Journal of Indian Geomorphology
Volume 9, 2021 ● ISSN 2320-0731
Indian Institute of Geomorphologists (IGI)

Evolution of the Carbonate Landforms of Rameswaram Island, Tamil Nadu Coast, India

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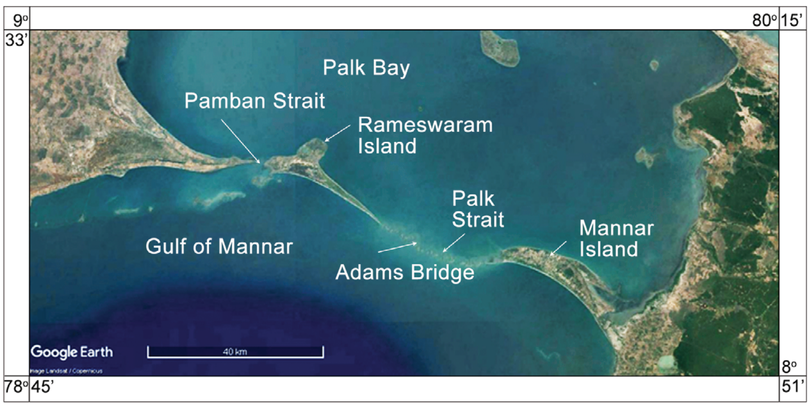
Abstract: *Various types of carbonate landforms of Late Pleistocene and Holocene epochs are found in the mainland coast of south India fringed by the Palk bay and the Gulf of Mannar in emerged and submerged forms. The Rameswaram island represents distinct signatures of sea level oscillations, local upliftment, development of coral reefs, present and past denudational processes, shore platform diversity and different coastal habitats under tropical coastal environment. The study aims to highlight and interpret the episodes of local sea level oscillations, shore platform geomorphology, landform assemblages of the island and adjacent areas, carbonate sediment deposition and associated processes and coastal habitats of sub-aerial, intertidal and shallow marine environments. Repeated field survey, complemented by satellite images and available C^{14} dates of carbonate materials helped to assess the evolution of the carbonate landforms. The study reveals that the tombolo shaped island was worked upon by fluvio-marine, marine and aeolian processes. The shore planation processes continued to work along the rocky shores with calcarenite deposits during the transgressive phases of Late Pleistocene and Holocene epochs. Calcification and cementation processes of carbonate sediments were stimulated with the concentration of reef and sea grass habitats in the shallow marine environment and subaerial weathering process at the coastal fringes.*

Introduction

The nearshore bathymetry and shoreline configurations of Ramanathapuram coast (Tamil Nadu) of India and northeastern coast of Sri Lanka (Jafna) indicate the presence of an ancient land bridge between the two countries across the Gulf of Mannar and Palk bay in the last glacial low–stand (Fig. 1). Development of the cuspate spits on the bay side of the Gulf of Mannar and Palk bay due to bidirectional sand transport from NNE–SSW direction and from SSW–NNE directions represent the unique shoreline configuration with pointed tip of the spits. The Ramanathapuram cuspate shore was connected with Rameswaram island by prograding sand and gravel ridge formed due to the accretionary activity of the dominant waves —from SSW in summer months and from NNE in winter months. This built up a tombolo in the shallow offshores of southern Tamil Nadu coast. The Dhanushkodi spit of Rameswaram island extended southeast over the submerged coral banks to connect with Mannar island of northeastern shoreline of Sri Lanka to build up another tombolo in the shallow offshores of the Gulf of Mannar and Palk bay. The result was an accretionary landform representing a 'double tombolo' over the submarine coral bank that developed due to the presence of strong wave energy, longshore currents and wind between India and Sri Lanka during the Holocene transgressive and regressive phases of the sea.

Presently, the Rameswaram island is fringed with diverse shore platforms backed by active and abandoned sea cliffs, submarine coral banks (Adams bridge), sand spits, barriers, sea beaches, extensive tidal flats, younger and older sand dunes, raised platforms of beach rocks, lithified dunes, fossil coral banks, marshes and terraces (Fig. 1). Topographically, the island is about 27 m in height at and around the north and northwestern parts and the highland surface is surrounded by interior platforms of 5 m and 10 m elevation. Large sand dunes of unconsolidated sand, weathered sand and lithified sand are seen over the interior platforms or marine terraces. Relatively younger sand dunes border the spits and barrier surface of the western and southeastern shores of the island. However, the sea beaches fringing the spits of Dhanushkodi are steeper in gradient on the western shore and gentler in gradient on the southeastern shore. The 'double spit' landform of Dhanushkodi is backed by tidal flats and back waters. Both emergent and submergent features are found in and around the spits and barriers of Dhanushkodi (Fig.1).

There are sloping and sub horizontal shore platforms across the intertidal zone of the island up to a certain extent at the sides of Palk bay and they are terminate in the low tide cliff or ramp surface below 1.5 m tide water level. The shore platforms are flooded by tide twice daily and are backed by cliffs of 1.5 m to 2.5 m elevation. The sea cliffs are karstified and affected by strong wave action on the northeast side of the island towards the Palk bay. Rocky promontories are dissected by series of caves to form natural arches along the shore cliffs, which in places have collapsed and left stacks that are gradually being reduced by erosion. Wave cut notches at the cliff base and collapsed roof material of caves have produced graveliferous beds with coral rubbles on the shore platforms. Debris of sea grasses and calcareous algal material are dumped on the beaches usually after the events of strong sea winds and swell waves. The decomposed leaves of sea grasses and calcareous algal fragments also contribute as cementing agents for the clastic materials on the shore platforms (Fig. 2).



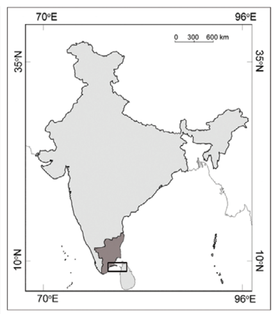


Figure 1. Rameswaram island and adjacent areas showing the land bridge between Tamil Nadu and northeast Sri Lanka and location of Pamban strait and Palk strait

The study reveals that exposure of the shoreline to wave attack, subaerial weathering, configuration of the shoreline; shore fringe rock types and variation in seasonal water levels of the sea have played a significant role in modification of shore

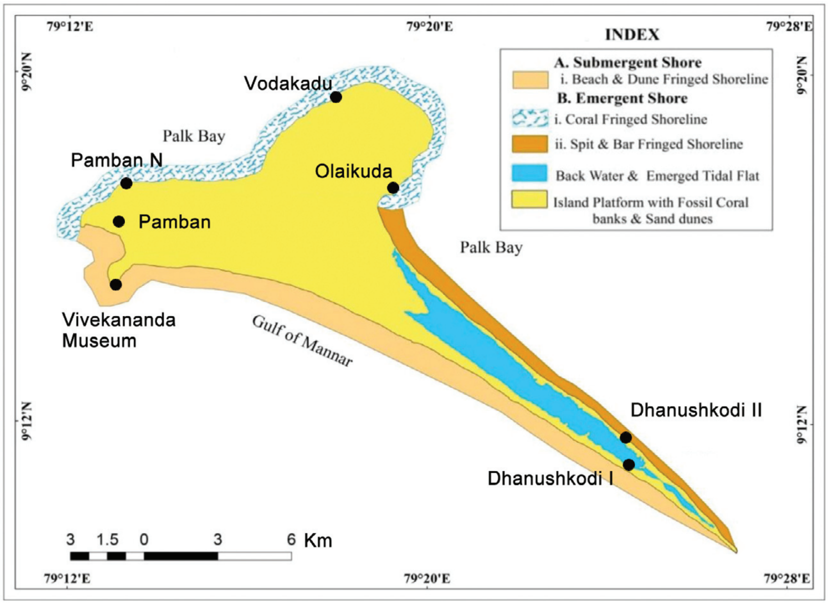


Figure 2. Compound coast of Rameswaram island showing various emergent and submergent features along the shore

platform morphology. Sandy sediment on the southwestern shores is supplied by longshore currents from the coastal fringe of the Gulf of Mannar. Rameswaram island is unique due to abundance of carbonate rocks at the basement, submarine coral banks and fringe corals along the sides of Palk bay, apron of sands on the beaches, spits, barriers and sand banks along the coastal fringes of the Gulf of Mannar. The embayed coasts of the region exhibit sand dunes overlying marine terraces, raised platforms of the interior island and extensive back waters with tidal flats between the spits and embayed coasts. Many researchers have attempted to study the coral reefs, beach rocks, general morphology, sea level variations and ecology of the southern Tamil Nadu and Ramanathapuram coast (Stoddart and Pillai, 1972; Loveson and Rajamanickam, 1988a, 1988b; 2000; Chandrasekar, 2011; 2017; Gardner, 1981; Loveson and Nigam, 2019; Loveson *et al.*, 1990; 2000; Sarma, 1978; Sewell, 1932; Bruckner,1988; Patterson et al.2004). There are 39 islands along the shallow offshore zone of the Gulf of Mannar extending from Tuticorin to Rameswaram island fringed with Ramanathapuram coast. All these coral islands of the region harbour multiple habitats of stony corals, sea grass colonies and mangroves within the geomorphic settings of lagoons, shore platforms, tidal flats and sea beaches.

