Climbing ripple structure and associated storm-lamination from a Proterozoic carbonate platform succession: Their environmental and petrogenetic significance

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The Mesoproterozoic Pandikunta Limestone, a shallow water carbonate platform succession in the Pranhita–Godavari Valley, south India, displays well developed climbing ripple lamination and storm deposited structures, such as HCS, wave ripple-lamination, combined-flow ripple-lamination and low angle trough cross-stratification. Different types of stratification developed in calcisiltite with minor amounts of very fine quartz sand and silt. The climbing ripple structures exhibit a complex pattern of superposition of different types (type A, B and S) within cosets pointing to a fluctuating rate of suspension deposition *versus* bedform migration, and an unsteady character of the flow. Close association of climbing ripple structures, HCS with anisotropic geometry, wavy lamination and combined-flow ripple-lamination suggest that the structures were formed by storm generated combined-flow in a mid-shelf area above the storm wave base. The combined-flow that deposited the climbing ripple structures had a strong unidirectional flow component of variable magnitude. The climbing ripple structure occurs as a constituent of graded stratified beds with an ordered vertical sequence of different types of lamination, reflecting flow deceleration and increased rate of suspension deposition. It is inferred that the beds were deposited from high-density waning flows in the relatively deeper part of the ancient shelf. The structures indicate that the Pandikunta platform was subjected to open marine circulation and intense storm activities.

The storm deposited beds, intercalated with beds of lime-mudstone, consist primarily of fine sand and silt size carbonate particles that were hydrodynamically similar to quartz silt. Detrital carbonate particles are structureless and are of variable roundness. The particles were generated as primary carbonate clasts in coastal areas by mechanical disintegration of rapidly lithified beds, stromatolites or laminites, and the finest grade was transported to the offshore areas by storm-generated currents.

1. Introduction

Climbing ripple cross-lamination occurs in diverse sedimentary environments, such as river flood plains, deltas, esker or glacial out-wash plains and submarine fans dominated by strong unidirectional flows (Kuenen 1957; Bouma 1962; Walker 1963, Coleman and Gagliano 1965; McKee 1966; McKee *et al* 1967; Jopling and Walker 1968; Allen 1971; Stanley 1974). Studies in recent sediments, ancient rocks and flume experiments (McKee 1965, 1966; McKee *et al* 1967; Jopling and Walker 1968; Allen 1970, 1971) have established that the structure forms under unidirectional flow, with concurrent deposition from traction and suspension. The morphology of the structure varies due to variations in the rate of bedform migration and the rate of deposition from suspension (Jopling and Walker 1968; Allen 1971). Events with episodic rapid accumulation of sediment would consequently favour

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Table 1. *Lithostratigraphic succession of Proterozoic Formations around Ramgundam in the Pranhita–Godavari Valley (after Chaudhuri and Howard 1985).*

		Group	Formation	Lithology	Depositional setting
GODAVARI SUPERGROUP	PAKHAL GROUP	Sullavai Group	Venkatpur Sandstone (300 m)	Fine-grained subarkose	Erg deposit
			Encharani Formation (90 m)	Ferruginous quartzose sandstone, pebbly arkose, arkosic sandstone	Fan – braided fluvial
			Unconformity		
		Mulug Subgroup	Rajaram Formation (735 m)	Calcareous sandstone with lenses of sandy limestone, intraclastic limestone, limestone and dolomite interbedded with green calcareous shale	Bank-lagoon
			Ramgundam Sandstone (120 m)	Arkosic and subarkosic sandstone with interbedded shale	Intertidal bar-shoal
			Jakaram Conglomerate (90 m)	Conglomerate, pebbly arkose and coarse-grained arkose	Alluvial fan
			Unconformity		
		Mallampalli Subgroup	Pandikunta Limestone (340 m)	Flat bedded limestone, dolomitic limestone with intercalated lenses of glauconitic sandstone; **K-Ar date 1330 ± 53 Ma** Stromatolitic limestone/dolomite	Shallow water platform
			Bolapalli Formation (50 m)	Interbedded quartzose sandstone, limestone and dolomite with small lenses of basal conglomerate and arkose	Coastal marine and shoreface
			Unconformity		
				Archaean basement	

development of the structures, whereas those characterized by much reworking, without addition of new sediments, are unfavourable. As a consequence of hydrodynamic constraints, the structure is not commonly reported from tidal flats (McKee 1965, 1966; Reineck 1972) or shallow marine shelves. There are only a few reports of climbing wave ripple-lamination, very similar to hummocky cross-stratification, from storm dominated shelf sequences (Kreisa 1981; Aigner 1985), though climbing current ripple-lamination is rarely reported from storm sequences (Kreisa 1981; Handford 1986).

Various types of climbing ripple structures were reported by Chaudhuri (1970a) from the Pandikunta Limestone (table 1), an extensive Mesoproterozoic carbonate platform in the Pranhita–Godavari Valley, south India (figure 1) dominated by lithographic limestone. In the present paper, different types of climbing ripple-lamination and associated wave generated lamination will be described, and the structures will be related to the processes and environments of a shallow water carbonate platform. Palaeogeographic implication of the structures will be discussed, and an attempt will also be made to address the bearing of the structures on the question of occurrence of non-skeletal carbonate silts and their identification in fine grained carbonate deposits.

