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Coastal landscape evolution in the Wilpattu National Park (NW Sri Lanka) linked to changes in sediment supply and rainfall across the Pleistocene–Holocene transition

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Coastal sand dunes are sediment archives which can be used to reconstruct periods of aridity and humidity, past wind strength and variations in the sediment supply related to sea-level changes. In this manner, the sedimentary record of fossil coastal dunes in Sri Lanka provides evidence for environmental and climatic changes during the late Pleistocene and Holocene. As yet, these environmental shifts are poorly resolved because the sedimentary facies and their depositional architecture have not been studied and only very few age constraints are available. Facies analysis of a lithological section at the Point Kurdimalai sea cliff in the Wilpattu National Park (NW Sri Lanka) reveals a striking resemblance to the stratigraphic succession associated with the Teri Sands in southeastern India, which is better dated. The reason is that deposition occurred under the same geological, climatic and geomorphological conditions in the two regions. This special situation allows for litho- and climate stratigraphic correlations across the Gulf of Mannar and links the landscape evolution at Point Kudrimalai to late Quaternary climatic events and sea-level changes. Our results show that the formation of red coastal dunes (Red Beds) in Sri Lanka was a multi-phase process across the Pleistocene–Holocene boundary and hence the differentiation between an Older Group of Plio-Pleistocene age (including the Red Beds) and a Younger Group of Holocene age in the Quaternary stratigraphic chart for Sri Lanka is not justified.

KEYWORDS
Gulf of Mannar, Indian winter monsoon, palaeo-environment, post-glacial transgression, red coastal dunes, sea level, stratigraphy

1 | INTRODUCTION

Point Kudrimalai ('Horse Point') at the northwestern edge of the Wilpattu National Park in Sri Lanka has a fascinatingly bizarre labyrinthic landscape of up to 2-m-high conical sandstone pinnacles covered by deep red sand (Figure 1). It is therefore not surprising that this place has a legend-rich past (Brohier, 1973; Green, 1990). Most importantly, the locality is associated with the arrival of the ancestors of the Sinhalese ethnic group. According to the Mahavamsa ('The Great Chronicle of Ceylon'), Prince Vijaya, the first recorded king of Sri Lanka, and his followers came ashore at Kudrimalai in 543 BC after being expelled from an Indian kingdom. After landing, they rested on the shore and observed that their hands were reddish due to the red coloured sand. Thus, Vijaya named the country 'Tambapanni', which

FIGURE 1 Pinnacle field exposed beneath deep red dune sands at Point Kudrimalai (Wilpattu National Park, NW Sri Lanka) [Colour figure can be viewed at wileyonlinelibrary.com]

means copper coloured. This name is still used by the locals to refer to the area. Likewise, the geological origins of Kudrimalai are shrouded in mystery. There is a popular belief that the site was created by a meteor strike due to the deep red coloured sand, which looks burned. Wayland and Davies (1923) were the first who described a lithological section and undertook an attempt to determine the age of terrestrial gastropod fossils from the sandstone pinnacles. But in the end, it has remained unclear whether they are pre- or post-Miocene. Nevertheless, the underlying deposits, which form a steep sea cliff at the study site, have been later identified as Miocene limestone (Katz, 1975). Today, the red sand is assigned to the informal lithostratigraphic unit of the Red Beds which comprises red dune and beach sands of late Pleistocene age (Katupotha, 1994). With the heavy mineral deposit at Aruwakkalu Hill south of the Wilpattu National Park (PQ deposit), the Red Beds contain one of the few identified significant global heavy mineral sand deposits yet to be mined (Wallace, 2016). The research of red sands in Sri Lanka therefore concentrates on their mineralogy and economic significance along with a few studies on pedogenesis and archaeological content (Cooray, 1995; Deraniyagala, 1976, 1986; Panabokke, 1996; Wallace, 2016), whereas the depositional architecture and history remains unclear (Katupotha, 1994). On the opposite side of the Gulf of Mannar (SE Tamil Nadu, India) a facies equivalent to the Red Beds is present with the Teri Sands (also referred as 'Teri Red Sands/Teris' in the literature; Alappat, Joseph, Tsukamoto, Kaufhold, & Frechen, 2016; Gardner & Martingell, 1990; Singhvi, Deraniyagala, & Sengupta, 1986; Wallace, 2016). The basic concept in interpreting the depositional history of the red fossil dunes is that periods of sand accumulation are related to (semi-)arid climatic conditions and the reddening occurred when the climatic conditions became more humid with enhanced precipitation (Gardner & Martingell, 1990). More recently, it has been shown that dune development in the coastal area of eastern Tamil Nadu was linked not only to dry climatic conditions but also to wind strength and supply or availability of sediment, controlled by vegetation cover and sea-level changes (Alappat et al., 2016; Alappat, Seralathan, Shukla, Thrivikramji, & Singhvi, 2013; Jayangondaperumal, Murari, Sivasubramanian, Chandrasekar, & Singhvi, 2012; Kunz, Frechen, Ramesh, & Urban, 2010). Red palaeo-dunes are widely distributed in the coastal area of South China (Old Red Sand) as well and have been used there as palaeo-climate archive for investigating variations in the East Asian Winter Monsoon intensity during the late Quaternary (Hu et al., 2013). Sea-level fluctuations on glacial–interglacial time scales have been identified as the dominant driving force for aeolian sand accumulation in this region (Jin et al., 2018). In this study, we describe the lithological sequence at Point Kudrimalai in order to understand the palaeo-environmental changes that led to this peculiar landscape and to place the Red Beds in a stratigraphic context to the Teri Sands and past patterns of climate change in the Indian monsoon region.

2 | GEOLOGICAL, GEOGRAPHICAL AND CLIMATIC SETTING

Sri Lanka is located between 5° and 10° northern latitudes at the southern tip of the Indian subcontinent. It is bounded to the west by the Gulf of Mannar, being part of the Laccadive Sea, and to the east by the Bay of Bengal (Figure 2a). The island has formed as a result of East Gondwana breakup in the Early Cretaceous and was situated in a tectonically stable region of the Indian Shield over the last 50 million

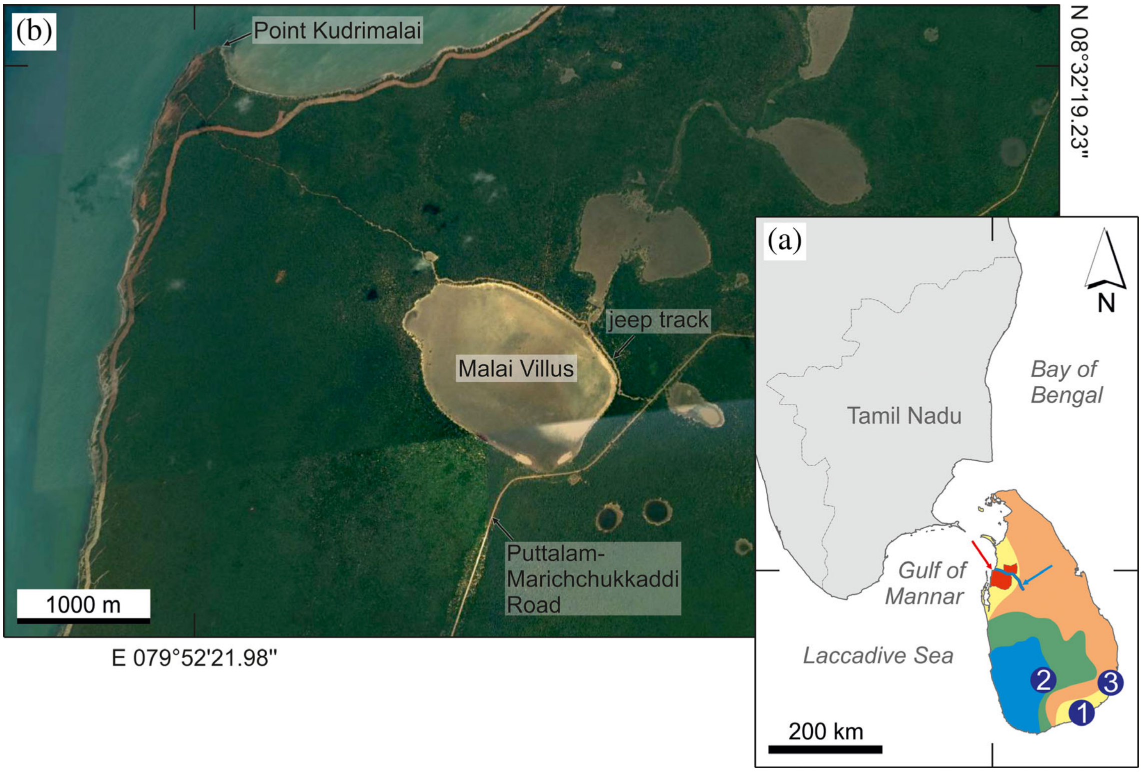

FIGURE 2 Geographic location of the study site in NW Sri Lanka. (a) Overview map of the Gulf of Mannar region indicating the climatic zones of Sri Lanka [blue: Wet Zone; green: Intermediate Zone; peach colour: Dry Zone (1,200–1,750 mm/a); yellow: Dry Zone (<1,200 mm/a)] as well as the positions of the Wilpattu National Park (red), Bundala and Patirajavela localities (1: Singhvi et al., 1986), the Horton Plains (2: Premathilake & Risberg, 2003) and the Panama estuary (3: Ranasinghe et al., 2013). The arrows indicate the study site at Point Kudrimalai (red) and the Modaragam Aru (blue). (b) Detailed map showing the access roads to Point Kudrimalai and several villus on the flat coastal plain (Google Earth Image, Image © 2017 DigitalGlobe, CNES/Airbus; image taken in 2014) [Colour figure can be viewed at wileyonlinelibrary.com]

