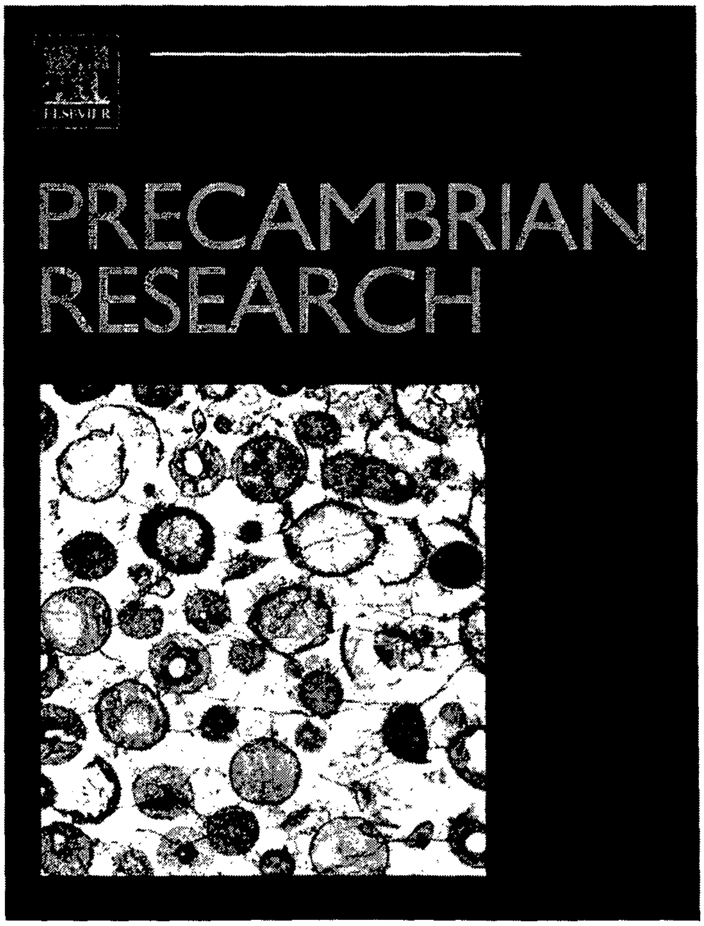
To
Prof. Supriyo Sengupta
with regards



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Shallow marine and coastal eolian quartz arenites in the Neoarchean-Palaeoproterozoic Karutola Formation, Dongargarh Volcano-sedimentary succession, central India

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Received 2 August 2006; received in revised form 24 February 2007; accepted 2 April 2007

Abstract

The Neoarchean-Palaeoproterozoic Karutola Formation, a >200 m thick supermature quartz arenite, occurs interlayered between two thick units of intermediate to basic volcanic rocks of the Dongargarh Group. Despite metamorphism and deformation, detrital texture and sedimentary structures are well preserved, allowing detailed process-based facies analysis. The facies recognised include: (1) inner shelf, (2) shoreface, (3) delta mouth/lower delta plain, (4) tidal flat, and (5) foreshore/backshore. A coastal sand sheet, dominated by adhesion structures and consisting of alternating eolian and foreshore aqueous deposits, records eolian processes operative in the Karutola coastal area. Textural characteristics hint at a significant eolian contribution to the shallow marine sand. Overall palaeocurrent indicates a NW–SE shoreline trend with hinterland to the west of the present outcrop belt. A surface indicating an abrupt increase in the water depth divides the Formation into two units. The lower part encloses inner shelf to foreshore–backshore deposits and the upper part of the succession records deposition from the shoreface to lower deltaplain environment. A tidal flat sandstone–mudstone unit is developed only in the north-western end of the study area. A granite gneiss source terrain cropping out to the west and a hot, humid climate appears to have supplied the abundant quartz sand to the Karutola shoreline, and the sand population attained textural maturity through eolian and aqueous reworking. It is postulated that the aqueous–eolian interaction inferred for the Karutola sand should be common in sandy depositional environments that lacked land vegetation.

Keywords: Dongargarh Supergroup; Palaeoproterozoic; Volcano-sedimentary succession; Quartz arenite; Adhesion structures; Eolian sand sheet; Shallow marine sediments

1. Introduction

The origin of Precambrian supermature quartz arenites has been enigmatic (Pettijohn et al., 1987; Suttner and Basu, 1981; Dott, 2003), since a unique combination of crustal stability, appropriate climate and suitable sedimentation processes was assumed necessary to produce such mineralogically and texturally mature sand. Supermature quartz arenites are commonly interlayered with Archean greenstone belts (Srinivasan and Ojakangas, 1986; Donaldson and de Kemp, 1998; Eriksson et al., 1998; Thurston and Kozhenikov, 2000). These early Precambrian Volcano-sedimentary successions are traditionally believed to have been formed in unstable tectonic conditions (Condie, 1994) thereby contradicting the assumption of crustal stability believed to be required for their mineralogical and textural maturity. Dott (2003) pointed out that textural maturity, particularly the grain roundness is much better developed in the early Palaeozoic and Precambrian arenites than those formed later and probably implies a much greater role of aeolian processes in transporting these sand grains. Eolian facies have been documented in many Precambrian and early Palaeozoic sandstones (Ross, 1983; Pulvertaft, 1985; Dott et al., 1986; Deynoux et al., 1989; Jackson et al., 1990; Chakraborty, 1991; Williams, 1998 and many others) but similar reports are uncommon from 'greenstone'-belt successions (see Donaldson and de Kemp, 1998; Eriksson et al., 1998 for notable exceptions).

The Neoarchean-Palaeoproterozoic Karutola Formation of the Dongargarh Supergroup, is a >200-m-thick supermature quartz arenite unit over- and underlain by two mafic/intermediate volcanic units (Sitagota and Mangikhuta Volcanics,

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doi:10.1016/j.precamres.2007.07.024

Table 1
Stratigraphic succession of the study area

	Unit	Lithology	Group
	Bijepar Formation	(*low-dipping arkosic sandstone and conglomerate*)	
	~~*Unconformity*~~~~~~~~~~		
	Dongargarh Granite		
	~~ *Intrusive contact* ~~~~~~~~~~		
	Mangikhuta Volcanics	(*Mafic volcanics*)	DONGARGARH GROUP
Study unit →	**Karutola Formation**	(*Quartzarenite*)	
	Sitagota Volcanics	(*Mafic volcanics*)	
	Chandsuraj Formation	(*Volcaniclastics*)	
	Pitepani Volcanics	(*mafic volcanics*)	
	Bijli Rhyolite (with Halbitola Rhyolitic breccio-conglomerate Member)	(*Felsic volcanics*)	
	~~		
	Basement ? ?		

Stratigraphic succession of the Dongargarh Supergroup, Central India (*after Sensarma* and *Mukhopadhyay*, 2003).

respectively; Table 1; Sarkar, 1994; Sensarma, 2001, 2005). Despite deformation, in many of the Karutola exposures detrital texture and subtle sedimentary features can be recognised. In this paper we first provide a detailed facies analysis of the Karutola Formation emphasising diagnostic stratification and other textural evidences for eolian sedimentation. We then discuss the possible importance of eolian processes in producing Precambrian supermature qurtzarenites.

2. Geologic setting

The Palaeoproterozoic Dongargarh Group is a several km thick, predominantly volcanic succession, located in the central Indian Craton. It constitutes a NNE-trending, 90 km wide belt that stretches for more than 250 km into Kotri area, Bastar (Sensarma, 2007). It is flanked by the Sakoli synclinorium on the west and the Mesoproterozoic Chattisgarh sedimentary basin on the east (Fig. 1a inset).

The Dongargarh succession of rocks in the study area is folded into a NNE-trending synclinal structure and is cut by a number of faults, including the Darekasa Fault (Fig. 1b; Sarkar, 1994; Sensarma, 2001; Sensarma and Mukhopadhyay, 2003). The succession contains a thick basal Volcano-sedimentary unit (the Dongargarh Group) that has been intruded by Dongargarh Granite. Both the Dongargarh Group and Dongargarh Granite are unconformably overlain by gently dipping cover sediments of the Bijepar Formation (Table 1).

