Tidal shelf sedimentation in the Neoproterozoic Chattisgarh succession of central India

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The Neoproterozoic Kansapathar Sandstone of the Chattisgarh basin, a shallow marine shelf bar sequence, consists of mineralogically and texturally mature sandstones with subordinate siltstones, mudstones and conglomerates. The sediments were transported, reworked and deposited in subtidal environments by strong tidal currents of macrotidal regime as well as storms, and accumulated as discrete shoaling-upward features, separated from each other by muddy to low-energy sandy deposits. The sandbodies developed into shoaling up linear bars, often more than a kilometre in length, through accretion of thick cross-stratified units in transverse directions under the influence of ebb and flood tidal currents, as well as in longitudinal direction affected by southeasterly flowing along-shore currents. The aggrading upper surfaces of the bars experienced protracted reworking by strong oscillatory wave currents leading to extensive development of subaqueous 2D or 3D dunes mantled with lag pebble deposits at different points. With continued shoaling and progradation, the bars amalgamated into large sandstone sheets with the development of high energy beach deposits and coastal sand flats in the uppermost part of the sequence. The presence of rill marks, flat-topped ripples, wrinkle marks, desiccation cracks and adhesion warts point to intertidal conditions with intermittent exposure. The high energy sandstone bars overlie a thick mudstone-dominated shelf sequence across a sharp interface indicating rapid change in the sea-level, provenance, rate of sediment generation and sediment input, and circulation condition in the shelf. A quiet muddy shelf was replaced by a major sand-depositing environment with strong, open marine circulation. An interplay of tidal currents, oscillatory wave currents and storm currents generated a complex flow pattern that varied in time and space from bimodal–bipolar to strongly unimodal flows. Close parallelism of wave ripple crests, trend of linear bars and unidirectional flows suggest that the elongate bars were parallel to sub-parallel to the coastline, and were strongly influenced by along shore drift. The inferred coastline was broadly N–S. The large-scale structures in the bar sandstones, emplacement of vast amount of sand and migration of large bedforms under strong macrotidal currents collectively indicate that the Kansapathar shelf was intimately connected with an open ocean basin towards north–northwest.

1. Introduction

Shallow marine shelves are repositories of thick sedimentary sequences that are characterized by highly variable facies, complex organization of facies associations and stratigraphic architecture. The complexity is generated by a combination of tidal and storm processes, and fluctuation of sea level. Shelves still appear to be one of the least understood of all sedimentary environments in terms of sediment transport mechanism and depositional processes. Recent studies of modern shelves as well as of many rock records indicate that facies organization and dynamic stratigraphy of shelf deposits are much more variable and complex than was realized before. Analysis of Proterozoic shelf

Keywords. Neoproterozoic; Kansapathar Sandstone; shelf sedimentation; macrotidal.

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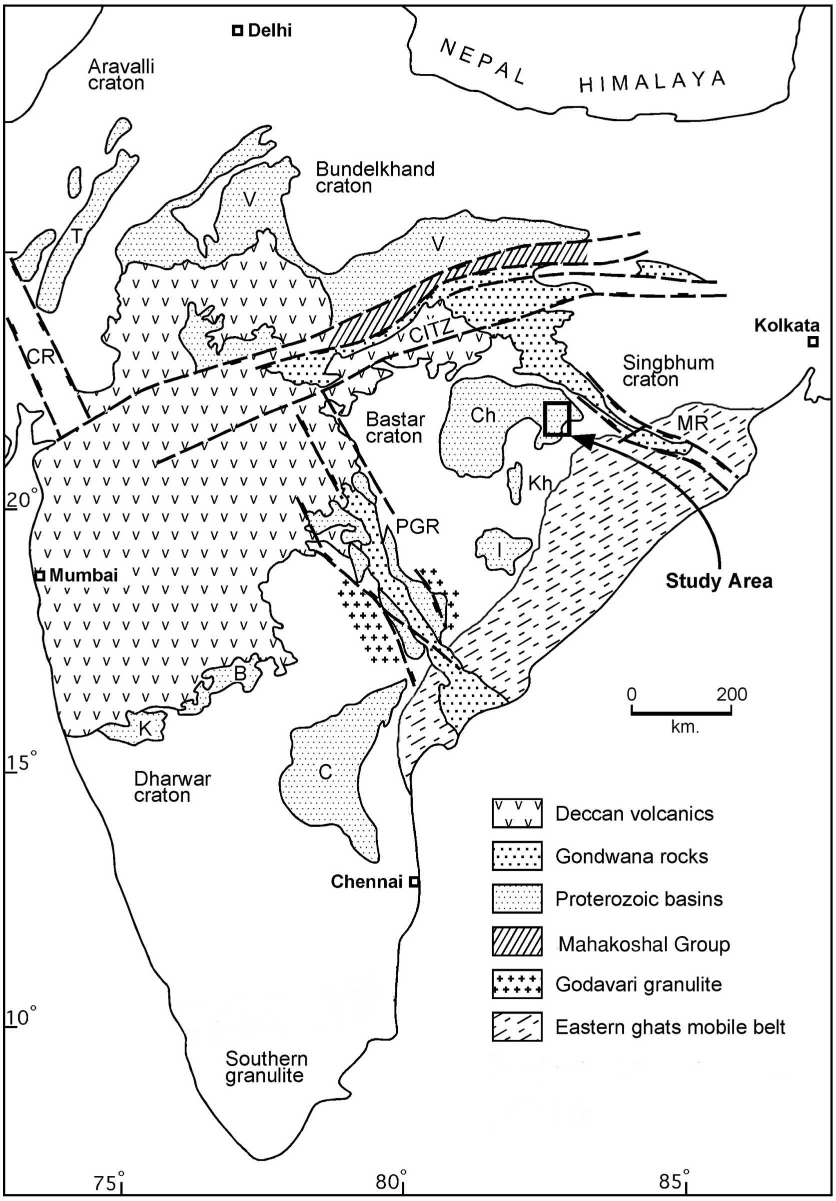

Figure 1. Distribution of Chattisgarh and other Purana basins in south Indian craton: Ch., Chattisgarh; Kh., Khariar; PGR, Pranhita–Godavari Rift; CR, Cambay Rift; C, Cuddapah; B, Bhima; K, Kaladgi; V, Vindhyan; T, Transaravalli. CITZ, and MR refer to Central Indian Tectonic Zone and Mahanadi Rift.

sequences is further constrained by the absence of fossils, and also probably by the paucity of well preserved records.

The Neoproterozoic succession in the eastern part of the Chattisgarh basin, India (figure 1) preserves a thick sequence of shelf deposits. The lower part of the shelf succession is characterized by mud dominated sequence with signatures of deposition in storm dominated environments, whereas its upper part comprises large positive relief sand bodies, often amalgamated as extensive sand sheets. The linear positive relief sandbodies resemble shelf bars or ridges, and bear the signature of deposition under complexly interacting tidal and storm currents (Patranabis Deb 2001). The present paper documents the architecture of linear, positive relief sandbodies from the Chattisgarh basin, and attempts to reconstruct the shelf processes that controlled the development and growth of the sandbodies.