years (Blankenburg, Hewawasam, & Kubik, 2004; Cooray & Katupotha, 1991; Curray, 1984; Emmel, Lisker, & Hewawasam, 2012; Gibbons, Whittaker, & Müller, 2013; Gunatilaka, 2007). Sri Lanka's basement consists of Precambrian metamorphic units of the Southern Granulite Terrane (Kumar, Zeyen, Singh, & Singh, 2013). Only small intracratonic occurrences of Jurassic to Lower Cretaceous terrestrial siliciclastics are preserved at Tabbowa, Andigama and Pallama in the northwestern part (Cooray, 1984; Emmel et al., 2012). On the Jaffna Peninsula and the surrounding islands, the crystalline basement is extensively covered by shallow-marine limestones of Miocene age. Towards the south, this limestone occurrence extends along the west coast as far as Puttalam as a gradually narrowing belt (Cooray, 1984). The Quaternary succession is subdivided in (a) an Older Group of Plio-Pleistocene age, comprising the Basal Ferruginous Gravels and the Red Beds, which are summarized as the Iranamadu Formation (Deraniyagala, 1992), as well as terrace gravels, and (b) a Younger Group of Holocene age, including lagoonal and estuarine sediments, buried and emerged coral reefs, shell beds, beachrock, coastal dunes, beach and dune sands, and peat (Katupotha, 1994). The Red Beds were assigned to the Older Group on the basis of five thermoluminescence (TL) dates, obtained from red sands at Bundala and Patirajavela in southeastern Sri Lanka (Figure 2a), which suggest at least two episodes of sand accumulation in this area, at ca. 70 ka and at ca. 25 ka, (Singhvi et al., 1986). Red dune sands in western Sri Lanka are not radiometrically dated.

Topographically, the island comprises central highlands in the south-central part, which range in elevation from 300 m to about 2,500 m and are surrounded by large lowland plains extending up to the coastal areas (Ratnayake, Premaratne, & Sonnadara, 2011). Sri Lanka has a tropical monsoon climate with two principal monsoon rainfall seasons (southwest monsoon: May through September; northeast monsoon: December through February) which is considered to be at least as old as the late Pleistocene (Domroes, 1979; Malmgren, Hulugalla, Hayashi, & Mikami, 2003; Wallace, 2016). The central highlands act as important physiogeographical barrier, which controls the prevailing moisture-laden monsoon winds (Malmgren et al., 2003). This causes a major climatic zonation into a Wet Zone, a Dry Zone and an Intermediate Zone (Wijesinghe, 1979; Domroes & Ranatunge, 1993; Malmgren et al., 2003; Karunaweera, Galappaththy, & Wirth, 2014; Figure 2a). The Wet Zone (>2,500 mm/a) essentially comprises the southwestern part, which receives rainfall throughout the year and is directly exposed to the SW monsoon winds. The northern and eastern regions of Sri Lanka constitute the Dry Zone (<1,750 mm/a) with long drought periods and substantial precipitation during October to January from the NE monsoon. Within the Dry Zone, the least amount of rain (800–1,200 mm/a) falls in the southeastern and northwestern coastal areas, including the Wilpattu (Figure 2a). The Intermediate Zone receives a mean annual rainfall between 1,750 and 2,500 mm with a short and less prominent dry season. Coastal dunes of various types (foredunes, foredune plains, transgressive dune fields) occur along 300 km of the Sri Lankan coast (Hesp, 2004). The best dune development occurs in areas of strong, persistent onshore winds and long dry season (Swan, 1979).

Wilpattu National Park is a 1,317 km^2 large wildlife sanctuary located in the northwestern coastal lowland of Sri Lanka 26 km north of Puttalam and 30 km west of Anuradhapura (Figure 2a). Its geology is dominated by Precambrian gneisses of the Vijayan Complex forming low NW–SE aligned ridges in the eastern part of the national park. In the western part, the crystalline basement is unconformably overlain by flat-lying limestones of Miocene age. This limestone area is a rather flat doline plain with many sand-rimmed shallow lakes, or 'villus' (Figure 2a), that are name-giving for the Wilpattu ('Land of Lakes'). The limestone is mantled by red earth or sand (Red Beds) varying in thickness from 1 m to about 7 m (Coates, 1935; Cooray, 1967; Katz, 1975). Since the distribution of red earth/sand is largely consistent with the Miocene limestone occurrence, it has been proposed to represent a type of terra rossa that in part derived from insoluble residue of the underlying limestone (Katz, 1975). In the soil map of Sri Lanka, by contrast, this sedimentary unit is indicated as red-yellow latosol that formed on old beach-, beach ridge- and nearshore-deposits on a Pleistocene coastal plain (Panabokke, 1996). A narrow beach with a zone of dunes, which can extend inland up to 2 km, characterizes the present-day shoreline. The dunes can be 7 m high and are often covered with vegetation. Their alignment is NE–SW in the direction of the prevailing winds during the SW and NE monsoons (Katz, 1975). Only at Kollankanatta and Point Kudrimalai (Figure 2b) as much as 10 m high sea cliffs occur supposedly where Miocene limestone intersects the coastline at embayments (Katz, 1975). Sand spits and bars are also occasionally present along the coast.

3 | LOCALITY AND METHODS

The studied outcrop is located at the coastal cliff of Point Kudrimalai in the Wilpattu National Park (North Western Province; N 08°32′19.23″, E 079°52′21.98″). This place is accessible via a rough track leading at the Malai Villus from the Puttalam-Marichchukkaddi Road to the coast (Figure 2b). The sedimentological dataset consists of information gathered through field observations along a 19-m-long continuous stratigraphic section that was measured bed by bed (Figure 3). A grain-size comparator chart (Switzer, 2013) was used to estimate the grain-size of clastic sediments in field. Five depositional units (beds) were distinguished based on their different lithological and textural characters, sediment structures and separating discontinuity surfaces (Figure 3). In order to constrain the age of the yellow red sand at the top of the Point Kudrimalai section (Bed 5), a ceramic shard from the basal gravel sheet was TL-dated in the Laboratory Kotalla (Haigerloch, Germany). The determined age refers to the burning age of the pottery, which means the time of its last heating to a temperature of more than 500°C. Detailed information on the analytical equipment, procedures and errors are given in the Thermoluminescene Report No. 01R200517 (Supporting Information). Fossil bones and shells from Point Kudrimalai are not suited for radiocarbon dating because of their strong diagenetic alteration (replacement of primary aragonite by calcite spar, silicification; pers. communication R. Hatfield, BETA Analytic Inc., Miami, FL). Due to the lack of other luminescence and radiometric ages, an integrated

