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Geomorphological Studies of Southern Part of Ganjam Coast, Orissa, India

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Abstract

Geomorphological studies along the southern Ganjam coastal stretch of Orissa was carried out with the aid of IRS 1C PAN image data followed by ground truthing. The study revealed various coastal landforms like beach, berm, dune ridges, spits, estuaries, tidal flats, tidal swamps, palaeo-channels, palaeo-strandlines, earthen mound and extension of Eastern Ghats Metamorphic Province under the coastal sediments. Taking into account of the occurrence of palaeo dune ridges, abrupt termination of palaeo-channels, disposition of the geomorphic units, associated marine and fluviomarine faunal assemblages and critical examination of sediments, three palaeo-strandlines of past sea level have been interpreted in the study area.

Key-words : geomorphology, satellite data, Bahuda River estuary, earthen mound, palaeo-channels, palaeo-dune ridges, Ganjam coast.

INTRODUCTION

Satellite data provides an insight to the landforms present in an area alongwith synoptic coverage. Various geomorphological features can be interpreted with optimum accuracy and more precisely in case of coastal landforms based on the image characteristics. Coastal zones witness interplay of different natural processes like tide, wave, current, wind and fluvial water, each contributing their characteristic geomorphological units in time and space. Niyogi (1975), Mahalik (2000), Maejima *et al.* (2000), Mohanti (1996), Samal (1995) and Mohanty *et al.* (1988, 1989) have studied the coastal landforms of Orissa using remote sensing data, but the southern Orissa coast is less studied as compared to the northern and central coastal stretches of Orissa. Although Mohanty *et al.* (1989) and Tripathy *et al.* (1996) studied the geomorphology of the Ganjam coast based on interpretation of satellite data, sufficient ground truthing was not taken up and broader classifications of geomorphic units were suggested. Now an attempt has been made to study the geomorphological features present in the area between Andhra Pradesh–Orissa border and Gopalpur in a finer resolution with adequate field checkups.

STUDY AREA

The study area is bounded by lat. 19°05′00″ to 19°17′00″N and long. 84°45′00″ to 84°57′00″E, and is situated on the southeastern margin of Ganjam coast in Orissa featured in Toposheet No.74 A/16 and 74 A/15

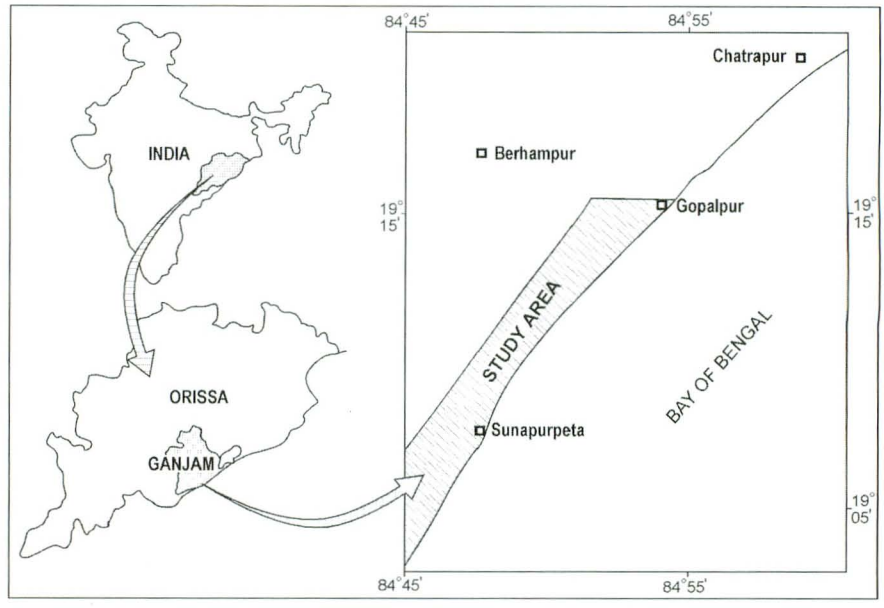

Fig. 1 Location map of the study area.

(Fig. 1). The area extends for a coastal length of about 20 km and width of 6 km bordering the Bay of Bengal on the east, Bahuda River estuary in the south, Gopalpur creek on the north, and hilly submotane region of Eastern Ghats Super Group towards the west.

This part of the coastal tract is characterized by subtropical transitional climate with temperature ranging from 15℃ to 37℃. The area experiences south and southwest wind during summer seasons with wind speed of 16 to 34 km/hr and northwest wind from December to February with wind speed of 16km/hr. The coast is microtidal with tidal range of 1 to 2m. Bahuda is the only major river which is a rapid flowing river having short course of about 90 km that discharges into the Bay of Bengal near Sunapurpeta forming a microtidal estuary. Furthermore, Markandi Nala and Ambaghai Nadi are two minor channels draining the area. The littoral drift in Bay of Bengal is at its maximum during monsoon accounting for 90% of the estimated 0.74 million m^3 of the net annual drift towards north (Mallick, 1972).

The geology of the Eastern Ghats, exposed in this part of the region, was studied by Pascoe (1950), Krishnan (1982), Mohanty *et al.* (1988, 1989), Rao (1989), Mishra (1972), Mahalik (1998) and Tripathy *et al.* (1996). The Eastern Ghats are represented by Khondalite suite of gneisses, basic granulites, granite gneisses and their migmatised variants of Archaean age which have been permeated by quartz veins and quartzo-feldspathic neosomes. The Archaeans are overlained by Cenozoic sediments at coastal margin. Mohanty *et al.* (1988, 1989), Tripathy *et al.* (1996), Mishra *et al.* (2004) and Mishra *et al.* (2005) have studied various geomorphological features developed along this sector. The earlier studies in this sector were at macro level with very limited field checkups but the present study is aimed at highlighting the detailed geomorphology of this part of the coast using remote sensing data and detailed field studies.

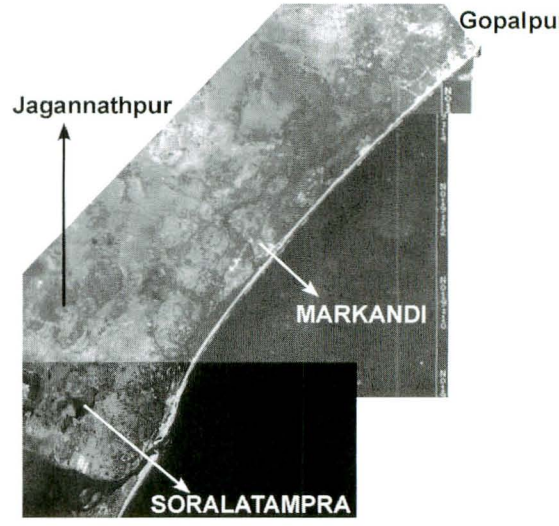

Fig. 2 Satellite Image of T.S. No.74A/ 15 SE (April 2002) & A/16 NE, SE (March 2001) (part).

