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COASTAL EVOLUTION AND SEDIMENT SUCCESSION OF SRI LANKA: A REVIEW ON QUATERNARY SEA LEVELS, CLIMATES AND SEDIMENTATION PROCESSES

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ABSTRACT

In spite of the small size, the coastal environments of the four cardinal quadrants of Sri Lanka indicate different morphologies and evolutionary characteristics. Therefore, a review of the coastal evolution and sediment succession of Sri Lanka is presented with formal published data and multi-proxy data using modern techniques. The Sri Lankan coasts have provided insightful evidence of paleo-sea level oscillations during the last glacial period and Late-Holocene epoch. The prevailing climate since the last glacial maximum has provided excessive sediment to coastal lowlands and produced Pleistocene sedimentary signatures driven with aeolian and fluvial processes. Major coastal sediment barriers developed during late Holocene transgressions and were modified afterwards. Both northwestern (NW) and southeastern (SE) coastal zones experienced the monsoon rain-shadow effect. In the NW quadrant, the shielding effect of the Indian sub-continent preserved much of the evidence for paleo-sea level oscillations and paleo-climate, although the basement rock is Miocene limestone. In contrast, the rocky crystalline SE coast has less preservation due to its considerable exposure to the wind driven forces. The energy of the eastward moving currents is higher due to the combined effect of westerly wind bursts (WWB) and SW monsoons, and hence, southwestern (SW) and southern coastal areas show regressive coasts due to current generated coastal processes. However, the eastern zone of the SE quadrant is progressive due to its position in the conjunction zone of the eastward moving sea currents and westward moving low-salinity water flows of the Bay of Bengal. The pattern of sea currents and monsoon strength controlled the wind driven morphologies of the NE and SW quadrants. Though the geology is similar in the NE and SW quadrants, the general geological strike of the SW coast is parallel to the turning SW monsoon currents and most likely the rock types has supported erosion. Sediment loads generated from NE monsoon and east India coastal currents (EICC) are upwelled with the strong circulations within the Bay of Bengal and deposit on the NE coasts indicating heavy mineral beds that were sorted by swash and backwash activities. This review notes how tropical monsoon induced sea currents and other currents around the Bay of Bengal region are factors in the differences in the geology and structure of coastal morphologies in four quadrants of Sri Lanka. These factors traced/erased the global melting events on a tropical small island during the Quaternary.

Key words: Coastal geomorphology, sea current, sea level, Quaternary, Sri Lanka,

INTRODUCTION AND BACKGROUND

Quaternary period sea level fluctuations and consequent coastal environmental evolutions are well studied and documented in different regions of the world; yet contradictory data have been obtained from different geographical locations (Angulo *et al.*, 2006, Leonard *et al.*, 2018). Principally, the global active periods of inter and intraglacial events during the Pleistocene and Holocene epochs are recorded as eustatic sea level changes in different coastal regions of altered heights. Records of global glacial melting events are controlled by factors such as the size of the land mass (continental land or island), distance from the melting ice sheets, geographical position in the earth (equatorial region or sub equatorial region) and the rheological structures of each region (Camoin *et al.*, 1997, 2004). Therefore, Quaternary sea level records in regional scales are needed to rectify global inconsistencies.

Except for local lineament adjustments, the Indian Ocean region has remained tectonically stable during the Quaternary period (Curry *et al.*, 2003; Roy and Chatterjee, 2015). The geographical position of tropical zones remain far afield from glacial regions, making the Indian Ocean the best zone to study global melting events in the Quaternary. However, few studies in the literature have recorded these eustatic sea level oscillations in the Indian Ocean region with scientific evidence (Colonna *et al.*, 1996; Hanebuth *et al.*, 2000; Yokoyama *et al.*, 2000; Camoin *et al.*, 2004).

Sri Lanka is located at the tip of the Indian subcontinent and is characterized as a tectonically stable island (Richmond *et al.*, 2006). The Sri

Lankan coastline is approximately 1920 km long and open to the Indian Ocean (Katupotha, 1988). Limited scientific research and theory-based articles addressing the evolution and Quaternary sea level changes around Sri Lankan coasts have been published, but several aspects are problematic and debatable due to the coastal zone (Weerakkody, 1988; Cooray and Katupotha, 1991; Ranasinghe *et al.*, 2013). Despite Sri Lanka is a small island, preserved coastal morphological features of it provides diverse evidences in the four cardinal quadrants of the island (Cooray and Katupotha, 1991).

Scientific studies on the coastal evolutions and paleo-sea levels of Sri Lankan coasts have increased since the 2004 Indian Ocean tsunami (Goff *et al.*, 2006; Dahanayaka and Kulasena, 2008; Morton *et al.*, 2008; Goto *et al.*, 2011; Ranasinghe *et al.*, 2013). In essence, tsunami deposits further highlighted that the forces governing sedimentation on the each coasts of Sri Lanka are different (Wang *et al.*, 2007; Morton *et al.*, 2008; Goto *et al.*, 2011). The western coast is partially covered by the Indian peninsula, and the rest is directly exposed to the open ocean. In contrast, the eastern coast is exposed to the Bay of Bengal, and remnants of the tectonic settings of Java-Sumatra are preserved in undisturbed environments (Jackson, 2008). Hence, this article reviews the scientific evidence from the island and Indian Ocean region to resolve the sea level records, problematic evolutions and sediment successions of Sri Lankan coasts.

