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Interpretation of coastal morphodynamics of Subarnarekha estuary using integrated cartographic and field techniques

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Cartographic techniques are frequently applied for coastal mapping, but their application for the study of coastal morphodynamics is unpopular, as they only give limited parameters like plan-view, geometry, area–length measurement and lithology. On the other hand, detailed study of morphodynamics requires extra information like depthwise variation in lithology and absolute dating. Since both these techniques are expensive, cartographic techniques can be cost-effective supplementary. In the present study, morphodynamic history of Subarnarekha estuary from 7000 years BP has been interpreted applying data from cartographic techniques along with shallow wells, ^{14}C-dating and literature survey. Geomorphologic features of the coastal plain were identified in the order of hierarchy, viz. chenier plain (first order); beach ridge complex, spit complex, chenier complexes (second order); cheniers (third order); and simplest ridge, spit, washover beach (fourth order). Following this field-investigated geological history of river dynamics (both Ganges and Subarnarekha) and sea-level changes identified by earlier researchers were merged with cartographically observed features. The studied ridge chronology provides six sequences of chenier complex development agewise, whereas geometry of spit complexes suggests chronological conversion of Subarnarekha estuary from initial wave-dominated to tide-dominated flow.

Keywords: Cartographic techniques, coastal morphodynamics, chenier complex, geomorphological hierarchy.

CARTOGRAPHIC techniques are popular for regional-scale mapping of any natural phenomenon or resource. The technique proves its effectiveness in decadal coastal change studies[1–3]. Understanding past mechanism of coastal dynamics on a regional scale is significant for hydrocarbon exploration. Such knowledge is broadly described under the studies on coastal morphodynamics. However, cartographic technique is unpopular, because this branch of science got limited scope to provide information, such as depthwise detailing of lithology, absolute age, etc. The present study shows the effectiveness of cartographic techniques by involving data from a few shallow wells and radiometric dating. The study also illustrates 7000 years past history of geomorphologic development of a coast. The coast being susceptible to environmental changes, indeed documents several centennial phenomena of gradual changes in climate, associated sea-level changes and fluctuating characters of estuaries. Therefore, through a study of coastal morphodynamics, one can interpret palaeoclimate and many past geological consequences. In the present study, Subarnarekha estuary situated in the Midnapur–Balasore coast has been considered for detailed understanding of coastal morphodynamics.

The Midnapur–Balasore coastal plain extends over 113.5 km length from Panchpara River (Odisha) to Rasulpur River (West Bengal), and also extends inland from the shoreline for 18 km. The coordinates for the area are 87°08′44″E, 21°49′12″N to 87°55′56″E, 21°31′58.82″N. The chenier complex of Subarnarekha also follows similar extension covering the whole coastal plain. The complex consists of a series of low linear hummocks of

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Table 1. Geomorphic Hierarchy of Chenier development (from simplest 4th order to highest 1st order); their identification criteria in field and satellite image and various formation processes in variable sea level and sand supply

Feature	Field description	Aerial description from standard FCC of ETM+ satellite image	Formation process	Order
Sand ridge (Beach ridge)	Elevated (5–7 m) bodies of sand parallel to the present day coast	Appear as red colour elongated (>10 km), when covered by vegetation; otherwise as white	Regressive	4
Spit	Curved narrow ridges; opened at one side. 30 to 500 m wide and <10 km long	Curved red colour lines (5 to 10 km)	Lateral accretion, due to reduced tidal prism of inlet with respect to longshore current	4
Mudflat	Mud dominated extended plane; in many cases modified into agricultural field	Appeared as gray colour when associated with wetlands; or pink colour when converted as agricultural field	Regression (relative sea level fall with high amount of sediment supply)	4
Palaeo-river channel	Anastomosing and multi-curved; little elevated (1–2 m) places and forested.	Red colour multi-curved narrow zones	Regression	4
Washover beach	Sand ridges spread over mudflat	Red-coloured ridges spreaded over grey coloured area	Transgression	4
Chenier	Combination of sand ridges and mudflat (extended 30 to 300 sq. km region)	Two elongated red coloured sand ridges are separated with grey colour mudflat (<300 m)	Transgression (in few cases they can be described as transgressive ridges)	3
Regressive ridges	Sand ridges cumulated near estuary	Red colour lines juxtaposed together for small region (10 km length)	Regression with high tidal prism of estuary	3
Chenier complex	Superimposed Chenier within mudflats	Multiple red colour lines with	Net progradational	2
Beach ridge complex	Multiple beach ridges superimposed without mudflats	Red or white colour lines in white or less vegetated places	Net progradational	2
Spit complex	Multiple spits superimposed together; usually curved in end	Multiple redlines interspersed between mudflats or sand bodies	Lateral accretion (stationary shoreline)	2
Chenier plain	Summation of Chenier complexes	Very broad zone (>20 km) and long (>100 km) covering around 5000 sq. km	Net progradational	1