2. Geologic setting

The Pranhita–Godavari Valley is a major repository of Meso- and Neoproterozoic sedimentary rocks in the south Indian craton (figure 1). The basin has been inferred as a NW–SE trending cratonic rift (figure 1), and has been related to fragmentation of a Mesoproterozoic supercontinent (Chaudhuri *et al* 2002; Chaudhuri 2003). The complex history of multiple opening and closure of the basin is manifested in the development of multiple unconformity-bound sequences (table 1). The basal sequence, the Mallampalli Subgroup, unconformably overlies the granulites and granite gneisses of the Archaean basement complex, and is well exposed along the southwestern margin of the basin. Around Ramgundam, in the central

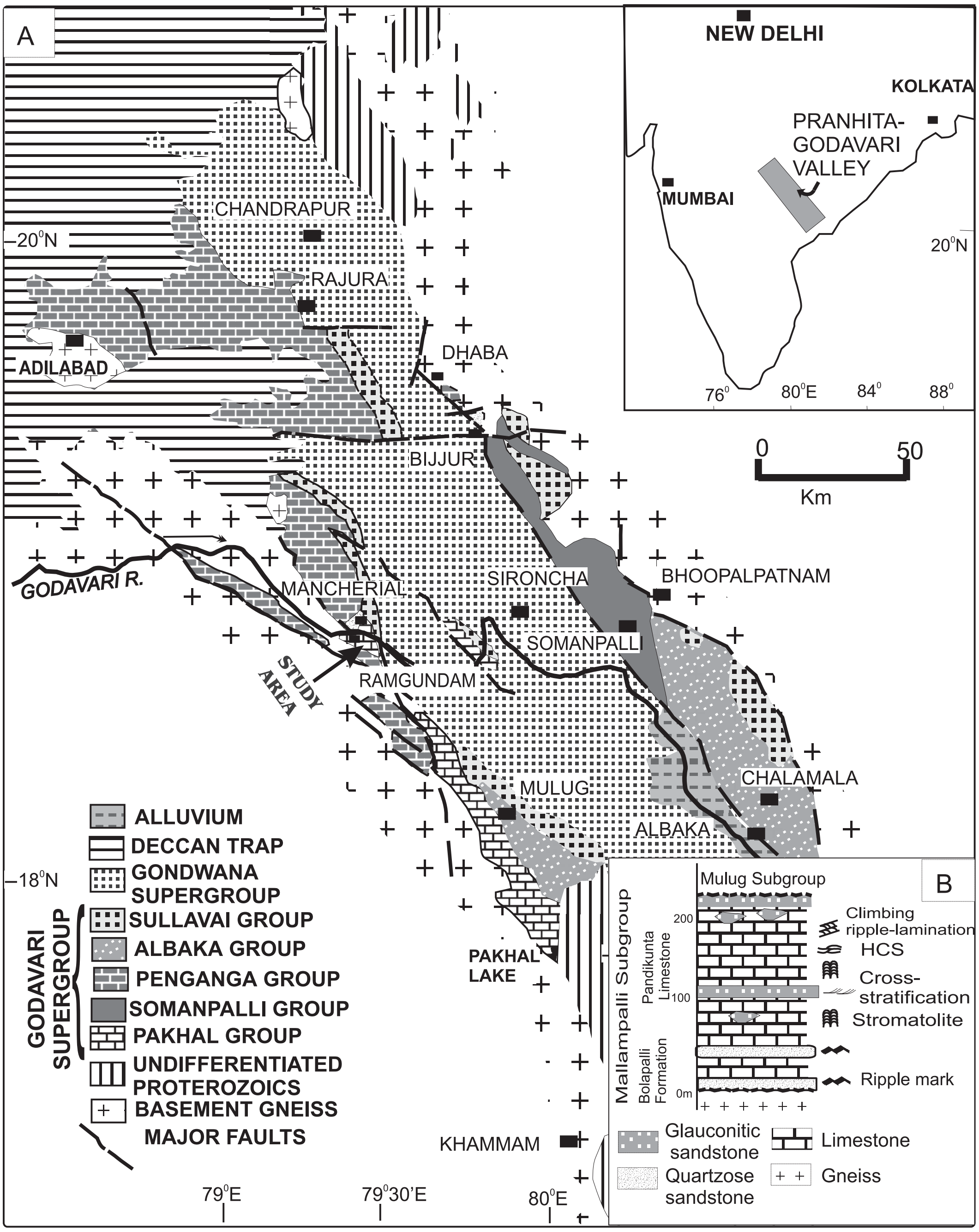

Figure 1. **(A)** Geological map of the PG Valley, showing distribution of the Pakhal Group, location of Ramgundam, the study area; **(B)** lithological log of the Mallampalli Subgroup showing the stratigraphic interval of limestone with climbing ripple structures, and glauconitic sandstone horizons.

part of the southwestern Proterozoic outcrop belt (figure 1) and the area of the present study, the Mallampalli Subgroup comprises a sandstone dominated Bolapalli Formation at the base, and a carbonate dominated Pandikunta Limestone at the top (table 1). The subgroup comprises a fining- and deepening-upward succession with increasing marine influence. The Pandikunta Limestone represents the subsidence stage of basin evolution with the development of an extensive carbonate platform under open marine conditions. The platform is exposed for about 170 km along the strike, from Ramgundam in the NW to the Pakhal Lake in the SE (figure 1), with similar fining- and deepening-upward motif marked by upward transition from siliciclastic to carbonate deposition, through a mixed carbonate-siliciclastic zone. K–Ar dating of glauconitic minerals from the lower part of the Pandikunta Limestone at Ramgundam yields ages of 1330 ± 53 Ma (Vinoagradov *et al*

1964) and 1276 ± 20 Ma (Chaudhuri and Howard 1985).