2. Regional geological setting

The Proterozoic (Purana) Chattisgarh succession developed within the Bastar craton, an Archean crystalline block bounded by the Godavari and Narmada rifts to the southwest and northeast

Table 1. *Stratigraphic succession in the eastern Chattisgarh basin after Patranabis Deb (2001).*

Chattisgarh Supergroup	Raipur Group	Gunderderhi Shale		Brown calcareous shale, GREEN shale, dolomite, small stromatolitic mounds at the base	Platform margin, slope to basin
		Sarangarh Limestone (150m)	Timarlaga Member	Black, mauve and brown flat bedded micritic limestone (without any sand)	Slope to basin
			Gadhabhata Member	Brown and gray micritic limestone with sand sheets and lenses	Platform
		Bijepur Shale (100 m)		Green and brown calcareous shale, thinly laminated, locally with sandy graded beds, sole marks	Muddy shelf and shelf lagoon
	Chandarpur Group	Kansapathar Formation (60 m)		Subarkosic and quartzose sandstone, and shale	Storm-tide influenced shelf – shoreface bar, and wind flats
		Gomarda Formation (650 m)	Daihan Sandstone Member	Sandstone, sandstone–mudstone heterolithic, shale	Prodelta and prograding shelf
		Lohardi Formation (150 m)		Conglomerate, pebbly sandstone, coarse sandstone	Fandelta
		∼∼∼Unconformity∼∼∼			
		Archean Greenstone belt and Granite Gneiss			

respectively, and is bordered by the Central Indian Tectonic Zone (CITZ) and the Eastern Ghats Mobile Belt (EGMB) to the northwest and southeast respectively (figure 1). The succession is mildly deformed and unmetamorphosed, and overlies strongly deformed rocks of the basement complex across an angular unconformity. The basement comprises granitoids and gneisses, and volcanosedimentaries of the Sonakhan greenstone belt of probable Archaean age (Das *et al* 1990; Sarkar *et al* 1990; Chaudhuri *et al* 1999). Authigenic glauconitic minerals from the sandstones in the lower part of the Chattisgarh succession yield ages of 700–750 Ma (Kruezer *et al* 1977). The sequence in the western part of Chattisgarh is dominated by a stable platformal assemblage dominated by stromatolitic limestones and quartzose sandstones (Moitra 1995; Murti 1996). The eastern part of the basin, in contrast, consists of thick wedges of conglomerates, pebbly sandstones and coarse-grained, immature feldspathic sandstones, thick sequences of mudstone or mud-dominated heterolithics, lithographic limestone and pyroclastics deposited in varied depositional milieu. The succession in eastern Chattisgarh has been classified into a lower assemblage deposited on alluvial plains, coastal marine to outer shelf environments, and an upper assemblage deposited primarily in outer shelf, slope and basinal environments (table 1; Patranabis Deb 2001).

The lower assemblage, designated as the Chandarpur Group, is about 400 m thick, and comprises conglomerates, sandstones, and greenish shale, characterized by rapid facies changes. The distal assemblage, designated as the Raipur Group, is more than 1750 m thick and consists of a succession of laterally persistent facies belts of lime mudstone and brown shale with interbedded intervals of pyroclastics. The rapid transition from immature coarse clastics of the Chandarpur Group to the deep water limestone-shale of the Raipur Group, as well as the occurrence of pyroclastics in the Raipur Group point to unstable conditions and rapidly changing configuration of the eastern Chattisgarh basin and its hinterland.

The upper part of the Chandarpur Group, designated as the Kansapathar Formation (table 1) is dominated by medium grained, well-sorted, subarkosic sandstone to quartzarenite. The coarse clastics at the basal part of the Kansapathar Formation occur as discontinuous positive-relief bodies enclosed within mud-dominated lithologies, and coarsen upward to a shallowing-up sequence of sandstone sheets. The Chandarpur succession was deposited within a major transgressive–regressive cycle. The lithostratigraphy of the eastern Chattisgarh is shown in table 1.

The sandstones of the Kansapathar Formation overlie mudstones of the Gomarda Formation across a sharp interface. The sandbodies exhibit evidence for shallowing and frequent emergence attesting to the deposition of the upper part of the Formation in intertidal environments. Two major linear sand bodies were studied during the present work, a subtidal one in the lower part of the formation and an intertidal one in the upper part.

The intertidal sand body was studied in road-cut sections along the Lath Nala and in the bed of the Mahanadi river near its confluence with the Lath Nala. The subtidal sand body was studied along the Kinkari Nala near the sluice of the Kinkari dam that exposes an excellent transverse profile in an east–west section.

3. Principal facies

The Kansapathar succession has been classified into five facies that occur in two genetically related facies associations. Wavy to lenticular bedded, cross-stratified medium-grained quartzose sandstone, and thin-bedded ripple laminated sandstone, siltstone and mudstone are the two major facies in the Kansapathar Sandstone. Lenticular or wedge shaped cross-stratified sandstone, plane laminated sandstone, conglomerate and rippled sandstone with or without adhesion warts occur as subordinate facies.

3.1 *Facies 1: Wavy to lenticular bedded, cross-stratified medium-grained quartzose sandstone*

The facies consists of well-sorted, medium-grained, subarkosic sandstone to quartzarenite and comprises more than 60% of any section of composite sandbodies. The facies units occur as linear positive relief bodies with thickness ranging from 2–6 m. Smaller lens shaped bodies generally possess sharp crests and gently sloping (≅ 5–8°) margins, though a few may have steep (≅ 25°) slopes. The larger bodies, in contrast, have broad round crests and gently sloping margins. Successive sandbodies are separated by relatively thin intervals of mud dominated sandstone–mudstone heterolithics or mudstone.

The positive-relief sandbodies are made up of wavy to lenticular beds about 0.2–4.5 m in thickness. Most of the beds pinch out laterally within 2–3 m, but a few thicker beds could be traced laterally for over 25 m (figure 2a, b). The beds have developed as lateral accretionary elements at the margins of positive relief bodies (figure 3), and also as aggradational elements on upper surfaces of sandbodies. Successive beds are separated by slightly irregular, planar erosional surfaces or by thin units of mud or fine-grained rippled sandstone. Upper surfaces of a majority of thick beds show profuse development of coarse-grained wave ripples (figure 4), locally with marked concentration of very well-sorted and well-rounded coarse sands and granules in the troughs. The ripples are generally symmetrical to slightly asymmetrical, straight to slightly sinuous crested, and often exhibit tuning fork bifurcation. The crests may be sharp, round, or flat. The ripples frequently show form discordant chevron or vertically upbuilding bundles of internal laminae, off-shooting and draping foresets or bidirectional foresets. In few exposures, smaller ripples occur within the troughs of larger ripples (figure 5). The bedding surfaces also exhibit spindle shaped desiccation cracks (figure 6), and adhesion warts (figure 7) in upper part of the sequence. The extensive bedding plane surfaces with ripples of different scales have been referred to here as ‘master bedding surfaces’ (Walker 1985), and are a characteristic feature of the facies. The master bedding surfaces are the interfaces between sandy and muddy intervals.