The age data from the Dongargarh succession is not well constrained. However, U–Pb single crystal zircon dating of the oldest and youngest rhyolite layers from the Kotri area, correlatable with Bijli Rhyolite, yielded emplacement ages of 2525 ± 15 and 2506 ± 4 Ma, respectively (Ghosh, 2002, 2004). The intrusive Dongargarh Granite is correlated to the well-known Cu–Mo–Au-bearing Malanjkhand Granite (U–Pb zircon ages of 2478 ± 9 and 2477 ± 10 Ma and an age of ~2500 Ma obtained by Re–Os geochronology), located about 120 km north of the study area in the craton (Panigrahi et al., 2002; Stein et al., 2004). Similar Volcano-sedimentary successions, particularly with basaltic komatite, as reported from Sitagota Volcanics (Sensarma, 2005, 2007), occur across the continents and are reported to have a Neoarchean to Palaeoproterozoic age. Based on these age data Karutola Formation appears to be of late Archean to Palaeoproterozoic age.

3. Facies characteristics of the Karutola Formation

Parts of the Karutola Formation, particularly exposures close to major faults, have been rendered massive and structureless due to brecciation, recrystallisation and silicification. Locally folded beds dip steeply (~55°), and schistosity is well developed in finer grained lithologies. However, away from the faults, many of the Karutola outcrops preserve primary textural features and display a variety of sedimentary structures. Most of the Karutola Formation consists of well rounded, very fine- to coarse-grained, very well to moderately well sorted quartz arenite, and minor mudstone.

Based on sedimentary structure and lithology, five facies are identified in the Karutola Formation: (1) inner shelf to lower shoreface fine-grained sandstone–mudstone facies; (2) shoreface medium- to coarse-grained sandstone facies; (3) delta mouth very coarse to pebbly sandstone facies; (4) tidal channel and tidal flat fine sandstone–mudstone facies; (5) foreshore–backshore fine-grained sandstone facies. Individual facies are described and interpreted in the following section.

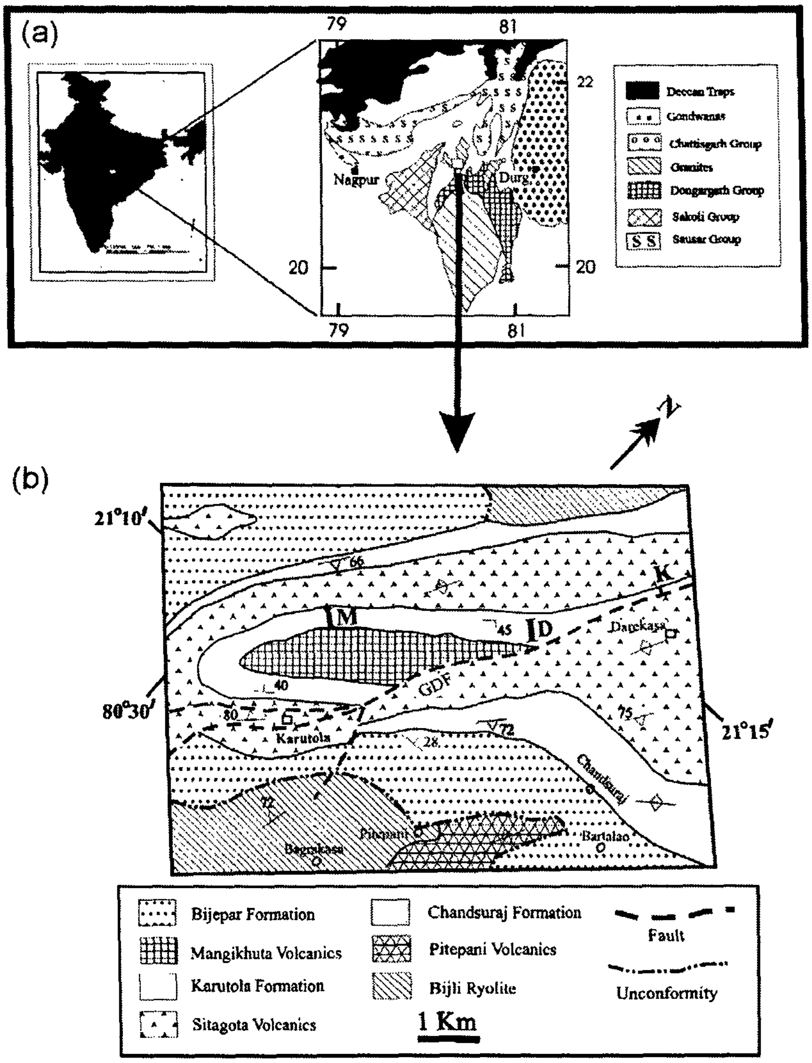


Fig. 1. (a) Generalised outline map of central Indian Craton (after Naqvi and Rogers, 1987). (b) Geological map of the study area (after Sensarma, 2001). M, D and K indicate location of measured sections shown in Fig. 2. GDF, Great Darekasa Fault.

3.1. *Facies 1 (f1): inner shelf to lower shoreface sandstone and mudstone*

This facies consists of very fine sandstone–mudstone units with sparse interbeds of white, medium to coarse-grained sandstone. The facies forms the base of the Karutola succession and attains a maximum thickness of 42 m (Fig. 2). The fine-grained sandstone beds, <10–50 cm thick, have sharp planar contacts with underlying mudstones (Fig. 3). They display low-angle to undulating parallel lamination (Fig. 4) and wave- or combined-flow ripple lamination (Fig. 5). Locally low-angle discordant surfaces separate thinner subsets of parallel lamination and parallel strata at places grade into ripple lamination. Sandstone beds alternate with up to 2–12 m thick mudstone units that show well-developed silty laminae. Few very fine sand or silt laminae show internal ripple foresets (Fig. 3). Wave-ripple crests show a broadly north–north-west trend. The medium to coarse-grained sandstones form 1.5 to 5 m thick bodies with cosets of large planar and trough cross-sets; individual cross-sets are up to 45 cm thick. The coarse sandstones show well sorted, sub-angular to well-rounded grains. Cross-strata (rotated) show a general north-east palaeoflow direction (Fig. 2).

3.2. *Interpretation*

Abundant laminated mudstone, common wave- and combined-flow ripples and an absence of emergence features suggest wave-influenced but generally calm sub-aqueous environment. Sharp based sandstone with parallel lamination, at places grading into ripple lamination, resemble deposits of distal storm-related currents in the inner shelf-lower shoreface environment (cf., Simpson and Eriksson, 1990; Myrow and Southard, 1996). Low-angle truncation between subsets of parallel laminae and their up-arched nature (Fig. 3) resemble hummocky stratification (cf., Cheel and

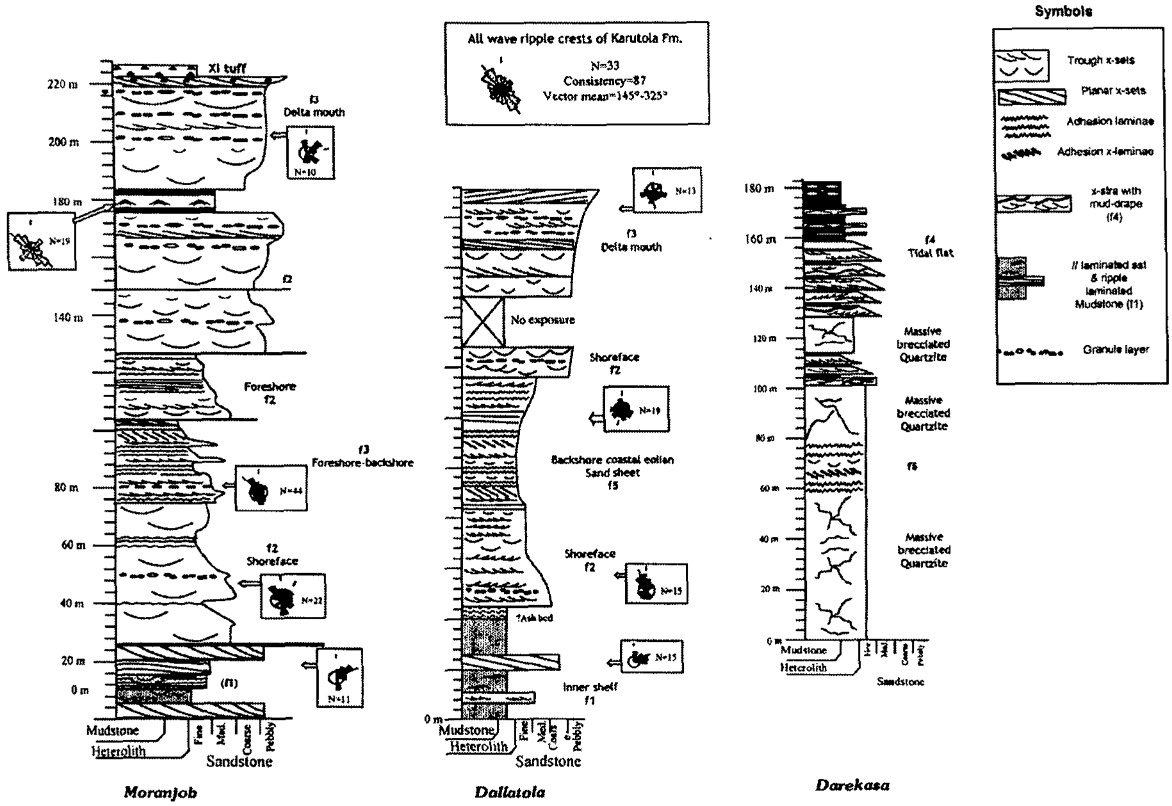


Fig. 2. Correlation diagram of three measured sections of Karutola Formation of the study area. Bi-directional wave ripple crests shown as stippled roses and data from cross-strata are in black. Palaeocurrent azimuths collected in the field were rotated using programme by Saha and Chakraborty (1990) and equal area rose diagrams were prepared using software of Kutty and Ghosh (1992).