3. The Pandikunta Limestone: Sediment, sequence and facies

The Pandikunta Limestone consists of a succession of lime-mudstone, sandstone and siltstone. Terrigenous shale or mudstone is nearly completely absent in the preserved section in the study area. The lime-mudstone constitutes about 90% or more of the succession, and consists almost entirely of microcrystalline ooze or micrite, often neomorphosed to microspars and dolomitized. Intraclasts, ooids and pelloids occur sparsely.

The Pandikunta Limestone was deposited during a transgressive–regressive cycle. Four broad facies are recognized within this overall onlap-offlap sequence, on the basis of the presence/absence of stromatolite, microbial laminite and terrigenous sand/silt content: stromatolitic facies, sandstone facies, mixed carbonate-siliciclastic facies and carbonate facies.

The stromatolitic facies comprises microbial laminite and algal stromatolite of different morphologies that form wave resistant, small bioherms and biostromes (Chaudhuri 1970b). The columnar stromatolite structures often contain coarse to medium grained terrigenous sands, transported by high-energy storm currents, within the intercolumnar areas. The facies occurs at the lower part of the succession, and represents tidal flats and near shore environmental complexes.

The sandstone facies comprises medium-grained sands that formed positive relief sandstone lenses and linear subtidal bars at different stratigraphic levels. The sandstone is arkosic to subarkosic, contains high amount of authigenic glauconite (Dasgupta *et al* 1990; Chaudhuri *et al* 1994). The sandstone bars are profusely trough cross-stratified, and were deposited in shoreface and inner shelf areas (Chaudhuri and Howard 1985). The facies represents episodes of sea level fall and progradation. Large amount of sand was transported from the exposed coastal areas to the carbonate depositing shelf by high energy storm currents and tides. The sandstone contains a high amount of very well rounded grains of quartz and feldspar, which were rounded by intense eolian reworking in coastal areas (Chaudhuri 1977).

The mixed carbonate–siliciclastic facies is carbonate dominated, and consists of medium to fine sandstone and siltstone which commonly occur as small lenses and thin graded beds intercalated with lime-mudstone. The facies reflects transgression. It was deposited on the marine platform that lay offshore from the areas of major terrigenous sedimentation. The climbing ripple structures and associated laminated beds studied in the present work occur in this facies. The facies occurs in close association with sandstone facies, and the two constitute the middle part of the limestone succession.

The carbonate facies comprises almost entirely of micrite that occur as laterally persistent thin beds. Virtual absence of siliciclastics or shallow water carbonate allochems indicates that the facies was deposited in a deeper part of the platform, beyond the zone of sand transportation below the storm wave base.

Different facies developed in the Pandikunta platform have been recorded in vertical profiles. The interpretation of the structures has been made on the basis of stratinomic analysis (Aigner 1985).

4. Lamination in the mixed carbonate–siliciclastic facies

Many limestone beds in the studied profile display poorly to well developed lamination of different types. Major types of readily recognizable lamination are:

- climbing ripple-lamination,
- horizontal to wavy lamination,
- cross-stratification,
- hummocky cross-stratification,
- combined-flow ripple-lamination.

In addition, there are about 1.0 to 1.5 cm thick graded or ungraded massive layers. The limestone beds commonly vary between 8 and 10 cm in thickness, and include more than one type of lamination. Different types of lamination occur in ordered vertical sequences, though all the types do not occur in each bed.

4.1 *Climbing ripple-lamination*

Three distinct types of climbing ripple structures, comparable with type A, type B, and sinusoidal type (type S of Allen 1973) of Jopling and Walker (1968) are identified.

Type A: The cross-lamination (figure 2) is composed of climbing sets of concave-up lee side laminae, stoss side laminae being removed by erosion during ripple migration. A few laminae, however, have preserved stoss side and continue from one ripple to the next one. The two types of laminae are found intercalated with each other. The angle of climb of the ripples shows significant variation, from supercritical to subcritical (Hunter 1977). The type A laminae grade upward to laminae with

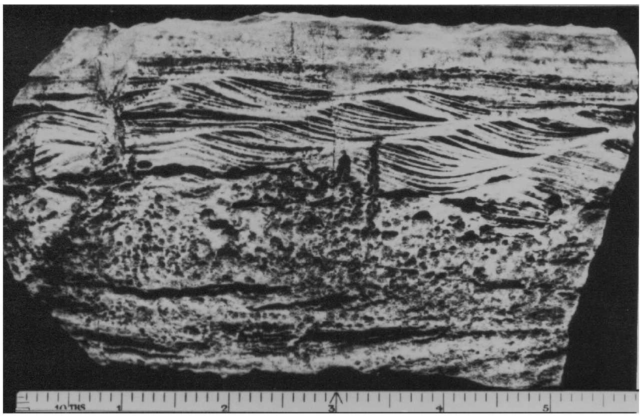

Figure 2. Climbing ripple structures dominated by type A lamination, with strong erosion of the stoss side laminae. Note the intercalated lamination of type B.