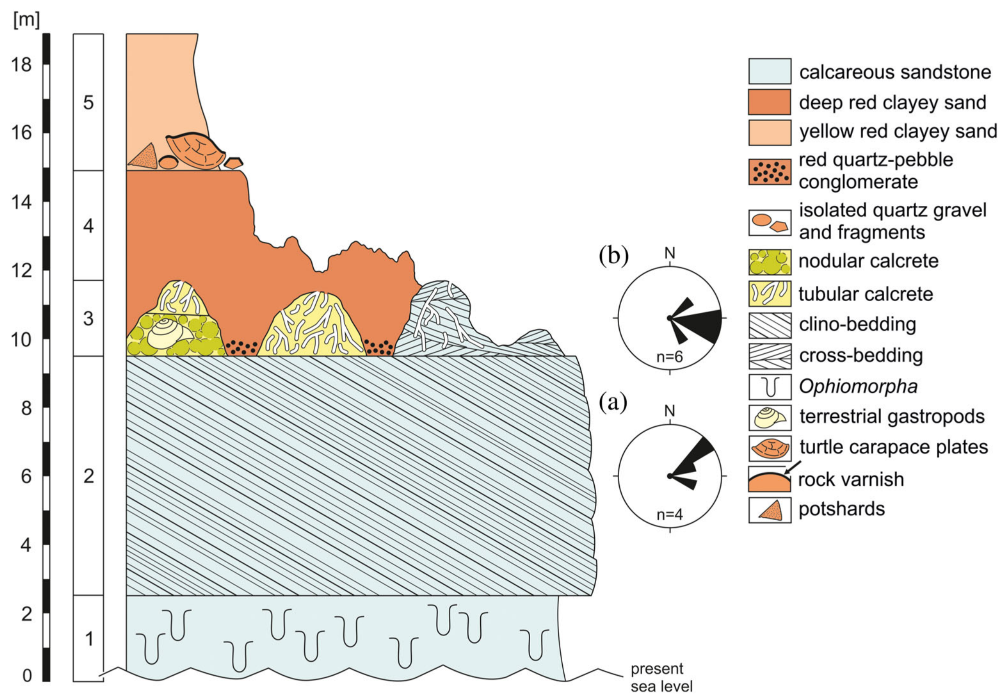

FIGURE 3 Point Kudrimalai section. Lithological log and measurements of cross-bed dip directions as proxy for palaeocurrent (a) and palaeo-wind (b) directions [Colour figure can be viewed at wileyonlinelibrary.com]

stratigraphic approach including information from lithostratigraphy, altimetry and TL dating is therefore used to resolve environmental changes with the best possible time resolution.

4 | RESULTS

An at least 2.4-m-thick sedimentary unit of horizontally thick-bedded and intensely bioturbated calcareous cemented, fine- to medium-grained sandstones is exposed at the foot of the sea cliff (Bed 1; Figure 3). The sand fraction is dominated by quartz but other red and black mineralic grains are common as well. Bedding planes show scattered cross-sections of up to 6 cm wide vertical shafts of crustacean burrows having a thick lining (*Ophiomorpha*; Figure 4a). Above and in sharp contact (Figure 4c) follows an about 7-m-thick sedimentary unit showing a distinct clinoformal internal architecture (bed 2; Figure 3). It consists of oblique foresets of 40–50 cm thickness and inclined around 30° towards the NE (Figure 4b). The sediment is coarse-grained calcareous-cemented quartz sandstone, showing a centimetre-scale parallel layering (Figure 4c). On top of the clinostratified sedimentary unit is a dense field of isolated conical pinnacles up to 2.5 m high and 1.5–2.4 m (distance measured between the highest points of neighbouring pinnacles) apart (Bed 3; Figures 3 and 5a). The pinnacles are formed of hollow tube-shaped carbonate concretions (tubular calcrete; Figures 5e,f). The host sediment is a coarse-grained quartz-sand with minor additions of heavy minerals. The density of carbonate tubules generally decreases on a distance of ca. 60 m in direction to the sea and the sandstone shows cross-bedding with high 24°–26° angles towards E–SE (Figure 5b). A flat-topped, yellowish-grey nodular calcrete with a high content of coarse-grained quartz-sand and abundant terrestrial gastropods (shells replaced by secondary calcite; Figure 5d) is found below the tubular calcrete in the SW part of the pinnacle area (Figure 5c). This more than 1-m-thick deposit is in sharp contact to the tubular calcrete (Figure 5c) and disappears towards the NE. A 5.4-m-thick unit of deep red siliciclastics follows above (Bed 4; Figures 3 and 6a). It starts with a deep red conglomerate composed of well-rounded quartz pebbles in a deep red clayey sand matrix, which occurs only between the pinnacles (Figures 3 and 6b). Overlying is a compact deposit of deep red, homogeneous, clayey sand that is eroded to a mass of small columns (Figures 1, 3 and 6c). Main components are medium- to coarse-grained quartz-sand grains and dark heavy mineral grains. Rhizoliths and root moulds filled with red sediment are present is the dark red sand (Figures 6c,d). The section ends with a homogeneous deposit of yellow red, medium- to coarse-grained, clayey quartz-sand of approx. 4 m thickness (Bed 5; Figures 3 and 6e). Gravel of any type is absent in the red sands except of an only one-clast-thick sheet of loosely packed and poorly sorted gravel at the base of Bed 5 (Figures 3 and 6f). It yields well-rounded and cracked quartz gravel (fine pebble to cobble fraction) and large (5–8 cm) angular quartz clasts together with abundant iron nodules (shiny granules and fine pebbles), rhizolith fragments, some carapace plates of terrestrial turtles and ceramic fragments. The turtle carapace plates are completely stained red and permineralized. Typically, the large quartz components and turtle

FIGURE 4 Shallow-marine facies. (a) Calcareous sandstone with abundant *Ophiomorpha* burrows (dashed circles), Bed 1. (b) Large NE-inclined clinoform foresets (white arrow heads) exposed on the sea cliff at Point Kudrimalai, Bed 2. In contrast, Miocene limestone occurrences in NW coastal Sri Lanka are horizontally bedded. (c) Sharp contact (white arrow head) between the bioturbated calcareous sandstone of bed 1 and the internally laminated sandstone foresets of Bed 2. This outcrop shows a horizontal bedding since it cuts the inclined beds parallel to strike [Colour figure can be viewed at wileyonlinelibrary.com]

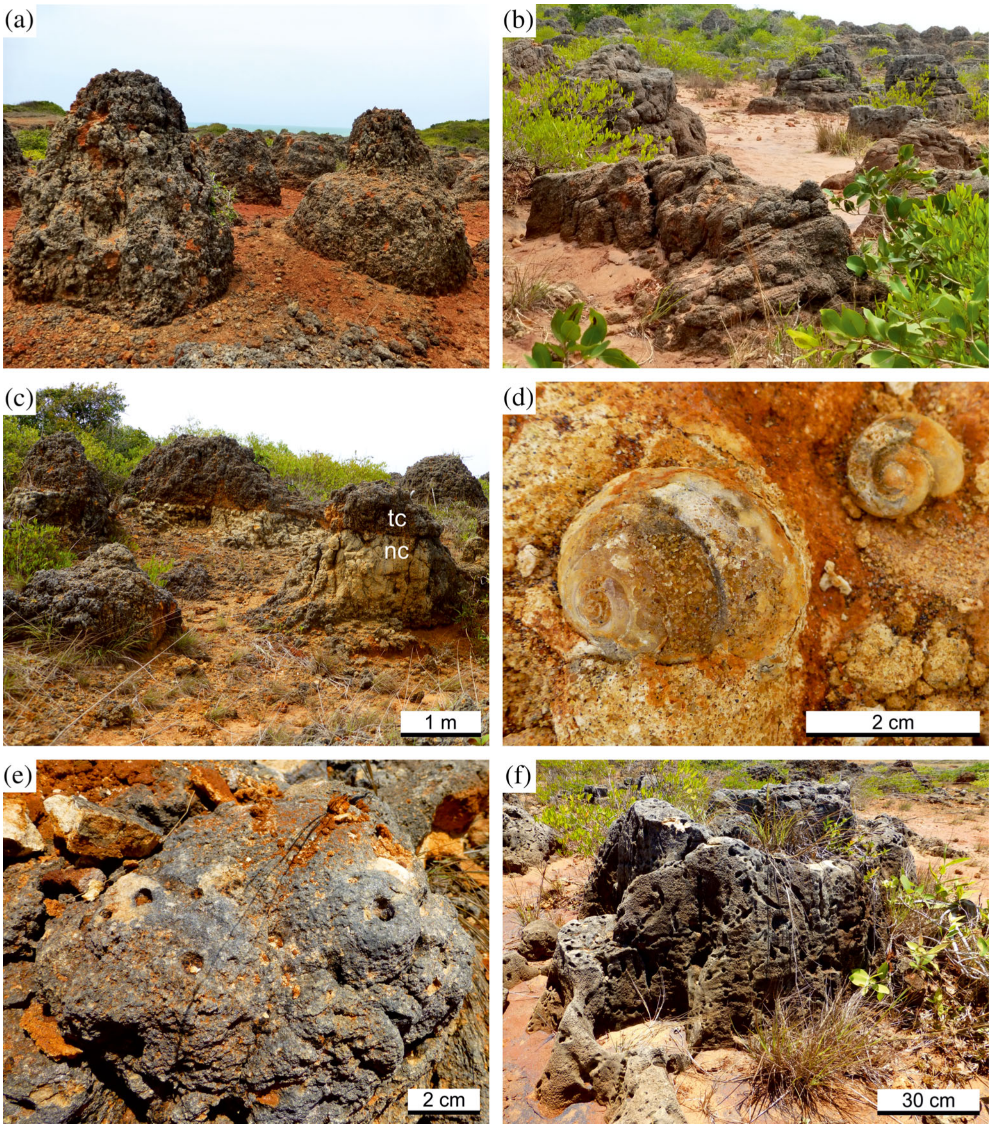

FIGURE 5 Sandstone pinnacles (Bed 3). (a) Isolated conical pinnacles up to 1.8 m in height. (b) Dune cross-bedding in sandstone from the pinnacle horizon. (c) Sharp contact between tubular (tc) and nodular (nc) calcrete. (d) The nodular calcrete contains numerous acavid gastropods. (e) Hollow tube-shaped rhizocretions (tubular calcrete) forming the sandstone pinnacles. (f) Densely rooted sandstone pinnacle showing subcutaneous solution features (rundkarren) [Colour figure can be viewed at wileyonlinelibrary.com]