Leckie, 1993), commonly inferred to be the product of storm waves (e.g., Southard et al., 1990; Arnott and Southard, 1990).

We infer the coarser grained, well-sorted sandstone with thicker unidirectional cross-strata as isolated patches of sand flushed out of the shoreface or detached from the coastal area through drowning (cf., Anderton, 1976; Johnson and Baldwin, 1996). Close association of these sandstones with inner-shelf sandstone–mudstone deposits, their well-sorted nature, and stratigraphic position conformably below tide-affected shoreface deposits (see facies 2 described below) argues against an intertidal or fluvial origin.

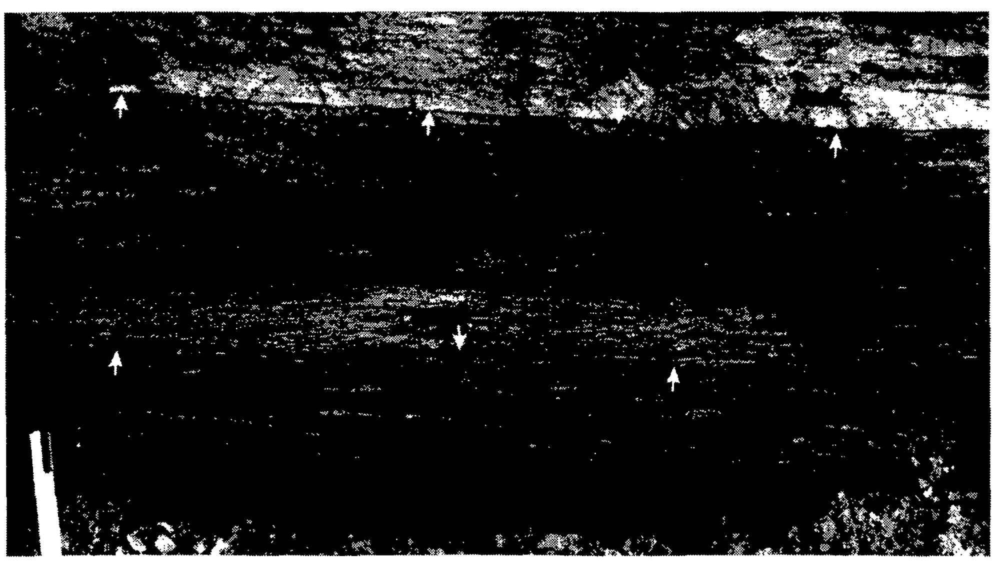


Fig. 3. Sharp-based fine sandstone beds (white arrows) within laminated mudstone, facies 1, Moranjob section. Foresets are visible in the lower sandstone layer.

Fig. 4. Gently up-arched parallel laminations, fine-grained sandstone, facies 1, Moranjob section.

3.3. *Facies 2 (f2): upper shoreface medium- to coarse-grained sandstone*

This facies is a major component of the Karutola Formation. It comprises fine- to coarse-grained, moderately well sorted, well-rounded, red sandstone, with abundant, 7–30 cm thick, planar and trough cross-beds. Facies units attain thickness up to 35 m (Fig. 2). This facies grades up either to the finer grained foreshore deposits (facies f5 described below) or to the very coarse-grained delta mouth facies (f3 described below). Commonly, both planar and trough beds show reversal of foreset dip direction (Fig. 6). Low-angle strata, straight crested wave ripples, and laterally extensive planar sheets of granules (Fig. 7) are common. Foresets are locally draped with mud/silt. Some of the sandstone bodies, ~1.3–2.5 m thick, show a plano-convex geometry, coarsening upward trend and their tops are marked by well-developed wave ripples. In the Moranjob and Dallatola sections upper part of the facies units are characterised by coarser grain size and thicker cross-sets (Fig. 2). Palaeocurrents from cross-beds display wide dispersion (Fig. 2).

3.4. *Interpretation*

The well-sorted, cross-bedded sandstone with wave-rippled pavements and widely dispersed palaeocurrents suggest wave-

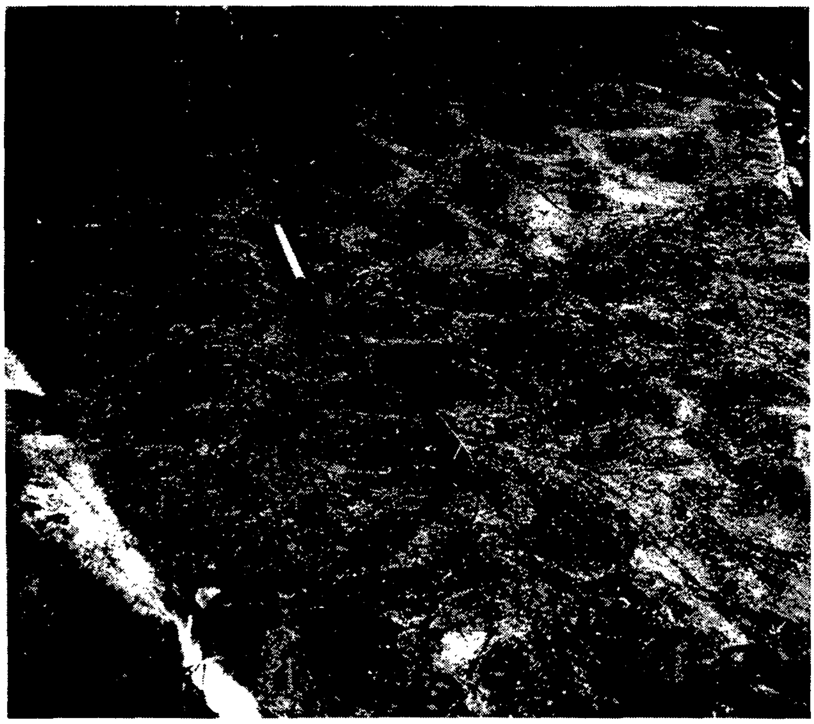


Fig. 5. Bedding plane view of interference wave ripples in facies 1 fine sandstone, Moranjob section.

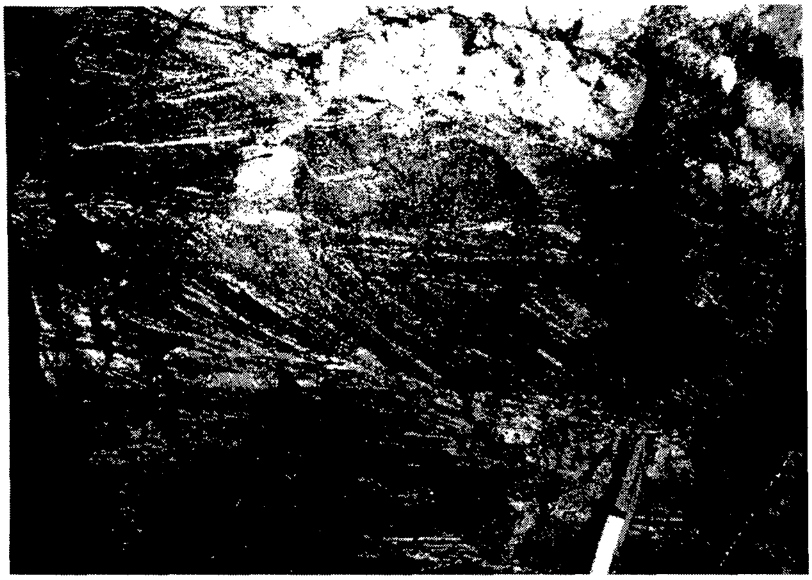


Fig. 6. Adjacent planar cross-sets showing reversal of palaeoflow direction. Note three-dimension nature of the section; facies 2. Moranjob section.

dominated shallow marine environment. Oppositely oriented foresets are consistent with a tidal influence (cf., Johnson and Baldwin, 1996); similarly silt drapes on the foresets suggest fluctuation of tidal currents (cf., Eriksson and Simpson, 2004). The laterally extensive granule layers common within f2 sandstone probably represent wave-winnowed lags (cf., Level, 1980). Increase in the thickness the cross-sets in the upper part of the Dallatola and the Moranjob sections (Fig. 2) imply greater height of the bedforms and thus to greater water depth (Leclair, 2002).