The present work highlights the geomorphological diversities, shore platform processes and evolutionary stages of Rameswaram island of Ramanathapuram coast. The geomorphic features, sediment characters, stratigraphic signatures and shape of the island indicate the role of sea level variation and tectonics in the evolution of island system. Modern coastal habitats are influenced regional-scale variations in climate, hydrodynamics and sediment supply.

Materials and methods

Survey of India topographical sheets, ALOS PALSAR DEM, Google Earth images, bathymetric charts, wave climate data from INCOIS, existing literatures, available C^{14} dates and extensive field works (1997, 1999, 2012, 2016, 2018 and 2019) in Ramanathapuram and Rameswaram island have provided the data base for the study. Several transects across the island fringe and the active shore platforms were surveyed during the low water phase (LLW in the month of February) by Auto Level. Different exposure sites of the shore cliffs were documented to record the nature of stratigraphy and rock types around the island fringes. The relationships between platform gradient and tidal range and; between platform morphology and exposure to wave Earth images with field truth verification. The C^{14} dates of lithified corals of different reef terraces have been used to identify the evolutionary stages of the island.

A methodology flow chart is prepared to represent the data types, analysis and output of the present study. Data base regarding the diversity in sediment types, shoreline configurations, wave heights, tidal ranges and habitat types of the island system has also been generated during the field surveys (Fig.3).

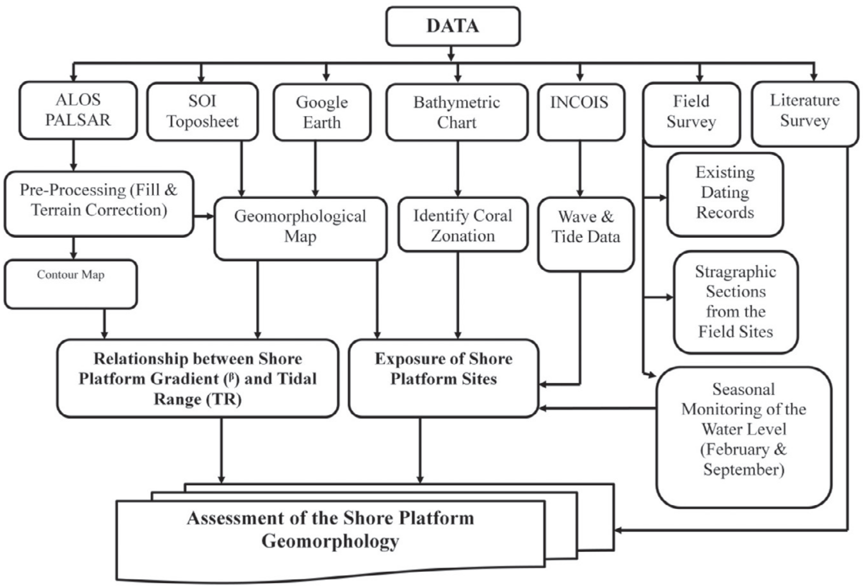


Figure 3. The flow chart of methodology

attack were estimated to identify exposure and buffer-based risk values for representative shore platforms in the island. Finally, the different sections of Rameswaram island have been ranked on the basis of their estimated risk from the intensity of wave impact and the potentiality of waves in modification of platform morphology.

The physiographic features of Rameswaram including Teri sands, older dunes, younger dunes and primary dunes have been delineated from the Google

Geomorphic setting

The Rameswaram island flanked by Palk bay on the north and northeastern sides and by Gulf of Mannar on the south and south western sides is influenced by both the northeast and southwest monsoon drift currents. Strong waves (> 2 m in heights), seasonal rise of sea level in the months of September, October and November, occurrences of swell waves, vigorous activities of onshore sea winds during the monsoon months and infrequent storms or cyclones characterise the dynamic nature of this coastal system (Fig.4). The hydrodynamic stress is relatively less during the months of March–May, when maximum low tide exposures and low wave heights the high tide limit. The narrow beaches of the region contain siliciclastic sand; carbonate sands graveliferous carbonate sediments and other bioclasts including the debris of marine

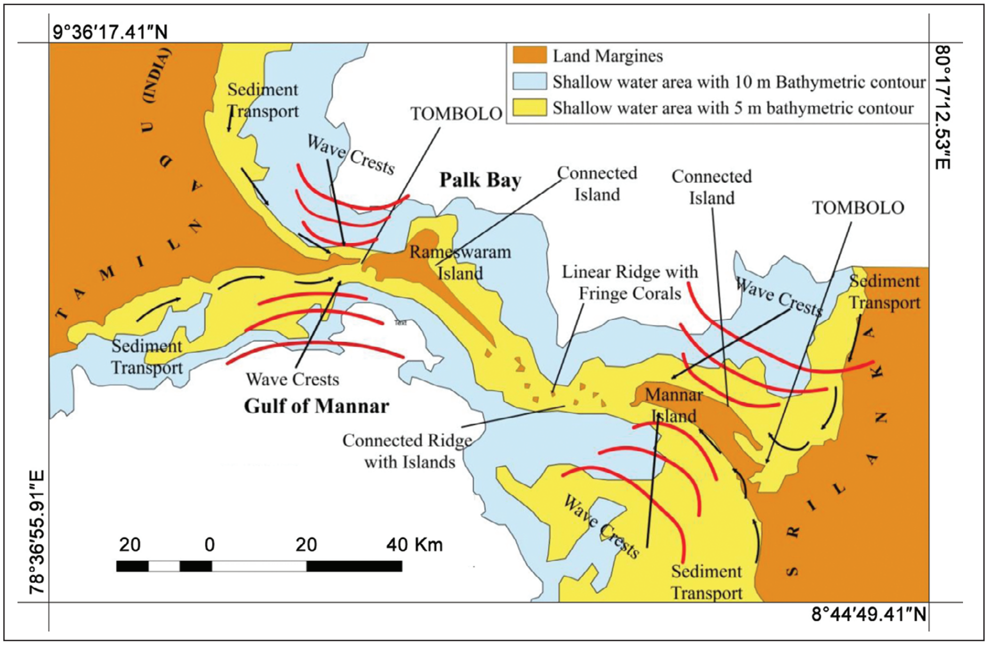


Figure 4. Formation of double tombolo, connecting the islands of India and Sri Lanka. Favourable conditions of accumulation, erosion and modification of the carbonated rocks and landforms in the regional coastal systems

regulated the energy and materials along the island–fringe shore platforms (Woodroffe, 2002).

The near horizontal shore platforms are wide and extensive along the shore fringes extending from Olaikuda to Vodakadu section of the eastern and northeastern coast of the island. There are patches of algal stromatolite reefs, oyster reefs, worm reefs, vermetid gastropod reefs and sea grasses in the low gradient shore platforms of the region. However, extensive coral reefs start from the low tide break of the shore platform on the seaward side below 2 m to 5 m frontal depths. Dead coral debris, rubbles and boulders, carbonate sediments eroded from cliff materials, along with algal debris and heaps of uprooted sea grasses are distributed at the cliff base along the curved shores near shells and stony corals in unconsolidated deposits.

Relatively flat shore platforms are extended into the sea along the northern shoreline section of the island from Vodakadu to Pamban. The shore platform of the region is backed by reef terraces and Teri sand deposits. Rameswaram Teri sands are weathered and reddened by oxidisation of the aeolian sand, which was deposited over the emerged reef terraces during the glacial low stand. They are particularly located over the Late Pleistocene reef terraces dominated by Porites and Acropora. The younger sand dunes of Holocene epoch are overlying the reef terraces, lithified dunes and beach rocks around Pamban and Rameswaram bordering the Gulf of Mannar. Primary sand dunes are located over the sand spit of Dhanushkodi

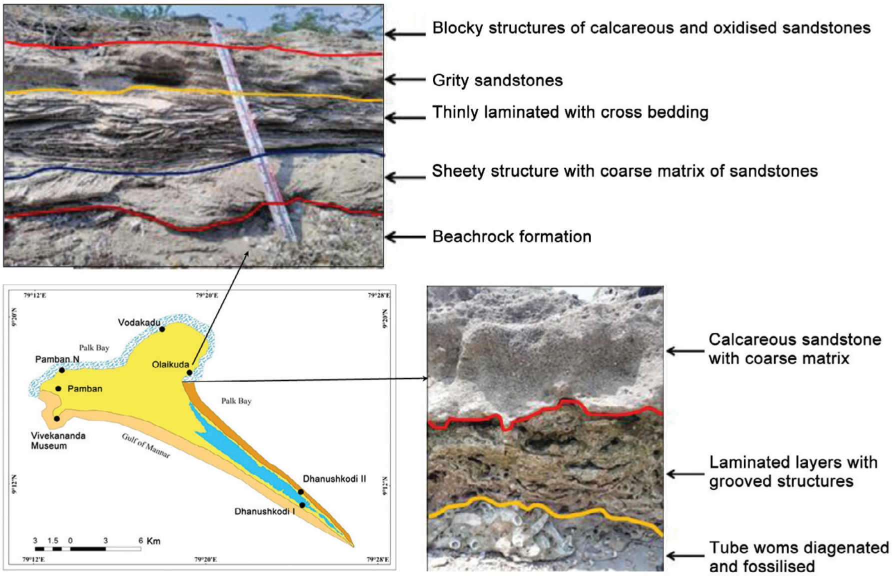


Figure 5. Stratigraphic sections exposed on the cliff face of the Palk bay fringe shoreline of Rameswaram island. Active shore cliff sections of Rameswaram Island on the eastern side of the Palk bay near Olaikuda.

and along the beach fringed shores of Pamban (Fig 5, 6 and Plate 1).