Thicker sandstone beds are all internally cross-stratified. The cross strata generally occur in 0.1–1 m thick sets, and less commonly in cosets. The sets are almost always separated by thin mud layers. The foresets are tabular, sigmoidal or concave up with slightly asymmetric toes. The concave-up foresets in many instances pass downcurrent into sigmoidal ones. The foreset angle within a set also commonly changes from steep (≅ 20°) to gentle (≅ 10°) in the downcurrent direction, and the foresets often tangentially merge with the bottom set. The larger sets often exhibit multiple reactivation surfaces (figure 8), commonly strewn with mudclasts and marked by ripples or wrinkle marks. The outcrops of the subtidal sandbody near the Kinkari Dam in the southern part of the study area exhibit distinct bipolar–bimodal distribution of foreset azimuths, with the modes between NE and SW. The two modes may either be of equal strength or one may be stronger (figure 9). In few outcrops a dominantly southeasterly mode is also observed. Mudclasts are abundant within the sandstone, and are either strewn over the erosional surfaces or aligned parallel to the foresets.

3.1.1 *Interpretation*

The beds were deposited by large, migrating bedforms such as 2D and 3D subaqueous dunes or large wave ripples (*sensu* Leckie 1988; Ashley 1990) in high energy subtidal to intertidal shoals. The thin mudstone layers separating the foreset laminae within a set, the sets, the cosets, as well as the beds are the testimony to deposition in a tidal regime (Brenner and Davies 1974; Tankard and Hobday 1977; Walker 1985; Deynoux *et al* 1993).

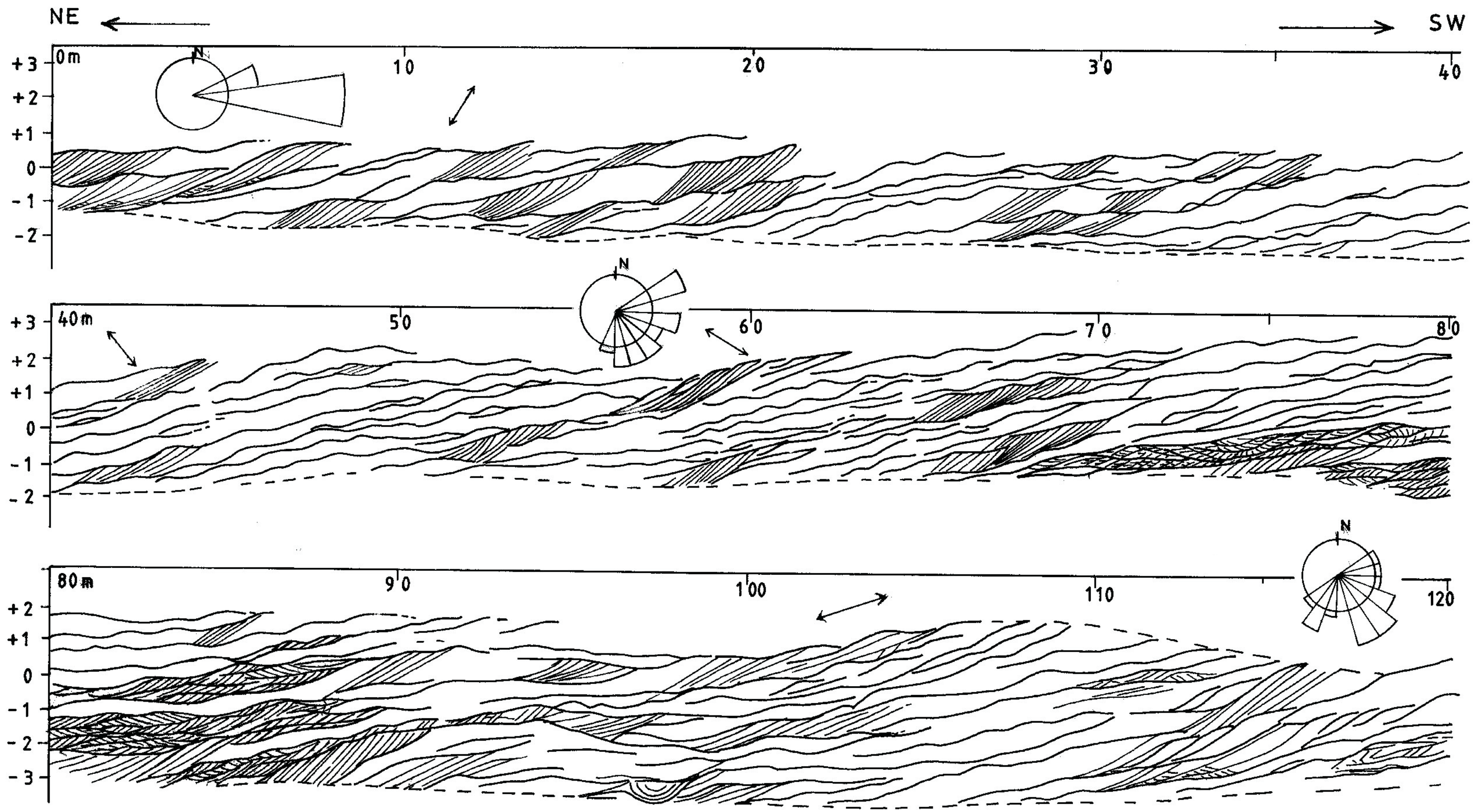

Figure 2(a). Panel diagram of a longitudinal section of a sandstone bar in the Kansapathar Sandstone showing lateral accretion of the beds caused by bedform migration and the master bar accretion surfaces. Small countercurrent ripples occur at the base of several foresets. Rose diagrams exhibit current directions measured from the larger foresets. Double-headed arrows indicate orientation of wave ripple crests.

Figure 2(b). Transverse profile of a large composite bar in the Kansapathar Sandstone at Kinkari. Upper photo shows western side and lower photo shows eastern side. Note the wedging and pinching of component bars sloping in different directions. Scale bar 10 m.

