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Effects of transgression on sedimentation system vis-à-vis coastal erosion on the Chandipur coast, Odisha, India

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ABSTRACT

There has been a decade-long debate about global warming and its far-reaching effect on sea level rise. However, little attention has so far been given to the effects of transgression in sedimentation systems. The present paper deals with the effects of transgression on sedimentation dynamics of a meso - to micro - tidal coastal environment. The sediment characteristics, flow dynamics, current flow patterns giving rise to facies of the individual environments have been analysed in detail. Shallow vertical trenches excavated in different parts of the coastal area elucidated facies characteristics and shifting of facies in response to transgression. The temporal variation in facies gave rise to a facies model that can be used as an authenticated tool for interpreting similar ancient environments. The coastal erosion resulting from on-going transgression and other short-term causes has also been evaluated with the help of facies mapping for last ~15 years and modifications in geomorphic features along and across the coastline. The coastal erosion concomitant with anthropogenic interventions cause serious stress on biological inhabitants of coastal areas. Coastal conservation and management studies will help in protecting further degradation of coastal areas and also help to maintain the biodiversity and ecosystem.

KEY WORDS: Transgression, sedimentary facies, facies model, coastal erosion, biological crisis, coastal management

INTRODUCTION

Water covers around 71 % of the Earth's surface and total length of global coastlines is about 356,000 km. India is also surrounded by the Arabian Sea in the West, the Indian Ocean in the South and the Bay of Bengal in the East and the total coastline of India is about 7,517 km. The landward retreat of the shoreline caused by the forces of wave action, tidal currents along with human activities is termed 'coastal erosion'. Effects of coastal erosion can be witnessed from cliff areas, tidal flats, marshes and beaches. Seventy percent of global shorelines are retreating landward because of coastal erosion and as a result, it has become a global concern (Bird, 1985). Shifting of the shoreline is one of the most dynamic processes in the coastal zone that also has large environmental significance (Chen et. al., 2005). These shoreline changes, which occur over both long and short periods of time, involve hydrodynamic, geomorphic, tectonic and different climatic forces (Scott, 2005; Thom and Cowell, 2005). The combination of different factors of different intensities result in coastal erosion, among which sea level rise, frequency and intensity of coastal-area storms, and anthropogenic interventions are the major contributing factors. The shifting of shoreline towards the land, causing coastal erosion, is recognized as a very real threat because of global climate change and other anthropogenic activities that change the natural processes of beaches and coasts. Human populations are concentrated along coasts, and consequently coastal ecosystems are some of the most impacted and altered worldwide. Topography and morphology of the coastal area, the geological character of the coastal zones, climate, frequency and intensity of the waves and sediment supply in the coastal area also affect coastal erosion. For the last decade, sea level rise has become a well-discussed subject among the scientific community and also among government agencies because of coastal erosion. In addition, continuous and arbitrary coastal development, tourism development and destruction of coastal landforms also create different hazards along the coastal areas along with erosion.

Indian coasts are no exception in experiencing transgression, and several works point out the vulnerability of the Indian coastline. The southern coastal area of Tamil Nadu faces a severe threat due to rapid changes in geology and geomorphology along the coast, sea-level change, tropical cyclones and associated storm surges (Sheik Mujabar and Chandrasekhar, 2013). Coastal erosion at Sagar

Fig. 1: Location Map: Geographic details of the study area. Note that the River Buribalam confluences with the Bay of Bengal forming an estuary, the large barrier bar near the mouth of the river and a swamp developed behind the barrier bar.

Island of the Sundarban delta is a matter of concern, and has been subjected to erosion by natural processes and to a lesser extent by anthropogenic activities over a long period (Gopinath and Seralathan, 2005). The effects of sea level change and anthropogenic interventions resulted in serious threats to the survival of biological communities and their life modes throughout the eastern Indian coast (Sur et. al., 2006; Das et. al., 2014). The coastal zone of India is under increasing pressure due to rapid urbanization, tourism development, discharge of waste effluents, municipal sewage, over-exploitation of coastal resources and continued development in hazard prone areas (Barman et. al., 2015 b).

Despite critical concern about the detrimental effects of transgression none of the published work deals with the sedimentological aspect. The present work takes a holistic approach to determine the effects of sea level changes in sedimentation and concomitant erosion of coastline in response to sea level rise. The present study area gives an opportunity to investigate the sediment transport mechanism, grain size, sediment dispersal and (palaeo-) current pattern in different environments associated with meso- to microtidal sea coasts. The facies maps of the last 15 years have been utilized to compare the changes in geomorphic relief features and shifting of coast lines through erosion. Shallow trenches, not exceeding 2 m, have been excavated to record the temporal shift of (palaeo-) environments in response to sea level rise giving an opportunity to understand the facies model of a meso- to microtidal coastline (cf. Walker, 1984). The on-going transgression in combination with others factors resulting in coastal erosion can be determined from geomorphic alterations along and across the coastline. The resulting coastal erosion causes a severe crisis for many organisms to thrive in altered ecological niches.

STUDY AREA

The present study area is situated near the confluence of the River Buribalam with the Bay of Bengal in the eastern coast of Chandipur, Balasore district of Odissa, India representing a stretch of coastal plain of around 4 km length (Latitude: 21.4399°N, Longitude:87.0149° E) (Fig. 1). The Chandipur coast is characterized by a very low-energy environment with semi-diurnal tidal cycle of mean tidal range varying between 4.89 m (equinoctial, spring) and 1.87 m (equinoctial, neap) (Sarkar et. al., 1991), and with seasonal storm surges never exceeding 1 m (Mukherjee et. al., 1987). The micro- to mesotidal coast trends in a northeast – southwest direction and documents a wide variety of sedimentary environments within the studied stretch. The study area holds a vast, gently dipping (<2° dip) tidal flat (almost 3.8 km wide) with a narrow beach on the landward side (40 – 140 m in width) (Sarkar et al, 1991; Chakrabarti, 2005). Towards the north-eastern margin, the River Buribalam formed an estuary at the confluence with the sea (Fig. 1). The boundary between the estuary and the tidal flat is demarcated by development of a huge spit-transformed barrier bar, resulting in the formation of a calm and quiet swampy environment on the landward side (Fig. 1). The sediments are mainly supplied by the River Buribalam and get dispersed by the marine processes forming a concentration of barrier bars near the confluence; however, several minor shore-parallel bars are also dispersed along the vast tidal flat. These barrier bars eventually get merged with the aeolian dune field along the coastline, which is migrating over the tidal flat. The minor barrier bars on the tidal flat produce local swamps on the landward side which promote a patchy calm and quiet environment where mud can settle. The few tidal channels traversing the tidal flat are the conduits for river water to enter into the tidal flat and to drain from it.