METHODOLOGY

The geological and geomorphological mapping were carried out with the help of IRS IC, ID PAN image (5.8m resolution, March, 2001 and April, 2002) hard copies (Fig. 2) on 1:25,000 scale of Toposheet No.74 A/15 SE, 74 A/16

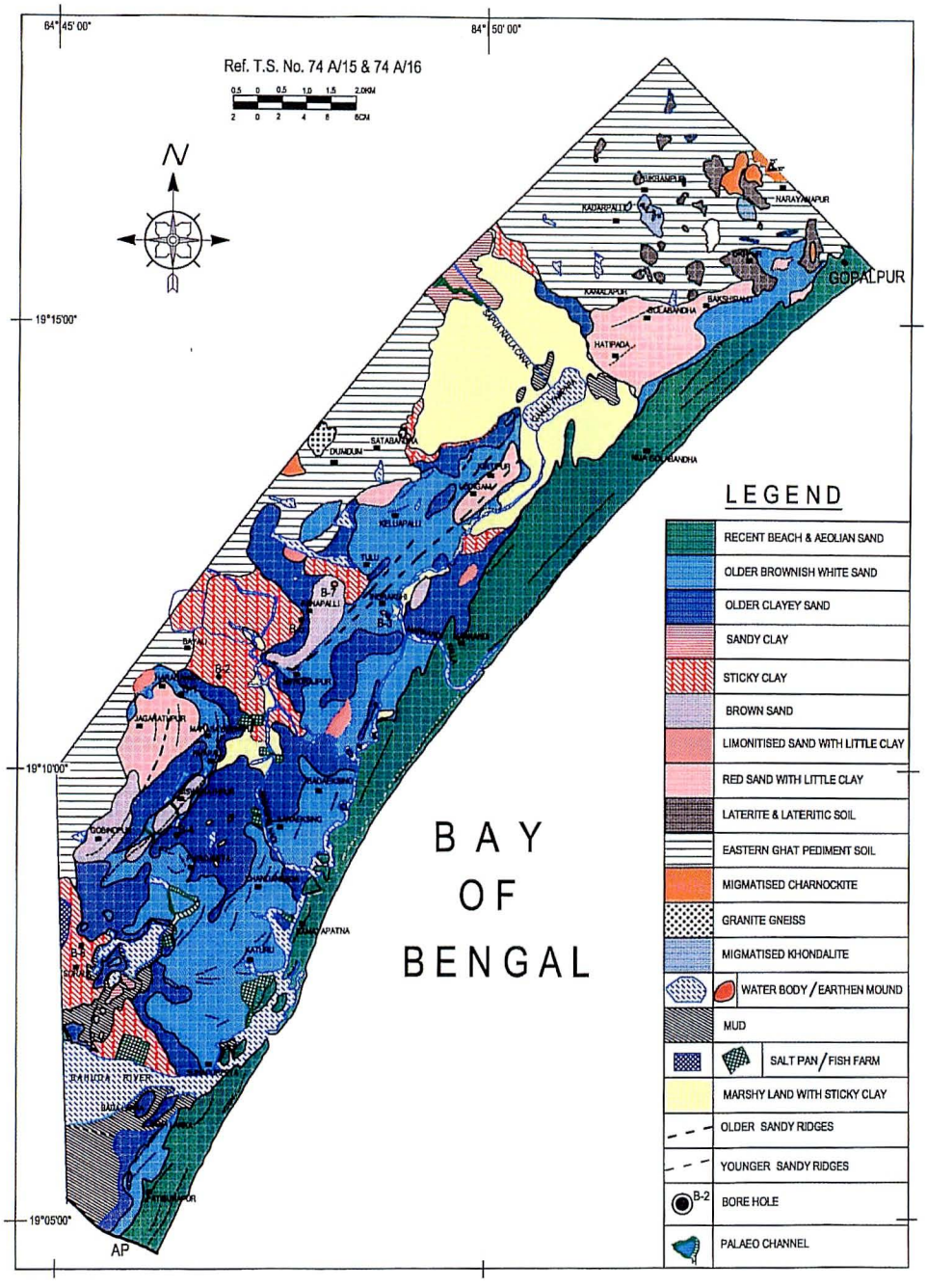

Fig. 3 Geological map of the study area.

NW, NE, SW for their better resolution and synoptic coverage. Based on the image characteristics like tone, texture, colour, pattern, shape, location and association, various geological and geomorphological units were delineated and superimposed on a base map prepared with reference to Survey of India Toposheet No.74 A/16 and 74 A/15 (part). Ground truthing was taken up for validation of the interpreted data followed by necessary rectification. Sediment samples were collected from different geomorphic units and from few boreholes given by hand augers at random to know the subsurface geology. Besides IRS IB LISS IIA FCC (band 2, 3, 4) was also visually interpreted to draw the palaeo-strand lines and palaeo-channels.

RESULTS AND DISCUSSION

GEOLOGY

The geological map prepared by visual interpretation of the satellite imagery and field verification (Fig. 3) indicates that the litho units of Eastern Ghats Supergroup of rocks are mainly exposed in the northwestern and