The repetitive occurrence of sand transport, slack water phases as well as reversal of flows indicated by bimodal–bipolar distribution of palaeocurrents, strongly support tidal cycles and tidal reversals. The flow depth and flow velocities were highly variable. The lenticular sets with foresets arranged in bundles are commonly reported from subtidal and lower intertidal zones (Kreisa and Moiola 1986). The reactivation surfaces with mud drapes or small ripples and wrinkle marks, in contrast, indicate lateral accretion and modification of bedform surfaces by late stage emergence run off. Emergence or near emergence is also indicated by smaller ripples within troughs of larger ripples and flat crested ripples. Emergence is testified by spindle shaped ridges or sand filled cracks (Chaudhuri and Howard 1985) and by adhesion warts that formed by adhesion of wind blown sands on wet, exposed bedding surfaces (Van Straaten 1953; Allen 1982; Reineck and Singh 1986). The strong tidal fluctuation, attested by bedforms of different scales, speaks for macrotidal regimes and temporally varied flow paths for ebb and flood, as well as spring and neap tidal cycles (Boersma 1969; Terwindt 1971; Visser 1980; Boersma and Terwindt 1981; Ashley 1990). Superimposition of strong waves of different scales on tidal flows is indicated by extensive development of coarse-grained wave ripples on master bedding surfaces at different levels within larger bedforms. Morphologies of coarse-grained ripples and their internal structures attest to their origin by oscillatory wave currents (De Raaf *et al* 1977). The slight asymmetric form of the ripples is possibly a product of combined wave and unidirectional current processes, or alternatively, formed by asymmetry of landward and seaward orbital velocities in the near shore zone (Clifton *et al* 1971). Concentration of well-rounded sand grains within troughs of the ripples as well as thin granule lags attest to strong protracted winnowing by waves and or tides.

The positive relief geometry of lens-shaped, cross stratified sandbodies shows them to be vertically aggrading depositional features, the margins of which always slope down and away from the thickest part of the lenses. The lens shaped sets with decreasing inclination of foresets in the downcurrent direction are interpreted to represent dunes that originally migrated by slip face avalanching, and progressively developed by thickening of the bottomset with increasing flow strength until the lee side separation bubbles disappeared, and were converted into low height bars (Jopling 1965;

Figure 3. Laterally accreted bar bedding. Clinometer cover is 10 cm.

Figure 4. Straight crested megaripples on the upper surface of the large bar at Kinkari.

Figure 5. Smaller ripples within the troughs of larger ripples.

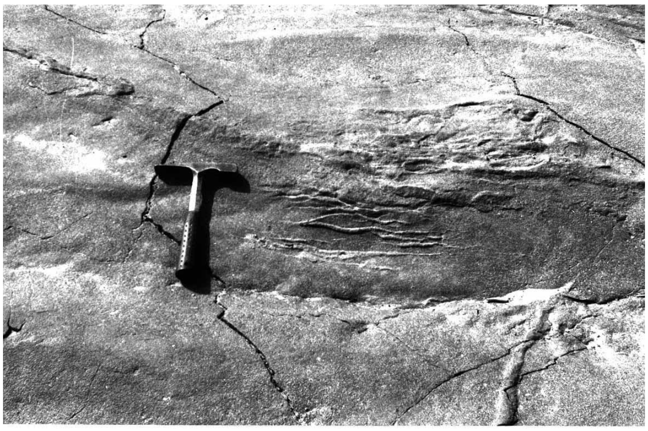

Figure 6. Spindle shaped desiccation cracks on the upper surface of rippled bed.

Figure 7. Adhesion warts on a bedding surface in the upper part of the Lath Nala bar.

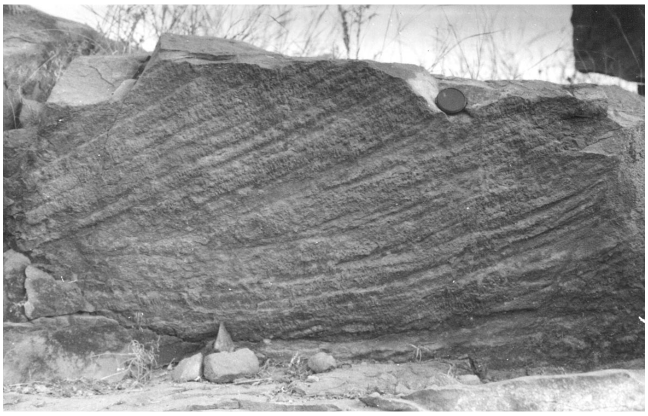

Figure 8. Bundles of foresets separated by reactivation surfaces in a bar sandstone bed.

Imbrie and Buchanon 1965; Anderton 1976). The bars accreted laterally and aggraded vertically. The variable relief in different parts of the sandbodies further points to uneven vertical aggradation associated with lateral accretion, indicating changing flow structure within short distance. Relatively weak currents continually modified the larger bedforms resulting in wavy undulatory geometry that represented a quasi-equilibrium adjustment of opposing flows (Ashley 1990).

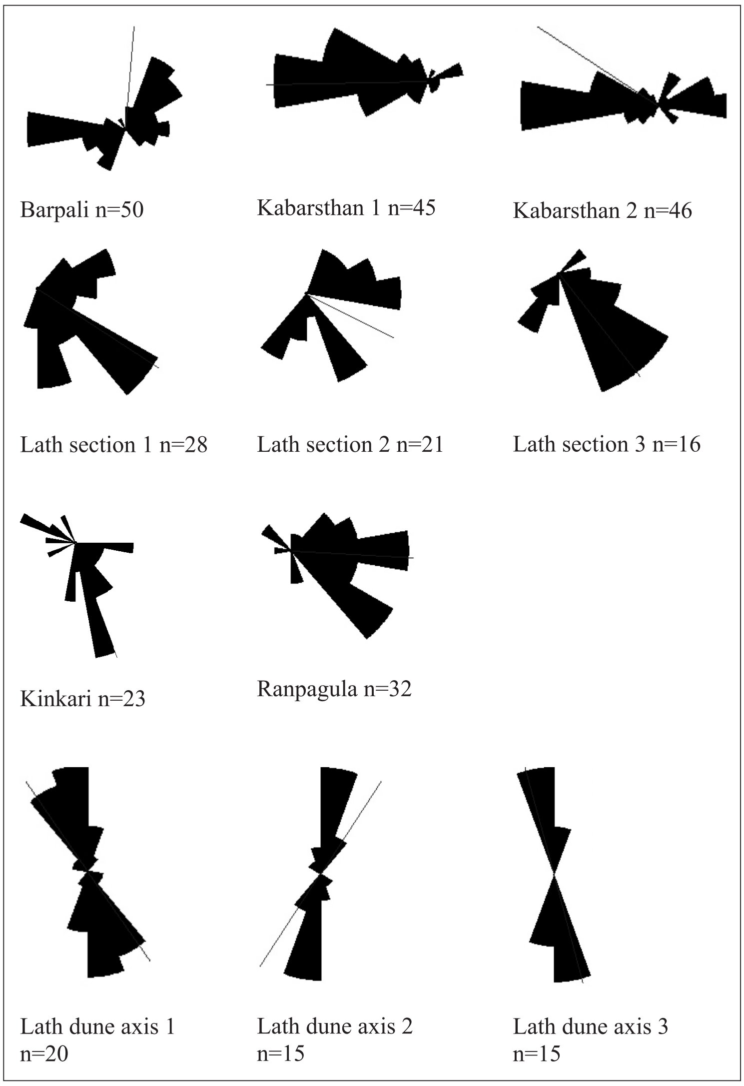

Figure 9. Rose diagrams showing palaeocurrent pattern in different areas of the Kansapathar Sandstone.