carapace plates show a shiny reddish-brown coating on the exposed upper side (rock varnish). The ceramic remains include coarse (sand-tempered) undecorated body and rim sherds of simple utility pottery. TL dating of a pot shard indicates an age of 1,080 ± 216 years.

5 | DISCUSSION

5.1 | Palaeo-environments and sedimentary evolution

5.1.1 | Clinoformal sedimentary body (Beds 1 and 2)

The sandstone at the base of the section (Figure 3) is characterized by *Ophiomorpha* trace fossils (Figure 4a). This substrate-controlled ichnogenus occurs almost exclusively in fine- to medium-grained sandy bottoms and is very abundant in shallow-marine environments (de Gilbert, Netto, Tognoli, & Grangeiro, 2006). Their thick wall linings prevented the burrows from collapsing in an unstable substrate and indicate a prolonged occupation (Domichnia sensu Vallon, Rindsberg, & Bromley, 2016). The unidirectional dip direction of the overlying clinobeds towards the NE (Bed 2; Figure 4b) shows sand transport by longshore currents flowing from the southwest to the northeast (Figure 3) and accreting a shifting sand bar or spit. Gravity-flow processes on the steep foreset slope are indicated by the internal layering of clinoforms (Zecchin, Caffau, Civile, & Roda, 2010; Figure 4c).

5.1.2 | Sandstone pinnacles (Bed 3)

The association of cross-bedded sandstone with calcrete shows a terrestrial dune environment for Bed 3 that established after a relative sea-level fall. The coarse grain-size of the aeolian sand seems characteristic for coastal dunes and might be explained by continuous wind

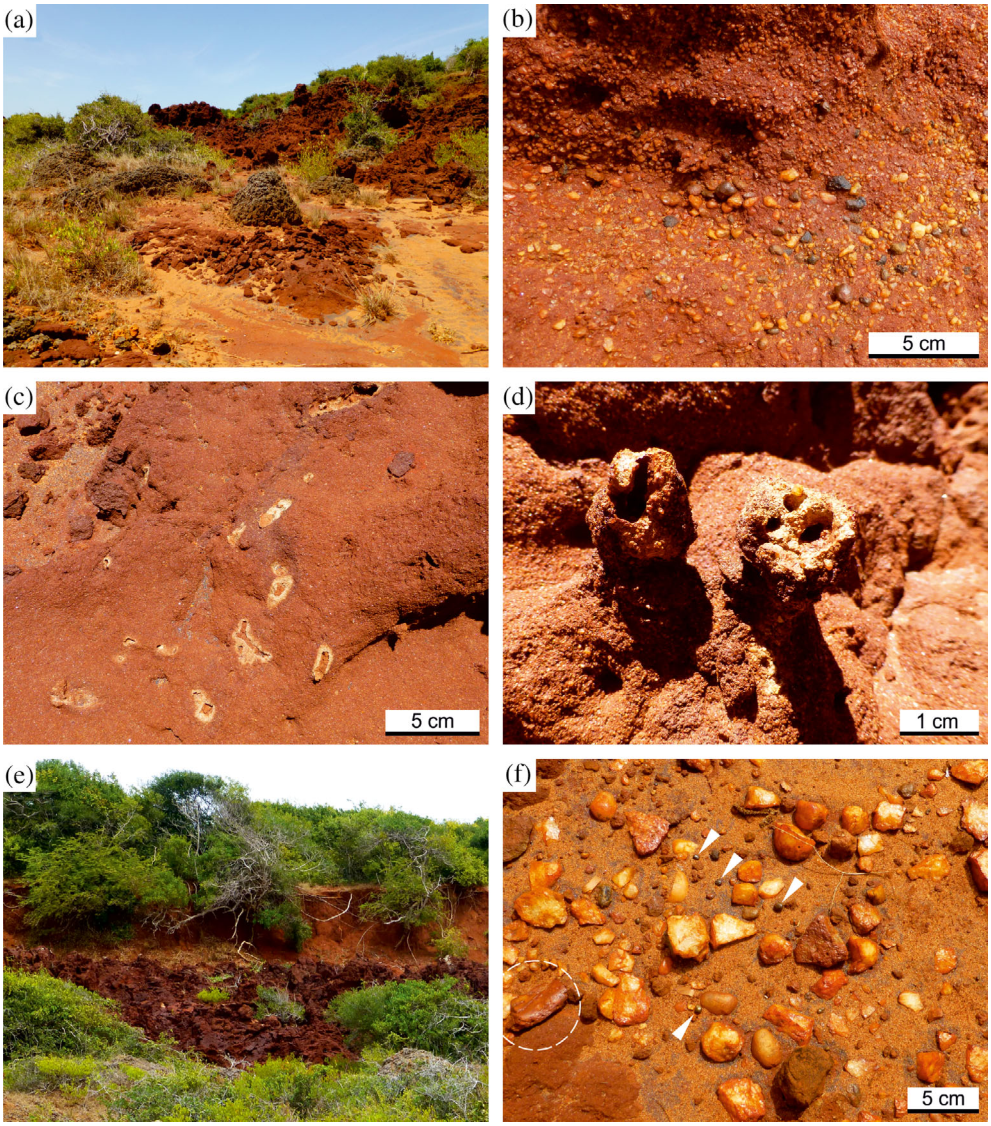

FIGURE 6 Facies of the Red Beds (Beds 4 and 5). (a) Deep red clayey sand sealing the pinnacle topography, Bed 4. (b) Ferruginous quartz conglomerate at the base of the Red Beds succession. (c–d) Rhizoliths filled with red sediment in the otherwise structureless red sand, Bed 4. (e) Contact between deep red (Bed 4) and yellow red (Bed 5) clayey sands. (f) Deflated surface at the base of the yellow red sand deposit. The heterogeneous population of clasts present on this surface comprises well-rounded quartz gravel, iron nodules (white arrow heads) and turtle carapace plates (dashed circle). Typically, the large quartz components are broken and, as well as the turtle carapace plates, exhibit rock varnish [Colour figure can be viewed at wileyonlinelibrary.com]

deflation along the coast together with wave and tidal activities that concentrated coarser grains (Koeshidayatullah, Chan, Al-Ghamdi, Akif, & Al-Ramadan, 2016). Accordingly, cross-bed measurements in Bed 3 indicate an E–SE palaeo-wind direction (Figure 3), which documents a local onshore wind blowing from the Gulf of Mannar (Figure 7b). A further feature of coastal dunes is their significant carbonate content from wind-blown marine shell debris that became an important source for calcrete precipitation if leached by meteoric water (Chen, Lintern, & Roach, 2002; Owen & Shakesby, 2014; Warren, 1983). Two major phases of calcrete genesis can be differentiated at Point Kudrimalai. The first phase is represented by nodular calcrete that contains features (nodules, terrestrial gastropods; Figure 5d) intimately linked to a near surface soil zone (pedogenic calcrete; Warren, 1983; Chen et al., 2002). The second phase is distinguished by tubular calcrete (Figures 5e,f) forming the pinnacles. Occurrences of tubular calcrete are related to heath and shrubs inhabiting the dunes, which exploit vadose water and induce precipitation of calcrete around roots to develop rhizocretions (Semeniuk, 1986). According to this, the distinctly separated pinnacles (Figures 1 and 5a) likely originated from the local cementation of aeolian sand in the rootstocks of shrubs and small trees. In the following, the rhizoliths were uncovered by the removal of the loose sediment amongst them. Since calcrete development in dunes is commonly associated with vegetation from woodland to heath shrub (Semeniuk, 1986; Semeniuk & Meagher, 1981; Warren, 1983), the disappearance of the nodular calcrete deposit towards NE and the gradual transition from tubular calcrete (Figure 5e,f) to cross-bedded aeolian sandstone facies (Figure 5b) in the same direction is interpreted to show a decrease of soil production along with a loss of natural vegetation towards the sea.