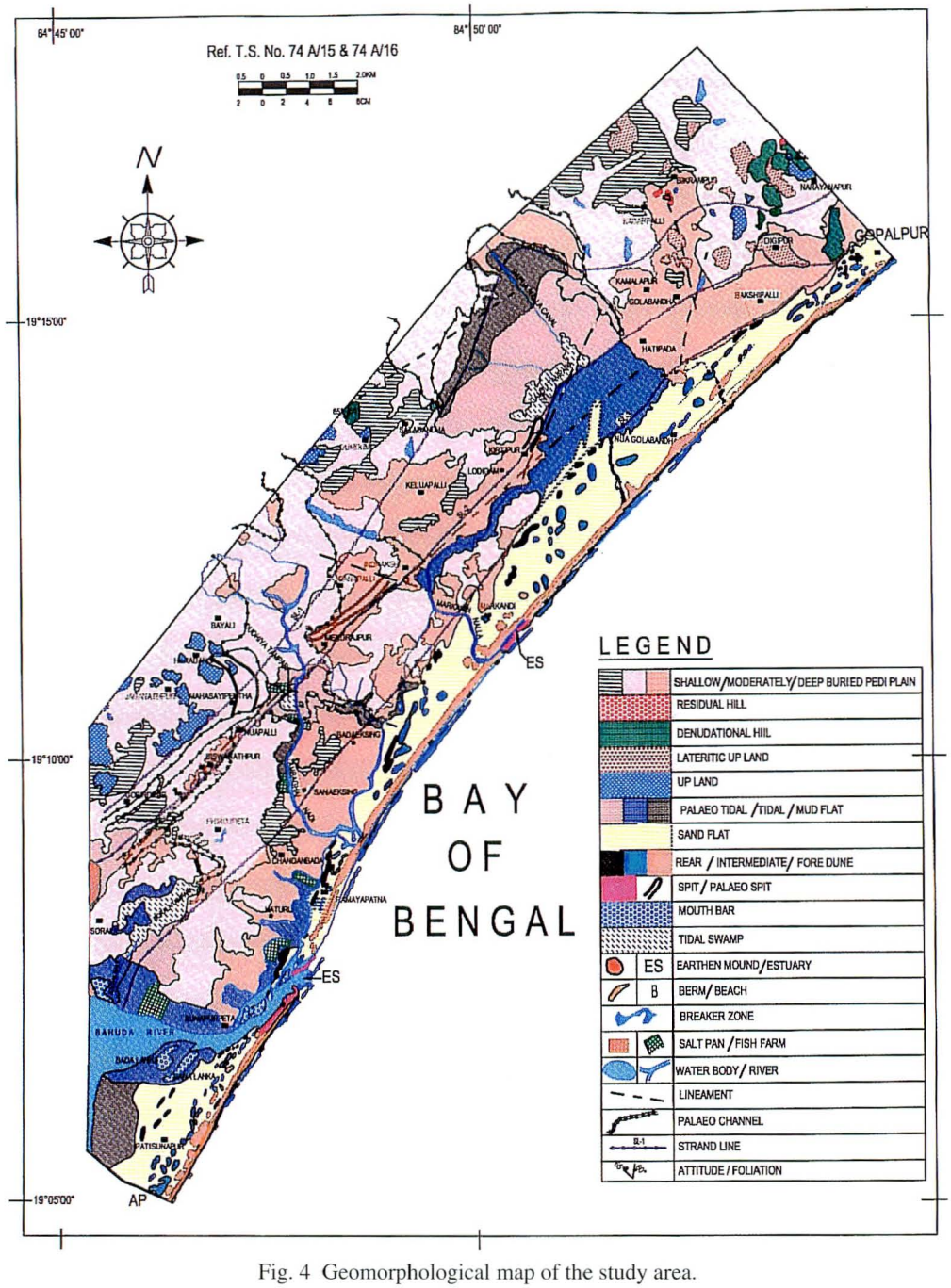

Fig. 4 Geomorphological map of the study area.

northern margin of the area around Dumdum, Majhigaon and west of Gopalpur. The metamorphics are highly dissected and weathered. Garnetiferous granitic gneisses with well-developed joints exhibit brighter tone with prominent foliation features, which rather extend to the study area being covered by weathered/sedimentary layers. Granulites are represented by basic charnockite often migmatised with granite gneiss and are found near Dumdum, Majhigaon, Bikramkpur etc. that exhibit a relatively darker tone with rough texture.

The khondalite suite of rocks is highly migmatised with the signature of shearing and highly weathered exhibiting foliation and mottled texture with a grayish tone. The laterites mostly found in the northern part of the area around Golabandha are weathered products of Eastern Ghats Supergroup of rocks as mainly Khondalites and Charnockites being rich in iron, manganese, magnesium etc. The lateritic mounds occur in the form of small domes with or without vegetation and exhibit fine to mottled texture.

The Quaternary formation in the peripheral regions of Eastern Ghats extending up to Bay of Bengal could easily

be identified from their bright signature and characteristic localization. Because of variable moisture content the alluvium exhibit varied shades of grey and light tone while the sand dunes adjacent to the coast exhibit a very bright tone.

The Eastern Ghats Supergroup of rocks in the region has been affected by polyphase deformation exhibited by fold axes lineaments of three phases (Mohanty, 1989). Mahalik (2006) also indicated that the eastern boundary of the Eastern Ghats is a fault related lineament, responsible for the formation of coastal depression in the Orissa sector. The present study also indicates two sets of fault lineaments trending in NE–SW and WNW–ESE directions (Fig. 4). The NE–SW lineament runs parallel and adjacent to the present shoreline within the study area extending from Sorala to Kirtipur while the WNW–ESE lineaments are parallel to each other having limited extension. Also, minor N–S lineaments are noticed in the north central part. It is believed that the NE–SW and NW–SE lineaments control the drainage of the area (Mishra *et al.*, 2004). Moreover, two sets of joints in NE–SW and NW–SE directions with sub-vertical dip have been noticed in the granitic gneisses and granulites. The NE–SW joint being parallel to the present coastal alignment clearly follows the NE–SW mega lineament and is responsible for the present coastal depression.

GEOMORPHOLOGY

Taking into account of the image interpretation criteria like tone, texture topography, relief, sediment thickness, slope factor, surface cover, soil and vegetation cover and ground truthing data, various geomorphic units have been delineated and mapped. The study area is characterized by two prominent geomorphic provinces, i.e. Eastern Ghats Metamorphic Province and Coastal Sedimentary Province (Fig. 4).

Eastern Ghats Metamorphic Province

The Eastern Ghats Metamorphic Province consists of denudational and residual hills mostly found in the western and northern margin of the area which extend into the study area being masked by scree and debris cover at the foothill or covered by weathered sedimentary layers called pediplains.

Denudational hill

The hills formed by the process of denudation are known as denudational hills. Denudational hills are marked by sharp to blunt crest lines with coarse and rough texture and irregular slopes with dark grey to medium grey tone. They are well drained and occur in topographically higher areas. They are devoid of prominent structural features. There are rocky/stony wastes with sparse vegetation and bushes on these hills. They could be easily interpreted from their massive size and domal to elliptical shape. The lithological constitution of these units vary from granite gneiss to khondalites and acidic to intermediate charnockite and are found near Dumdum, Bikrampur, Satabandha, north of Narayanpur etc. Hills are usually surrounded by shallow buried pediments.