The analysis in this article emphasizes the difference in sedimentary processes on the four cardinal coastal quadrants of Sri Lanka. The results support the ability to reconstruct the effect of global ice sheet melting on small

islands in tropical regions and subsequent changes during the Quaternary period, which can lead to

misinterpretations of global paleo-events.

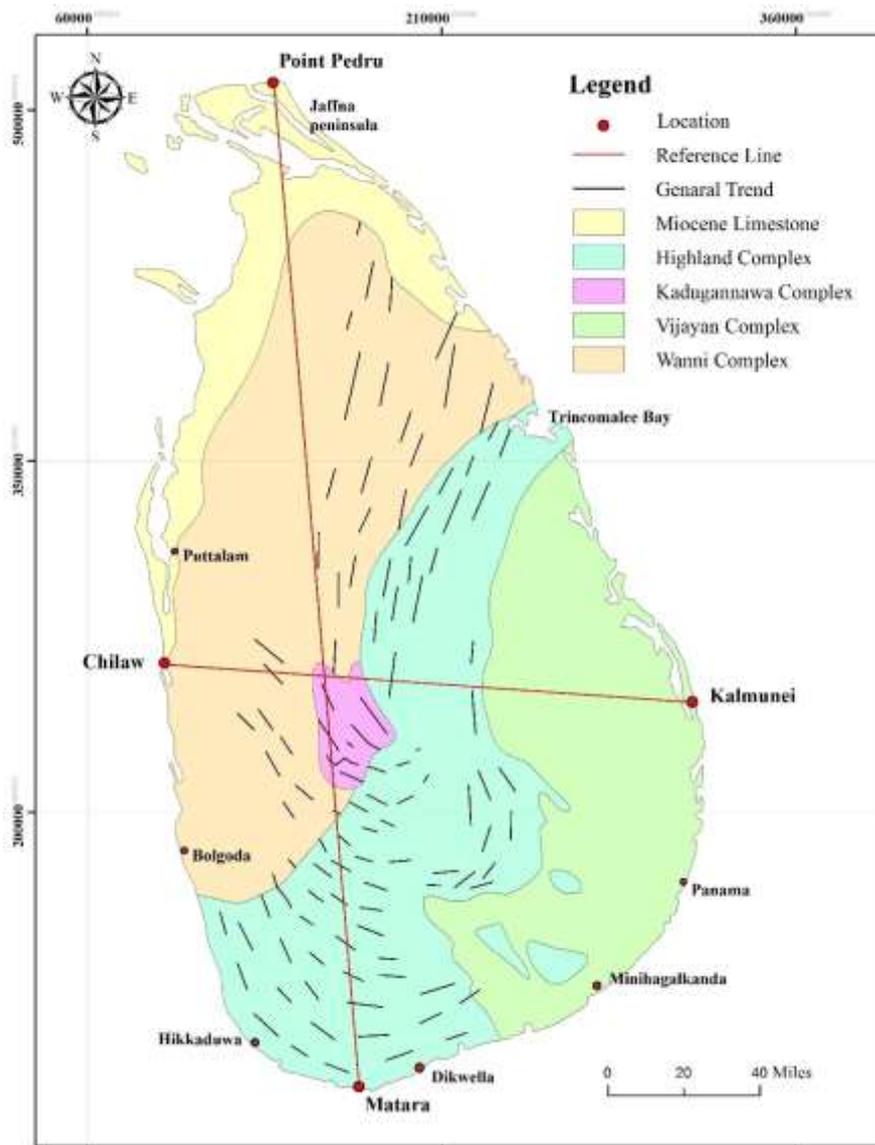


Fig. 1 General geology and structure of Sri Lanka. The reference lines indicate the four cardinal quadrants of this review which having different geological backgrounds and coastal geomorphologies.

BASEMENT OF SRI LANKA

Sediments generated as a result of weathering and erosion of central hill countries of Sri Lanka may be the main sources for the coastal sedimentations. The Precambrian basement of Sri Lanka is subdivided into four metamorphosed lithotectonic units based to lithology, structure, metamorphic grade, isotopic

characteristics and geochronological data (Cooray 1994; Kröner *et al.*, 2003; Kehelpannala, 2003). The NE part of the country is covered by fossiliferous Miocene limestones that were laid on the metamorphic basement (Figure 1; Cooray, 1984; Dahanayake and Jayawardhana, 1979; Katupotha and Dias, 2001).

QUATERNARY EVOLUTION OF COASTAL MORPHOLOGIES

Quaternary deposits cover the Precambrian rocks and Miocene limestone around the country with various thicknesses and in different forms traced by erosion and depositional processes of marine, fluvial and aeolian nature (Katupotha, 2007). Further, these quaternary formations belong to either the Pleistocene or Holocene have been formed and modified by regional, local, coastal and climate constraints (Katupotha, 2014).