Tidal wetlands with mangrove colonies and backwaters characterise the shore-fringe recent deposits along embayed coasts. There are some depressions on the Late Pleistocene raised platforms of carbonate rocks and fossil corals in the inner parts of the island which contains fresh water with carbonate clays on the beds. They are termed as marsh lands over the abandoned shore platforms in Rameswaram island. It is interesting to note that no active channel or river system is draining across the island except one narrow link channel which discharges seepage water and runoff into the Palk bay near Vodakadu during the rainy months. Drainage development is not possible in the island due to porousness of the carbonate rocks, raised coral reef platforms and unconsolidated sands. The island is mostly vegetated by palm trees, growing over the sandy alluvium. The shallow ground water table is affected by encroached saline water in and around Rameswaram city.

The entire island is within the elevation range of 5 m to 25 m (Fig. 8) and topographically classified as high land surface (15 m–27 m), mid land surface (10 m–15 m), island fringe terrace (5 m–10 m) and low lands (2 m–5 m) with back waters (Raman, 2018; Vidyasakar *et al.*, 2018). The southwestern sand spits of Dhanushkodi are extended over the linear reef of submerged corals. Adam's bridge lying at 2 m to 3 m depth with living corals and sand banks represent the ancient land bridge between Dhanushkodi and Mannar island of Sri Lanka. The island fringe lying between bathymetric contours of 5 m and 10 m are densely covered by fringing corals of *Acropora sp., Porites sp., Montipora sp., Goniopora sp. and Faviasp* (Stoddart and Pillai 1972, Patterson *et al.*, 2004).

Quaternary sea level variation

The abandoned shore cliffs, reef terraces, shore platforms, stratigraphic layers of fossil corals, calcareous sandstones, fossilised beds of tube warms, oyster reefs and layers of beach rocks represent the role of past sea

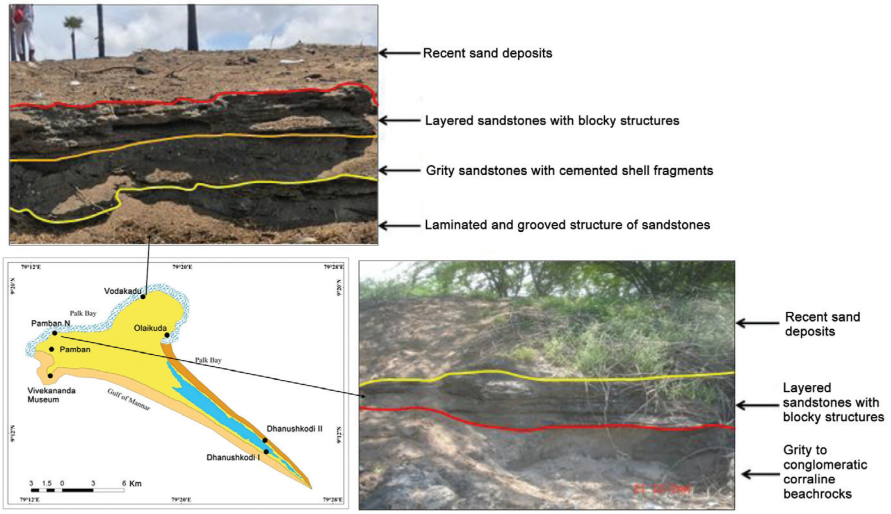


Figure 6. Stratigraphic sections exposed on the cliff face of the Palk bay fringed shoreline of Rameswaram island (Vodakadu and Pamban Noth)

Plate 1. Accumulation of uprooted sea grasses by wind waves along the shore fringe. The sedimentary surface anchors the calcareous organisms stimulating calcification process

level fluctuation in evolution of the island. In the last glacial low stand of Late Pleistocene epoch, the sea level was 130 m lower from the present day sea level in the east coast of India (Loveson and Nigam, 2019). During that period of low stand the continental shelf breaks were fringed with coral reefs in the Tamil Nadu coast. The older reef terraces of Rameswaram island date to 21,000 YBP to 32,000 YBP (Stoddart and Pillai, 1972), which indicates that sea level was slightly higher than the low stand position in the areas of Ramanathapuram coast when fringing coral reefs were extensive on the shelf.

The available sources of information from the C^{14} Dates of reef terraces and the contour map of the island are the evidences in favour of significant stages of sea level oscillations between Late Pleistocene to Holocene and Holocene to recent and sub recent. Following the bathymetric contours and the corresponding levels of break of slope along shelf profiles along the Gulf of Mannar and Palk bay, supported by the available radio carbon dates of coral rocks, fossils and marine shells a local sea level curve of southern Tamil Nadu coast is generated.

The local sea level curve shows a similar

Table 1. Sea level oscillations since 32000 YBP to the present day in and around Rameswaram Island estimated on the basis of bathymetric charts, levels of break of slope in shelf profiles and available C14 dates (Loveson, 1994; Banerjee, 2000)

Sl. No	Age (YBP)	Bathymetric contour (m)	Sea level (m)	Actual rise (m)	Rate of rise (m)
1	32000–21000	150.00	–128.0	22.00	$0.20m^{-100\ yr.}$
2	21000–18000	128.00	–116.0	12.00	$0.40m^{-100\ yr.}$
3	18000–14800	116.00	–98.5	17.50	$0.50m^{-100\ yr.}$
4	14800–10800	98.50	–63.3	35.20	$0.88m^{-100\ yr.}$
5	10800–9200	63.30	–30.3	32.90	$2.06m^{-100\ yr.}$
6	9200–8100	30.34	–21.3	9.02	$0.82m^{-100\ yr.}$
7	8100–7200	21.32	–1.3	19.90	$2.22m^{-100\ yr.}$
8	7200–5600	1.34	–0.3	1.60	$0.10m^{-100\ yr.}$
9	5600–5200	0.26	–0.6	0.30	$0.08m^{-100\ yr.}$
10	5200–4200	0.58	1.6	1.00	$0.10m^{-100\ yr.}$
11	4200–3000	1.58	2.7	1.10	$0.09m^{-100\ yr.}$
12	3000–700	2.66	4.5	1.80	$0.08m^{-100\ yr.}$

trend of sea level rise as of the East Coast of India in the Quaternary period. However, local tectonics of the coastal belt, as evidenced from raised reef terraces, drowned reefs, submerged and emerged sand etc. influenced the variation of relative sea level in the region particularly during the Holocene epoch. The long stretch (140 km) of barrier reef with 21 islands extending from Pamban to Tuticorin in E–W direction lying 8 km off the

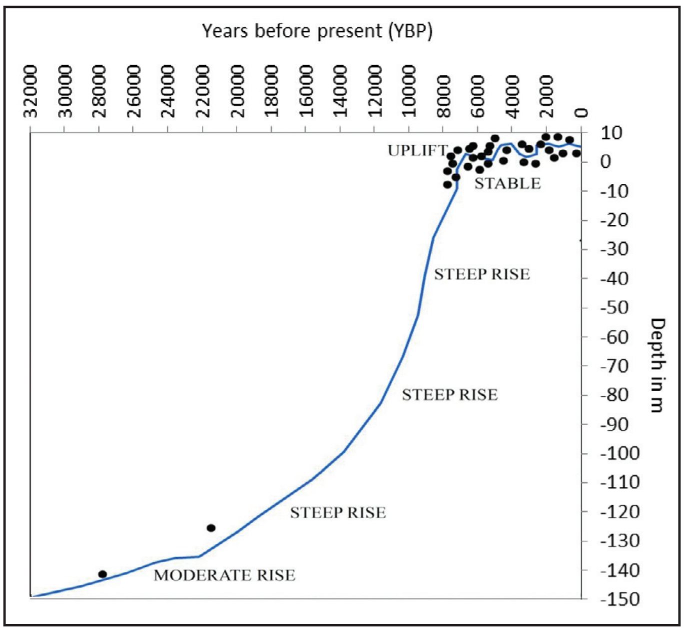


Figure 7. Local Sea Level curve for Rameswaram Island

Table 2. Available relevant data on Radio Carbon Dates along the coastal fringes of Ramanathapuram mainland coast and Rameswaram Island