unconsolidated sand, covered at places by soil and vegetation. The term ‘chenier’ comes from the French word ‘chene’, which means ‘oak tree’. These show up as thick red lines in the standard False Colour Composite (FCC; 4 (near infrared)-3 (red)-2 (green) band; Figure 1) of Landsat ETM and are aligned in stripes sub-parallel to the coast. These are marked as reserve forest area in Survey of India (SoI) topographic map of 1973. The goals of the present study are (1) to provide a comprehensive description of chenier form and orientation to infer past processes, (2) to present a relative chronology of chenier plain development and (3) to present an evolutionary model.

In this study, SoI topographic sheet of 1973 (scale 1 : 50,000), satellite image Landsat ETM of 2002, SRTM data and shallow well data were used as the primary data source. In order to obtain the detailed layout of chenier complexes, merging of shaded relief of SRTM data with standard FCC of Landsat ETM satellite imagery was performed[5]. This gives topographic perception along with multispectral property of an image. The fusion image was interpreted with a few elevated linear, parallel or sub-parallel and reddish-coloured features (in 4-3-2 band combination). Besides, a few zones of depression with darker tone between ridges and sinuous vegetated zones were marked. GPS surveys on the field and SOI topographic sheet confirm those as beach-ridges, mudflats and palaeo-channels. In next stage, geomorphic hierarchy of landforms was used for understanding the dominant process for Subarnarekha delta chenier plain[6]. In this hierarchy, the chenier plain was chosen as a first-order feature, indicating the highest stage of complexity. Second-order features are represented by chenier complex, beach ridge complex and spit complex. The third-order features (e.g. chenier) show lesser complexity and association of two or more fourth-order features. Fourth-order features (e.g. washover beach, beach ridge, spit, etc.) are the simplest and are also present in the present-day coast, exhibiting local influences of relative sea-level changes, wave–tide–river dominance and sediment supply. Table 1 summarizes all these orders with their identification criteria and formation processes.

In order to understand the chronological sequence of various cheniers, the distance of the chenier from present-day shoreline was considered. Larger the distance, older