PLEISTOCENE COASTAL REMARKS AND EVOLUTION

Around the SE Asian region, approximately 50 glacial cycles have been noted with evidence of biogeography (Woodruff, 2010). However, the Sri Lankan coasts hold evidence of a sea level high stand before the Last Glacial Maximum (LGM) but no scientific evidence to prove an exact time period or additional glacial periods prior to or after that (Swan, 1983; Cooray and Katupotha, 1991). This foremost sea level high stand is recorded as 'basal gravel beds which are composed of quartz, chert and limestone pellets bound by ferruginous materials' (Cooray, 1967). In the NW region of Sri Lanka, 'basal gravel beds' are laid on Miocene limestones or Precambrian basements, their origin proposed as probable fluvial system sheet flood events or a sea level fluctuation (Cooray, 1967; Cooray and Katupotha, 1991). Similarly, in the SE coasts, 'basal ferruginous gravels' that were laid over the Miocene's of *Minihagalkanda* are suggested to have originated during the Pleistocene, the base of the Quaternary deposits (Figure 1; Weerakkody, 1992).

Sri Lankan coasts are indicative of wet and dry sedimentation processes during the glacial and interglacial periods (Cooray and Katupotha, 1991). Studies around the Indian Ocean indicate that the sea level was approximately 110-130 m below the present sea level during the LGM period and has gradually increased since (Colonna *et al.*, 1996; Hanebuth *et al.*, 2000; Yokoyama *et al.*, 2000; Camoin *et al.*, 2004; Fürstenau *et al.*, 2010). A Pb isotope evolution study on the Indian Ocean revealed that a warm and wet climate prevailed, enhancing continental chemical weathering processes during the interglacial periods (Wilson *et al.*, 2015). Likewise, weathering processes in Sri Lanka were activated during before the LGM, and huge amounts of sediment were deposited in exposed coastal plains (Cooray and Katupotha, 1991; Katupotha, 1994). Similar to Indian coasts, fluvial and aeolian processes activated from the strong monsoon climate and sea level low stands reworked the coastal plane and brought sediments back to coastal lowlands (Jayangondaperumal *et al.*, 2012). The well-known 'red beds' recorded in the NW and SE coasts developed with such aeolian actions (Dahanayake and Jayawardana, 1979; Cooray and Katupotha, 1991; Weerakkody, 1992). The depositional ages of the NW 'red beds' are calculated as 25000 BP, corresponding to the sea level low stands of Sri Lanka (Singhvi *et al.*, 1986). Similarly, the red sand deposits that are found in the east and SE regions of India are more comparable with the NW 'red beds' of Sri Lanka (Gardner, 1995). They also appear to have originated from fluvial and coastal dunes and are located about +12 m from the present sea level, indicating the strength of the aeolian processes (Gardner, 1995; Rao *et al.*, 2006). Chronological data from the

Indian red dunes suggests that they could have been deposited post LGM (Rao *et al.*, 2006; Srivastava *et al.*, 2016).

In Sri Lanka, there are several elevated (approximately 15 m above mean sea level) gravel deposits, and extensive sandy deposits are found in localized areas in the southern and western coastal regions (Cooray and Katupotha, 1991). The origin of these has been suggested as a result of fluvial processes during a sea level high stand (Deraniyagala, 1958; Wicramaratne *et al.*, 1988; Cooray and Katupotha, 1991; Wijayananda, 1994). Wickramagamage (2011) noted that similar terrace gravels, raised beaches and lagoonal deposits in the elevated localities of *Bolgoda* Lake and the *Kalu Ganga* River regions of western Sri Lanka (Figure 1). He suggested the formation of these deposits is during the sea level high stand period between the LGM and the Holocene. However, the age of the 'terrace gravels' is problematic since sea level high stands are not recorded after the LGM of the Pleistocene period, and hence a previous glacial period is suggested, which requires future studies to confirm.

HOLOCENE COASTAL REMARKS (0.0117 MA – RECENT)

As a result of the Late Quaternary marine transgressions, most worldwide coastal lagoons and their relevant features have been formed and developed in lowlands or valley mouths (Bird, 1994). Afterward, locally generated coastal processes, sea level changes and climatic actions reshaped the coastal morphologies (Martin and Dominguez, 1994). As described by Camoin *et al.* (2004) and references therein, there are two types of sea level oscillations identified around the Indian Ocean during the

Holocene. Type I indicates a regressive sea level for the Holocene compared to the present mean sea level, with sediments laid down with LGM (Camoin *et al.*, 2004; Jayangondaperumal, 2014). Type II indicates regressive as well as transgressive events with different increment rates (Brückner, 1989).

The mid to late Holocene period of Sri Lanka is recorded as a sea level high stand or as a transgressive coast corresponding to Type II oscillations (Katupotha and Fujiwara, 1988; Ranasinghe *et al.*, 2013; Ratnayaka *et al.*, 2017). For example, the marine originated fossil shell deposits emerged in coastal embayments of the southern and SE coastal zones of Sri Lanka are evidence for marine transgressions during the mid to late Holocene. Similarly, several inland buried coral deposits found in the SW coasts and many locations in the southern coasts are a few kilometers from the current shore line and are also evidence for marine transgressions (Cooray and Katupotha, 1991; Katupotha, 1995). The shell deposits and gravel deposits of eastern coastal areas also indicative of paleo sea level oscillations. Adikaram *et al.* (2017) noted fossilized tidal deposits at eastern coasts above 5 m from the present sea level and suggested a sea level high stand during the Holocene. In addition, the *Bolgoda* lake area of the western coast and barrier formations of the SE coasts also prove the sea level high stand of the mid to late Holocene (Ranasinghe *et al.*, 2013; Ratnayaka *et al.*, 2017). The maximum height of the sea level high stand is recorded as 6.5 m (Katupotha and Wijayananda, 1989; Ratnayaka *et al.*, 2017). The marine transgression event of the mid to late Holocene was terminated 3000 years ago when the

sea level reached its present level (Ranasinghe *et al.*, 2013).