Residual hills

Isolated hillocks with low relief that stand above the vast plain country are termed as residual hills. Residual hills are marked by medium to smooth texture, elliptical to circular shape, well drained, and covered with bushes, shrubs and sparse vegetation. Isolated hillocks or mounds resulted from the prolonged process of denudation and left out as resistant hillocks. These are found near Bikrampur, Narayanpur etc. and chiefly represented by khondalites and charnockites.

Shallow buried pediplains

Coalescence of buried pediments with thick cover of weathered materials forms the buried pediplains. These are characterized by a very light grayish to white tone, smooth texture and irregular shape with little undulations bordering the denudational and residual hills. They are remarkable around Dumdum, NE of Narayanpur, Hantulu, Ekasing, north of Golabandha, East and west of Gobindpur etc. The shallow buried pediplains around Dumdum have been developed probably due to a batholithic granitic intrusion. These are either bare or thinly vegetated with accumulations of partly limonitised clayey sand and gravel. Groundwater condition is poor to moderate. Thickness of the weathered zone varies from 30 cm to 5 m. The low moisture content of the unit gives a bright signature on the imagery.

Moderately buried pediplains

Moderately buried pediplains have a 5 to 20 m thick cover of weathered materials. These pediplains are characterized by a medium grey to light grey tone due to slightly higher moisture content of relatively thicker sediment cover with mottled texture and irregular shape and are mostly located adjacent to shallow buried pediplains. They constitute a larger part in the SW part of the study area around Bayali, Biswanathpur, Phirojpeta, Panapalli, south of Satabandha, NW of Golabandha, Narayanpur and Bikrampur etc. Here thickness of sediments ranges from 4 to 20 m and the sediments also form part of the ancient coastal plain of Holocene sea level within which palaeo geomorphic units have been noticed. Sediments are observed to be a mixture of transported and insitu materials, and groundwater condition is good to moderate.

Deep buried pediplains

Deep buried pediplains are leveled out areas characterized by a dark grey tone adjacent to the coastal sandy tract and on either side of the streams around Indrakshi, Kirtipur, Ekasing, Mendrajpur, Chandanbarha, Bisawanathpur, Markandi, Bakshipalli, Sunapurpeta etc. These units display dark grey tone due to thick soil profile and higher moisture content, smooth texture and irregular shape. It is noticed that the deep buried pediplains are stretched and aligned in conformity to the major NE-SW lineament, which corroborates its persistence in the event of thick sediment accretion. These pediplains are comprised of older fluviomarine and/or marine sediments represented by sand, sandy clay, clayey sand, and sticky clay with shallow marine organic shell remains. Few red soil uplands of low amplitude having linear to a curvilinear shape with vegetative cover were noticed near Jagannathpur, Lodigam, Golabandha and Bakshipalli, which are actually sand dunes (oxidized) corresponding to ancient shoreline within the deep buried pediplains. Groundwater condition is good to excellent, but effect of intrusion of saline water is a conspicuous phenomena.

Uplands and lateritic uplands

Isolated landmass of either resistant rock or lateritic mass with higher relief than the surrounding plain are termed as uplands. Insitu lateritic uplands are mostly localized along northern part of the area around Golabandha, where the khondalite suite of rocks have undergone subtropical weathering, and the elevation rarely exceeds 30 m above m.s.l. These laterites are well drained; sparsely vegetated; exhibit a dark to medium grey tone, coarse to rough texture, irregular shape that is medium to large in size; and associated with pediplains. At times they resemble red soil uplands interpreted around Golabandha, Jagannathpur, and Bakshipalli etc. Tripathy *et al.* (1996) has indicated vast areas around SW of Gopalpur as insitu lateritic mound, but the present study indicates that these are red soil uplands with few insitu laterite mounds and a charnockite mound in the area around Venkataraipur, Golabandha, Bikrampur, Gopalpur, Narayanpur etc. The red soils are altered remnants of palaeo-dunes/beach ridges. The uplands interpreted around Jagannathpur are actually part of the partly stabilised and oxidized palaeo-beach ridge and/or dune complex (Fig. 3) that attained maximum elevation of 30 m above m.s.l., and the sediments have been significantly reddened by prolonged oxidation and alteration of ferromagnesian minerals (Mishra *et al.* 2005).

Coastal Sedimentary Province

The coastal landforms developed adjacent to the coast are products of diverse geological processes, such as wave, tide, littoral drift, longshore current, wind, fluviomarine and fluvial, operating along the marine marginal zones, each contributing to their characteristic landforms. The bright toned flat surface with linear ridges adjacent to the coast demarcates young coastal plain chiefly composed of recent sand, which attain maximum width of about 1.6 km (South of Nua Golabandha) and tapers southwestward and northeastward. The geomorphic units encountered within this province are as follows:

Beach

The PAN image exhibits a narrow zone at the land-sea water contact and parallel to shoreline with smooth texture and whitish bright tone. Because of the microtidal nature of the coast, sandy beaches are well developed all along the coast with width varying from 8 to 58 m. The beach face slopes at an angle ranging from 2° to10° (13° rarely) and exhibit one or two kinks at places. Both concavity and convexity of the beach face at different periods have been noted by profiling. Development of berm is intermittent around Golabandha, Ramayapatna, Markandi, Ekasing, Rhankalparhu etc. As observed over the years, beaches receive sediments during monsoon months and show evidence of erosion during winter months, which is apparent from cliffing of the berm crest (Fig. 5). Such cliffings are more pronounced around south of Nua Golabandha-Garampeta beach and Ramayapatna–Ekasing beach section. In the Ramayapatna–Ekasing sector cliffing from the berm crest was noticed for a length of about 600 m during January 2006, which attained height of 2.10 m. In addition, small cusps of low amplitude have been noticed in south of Nua Golabandha, Bakshipalli, Ramayapatna beach section. A miniature but prominent cuspate foreland has been noticed to the south of Ramayapatna beach.

Sand dunes

Sand dunes are the most prominent coastal features developed adjacent to the sandy beaches. The dune ridges are easily recognizable owing to their localization adjacent

Fig. 5 Berm cliffing near Nua Golabandha exhibiting depositional layering.

Fig. 6 Beach ridge and spit at the mouth of Markandi Nala.