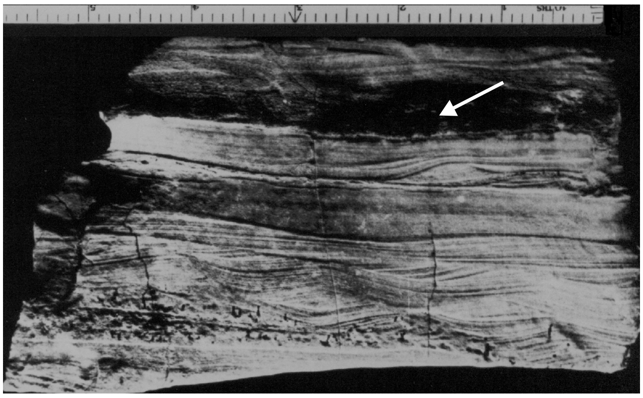

Figure 3. Type B laminae grading upward to type S, followed successively by planar and slightly wavy lamination and massive lime-mudstone with poorly developed lamination. A normally graded fine-grained sandstone bed (marked by arrow) with erosional basal surface. The sandstone passes up into mixed carbonate-siliciclastic with planar to slightly wavy lamination.

fully preserved stoss side (type B) to wavy laminae to plane laminae, and finally to massive lime-mud with poorly developed lamination at places.

Type B: The cross-lamination (figures 2–4) is composed of climbing sets of lee side laminae with complete preservation of stoss side laminae, and continuation of laminae from one ripple to the next one. The angle of climb is supercritical, and may change significantly, with the climbing laminae changing into other types of climbing laminae or planar laminae. The direction of ripple migration remains constant throughout the coset.

Type S (sinusoidal ripple-lamination): The structure consists of superimposed undulating laminae, usually showing a slight displacement of the ripple crests in successive laminae, rather than a perfect superposition (figure 5). The angle of climb may vary slightly, and the direction of shifting of the ripple crest may also change upward (figure 5, right hand ripple crest), giving rise to convergent and divergent asymmetry in adjacent ripples. The laminae are traced between the ripple crests, and are much thinner in the troughs than at the crests. The structure resembles climbing wave ripple-lamination reported by Kreisa (1981, his figures 8C and D).

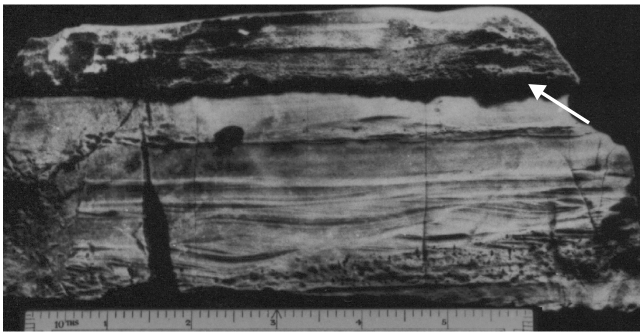

Figure 4. Vertical superposition of type A, type S and type B climbing ripple-lamination. Note the supercritical angle of climb in type B which grade up into planar to slightly undulating lamination and massive lime-mud with poorly developed lamination. A normally graded bed of fine-grained sandstone and sandy lime-mudstone at the top. Note the erosional lower bounding surface of the graded bed.

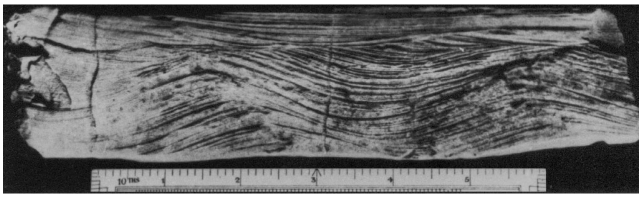

Figure 5. Sinusoidal ripple-laminae (type S) passing upward to storm generated wave cross-laminae (similar to type A climbing lamination with strongly tangential, off-shooting foresets (in upper right corner), the lamina set truncated by a sharp, planar surface of erosion. A set of low angle trough cross-strata at the top.

4.2 *Sequence of structure in climbing ripple-laminated beds*

The climbing ripple structures exhibit complex patterns of variation of different types of lamination within the cosets, and the beds exhibit a complex sequence of different types of lamination within them.

The coset of climbing ripple-laminae in figure 2 starts with a set of type B laminae, and passes upward into a zone dominated by well developed type A laminae with a few intercalated type B laminae. The coset is draped by a wavy lamina. The

Figure 6. Hummocky cross-stratification: planar laminae growing into laminae with strong upward convexity. The hummocky set is truncated along an erosional surface with wavy morphology; overlying strata follow the morphology of the erosional surface (marked by broken line) and grow up into an upward convex set. The coin diameter is 2.2 cm.

