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Sedimentology of a Proterozoic erg: the Venkatpur Sandstone, Pranhita–Godavari Valley, south India

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ABSTRACT

Reappraisal of the Late Proterozoic Venkatpur Sandstone indicates that the bulk of the sandstone is aeolian in origin. Aeolian stratification types, namely (i) inverse graded translatent strata, (ii) adhesion laminae, (iii) grainflow strata and (iv) grainfall strata, are present throughout the outcrop belt. Nine facies have been identified that represent both aeolian and related aqueous environments within a well-developed erg. Cosets of large cross-beds at the Bellampalli section in the NW of the study area record dune fields in the interior of the sand sea. To the SE, at the Godavari River and Ramgundam sections, a progressive increase in the relative proportion of the flat-bedded to cross-bedded facies and intercalated non-aeolian facies delineates the transition from the dune-field to sand-sheet environment. An alternating sequence of aeolian and marine sediments at Laknavaram, in the extreme SE, marks the termination of the sand sea. Palaeocurrent data suggest that the NW–SE trend of the sections represents a transect across the sand sea in a direction normal to the resultant primary palaeowind direction.

Abundant horizontally stratified units in the Vankatpur Sandstone do not always represent the interdune sediments. On the basis of the thickness and geometry of the units, nature of bounding surfaces and associated facies sequence, the facies is variously interpreted to represent interdune, inland sabkha, sand sheet and coastal sand flat deposits.

INTRODUCTION

Proterozoic sedimentary sequences in several isolated basins cover an extensive part of Peninsular India (Fig. 1). The sequences closely resemble the 'carbonate–orthoquartzite facies' in terms of lithology, composition and extensive sheet-like disposition. The carbonate and most of the sandstone sequences have been interpreted as deposits of shallow cratonic seas (Banerjee, 1974; Chanda & Bhattacharya, 1982; Chaudhuri & Howard, 1985; Singh, 1985; Nagraja Rao *et al.*, 1987).

Development of extensive sheet sandstones through shallow-marine processes alone, however, is being increasingly questioned (e.g. Dott *et al.*, 1986). Study of modern shelf processes (Swift, Stanley & Currary, 1971) suggests that these are less effective in dispersing sands over wide areas compared to aeolian and braided fluvial processes (Dott & Byers, 1981; Fuller, 1988). Non-marine processes might have been even more important in pre-Silurian times, before the advent of land vegetation, in spreading sand sheets (see Folk, 1968).

With this background, a Late Proterozoic sandstone sequence, the Venkatpur Sandstone of the Pranhita–Godavari Valley, south India, has been studied. Preliminary analysis of stratification types indicates that the sandstone, which is spread over a linear belt of more than 100 km (Fig. 1), formed essentially through aeolian processes (Chakraborty, 1988). This paper describes the stratification and facies of this sandstone and thus recognizes different aeolian sub-environments similar to those identified in modern sand seas; it also attempts to characterize the extensive Proterozoic sand sea, based on the analysis and interpretation of facies assemblages on a regional scale.