METHODS AND MATERIALS

In the present work, field study received the most attention. Equipment used was mostly inexpensive including chisels, measuring tape, shovels, clinometers, Brunton compass, Abni level, camera, GPS etc. Measurement and documentation of sedimentary features have been performed, encompassing bed thickness, mudball diameter and orientation, burrow size, depth and inclination, ripples amplitude and wave length, as well as (palaeo-) current direction. Recording also focused on patterns of sedimentary structures in detail and their mutual relationships. Shallow trenches have been excavated to determine the sedimentary structures that characterized each facies, in cross section. These trenches at different parts of the coastal area allowed the construction of vertical logs for documenting the facies characteristics and temporal facies transitions. Field data were, however, analysed and interpreted mostly in the laboratory.

FACIES ANALYSIS

The facies classification of the study area is done on the basis of lithology and sedimentary structures, both on bed surfaces as well as in transverse section, with the aim to characterize each environment.

Beach Facies

The beach (Fig. 2 A) at the Chandipur study site is confined between the tidal flat and coast line with sharp contact on the seaward side and erosional contact with the aeolian dune field on the landward side, respectively. The beach in Chandipur is not a true beach, but formed at the top of large barrier bars due to erosion. The beach, which widens towards the mouth of the river Buribalam, is divisible into two sub-facies namely back-shore and fore-shore.

Fore-Shore Subfacies

This subfacies occurs on the seaward side of the beach bordering the tidal flat (Fig. 2 A). The

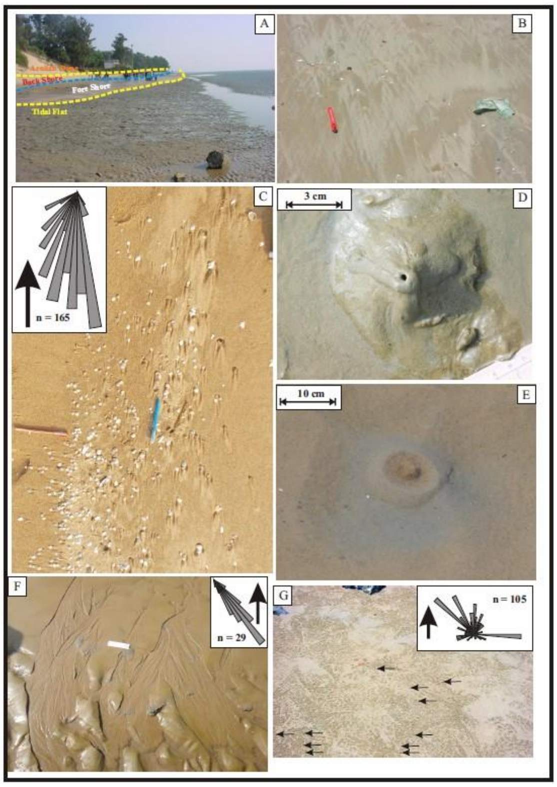

Fig. 2: Occurrence of different environmental zones (marked by dotted lines): Tidal flat on the seaward side followed by beach that is divided into Foreshore and backshore from seaward to landward side respectively and aeolian dune field further landward (A). Bed surface features within foreshore facies: rhombic ripples (B) Current crescent forming around coarser particles. Note the current directions are towards sea (C) Mud volcano (D), Sand volcano (E), Rill Marks. Note seaward current direction shown by palaeocurrent roses (F), numerous Crab Burrows. Note seaward inclination of the burrows shown by palaeocurrent roses (G).

surface morphology is generally planar, sediment is fine grained, sand sized with the occurrence of shells and shell fragments gradually increasing upslope. The sediment is highly compact and firm. The shale content is high and it is highest along the high water marks. The more or less planar surface is interrupted with minute and closely spaced ridges, recognised as current lineation and showing two divergent sets forming rhombic ripples (Fig. 2 B). There are also current crescents (Fig. 2 C) around coarser particles, oriented at high angles to the shore line and the crescents generally open in the seaward direction. The bed surface in the foreshore facies additionally contains sand and mud volcanos, rill marks and hermit crab burrows (Figs. 2 D, E, F and G). The burrows on the fore-shore are very small in diameter (1 – 2 mm) and of relatively shallow depth (4 – 5 mm) (Fig. 3 A). The burrow diameter generally increases away from the shore and the inclinations

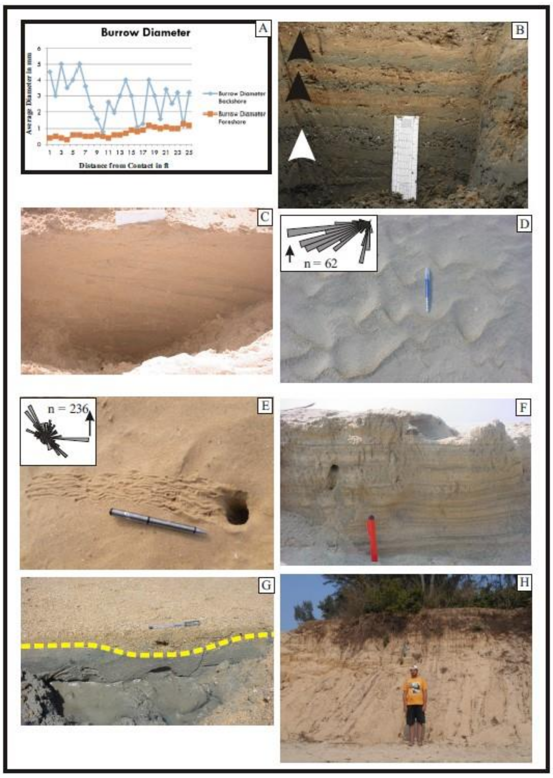

Fig. 3: Bi-variant plot showing differences in average burrow diameter against landward distance from the contact of foreshore and backshore facies. Average burrow diameter measured by constructing grids (1m × 1m), average of 4 to 5 grids for each reference point. Note that the average diameter is higher for backshore compared to foreshore. Also note that the average diameter gradually increases and decreases with distance for foreshore and backshore respectively (A) Shallow trench within foreshore showing vertical lithological constituents: alternations of planar laminated silt-mud and fine sand layer with frequent shell-hash layers (marked by arrows) (B) Low angle cross sets where set boundaries are defined by heavy minerals dipping seaward (C) Bed surface feature within backshore facies: Aeolian ripples. Note the current direction, shown by palaeocurrent roses, and coarse grain concentration along the crests of the ripples. Pen length 14 cm (D) Large crab burrow with trails. Note the variable inclination angle of the borrows but mostly directed landward (E). Shallow trenches within backshore showing vertical lithological constituents: Coarse grained, massive sand alternating with heavy mineral layers (F) Backshore coarse massive sand underlain by thick mud layers of palaeoswamp (G) Aeolian dune field. Note the sharp seaward cliff due to erosion (H).

are generally seawards (Figs. 2 G and 3 A). Besides the burrows there are numerous trails of gastropods, however despite their abundance, the preservation potential of these surface traces is thought to be minimal. In the upper part of the fore-shore there are shore parallel swash ripples, characterized by very low amplitude but very wide wave length.