Fig. 7 Embryo dunes covered by creepers, Golabandha backshore area.

to the coast maintaining parallelism with the shoreline. These are light toned, smooth in texture, light grey in colour, and elongated in shape either transverse (foredunes and rear dunes) or longitudinal (intermediate dune) to the global wind direction. The dune ridge facing the beach is fairly continuous and parallel to the shoreline, and may be termed as beach ridge, which are later masked by aeolian sand and its width varies from 8 to 25 m often covered by creepers (*Hydrophylax meritima* and *Ipomoea biloba*) in the windward side and marrum grass from crest to leeward slope. The windward slope of the beach ridge ranges from 14° to 40° (near Markandi) and attains a maximum height of 10 m above m.s.l. (Fig. 6). The beach ridge is flanked by sand dunes and dune flats (sand flats) towards its landward margin with an elevation break. Mainly three types of dunes, viz. fore, intermediate and rear dunes are found all along the coast except the estuary regions. The front dunes with single summit are of transverse type, attaining a maximum height of 22 m around northeast of Bakshipalli and run continuously with intermittent breaks; widths vary from 15 to 45 m. Around Markandi, the front dune exhibits maximum cumulative length of about 3 km. Because of the barren nature of beach ridge and thin vegetative cover of front dune, wind system plays a vital role to help the migration of the dunes landward, thus constant spilling of sand from the beach contributes to lateral and vertical growth of dunes along with development of intermediate dunes and rear dunes. The rear dunes at the margin of younger and older coastal plain are mostly discontinuous but maintain parallelism with the front dune while the intermediate dunes are longitudinal types being parallel to the prevailing wind direction and scattered throughout the area being separated from the fore and rear dunes by interdunal valleys. Sand flat and interdunal valleys of about 20−300 m width separate these dunes. Development of *embryo dunes* in the backshore between beach ridge and berm is a conspicuous phenomenon (Fig. 7) in the Golabandha and Markandi–Garampeta sector, which can only be identified in the field. These aeolian sand dunes are of small amplitude (30 cm to 1m) being covered by salt tolerant creepers (*Ipomoea biloba*) and gradually grow laterally and vertically to give rise to a new beach ridge over time and space leaving the older beach ridge to be regarded as fore dune, but when barren, embryo dunes are readily blown out towards the land.

Besides the recent dunes adjacent to coast, fairly continuous sandy ridges corresponding to ancient shore

Fig. 8 Cross section of Jagannathpur red sand ridge showing depositional layering.

Fig. 9 View of Jagannathpur red sand ridge flanked by swale and palaeo-tidal flat.

Fig. 10 View of a palaeo-beach ridge covered by vegetation and surrounded by palaeo-tidal flat near Biswanathpur.

line of Holocene age have been identified from image data and ground truthing around Jagannathpur, Gobindpur, Haradanga, Sorala, Biswanathpur, DhepiNuapada–Kirtipur and Katuru–Ekasing, Golabandha (Fig. 4) indicating deposition of older coastal sediments in the earlier discussed pediplains. The Gobindpur–Haradanga ridge has been found to be red sand ridge with a mixture of silt and clay, highly indurated (Figs. 8 & 9), and in the imagery appears to be a lateritic upland supporting luxuriant vegetation. This ridge extends for a cumulative length of 3.5 km with intermittent breaks and width varying from 500 m to 1.5 km aligned in NNE–SSW direction having a maximum elevation of 30 m around east of Jagannathpur (Fig. 9). Partially stabilised alternate parallel sand ridges with intervening valleys do occur in the area resembling the present day coastal dune system. Around Golabandha sector, similar red sand dunes and interdunal valleys have been observed. They have been described as palaeo-beach ridges by Mohanty *et al.* (1989). Prolonged exposures to sub aerial weathering, alteration and oxidation of the ferromagnesian minerals imparted red colour to the sediments and gave rise to duricrust like that of coastal teris of T.N. (Thrivikramji, 1994). These sediments are thought to be of marine equivalents of the older alluvium of north Orissa sector. The Gobindpur–Haradanga red sand ridge is interpreted to be a palaeo-beach/dune ridge complex corresponding to the marine transgression, and its northeastern continuity has been obliterated due to a palaeo-estuary, which is discussed later. But its northeastern extension is noticed again around west of Panapali, west of Keluapali and Golabandha being separated by palaeo-estuary. Granulometric analysis of samples from different locations along the sandy ridges indicated beach, shallow marine and aeolian environment of deposition suggesting palaeo position of sea level in this sector (Mishra *et al.*, 2005). Following recession of sea and lowering of sea level, the strand plane shifted further east and another beach probably developed as discussed below.

Another palaeo sandy ridge has been located from north of Sorala to Biswanathpur with intermittent breaks and again from Dhepi Nuaparha to Kirtipur with an intervening palaeo-estuary between northeast of Biswanathpur and Mendrajpur (Fig. 10). This sand ridge extends in N40°–45°E to S40°–45°W direction almost

Fig. 11 Bahuda River spit showing incremental growth in time and space enclosing the estuary.

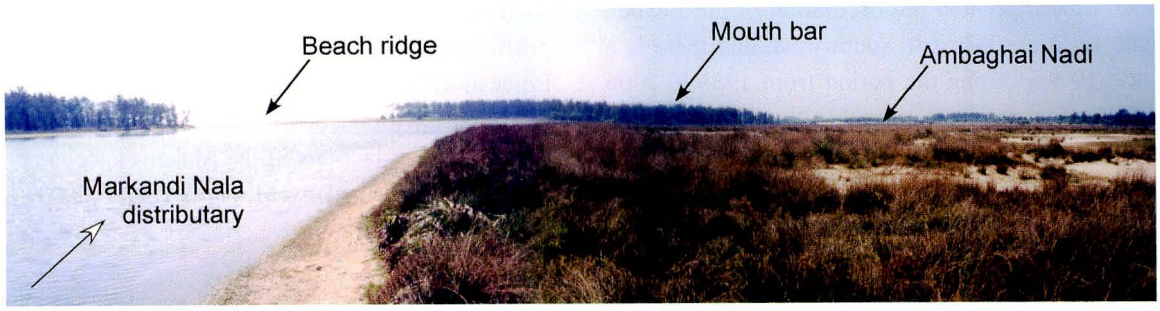

Fig. 12 Confluence of Ambaghai Nadi and Markandi Nala distributary, Ekasing east. The barren sand ridge indicates the old mouth.

parallel to the present coastline and attained maximum elevation of 10–12 m above m.s.l. near Lodigam. Width of this palaeo sand ridge varies from 6–150 m, and its continuity is interrupted by a palaeo-estuary that occur around east of Mahashayipentha, now represented by Dudhiya Tampara encircled by tidal flat and northeast of Kirtipur, which is now represented by Ganju Tampara, where hook-shaped sandy ridges having landward connectivity with abrupt terminations resembling present day spit configuration have been observed. The Kirtipur-Mendrajpur ridge has also been proven to be a palaeo beach ridge with spit like termination in an erstwhile estuary located around Ganju Tampara (Mishra *et al.*, 2005). The Jagannathpur sandy ridge and Biswanathpur ridge are separated by a swale, and a palaeo-channel has also been interpreted from the LISS II data in the place (Fig. 4). Settlements and orchards have been developed over these palaeo dunes.