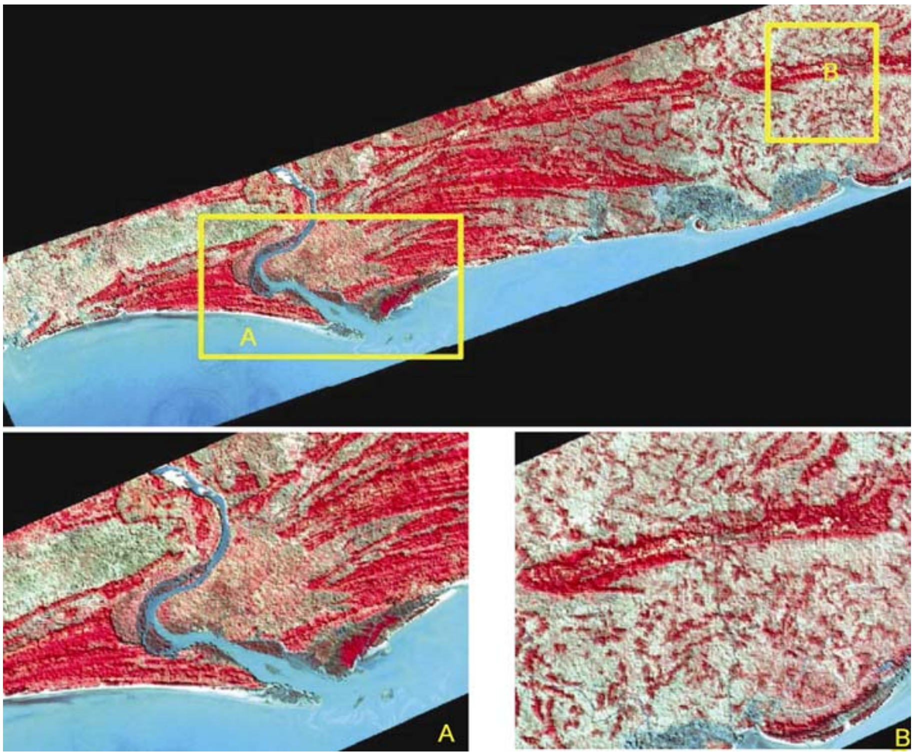

Figure 1. Merged image of Landsat ETM+ (False Colour Composite) and shaded topographic SRTM data showing overview of Subarnarekha chenier complex with zoom boxes A and B. Zoom box A exhibits elevated regressive ridges and depressed floodplain area. Zoom box B shows past and recent (nearer to the coast) spit complexes.

will be the age of formation. Although in a few cases, the chenier is cut by present-day shoreline and river, its continuity can be observed in the field. Compared to present-day ridges, oldest ridges are vegetated and usually contain brownish-white colour sand. Both ancient and present-day mudflats are grey in colour in FCC satellite images and coincide with wetland zones. In a few cases, they are altered as agricultural field. Old beach ridges are usually associated with mudflats, whereas youngest ones are juxtaposed together. In Figure 1, these ridges can be perceived as elevated areas, whereas mudflats and floodplains appear as depressed zones. The merging of shaded topographic SRTM data with standard FCC of Landsat ETM+ makes such interpretation easier. A six-stage chenier development can be identified. In Figure 1, zoom box A indicates these stages. Here, younger ridges are more regressive in nature, whereas older ridges are transgressive. In zoom box B of Figure 1, past spit complexes are present 15 km inland; whereas recent spit complexes appear nearer to the coast. Detailed subsurface lithology with combination of sand and mud clearly distinguishes cheniers (transgressive) and regressive ridges, as discussed later.

Thus in the present study different geomorphic features like spit, spit complex, chenier, chenier complex, beach ridge and washover beach were identified and different stages have been marked with different colours as shown in Figure 2. Subsurface interpolations of mud and sand layers were performed for shallow wells using Rockworks software. Finally, using age interpretation by earlier workers, six-stage morphodynamic development of Subarnarekha coast was sketched.

Six stages of chenier development can be identified from Figure 2. They are marked with different colours like red, magenta, green, etc. The first chenier is longest and its tips are exposed in Rasulpur and Panchpara River ends, whereas the second and third cheniers are limited to Deopal and Ramnagar regions and are completely absent crossing the western bank of present-day Subarnarekha River. An extended mudflat is present between the first and fourth cheniers. After crossing the eastern bank of Subarnarekha, mudflat is noticed with palaeo-meandering channels. Besides, the first chenier consists of numerous spit complexes. Except present day, these spit complexes are not found for cheniers of other stages. The fifth and sixth stages of chenier development show lack of mud content and these are interpreted in the field as beach barrier complex and washover deposits. Based on hierarchy of geomorphology, chenier from each stage was scrutinized for simplest fourth-order unit to second-order unit. It has been seen that the first-stage chenier has majority of spit complexes; whereas the second and third stages have chenier-mudflats and the last stage cheniers have washover deposits and beach barrier