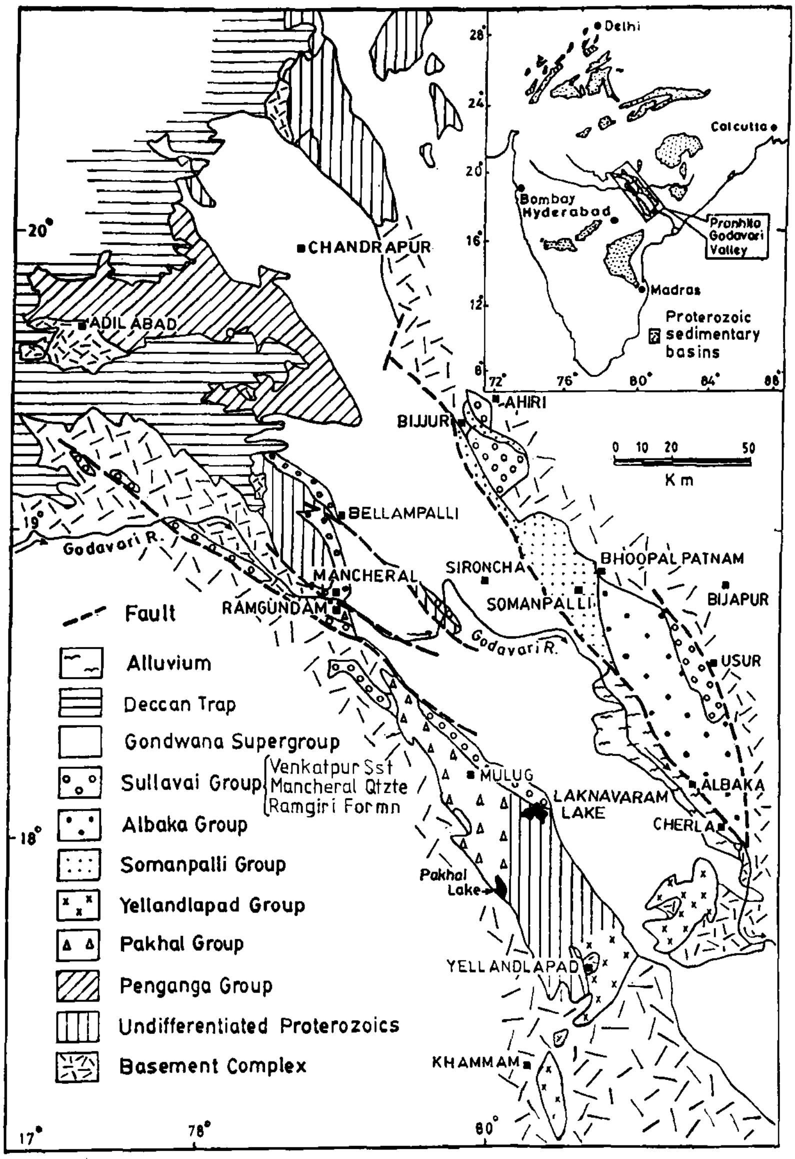

Fig. 1. Geological map of the Pranhita–Godavari Valley. The inset shows the Proterozoic sedimentary basins of Peninsular India.

THE VENKATPUR SANDSTONE

The Venkatpur Sandstone, the top-most formation of the Sullavai Group, occurs as an extensive sheet, exposed in two NW–SE-trending linear outcrop belts along two flanks of the Pranhita-Godavari Valley basin (Fig. 1). The formation consists of medium- to fine-grained, red, subarkosic sandstone and is characterized by the profuse development of large planar cross-beds. The sandstone occurs in close association with fluvial quartz arenites and arkoses (see Table 1; Chakraborty, 1988). Extensive development of a salmon-red colour, high textural maturity and presence of considerable amounts of well-rounded first-cycle sand grains (Chaudhuri, 1970, 1977) characterize the sandstone throughout the studied area. The sandstone

Table 1. Stratigraphic sequence of the Proterozoic rocks of the Pranhita–Godavari Valley (after Chaudhuri & Howard, 1985; Chaudhuri & Chakraborty, 1987 and A. Chaudhuri, unpublished data).