Spit

Spits are elongated narrow sandy ridges characteristically developed at the river mouth with a hanging end protruded into the sea. In the imagery they are light in tone, smooth in texture, white in colour, linear and elongated in shape with a curvilinear termination at the river mouth region. Hook-shaped linear dynamic sandy ridges enclosing estuaries have been developed at the confluence of Bahuda River and Markandi Nala due to longshore drifting of sediments towards the northeast (Figs. 6 & 11). Comparison of toposheets data and present geographic setup indicates continuous accretion of sediments resulting in growth of the spit and simultaneous shifting of the estuary mouth. Mishra *et al.* (2004) indicated that the Markandi Nala spit is advancing to NE at the rate of 11 m per year and that of Bahuda spit is more dynamic and is a oscillating one showing breaching and accretion over the years (Mishra *et al.*, in progress). The southwestern spit of Bahuda River exhibits incremental growth (5 phases?) at various phases, as evident from the present disposition (Fig. 11).

In addition, three palaeo-spits have been interpreted from the imageries and verified in the field. These units have the characteristic hook-like shape with abrupt termination within the palaeo tidal flats and are connected to a sandy trunk of palaeo beach ridge around north of Hardanga (Fig. 14), Mendrajpur and Kirtipur. The borehole given on the southeast of Hardanga revealed less indurated medium to fine brownish white sand up to a depth of 7 m that abuts against the red sand towards the west and tidal flat in the east with a visible level of difference. These palaeo spits indicate palaeo position of sea level and palaeo-channel mouth regions.

Estuary

Because of their characteristic localization along river mouths, they are easily recognized in the image by darker tone, smooth texture and dark grey to light black colour with narrow and elongated shape. The spits developed at the mouth of Bahuda River and Markandi Nala enclose estuaries behind the recurved spits.

Formation of these spits obstructed direct entry of river to sea, thus deflecting the flow into NE direction due to longshore drift and running parallel to the coast before emptying its water. The Bahuda River, having a short course, forms a microtidal estuary around Sunapurpeta with a narrow opening to the Bay of Bengal. Study of toposheets, imageries and ground features suggest that the Bahuda River estuarine system probably existed around east of Chandanbarha where the Ambaghai Nadi and a distributary channel of Markandi Nala presently meet. Subsequently due to growth of spit, beach ridge, longshore transport from SW to northeast and maybe neotectonic activity, the estuary shifted to southwest following closure of the mouth. Fig. 12 also gives the impression of an older mouth at the confluence of Ambaghai Nadi and Markandi distributary channel, which has been sealed off by present day beach ridge. This is further corroborated from the study of 1934 toposheet of this area in which the mouth of the Bahuda River was roughly east of Katuru, but the present estuary mouth is around northeast of Sunapurpeta.

Mishra *et al.* (2008) pointed out oscillation of the Bahuda River mouth from north-east to south-west, and there is a net shift of 1.19 km during the period from 1934 to 2006 and recorded sediment accretion within the estuary region modifying the tidal flat and mouth bars. As observed during 2004–06, the Bahuda estuary mouth region is very dynamic and oscillating at par with the long shore drifting within 200 m to 300 m seasonally. The tidal water within the estuary reaches about 5 km upstream through the tidal inlets like the Ambaghai Nadi, Markandi Nala etc. The Bahuda estuary region favours growth of *Oyster* colonies within the estuary, which gets exposed during low tide. The Markandi Nala meets the Bay of Bengal around east of Markandi forming a small estuary. Since it is a small nala with less flow of water estuarine mechanism is not pronounced (Fig. 6).

Tidal swamps

The Kaitha Nala, Markandi Nala, the Ambaghai Nadi and their distributaries act as tidal creeks/inlets during high tide which cause submergence of the low lying areas; the effect of tidal water has been observed up to more than 5 km inland where tidal swamps have been formed due to stagnation of tidal water, which are being utilized for aquaculture. Three such inland tidal swamps lying farther from the sea, i.e. Ganju-Tampara in NE, Dudhiya-Tampara in the central part and Sorala-Tampara in the extreme southwest surrounded by marsh, have been noticed in the area. These are localized along the palaeo-strand lines and at terminating ends of palaeo-channels (Fig. 4). These tidal swamps are thought to be remnants of the palaeo estuaries/lagoons corresponding to the ancient shorelines and spits discussed earlier. The Sorala swamp is believed to be formed by embayment of a part of the sea by bars of earlier coastline and is still under active influence of tidal ingress. Sedimentological study by Mishra *et al.* (2005) of Ganju-Tampara west samples shows the estuarine environment of deposition suggesting a palaeo-estuary. However, the coast parallel alignment of the Ganju Tampara and adjoining sand bars along the strand line (SL-2, Fig. 4) suggest the Tampara to be an earlier lagoon formed by embayment of sea. Further, Rao (1989) postulated a hyperbolic embayment of sea from Andhra Pradesh–Orissa border to Chhatrapur with centre around Gopalpur, which corroborates to the present findings. Similar palaeo lagoons in the Mahanadi delta region have also been described by Maejima *et al.* (2000) along the palaeo-strand lines.

Fig. 13 Tidal flat around Markandi Nala, east of Lodigam.