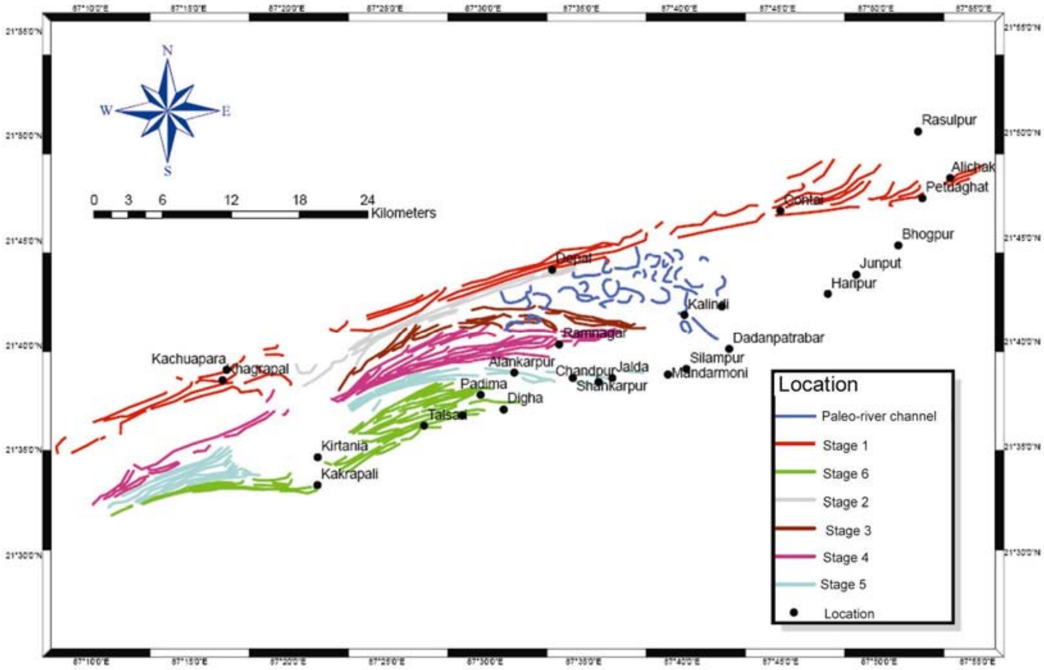

Figure 2. Six stages of chenier and palaeo-river channel map.

complexes. Besides, the spit complexes in first-stage chenier are more clustered towards the eastern side. Development of spit complexes disappeared in the second to sixth stages. This indicates gradual shift of initial wave-dominated coast to tide-influenced coast.

The subsurface lithology of Midnapur–Balasore coast was interpolated on the basis of shallow well data up to maximum depth of 300 m. Interpolation demonstrates that the top 1 m of deposits are made up of mainly muddy sediments with a few sandy horizons. The elevated sandy horizons are limited up to a depth of 30–40 m. Calcrete or medium to coarse sand deposit is present in the lowest part of the profile *XY* (Figure 3). The generalized shallow profile (up to 10 m) exhibits the appropriateness of our interpretation from satellite imageries. However, beach barrier complexes are prominent towards the sea (*X* region). Thus, along the *X*–*Y* section, sixth to first stage cheniers and their subsurface association can be interpreted. Younger cheniers contain less mud between ridges compared to the older ones. This confirms gradual transition from transgressive to regressive ridges. The fence diagram (Figure 3) verifies the above-discussed interpretations.

Four prominent palaeo-sand ridges showing development of aeolian dunes were interpreted by earlier workers[7–9]. Their field surveys specified that the youngest chenier is exposed at Digha beach. These palaeo-sand ridges alternate with three broad flats or marine terraces (identified here as mudflat for chenier and sandy palaeo-beach for beach barrier complexes). The following dates were observed: 5760 ± 160 years BP for W-part of Rasulpur River upstream section of ancient fluvial flat and 2900 ± 160 years BP for Pichaboni channel bank ancient inter-tidal flat at 2.4 m. The ancient dune complex 10–15 km inland along Digha–Junput coast plain was dated at 5760 ± 140 years BP. At 3000 years BP older beach ridge, 5–7 km inland, there was formation of dune complex. Flat terrain of ancient intertidal flat near Digha formed 2920 ± 160 years BP. Around 7000 years BP, Rasulpur and Pichhabani separated from Subarnarekha. At 6000–3000 years BP development of significant marine terraces occurred in Kanthi Paniparul dune ridges. The above observations by earlier workers are summarized in Table 2, with interpreted significance of tidal dynamics, wave characteristics, sea level and sediment supply.

The results derived from cartographic techniques, field data and literature survey lead to a six-stage development model for the coast (Figure 4) as given below.

First stage: 7000 years BP; sea level was high. Due to eastward longshore current, many spits were formed in the eastern part where Subarnarekha appeared as a small river, but sediment supply from the Ganges was absent.

Second stage: 5000 years BP; sea level was high. Subarnarekha river avulsed from east to west and Ganga supplied major sediment from its present Hooghly estuary. A huge amount of sediment supply from the Ganga built up extensive mudflats along the eastern part of this coast.