Sl No	Shore fringe Section	Dated Materials	C^{14} Dates (YBP)	References
1	Rameswaram north	Coral	12010 ± 120	Loveson (1994)
2	Olaikuda marine terrace	*Porites*	13170 ± 200	Banerjee (2000)
3	Narikulam (Rameswaram)	Shell *Arca*	4350 ± 140	Banerjee (2000)
4	Narikulam Terrace	*Cardita*	4860 ± 100	Banerjee (2000)
5	Rameswaram island Terrace	*Porites* (+ 2.90 m)	1799 ± 89	Banerjee (2000)
6	Rameswaram island Terrace	*Porites* (+ 2.90 m)	1804 ± 96	Banerjee (2000)
7	Rameswaram island Terrace	*Porites* (+ 2.40 m)	1799 ± 83	Banerjee (2000)
8	Rameswaram island Terrace	*Porites* (+ 2.90 m)	1801 ± 85	Banerjee (2000)
9	Rameswaram island Terrace	*Porites* (+ 2.90 m)	1799 ± 89	Banerjee (2000)
10	Near Narikulam Beach	*Porites* (+ 2.40 m)	1798 ± 85	Banerjee (2000)
11	Villundi Teertham (Rameswaram)	*Porites* (+ 1.40 m)	5700 ± 120	Banerjee (2000)
12	Pisasu Munai (Rameswaram)	*Porites* (+ 1.00 m)	6450 ± 160	Banerjee (2000)
13	600 m west of Villundi base Teertham	Embedded shells with *cardium* (+2.40 m)	3840 ± 130	Banerjee (2000)
14	Rameswaram island North shore	*Acropora* (+1.10 m)	1816 ± 96	Banerjee (2000)
15	Pamban	Coral (+ 0.47 m)	4020 ± 160	Stoddart and Pillai (1972)
16	Ramakrishnapuram	Coral (+ 0.20 m)	1808 ± 103	Loveson (1994)
17	North of Mandapam	Coral (+ 0.62 m)	2630 ± 65	Loveson (1994)
18	North of Mandapam	Coral (+ 0.42 m)	3670 ± 65	Loveson (1994)
19	Pamban	Coral (+ 0.48 m)	3920 ± 160	Loveson (1994)
20	Ariyan Kundu	Coral (+ 0.55 m)	5440 ± 60	Loveson (1994)
21	Villundi Teertham (Rameswaram island)	*Porites* (+1.40)	6210 ± 120	Banerjee (2000)
22	North of Pamban	*Porites* (+1.40)	5310 ± 120	Banerjee (2000)
23	1 km NE of CMFRI from at Munaikkadu	*Porites* (+1.20)	5410 ± 110	Banerjee (2000)
24	600 m west of Villundi Teertham	Shell (+2.40 m) *Erronea*	4860 ± 100	Banerjee (2000)
25	600 m west of Kovakulam	Shell (+2.40 m) *Scapharca*	4400 ± 100	Banerjee (2000)
26	1 km NE of CMFRI from at Munaikkadu	Shell (0.5 m) sandstone	4162 ± 115	Banerjee (2000)
27	Pamban coast, unconsolidated dune over shelly sandstone	Shells (2.90m)	3800 ± 130	Banerjee (2000)

Sl No	Shore fringe Section	Dated Materials	C^{14} Dates (YBP)	References
28	Mandapam (4 km west)	Shell above HTL	2740 ± 60	Bruckner (1989)
29	Mandapam (east)	Coral above HTL	3660 ± 65	Bruckner (1989)
30	Mandapam Point (north)	Shell above HTL	6240 ± 50	Bruckner (1989)
31	Mandapam (4 km west)	*Cardium sp.* lagoonal loam	2740 ± 60	Bruckner (1989)
32	Tuticorin New Harbor (11.64 m depth)	Limestone with molluscs	29180–2675	Sarma (1978)
33	Tuticorin New Harbor (12.73 m depth)	Limestone with organic material	45000.	Sarma (1978)
34	Tuticorin New Harbor (11.41 m depth)	Rocky Calcareous materials	33000–2125	Sarma (1978)
35	Adams Bridge –94 cm and –132 cm depth	Shell shaped fossils	18400	Vidyasakar *et al*., (2018)
36	Adams Bridge –35 cm and –94 cm depth	Shell shaped fossils	700–780	Vidyasakar *et al*., (2018)

Ramanathapuram mainland coast also represent the Holocene oscillations of the local sea level along the shelf margins of Gulf of Mannar. Formation of 'sand cays' on the reef flats is another indicator of slow rate of uplift of the reef platform and oscillations of the late Holocene sea level of the region.

A local sea level curve has been plotted on the basis of the 36 available C^{14} dates of Rameswaram island, Adams bridge, Ramanathapuram mainland coast, Tuticorin New Harbour, and other information from

Table 3. Major units and sub units of landform assemblages in Rameswaram island

Sl no.	Major landform units	Assemblages of landform sub-units	Processes involved	Probable ages of development
1	Fluvio-marine landforms	Submerged platform of calcareous sandstone and limestone	Fluvial and marine deposits with diagenetic process	Late Pleistocene to terminal Pleistocene
2	Carbonate landforms	Fringing reef, barrier reef, reef flat, shore platform, submerged reef, inland reef terrace, reef rock outcrops, calcarenites, beach rocks	Calcification, coral growth, sea level oscillations, neotectonics	Middle Pleistocene to Holocene
3	Marine landforms	Sand cay deposits, sand banks, sand spits, sea beaches, shore cliffs	Wind waves, littoral deposits, tsunami surges, cyclonic storms, longshore currents	Early to late Holocene
4	Aeolian landforms	Sand dunes, lithified dunes, Rameswaram Teri sands	Aeolian activities, weathering process	Terminal Pleistocene to Holocene

5	Karstic landforms	Caving, notching, lappies, taffoni formation, limestone pavements	Subaerial weathering, wave sprays, evaporation rate	Early to late Holocene
6	Tidal landforms	Tidal lagoons, tidal flats, mangrove wetlands, salt flats	Tidal inundations, tidal exposures, variation in tide levels, evaporation rate	Late Holocene to recent

bathymetric charts and field observations along the Gulf of Mannar (Table. 1 and 2, Fig.7).

Regional geomorphology of Rameswaram island

Based on the contour patterns generated from ALOS PALSAR DEM and field survey on different seasons (February, September) between 1997–2019, the entire island can be classified into a number of geomorphic units (Table 3, Fig. 2).

Fluvio-marine landforms

Widespread fluvial deposits from Kaveri and Palar basins advanced on the Palk bay and also over the basin between southern Tamil Nadu coast and northwest Sri Lankan coast during the regression phase, probably c. 33000 YBP. Marine deposits from the Gulf of Mannar advanced towards north and northeast and deposited in the topographic depressions even before the fluvial sediments were deposited (45000 YBP). Thick limestone deposits with molluscs, organic materials and calcareous materials are encountered in the stratigraphy of Tuticorin New Harbor area between 10.91 m to 12.73 m borehole depths (Sarma, 1978). The Mandapam sandstone outcrops are visible at the low tide level

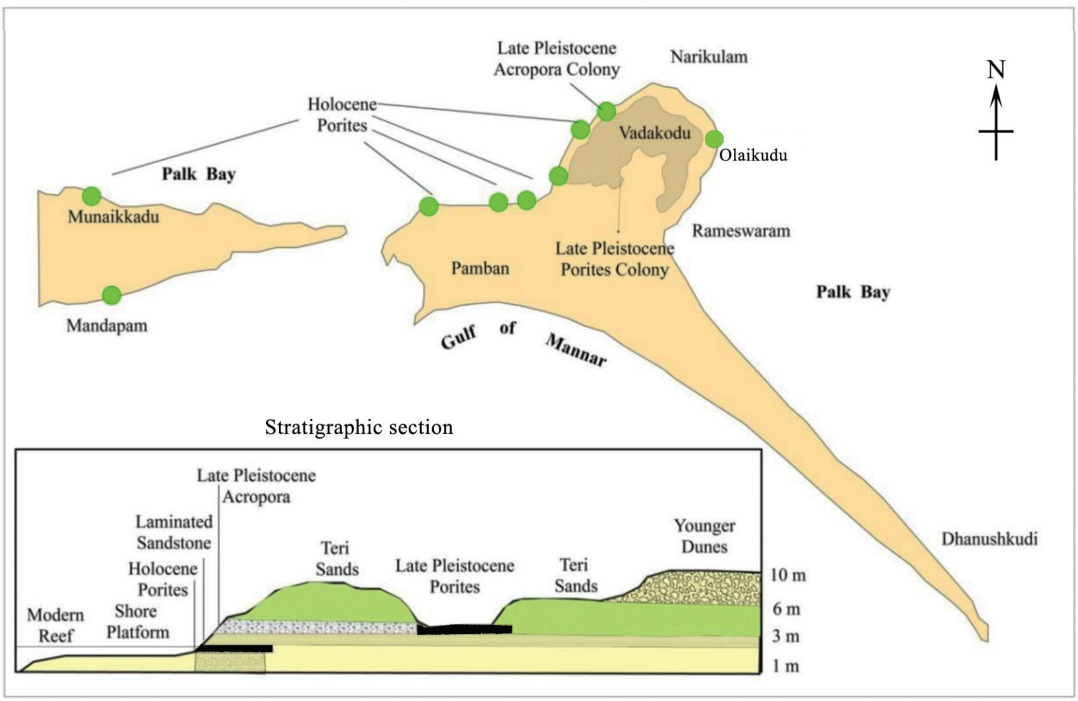


Figure 8. Hypothetical stratigraphy along the cross section from Olaikuda to Vodakadu in Rameswaram island

towards the west of Palk Strait (Fig. 8).

The basement rocks of Rameswaram island and the mainland Ramanathapuram coast are of fluvio-marine origin formed in middle Pleistocene and late Pleistocene periods. There are two formations of sandstones which are visible in the form of outcrops on the sea shore stretching from Pamban strait to Pisasu Mandal point in Rameswaram island. These sandstone platforms are secondary in origin and raised subsequently due to neotectonics.