The local convex-up, coarsening upward sandstone bodies may record shallow marine sandstone shoals (Johnson, 1977; Cotter, 1985; Chaudhuri and Howard, 1985; Gozalo, 1985). Thick succession of mature quartz arenite with trough cross-stratification of variable grain size and set thickness, displaying polymodal to bipolar flow pattern, as observed in facies 2, are particularly common in many Precambrian deposits inferred to have formed in a shallow marine environment (Anderton, 1976; Level, 1980; Soegaard and Eriksson, 1985; Jackson et al., 1990; Simpson and Eriksson, 1991).

Fig. 7. Close-up of granule layers in facies 2. Note symmetrical ripple-form within the granule layers (arrow). White bands are late-stage quartz veins; exposure west of Moranjob village.

Fig. 8. Large planar cross-bed in coarse-grained sandstone of facies 3, Dallatola section.

3.5. Facies 3: delta mouth to lower delta plain very coarse to pebbly sandstone

The top of the Karutola Formation in Moranjob and Dallatola sections comprises poorly to moderately sorted, very coarse, pebbly sandstone. This facies gradationally overlies facies 2, shows a coarsening and thickening upward trend and varies in thickness from 28 to 44 m. Trough and planar cross-sets, 10–45 cm thick, are common. Locally planar cross-sets as large as 80 cm (Fig. 8) are encountered. Coarse granule layers, a few mm thick and laterally traceable for few meters are also common. Palaeocurrents are polymodal with major north-east and south–south-east mode (Fig. 2). A laterally impersistent sandy heterolithic unit, few meters thick, is present in the Moranjob section (Fig. 2). It consists of abundant wave-rippled sandstone beds (Fig. 9) alternating with thin units of muddy fine-grained sandstone. In this section, thin beds of crystal tuff of the Mangikhuta basic volcanics conformably overlie facies 3 (Fig. 2; Table 1).

3.6. Interpretation

A coarsening upward trend, interlayered wave ripples and high dispersion of the palaeocurrents are consistent with a marine origin of the facies (McCormik and Grotzinger, 1993; MacNaughton et al., 1997) and coarse-grained, poorly sorted, large planar cross-bedded sandstone, on the other hand, resemble braided fluvial deposits (Miall, 1996; Eriksson et al., 1998). We infer facies 3 were deposited in a delta mouth setting. Similar sand-dominated facies are common in modern delta mouth deposits (Bhattacharrya and Walker, 1992; Orton and Reading, 1993) and has been inferred from many ancient successions as braid-delta deposits (Pulham, 1989; Eriksson et al., 1995; MacNaughton et al., 1997). Conformable passage to

Fig. 9. A number of exposed bedding planes marked by straight crested wave ripples; facies 3, upper part of the Moranjob section. Note hammer for scale.

Fig. 10. Thin mudstone drapes (arrowed) separating wave-rippled units. These beds occur at the top of a ~2 m thick fining upwards sandstone body. Facies 4, Darekasa railway cutting. Diameter of coin is 2.3 cm.

Mangikhuta Volcanics through a bed of crystal tuff in the uppermost part of the Karutola Formation indicates contemporaneous volcanism and sedimentation.

3.7. Facies 4: tidal channel and tidal flat fine sandstone and mudstone

The facies is developed only in the northernmost part of the Karutola outcrop belt and comprise an overall fining-upward, 180 m thick succession of sandstone, heterolithic units and mudstone. The relationship of this facies to others cannot be evaluated due to poor exposure. In the lower part, the facies comprises stacked fining-upward amalgamated sandstone bodies, 95–405 cm thick, separated by 7–60 cm thick mudstone or heterolithic units. The lower parts of the sandstone bodies consist of 0.65–3.0 m thick medium to coarse-grained sandstone beds with 2–21 cm thick planar and trough sets, forming cosets 25–60 cm thick. Cross-sets show internal reactivation surfaces. Upper parts of the sandstone bodies are medium- to fine-grained, and their tops commonly marked by wave ripples and mudstone flasers (Fig. 10). The wave ripples are locally flat-topped (Fig. 11). Many of the thick sandstone bodies discordantly overlie mudstone or heterolithic units (Fig. 12).

The upper part of the succession is dominated by fine-grained lithologies (Fig. 2) and comprises alternation of 10–90 cm thick sandstone units with 15–120 cm thick heterolithic or massive mudstone units, forming depositional units up to 2 m thick. Heterolithic units locally show an upward increase in the proportion and thickness of the sandstone interlays, passing upward into erosively based sandstone units (Fig. 12). Flaser-lenticular beds (Fig. 13) are the commonest sedimentary structure within the heterolithic beds. Two to twenty centimetres thick fine-grained sandstone strata within heterolithic units contain parallel lamination, wave ripples and mud flasers. Water injection and load structures are common.

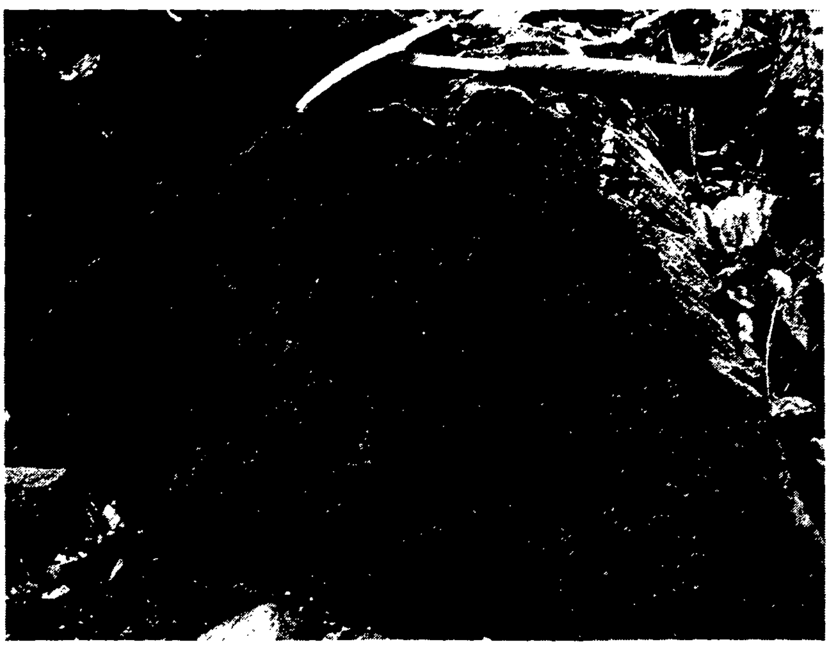


Fig. 11. Flat-topped wave ripples occurring at the top of a sandstone sheet, lower part of facies 4, Darekasa Railway Cutting.