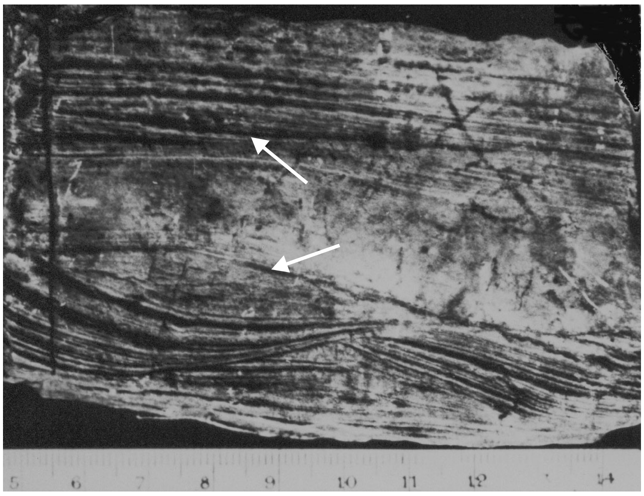

Figure 7. Hummocky cross-stratification: planar to slightly convex-up laminae followed up by a set of anisotropic hummocky laminae with a preferred direction of climb. The set is truncated along an undulating erosional surface (marked by arrow); the erosion surface is draped by a set of wavy laminae, overlain by a set of low angle planar lamina, low angle trough cross-strata and horizontal strata, with several very low angle erosion surfaces (marked by arrow).

coset overlies an interval of massive lime-mudstone without any well defined discontinuity, and, in turn, grades upward successively to wavy laminae to planar laminae to massive lime-mud with poorly developed planar-lamination.

In figure 3, the laminae change from type B to type S to type B within the coset. The latter grades upward successively to planar to wavy lamination and massive lime-mud with poorly developed planar-lamination. The lower bounding surface of the coset is sharp and planar. The sequence is also terminated at the top by a sharp, planar surface that is overlain by a planar-laminated interval. The laminated zone laterally passes into massive lime-mud with poorly developed lamination in the down current direction. The uppermost interval in figure 3 is composed of a normally graded bed of fine sandstone that passes upward into mixed carbonate and quartz sand, with gradually increasing calcareous component. The mixed carbonate-siliciclastic graded bed overlies the lime-mudstone bed across a broadly planar erosional surface with small scours. Figure 4 exhibits a vertical superposition of climbing ripple-lamination types A, S and B. Type B laminae grades up into slightly wavy laminae, and finally to a massive interval. The massive interval of lime-mudstone is overlain across a planar erosional surface by a normally graded bed of fine sandstone.

In figure 5, the sinusoidal ripple-laminae (type S) is followed upward by a set of wave ripple cross-laminae characterized by strongly tangential off shooting foresets that climb on the crestal part of the ripple in the downcurrent direction. The coset is truncated by a sharp, slightly wavy to planar surface. The erosional surface is overlain by a set of very low angle trough cross-strata.

4.3 *Hummocky cross-stratification*

The HCS dominated beds occur in close lateral and stratigraphic proximity with climbing ripple-laminated beds and sandstone–limestone heterolithic beds with combined-flow ripples. Different types of hummocky cross-stratification are shown in figures 6–8. The hummocky cross-stratification is closely associated with wave ripple cross-lamination (figure 7), or low-angle trough cross-stratification (figure 8). In figures 6 and 7, planar-stratification is followed upward by wavy lamination and wave ripple cross-stratification with scooped lower bounding surfaces and swale and hummock morphology. The overlying laminae conform to the morphology of the erosional surface, though these are thicker in the swales and become thinner and tend to converge on the hummocks. The laminae filling up the swales are asymmetric, and closely resemble strongly tangential off-shooting foresets of storm-generated wave ripples (De Raaf *et al* 1977). The undulating surfaces generated by climbing wave ripples are draped by wavy laminae that follow the morphology of the substrate. The curved laminae gradually become planar upward.

Figure 8 shows a set of accretionary hummocky cross-laminae, with the laminae thickening towards the crest. The accretionary set is draped by a

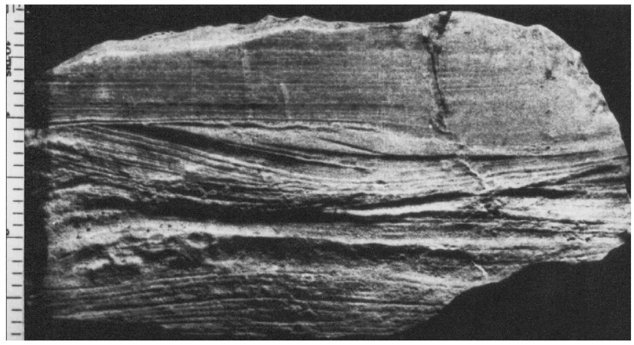

Figure 8. A set of convex upward accretionary strata grades up to massive lime-mud with poorly developed slightly wavy lamination. The massive zone is overlain by a set of low angle trough cross-strata with tangential foreset and long bottom set that curves upward in the down-current direction, and strongly scooped lower bounding surface. The cross-strata is overlain by a set of planar strata that truncates the foresets in the right hand side of the photo, but becomes thicker and conformable with the bottom-set in the left hand side.