In cross-section, the sediment is characterized by alternations of mm-thick planar laminae or low angle cross strata of light coloured fine sand and dark coloured heavy minerals with frequent occurrence of shell-hash layers (Fig. 3 B and 3 C). The low angle sets of cross strata are separated by low angle erosional surfaces giving rise to multiple sets dipping seawards. The laminations are often interrupted by the minute near-vertical burrows. This facies is underlain either by coarse sandstone of barrier bar or beach affinity, or by mud of palaeoswamp deposits (Fig. 3 B).

Backshore Subfacies

The backshore subfacies occurs on the landward side of the foreshore facies (Fig. 2 A). Backshore sand is coarser with respect to the foreshore sand, coarsens further towards the berm. The sand is fluffy in nature due to being dry and frequently reactivated by wind. Aeolian ripples (Fig. 3 D) especially aerodynamic ripples are present abundantly in its upper part, characterized by strong asymmetry, high wave length (4 – 5 cm) and low amplitude (0.5 – 1. 5 mm). The migration direction is landward, despite wide variability (Fig. 3 D). Shells are scarce and their sizes are larger than their foreshore counterparts. The burrows are relatively fewer in concentration and larger in size relative to foreshore equivalents (Fig. 3 E). The burrow concentration generally decreases away from the shore and the burrows show a preferred landward inclination (Figs. 3 A and E); the degree of inclination is about 60^0 – $75\ ^0$. Animal trails are infrequent except for a few crab trails.

In profile the backshore coarse grained sand particles are structurally massive, occasionally planar laminated and then dipping landward, with rare occurrence of shell-hash layers and/or heavy mineral layers (Fig. 3 F and G). The backshore sediments in cross section are underlain by thick mud layers of palaeoswamp deposits (Fig. 3 G).

Aeolian facies

This facies occurs on the landward side of the backshore (Fig. 3 H). This facies is characterized by fine grained, well sorted, well rounded sand. Abundant primary sedimentary structures observed on bed surfaces include adhesion ripples (Fig. 4 A), setulfs (Fig. 4 B) and aerodynamic ripples (Fig. 3 D), as well as dunes with ripple index generally > 20.

The setulfs are positive relief structures, diametrically opposite to flutes, spatulate in form with one end pointed and steep and flaring on the other end (Fig. 4 B; Sarkar et al., 2011). The flaring end represents the current direction and closely matches with the inferred airflow direction as they formed by aeolian processes (Fig. 4 B).

In cross section this facies is characterized by translatent strata and grain-flow and grain-fall cross strata (Fig. 4 C).

very low amplitude bar and inter–bar areas. Some active swamps are developed locally on the landward side of the bars providing low energy areas for deposition of mud. The ubiquitous occurrence of ripples of different forms, dimensions and orientations on the bed surfaces characterizes the facies (Fig. 4 D). Different varieties of ripples, like interference ripples, superimposed and ladder ripples are common (Figs. 4 H and I). Both straight and curved crested ripples are present, some are double crested. Both current and wave ripples, with bifurcation of crests, are observed.

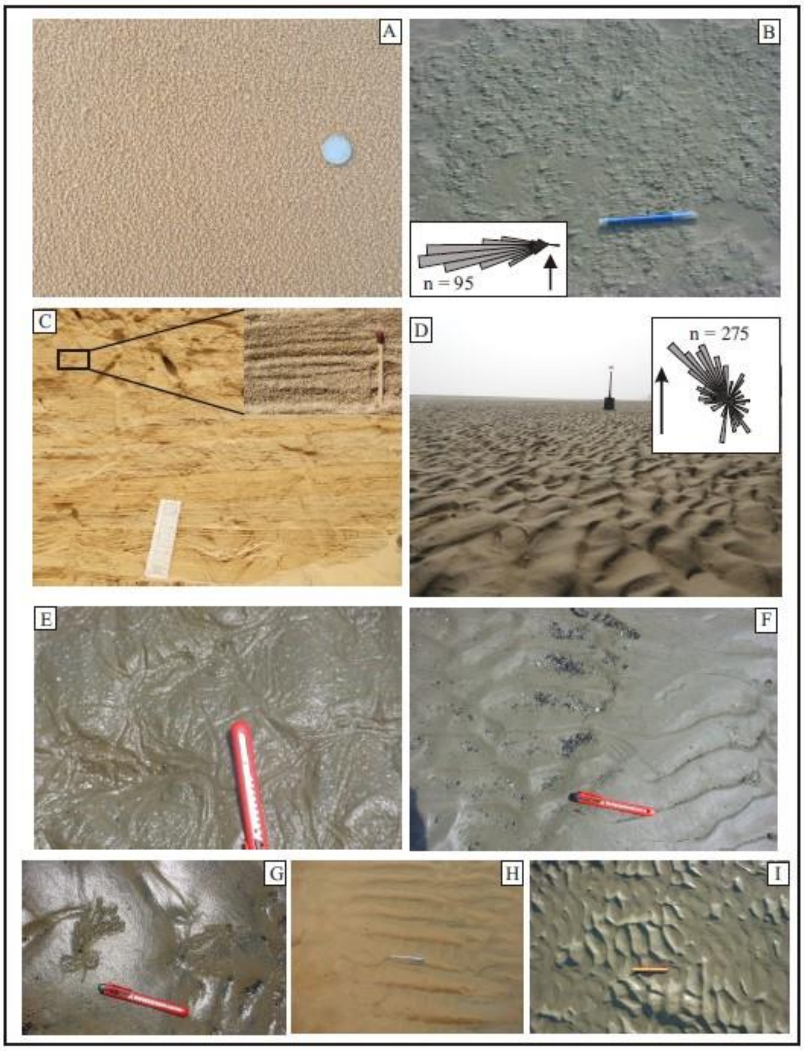

Fig. 4: Bed surface features within backshore facies: Adhesion ripples on wet surface (A) Setulfs. Note the current direction matches with the airflow direction (B) Vertical section of an aeolian dune: Translatent strata and grain- flow - fall cross strata. Note the reverse grading within the grain flow –fall strata showing within inset. Match-stick length 2.5 cm (C) Bed surface features within tidal flat: Occurrence of profuse ripples. Note the diverse current direction represented by palaeocurrent roses (D) Numerous trails of gastropods. Knife length 12 cm (E) Polychaete burrows (F) Crab burrows (G) Ladder ripples (H) interference ripples (I).