Third stage: 3000 years BP; sea level started to fall, sediment supply from the Ganges also got reduced. Subarnarekha continuously shifted towards the west abandoning the present Rasulpur river. As a result, a few

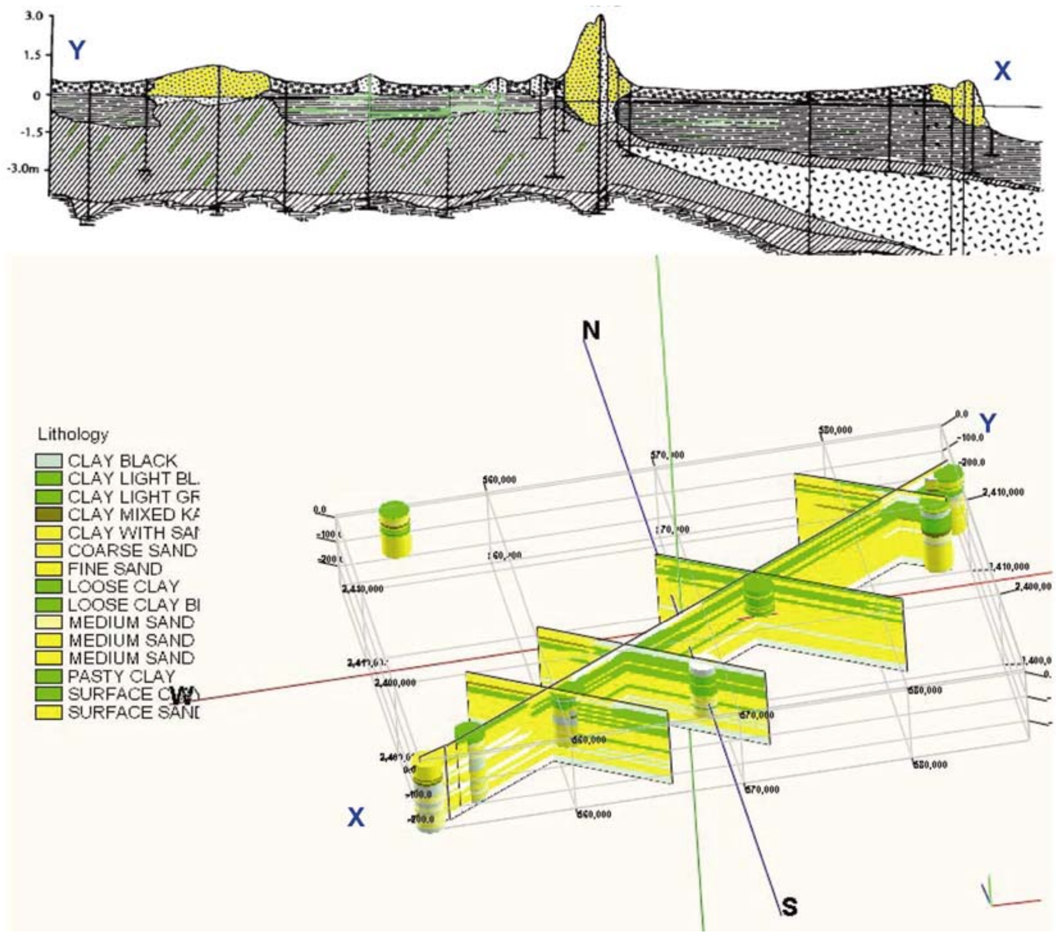

Figure 3. Subsurface lithology map of Subarnarekha delta and Contai coastal plain.

Table 2. Ridge chronology of Subarnarekha delta and Contai coastal plain

Age (years BP)	Stage	Type	Significance			
			Tidal dynamics	Wave characteristics	Sea level	Sediment supply
7000	First	Spit complex; transgressive ridge	Longshore drift > tidal prism	High	High	Sand supply mainly by longshore drift
5760 ± 160	Second to third	Chenier; washover; mudflat	Not significant	Low	High	Very high mud supply in initial stage
2900 ± 160	Fourth to sixth	Regressive ridge	Tidal prism high	High	Low	Low but equal sand and mud supply

cheniers were developed in this stage near the eastern bank of the river. However its western bank, hardly preserves any such sequence. Identifying the third stage is critical in both field and from satellite images.

Fourth stage: After the third stage, sea level fell significantly. At the same time Subarnarekha turned into a major river contributing significant amount of sediments with high value of tidal prism; this caused regressive beach ridges close to its estuary. This conversion also suggests initial wave-dominated coast to tide-dominated coast.