5.1.3 | Basal Ferruginous Gravels (base Bed 4)

Red quartz conglomerates, such as that overlying the erosional unconformity at the top of the pinnacles at Point Kudrimalai (Figures 3 and

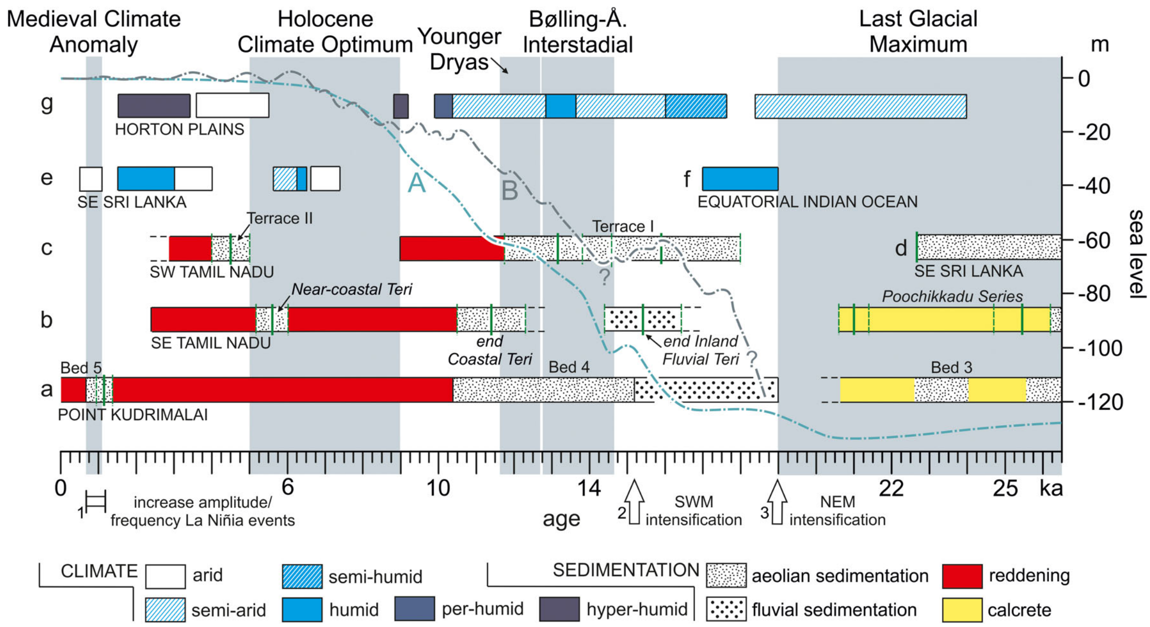

FIGURE 7 Comparison of red dune sedimentary records from Sri Lanka (a: this study; d: Singhvi et al., 1986) and Tamil Nadu (b: Jayangondaperumal et al., 2012; c: Alappat et al., 2013, 2016) and their correlation with records of palaeo-monsoon activity in Sri Lanka (e: Ranasinghe, Ortiz, Smith, et al., 2013; g: Premathilake & Gunatilaka, 2013) and with regional (1: Rein, Lückge, & Sirocko, 2004; Khider, Stott, Emile-Geay, Thunell, & Hammond, 2011; 2: Kessarkar, Rao, Naqvi, & Karapurkar, 2013; 3: f: Tiwari, Ramesh, Somayajulu, Jull, & Burr, 2005) and global climatic events. The green vertical lines indicate radiometric ages and the dashed curves show the eustatic (A: Lambeck, Rouby, Purcel, Sun, & Sambridge, 2014) and regional (B: Katupotha, 2015) sea-level records for the last deglaciation and Holocene [Colour figure can be viewed at wileyonlinelibrary.com]

6b), are documented in many coastal areas of Sri Lanka at the base of the Red Beds. These so-called Basal Ferruginous Gravels are interpreted as marine transgression conglomerate or sheet-flood deposits of an ancient river system (Katupotha, 1994; Wayland, 1919). The interpretation as transgression conglomerate is unreasonable because it is overlain by a succession of terrestrial sediments (Figure 3). The study site is located on a karst plain with subterranean drainage (Katz, 1975). The nearest possible source for quartz pebbles is the Modaragam Aru (river), which dissects the karst plain in the north of the Wilpattu Reserve and flows into the sea ca. 6 km northeast of Point Kudrimalai (Figure 2a). The deposition of conglomerate in this relatively far distance from a river bed may document an episode of increased fluvial activity.

5.1.4 | Red Beds (Beds 4 and 5)

The red clayey sands in the upper part of the Point Kudrimalai section (Beds 4 and 5; Figures 3 and 6e) represent Red Beds of aeolian origin (Wallace, 2016). Their characteristic red colour is post-depositional and due to the release of free iron oxides from the in-situ weathering of ferromagnesian minerals (e.g., garnet, amphibole and pyroxene; Jayangondaperumal et al., 2012; Alappat et al., 2016; Wallace, 2016). The released iron oxides are then precipitating as thin coatings around quartz grains and staining the clay matrix (Alappat et al., 2016). The latter is a product from the in-situ weathering of feldspars, which are supplied *en masse* by the island's metamorphic basement together with the ferromagnesian minerals and quartz (Alappat et al., 2016). Aeolian (Bed 3) and shallow-marine sandstones (Beds 1 and 2) below the Red Beds were not affected by the reddening process because they were already lithified when it happened. The gravel sheet overlying the deep red clayey sand (base Bed 5; Figures 3 and 6f) comprises a mixed assemblage of allochthonous (intact and fragmented quartz gravel components) and autochthonous (iron nodules, rhizolith fragments, turtle carapace plates, pottery shards) components. Due to the absence of pebble- and cobble-sized quartz grains within the underlying red dune sands the coarse quartz components must have been delivered from a different source. Rounded gravel has been generally subject to significant fluvial or shallow-marine transport. Fluvial/alluvial transport seems unlikely due to the isolation of the palaeo-dunes from hillslopes and streams (Katz, 1975; Nichol, Lian, & Carter, 2003; Figure 2b) as well as due to the low thickness of the deposit and the low packing density and poor sorting of the gravel size quartz fraction (Figure 6f). Such pebble lags are rather found in coastal environments where they form as a result of wave and tidal currents in the foreshore or as deflation apron in the backbeach zone (Cooper, Smith, & Green, 2013). The latter is defined as heterogeneous coarse clastic deposit, typically only one-clast-thick, like in the present case. A deflation apron is the product of periodic storm deposition of coarse clasts on the backbeach or dunes and their winnowing during dune migration together with rhizoliths and any other coarse material from the dune (Cooper et al., 2013). There, iron nodules typically concentrate on deflated soil surfaces and cracked and fragmented cobbles are common as a consequence of subaerial weathering (Cooper et al., 2013). Physically stable rock surfaces being exposed to the atmosphere under arid or semi-arid climatic conditions develop with time a dark red to black mineral coating (rock varnish; Dorn, 2009) as it is present on the upper side of larger quartz components and turtle carapace plates in the investigated gravel sheet (Figure 6f). The associated pottery shards by contrast possess no rock varnish because it does not form on friable material (Glennie, 1970).

