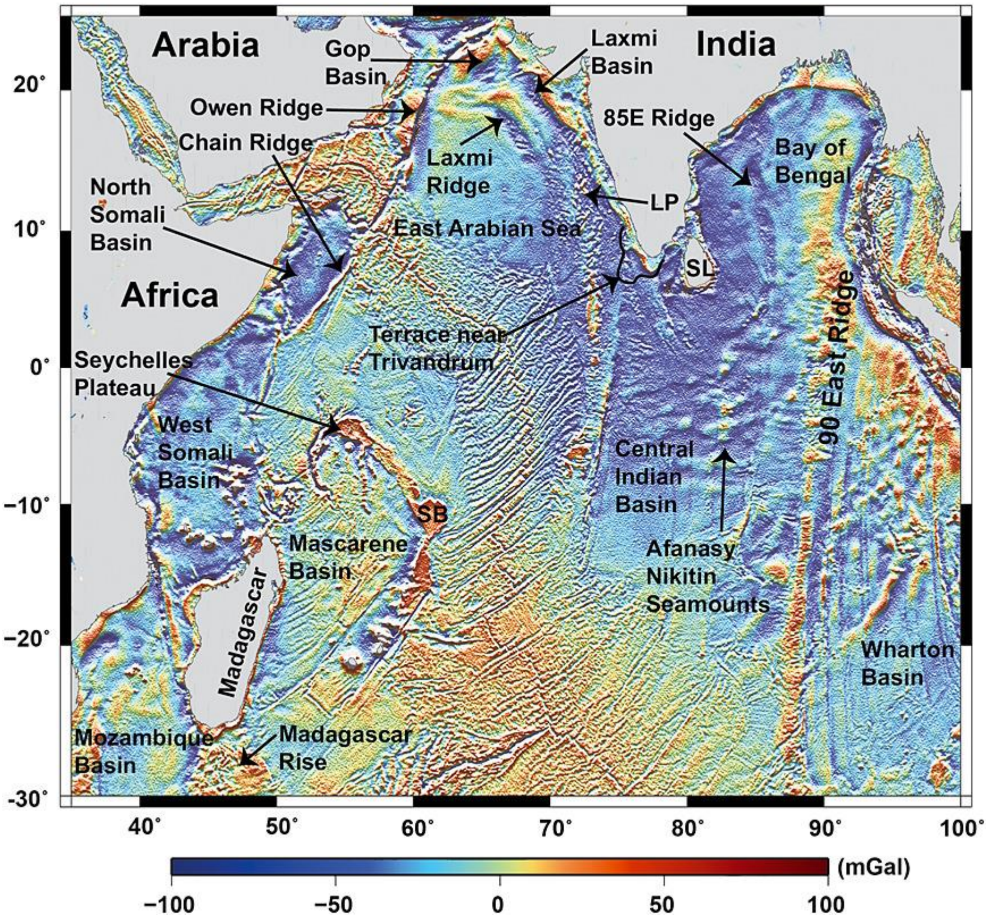


Figure 13

Figures 12 and 13. Location of Sri Lanka during Oligocene Period, 33.9 - 28.1 Ma and Location of Sri Lanka during Mid Miocene, 15.97-13.82 Ma.

In the north and northwest Sri Lanka, the Jurassic sediments were unconformably overlain by an extensive sequence of sandstones and limestone (important regional aquifers) of Miocene (23.03 - 7.24 Ma age. The deposition of the Puttalam-Jaffna limestone in the northwest and northern Sri Lanka and Minihagalkanda Beds in the southeast took place at this stage. By the Tortonian Stage (11.608 - 7.246 Ma) of the Miocene (Tertiary) period, Sri Lanka had passed the equator and located itself between 4°N - 8°N and 77°E - 78°E.



Present configuration of the Indian Ocean. Free-air satellite-derived gravity anomalies showing the anomalous tectonic features in the North and West Indian Ocean; seafloor along the East Indian margin was conjugate to the Enderby Basin (LP is Laccadive Plateau, SL is Sri Lanka and SB is Saya de Malha Bank (*Sandwell and Smith* 2009).

Modern lands and oceanic features including Sri Lanka, of the Indian Ocean were essentially at their present positions during the Pleistocene Epoch, and by the Holocene Epoch. Accordingly, the island of Sri Lanka and its present-day lithology, mineral resources, structural features and stratigraphy settled down between 5° 52´N - 9° 54´N and 79° 30´E - 81° 55´E in the Indian Ocean to the southwest of the Bay of Bengal and southeast of the Arabian Sea. Such changes can be clearly identified from Paleo-configurations of Sri Lanka, and from bathymetry as well as fluvial and marine deposits in and around Sri Lanka (Katupotha 1988a & 1988b).

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