Therefore, it can be concluded that the formations of most sediment barriers in coastal lakes, estuaries and lagoons around Sri Lanka are the result of sea level transgression during mid to late Holocene. Thereafter, fine adjustments of coastal morphologies occurred, with consequent environmental changes throughout the late Holocene.

POTENTIAL EFFECTS FOR MORPHOLOGICAL VARIATIONS ALONG SRI LANKAN COASTLINE

Sri Lankan's modern coasts are differentiated into four quadrants divided by the four cardinal directions; the coastal environments are discussed in the present study accordingly. The NW quadrant extends from Point Pedro to Chilaw on the western coast, and the SW quadrant extends from Chilaw to Matara (Figure 1). The SE quadrant extends from Matara to Kalmunei (extending southward to Batticaloa Lagoon), and the remaining coastal area of the island makes up the NE quadrant.

GEOLOGICAL AND GEOMORPHOLOGICAL CHARACTERISTICS OF FOUR QUADRANTS

It is well noted that the NW coast sedimentations can be discussed presuming an identical geological background. This is because the crustal basement of the region is composed of WC rocks and thick deposits of Miocene limestone cover the crustal rocks. Quaternary deposits overlay the

Miocene's, developing a progressive coast (Cooray and Katupotha, 1991). Therefore, Quaternary sedimentation processes of the NW sector typically are controlled by the crystalline rock structures. Most of this quadrant's coastal zone is covered by sediment from the Indian subcontinent, and hence, small islands have distinctive characteristics from the coast. Another characteristic feature of this coastal zone is windblown sand dunes, probably the origin of most of the Quaternary beds since the Pleistocene (Figure 2; Cooray 1984; Dahanayake and Jayawardhana 1979; Jayasingha *et al.*, 2014).

The SW coast of Sri Lanka is known as a regressive coast, and hence, most of the weathered metamorphic rocks are exposed (Cooray and Katupotha, 1991). The world-famous blow hole 'Hummanaya' at *Dikwella* is a good example of the coastal erosion process which is controlled by geological structures. The basement of the SW coast is composed of HC and part of the WC. The trend of majority of the crystalline rocks is parallel to the coast line which is able to bare depending on the rock strength against the coastal forces (Figure 3; Kehelpannala, 2003). Rocky, steep cliffs are found in many localities of the SW coasts (Katupotha, 2007).

In contrast to the SW coasts, the SE coast is considered a progressive coast (Cooray and Katupotha, 1991). The Quaternary sedimentation basement of the SE quadrant is VC. Though the southern zones indicate a regressive character, the eastern zones starting from the *Panama* area indicate huge,

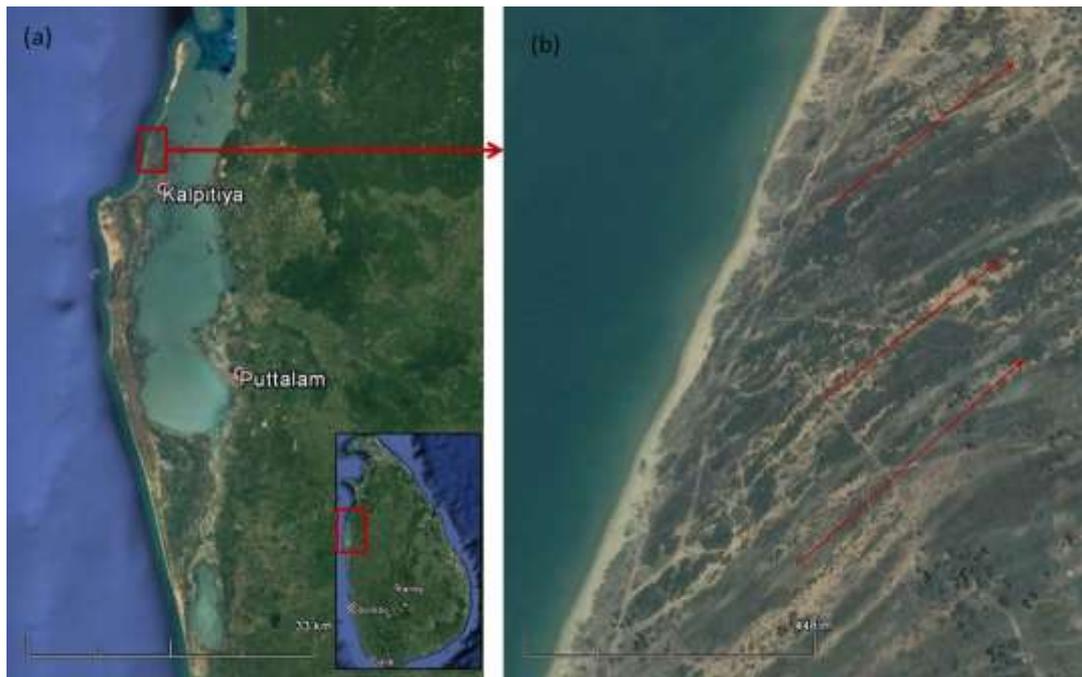


Fig. 2. (a) Development of sand barriers in NW coastal margins (b) Sedimentation is aligned along the wind-blown direction.