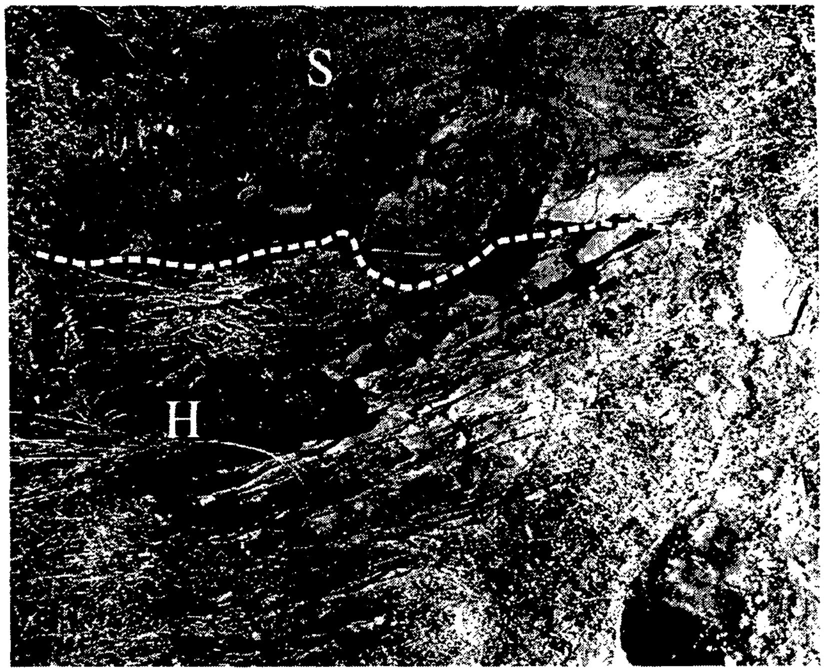


Fig. 12. Thick sandstone bed (S) discordantly overlying sandstone-dominated heterolithic unit (H) in facies 4. Note a gutter-like feature at the base of the sandstone (near the hammer). The photo frame has been rotated 90° counter clockwise to emphasise the discordant relationship of the thick sandstone body.

3.8. Interpretation

The prevalence of heterolithic or mudstone units in this facies indicates a relatively low-energy environment and abundant of wave ripples imply wave influence. Flaser-lenticular beds, flat-topped wave ripples, mud drapes or partings and reactivation surfaces signify fluctuating flow strength such as is common in tidal flat environments (Reineck, 1972; Reineck and Wunderlich, 1968; Nio and Yang, 1991). The erosively based, fining-upward cross-stratified sandstone with internal mud-drapes, and flaser-lenticular bedded heterolithic caps, compares well with tidal channel deposits (Moslow and Tye, 1985; Dalrymple, 1992). Sheet-like geometry of the cross-bedded sandstone in this facies probably reflect wide, poorly defined tidal channels in a vegetation-free sandy shoreline, such as has been interpreted for other Precambrian successions (cf., Tirsgaard, 1993). Heterolithic and mud-dominant units in the upper part of facies 4 (Fig. 2,) were probably laid down in shallower water tidal flat environment (cf., Dalrymple, 1992; Deynoux et al., 1993). Parallel or wave ripple-laminated sandstones probably document periodic intense storms in the lower mixed flat environment (Elliott, 1986). Increased proportion of sand in heterolithic units, present locally, might represent prograding levees of associated tidal channels (Wanless et al., 1988; Cloyd et al., 1990). The overall fining-upward trend (Fig. 2) probably resulted from the progradation of the tidal depositional system (cf., Reading and Collinson, 1996)

Fig. 13. Flaser-lenticular beds of facies 4, Darekasa Railway Cutting. Note rounded, near-symmetrical nature of the ripple-forms. Flattened nature of the ripples is due to tectonic deformation.

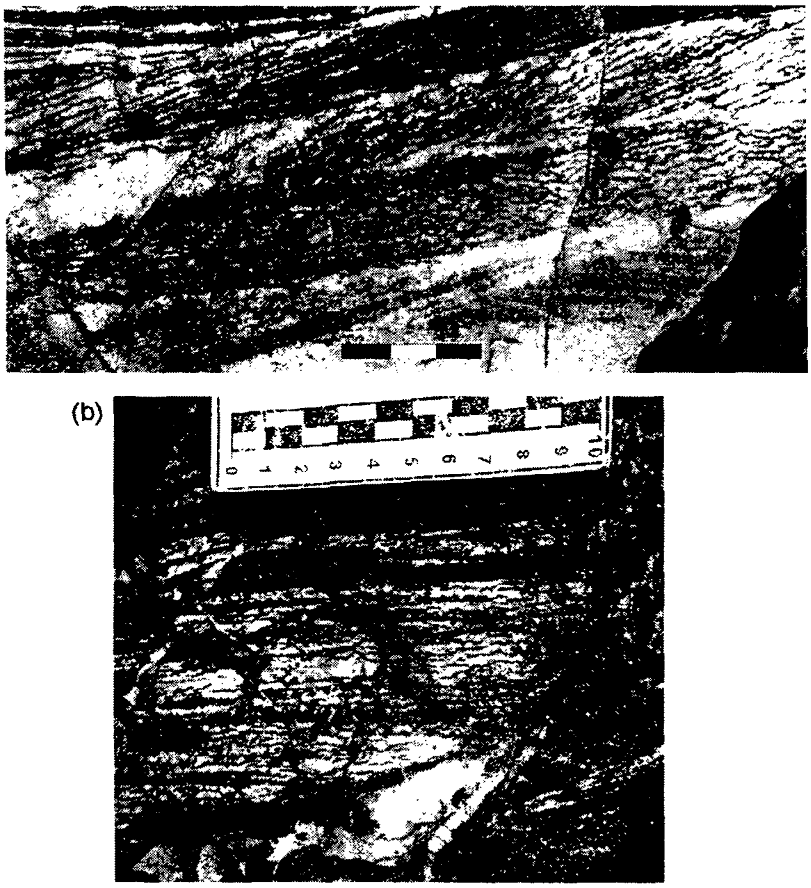
(a)
(b)


Fig. 14. (a) Adhesion cross-laminae and adhesion plane bed, facies 5 Moranjob section. Note small cross-strata underlie the adhesion plane bedded unit. Scale bars in cm. (b) Vertically stacked three units of adhesion laminae. Scale bars in cm; facies 5, Dallatola section.

3.9. Facies 5: foreshore–backshore medium-fine sandstone

The facies, 24–40 m thick, comprises medium- to very fine-grained, well-sorted, red sandstone with cross-sets 1.5–7 cm thick, massive beds, parallel lamination, and a variety of adhesion structures (Figs. 14 and 15). Some sandstone shows a well-developed bimodal texture (Fig. 16), in which the medium-sized grains are very well rounded whereas the finer grains are sub-rounded. Palaeocurrents display a polymodal pattern (Fig. 2).

The facies displays repeated but non-cyclic interlayering of adhesion structures, massive sandstone and cross-strata in beds 6–30 cm thick (Figs. 17 and 18). The beds are typically sheet-like imparting a distinctive thinly bedded appearance. Massive beds are common, some of which are marked by slightly coarser grain size and erosional basal surfaces (Fig. 18). Adhesion laminated units can be observed locally to merge laterally with massive strata. Parallel stratification, similar to pin stripe lamination (cf., Fryberger and Schenk, 1988), are typically few mm thick and laterally traceable over several decimetres (Fig. 15). Thin sections of these pin stripe laminae show inverse grading (Fig. 19).

Small trough beds occur as nested sets and consist of medium-grained sandstone that is coarser than adhesion laminated units (Fig. 18). Bipolar herringbone cross-strata are present locally (Fig. 20). The proportion of adhesion-dominated and cross-strata dominated units change vertically forming small-scale (~5 m) coarsening and thickening upward successions (Fig. 17).

Some of the planar cross-strata within fine-grained sandstone encased within parallel or adhesion stratified units show conspicuous grain size differentiated, wedge-shaped foresets layers (Fig. 21).

3.10. Interpretation

We interpret that facies 5 represents a broad coastal eolian belt that was periodically subjected to marine flooding. Adhesion structures form as wind-blown dry sands stick to a wet or damp substrate (Kocurek and Fielder, 1982). Hence abundant adhesion structures in facies 5 indicate subaerial exposure. The laminae in which inverse grading could be identified in thin sections are translatent wind-ripple strata (cf., Kocurek and Dott, 1981). Planar cross-sets with well-developed, grain size differentiated, wedge-shaped foresets (Fig. 21) are inferred as remnants of small eolian dunes with coarser grainflow wedges pinching out down the dune foreset and irregularly alternating with finer grainfall strata (cf., Hunter, 1977). Bimodal texture such as observed in facies 5, is typical of some desert dunes (Folk, 1968). Role of wind as a much more efficient agent than