Ramgundam: Stratigraphy			Ramgundam: Lithology and primary structure	Mancheral: Stratigraphy		Mancheral: Lithology and primary structure
Gondwana Supergroup (Permian–Jurassic)				Gondwana Supergroup		
~~ Angular unconformity ~~~				~~~ Angular unconformity ~~~		
Sullavai Group	Venkatpur Sandstone		Salmon-red, medium–fine, quartzose subarkosic sandstone. Well-rounded grains. Alternation of large planar cross-beds and horizontal beds	Sullavai Group	Venkatpur Sandstone	
	Mancheral Quartzite (23 m)	Ramgiri Formation (456 m) (K–Ar date 871 ± 14 Ma)	Mancheral Quartzite: medium to pebbly quartzose sandstone; thin lenses of conglomerate and well-sorted fine sandstone. Profuse planar and trough cross-beds; channel forms; locally abundant adhesion structures		Mancheral Quartzite (76 m)	
			Ramgiri Formation: medium–coarse arkosic sandstones and conglomerates. Thoroughly trough cross-bedded		Ramgiri Formation (250 m +)	
~~ Angular unconformity ~~~				~~~ Angular unconformity ~~~		
Pakhal Group	Mulug Subgroup	Rajaram Limestone (735 m)	Micritic and intraclastic limestone, calcareous shale; cross-beds and channels	Pengnga Group	Set Nata Shale	Reddish brown shale with very persistent thin lamination
		Ramgundam Sandstone (120 m)	Arkosic to subarkosic sandstone with minor shale; abundant glauconite; well-rounded grains; well-developed trough cross-beds, wave ripples, mudcracks		Chanda Limestone	Limestone with minor shale and glauconitic sandstone; thin persistent bedding; matrix-supported limestone-clast conglomerates
		Damla Gutta Conglomerate (90 m)	Pebbly arkose, chert pebble conglomerate with graded beds and cross-beds at the base			
	~ Disconformity ~~~					
	Mallampalli Subgroup	Pandikunta Limestone (340 m) (K–Ar date 1330 ± 53 Ma)	Flat-bedded limestone and dolomite; lenses of shale and glauconitic sandstone. Abundant stromatolites; silcrete horizon at top			
		Jonalarasi Bodu Formation (50 m)	Interbedded limestone and quartz arenite; abundant well-rounded grains and salt pseudomorphs. Graded beds, trough cross-beds, mudcracks			
~~ Angular unconformity ~~~				~~~ Angular unconformity ~~~		
Archaean (?) basement complex				Archaean (?) basement complex		

has previously been interpreted as a shallow-marine to beach deposit (Johnson, 1965; Chaudhuri, 1970).

EVIDENCE FOR AEOLIAN DEPOSITION OF THE VENKATPUR SANDSTONE

In addition to the abundance of well-rounded sand grains (Chaudhuri, 1970, 1977), two distinctive aeolian features are clearly recognizable throughout the outcrop belt: adhesion structures (Hunter, 1973, 1980; Allen, 1982; Kocurek & Fielder, 1982; Figs 2 & 3) and wind-ripple strata. Two types of wind-ripple strata are recognized: (i) thin, inverse-graded translatent strata (Hunter, 1977a,b; Kocurek & Dott, 1981; Fig. 4) and (ii) interlayered lenticular, discontinuous, coarse to medium sand layers and associated granule lag surfaces (Bagnold, 1954; Sharp, 1963; Fryberger, Ahlbrandt & Andrew, 1979; Kocurek, 1981a,b). Though not diagnostic, other common types of aeolian

Fig. 2. Climbing adhesion ripple cross-laminae (zone below the scale) in the flat-bedded unit at Bellampalli. The upper part shows alternate finer-grained deep-red sandstone and clean white sandstone. Scale = 5 cm.