Tidal flats

Tidal flats are located around west of Sunapurpeta and at the marginal zones of estuaries and tidal channels (Fig. 4). The aforesaid palaeo estuaries are also surrounded by palaeo tidal flats. Palaeo tidal flats are located much inland from seashore where tidal activity has been completely ceased. In the imagery palaeo tidal flats are identified from their distinct dark tone, dark grey colour and semi circular shape fringing inland water body. The oldest tidal flats are farthest from the sea around east of Bayali, which surrounds the Dudhiya Tampara and northeast of Satabandha, which surrounds Ganju Tampara; these are now under active cultivation. The next generation of tidal flats are flat open grass-covered landmasses found east of Mahasayipentha, Kirtipur, northeast and SW of Mendrajpur, SW of Hatipada, southeast of Sorala etc., whereas the latest tidal flats are close to the sea, i.e. southeast of Kirtipur, southeast of Indrakshi, south and north of Sorala, north of Sunapurpeta, Katuru and adjacent to the tidal channels which are tidally flushed during monsoon (Fig. 13). The palaeo-tidal flat around east of Bayali is evidenced from borehole given around southeast of Bayali revealing the presence of shallow-marine/ fluviomarine faunal assemblages (*Placina, Arca, Anadara, Cerithedia Cingulata, Natica, Tellina, Gemma Gemma, Epitonium, Meretrix, Oyster* etc.) within dark grey sediments at a depth of 2.10 m from the surface which thrive in a sub-tidal condition while the top 2 m layer is fine sticky clayey sediments. The sticky clay horizon indicates a quiet water condition that might have prevailed during embayment, following recession of sea. The depth samples indicate coarse to fine estuarine sediments rich in open and close bivalve shells confirming their insitu existence in shallow marine agitated environment. The palaeo-estuaries and flats have subsequently been buried by fine silt and clay deposited by flocculation. The estuarine sediments are underlain by coarse to fine sand of marine origin later modified by aeolian action as revealed from borehole cuttings. The present tidal flats are being used for shrimp culture around Sunapurpeta, Katuru, Sorala, Ramayapatna, Eksing etc.

Mud flats

Mud flats are accumulation of mud in the low-lying areas of deltaic plain by fluvial processes. Mud flats are

Fig. 14 Papul Creek, abandoned palaeo-tidal creek, south of Nua Golabandha sealed off by recent beach ridge.

recognized by their dark tone and smooth texture and are adjacent to river or nala course often associated/mingled with tidal flat. These are found around upper reaches of Ganju Tampara tidal flat, Sorala, west of Patisunapur etc. The mud flat sediments are mostly silt and clay of deep black colour with higher moisture content and often inundated.

Palaeo-channels

A number of palaeo-channels have been interpreted from the imagery based on image characteristics like dark tone, sinus imprints of course and alignment of irregular water bodies, swampy linear stretches of land etc. These are related to early strandlines and characteristically terminate abruptly in the palaeo-estuaries (tidal swamps) and/or in older coastal plain or along palaeo-strandlines. The farthest channels are found around north and east of Haradanga (Fig. 4), which are larger buried channels and now under active cultivation. The area is being drained by two small nalas, Ambaghai Nadi and a tributary-Ghatak Nala, which is active in its lower course. Another big palaeo-channel was noticed around northwest of Ganju-Tampara, which is now represented by mud flats, tidal flat and marsh. This is also dead and buried; a major part is covered by cultivated land and grass in the upper reaches. In the upper reaches of this palaeo-channel, Sapua Nala discharges its water that is drained into the marshy land. Subsequently a canal has been constructed to direct the flow into the Ganju Tampara. The mud flat and tidal flat witness encroachment of tidal water during monsoon. Lowering of sea level probably enforced the earlier channels to carve out their path further downstream to meet the restored sea. As such next generation palaeo-channels are observed on both sides of Biswanathpur palaeo beach ridge. The palaeo-channel west of Biswanathpur is of second generation and buried by coarse limonitised sediments resembling channel sands. These palaeo-channels had a flow direction towards SW to meet the sea near Sorala. Another abandoned defunct tidal creek named as 'Papul' creek has been noticed around south of Nua Golabandha and is now sealed off from the sea by recent beach ridge (Fig. 14). The Papul creek is thought to be an extended arm of the interpreted palaeo-estuary that was discharging the tidal and fluvial load of the erstwhile estuary around Ganju Tampara following recession. Mishra *et al.* (2005) have studied the sedimentological characteristics of the Papul creek, which shows both fluvial characteristics in its upper reaches and high energy regime indicative of wave action in its lower course.

Mouth bar

Mouth bar is an elongated bar localized near the mouth of the river where the longer end of the ellipse orients in the flow direction of river. In the imagery they can be well identified from their elliptical shape within the mouth region of Bahuda River estuary. Sana Lanka and Bada Lanka are two prominent mouth bars that exhibit bright tone, smooth texture and light grey colour. Small bars are also found within the estuary system of Bahuda River and Ambaghai Nadi around NE of Sunapurpeta, east of Chandanbarha.

Earthen mound

An isolated earthen mound (Fig. 15) with extensive faunal bioturbation over a surface area of about 8000 m^2 attaining 20 m height above m.s.l. has been located around Indrakshi village which was not picked up during satellite interpretation. However, the mound gives a bright tone and elliptical outline with little elevation effect and localised at the intersection of NE–SW and WNW–ESE lineaments at a distance of 2.5 km inland from the present sea shore. The mound exposes thick pile of alternate layers of fluvial and shallow marine sediments with occasional clay drapes embodying sub tidal faunal assemblages. Mishra *et al.* (2004) interpreted near shore shallow marine agitated water coupled with fluvial environment of deposition for the sediments of the mound through sedimentological studies and suggested it to be an uplifted palaeo-estuary of the Markandi Nala corresponding to the afore said second strand line interpreted from NE of Sorala to Kirtipur. Physical examination of the ridge on both sides of the mound indicates that the sediments on either ends of the ridge are