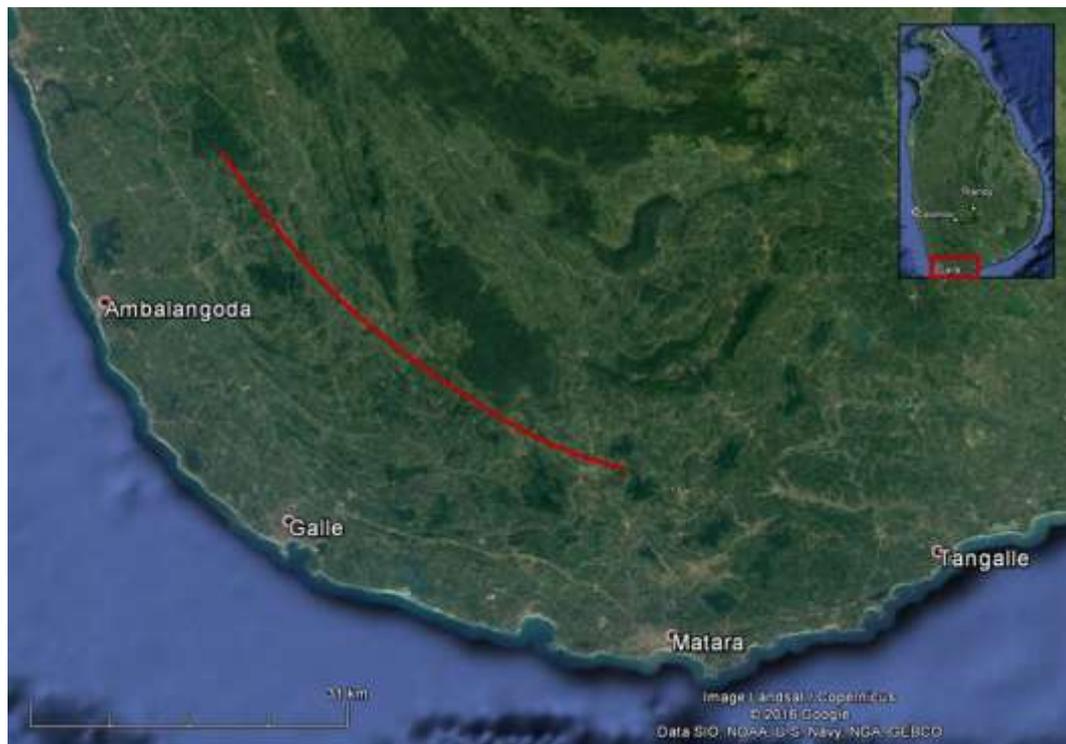


Fig. 3. Southern and SW coasts showing the erosive beaches. The coastline follows the general rock structures (red line indicate the trend of the rocks).



Fig. 4. SE coastal zones (a) development of spits following high energy current paths (b) Sediment deposition along spit.