3.2 *Facies 2: Wedge to sigmoidal shaped beds of cross-stratified medium-grained sandstone*

The facies comprises medium-grained, very well-sorted subarkosic to quartzose sandstone, and occurs in close association with F1. They occur as 0.2–2 m thick, wedge shaped beds dipping between 10 and 20° (figure 10), or as 0.5–4 m thick sigmoidal lenticular beds, and may be referred to as foreset beds (figure 2b) (Allen and Homewood 1984), bar beds (Reineck and Singh 1986) or sigmoidal bundles (Kreisa and Moiola 1986). The bounding surfaces between successive beds may be erosional, but the majority are non-erosional and are marked by small asymmetric ripples on them. Successive beds are almost always separated by 2–20 cm thick, dark coloured rippled or thinly laminated fine-grained siltstone or mudstone. Amalgamated lenticular beds occur at places.

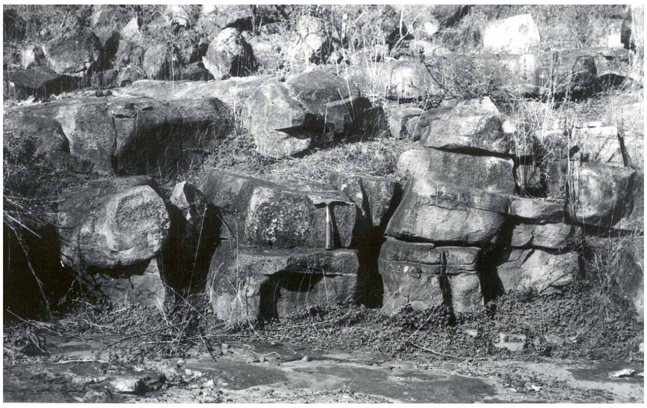

Figure 10. Relatively steeply dipping, wedge-shaped beds in the Kansapathar Sandstone.

The beds are composed of planar or sigmoidal foresets, occurring either in cosets or in single set. The sets are separated by thin layers of fine-grained

Figure 11. Alternation of fine-grained muddy sandstone and medium grained sandstone. Photographs represent the basal part of the Lath Nala bar. The sequence changes from muddy heterolithics to sandstone both upwards and in the downcurrent direction. The vertical stick is 1.5 m.

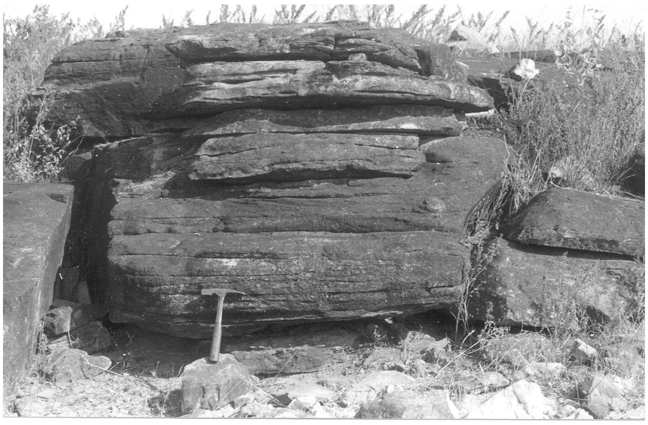

Figure 12. Plane parallel stratified coarse- to medium-grained sandstone. Note the low angle truncation between the strata sets.

sediments or are truncated by reactivation surfaces. The reactivation surfaces truncate several foresets at low angles, and are commonly mud draped. The sets are as much as 80 cm thick and may extend up to 15 m in the downcurrent direction. The foresets exhibit persistently unimodal dip direction. In several beds, the sigmoidal sets are overlain by 5–10 cm thick set of tabular cross strata, across a planar to slightly undulatory erosional surface. The tabular cross strata almost always dip in the direction opposite to that of the sigmoidal sets.

3.2.1 *Interpretation*

The high angle wedge shaped beds represent avalanching foresets of 2D dunes and indicate bedform migration under the dominant current stage in subtidal settings (Allen 1980). The sequence of internal strata within the sigmoidal sets represents tidal bundles, and points to current acceleration, maximum flow and dune migration, and deceleration during individual tidal episodes (Boersma and Terwindt 1981; Kohsiek and Terwindt 1981; Kreisa and Moiola 1986). The planar strata at the the basal part of thicker beds points to development of shear drag along the lee faces in the upper flow regime condition, whereas steeply dipping foresets represent maximum flow intensity with steepening of the lee slopes of the dunes (Boersma and Terwindt 1981). The tabular foresets or ripples on the upper surfaces of some of the sigmoidal beds indicate oppositely oriented migration of smaller 2D dunes up the lee side of bars, representing reversing tidal currents that modified upper bedding surfaces. Deposition of each set was followed by a pause leading to suspension settlement of mud.

3.3 *Facies 3: Interstratified sequence of thin-bedded ripple laminated sandstone, siltstone and mudstone*

The facies consists of thin bedded, medium- to fine-grained rippled sandstone and siltstone interbedded with mudstone (figure 11). The facies units range in thickness from 0.5–1.5 m, and thicker units can be traced laterally up to 25 m. The sandstone beds range in thickness from 5–20 cm, and are characterized by sharp, erosional basal contacts and sharp or gradational upper contacts. The beds may show pronounced pinch and swell or may be tabular. The tapering ends of the beds often climb on the laterally adjacent ones, and are often separated by thin laminae of mudstone and siltstone. The sediments of this facies fill in and conform to the undulations in the upper surfaces of the underlying bedforms.

The sedimentary structures include flaser, wavy, lenticular and parallel stratification, with locally developed current lineation and trough cross stratification in relatively thicker beds. The stratal sequence is often punctuated by slightly undulatory erosional surfaces that truncate several beds. Wave ripples, often with interference pattern of various types, occur profusely on upper surfaces of the sandstone beds.

3.3.1 *Interpretation*

Thin ripple laminated sandstone beds indicate deposition by low-energy waves and currents. Wavy bed morphology with internal wavy lamination and wave ripples on upper surfaces of the beds collectively point to wave dominance in the depositional environment. The alternation of sandy and muddy sediments indicates fluctuating current strengths. Mud, silt and probably some of the thinnest sandy

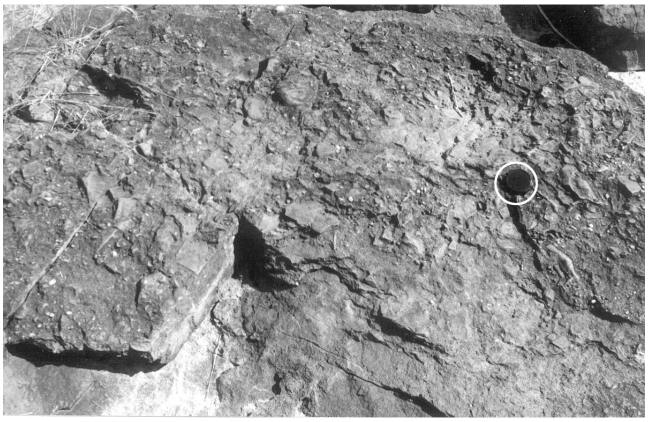

Figure 13. Platy clast, in a matrix supported conglomerate bed. The lens cap for the scale.

laminae were deposited directly from suspension (Banks 1973; Levell 1980a, b). The presence of slack water conditions and tidal activity with intermittent storm deposition may be inferred.