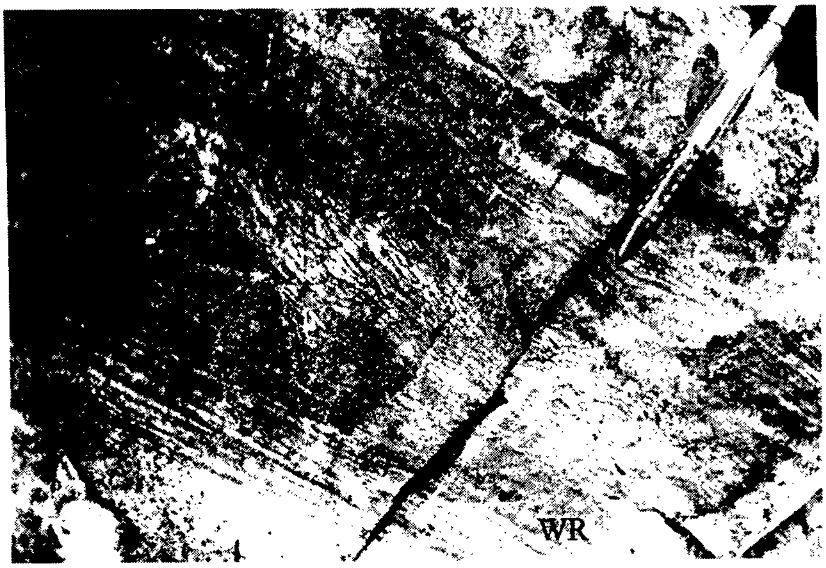


Fig. 15. Pin-stripe parallel laminae (WR) in the lower part of the section, overlain by indistinct parallel laminae and a set of adhesion cross-strata (A). Note the foresets of adhesion cross-laminae grade into low-angle adhesion laminae in the down current direction. Length of the pen is 14 cm.

water in producing grain roundness is well established and abundant well-rounded, well-sorted sand grains is typical of many eolian deposits, particularly those of the pre-Silurian age (Dott, 2003).

Nested small trough sets and other planar sets that lack typical wedge-shaped foresets are inferred to be the products of migrating 2D and 3D aqueous dunes. Slightly coarser massive beds with erosional lower contacts probably represent shallow, aqueous deposits in which rapid deposition inhibited development of bedforms. Polymodal palaeocurrents is typical of shallow marine environment; bi-directional trough strata imply reversing tidal currents. Polymodal palaeocurrent pattern, bimodal cross-strata, abundance of adhesion structures and stratigraphic position gradationally above shoreface deposits (f2) indicate an overall sandy foreshore–backshore depositional environment. In contrast to the common presence of mudrocks in the supratidal region of many present day coasts (Reading and Collinson, 1996) the mud-free clean sandy nature of the f5 deposits coupled with the presence of mudstone in off-shore deposits of Karutola Formation probably reflect the combined effect of wave and eolian winnowing (Dalrymple et al., 1985). Similar sand-dominated marine or lacustrine coastal deposits have been reported from a number of pre-Silurian successions (Dott et al., 1986; MacNaughton et al., 1997; Aspler et al., 1994).

Successions of aqueous, adhesion and wind ripple strata are inferred to indicate decreasing or increasing substrate moisture

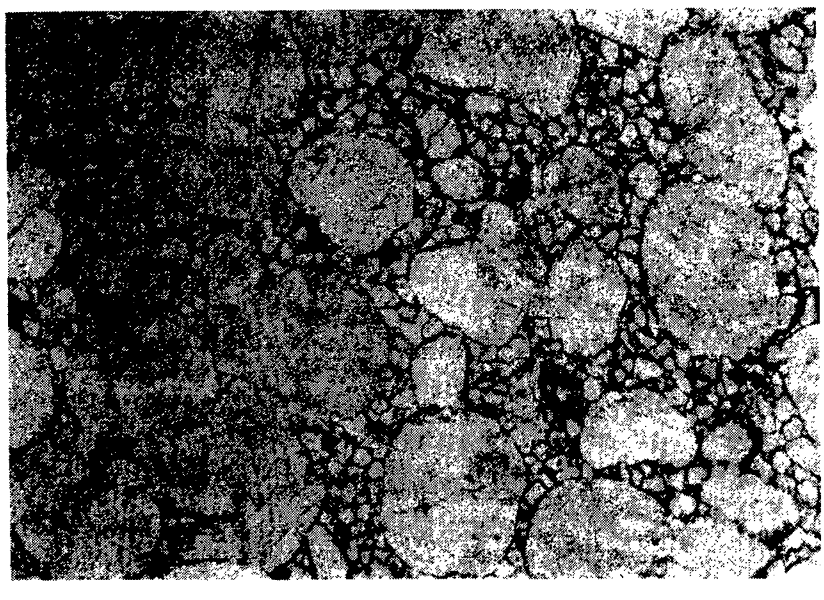


Fig. 16. Thin section of facies 5 sandstone showing well-developed bimodal texture. Note coarser grains are very well rounded and comparatively finer grains are less well rounded. Scale bar in top left is 200 μm.

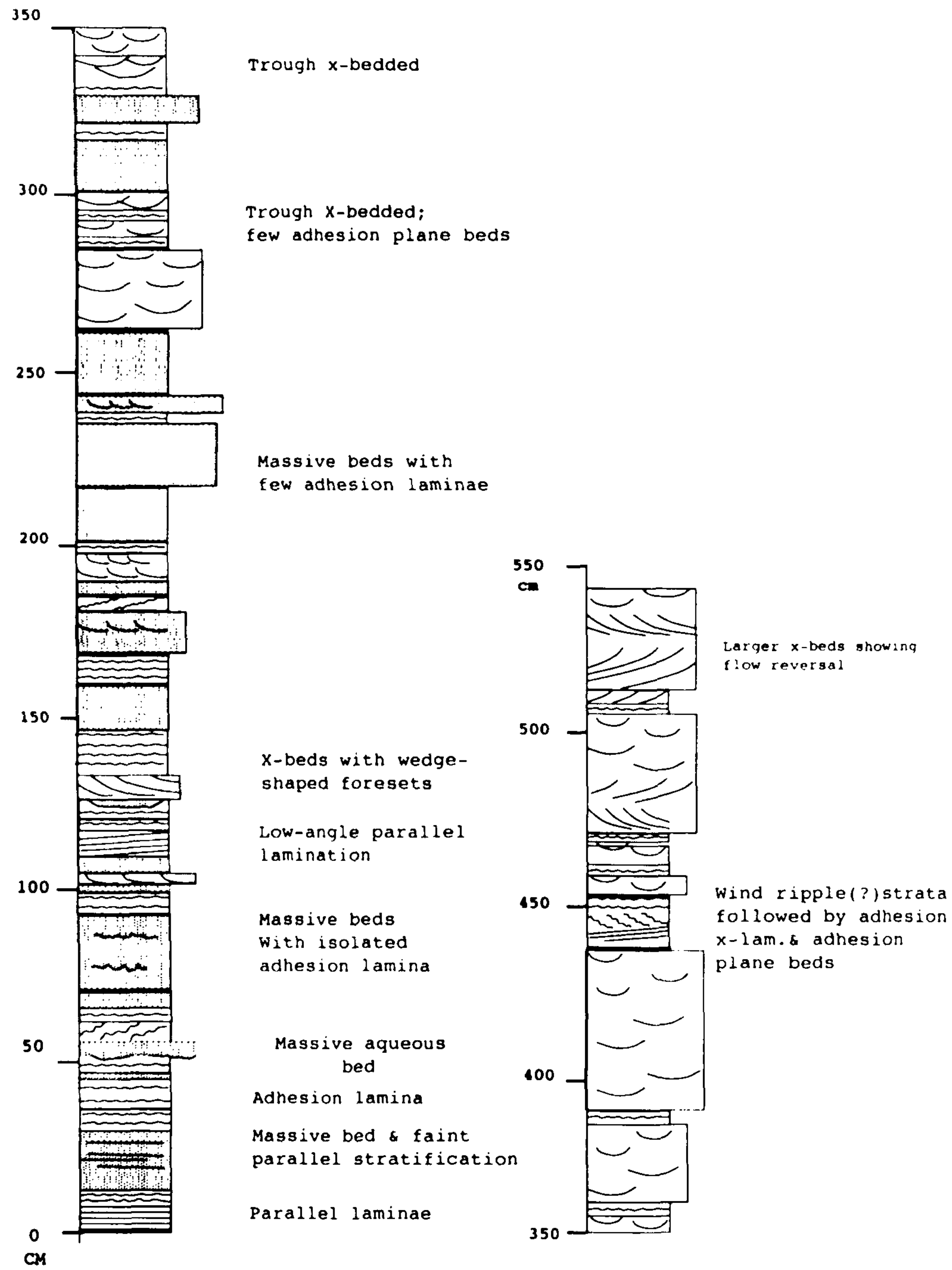


Fig. 17. Detailed log through a portion of facies 5, Moranjob area, showing the details of interlayered adhesion strata, cross-strata and massive strata. Note random superposition of these strata, domination of adhesion structures over other types of eolian strata and paucity of eolian dune cross-strata in the succession.