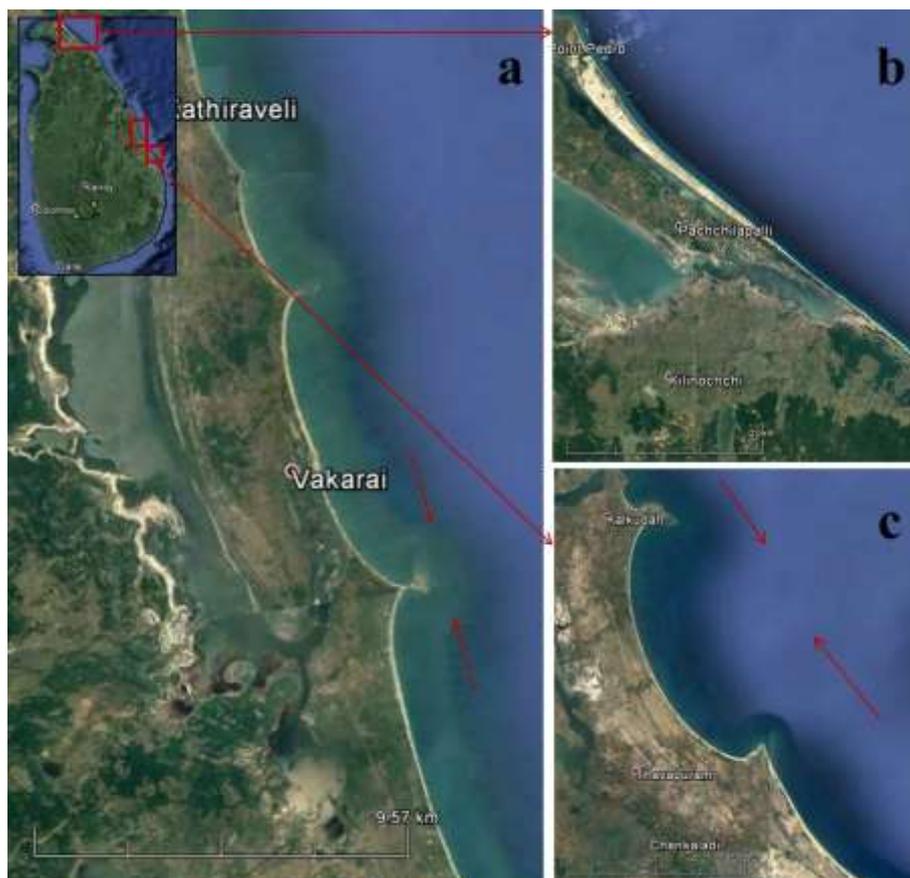


Fig. 5. Selected zones of NE coasts of Sri Lanka. (a) Development of spits indicating longshore depositions and they do not show extensions with current directions. (b) Linear coastline of Jaffna indicating sharpening of coasts from East Indian coastal currents (EICC) (c) Curved beach resulting from wind system.

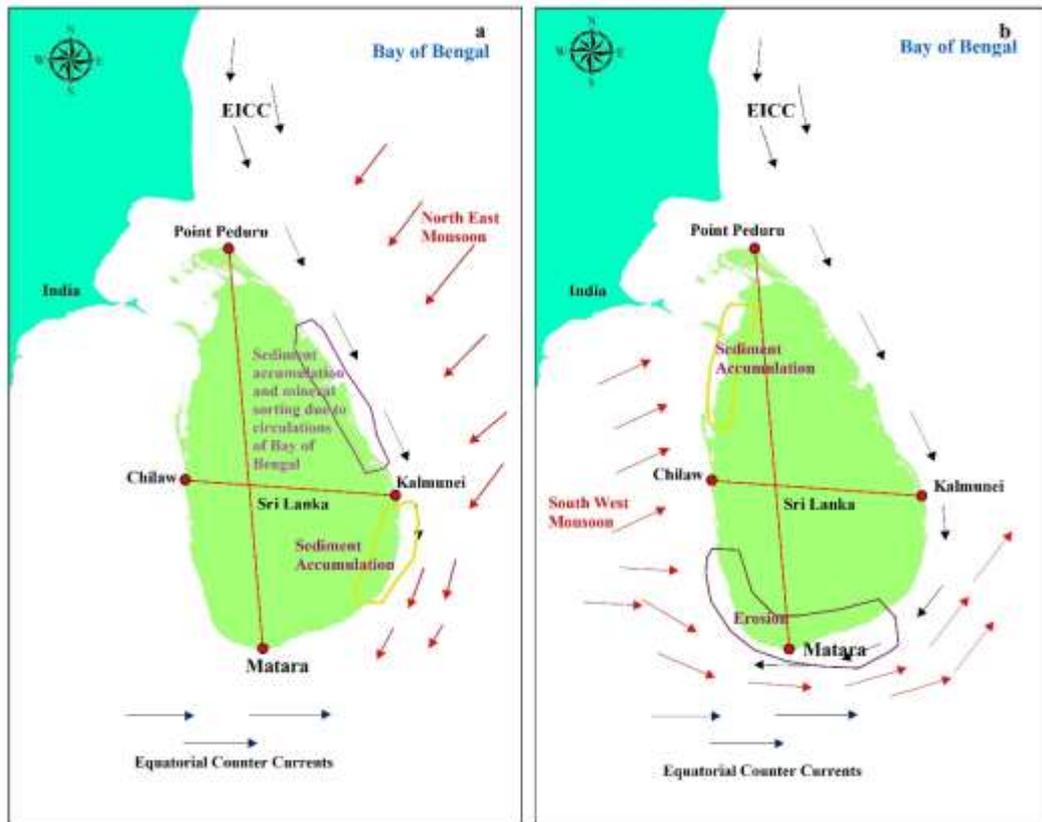


Fig. 6. The paths of the ocean currents that control the coastal evolution of Sri Lanka. Prominent sea current paths during (a) NE monsoons (b) SW monsoons.

progressive sand barriers or spits (Figure 4). Such huge sandy barriers with small dunes cover the old heritage site known as ‘*MuhuduMahaViharaya*’, close to Panama.

The NE coasts of Sri Lanka are also a progressive beach, evident from the barrier lagoon formations and sandy coastal planes (Cooray and Katupotha, 1991). This coastal zone is underlined by VC in the south, HC in the central part and a Miocene cover at the northern end. Meanwhile, the Gulf of Mannar, in the NW and NE offshores of the Sri Lankan coastline, is characterized by larger fringing reef corals (Rajasuriya *et al.*, 2000). These developed on the limestones and related sedimentary basins, probably favoring shallow marine environments. The bar reef marine sanctuary in the NW coasts is

the coast is well known for its mineral sand deposits. Sedimentary geochemical studies of the coastal zone provide evidence of mineral sorting by ocean currents in the Bay of Bengal (Young *et al.*, 2014). In contrast, the *Trincomalee* area has outcrops of the basement rock. Steep, rocky cliffs are found in the *Trincomalee* area, which is covered by Highland complex rocks. The southern portion of the coast is covered by massive sedimentary barriers and spits extending towards the Batticaloa (Figure 5).

well extended towards the north, parallel to the coasts. These coral reefs likely acted as a platform for the formation of the islands in the NW coasts. The *Hikkaduwa* reefs are the healthiest, with living coral cover (Rajasuriya *et al.*, 2000). Shore platforms developed on hard rocks,

which is favorable for coral growth.