The parallel lamination with primary current lineation on a few beds indicates episodic development of high energy flows. The planar erosional surfaces affecting multiple beds also attest to the occurrence of episodic high intensity flows. The high energy environment is probably attributable to rapid flows resulting from wave breaking in front of emerging bars (Chaudhuri and Howard 1985) and developed in open marine circulation conditions.

3.4 *Facies 4: Tabular bedded plane stratified, medium-grained sandstone with strong grain segregation*

The facies is represented by mature, medium to coarse-grained quartzose sandstone that occurs as extensive sheets in the uppermost level of the Kansapathar Sandstone. The beds are about 10–20 cm thick, laterally persistent and tabular with planar bounding surfaces. They often amalgamate to form up to 1 m thick units. Successive beds, when not amalgamated, are separated by thin concentrates of micaceous minerals. The beds consist of $\cong$ 5 mm thick planar strata (figure 12), characterized by high grain-size sorting. Most of the beds exhibit multiple lamina-sets, generally between 4 and 10 cm in thickness, with slightly discordant, very low angle planar erosional surfaces between them. The majority of the lamina-sets are gently inclined between 2° and 4° towards the basal contact, though a few sets are inclined in the opposite direction. Strong segregation of grains according to size, with a clear cut-off limit at coarse sand, within the lamina-sets is the hallmark of this facies.

3.4.1 *Interpretation*

Well-sorted sand with a clear cut-off limit of size at coarse sand fraction, high degree of size segregation of grains in different strata, and preponderance of gently inclined planar strata with occasional reversal in the direction of inclination collectively point to deposition in high energy foreshore beach environment. Lateral continuity of beds and lamina with low angle truncation between lamina-sets are typical of high energy foreshore beach deposits (Bluck 1967; Clifton 1973; Clifton 1976; Maejima 1982; Nemec and Steel 1984; Ethridge and Wescott 1984). Concentration of mica rich layers among sandy layers, lamina-sets or beds, and segregation of sands in different lamina on the basis of size is a manifestation of swash and backwash processes (Reinson 1984). The direction of inclination of most of the lamina-sets represents the slope of the beach face, whereas a few sets with opposite inclination represent landward sloping swash deposits. The low angle truncations between lamina-sets indicate slight fluctuations in flow direction, and dominance of discordant sets of plane strata represents the lower part of the beach face (Bluck 1967; Dupré *et al* 1980; Massari and Parea 1988).

3.5 *Facies 5: Conglomerate and cross-stratified pebbly sandstone*

The facies comprises lenticular bodies of conglomerate and cross-stratified pebbly sandstone, 25–50 cm in thickness and 1–2 m in length. The basal surfaces of the beds often preserve sole marks with well-developed gutter and load structures. Rarely, however, they also occur as thin sheets. The lenticular bodies have concave up basal erosional surfaces, whereas the sheet-like beds exhibit sharp, subhorizontal scour surface. The upper bounding surfaces are gently undulating. The beds range in thickness from 5–30 cm. The facies units, either channel fills or sheets, normally consist of matrix supported conglomerate mostly with platy clasts (figure 13) of well-sorted quartzarenite and subordinate amount of mudstone, and a few well rounded quartz pebbles. In cross-stratified pebbly sandstone, the clasts are aligned along the foresets. The sandstone clasts are commonly 0.5–1 cm thick and 3–8 cm long, and are nearly identical to the matrix in composition. The platy clasts are highly angular and may fit together like a jigsaw puzzle to form a sheet. Upper surfaces of some of the beds show concentration of granules and large pebbles occurring in single grain thick to a few cm thick layers. They generally pinch out within a metre, and only occasionally can be traced up to 4–5 m or more. Locally a bed may comprise massive sandstone at its basal part, and is followed upwards by coarse tail inversely graded interval.

Figure 14. Gently inclined bedding plane surface with closely spaced straight crested ripples having shallow, wide troughs. Length of the pencil is 15 cm.

3.5.1 *Interpretation*

The matrix supported conglomerate with coarse tail inverse grading and gently undulating upper bounding surfaces collectively suggest deposition from debris flows with arrested settling distribution (Johnson 1970; Fisher 1971; Middleton and Hampton 1976; Lowe 1982; Nemec and Steel 1984, Nemec and Muzynski 1982). The flows possibly developed from sheet floods on the sandstone sheets, and the deposits were preserved mainly within shallow channels and scours sculptured on exposed surfaces. The cross-stratified pebbly sandstones represent deposits of associated fluidal flows or remobilized debris flow deposits. Sandstone clasts with platy nature and high angularity suggests minimal transport. Lithification of sand and brecciation of thin sandstone sheets into intraclasts is rare in a marine setting. Similar features have been documented in a few modern and ancient upper foreshore settings and attributed to episodic development of subsequent destruction of beach rock that formed in the splash zone and intertidal areas (Roep *et al* 1979). The upper part of the Kansapathar Sandstone thus represents repeated episodes of foreshore aggradation, lithification and subsequent destruction. The destructive events were characterized by the development of shallow, wide channels incised into the foreshore and upper shoreface, undercutting the beach rock that was incorporated within the channel-fill deposit. The episodic erosion and deposition in beaches may be related to episodic storms and seasonal changes, as well as larger scale base-level change (McCubbin 1982).

3.6 *Facies 6: Planar stratified medium- to fine-grained sandstone with microripples and adhesion warts on bedding surfaces*

The facies comprises medium to fine-grained, very well-sorted quartzose sandstone that occurs as laterally persistent tabular beds, with very well developed planar stratification and low angle cross stratification. It occurs as a distinctive interval in the uppermost part of the Kansapathar Sandstone. The beds range in thickness between 10 and 45 cm, whereas the laminae are 1–2 mm thick. The intrastratal surfaces are marked by high concentration of micaceous minerals. The beds commonly exhibit adhesion warts and wind ripples on bedding plane surfaces. The crests of adhesion structures are characterized by concentration of relatively coarser grained sands compared to the troughs. Wind flow direction measured from the ripples is highly variable.

The facies also exhibit closely spaced straight crested ripples with shallow, wide troughs on the upper surfaces of gently inclined beds along the flanks of shallow pools or channels (figure 14). Their ripple amplitude ranges between 2 and 4 mm and wavelength varies around 4 cm. The crests are narrow and sharp, and join at intervals of 5–10 cm at tuning fork junctures. The furrows, at places, are crossed by evenly spaced ridges, creating a ladder-like appearance. Thin mud layers drape several bedding plane surfaces.

3.6.1 *Interpretation*

The planar stratified tabular beds separated by thin mudstone layers attest to periodic development of high energy sheet flows separated by quiet depositional phases. The beds could have formed by high energy reversing flows with large wave orbital diametres where sands moved as a high concentration carpet near the bottom, under intense shear within the breaking waves (Allen 1982). The conditions are achieved during high intensity storms on the foreshore or upper shoreface regime. The high concentration of phyllosilicate minerals along the stratal interface strongly supports deposition by swash and backwash on the foreshore (Clifton 1973).