Carbonate landforms

These landforms are the product of calcium carbonate saturated sediment deposits under shallow marine environment, as well as the result of growth cycle of coral reefs affected by sea level oscillations, supply of other marine organic materials into the coralline environment and neotectonics. Carbonate landforms occupy a large tract of Rameswaram island, Ramanathapuram coastal fringe, Gulf of Mannar shelf areas and areas along Palk bay. About 21 islands of the shallow shelf off the mainland coast of Ramanathapuram, extending from Tuticorin to Rameswaram island as barrier reef. The northern part of Rameswaram island was raised or elevated relative to the southern tip of the island. A linear coral reef ridge was extended southwest of Rameswaram island up to the Mannar island in the northwest of Sri Lanka as a land bridge. Later the shallow ridge was affected by subsidence and slow rate of upliftment due to coastal neotectonics. The 'double tombolo' formation took place in the later stage due to geomorphological modifications induced by marine deposition of sand cay sediments over the coralline platforms (Davis *et al.*, 2004)

The shallow marine fringing coral reefs are overlying the basement rock of calcareous sandstone along the sides of Palk bay and Gulf of Mannar in Rameswaram island with dense colonies of *Acropora sp., Montipora sp., Porites sp., Favia sp.*(Stoddart and Pillai 1972) and other stony corals. Near horizontal shore platforms of cemented carbonate sediments with dead coral debris, sand cays, reef flats and other organic materials are extended seaward from the high tide line (HTL) to the intertidal and shallow subtidal

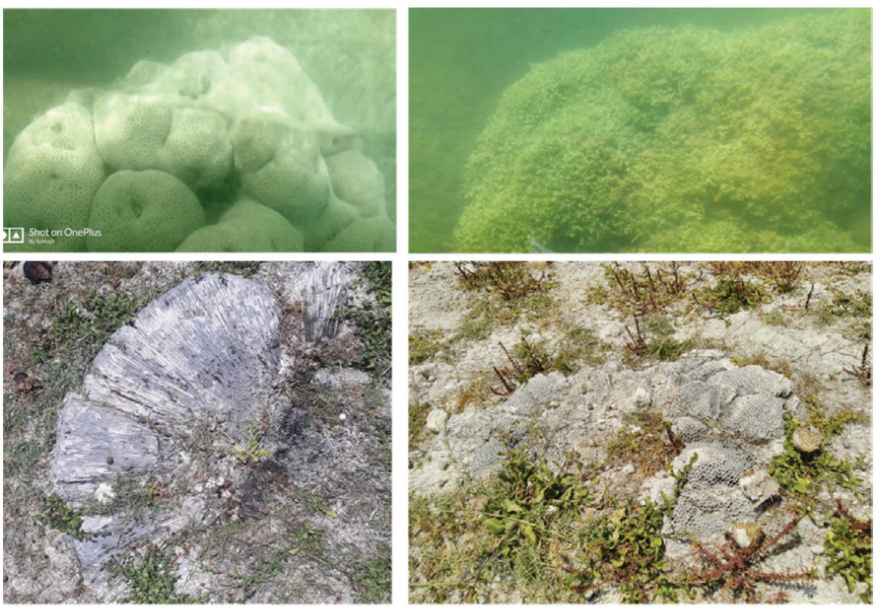


Plate 2. Live corals and the Pleistocene fossil corals of Rameswaram island in the subtidal and supratidal environments

region (1.5 m to 2.5 m depth below the HTL) which are fringed with reef rims and backed by shore cliffs. The low gradient shore platforms support a very good habitat for sea grass, algae, vermetid gastropod reefs, oyster banks, stromatolite reefs and worm reefs along the northeastern shores of the island from Pamban point to Rameswaram temple point.

The ancient reef flats comprising of shelf corals, sand cays, marine shells, grain stones, fossil corals of *Acropora* and *Porites* are tightly cemented as grits and raised as reef terraces along the eastern and northeastern shores of the region (1.65 m, 1.5 m and 3.2 m above the present HTL). The late Pleistocene reef terraces of *Acropora* and *Porites* colony can be seen further inland raised up to 5 m above the HTL. The aeolianites are located over the fringe terrace and carbonate beach rocks along and above the HTL in Olaikuda region. There is no exposure of carbonate rocks in the low gradient shore platform along the southwestern shore near Vivekananda Museum. The shore platform is blanketed by thick sand deposits and backed by shore cliffs. Disintegrated calcarenites from the shore cliffs and calcareous sands from the shelf area provide sand-sized sediments with shells which are reworked by strong wave actions in the shore fringe of the Gulf of Mannar (Fig. 8 and Plate 2).

Heaps of sea grass hay is piled up on beaches and upper shore platforms notably around the eastern shores of the Palk bay near Vadakodu, Narikulam, Olaikuda and Rameswaram. Decomposition of sea grasses on beaches and shore platforms play a significant role in cementing the carbonate sediments and shelly sands in the region.

Marine landforms:

The discontinuous barrier reef surface of the Gulf of Mannar and the drowned reef flats of Adams bridge are surrounded by sand cay deposits. Sand cays are mostly developed on

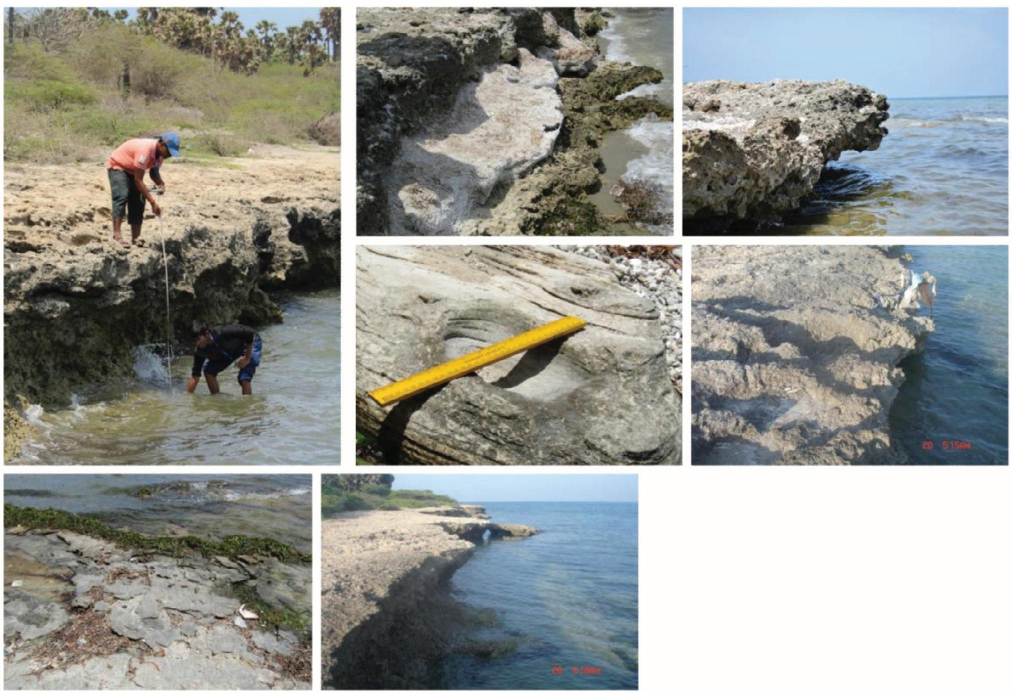


Plate 3. The carbonate platform east of Rameswaram Island exhibit different features of wave erosion and abrasion like notches, potholes, smooth pavements, wave cut terraces, spurs and grooves

the edge of the coral platforms when ocean waves and tidal currents transported the unconsolidated sands across the sea shores. In most cases, the sand cays are vegetated by sea grass patches in the shallow sea platforms.

Sand banks are found in the form of isles along the shallow linear ridges of Adams bridge transported by currents from the shelf areas. Series of sand banks are visible on the southwestern shores of Rameswaram island which usually emerge in the low tide and remain submerged in the high sea water. Sand banks over the Adams Bridge are located at a depth of 2 m–3 m below the water level. During the months of February and March the sand banks are visible at low tide.

Widespread beaches, sand spits and bars are aligned with the approach angle of ocean waves and direction of longshore current guided by prevailing winds around the Gulf of Mannar and Palk bay. The siliciclastic sands with shell fragments, disintegrated gastropods and bivalves and rhizomes of sea grasses are drifted from the shallow offshore zone by storm waves and washed on to the sea beach at Dhanushkodi. High gradient sea beach (>140) with berm crest and terraced surface of the upper foreshore area represent a trend of submergence on the western side of Dhanushkodi fringed by the Gulf of Mannar. Very gentle gradient (<30) to flat beach fringed by Palk bay however, represents slow rate of emergence. The beach, backed by wide expanse of primary sand dunes on the eastern side of Dhanushkodi indicates contrasting beach features within a short distance. Wave heights in the month of September usually range from 2 m to 2.5 m in the nearshore zone on the southwestern and western sides but only 0.7 m to 1.20 m at the eastern side during the same month.