(drying or wetting upward successions; cf., Kocurek and Fielder, 1982). But interlayering between aqueous and adhesion strata, and lateral gradation of one to the other (Figs. 14a and 17), probably indicate repeated marine inundation of a sandy coastal plain where eolian processes continuously reworked the available dry sands. General paucity of eolian dune cross-strata in the succession underlines the differences in the depositional setting of f5 with that of coastal interdune–dune complex (cf., Hummel and Kocurek, 1984; Kocurek, 1996).

Adhesion structures in swash zones of sandy shorelines are well known (Reading and Collinson, 1996, p. 166; Schenk, 1990), but their preservation is relatively uncommon (Elliott, 1986). However, adhesion and other eolian strata comprise 10–60% of f5 (Fig. 17) and low-angle parallel stratification, a common deposit in swash zones, is sparse. Hence, this facies probably represents a wide sandy coastal belt where coastal aqueous processes closely competed with background wind transport and deposition.

Fig. 18. A polished section of f5 sandstone. Note vertical interlayering of thin wind ripple strata (WR), adhesion plane beds (ADP), massive bed (MB), adhesion cross-laminae (ADX) and aqueous cross-strata (AQ). Note erosive lower contact (dashed line) and coarser grain size of the aqueous bed (AQ). Thin section of lower wind ripple strata is shown in Fig. 19.

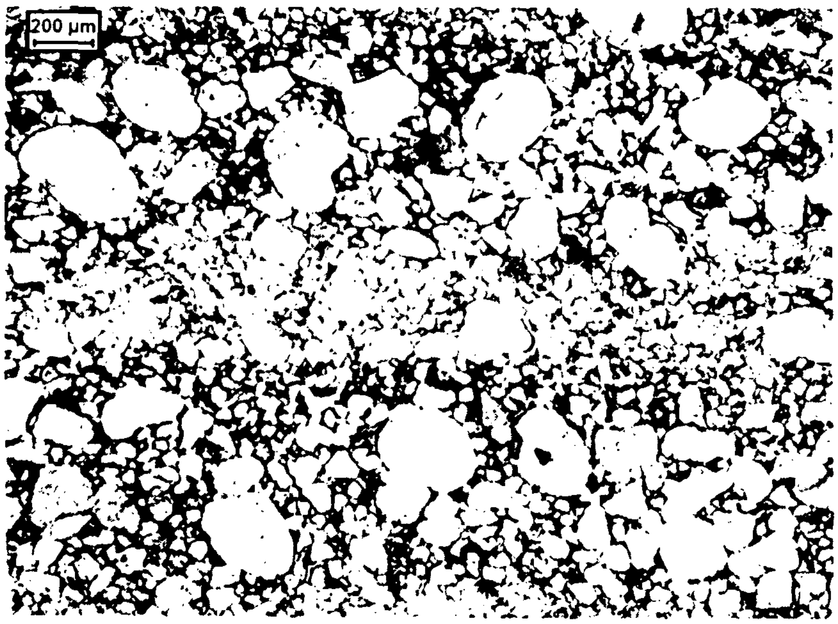


Fig. 19. Photomicrograph of thin parallel laminated unit of f5. Note distinct inverse grading in two successive layers. Plane polarised light.

4. Facies succession and palaeogeography of the Karutola Formation

The Karutola Formation is well exposed along the western limb of the Karutola syncline and sedimentological logs have been constructed from three different profiles along this limb (Figs. 1 and 2). Whereas basal contacts of the Karutola Formation with the underlying Sitagota Volcanics cannot be evaluated due to scree cover, the gradational passage of Karutola arenite to the overlying Mangikhuta Volcanics is well documented in the Moranjob section. Extensive brecciation and silicification associated with the Darekasa fault system obscures the stratigraphic position of the Darekasa section. The Moranjob and Dallatola sections show development of a comparable succession and the characteristic thin-bedded adhesion structure dominated foreshore–backshore facies can be physically traced across the sections >3 km apart (Fig. 1). The Darekasa succession has been tentatively correlated with the other two sections on the basis of the occurrences of foreshore–backshore facies (Fig. 2).

The NW–SE-trending mean orientation of all the rotated wave ripple crests (Fig. 2) is inferred to indicate the general trend of the Karutola shoreline. A northeast to southeast component of the delta mouth facies (f3) is inferred to reflect the off-shore direction. The north-eastward mean direction recorded from the large cross-bedded units of inner shelf facies (f1) probably record off-shore directed current system, as is common in many present day shelves (Johnson and Baldwin, 1996). The lower part of the Karutola succession represents a progradational facies succession where inner shelf-lower shoreface facies is progressively overlain by the upper shoreface and foreshore–backshore succession. In both the Moranjob and Dallatola sections, fine-grained, eolian-aqueous foreshore–backshore deposits of f5 are sharply overlain by a succession of coarser grained f2 shoreface

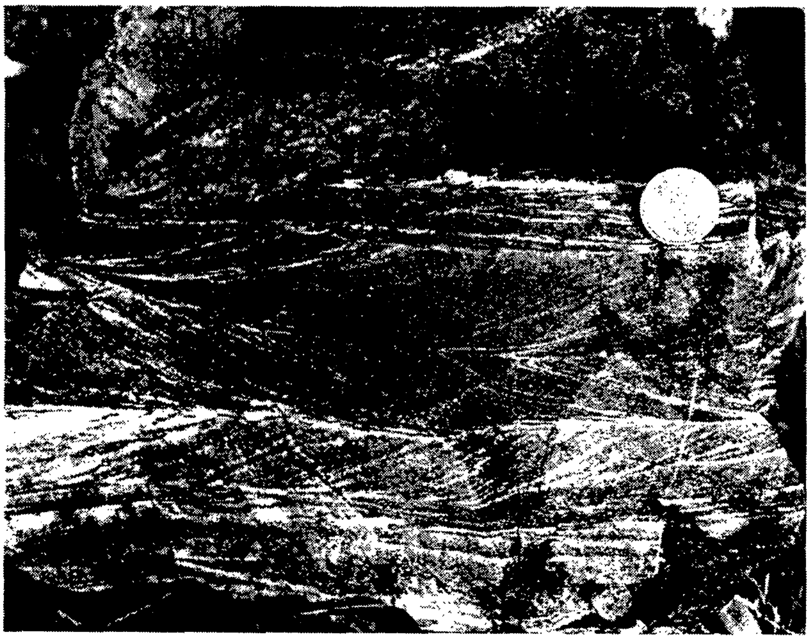


Fig. 20. Three-dimensional slab exposing small trough cross-strata of facies 5. Trough sets show reversing palaeoflow direction. Note deep red colour of the sandstone. Diameter of the coin is 2.3 cm. Moranjob section (For interpretation of the references to colour in this and other figure legends, the reader is referred to the web version of the article.)

deposits. Generally thicker cross-sets and coarser grain size of this unit of f2 may imply an abrupt increase in water depth and coarse sediment supply at the Karutola shoreline. A coarsening upward trend in the upper part of the Karutola succession, culminating in the poorly sorted pebbly sandstone (f3) probably denotes development and progradation of a braid delta system.

Assuming NW–SE overall shoreline trend, palaeocurrent measured from all the shallow marine deposits show a strong shore-parallel flow component (Fig. 2). This probably implies significant longshore drift. The mud-dominated tidal channel and tidal flat succession in the northwestern-most studied section (Darekasa section, Figs. 1 and 2) implies development of a protected embayment-type environment. Development of delta mouth farther southeast (Dallatola area) probably protected the Darekasa area from longshore currents and high-energy fluvial discharge favouring development of muddy tidal flat. Interlayered crystal tuff beds at the topmost part of the Karutola Formation (Fig. 2, Moranjob section) indicate contemporaneous volcanism in other parts of the basin that eventually gave rise to Mangikhuta volcanic succession. Fig. 22 schematically shows the reconstructed palaeogeography for the Karutola Formation during the final phases of its deposition.

Fig. 21. Nine centimetres thick planar cross-set showing well-developed wedge-shaped alternate coarse (lighter coloured) and fine (darker) foreset layers. Facies 5, sections NE of Moranjob section.