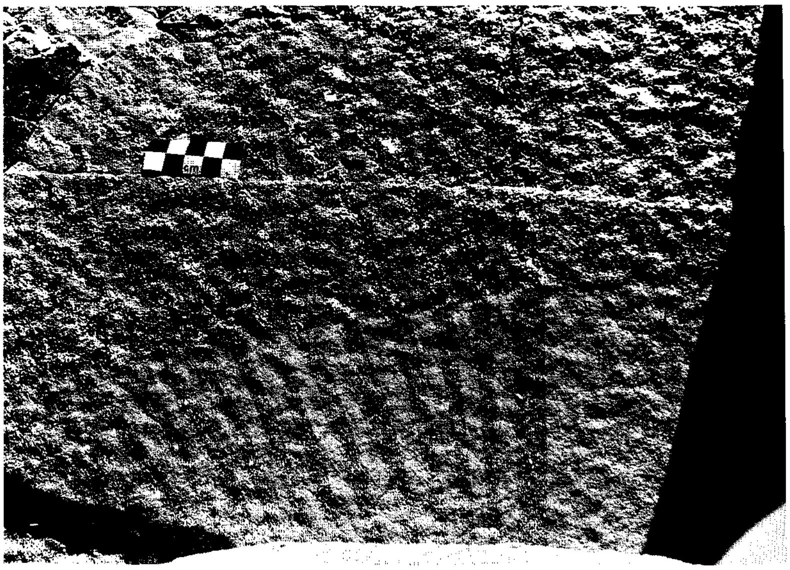

Fig. 3. Plan view of adhesion ripples, Bellampalli quarry. Scale = 5 cm.

features recognized in the Venkatpur Sandstone are grainflow and grainfall laminations (Hunter, 1977a; Kocurek & Dott, 1981). Grainflow cross-strata are typically wedge-shaped, pinch out within wind-ripple or grainfall strata near the base of the cross-sets (Fig. 5) and have irregular spacing between them (Fig. 6; Hunter & Kocurek, 1985). Grainfall strata on the other hand are fine grained, drape pre-existing topography and thin out in the downwind direction (Fryberger & Schenk, 1981; Anderson, 1988).

FACIES

The Venkatpur Sandstone has been classified into nine facies mainly on the basis of stratification and other sedimentary and lithological attributes (see Table 2).

Facies 1 (F1): large-scale cross-bedded sandstone

Facies 1 consists of fine- to coarse-grained sandstone with large tabular or wedge-shaped cross-beds. Cross-

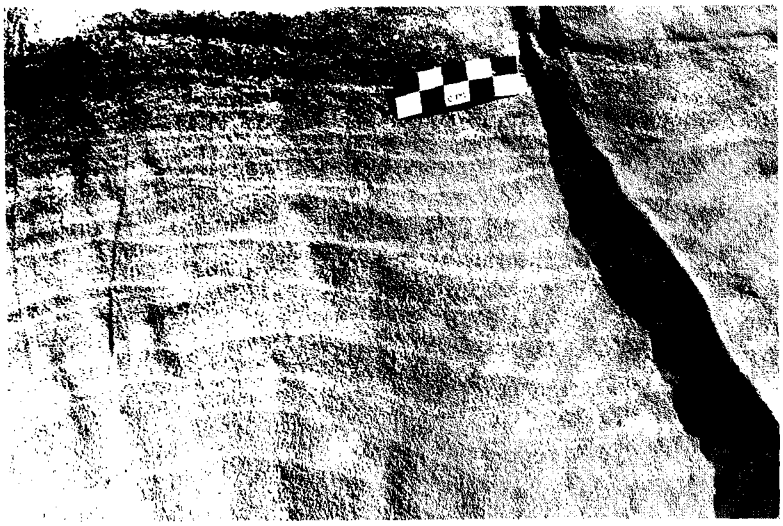

Fig. 4. A low-angle section of translatent strata from the Venkatpur Sandstone showing inverse grading and occasional faint traces of gently dipping foreset laminae. Scale = 5 cm.