5.2 | Stratigraphic correlation, sea-level and climate history

The herein presented lithological sequence compares strikingly with the depositional succession associated with the Teri Sands in coastal SE Tamil Nadu. The reason is that they were deposited under equal environmental conditions, namely (a) a flat topography of the depositional environment, (b) the same metamorphic lithologies in the mountainous hinterland, which has been the primary source of clastic sediment to the coasts and shelf regions, (c) the same weathering conditions in a NE monsoon-dominated tropical climate and (d) a tectonically inactive setting (Banerjee, 2000; Dixit & Tandon, 2016; Jayangondaperumal et al., 2012; Kayal, 2008; Kumar et al., 2013; Kunz et al., 2010; Murthy, Subrahmanyam, & Subrahmanyam, 2012; Wallace, 2016). As a consequence of tectonic stability, Sri Lanka and southeastern India were affected by relative sea-level fluctuations in the same order of magnitude and rate of change during the late Quaternary (Mann et al., 2019). Taking also account of the other environmental similarities between coastal NW Sri Lanka and SE Tamil Nadu, this allows for litho- and climate stratigraphic correlations on a regional scale across the Gulf of Mannar. In Sri Lanka, three Holocene relative sea-level highstands of at least +1 to +2.5 m (relative to present sea level), were identified at 6,240–5,130 years BP, 4,390–3,930 years BP, and 3,280–2,270 years BP on the basis of radiocarbon dating of palaeo-sea-level indicators that are presently emerged (Katupotha, 1990, 1995, 2015; Figure 7). Local differences in the region concerning the timing, and absolute amplitudes and rates of relative sea-level changes (Ranasinghe et al., 2013), however, can be due to problems in interpreting palaeo-sea-level indicators and their relationship to mean sea level and/or imprecise age determinations. Although the tectonically passive setting makes Sri Lanka and SE India principally sensitive to climatically controlled eustatic changes, relative sea-level data from this region deviate from the global mean because of glacial isostatic adjustment effects, which are the primary driving process for the Holocene relative sea-level changes (Mann et al., 2019). Glacial isostatic adjustment is, however, insufficient to explain differences of 20 to about 60 m amongst the relative sea-level record of Sri Lanka (Katupotha, 2015) and the global eustatic record (Lambeck et al., 2014) during the late Pleistocene to early Holocene sea-level rise (Figure 7). In our opinion, the relative sea-level curve for Sri Lanka should be considered with some caution in the respective part because the former sea-level positions are deduced from geomorphological features on the submerged shelf of Sri Lanka (e.g., remains of channels of larger rivers, sunken forests, marine terraces; Deraniyagala, 1958; Katupotha, 1993, 1994), which were only speculatively dated and have not been further described and discussed.

5.2.1 | Eemian interglacial (ca. 130–115 ka): Clinoformal sedimentary body (Beds 1 and 2)

The oldest coastal deposits in Tamil Nadu belong to the Ovari Series, which directly rest on crystalline basement and includes lagoonal siltstones, nearshore sandstones and coral reefs (Gardner & Martingell, 1990; Jayangondaperumal et al., 2012). These have, however, no equivalent in the Point Kudrimalai section. Above, follow shallow-marine calcareous-cemented coarse-grained siliciclastics (gravel, sand) of the Idindakarai Series. Based on uranium–thorium ages of marine shells, this informal lithostratigraphic unit is dated to ca. 124.0–112.0 ka (Brückner, 1988, 1989) corresponding to the Eemian interglacial period. This was the last time global sea level rose well above (6.0–9.0 m) the present level (Dutton & Lambeck, 2012; Kopp, Simons, Mitrovica, Maloof, & Oppenheimer, 2009; Rohling et al., 2019). Accordingly, shallow-marine sediments of the Idinakarai Series are confined to a topographic level 6.0–9.0 m AMSL. Likewise, the upper surface of the shallow-marine prograding sandstone body in the lower part of the Point Kudrimalai section (Beds 1 and 2) is situated 9.0 m AMSL. The revealed SW-to-NE palaeo-current direction (Figure 3) is consistent with a net annual littoral drift towards the north at the present-day, which is associated with the SW monsoon (Ratnayake et al., 2019; Figure 8a). As the western coast of Sri Lanka is on the lee side of the island during the NE monsoon, there is no longshore drift from the northeast that might affect the coastal morphology (Venkataraman, 2011).

5.2.2 | Last Glacial Maximum (ca. 26.5–19 ka): Sandstone pinnacles (Bed 3)

The Idindakarai Series in Tamil Nadu is covered by aeolian, calcareous-cemented sandstones of the Kanyakumari Series, which are capped by calcrete of the Poochikkadu Series. The Point Kudrimalai section (Figure 3) shows a comparable lithological development in Bed 3. There, the association of cross-bedded sandstone (Figure 5b) with calcrete (Figures 5c,e) represents an equivalent to the Kanyakumari and Poochikkadu series. Radiocarbon ages of terrestrial gastropod shells from the Poochikkadu Series in SE India indicate an age between ca. 25,450 ± 750 and 21,000 ± 400 years (Gardner, 1986), which coincides with the Last Glacial Maximum (LGM; Figure 7). A eustatic sea-level fall of about 130 m (Lambeck et al., 2014) was associated with the LGM and caused subaerial exposure of the clinoformal sedimentary body at Point Kudrimalai linked to the emergence of a wide land bridge between India and Sri Lanka across the Palk Strait (Clark et al., 2009; Gardner & Martingell, 1990;

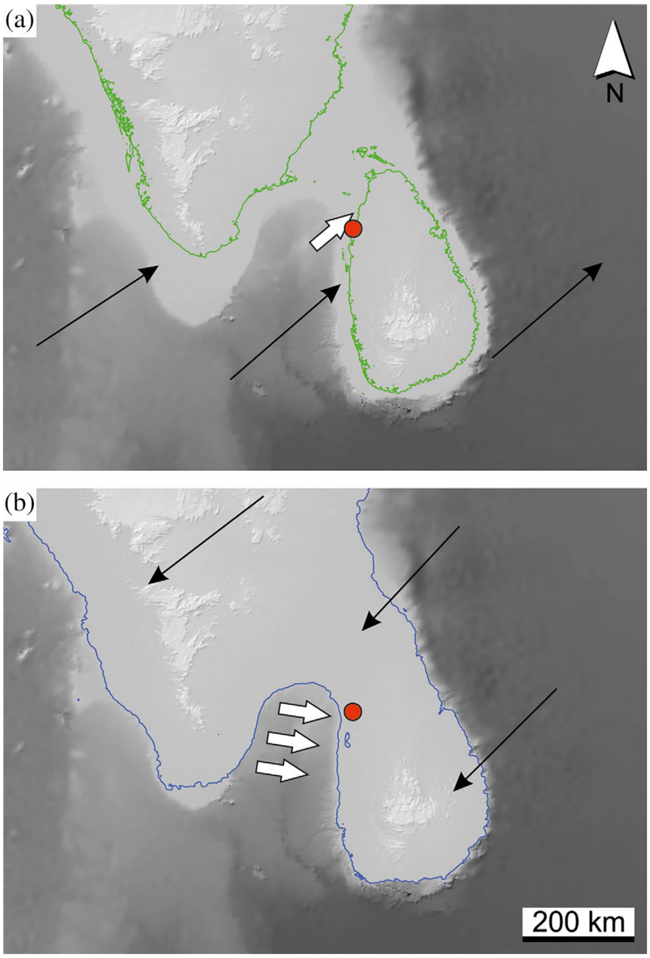

FIGURE 8 Digital elevation model (Jarvis, Reuter, Nelson, & Guevara, 2008) showing the palaeogeography of Sri Lanka and southern India. (a) +9-m contour line as estimated for the Eemian shoreline. The measured palaeo-current direction in Bed 2 of the Point Kudrimalai section (white arrow) corresponds to the direction of the SW monsoon (black arrows). (b) −130-m contour line representing the sea-level lowstand during the Last Glacial Maximum. Dry climatic conditions associated with a prevailing NE monsoon (black arrows) are indicated for this time (Chabangborn, Brandefelt, & Wohlfarth, 2014). The wind direction (white arrows) documented in coastal palaeo-dunes at Point Kudrimalai (Bed 3) relates to a local onshore wind; red dots indicate the study locality [Colour figure can be viewed at wileyonlinelibrary.com]

Roberts, Boivin, & Petraglia, 2015; Figures 7 and 8b). It was thus assumed that aeolian deposition in southeastern India and Sri Lanka during the LGM sea-level lowstand was favoured by the exposure of large shelf areas (Figure 8b), which acted as a sediment source (Gardner & Martingell, 1990; Jayangondaperumal et al., 2012). Consistently, coastal dunes that formed at this time in the surroundings of the Gulf of Mannar are characterized by a strong calcareous cementation (Jayangondaperumal et al., 2012; this study), which points to a high amount of marine shell debris originally present in the dune sands. The second episode of dune accumulation at Bundala and Patirajavela (Figure 2a; Singhvi et al., 1986) also relates to this period of increased dune-building activity in coastal areas (Figure 7). Palaeo-proxy data and climate simulations indicate a weak LGM SW monsoon relative to today and a stronger NE monsoon (Chabangborn et al., 2014; Clark et al., 2012; Sarkar, Ramesh, Bhattacharya, & Rajagopalan, 1990). The proposed cause for a weaker SW monsoon during glacial times is that the Tibetan Plateau was covered with glaciers. Hence, during summer, a lower land–sea pressure difference caused the SW monsoon winds to weaken; likewise, during winter, the land was cooler than present (due to permanent ice cover) in the vicinity of a warmer (than land) ocean resulting in a relatively strong NE monsoon (Tiwari et al., 2005 and further references therein). Consistent with this climate scenario, semi-arid conditions due to a weak SW monsoon have been reconstructed for the central highlands of Sri Lanka during >24,000 until 18,500 years ago based on a pollen record from the Horton Plains (Figures 2a and 7; Premathilake & Risberg, 2003; Premathilake & Gunatilaka, 2013). For the areas that are influenced by the NW monsoon, a modern-like dry climate is indicated as well by the widespread formation of calcrete on the coastal plains of Tamil Nadu and northwestern Sri Lanka. Although the latter conclusion appears contradictory to the basic assumption of a stronger NE monsoon during the LGM, it is in full agreement with the results of Tiwari et al. (2005) that the NE monsoon did not strengthen relative to the present during the LGM because of 2–3°C lower sea surface temperatures in the tropical Indian Ocean.