Tidal Flat Facies

The tidal flat facies occurs on the seaward side of the beach and away from the river mouth, and covers most of the study area (Fig. 2 A). The tidal flat sediments are marked by ripples on the bed surfaces and get nearly completely exposed twice daily; however, a thin film of water remains on the bed surfaces, even during the ebb. This flat has a gradient lower than that of the foreshore and as a result a distinct slope break occurs at the boundary with the beach (Fig. 2 A). This flat surface however bears very broad undulations, representing a set of

Numerous trails of gastropods, bi-valves and a large variety of worms occur in crisscross pattern on the sediment surface (Fig. 4 E). Burrows of relatively small diameter are also present in medium frequency. The burrows include polychaetas (Fig. 4 F), which preferably occur towards the outer part of the flat and concentrate near the tidal channels traversing the tidal flat. The crab burrows are relatively common on the landward side (Fig. 4 G).

In cross section the tidal flat sediment is characterized by alternations of silt and mud laminae with lenses of sand and shell-hash (Fig. 5 A). Most of these layers with different lithologies are massive with rare occurrence of planar laminae within the sand lenses (Fig. 5 A). The facies is underlain by coarse sand of barrier bar or backshore affinity, fine sand and silt layers of foreshore genesis, or mud deposits of palaeoswamp deposits (Fig. 5 A).

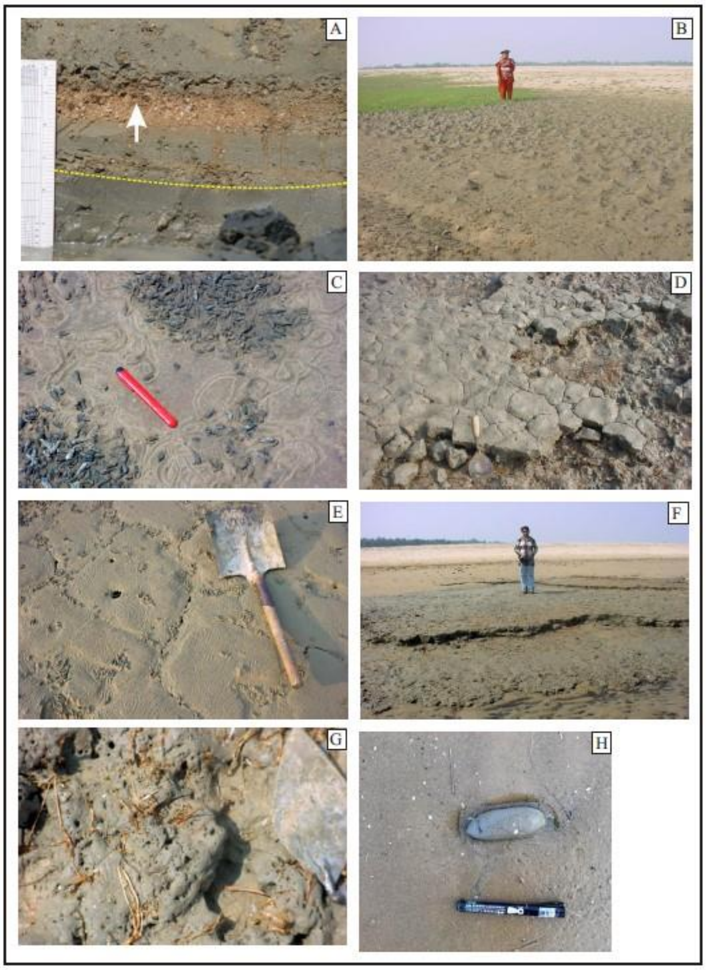

Fig. 5: Shallow trench showing vertical lithological constituents within tidal flat: alternations of find sand-silt with mud layers with infrequent occurrence of sand lenses (arrow). Note that the tidal flat sediments underlain by palaeoswamp mud (demarcated by dotted line) (A) Active swamp deposits: numerous *Ophiomorpha* burrows with vegetable (B) Occurrence of *Cerithium* sp and *Telescopium sp.* with their trails (C) Desiccation cracks (D) Desiccation cracks draped by sandy layers thereby filling the cracks (E) Exhumation of palaeoswamp in front of barrier bar due to erosion (F) Occurrence of numerous rootlets within the palaeoswamp (G) Elongated mudballs, transported and mostly concentrated near the contact of beach and barrier bar. Note that their long axis oriented parallel to the shoreline (marked by the marker pen) (H).

Barrier Bar facies

The barrier bars occur on the landward side of the tidal flat, the largest one situated on the northeastern side of the study area near the river mouth encircling the swamp area (Fig. 2 A). However, some smaller bars are also present within the tidal flat itself, with low relief. The largest bar in the study area, representing the maximum recorded height up to ~ 2 m, above the tidal flat surface, has a length of one and half kilometres. The bars have more or less straight or broadly sinuous crests with their lee sides oriented in the landward direction. The largest bar has already merged with the shoreline, passing laterally into the beach and aeolian dune field. Most of the smaller bars in the tidal flat region have either been eroded away or have the tendency to migrate landward. The top of the bars with higher elevations often interact with aeolian activity and numerous aeolian features, such as aeolian ripples, setulfs and adhesion ripples are frequently present on them (Figs. 3 D, 4 A and 4 B).

Swamp facies

The swamp facies comprises both active swamps, occurring on the landward side of the barrier bar or beach facies, and palaeoswamps. The former swamp facies is dominated by thick mud deposits with black to grey colour with vegetation and abundant *Ophiomorpha* burrows (Fig. 5 B). Numerous *Cerithium* sp. and *Telescopium sp.* and their trails are present on the bed surfaces (Fig. 5 C). Desiccation cracks (Fig. 5 D) are often found, sometimes filled by coarser sand (Fig. 5 E). The palaeoswamps are found as patches within the tidal flat or even on the beach (Fig. 5 F). These older deposits represent pre-existing swamps which were buried due to facies shifting landward, and then became re-exposed during later erosion by waves and tides (Fig. 5 F). The characteristics of the sediments are similar to those of the active swamps where the occurrence of earlier vegetation is represented by rootlets (Fig. 5 G). The palaeoswamp muds are more thixotropic because of dewatering during burial and frequently produce mudballs that are abundantly present immediately adjacent to the palaeoswamp deposits. These mudballs were later transported to other parts of the study area, being concentrated mostly near the beach and barrier bars (Fig. 5 H).