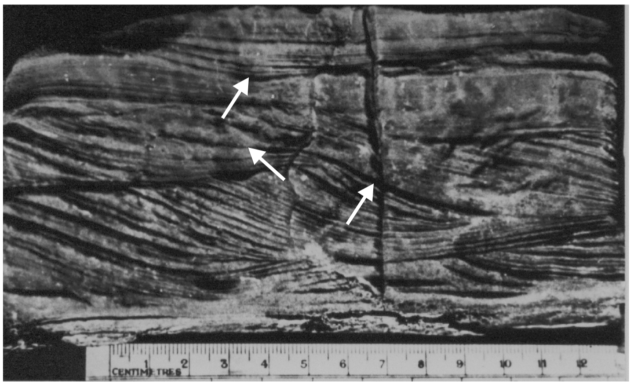

Figure 9. A bed with complex arrangement of lateral gradation and vertical superposition between sets of cross-strata with strongly tangential foresets and prominent bottom set, and low angle trough cross-strata (arrow). Note that two sets of cross-strata, separated by a planar erosional surface in the left side of the photo, merge into a single set in the down-current direction. Also note, low angle discordance (reactivation surfaces) between bundles of foresets within a set. The reactivation surface marked by arrows is undulatory, and is draped by thin laminae that follow the morphology of the reactivation surface. Complexly arranged foreset-bundles are overlain by a set of slightly wavy strata, which, in turn, are followed by a set of low angle trough cross-strata.

zone of massive lime-mud with poorly developed planar-lamination that, in turn, is overlain by a set of low-angle trough cross-strata, with a strongly scooped lower bounding surface and concave-up long toe-sets with a preferred direction of down-lap. The curvature of the foresets decreases upward. The low-angle trough-set is overlain by a set of planar strata that truncates the underlying foresets on the left, but becomes thicker and conformable to the gently curved foreset of the latter in the down current direction. The structure is similar to the low-angle cross-strata interpreted by Nottvedt and Kreisa (1987) as hummocky cross-stratification of combined-flow origin.

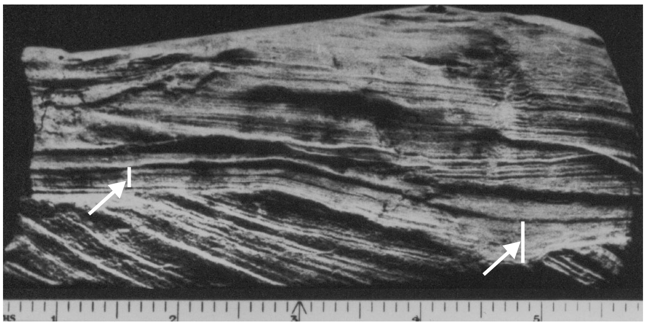

Figure 10. A set of planar cross-strata truncated by planar erosion surface in the top set region, and strongly scooped, irregular erosion surface in the lee of the bed form. The erosion surface is draped by a set of thin laminae that follows the morphology of the erosion surface (vertical bars and arrows). A set of low angle planar strata in the upper part of the bed.

4.4 *Cross-stratification*

Figures 9 and 10 show sets of cross-strata with discordance and erosion between bundles of foreset. The cosets show a complex arrangement of lateral gradation and vertical superposition. The interface between different sets may be either erosional or non-erosional. The sets of cross-strata in figure 9 are characterized by scooping or undulatory lower set boundaries, and strongly tangential, off-shooting and draping foresets, and reactivation surfaces. The coset is overlain by a set of planar to slightly undulatory strata followed upward by low-angle trough cross-strata. The planar to slightly wavy to hummocky strata, low-angle trough cross-strata and wave ripple cross-lamination appear to manifest different aspects or stages of development of hummocky cross-stratification.

In figure 10, the basal set of planar tabular cross-strata is truncated by a planar to scooping erosional surface. The erosional surface is draped by a set of laminae that follows the morphology of the substrate, which, by turn, is overlain by gently concave-up to gently inclined planar strata.

The complex arrangement of different types of stratification and depositional-erosional events reflect the spatial and temporal complexity of the current regime. The reactivation surfaces affecting successive sets, and sets of strata draping erosional irregularities of the substrate closely resemble elements formed under ebb–flood tidal cycles (Reading and Collinson 1996).

4.5 *Combined-flow ripple-lamination*

Figure 11 shows a heterolithic bed of alternating thin laminae of sandstone and limestone.

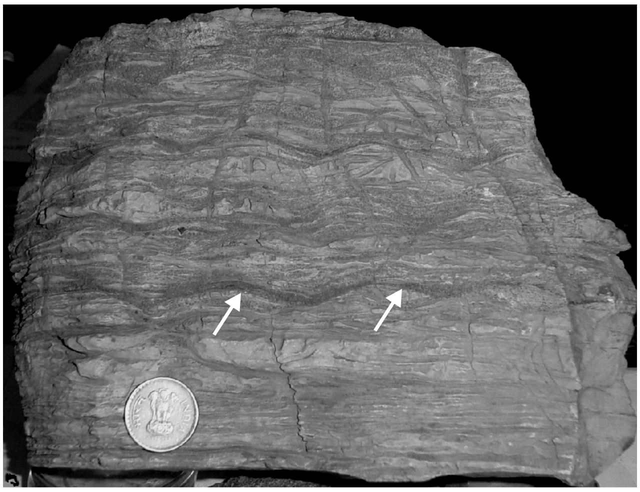

Figure 11. A coarsening upward, heterolithic bed with couplets of thin lamina of fine grained sandstone and limestone. Lower part of the bed is planar laminated and the upper part is ripple laminated. Note well developed combined-flow ripples marked by arrows.