COASTAL PROCESSES MODIFIED THE COASTLINE AROUND SRI LANKA

The coastal geomorphology of an island such as Sri Lanka is mainly controlled by oceanic processes on the lithology. In particular, a wind driven longshore sediment transport pattern is one of the major factors for a coast to be considered either a progressive or regressive (CERC, 1984). A coast is considered progressive if the erosion rate is less than the deposition rate and regressive if the opposite is true

(Komar, 1998). However, characteristics of the beach face such as the headlands do not deposit longshore sediments and hence can be considered regressive coasts.

Geomorphologically, the headlands of the SW coastal zone of Sri Lanka are characterized by well-exposed escarpments and rocky beaches of HC rocks (Swan, 1983). Thus, longshore sediments generated by SW monsoons are not trapped at the SW and southern coasts (Figure 6). On the other hand, the easterly moving currents of SW

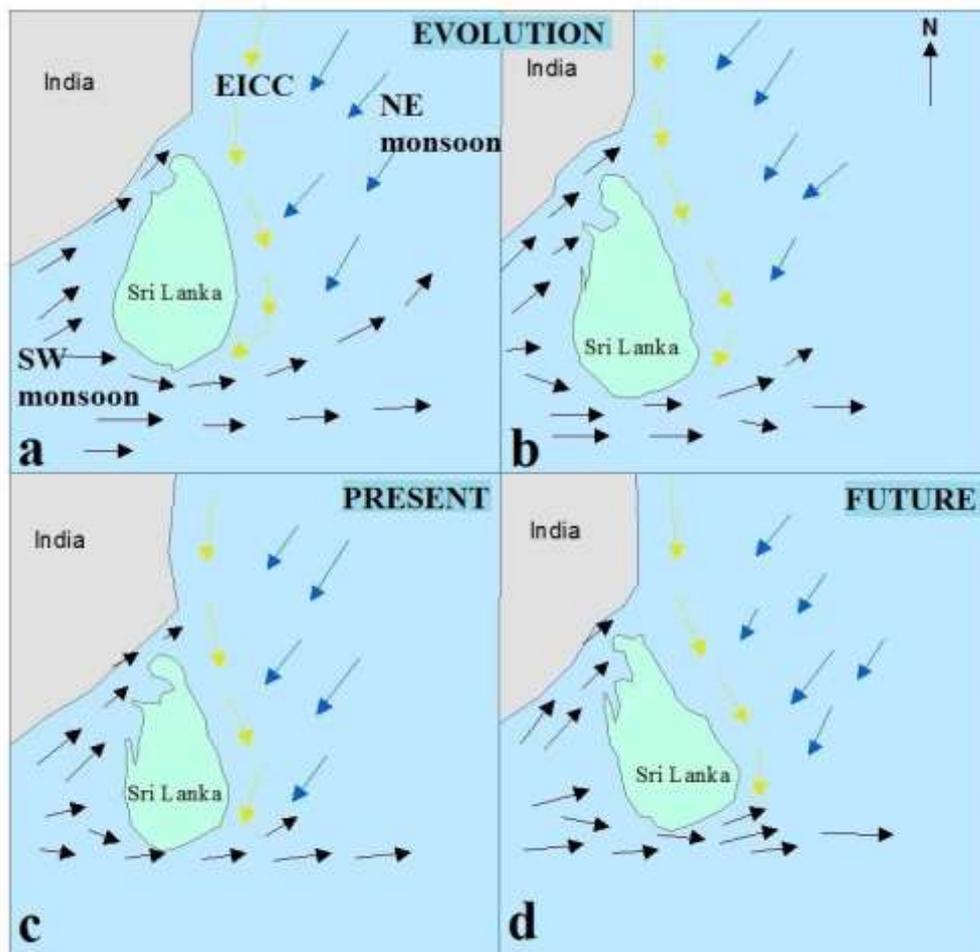


Fig. 7. Hypothetical model for evolution of Sri Lankan coasts; (a) Erosion of NE coast and south – SW coast by EICC and NE monsoon currents and EICC and SW monsoon currents, respectively. (b) Resulted sharp boundary along India-Sri Lanka, (c) Current status of Sri Lankan coasts, (d) Future status of Sri Lankan coasts with well-developed sediment depositions in SE and Negambo area.

monsoons are complicated and move little away from the Sri Lankan coasts (Schott *et al.*, 1994). A layer of low-salinity water is coming from the Bay of Bengal and they move towards the West (Schott *et al.*, 1994; Vinayachandran and Yamagata, 1998). As a consequence, the longshore currents driven from the SW monsoons do not deposit sediment along the SW and southern coasts of Sri Lanka. The current path of the SW monsoon changes at the SW coasts of Sri Lanka rather than forming a deposition zone for current generated sediments (Vinayachandran and Yamagata, 1998). Instead, the SW monsoon currents are further energized with *westerly wind bursts* (WWB) of the world.