EVIDENCE OF COASTAL EROSION

Comparison of facies maps

Facies maps of the coastal area of Chandipur have been prepared each year for the last

15 years to document the temporal variations within this short time interval. Three maps, from 2003, 2005 and 2018 are presented here to manifest the differences in physiographic features and coast line shifting. The maps clearly show that the coast line has gradually moved landwards (Figs. 6 A, 6 B and 6 C). The facies belts move in the landward direction, eroding the beach area and reducing the width with concomitant increase in the tidal flat area (Figs. 6 A, B and C). The bars within the tidal flat have either been eroded away or migrated landward to merge with the present coastline (Fig. 6 B). The largest bar of the study area has been gradually moving landward, even migrating over the present active swamp and exposing palaeoswamp deposits on the seaward side (Fig. 6 C). The erosional effects of transgression are clearly visible from the patchy exhumation of palaeoswamps in different parts of the present beach and tidal flat facies belts (Fig. 5 F).

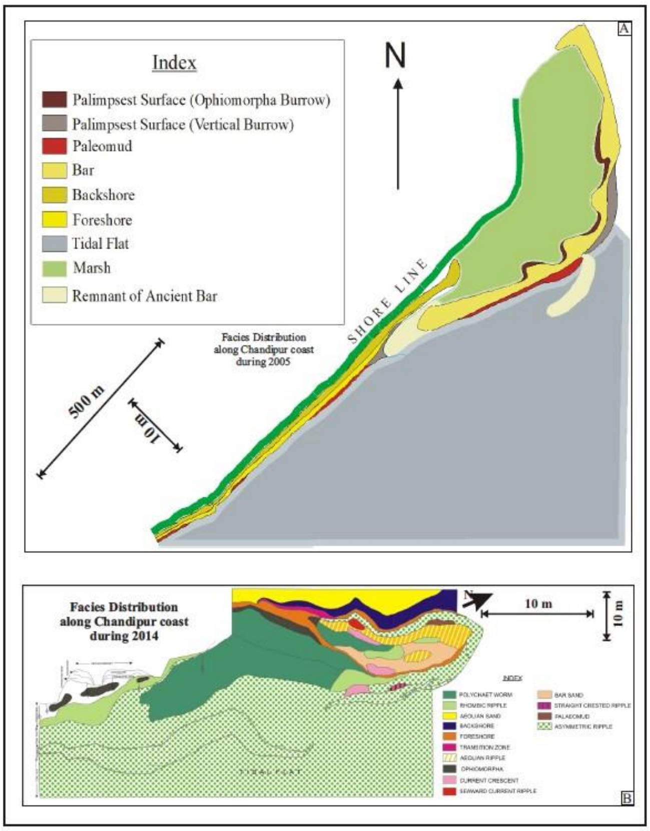

Fig. 6: Facies maps of the study area: 2005 (A), 2014 (B) and 2018 (C). Note the differences of geomorphic features through time: Destruction and re-appearance of smaller bars within the tidal flat, migration of smaller bars landward over the tidal flat thereby exhumation of palaeoswamp as patches within the tidal flat. Gradual increase in width of tidal flat. Gradual shifting of large barrier bar landward thereby exhumation of palaeoswamp in front of the large barrier bar. Gradual decrease in width of beach and shifting landwards (A) Relict bar at the study area depicting coastal erosion.

Physiographic Evidence

Relict Bar

The top of this bar eroded away due to ongoing transgression and a beach developed on this wave-cut bar top (Figs. 6 A, 6 B, 6 C and 6 C). The litho-succession shows large scale tabular cross strata in which alternate sand-mud laminae represent tidal bundles. Uncommon shell-hash and heavy mineral layers are also present within the transverse section. The tabular cross strata are overlain by fine sand/silt and shell-hash alternations repressing deposition within the foreshore environment, suggesting the shifting of the beach and thus of the shoreline.

Drowned River Channel

The old channel of the Buribalam River still exists within the intertidal flat and provides the main sea way for fishermen who use the flood–tide to get out to sea (Fig. 7 A). From the river–mouth the channel sweeps southwestward and runs obliquely across the intertidal flat and eventually becomes drowned below the eroding coastal deposits. This drowned river channel provides most conspicuous evidence of transgression.

Exhumation of Palaeoswamp

As already mentioned, due to ongoing transgression, the present swamp on the landward part of the aeolian dune-field may not be in equilibrium with the present marine system at Chandipur. The more interesting feature in the study area is the patchy exhumation of older swamp (Fig. 5 F) across the boundary between the present beach and tidal flat, and in all other areas of the tidal flat. Abundant *Ophiomorpha* burrows (Fig. 5 B) are concentrated on the surface of the palaeoswamp. In vertical section numerous plant roots and burrows characterize the litho-units of the palaeoswamp. The sticky mud gets desiccated, thereby losing its cohesion, and is then eroded during strong tidal and wave surges generating mud-clasts. These clasts are mostly elliptical and have various dimensions. The orientations of these mud-clasts are found to be diverse but long axes are oriented preferably parallel to the shore-line (Fig. 5 H). The mud-clasts are mostly armoured with shell fragments, indicating their transportation by rolling as bed-load sediments.

Wave Cut Dunes

The berm at the landward extremity of the beach at Chandipur is erosional and is represented by the steep wave cut face on the seaward side (Fig. 3 H). It is apparent that the existing dune field is in no way in equilibrium with the contemporary marine system. Ongoing transgression has washed off the sandy soil concomitant with uprooting of big trees (Fig. 7 B).

All this evidence clearly suggests that the coast line is retreating landward due to transgression. However, extreme waves formed during high-tide conditions, may also have caused wave cut dunes.

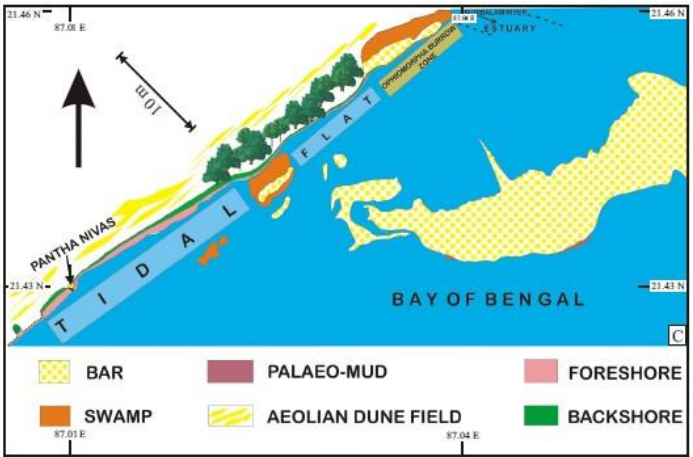

Fig. 6

Fig. 7: Note the occurrence of numerous ripples on top of the bar indicating reworking of the bar top by waves and currents (A) Relict occurrence of earlier river channel within the intertidal flat now drowned under the sea (B) Washed off the sandy soil causing uprooting of big trees (C).