5.2.3 | Early deglaciation (ca. 19.0–15.0 ka): Basal Ferruginous Gravels (base Bed 4)

In southeastern Tamil Nadu, calcrete of the Poochikkadu Series is unconformably overlain by red sands (Teri Sands) that are considered as an equivalent of the Red Beds in Sri Lanka (Alappat et al., 2013; Jayangondaperumal et al., 2012; Wallace, 2016). As in Tamil Nadu, the calcrete succession at Point Kudrimalai (Bed 3) is terminated by an erosive surface with pronounced topography (Figures 1, 3, 5a and 6a). The overlying Basal Ferruginous Gravels (Figures 3 and 6b) seem to indicate a phase of enhanced fluvial activity in Sri Lanka preceding the aeolian Red Bed sedimentation. Likewise, fluvial sandstone (Panamparai calcareous sandstone of unknown age) below the Teri Sands at sites P1 and P2 of Jayangondaperumal et al. (2012) points to a phase of increased precipitation prior to Coastal Teri sedimentation. Precipitation erosion of the uplands of the Western Ghats around >15 ka is further held responsible for the deposition of Inland Fluvial Teri, which formed by fluvial and mass wasting processes at the foothills of the Western Ghats (Joseph, Thrivikramaji, & Anirudhan, 1997) and indicates a strengthening of the NE monsoon (relative to present and the LGM) during the early deglacial period (Figure 7; Jayangondaperumal et al., 2012; Tiwari et al., 2005). Also in the central highlands of Sri Lanka, where the rivers of the island originate, the early deglaciation was accompanied by an increase in humidity between ca. 18.35 and 16.0 ka (Figure 7), which has been suggested to reflect either climate warming and/or strengthening of the monsoon (Premathilake & Gunatilaka, 2013). At this time, the SW monsoon was still in a weakened mode due to the presence of considerable ice cover on the Tibetan Plateau, whereas the SSTs in the equatorial Indian Ocean rose by ca. 1°C resulting in further enhancement of the NE monsoon (Tiwari et al., 2005). The end of Inland Fluvial Teri deposition in Tamil Nadu at 15.4 ± 1.0 ka (Jayangondaperumal et al., 2012) coincided with the onset of a semi-arid phase between ca. 16.0 and 13.7 ka in the central highlands of Sri Lanka (Horton Plains; Premathilake & Gunatilaka, 2013; Premathilake & Risberg, 2003) and with the beginning post-glacial intensification of the SW monsoon at ca. 15 ka linked to the disappearance of the Tibetan ice cover at the onset of the Bølling-Ållerød warming event (ca. 14.7–12.7 ka; Dutt et al., 2015; Kessarkar et al., 2013; Tiwari et al., 2005; Figure 7).

5.2.4 | Late deglaciation to mid-Holocene (ca. 15.0–4.2 ka): Red Beds (Bed 4)

The post-glacial trend of SW monsoon intensification, which started at the onset of the Bølling-Ållerød warming event, maximized around 10.0–8.0 ka after a short period of weakening during the Younger Dryas cooling event at 12.9–11.7 ka (Kessarkar et al., 2013). OSL datings of Teri Sands indicate a return to aeolian sedimentation throughout the Gulf of Mannar rim during this period of time and constrain this major episode of dune-building activity to 15.9 ± 2.1–13.2 ± 1.4 ka in the area of Muttom in southwestern Tamil Nadu (Terrace I; Alappat et al., 2016) and to before 11.4 ± 0.9 ka in southeastern Tamil Nadu (Coastal Teri; Jayangondaperumal et al., 2012; Figure 7). It is assumed that the late Pleistocene deposition of sand in southern India was linked to an increased sediment supply from the still widely exposed shelf and that a stronger (compared to present) landward northeasterly and easterly wind associated with the NE monsoon facilitated sedimentation of the Coastal Teri east of the Western Ghats (Alappat et al., 2016; Jayangondaperumal et al., 2012). Stabilization of the near-coast dune fields in India and Sri Lanka is thought to be due to depletion of sand during the rapid early Holocene transgression (9 mm/year eustatic rise in sea level before 8.0 ka; Lambeck et al., 2014) and a humid climate due to strong SW and NE monsoons (Figure 7). These environmental conditions are seen responsible for the development of a proliferating vegetation as well as the weathering and reddening of dune sands (Alappat et al., 2016; Gardner & Martingell, 1990; Jayangondaperumal et al., 2012; Wallace, 2016). Consistent with this interpretation, the early Holocene precipitation maximum on Sri Lanka is recorded at ca. 9.2–8.8 ka when the montane rainforest on the plateau of Horton Plains in the central highlands, which is affected by the SW monsoon, reached its highest diversity (Figure 7; Premathilake & Gunatilaka, 2013; Premathilake & Risberg, 2003). But thereafter, pollen spectra from the Horton Plains peat sequence suggest a major rainforest decline and aridity between ca. 8.1 and 3.4 ka (Figure 7; Premathilake & Gunatilaka, 2013; Premathilake & Risberg, 2003). It has been suggested that this middle to late Holocene arididity indicates a major downturn of the monsoon that probably affected the entire island (Premathilake & Gunatilaka, 2013). Accordingly, the middle to late Holocene climate record from southeastern coastal plain of Sri Lanka (Figure 2a), which receives rainfall mainly from the NE monsoon, document an episode of prolonged aridity from >7.3 to ca. 6.75 ka that was only interrupted by a short wet interval from ca. 6.5 to 6.25 ka and followed by a semi-arid phase at ca. 6.25–4.6 ka and aridity between ca. 4.0 and 3.0 ka (Figure 7; Ranasinghe, Ortiz, Smith, et al., 2013). At first sight, the mainly dry climatic conditions, which prevailed during the middle to late Holocene, appear inhibitory to chemical weathering and mineral alterations that are responsible for reddening of dune sands. But in fact, suitable conditions for the reddening occur in humid as well as arid tropical regions, albeit the rate of reddening is much slower in arid and semi-arid climates due to the limiting effect of moisture availability on the rate of mineral weathering (Gardner & Pye, 1981).

5.2.5 | Late Holocene (since 4.2 ka): Yellow red sand (Bed 5)

The deep red sand at Point Kudrimalai (Bed 4) is truncated by a deflation lag (Figure 6f), which is overlain by yellow red sand (Bed 5; Figures 3 and 6e). Likewise, the dark red Coastal Teri is covered by yellow red dune sand in southeastern Tamil Nadu. This sedimentary unit is termed Near-coastal Teri and was deposited at 5.6 ± 0.4 ka due to reworking and re-deposition of older Teri Sands along a narrow coastal strip (Jayangondaperumal et al., 2012). The reason is to be seen in the second Holocene pulse of relative sea-level rise (Jayangondaperumal et al., 2012). Reddening is assumed to have occurred post-depositional between 5.6 and 2.3 ka and it is concluded that the less intense coloration reflects the shorter duration of the reddening process compared with the Coastal Teri (Jayangondaperumal et al., 2012). The white modern dunes along the coast in this area formed since 2.3 ± 0.2 ka when the relative sea level stabilized at the present level and the region became persistently semi-arid (Figure 7; Banerjee, 2000; Jayangondaperumal et al., 2012; Joseph et al., 1997; Joseph, Thrivikramji, & Anirudhan, 1999). In southwestern Tamil Nadu (Muttom area), a second stage of dune accretion (Terrace II) and subsequent reddening was identified at 4.5 ± 0.5 ka (Figure 7) and interpreted as the result of sand deposition in the backshore region also associated with a relative sea-level highstand (Alappat et al., 2013, 2016). In Figure 7, we correlate the episodes of Near-coastal Teri and Terrace II dune formation with the relative sea-level curve of Sri Lanka (Katupotha, 2015) and it seems that these episodes of aeolian activity in southern coastal India coincide with relative sea-level lowstands, which increased the source areas for sand at the coast, rather than with relative sea-level highstands. At Point Kudrimala, the second red sand unit begins with a deflation lag (Figure 6f) comprising pottery shards burned at 937 ± 216 AD. This young age is consistent with a high coastal sand dune accretion rate but clearly corresponds not with the ages of Near-coastal Teri (SE Tamil Nadu) and Terrace II (SW Tamil Nadu) dune sands. In contrast, to the Near-coastal Teri and Terrace II, this episode of sand mobilization occurred during a period of stable sea level