The lower part of the bed is dominated by carbonate and is planar laminated. Occurrence of sand increases upward where thickness of sandstone laminae increases gradually, and the laminae become wavy and rippled. Several laminae show well developed combined-flow ripples (Yokokawa *et al* 1995) with smoothly rounded wide crests and relatively sharp, narrow troughs. The sandstone layers exhibit erosional or sharp lower contacts and gradational upper contacts. Out-of-phase superposition of the ripples, and pinch and swell structures are common. The heterolithic bed shows well developed coarsening-up trend.

5. Interpretation

The morphology of type S structure presented here is analogous to the climbing wave ripple-lamination described by Kreisa (1981) or combined-flow ripples (Myrow and Southard 1991; Yokokawa *et al* 1995). The convergent–divergent asymmetry in the ripples of figure 5 indicates its origin by combined oscillatory and unidirectional flows, rather than by purely unidirectional currents. Combined-flow origin of the structure is also advocated by the set of cross-strata with strongly tangential and climbing foreset laminae with a preferred direction of migration. Intercalation of type S laminae with type A and type B laminae (figures 3 and 4) indicates that the two latter types also formed under combined-flow with a strong unidirectional flow component.

The climbing ripple structures documented from the Pandikunta Limestone display a relatively uncommon complex pattern of variation (Pattern IV of Allen 1973) which points to pulsating and unsteady flow condition. The beds with type A and B lamination at their basal part show gradual upward decrease in the amplitude of ripple lamination and their transition into wavy lamination followed by massive lime-mud at the top of several beds, and overall grading within the beds. The graded stratified beds indicate deceleration of the current during deposition and increasing deposition of lime-mud from suspension. The depositional motif is common in storm deposits, and is best developed where unidirectional flow dominates over oscillatory flow.

The wave ripple-lamination as well as hummocky cross-stratification attest to the emplacement of sediments by storm generated processes (Dot and Bourgeois 1982; Duke 1985; Nottvet and Kreisa 1987; Myrow and Southard 1991; Duke *et al* 1991). However, the exact nature of the flows that deposit hummocky cross-stratification is still in controversy. The experimental studies on bed configuration in fine sands indicate that isotropic hummocky cross stratification is generated under bidirectional, purely oscillatory flow (Southard *et al* 1990). This is consistent with what has been suggested by Harms *et al* (1982), Dott and Bourgeois (1982), Duke and Leckie (1986) and Duke *et al* (1991). Experiments on combined-flow bed configurations (Arnott and Southard 1990), on the other hand, indicate that anisotropic hummocky cross-stratification with a preferred dip direction of the coset laminae, as seen in the Pandikunta Limestone, is produced by combined-flow at high oscillatory velocities and small to moderate unidirectional velocities. The experimental results are consistent with what has been recorded from many ancient sandy tempestites (Beukes 1996; Nottvedt and Kreisa 1987; Midtgaard 1996). The experimental results also indicate that application of even a weak unidirectional velocity component transforms purely oscillatory bed forms to plane beds with gentle undulations (Myrow and Southard 1991; Duke *et al* 1991).

Closely related occurrence of hummocky cross-stratified, wavy-laminated and climbing ripple-laminated beds as well as beds with combined-flow ripples, both stratigraphically and laterally, in the Pandikunta Limestone suggests that the structures were formed in a combined-flow dominated environment with widely variable combinations of unidirectional and oscillatory flow components. The complex current system in the Pandikunta shelf had an overprint of tidal currents also. The variations in the vertical stratification sequence within beds were controlled by the interplay between unidirectional and oscillatory flows that changed through time, and from event to event, both in intensity and in direction. The highly unsteady

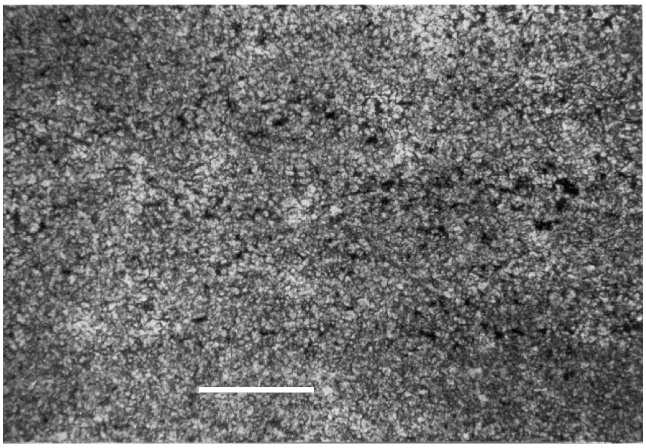

Figure 12. Photomicrograph of lee side laminae from type A climbing ripple structure; very well sorted silt size grains; plane polarized light. Scale bar is 500 μm.

character of the flow is indicated by abundant internal scours and drapes (figures 6–10).