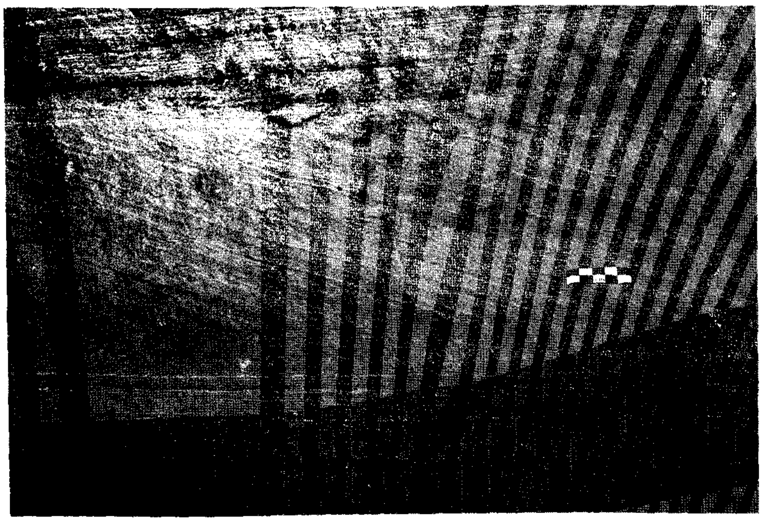

Fig. 5. Wedges of grainflow strata pinching out within a grainfall deposit in the lower part of a small dune cross-bed at Bellampalli; layers of flat-bedded wind-ripple strata enclose the cross-set. Scale = 5 cm.

Table 2. Summary of facies recognized in the Venkatpur Sandstone.

Facies no.	Brief description	Interpretation
F1	Large planar cross-beds with either (a) steeply dipping (23–30°) foresets abutting at high angle to the lower bounding surface, having a significant proportion of grainflow strata or (b) long tangential foresets comprising finer-grained grainfall strata. Rare, gently convex-up low-angle strata and cross-strata consisting entirely of fine-grained wind-ripple laminae and having a radial dip pattern in adjacent sets (Fig. 8)	Aeolian dune cross-beds; convex-up laminae may be transverse section of a cresentic dune complex or in-phase cresentic dunes or dome dunes(?)
F2	Very coarse- to fine-grained flat-beds mainly of wind-ripple strata; occasional sets of low-angle (10–15°) cross-beds comprising bimodal, coarse-grained wind-ripple strata; rare adhesion or salt-related structures and small aqueous cross-beds. Generally 0·1–0·7 m thick but can be several metres in thickness	Dry interdune or sand sheet with low-angle zibar cross-beds(?)
F3	Medium to muddy fine-grained flat-beds with abundant salt-related deformational features, adhesion structures, 'DU' sequences, close spaced erosion surfaces with microrelief (Figs 10 & 11) and occasional wave ripples. Extensive tabular units of average thickness of 0·6–1·0 m but may be up to 5 m.	Sabkha/coastal sand flats/ periodically wetted interdune or sand sheet
F4	Areally restricted, up to 1·5 m thick, thinly laminated mudstone; occurs in close association with other aeolian facies	Shallow pool of quiet water within the sand sea
F5	Massive, poorly sorted, fine- to very coarse-grained sandstone forming FU lenticular sandbodies with erosional lower contact; 0·35–1·5 m thick (Fig. 12)	Small, isolated channel-fills
F6	10–40-cm-thick trough cross-bedded mudclast conglomerate and feldspathic sandstone; occasional large, wavy bedforms with mud-draped, low-angle accretion surfaces (Fig. 13); sharp base, gradational upper contact with F7	Tidal channel deposits
F7	Muddy, fine-grained sandstone with symmetrical megaripples, often interference type; gradationally overlie F6	Low-energy coastal environment/ upper part of the tidal channel sequence
F8	Fine to silty sandstone with ripple-drift cross-lamination; few centimetre thick pseudobeds, well-preserved internal foresets and lack of within-laminae grading; gradationally/sharply overlie F9	Aqueous ripple-drift cross-lamination
F9	Fine- to medium-grained sandstone with plane beds and well-developed parting lineation; extensive tabular bodies	Upper-flow-regime plane beds