CAUSES OF COASTAL EROSION AT CHANDIPUR

Although coastal erosion is a natural phenomenon, resulting from the interactions between different types of natural processes and different geomorphological systems, anthropogenic interventions sometimes inhibit these processes and change the patterns of erosion and accretion. Coastal erosion caused by natural and / or anthropogenic processes alter the sediment itself, both sources and sinks of the beach sediment budget or the processes that influence the sediment budget. Notwithstanding that transgression is the key factor causing coastal erosion at Chandipur. However, there are other factors that probably influenced the process of coastal erosion including *waves, winds, tides, tsunami of 2004* and *Nisha cyclone of 2008* and because of these natural phenomena, the sediments are deposited on the seabed, aeolian erosion, cliff undercutting and the extensive damage of the coastal region took place, respectively.

Storms:

The entire coastline of Odisha is highly vulnerable to periodic and frequent cyclones and storms especially during monsoon time (Chittibabu et. al., 2004; Mohanty et. al., 2004; Sundar et. al, 2007). These tropical monsoons and cyclonic depressions, invariably after origination in the Bay of Bengal, are associated with heavy precipitation and frequent flooding. Normally the storm surges of around 6 to 7 m height may go up to 10 – 12 m depending on the severity of cyclones the (Mohanty et. al., 2004) and storms can be simple storms, severe storms, cyclones or severe cyclones depending on speed of wind. In the October, 1999, a super cyclone, accompanied by heavy rainfall and flooding hit the coast of Odisha that lasted for a week and caused extensive damage to the coastal infrastructures, beaches and dune field of Chandipur.

Anthropogenic Causes:

Chandipur coast is also affected by human influence, particularly through urbanisation and economic activities in the coastal zone. Along with different natural phenomena as mentioned above, the activities of mankind have increased the risk of coastal erosion on the Chandipur coast. Coastal tourisms and coastal resources have changed the socio-economic conditions of the local communities of Chandipur and adjoining areas throughout the Odisha Coast. But this mass tourism on the Chandipur coast is producing sewage and solid waste pollution, and causing deforestation, coastal erosion and sedimentation from construction activities (Biswas, 2014). Moreover, the conditions of the beach area along the Chandipur coast are degrading at a faster rate because of the tourism industry, depending upon the increasing number of tourists, the increased rate of growth of the tourism industry, improper planning and lack of controls (Gossling, 2003; McLaren, 2003; Neto, 2003). Physical changes like tourism-related hotels, resorts, shops, roads and other infrastructures like dredging of tidal entrances, construction of fisheries, construction of jetties, hardening of shorelines with seawalls or revetments, destruction of mangroves and other natural buffers, poor coastal zone management, over-exploitation of marine resources & biota are also widespread. Thus, factors such as human activities, increased storminess, the change in angle of wave approach, reduction in sediment supply to the beach systems together play a significant role in inducing coastal erosion (Nair et. al., 2018).

Only 8 % of Earth's habitable terrestrial surface is occupied by the coastal zone of the world and, as of 1994, this coastal zone accommodates about 37 % of the World's population within 100 km and 44 % within 150 km of a coastline (Cohen et al., 1997). As these coastal zones contribute one-fifth of total global primary production and enjoy rich natural resources, they are becoming highly populated (Mohanty et. al., 2008). Therefore, the ecosystems of these coastal zones are experiencing tremendous pressure.

The environment first began to change from anthropogenic activities when human societies changed their role from hunter-gatherer communities for sustaining life, and started to settle in one place as agriculture developed. Due to a rich abundance of food and water, particularly in the shallow estuaries and seas, mankind commonly started settlements near coastal zones. At the very beginning of human settlements in these coastal zones, they had little impact on the natural development of those coastal areas. Moreover, they had to accept sea level changes, tidal movement and storms as the cost of living there in coastal zones (Doddy, 2001). Now due to rapid urbanization, coastal tourism, discharge of waste materials into sea or ocean, sewage discharge through rivers, over-exploitation of marine resources and infrastructural development within these hazard prone areas, the coastal areas of India are under increasing environmental pressure, like rest of the World too. The coastal zones of India also suffer from over-population. Different types of natural hazards such as cyclones, floods, tidal waves etc. along with on-going transgression are responsible for coastal as well as environmental changes along the Chandipur coastal area. The Chandipur coastal zone is very vulnerable to cyclones, storms and floods; these events cause considerable damage to life and property as well. There were 72 and 56 flood associated cyclones in the nineteenth century and in the twentieth century, respectively, along the Odisha coast (Dube et al., 2002). As a result, there were rapid changes of the marine environment along the Chandipur coast.

The Chandipur area is over populated by poor people, mainly fishermen. For this growing population, housing construction, both legal and illegal, is increasing day by day. Some of this construction is well within the coastal zone, violating coastal zone management (CZM). As a result, the interplay of natural factors is facing an additional problem which is changing the geomorphology of the coastal zone. Moreover, excess land use and increased pressure of population on limited energy and freshwater resources of Chandipur are damaging the coastal ecosystems due to deforestation, erosion, disruption of ecology & biological diversity, pollution and waste generation (UNWTO-1994). Due to the increasing number of fishermen, over exploitation of natural resources is taking place which directly affects the biodiversity of the region and thus damages the ecological balance. Due to this rampant fishing, there is a fish market along with another, accessory materials market at Balaramgadi, near the mouth of Buribalam estuary (Fig. 1). To accommodate the huge number of fishermen, there is also a boat industry at Balaramgadi near the estuary of Buribalam river. Both these industries are degrading the ecological balance of the Chandipur coastal area. This is also accelerating the landscape change of the area. Another alarming fact due to excess fishing, is that sometimes the Olive Ridley sea turtle (*Lepidochelys olivacea*), an endangered species which is especially known for its mass nesting, come to the beach and then fishing nets, the local people as well as fishermen do not allow them to go back to sea again. As a result, the population of this beautiful species is decreasing day by day.

There is no doubt that the "Tourism Sector" builds up much more job opportunities in comparison to any other sector in respect of investment (Barman et al., 2015 a). Chandipur is also not an exception. The Chandipur beach is wide, golden and calm. The sea water advances towards the shore as much as 5 km at the time of high tide and retreats by the same during the low tidal ebb. There is huge scope for tourism and its expansion because of the location of Chandipur along the eastern coastal area of India and the significant cultural heritage of Odisha. Because of vast diversity in both fauna and flora, the history of the area, its location and local culture, tourists from both India and foreign countries are increasing in Chandipur and adjoining areas of Odisha.