There are two significant sand spits on the sides of Palk bay and Gulf of Mannar (double spit landform) extended southward from Rameswaram to Dhanushkodi (about 15 km long) and separated by an elongated lagoon in the region. The stratigraphic cores from Kothandaramar temple site and abandoned railway station of Dhanushkodi indicate that both the sand spits are overlying the submerged reef platform. Sand spits are linear sand accretionary features developed by strong longshore currents. They are elevated up to 3.5 m above the MSL at places and relatively low (2.5 m) at the tip of the connected spits adjacent of Adams Bridge. Shelly sands are deposited over the spit surface by over-wash process.

Shore cliffs of different types and elevations (1.5 m, 2.10 m, 4.0 m and 1.2 m) are found along the sides of Palk bay with diversity in composition. They are composed of tightly cemented grits with shells and corals, calcareous sandstones, coralline reef limestones, dune calcarenites and beach rocks in places. Shore cliffs are lined by present day shore platform and affected by wave erosion and weathering activities to produce multiple features of coastal erosion. Significant cliff recession is taking place at the southeast and northeast sides of the Palk bay shores in Rameswaram island. The cliff base is notched by wave and tidal currents and broken into strips due to collapsing in many locations (Plate 3).

Aeolian landform

Past and present aeolian deposits can be categorised as younger sand dunes, lithified dunes or dune calcarenites, older sand dunes of Rameswaram Teri sands, and aeolianites. Immediately behind Rameswaram urban fringe area, the young dunes of unconsolidated sand can be observed up to 20 m elevation. Strong onshore winds in the dry season prevail around the Palk bay and they transport finer sand into the raised platform to build such lofty sand dunes in the region. Such dunes of unconsolidated sands are also found to the south of Pamban railway station and vegetated by palms, palmyra and prosoporus trees. The shore fringe primary sand dunes along the seashores of the Gulf of Mannar are ranging from 3 m to 8 m in elevation and mostly vegetated by creepers like Spinifex sp. and Ipomoea pes carpae sp. Primary dunes are extensive over the back-spit surface in Dhanushkodi (Plate 4).

Shelly sands over the carbonate platforms or reef terraces are firm, compact and lithified

Aeolianites of cross bedded structures with cemented dune sands are overlain by raised beach platforms in and around Olaikadu and Narikulam sections of Rameswaram island. Calcareous sandstones with coarser matrix in layered and massive structures are exposed along the shore cliffs.

The brown colour sands of Rameswaram Teri dunes are composed of 64.24 % silica, 9.33 % aluminium, 4.15 % iron and remains

Plate 4. Younger and older sand dunes of Pamban and Rampatham. The migratory sands move across the fencing and highway from southeast to east—northeast direction.

towards the shore fringe areas of Rameswaram island (northeast and southwest). They are also known as dune calcarenites over the shore cliffs along the sides of the Gulf of Mannar. In the Pleistocene period calcareous beach sands supplied materials for aeolian deposits that were lithified to form such dune calcarenites in the region. These rocks are also sufficiently consolidated and resistant to have been eroded into cliffs, shore platforms and near shore reefs (Bird, 2008).

of strontium and molybdenum (Sarma, 1978). In an acidic and quick oxidising environment with high rainfall (> 900 mm) and high temperature of over 20^{o}C (average annual), the older deposits of sand are weathered to develop coastal Teri dunes. In Ramapatham, the Teri dunes are elevated to 25 m above MSL over the late Pleistocene reef terrace. Similar dunes, mainly on the southern coasts of Rameswaram, Pamban and Narikulam have achieved 10 m and 20 m elevation. Red coating of the sand grains of coastal Teri dunes occurred in the post deposition environment after 11 ka in the southeast coast of Tamil Nadu and after 5–6 ka (mid Holocene) for the nearshore Teri dunes (Alappat *et al.*, 2013 and 2017; Jayangondaperumal *et al.*, 2012; Jayangondaperumal, 2014). The coastal Teri dunes of Rameswaram island represent early Holocene and mid Holocene high stands.

tidal lagoon in Dhanushkodi and near Kothandaramar temple. Tidal flats of the embayed shores are silty and sandy in composition and they are flooded by semi diurnal tides. The upper flats are characterised by mangroves and saltmarsh tracts but the lower flats contain rippled flats and tide pools. A few tidal creeks at the low gradient tidal flats develop in the falling tides following

Plate 5. Karstification and wave abrasion processes modified the shore fringe reef terraces in the Rameswaram Island by forming lappies, pseudokarstic caves, natural arches, taffoni and surface encrustation with boring features.

Karstic landform

Coastal fringe reef terraces are karstified in the zone affected by wave spray weathering process in Rameswaram island. Karstification on the carbonate platforms by dissolution along the coastal fringes of the Palk bay have produced lappies, pseudokarstic caves, natural arches, taffoni and surface encrustation with boring features by rock borers. Cavernous grain stone s and shelly peloidal limestones are affected by dissolution process in the spray zones (Plate 5).

Tidal landforms

Tide dominated landforms are produced along the embayed shores of Pamban west, along the coastal fringe of the elongated

the seepage flow paths. Sands are piled up at the rim of marshy tracts through overwash deposits along the embayed shores (Plate 6).

Behind the barrier spits, the extensive tidal lagoon exhibits seasonal differences in terms of tidal inundation. The silty-clay beds of the elongated lagoon hold both sea water and rain water during the southwest monsoon season but experience shrinkage of water bodies in the dry months due to high rate of evaporation. A large tract of salt flats with desiccated condition emerges in the lagoon bed during the dry period. Depth of the water bodies in the lagoon ranges from 50 cm to 90 cm with saltmarshes and dwarfed mangroves (Plate 6 and 7).

Shore platform morphology

The shore cliffs of Rameswaram, Olaikuda, Narikulam, Vodakadu, Pisasu Mundal Point, Paikkarumbu and Pamban are bordered by wide shore platforms. Strong wave attack, subaerial weathering process, tidal currents and water-layer weathering process have resulted in shore planation in

Plate 6. The mangrove fringed tidal flats in the western embayed shores of Rameswaram Island behind the spit near Vivekananda Museum.

Plate 7. Extensive salt flats in desiccated condition during the month of September 2019 in the back water lagoon between the Bauble spit near Dhanushkodi. The loamy sands are converted into salt flats after desiccation

the region fringing the Palk bay. The rocky shore platforms of north, northeast and east are considered along with the sandy shore platforms of south and southwest to estimate the relationship between platform gradient and tidal range. Such relationship is tested along 12 transects in 6 stations (Table.4).

Olaikuda Surface:

A wide shore platform formed by wave abrasion, backed by cliff continues underwater as a gently sloping coral bank. The reef terrace surface is composed of tightly cemented grit with shells, blanketed by overlying sand dunes. Teri sands are seen in the landward part.

Table 4. Shore platform gradients and tidal ranges around the shore fringe areas of Dhanushkodi spits, Olaikuda, Vadakadu, Pamban and Vivekananda Museum points of Rameswaram Island

A. Double spit shorelines				
Bay of Bengal fringe spit: Wide beach plain with giant cusps and insignificant beach berms backed by isolated sand dunes				
Station	**Slope Segment**	**Slope amount (in degree)**	**Average Slope**	**Tidal Range (m)**
1	Upper	3.5	4.3	0.9
	Middle	3.9		
	Lower	5.5		
2	Upper	3.0	3.4	0.9
	Middle	3.3		
	Lower	4.0		
Gulf of Mannar Spit: Steeply sloping beach face with wide beach berm surface and backed by sand dunes of frequent ridges and sandy tracts				
Station	**Slope segment**	**Slope amount (in degree)**	**Average slope**	**Tidal range (m)**
3	Upper	12.0	10	1
	Middle	8.5		
	Lower	9.5		
4	Upper	17.5	13	1.05
	Middle	12.5		
	Lower	9.0		
Olaikuda Surface				
Station	**Slope segment**	**Slope amount (in degree)**	**Average slope**	**Tidal range (m)**
5	Upper	4.0	4.2	1.1
	Middle	3.8		
	Lower	5.0		
6	Upper	3.5	3.8	1.2
	Middle	3.5		
	Lower	4.5		

Vodakadu Surface: Sloping shore platform backed by cliff is extended up to the coral bank towards Palk bay in the north. Three reef terraces on the bank margins are karstified and overlain by sand dunes on the landward side				
Station	**Slope Segment**	**Slope amount (in degree)**	**Average Slope**	**Tidal Range (m)**
7	Upper	5.0	6.16	0.8
	Middle	6.0		
	Lower	7.5		
8	Upper	4.5	6.66	0.9
	Middle	7.0		
	Lower	8.5		
Pamban Surface				
Station	**Slope Segment**	**Slope amount (in Degree)**	**Average Slope**	**Tidal Range (m)**
9	Upper	12	8	0.8
	Middle	7.0		
	Lower	5.0		
10	Upper	11.0	7.3	0.75
	Middle	6.0		
	Lower	5.0		
Vivekananda Museum Point				
Station	**Slope Segment**	**Slope amount (in Degree)**	**Average Slope**	**Tidal Range (m)**
11	Upper	12	7.3	1.1
	Middle	6.0		
	Lower	4.0		
12	Upper	10.0	5.6	1
	Middle	4.0		
	Lower	3.0		

Vadakuda Surface:

A sloping shore platform backed by calcarenite cliff is extended up to the coral bank towards Palk bay in the northeast of the island. About three reef terraces on the bank margin are significantly karstified and overlain by sand dunes on the landward side.