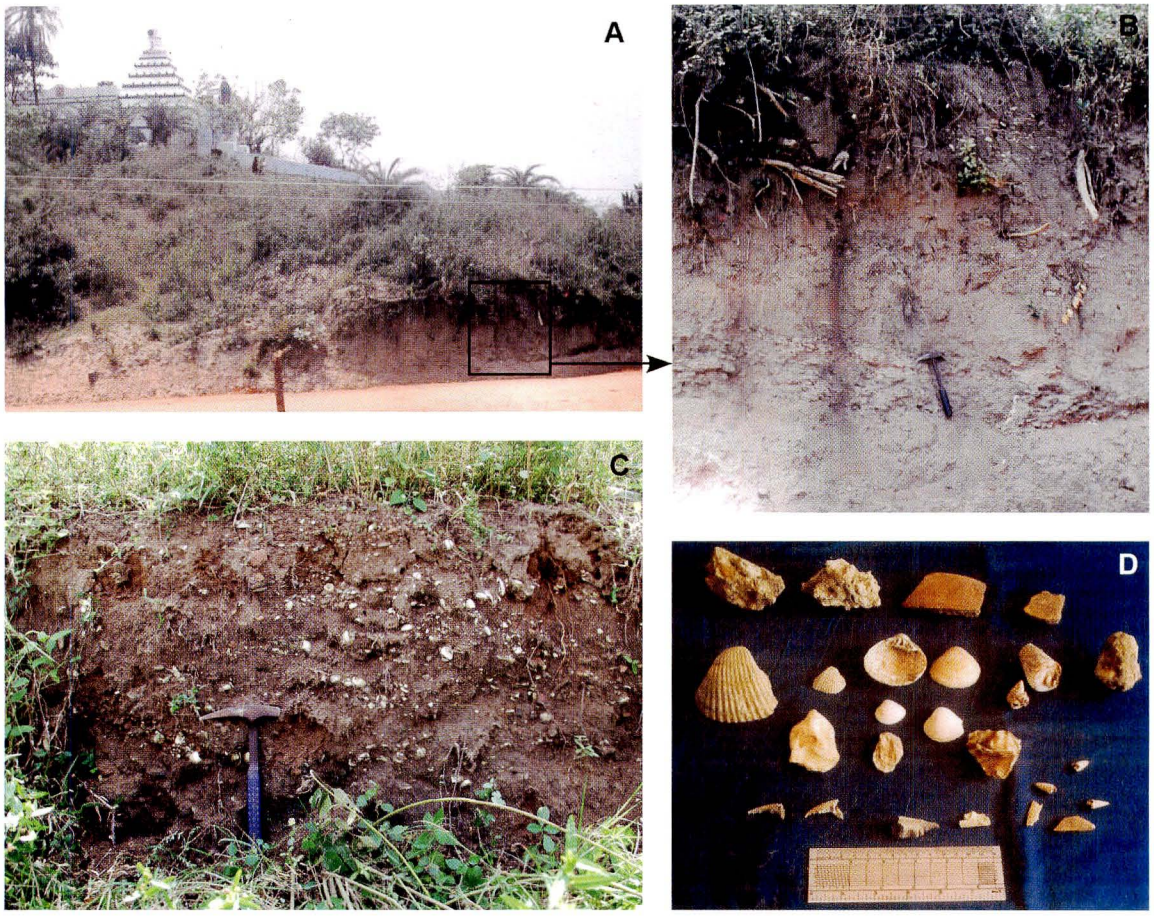

Fig. 15 Indrakshi earthen mound (A) showing layered sediments (B), shell-rich sediments (C) and faunal assemblages (D).

highly indurated and oxidized while around the earthen mound the sand is rather fresh and clean with molluscan remains (Fig. 15) indicative of breaching of the continuous ridge which may be due to presence of an old estuary as interpreted earlier. The borehole given on the eastern base of the earthen mound reveals fresh coarse to fine sand up to a depth of 10 m with organic remains resembling spit sand. Evidence of a spit corroborates to the earlier interpretation of palaeo-estuary. The faunal remains recovered from the mound and the bore hole include *Arca, Anadara placina, Cerithedia Cingulata, Natica, Tellina, Gemma gemma, Epitonium, Meretrix, Oyster, Buccinum, Mercenaria, Umbonium, Telescopium, Turritella, Donax*, crab legs, skeletal remains etc. which substantiate a shallow marine environment of deposition with interference of fluvial processes.

Palaeo-strandline

Based on image data, geomorphological setup, sedimentological characteristics and field evidences three palaeo-strandplanes are suggested in addition to the present one (Fig. 4), which has been stabilized 6000 years B.P. (Vaidyanadhan, 1989). As discussed earlier, the farthest strand line (SL1) lies at a distance of 4.5 to 5 km inland from the present coast around east of Jagannathpur, which is evidenced from parallel linear sandy ridges akin to the present dune systems extending from Gobindpur to Haradanga over a length of about 4 km with variable width and its northeastern counterpart again appearing around Golabandha being intervened by palaeo estuaries like Dudhiya Tampara and Ganju Tampara. The second strand line (SL2) inferred at about 3 km inland in Biswanathpur–Kirtipur stretch, is evidenced from abrupt termination of palaeo-channels, abandoned estuaries, palaeo-channels and development of sandy ridge parallel to the coastline and granulometric studies. The third palaeo-strandline (SL3) has been interpreted at 1.5 km inland behind the present rear dunes where coarse sandy sediments (negatively skewed) occur at the base of the aeolian sand around Katuru, Nakavaram, Ekasing etc. Critical examination of subsurface samples up to 8 m depth also points to existence of high-energy beach environment in the area in the geological past. Examination of borehole samples indicates presence of fine oxidized/limonitised sandy sediments from 5 to 8 m below the ground level being

overlain by tidal flat sediments in the holes given around Sorala, 1 km northwest of Indrakshi, south of Panapalli which are of aeolian nature indicating subaerial exposure to drying condition. These oxidized aeolian sand are thought to be of sand dunes/sand flats of regressional phase of Last Glacial Maxima, i.e. 18,000 years B.P. when the sea level went down 120 m exposing about 25 km of shelf from where wind carried out the sediments inland (Dash *et al.* 2005). They have been oxidized significantly due to prolonged exposure to subaerial insitu weathering and alteration of iron bearing heavy minerals during Holocene. The above findings corroborate to the earlier postulation of Rao (1989) who suggested a hyperbolic embayment of sea with center around Gopalpur.

CONCLUSIONS

The following conclusions can be drawn from the aforementioned geomorphological studies.

1. The present study has brought out a detailed picture of the various geomorphic units present in the area with the aid of PAN data of IRS IC and ID satellite followed by ground truthing.
2. In the event of sediment accretion and subsequent peneplanation it would have been difficult to identify and characterize the geomorphic units, lineaments, palaeo-channels in the field visually; but in this case remote sensing data of higher resolution have been effectively used to identify and map them systematically.
3. The area is mostly characterized by older and younger coastal alluvium corresponding to the strandlines of Bay of Bengal in time and space, which gave rise to different geomorphological units with subsequent modifications.
4. The Eastern Ghats exposed in the western and northern extremities were probably promontories during high stand of sea level and extend into the study area below the older coastal alluvium.
5. The study indicates three palaeo-strandlines of Bay of Bengal within the study area. However effort is continuing to assign the geological age of the formations and units through dating for conceptualization of evolution of these strand lines (marine marginal zones) where varied geomorphological features have been developed.
6. During 2007, this part of the coast experienced unusual frequent high tides causing extensive erosion of the beach face and inundating the earlier berms that put coastal population at panic. With a view to save the life and property of the vulnerable areas a detailed study of the present day coastal processes, offshore geomorphology, micro seismic activities in the ocean floor and climatological factors need to be studied with the aid of latest remote sensing and GIS techniques.

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