Due to the overpopulation along the coastal area and overcrowded tourists along the coastal zone of Chandipur, coastal landscapes are changing rapidly. Because of lack of knowledge, most of the time, these tourists are degrading the sand dunes, biking over the beach areas. As a result, these zones are becoming vulnerable during high tides or storms and thus rapid shifting is taking place among the different facies / zones of the coastal area (Fig. 6). Moreover, due to the increase in the tourism industry of Chandipur, number of hotels and associated business increased significantly over the time. As a result, hoteliers are building constructions which violate Coastal Zone Management Laws and Policies of the Government. Apart from this, these hotels are disposing off their waste materials along with sewage materials directly into the sea, polluting the regions. Also, they are building illegal retaining walls to protect their premises causing the tidal flat area to overlap the beach area, reducing the width of the beach day by day in Chandipur (Fig. 6).

According to Erwin (1982), there are over 30 million living species in the universe but taxonomically we know only less than 2 million species among them. We are forcing the Earth's faunas and floras into another neo-mass extinction by fishing, indiscriminate killing, destruction of habitat, food harvesting etc. (Simberloff, 1986). As a result, by doing so, human beings will be the one and only architect of their own demise (Ehrlich, 1986). This situation demands much concern since a vast majority of living species will go extinct silently before being identified, classified and studied.

There was an abundance of Horseshoe crabs (*Tachypleus gigas*), the blood of which has commercial and medical applications, at Balaramgadi, a small fishing village near the sea at Chandipur. But now dead crabs are commonly found along the beach. This is due to overcrowded, unaware tourists and their leisure activities along the beach. There was also an abundance of red crabs all along the wide, long beach of Chandipur during 2004-2005, now they are scant in occurrence, and are now restricted within the shore zone only.

Molluscs all over the world, like-wise most of the intertidal taxa, are threatened due to alteration of habitat and over-exploitation by man (Branch & Moreno, 1994; Lindberg, 1998; Roy et al., 2003). Molluscs contribute about 4-5% of the total annual Indian fishery production (Appukuttan, 1996). The Indian coastline is very rich in living resources. But, due to anthropogenic impact, the living resources are deteriorating at an alarming rate. Shells of molluscs are used for food, shell-craft and for other industrial purposes. Due to fishering boat construction, tourism, coastal population growth, shrinkage of wetland is causing drastic reduction of the population sizes of molluscs and sometimes even excluding them from their type localities (Subba Rao, 1998 and Bhattacharya and Sarkar, 2003). Trampling and removing of dead shells which act as microhabitats of other organisms also affects the biodiversity of coastal areas (Roy et al., 2003). In India, shells of bivalves are collected by netting and by handpicking from tidal flat areas (Bhattacharya and Sarkar, 2003). These shells are used for preparation of edible lime, poultry feed and shell crafts (Bhattacharya and Sarkar, 2003). Due to over-exploitation of shells in and around the coastal areas, immediate action must be taken as bivalves act as "ecosystem engineers" (Jones et al., 1994). Because they "modify" and "create" habitats and as they are highly sensitive to environmental change, they are good indicators of environmental degradation (Bhattacharya and Sarkar, 2003).

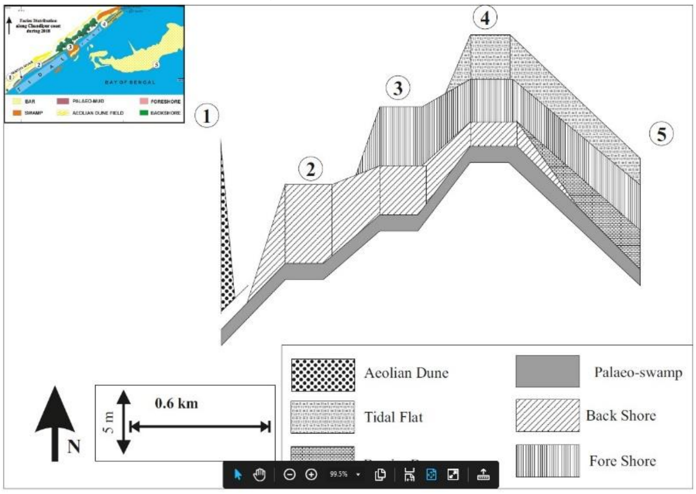

Fig. 8: The fence diagram is reconstructed from litho-successions of different locations within the study area, correlating the litho-successions, using palaeoswamp as reference surface. The log locations are shown (within inset) in facies map of 2018. Note the shifting of facies belts through time.

In response to these crises and to overcome these coastal problems, India, like other developed and developing countries of the world, implemented some rules, regulations and management laws. For this purpose, these countries, along with India, have developed Integrated Coastal Zone Management (ICZM) or Integrated Coastal Management (ICM) (Clark, 1991; Mohanty et. al., 2008) policies and practices to address these growing problems.