Fifth stage: 2000 years BP; sea level fell sufficiently; Subarnarekha river continued its westward shift. Therefore, formation of regressive beach ridges continued.

Sixth stage: From 2000 years BP to the Present, the coast experienced few stages of sea-level rise, documented as chenier complex. Continuous shifting of Subarnarekha towards the west, exhibits clear time gap between the last few stages.

At present, the Ganga supplies major part of its sediment load towards Bangladesh. Similarly, transgressive phase may have begun. Present inlet dynamics also shows gradual reduction in tidal flow and predominance of wave action with the formation of spits. Many spits are seen forming up to the Rasulpur region. Thus the coast retaining its earlier conditions (7000 years BP) of wave domination.

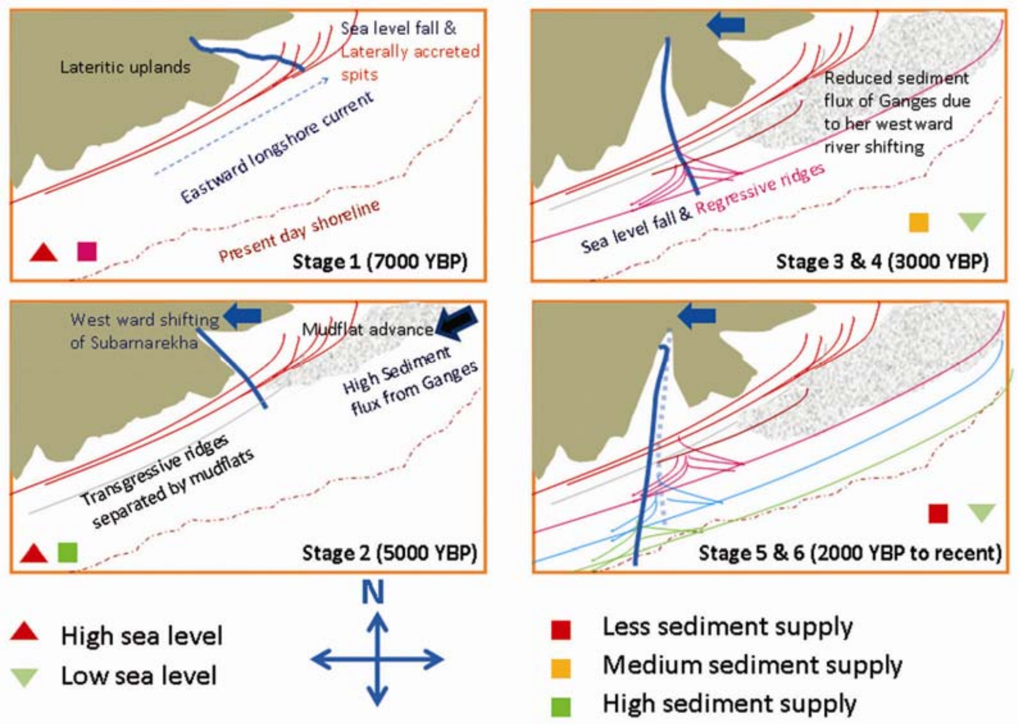

Figure 4. Six-stage geomorphic process–response model illustrating evolution of the Subarnarekha delta and Contai coastal plain.

With the initial objective of understanding morphodynamics through cartographic and field techniques, the study has brought out the following important facts:

(a) A geomorphic hierarchy of chenier development, viz. chenier plain (first order), beach ridge, spit, chenier complexes (second order), cheniers (third order), and spit, washover beach (fourth order), exists in this study area.

(b) Overall, chenier evolution was influenced substantially by transgressive processes in the early phase. Intermediate phases witnessed relative regression, sediment supply and predominant wave–tide dynamics. However, during intermediate phases longshore sediment transport and dynamic diversion at tidal entrances gave rise to regressive chenier deposits; seaward progradation in the form of beach ridges occurred if dynamic diversion of tidal prism was strong. Besides, laterally migrating spit complex formed if longshore sediment transport dominated. During the evolution of the first chenier complex (7000 years ago), such a condition prevailed, as interpreted from geomorphic facts. Other fifth and sixth stages show intermediate phases with transgression.

It can be concluded that Subarnarekha delta and Contai coastal plain not only exhibit transgressive ridges (traditional chenier), but also show development of intermediate regressive ridges (beach ridges) and laterally accreted ridges (spits) in its different stages of development.

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