Pamban Surface:

The shore platform is relatively narrow and extends up to the shelf break of shallow reef with moderate slope. The dune-cliffed calcarenite platform is fronted a sloping shore platform in the northern part of the island (Fig. 9).

Vivekananda Museum Point:

The sandy surface of the platform is fringed with shore parallel sand dunes and fronted by intertidal shore platform of compact sand with moderate gradient. Larger shells and coral fragments on the lower flat and disintegrated calcarenites on the upper flat are distributed along the Gulf of Mannar close to the barrier reef zone.

Dhanushkodi spit along the side of Gulf of Mannar:

The steeply sloping beach face with wide beach–berm surface represents wave dominated environment. Primary sand dunes are widely distributed over the spit surface. This part of the barrier spit shoreline is directly exposed to wave attack from the Gulf of Mannar during southwest monsoon drift. Beach-berm surface of the west-facing barrier spit usually gets affected by overwash process during extreme events and is vulnerable to wave erosion.

Dhanushkodi spit along the side of Palk bay:

Wide sandy shore platform on the eastern side of Dhanushkodi is gently sloping towards the Palk bay. Shallow offshore sandy shoals and bars have emerged on the eastern side of the barrier spit. The shore platform is backed by large sand dunes and fringed with cuspate bars and rhythmic features of accretionary origin (Fig. 10). Overwash process becomes effective on the shore fringe areas during the events of swell waves which transport sand into the foreshore and backshore. Calcareous sea grass hay on beaches after gradual decomposition and calcification under tropical climate provides cementing material for making the beach sands firm and compact (Masselink *et al.*, 2011; Masselink and Roland, 2015).

The relation between shore platform gradient and tidal range for all the twelve shore-transects showed very poor relation (R^2= 0.0024), however the correlation is more meaningful if the rocky platforms

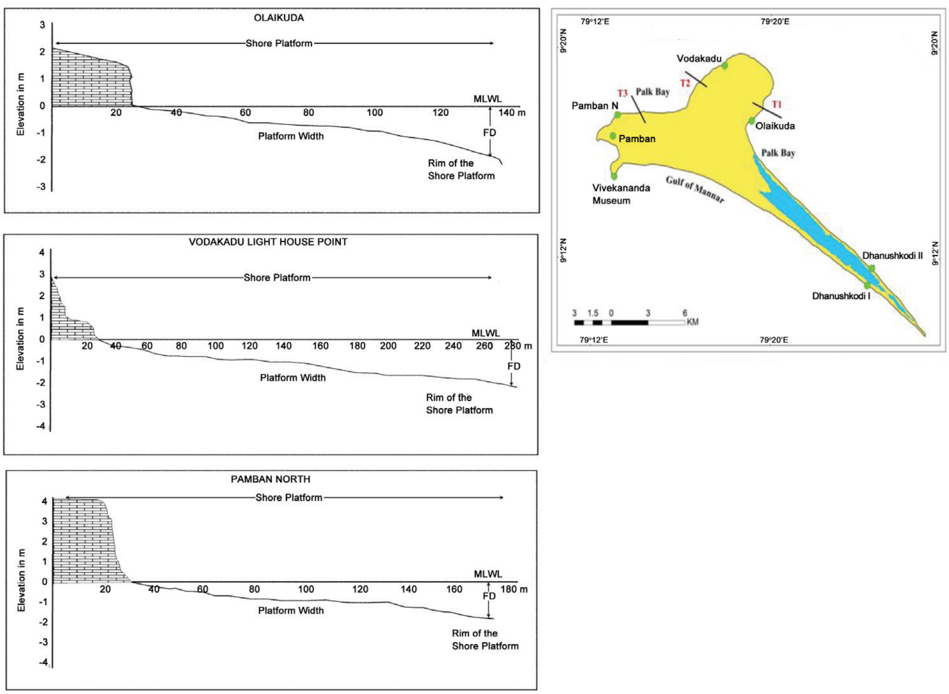


Figure 9. Shore platform transects across Olaikuda, Vodakadu and Pamban North to assess the exposure to wave attack.

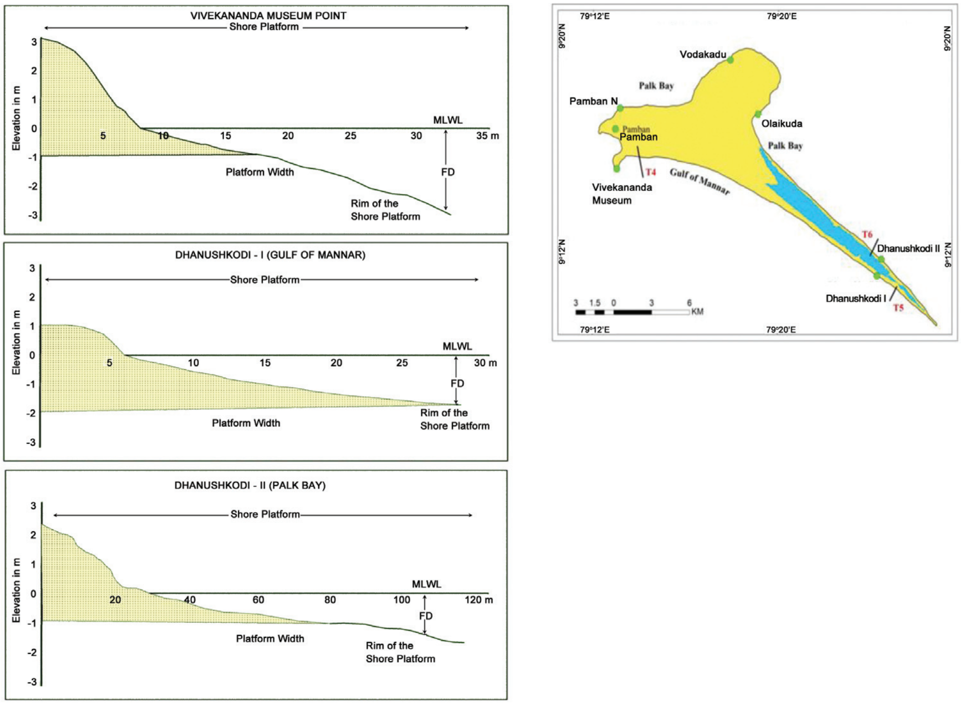


Figure 10. Shore platform transects across Vivekananda Museum Point, Dhanushkodi I and Dhanushkodi II to assess the exposure to wave attack..

and sand dominated platforms are dealt separately (Fig.11 and Table.5). In the eight transects surveyed along the coral fringed shore platforms there is moderately significant negative relationship between platform gradient and the local tidal range (R^2= 0.4969). But, in the four transects from beach and dune fringed shore platforms the relationship is weakly positive (R^2= 0.005). The gradient of the rocky shore platforms in the north and northeast parts of the island are not adjusted with the incoming tides and waves probably due to the slow and steady uplift of the surface.

The morphology of shore platforms and their exposure to wave impact has been studied with the respect to frontal depth (FD) and elevation for the six shore-transects of

Table 5. Assessment of exposure of the shore platforms through two different ways (FD x elevation and FD/elevation)

Exposure of the Shore Platform			
Location	**Frontal Depth (FD) in m**	**Elevation (in m)**	**Exposure in m (FD × Elevation)**
Olaikuda	–2.00	–1.3	2.60
Vodakadu	–1.70	–0.9	1.50
Pamban	–1.65	–0.9	1.49
Vivekananda Museum	–2.50	–1.0	2.50
Dhanuskudi I	–2.00	–1.5	3.00
Dhanuskudi II	–1.50	–1.0	1.50

Exposure of the Shore Platform			
Location	**Frontal Depth (FD) in m**	**Elevation (in m)**	**Exposure in m (FD / Elevation)**
Olaikuda	–2.00	–1.3	1.54
Vodakadu	–1.70	–0.9	1.89
Pamban (N and S)	–1.65	–0.9	1.84
Vivekananda Museum	–2.50	–1.0	2.50
Dhanuskudi I	–2.00	–1.5	1.34
Dhanuskudi II	–1.50	–1.0	1.50

Rameswaram island. Exposure is estimated by two methods — (i) Exposure =FD × elevation (Kennedy *et al.*, 2012, 2013 and Kennedy, 2016), and (ii) Exposure =FD/elevation (Kennedy et al., 2017). Result of the first method shows that Dhanushkodi spit facing Gulf of Mannar represents the highest value and Pamban in the north represents the lowest value. Computation of the same parameter following the second method reveals maximum exposure of the shore platforms at Vivekananda Museum point and Dhanushkodi spit bordering Gulf of Mannar shows the lowest value (Fig 12).