(Figure 7). In fact, it correlates to an interval of aridity ca. 1,100 to 500 years ago, which has been detected in a sediment core from the southeastern coastal plain of Sri Lanka (Panama estuary; Figure 2a) and provides evidence for a weak NE monsoon activity (Figure 7; Ranasinghe, Ortiz, Smith, et al., 2013). For recent decades it has been shown that interannual variations of NE monsoon rainfall in Tamil Nadu are closely related to El Niño–Southern Oscillation (ENSO) variability (Geethalakshmi, Palanisamy, Yatagai, & Umetsu, 2009). During extreme El Niño years, the Bay of Bengal exhibited a positive sea-level pressure (SLP) anomaly, and the Arabian Sea exhibited a negative SLP anomaly, which resulted in strong northeasterly winds, bringing moisture and precipitation to the southern part of India in November (Geethalakshmi et al., 2009). A strong negative anomaly by contrast was observed in the Bay of Bengal during La Niña years, which resulted in a weak NE monsoon (Geethalakshmi et al., 2009). In line with these relationships, it has been found that the Medieval Climate Anomaly (ca. 950–1,350 AD) was marked by persistently weak El Niños (Rein et al., 2004) and an increase in the amplitude/frequency of La Niña events compared to El Niño (Khider et al., 2011). It is therefore likely to assume that the last episode of sand mobilization at Point Kudrimalai reflects an extreme drought triggered by the Medieval ENSO anomaly. In addition, proxy records, historical accounts and archaeological studies indicate a series of megadroughts in monsoon Asia during the medieval period, which may have played a major contributing role for the collapse of the Rajarata civilization in Sri Lanka during the 13th century (Indrapala, 1971; Sinha et al., 2011). Jayangondaperumal et al. (2012) suggested that the reddening process in dune sands has finally stopped at 2.3 ± 0.2 ka because semiarid conditions became permanently established in the region. If this is correct, the less intense coloration of the upper red sand deposit at Point Kudrimalai must result from reactivation and reworking of older red sands. Remobilized red dune sands become paler due to the loss of iron coatings by abrasion and dilution amongst non-red grains (Gardner & Pye, 1981). But if we take also into account that favourable environmental conditions for the formation of red dune sand exist even in arid tropical regions (Gardner & Pye, 1981), it is more reasonable to assume that the relatively low degree of redness of the upper red sand at Point Kudrimalai is due to several factors: (a) reworking of older red sands, (b) a slow rate of reddening in the Dry Zone and (b) a short period of time available for dune sand reddening. It is, however, impossible to dissociate the effect of each factor.

5.3 | Consequences for the regional stratigraphy and sedimentology

So far, the Basal Ferruginous Gravels at the base of the Red Beds (Figures 3 and 6b) have been reported as being always in contact with crystalline basement or Miocene limestone and therefore they were considered as the oldest Quaternary stratigraphic unit in Sri Lanka (Cooray, 1967; Katupotha, 1994; Wayland, 1919). This stratigraphic interpretation, however, rests on confusion between Pleistocene calcareous sandstone (Beds 1–3) and Miocene limestone at Point Kudrimalai (Katz, 1975). Our new stratigraphic correlation further indicates that the Basal Gravel below red dune sands from the southeastern coast (Bundala and Patirajavela localities; Singhvi et al., 1986; Figure 1) cannot correlate with the Basal Ferruginous Gravels in northwestern Sri Lanka since it pre-dates the LGM. Most importantly, this study shows that Red Bed formation was a multi-phase process across the Pleistocene–Holocene transition (Figure 8), thus contradicting the general twofold stratigraphy for the Quaternary of Sri Lanka (Katupotha, 1994), which differentiates between an Older Group of Plio-Pleistocene age (including the Red Beds) and a Younger Group of Holocene age.

The herein presented stratigraphic interpretation raises also new questions about the origin of the coarse quartz clasts in the deflation lag at the base of Bed 5 in the Point Kudrimalai section (Figure 6f). Taking into account a sea-level rise of about 2.5 m AMSL for the Sri Lankan coast (Cooray & Katupotha, 1991) during the climax of the post-glacial transgression, storm deposition in the backbeach zone was unlikely since the load of storm flows is deposited within a zone relatively close to the beach (Morton, Gelfenbaum, & Jaffe, 2007) but the gravel lag rests on a vertical cliff 15 m above present-day sea level (Figures 3 and 4b). An analogous situation has been reported from late Holocene beach dunes of Great Barrier Island (Whangapoua Bay) in New Zealand, which are mantled to 14.3 m AMSL and 200 m landward from the beach by a single-clast-thick gravel sheet with rounded to sub-rounded granule to cobble-size lithoclasts that derived from the nearshore to inner shelf (Nichol et al., 2003). Due to the high elevation of the deposit shifting of the gravel by storm surge was excluded and tsunami run-up was considered the most probable mechanism for transport (Nichol et al., 2003). In the same way, distribution of locally eroded Basal Ferruginous Gravels by tsunami run-up offers a possible explanation for the erratic quartz gravel at the top of Bed 4 (Figure 6f). The tsunami hazard map for Sri Lanka (Sheet 24) indicates a medium hazard risk for Point Kudrimalai. This corresponds to a tsunami inundation of only 0.5 2.0 m. Tsunami inundation shown on the map is based on a computer model of waves generated by an event similar to the earthquake of moment magnitude 9.3 that occurred on 26th December 2004 in the Andaman-Sumatra subduction zone, which is considered as the worst-case scenario for any part of the coastline of Sri Lanka. However, the sediment record of Karagan Lagoon in southeastern Sri Lanka had revealed evidence for at least six palaeo-tsunamis during the Holocene, which were triggered by giant earthquakes that may had reached up to twice the size of the 2004 event (Jackson et al., 2014). Also, the hazard risk from tsunami waves that run-up from the SW can be expected higher at the northwestern coasts of Sri Lanka due to the funnel-shape of the gulf, which focuses tsunami energy. A potential source area for such tsunamis is the Mid-Indian Ridge (Kundu, 2007).

6 | CONCLUSIONS

The vertical sequence of facies at Point Kudrimalai in the Wilpattu National Park (NW Sri Lanka) is described and environmentally interpreted. A comparison with the sedimentary succession which is found associated with the Teri Sands in Tamil Nadu (SE India) on the opposite shore of the Gulf of Mannar reveals a strong lithological and environmental similarity that allows for lithostratigraphic correlations on a regional scale. The studied section in Sri Lanka starts with a shallow-marine clinoformal sandstone body. It correlates with the shallow-marine Idindakarai Series in Tamil Nadu corresponding to the Eemian sea-level highstand. The upper part of the Point Kudrimalai section records alternating episodes of coastal dune aggradation and coastal dune erosion or stabilization during the last deglaciation and Holocene, which can be linked to changes in sand supply and precipitation. Coastal dune aggradation was mainly controlled by the exposure of large sand reservoirs on the continental shelves of Sri Lanka and southern India related to the sea-level lowstand of the Last Glacial Maximum. The dune-building process was interrupted by fluvial sedimentation of the Basal Ferruginous Gravels, which are seen as an analogue of the Inland Fluvial Teri in Tamil Nadu and likely reflect an interval of increased NE monsoon rainfalls during the early deglacial period (ca. 19.0–15.0-ka). When the source areas for coastal dune sand had vanished during the rapid early Holocene sea-level rise, the dunes stabilized and started reddening under relatively humid tropical conditions due to increased monsoon rainfalls. The reddening process probably continued during the Holocene as long as the dunes remained stable, but the rate of reddening changed with variations in the NE monsoon intensity. A last episode of sand mobilization (yellow red sand) could be dated to 937 ± 216 AD and suggests an extreme drought related to a weakening of the NE monsoon during the Medieval Climate Anomaly. Since Red Bed formation continued across the Pleistocene–Holocene boundary, the differentiation between an Older Group of Plio-Pleistocene age (including the Red Beds) and a Younger Group of Holocene age in the Quaternary stratigraphic chart for Sri Lanka is not meaningful.

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CONFLICT OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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