The mm scale straight crested ripples resemble microripples or millimetre ripples (*sensu* Singh and Wunderlich 1978) that were sculptured on successive bedding surfaces at very shallow water depth, and define pause planes. The structures indicate minor perturbations on the sediment–water interface in upper shoreface-foreshore areas (Reineck and Singh 1986). The recurrence of the facies units in the sequence indicates storm cycles in a high energy foreshore to upper shoreface setting. The adhesion warts and ripples on bedding plane surfaces further point to intermittent exposure of the depositional interface, strong wind activity and deflation.

4. Facies associations and paleoenvironments

The facies can be grouped into two major, genetically related facies associations on the basis of their mutual relationship and frequency of transition in the profiles. Each association represents a different subenvironment namely,

- subtidal facies association, and
- intertidal facies association.

4.1 *Subtidal facies association*

This association comprises an assemblage of wavy to lenticular bedded, cross-stratified medium-grained quartzose sandstone (F1), wedge to sigmoidal shaped beds of cross-stratified medium-grained sandstone (F2), and an interstratified sequence of thin bedded, ripple laminated sandstone, siltstone and mudstone (F3). The association is very well developed in and around the Kinkari section and in the lower part of the Lath Nala section. In the Kinkari section, wavy lenticular beds (F1) are very thick, and are characterized by excellent preservation of coarse grained 2D and 3D dunes on upper surfaces of almost all the beds.

The rocks of F1, F2 and F3 facies form composite elongate bodies with large convex up geometry in transverse section. These bodies are generally 150–200 m in width, 25–50 m thick and can be traced for 2–5 km along their length. In the Kinkari section, the elongation directions vary from north–south to northeast–southwest and dip outward from the topmost portion of the concave up body from east–west to northwest–southeast respectively. In the Lath section, the bars are mostly north–south and dip is towards east and west. The sandstone bodies have convex upper surfaces and flat bases, and the geometry implies that they were built upwards as positive relief features from planar surfaces, a morphological character typical of bars of tidal origin (Chaudhuri and Howard 1985). The lens-shaped bodies thin laterally by sloping downward at their margins. Dimensions of the bars and of the bed forms point to macrotidal domain. The aggrading upper surfaces of the bars experienced protracted reworking by strong oscillatory currents leading to extensive development of coarse-grained wave ripples and dunes, mantled with lag pebble deposits at different points. All the above features collectively point to a subtidal origin of the facies association. The thin bedded, ripple laminated sandstones and mudstones (F3) represent a relatively quiet depositional setting behind or between the bars. Contact between the ripple-laminated sandstone facies and lens-shaped, trough cross-stratified sandstone bodies are sharp and is made obvious by abrupt change in bedding style. Flaser, wavy and lenticular strata indicate predominance of mud in the system. The F3 deposits are much thicker in the depression between bars and have developed in relatively restricted environment filling the lows between the bars.

4.2 *Intertidal facies association*

The association comprises an assemblage of wavy to lenticular bedded, cross-stratified medium-grained quartzose sandstone (F1), interstratified sequence of thin-bedded ripple laminated sandstone, siltstone and mudstone (F3), tabular bedded planar stratified, medium-grained sandstone with strong grain segregation (F4), conglomerate and cross-stratified pebbly sandstone (F5), planar stratified medium- to fine-grained sandstone with microripples and adhesion warts on bedding surfaces (F6). It is best represented in the upper part of the Lath Nala section and in the Mahanadi river bed where the intertidal character of the association is manifest by profuse development of flat topped ripples, desiccation cracks, wrinkle marks and recession ripples that formed within troughs of larger ripples. The uppermost part of the shoaling-up bar sequence is dominated by high energy beach deposits (F4) and wind flats marked by adhesion warts and wind ripples (F6).

The idealized summary facies log (figure 15) describes the assemblages of subtidal and intertidal association.

5. Sequence of facies association

The vertical changes in the facies succession have been depicted in a composite stratigraphic profile (figure 15). The Kansapathar Sandstone overlies the mud-dominant sequence of the Gomarda Formation across a sharp interface, and the abrupt superposition points to rapid relative sea-level fall ushering in changes in coastal geomorphology, rate of sediment influx, slope of the depositional interface and circulation condition. Sediments were transported, reworked and deposited by storm generated geostrophic flows and strong tidal currents. The profile exhibits large-scale coarsening- and shallowing-up character of the Kansapathar sequence (figure 15), marked by upward decreasing mud–sand ratio and increasing signatures of emergence. Within the large scale CU motif, small scale CU and FU depositional cycles are recognized.

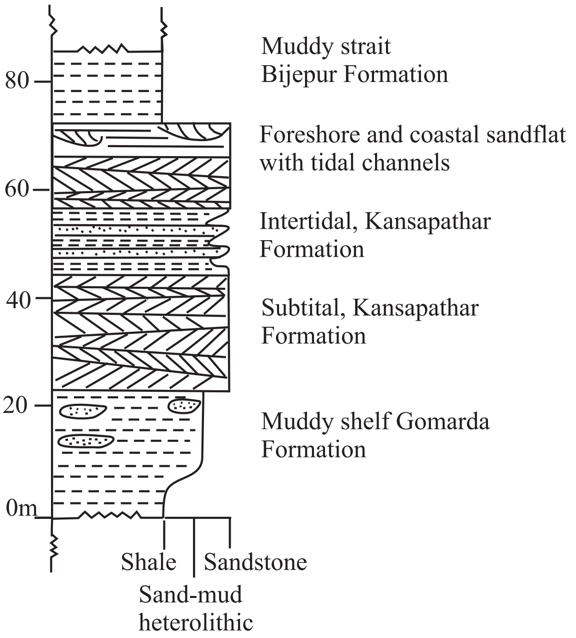

Figure 15. The idealized summary log of the Kansapathar Formation showing the large-scale coarsening- and shallowing-up character of the Kansapathar succession. The environment changes from muddy shelf to shallow marine coastal deposits with well preserved foreshore and tidal channels.

The lower part of the Kansapathar sequence is dominated by the subtidal facies association. In the subtidal regime, small positive relief cross-stratified sand bodies formed under the combined action of tidal and wave generated currents. The lens shaped sets formed by migration of dunes and progressively developed by thickening of the bottom set, and was converted into low height bars. The bars accreted laterally and aggraded vertically, and amalgamated into composite linear bodies comparable in dimension with shelf ridges. The dunes migrated laterally down the bar margins under the influence of strong tidal currents accreting thick wedge shaped bar beds.

The intimate physical association of high energy bar facies (F1 and F2) and the low energy facies (F3), and their complementary thickness variation indicate that development of high energy and low energy environments were closely associated in time and space. The linear bars created partially restricted low energy environments on their land ward side or between the bars, facilitating deposition of low energy, ripple laminated facies (F3). The low energy facies remains preserved as inter-bar deposits, or within broad swales on upper surfaces of the bars.