The width of buffers is also estimated for all the six surveyed shore platforms to calculate the risk factor of different shoreline sections of Rameswaram island and rank them accordingly. Greater width of buffer reduces the impact of incoming waves on the shore platforms, though the exposure favours concentration of wave energy. Thus, considering all the above factors of platform gradient, tidal range, exposure to wave

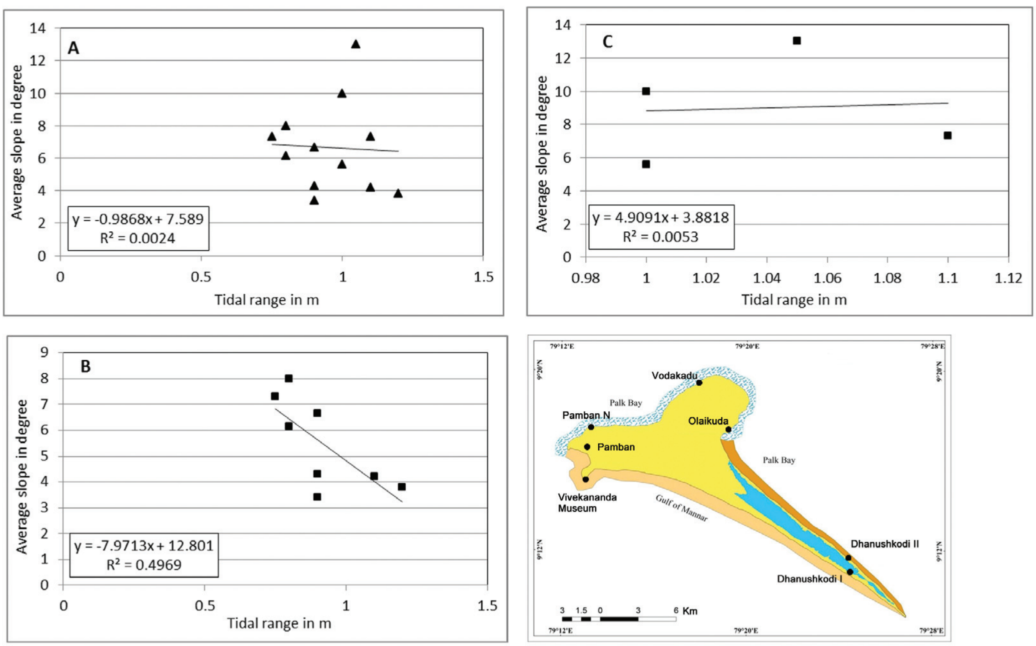


Figure 11. A) The relationship between shore platform gradient and tidal range along the twelve transects surveyed in seven stations; (B) the same relationship observed along the eight stations of the rocky part of shore fringe areas and (C) sand dominated shore platforms.

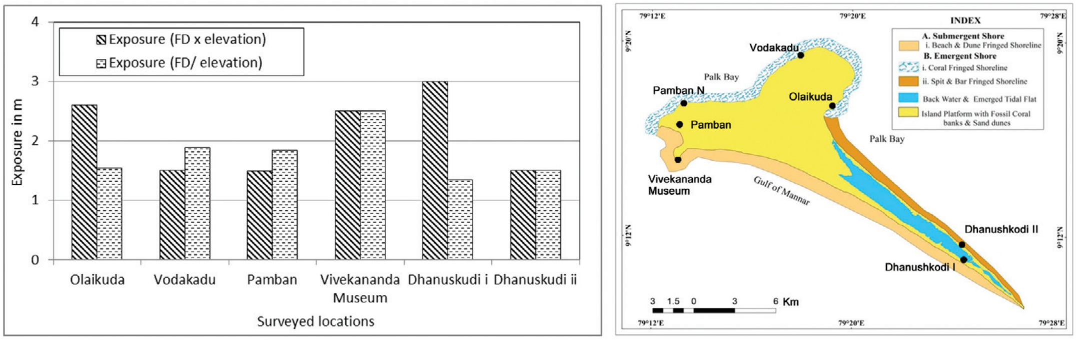


Figure 12. Estimated exposure of shore platform computed by two methods — exposure = FD × elevation and exposure = FD/elevation.

attack and width of buffers it is estimated that Vivekananda Museum point facing Gulf of Mannar records highest risk, north and northeast platforms of Olaikuda, Pamban and Vodakadu record moderate values of risk and the Dhanushkodi barrier spit on both the Palk bay and Gulf of Mannar side record low to risk values. The results of the study are also validated in the field through identifying actual geomorphological signatures of coastal vulnerability along the studied sections of the island (Table 6).

A platform close to mean spring low water (MSLW) with high FD (frontal depth) will be more exposed to waves than a higher platform with the same amount of FD. As per the calculations based on the first method (Exposure = FD × elevation) it has been observed that the Olaikuda platform and Dhanushkodi–I platform with high FD are highly exposed to waves in the island system. The alternative method of calculating exposure (Exposure =FD/elevation) is also attempted following the relationship between morphological variables of the shore platforms. By this equation the calculated exposure values are exponential with exposure increasing greatly as the platform approaches MSLW level. However, the buffer based risk values are applied to estimate the actual risk of the shore platforms. When the buffer will be wider the waves will be attenuated and dispersed in the shore platforms, but the areas under narrows buffer will provide the ideal condition for concentration of wave attack with increased exposure (Fig. 9 and 10).

Conclusion

Table 6. The width of buffers is estimated for the surveyed shore platforms to estimate the final risk rank of different sections of Rameswaram Island

Location	Highest buffer	Lowest buffer	Average buffer	Rank of overall risk
Olaikuda	175	91	133	Moderate - Rank 2
Vodakadu	330	207	268.5	Moderate - Rank 2
Pamban	210	132	171	Moderate - Rank 2
Vivekananda Museum	42	20	31	High - Rank 1
Dhanuskudi I	44	11	27.5	Low - Rank 3
Dhanuskudi II	108	96	102	Low - Rank 3

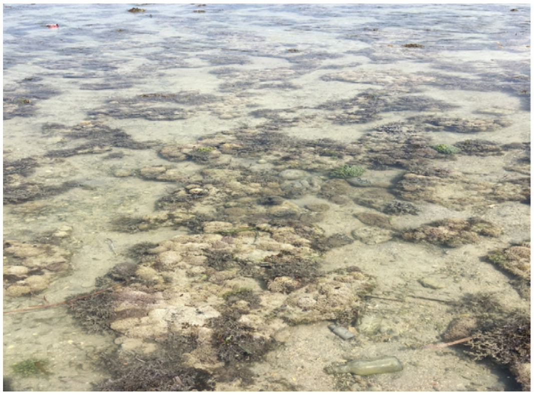


Plate 8. The algal stromatolite reefs on the shore platform of Rameswaram island visible in the dry months at low water stage.

Plate 9. The accumulation of sea grass hay and debris of carbonate sediment at the base of the shore cliff in Olaikadu. Coastal Teri sands are lying on the landward side over the reef terrace.

Geologically, and geomorphologically, the islands between southern Tamil Nadu coast and northeastern coast of Sri Lanka in the Gulf of Mannar represent identical signatures of ancient and modern coastal landforms. Proterozoic dykes are extended from west to east at the basement and appeared as linear ridges between Ramanathapuram coasts of southern Tamil Nadu and northeastern districts of Sri Lanka. The indurated sandstone of fluvio-marine origin and marine calcareous sandstone with dune calcarenites are unconformably lying over the dykes and have resulted in a land bridge between the two land masses in the geological past. With the regressive and transgressive phases of the sea the accumulated shelf sediments with marine organisms experienced cementation and diagenesis to form the basement platform. Barrier reefs and fringing coral reefs have been developed over such basement rocks of tightly cemented grits and shelly limestone under shallow marine environment. Reefs evolved in silt- free water and responded to sea level oscillations, local upliftment and subsidence along the coastal fringes. Various types of carbonate sediments were deposited on the reef flats and consequently affected by tectonics in the late Holocene period. Present day landforms are the result of weathering, erosion, sediment accumulation, sea level variations, wave impact, neotectonics, shoreline configurations, wind ward or lee ward position and habitat modifications of the island system (Plate 8).

The double tombolo was initiated with extension of spits in the shallow marine environment over the linear coral ridges between the islands of Rameswaram and Mannar. Pamban strait and Palk strait were formed after the submergence of the linear coral reef ridges in parts. Sea level variation in the late Quaternary period and local upliftment in the Holocene epoch have played a significant role in the evolution of the island. Identification of reef terraces at 3.0 m to 1.50 m and 1.10 m as sea level high stands highlights the events of upliftment in the coastal fringes (Rajamanickam and Loveson, 1990). Sediment of diverse origin contain cay sand, calcarenite, coastal Teri sand, siliciclastic sand, carbonate sediment, aeolian sand deposit, cavernous sediment and lagoonal loamy deposit in various sub environments of the island (Plate 8 and 9).

The relationship between platform gradient and tidal range indicates difference between sloping platforms and sub horizontal platforms in micro tidal environment. Both wave and weathering processes are playing a significant role in modification of sub horizontal platforms with carbonate rocks; whereas in the beach and dune-fringed sloping platforms waves are the only dominating process to modify the shoreline of the island. Both emergent and submergent coastal features are found in the region.

Acknowledgement

The author would like to thank the students of Geography, Coastal Management and Remote Sensing and GIS departments of Vidyasagar University for their assistance in different stages of field work in the Rameswaram island. The research was funded by the University Research Grant of Vidyasagar University, Medinipur, West Bengal. Special thanks to Anurupa Paul and Joydeb Sardar of Remote Sensing and GIS department of Vidyasagar University for assisting in field survey and for typing the manuscript of the paper.

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Date received : 25 December 2020
Date accepted : 26 January 2021