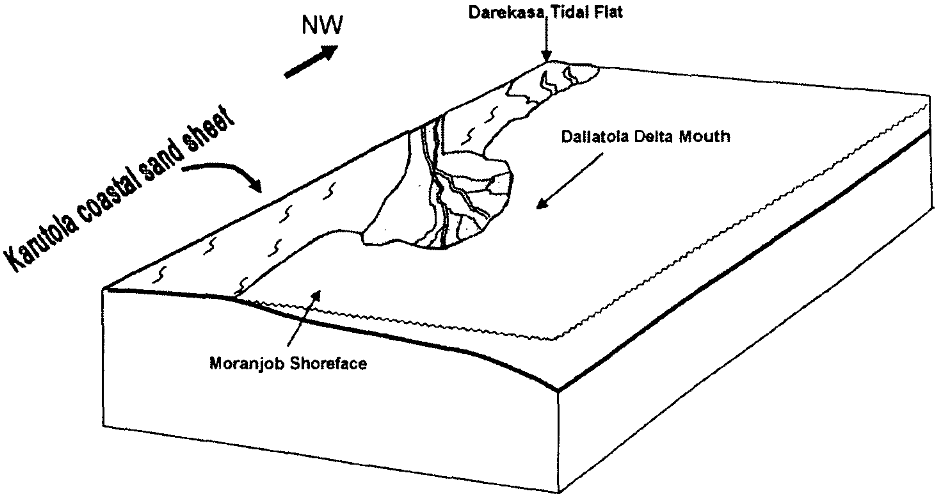


Fig. 22. The inferred palaeogeographic scenario of the Karutpla Formation.

5. Eolian deposits of the Karutola Formation

The eolian deposits of the Karutola Formation have several peculiarities compared to most other eolian deposits: (1) the eolian strata can be recognised throughout the 40 m thick facies succession (f5), although large eolian dune cross-beds are nearly absent; (2) adhesion structures, particularly adhesion plane beds dominate over other types of eolian strata in the succession; (3) aqueous deposits comprise a significant part of the facies and occur interlayered with eolian strata all through the facies; (4) facies characteristics of this unit differ markedly from other sand sheets deposits recognised in modern or Phanerozoic eolian deposits (e.g., Fryberger et al., 1979, 1988; Kocurek and Nielson, 1986; Porter, 1987).

A significant (up to 60% of individual depositional units) contribution of eolian deposits in the f5 identifies it as coastal eolian sand sheet rather than a simple foreshore–backshore deposit. Lateral (>6 km) and vertical extent (~40 m) of the depositional facies indicate that it was not an insignificant component of the coastal environment but developed as a major coastal sand sheet in the Karutola coastal flat. Similar eolian–aqueous deposition has been recorded in the winter-storm affected wet interdunes of the coastal eolian dunefield, Padre Island (Hummel and Kocurek, 1984) and a very similar coastal eolian sand sheet has been described from the Late Proterozoic Shikhoda Formation of India (Chakraborty and Chakraborty, 2001).

Development of ripples to large draas in an eolian environment is a function of competent wind regime, sand saturation and duration over which the bedform building processes operate (Wilson, 1972; Kocurek, 1996). In spite of absence of factors commonly identified from modern sand sheet environment to inhibit of dune developments (Fryberger et al., 1979; Kocurek and Nielson, 1986) like vegetation, salt crusts and deflationary wind regime, paucity of larger eolian bedforms in the Karutola is remarkable. Repeated but non-cyclic interlayering of eolian and aqueous deposits in the Karutola Formation indicates intermittent inundation by shallow sheet of marine water in wind reworked coastal flats. We interpret that rapid seepage of this water through mud-free clean sandy substrate in the Karutola coastal plain produced a wide area of wet sand. Invading sheets of water would have destroyed any incipient dunes that might have developed within the inundation area and created a large wet patch surrounding the water sheet. This wet patch would have drastically reduced dry sand supply to surrounding area for possible eolian bedform development or accretion. Within a short time a damp substrate would have developed from the wet patch, for possible accretion of adhesion bedforms (cf., Chakraborty and Chakraborty, 2001).

Eolian deposits appear to be more common in all pre-Devonian sandy continental or coastal environments (cf., Eriksson and Simpson, 1998; Dott, 2003). Many of these deposits are dominated by low-angle sand sheet facies with significant presence of adhesion structures (Eriksson et al., 1998; Simpson and Eriksson, 1991, 1993; Chakraborty and Chaudhuri, 1993; Tirsgaard and Oxnevad, 1998; Chakraborty and Chakraborty, 2001). Repeated flooding, either by marine waters (in coastal areas) or by overbank flows associated with shallow, wide channels (in alluvial plains) probably acted as main deterrent for dune growth in this facies and favoured abundance of associated adhesion strata.

6. Origin of the quartz arenite

Source of quartz sand for Karutola Formation, interlayered with thick mafic volcanic units (Mangikhuta and Sitagota Volcanics, Table 1) in Dongargarh Group is unknown. Limited palaeocurrent data obtained from shallow marine deposits of the Karutola Formation indicate a NW–SE-trending shoreline with major fluvial input coming from the west of the present day outcrop belt (Figs. 1 and 2). The Dongargarh Volcano-sedimentary succession is inferred to have been deposited in a rifted continental setting (Sensarma, 2001, 2007) and the entire Volcano-sedimentary package is floored by the Archean Sakoli Granite gneiss (Sarkar, 1994; see also Ghosh, 2004) that at present crops out about 30 km west of the study area. The Karutola Formation is underlain by Sitegota mafic/intermediate volcanics and thick unit of Bijli felsic volcanics. Both the volcanic successions outcrop west of the Karutola belt. The Bijli Volcanics contain abundant coarse sand sized clear, embayed quartz grains that could be a potential source rock for the Karutola Quartzite. However, petrographic investigation fails to identify any volcanic quartz grain in the Karutola arenite. On the contrary presence of coarse polycrystalline quartz grains are common indicating a granitoid source rock.

Recent studies indicate that climates exercise an overriding control on the development of first cycle quartz arenites over surface relief and tectonic setting (Johnsson et al., 1988). Johnsson et al. (1988) have demonstrated from the Orinico River Basin of South America that sediments derived from the highlands of the Andean fold-thrust belt and lowlands of the Guayana Shield both yield first cycle quartz sand provided that intense chemical weathering of the equatorial region can operate for fairly long time period.

The remarkable absence of salt pseudomorph or salt crusts in the supratidal eolian sheet sands implies a favourable balance between precipitation and evaporation. This in turn would imply a humid climatic condition during the deposition of Karutola sandstone. Given a warm humid climate favourable for intense chemical weathering, it is possible to derive significant amount of quartz sand from the gneissic basement. Recently Dott (2003) has emphasised the important role of eolian abrasion in producing Precambrian supermature quartz arenite. Many of the mature Precambrian quartz arenites have been interpreted to contain eolian deposits, but a similar imprint of eolian reworking is scanty from the Neoarchean-Palaeoproterozoic greenstone belt arenites, which are associated with thick mafic volcanic units. Recognition of coastal eolian sand sheet within Karutola Formation and abundance of well-rounded sand grains in it provide the evidences for eolian processes in the deposition and textural maturity of this ~2.5 Ga quartzose unit.

7. Conclusions

1. Five facies can be recognised in the Karutola Formation. These represent inner shelf, shallow marine shoreface, delta mouth, tidal flat and coastal eolian sand sheet environments.
2. The lower part of the succession records deposition from inner shelf sandstone–mudstone to foreshore–backshore units. The upper part of the succession coarsens into a delta mouth/lower deltaplain succession.
3. A coastal sand sheet developed in the backshore region of Karutola coastal flat, forming a succession comprising almost equal volumes of adhesion and shallow aqueous deposits. Eolian processes continuously reworked the sandy coastal plain, but intermittent flooding of the low gradient coastal plain inhibited dune development and favoured the development of adhesion structures over other types of eolian strata.
4. Abundance of quartz sand is attributed to intense chemical weathering under a hot and humid climate in a vegetation-free landscape. Eolian processes reworked them to produce supermature quartz arenite and transported them to the coastal domain.

Acknowledgements

We express our indebtedness to D. Mukhopadhyay of Calcutta University for many insightful discussions at the initial stage of this work. We are extremely thankful to Sanjib Chakraborty, Sanjoy Ghosh, Rimpal Kar and Samarpan Dey, all of Indian Statistical Institute for their enthusiastic and very competent assistance. Earlier version of the manuscript benefited from the comments by S.N. Sarkar and C. Chakraborty. Constructive comments by L.B. Aspler and an unknown reviewer significantly improved the manuscript.

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