However, SW monsoon generated longshore currents travelling to the northern coasts of Sri Lanka or western India are able to deposit the sediments along the NW coastal zones of Sri Lanka. Since the currents generated by SW monsoon are initially broad and become shallow, they can carry a huge sediment load along the continental shelf areas of NW Sri Lanka with advancing the monsoon rains (Vinayachandran and Yamagata, 1998). Further, the identical coastal geomorphologies of NW quadrant of Sri Lanka are fundamentally controlled by the Indian subcontinent and the wide and shallow continental shelf.

Though the geology is similar to that in the SW quadrant, the NE coasts are probably controlled by the rock structure of the basement due to the coastline being perpendicular to the general strike of the rocks or the intensity and patterns of the fracture systems (Hall *et al.*, 2008). In addition, the major controlling factor is monsoon driven circulations of water in the Bay of Bengal. During the NE

monsoon, the monsoon currents and east India coastal currents (EICC) flow south along the coastal belt of India and Sri Lanka (Figure 6; Shetye *et al.*, 1996; Mukherjee *et al.*, 2014). Kolla *et al.* (1976) noted that sediment-bearing wave generated energy move parallel to the coasts of India and Sri Lanka and are able to deposit along the coastal belt. It is probable that the cyclonic activities of the Bay of Bengal also control the sedimentation processes in the NE coasts, and sediments are therefore subjected to the mineral sorting effect. The cyclonic gyre created with the NE monsoons which are activated by the Ekman Pumping cause upwelling sedimentation associated to the SW regions of the Bay of Bengal (Vinayachandran and Yamagata, 1998; Vinayachandran and Mathew, 2003). The sedimentological parameters and the energy variations in such coastal environments are enough to remove the light minerals by winnowing actions (Kulgemeyer *et al.*, 2018). The morphological structures indicate no relative orientation with these circulations (Figure 5 b, c).

In inter-monsoon periods, WWB that have rapid eastward flowing jets are dominant, and hence the energy generated in the coastal currents of the southern coastal zones of Sri Lanka are subjected to erosion rather deposition (Moum *et al.*, 2014). In addition, since the SE coast was aligned in the juxtaposition of the SW monsoon currents and the low-salinity currents of the Bay of Bengal, progressive coasts are recorded in water dilution zones (Figure 6). Above current generated wind forces and the vertical salinity stratifications of this region intensify the suspended sediment loads in the mixing zone of SE region of Sri Lanka (Narvekar and Kumar, 2006). Hence, the energy dilutions in coastal

zones of SE regions get high sediment loads which can make progressive coasts. Therefore, the eastern part of the SE quadrant shows progressive characteristics, while the southern coasts show regressive characteristics. The eastward flows of SW monsoons and inter-monsoons are stronger than the low-salinity currents of the Bay of Bengal. Hence, the progressive nature of the eastern part is created with well-developed spits compared to other coasts (Figure 4). The sediments, likely derived from Indian river systems and rivers in eastern Sri Lanka mixed with low-salinity water currents from the Bay of Bengal and deposited in the eastern zone of the SE quadrant.

The evolution of coastal morphologies around Sri Lanka can be described as shown in Figure 7. In summary, the shape of the island bulges in the NW-SE direction and the coastal morphologies were essentially controlled by monsoon forces and regional sea currents. Hidden heritages such as sediment profiles of buried '*Muhudu Maha Viharaya*' near *Panama* of SE coasts will be an ideal location to prove the sedimentation history of Sri Lanka which is useful in environmental and archaeological investigations.

CONCLUSION

Sri Lanka's coasts yield evidence for a sea level high stand before the LGM. However, the time period for this has not yet been proven. Sea level low stand and monsoon climates during the LGM have provided excessive sedimentation on the coastal planes of Sri Lanka from weathering processes. Hence, Pleistocene coastal morphologies are well developed, with the prevailing climate and sediment supply dominated by fluvial and aeolian actions. During the late

Holocene, Sea-level high-stand is recorded. Subsequently, coastal morphologies have been modified by the geology, geological structures, sea currents and climate of each four cardinal quadrants of the island.

1. The NW quadrant is basically controlled by Miocene limestone deposits with the absence of Precambrian rock structures. The shielding effects of the Indian subcontinent has preserved longshore sediments that come at the beginning of the SW monsoon period. Hence, many islands and sediment barriers are characterized to the zone.
2. The SW and NE quadrants have similar geological conditions but different rock structures. Sea currents from SW monsoons turn around the SW quadrant in a rock strike parallel path. Hence, there are no sedimentation processes.
3. In the southern part of the SE quadrant, the SW monsoon generated sea current flows and *westerly wind bursts* gave the coast a regressive character. However, the eastern part is the dilution point of sediment bearing freshwater currents from the Bay of Bengal with easterly moving salinity waters and hence sediments are deposited, forming huge sediment barriers.
4. The NE coastal belt is above the sea current nodes and hence sediments loads are reworked with circulations of the Bay of Bengal. Therefore, sorted minerals are common in beaches of the area.

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