DISCUSSION

The coastal environment, generally, is a complex and dynamic system as it represents the interfaces of land, sea and air. It is continuously undergoing both gradual and sudden changes with many physical processes being active, such as tidal flooding, sea level rise, land subsidence, volcanic activity and erosion – sedimentation (Maiti and Bhattacharya, 2009). The coastal area of Chandipur represents an active, transgressing meso- to micro-tidal coast. The present study gives an opportunity to investigate the sediment grain size, sediment dispersion, flow dynamics and resulting primary sedimentary structures and facies composition in different environments of a meso- to micro-tidal coast. The vertical transition of facies clearly suggests shifting of facies belts landward concomitant with coastal erosion. The ongoing transgression results in shifting of facies landward, giving rise to a facies model that can be considered as a verified model for the said environment (Fig. 8). The sediment characters have a key role during shifting of facies. The sandy facies move landward more frequently in response to tidal current while the muddy facies do not because of their inherent cohesion. The sandy bars are migrating over the swamp, formed immediately behind (i.e. landward of) the bars, which makes the swampy mud more cohesive and more thixotropic. These swampy muds are later exhumed during subsequent strong current events and storms giving rise to patchy occurrence of palaeoswamp in different parts of the facies belts, particularly near the beach and barrier bar. It is found that at Sagar Island, which is laterally adjacent to the study area, the western part of the beach is sandy whereas the eastern part is silty to clayey, as a result of accretion in the western part and erosion along the eastern part (Purkait, 2009). However, in Chandipur, the beach is grossly sandy and erosion is taking place all through the beach and the sands are mostly dumped near the confluence of the River Buribalam. The aeolian dune fields are gradually being eroded and retreating giving rise to shrinking of the beach area and expansion of the tidal flat. In the adjacent Sagar Island, the coastal dune fields have retreated 20 m since 1985 (Purkait, 2009). Field measurements also suggest that the island's beach on the eastern part has been lowered by about 2 m since 1985 and that the beach area of the western part has been raised about 2 m since 1995 (Purkait, 2009). Like the present study area, Sagar Island is also suffering from frequent bank-failures, flooding, erosion of beach, siltation at jetties and navigational channels, and cyclones, together resulting in Sagar Island becoming increasingly vulnerable (Purkait, 2009). On the Udupi coast, a sandy beach in Karnataka along the west coast of India, the beach is affected by the accelerated sea level rise due to its low topography, and also as a result of the high ecological and tourist value. The Udupi beach eroded about 0.60 square km per year during 2005 – 2006 (Dwarakish et. al., 2009). The coastal zones of the Cuddalore, Pondicherry and Villupuram districts of Tamil Nadu along the southeast coast of India are experiencing threats from many disasters, such as storms, cyclones, floods, tsunamis and coastal erosion (Mahendra et. al., 2011). The 56 km long coastal line of Chennai, Tamil Nadu on the southeast coast of India includes tourist resorts, ports, hotels, fishing villages and towns. This coastline also experienced threats from storms, cyclones, floods, tsunamis, sea level rise and erosion (Kumar and Kunte, 2012). The Kalpakkam beach of Tamil Nadu, south-east coast of India, records a sand sheet deposit of the 2004-tsunami that begins at 25 m from the shore and extends up to 420 m in a landward direction (Srinivasalu et. al., 2007). The coastal areas are also sensitive to many hazards and risks, from floods to disease epidemics (Adger et. al., 2005). The coastal region along the east coast of India is a thickly populated belt and exposed to high risk and vulnerability from natural hazards such as tropical cyclones (Sahoo and Bhaskaran, 2018). The frequent tropical cyclones, developed over the Bay of Bengal are much more common than those of the Arabian Sea region. As a result, risk factors associated with storm surge, inland inundation, wind gusts, intense rainfall are always high on the east coast of India. The effects of anthropogenic intervention severely affect the invertebrate coastal inhabitants particularly the Mollusca. The shallow infaunal habitat of *Meretrix meretrix* makes them vulnerable to human exploitation (Sur et. al., 2006). The confamilial predation rates in the Chandipur area are very high and the predators are very efficient as is evident from high drilling frequencies (Das et. al., 2014). High drilling frequency on the species *Natica gualteriana* are attributed to its new arrival in the present study area where it is facing competitive elimination by sympatric naticid predators (Das et. al., 2014). The transgression results in changes in physicochemical environment that trigger severe stress on invertebrate populations pose a serious threat to their existence even with the potential to lead to extinction.

Over the last 100 years the average global sea level has been rising due to an increasing rate of global warming, resulting in shifting of coastlines landward, causing transgression. The rate of annual sea level rise is expected to be two to five times more than that of the present rate within the next 100 years (Cai et. al., 2009). Two-thirds of the world's major cities, containing about 60% of the total population with higher levels of economic development, are located in coastal zones (Chen and Chen, 2002). For example, more than 85 % of Australians live within 50 km of the coastline. According to Miller and Dauglas (2004) sea level is rising globally by 1.5 to 2 mm per year; since 1993, however, Church and White (2006) opined that it is increasing at the rate of 3 mm per year, that may lead to the global sea level rise of about 60 cm by 2100 (Solomon et. al., 2007). For socio-economic developments in coastal cities of China, erosion has become a major concern. The shoreline of the different low-lying areas of the Shandong Peninsula is retreating day by day (Zhuang, 1989). However, if global warming continues to increase and ice melts then it could rise up to 1 m by the end of the twenty first century (Pfeffer et. al., 2008). The sea level rise in association with the storms and flooding of coastal-areas results in coastal areas becoming more vulnerable to erosion. The coastal area is retreating 300 m per year at the Luanhe River mouth (Qian, 1994). Transgression and coastal erosion seem to be global phenomena, shorelines of about 70% of the sandy beaches around the world are retreating towards land (Bird, 1985). About 86 % of the barrier beaches of the east coast of the USA are witnessing coastal erosion for the last 100 years (Zhang et. al., 2004). Erosion is also seen in California (Moore et. al., 1999) as well as in the Gulf of Mexico (Morton and McKenna, 1999). In Southern California diminished river flow during droughts resulted in beach erosion, but the beaches were restored during intervening wet years when the fluvial sediment supply revived (Orme, 1985). Since the 1960s, intense urbanization encompassing the building of a sea wall, road and several high-rise buildings has been started on Balneario Camboriu Beach in southern Brazil. This urbanization reduced the amount of sediment exchange between beach and aeolian dune fields, resulting in coastal erosion during storms and the beach has become reduced in width (Temme et. al., 1997). Coastal management studies, involving planning and development of the coastal zone, zonation of hazardous areas, determination of coastal erosion, regional sediment budget estimations, and the study of shoreline position, is essential in order to mitigate coastal erosion and resulting distresses (cf. Sherman and Bauer, 1993; Zuzek et. al., 2003).

CZM programmes have been developed in different countries in response to their crises (Clark, 1991). Along the coastal area of Odisha, tropical cyclones are the most dangerous natural hazard and responsible for loss of life and property. So the Odisha State Disaster Mitigation Authority has been constituted by the Odisha government, which is dedicated to construction of shelters during cyclones, and in ensuring roads and communication facilities can be used during natural disasters along the coastal belt of Odisha in cooperation with other government and nongovernment bodies at national and international levels. Moreover, existing conservation rules and management practices are not sufficient to protect the vast coastline and coastal resources of Odisha (Dash & Kar, 1990; Pandav et al., 1998; Untawale, 1993).

A lack of cooperation in the sum of activities among the different departments may create problems regarding the effective conservation of coastal resources. Therefore, it is necessary to construct a coastal zone management authority with well-defined coastal zone management programmes. Moreover, any comprehensive, integrated and sustainable CZM programme should embrace components like conservation and restoration of mangroves, beach replenishment, protection and development of sand dunes, afforestation, catchment area management plans, and effective communications (Mohanty et. al., 2008).

CONCLUSIONS

The present study area offers an opportunity to determine the sedimentation dynamics, sediment dispersal pattern and facies compositions of a meso- to micro-tidal modern coastal environment. The on-going dynamics result in facies transitions and shifting of facies belts, giving rise to a facies model that can be used as a reference for future investigation of similar ancient environments. Transgression along with other factors leading to coastal erosion have been studied with the help of facies mapping carried out for the last 15 years and documentation of changes in geomorphic features along and across the coastline. The combined effects of transgression and other natural phenomena, anthropogenic interventions also contribute to coastal erosion and resulting environmental stresses which cause a severe threat for many thriving coastal communities including those of human beings. Coastal management and conservation rules need to be reinforced and implemented properly in order to save the ecosystem and life.

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CONFLICT OF INTERESTS:

The authors declare no conflict of interest.

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