The graded stratified beds with climbing ripple lamination at their basal part do not include any hummocky cross-strata. The absence of the latter may possibly be attributed to the dominance of unidirectional flow components over oscillatory flow components. The depositional motif of graded stratified beds may be related to turbidite sedimentation in a distal muddy shelf. The beds are, however, comparable with combined-flow modified turbidite beds deposited within storm wave base, and represents an alternative for the shelf turbidity concept (Higgs 1990; Myrow and Southard 1996; Myrow *et al* 2002).

6. Petrogenetic implication

The carbonate particles in storm deposited beds within the mixed carbonate–siliciclastic facies of the Pandikunta Limestone are mostly of fine silt and very fine sand-size (figure 12), and the grains behaved like fine quartz sand. The climbing ripple structures as well as other types of storm generated lamination indicate that the calcisilts were transported by combined-flow with a strong unidirectional component from near shore environments. The structures further indicate that these calcisilts are not the products of neomorphism, but are of primary origin.

Most of the calcisilt grains are equant, and have different degrees of roundness (figure 12), a possible manifestation of abrasion during transport. The photograph also displays a distinct break in size between the darker coloured microcrystalline ooze and lighter coloured silt grains. The calcisilts show recognizable difference in size between different laminae, but within a lamina these are very well sorted and are characterized by very uniform texture. Bathurst (1959) observed this kind of coarser carbonate mud or microspar, and inferred that these were detrital carbonate silts, rim cemented by calcite overgrowth, and not a product of recrystallization of normal 2–3 μ micrite.

Folk (1965) observed that it is impossible to tell whether certain small homogeneous objects found in some rocks were tiny intraclasts or large pellets. Origin of such structureless tiny carbonate particles is still unclear. Fine carbonate sands and silts in the carbonate tempestites described in literature (Ager 1974; Kreisa 1981; Wu 1982; Aigner 1982, 1985; Handford 1986; Sageman 1996) were all presumably derived through mechanical disintegration of bio-clasts in high-energy near shore environments. Bioclastic origin cannot be invoked for Proterozoic carbonate grains, and it is a distinct possibility that Pandikunta calcisilts were derived from mechanical disintegration of algal stromatolites and microbial laminites.

7. Palaeogeographic and stratigraphic implication

The lower part of the Pandikunta Limestone is marked by the development of diverse types of stromatolite structures and microbial laminites (Chaudhuri 1970b) that indicate tidal flat to shallow subtidal environments of deposition. The sandstone bars in the middle part of the limestone succession also were deposited in tidal flat environments (Chaudhuri and Howard 1985). Recognition of calcisiltites with climbing ripple lamination, HCS and associated lamination in the mixed carbonate-siliciclastic facies indicates deposition in relatively offshore area that was subjected to intense storm and tidal action. The calcisiltites intercalated with lime-mudstone are analogous to storm deposited fine-grained sandstone and siltstone interbedded with shale in mid-shelf environments. The occurrence of only fine sand and silt-size grains in these beds suggests that the facies was deposited at or close to the storm wave base. The finest grade of intraclast was transported by storm and tidal currents from coastal areas to the mud depositing offshore part of the platform. The calcisiltite beds provide proximality trends within the platform, as has been done with bioclastic limestones in Phanerozoic successions (Aigner 1985; Sageman 1996).

The recognition of storm deposited calcisiltite beds opens up the means for detailed facies analysis, recognition of environments and characterization of the carbonate depositional system. Two major sandstone intervals (figure 1B) represent two events of progradation (falling stage systems tract, FSST), whereas the mixed carbonate-siliciclastic facies with the calcisiltites represents the event of a major transgression (transgressive systems tract, TST, and high stand systems tract, HST). The storm and tide influenced shelf was connected with open marine environments.

8. Conclusion

The climbing ripple structures of various types and patterns were generated in the calcisiltite of the Pandikunda Limestone in response to storm generated combined-flow and tidal currents. The complex interplay of different types of currents also produced several kinds of lamination, such as hummocky cross-stratification, wave ripple-lamination, low-angle planar cross-stratification, combined-flow ripple-lamination, and couplets of fine-grained sandstone and limestone. Generation of different types of stratification was primarily controlled by the variable interplay between unidirectional and oscillatory flows. The climbing ripple structures and the associated lamination occur in an ordered vertical sequence forming graded stratified beds that share many attributes of the Bouma sequence. These were deposited from waning flows and may represent shelf turbidites modified by combined-flow. The storm generated beds consist mainly of structureless carbonate particles of fine sand and silt size. The particles were generated in the shallower part of the platform as intraclasts, probably by mechanical disintegration of stromatolites and microbial laminites, were transported to the deeper part of the platform and were deposited at or close to the storm wave base. The storm deposited beds indicate that the platform was affected by open marine circulation. In fine grained, mud-dominated limestone succession where sequence stratigraphic features may be difficult to recognize, the calcisiltites provide a tool for recognition of proximality trend, systems tracts and relative sea-level change.

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