The upper part of the sequence is dominated by the intertidal facies association with increasing frequency of features of emergence. The foreshore and wind flat deposits appear in the uppermost part. The sequence of facies association indicates gradual shallowing of the environment from subtidal to intertidal with intermittent exposure.

6. Depositional environment, palaeocurrent and palaeogeography

The combination of bed forms, facies and palaeocurrent pattern in different sections of the Kansapathar sequence points to tidal sedimentation under a macrotidal regime. The sediments deposited in intertidal environments, such as F4 and F6, further record signature of high intensity storm currents. The depositional milieu varied from subtidal to intertidal to coastal wind flats through time. The shallowing up from subtidal to upper intertidal to wind flats attests to the development of a major progradational sequence and decreasing water depth.

The record of tidal accretion through migration of large sandy bedforms, such as coarse grained wave ripples and 2D or 3D dunes, in high energy subtidal condition is inferred from the transverse section of the Kinkari bar (figure 2b). The section exhibits accretion of thick lenticular to wedge shaped beds in opposite directions (figure 2b). The accretion of bed in opposite directions is attributed to a system of bipolar–bimodal flows. A bipolar–bimodal current pattern is also recorded in exposures other than the Kinkari section. They are in E–W and NW–SE directions (figure 9). The wave ripple axes are mostly in the N–S to NNW–SSE direction (figure 9). Bipolarity of flow in a tidal regime attests to flood and ebb tidal currents and also indicate the trend of the palaeoshore line. The ripple axes orientation when combined with polarity direction of the paleocurrent measured from the trough axes indicate that the shoreline orientation during the development of Kansapathar sedimentation was mostly N–S. The data are concordant with the general notion that the wave ripples develop parallel or at low angle to the shoreline.

Dominance of thick cross-strata sets and of accretionary bar bedding points to reworking by strong tidal currents in subtidal environment (Klein 1971; Tankard and Hobday 1977; Dalrymple *et al* 1978). The tidal range in open ocean is small, and even lower in enclosed seas (10–30 cm in Mediterranean), but it is enhanced substantially as the tidal bulge from the ocean encounters embayed shallow seas (Ginsburg 1975). The scale of structures indicate high current velocity, possibly in a macrotidal regime, strong enough to migrate large bed forms in the Chattisgarh sea. Strong tidal influence suggests that the cratonic basin was connected with an open ocean (figure 16). The situation appears to be comparable with the conditions in the Bay of Fundy.

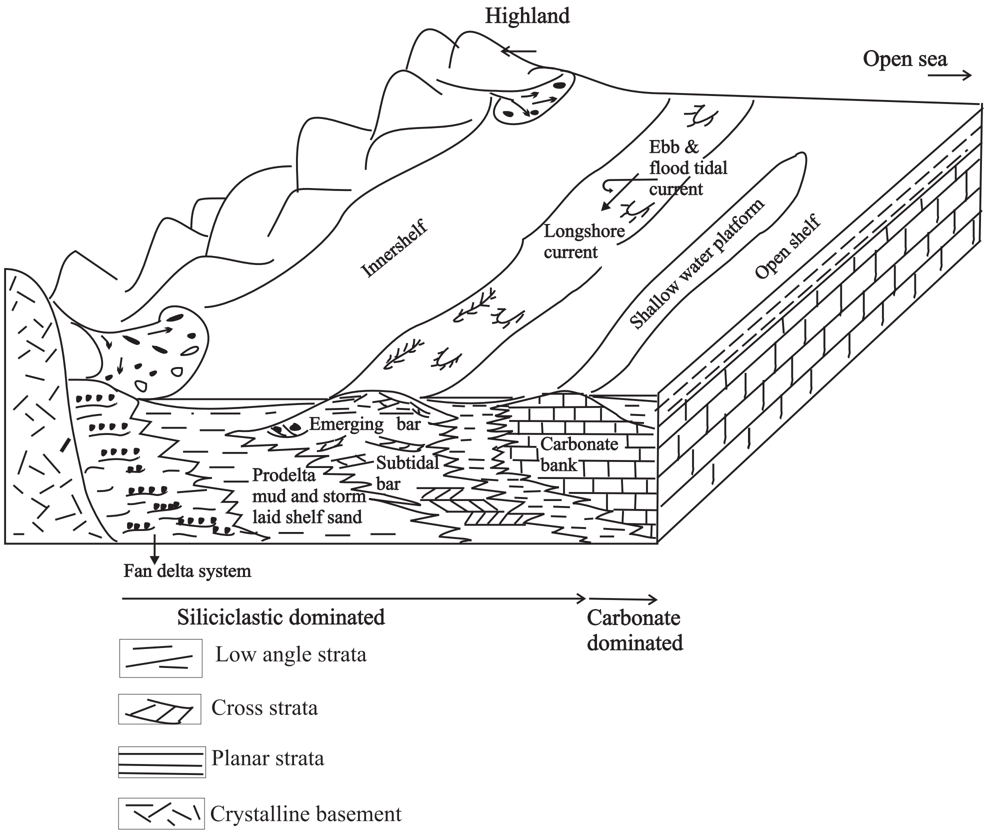

Figure 16. Cartoon diagram showing the palaeogeography.

7. Conclusion

The Neoproterozoic Kansapathar Formation in eastern Chattisgarh developed as a major progradational sandstone sheet in a tide dominated shelf depositional system. The sands were transported to a wide muddy shelf and reworked by strong tidal currents into a shoaling upward system of linear bars, parallel or at low angle to the coast. With continued accretion, the bars coalesced into a major sand sheet. Strong tidal current migrated large sandy bed forms that accreted laterally under the influence of ebb and flood currents, and longitudinally by south easterly flowing alongshore currents generating large linear bars, 2–5 km in length and 150–200 m in width. With continued aggradation, the shoaling up subtidal depositional system was replaced by intertidal depositional milieu with abundant signatures of combined tide and storm currents, and emergence. The emerging bars were reworked into extensive high energy strand plain deposits that were reworked by coastal wind system into wind flats.

The presence of strong tidal currents implies that the Chattisgarh sea was connected with a large ocean basin. Waves formed in the deep ocean and propagated into the adjacent Chattisgarh cratonic sea where the tidal amplitude as well as flow velocities were enhanced to rework vast amount of sand in the shelf region, generating large sandy bed forms. The current system and major directions of sediment dispersal speak for a broadly N–S orientation of the coastline during the deposition of the Kansapathar Formation.

The development of a thick coarsening up sand dominated sequence overlying a mud dominated shelf sequence with a sharp interface points to an abrupt fall in relative sea-level with consequent changes in the provenance, in the rate of generation of sands and the sand delivery system, as well as in depositional processes in the basin. A quiet mud depositing system was replaced by a major sand-depositing environment with strong open marine circulation open to an ocean basin in the north-western side. The changes collectively point to major tectonic control on the depositional system and evolution of the basin.

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