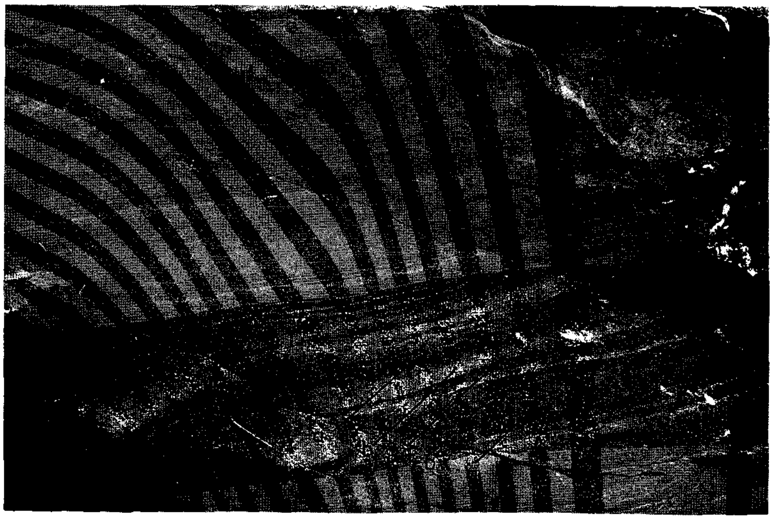

Fig. 6. Foreset bedding of a large planar cross-bed. Note the irregular spacing and wedge-like shape of the darker, coarse-grained grainflow strata ('a') alternating with lighter, finer-grained grainfall strata ('b'). The view represents about 2 m of the cross-bedded section.

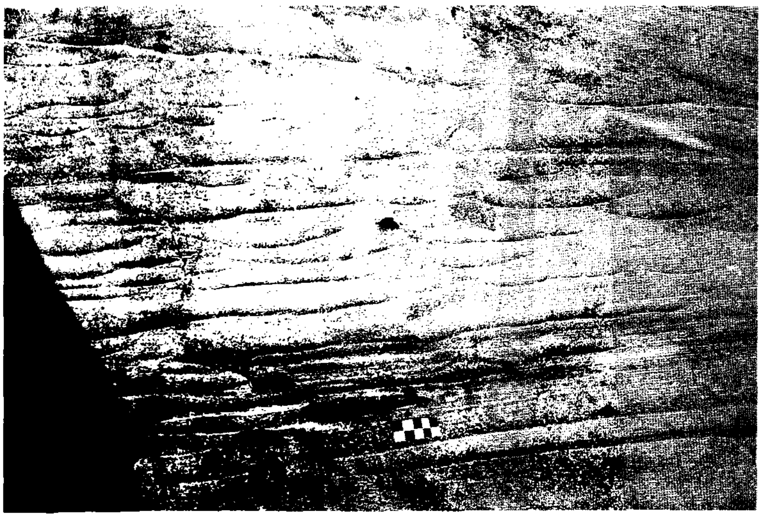

Fig. 7. Scalloped and lenticular shape of the grainflow tongues exposed in the bedding plane section, Bellampalli quarry. Uniform layers of wind-ripple origin are seen in the bottom and top right corners of the photograph. Scale = 5 cm.

beds occur in cosets or in isolated sets, and range in thickness from 0·3 to 3·0 m, averaging around 1 m. Two distinct types of cross-bed have been observed: (i) steeply dipping (23–31°) planar, medium- to coarse-grained foresets abutting at a high angle to the lower bounding surface; abundant grainflow strata alternate with grainfall and wind-ripple strata (Figs 5–7); (ii) medium- to fine-grained foresets of grainfall strata that sweep down asymptotically on the lower bounding surface for several metres and thin downdip. In plan view, foresets of the first type are generally straight but at places show gentle curvature. In a few sections fine-grained wind-ripple strata define some gently dipping cross-beds, some of which have foresets with a slight upward curvature (Fig. 8). The adjacent sets show divergent dip directions.

The cross-beds are preserved remnants of migrating large dunes, either straight-crested or cresentic. The angular foresets probably represent smaller dunes where grainflows frequently reached the bottom of the lee faces (Kocurek & Dott, 1981), whereas tangential foresets may represent the lower part of large transverse bedforms with abundant grainfall strata in the toe region (Hunter, 1981; Kocurek & Dott, 1981; Ross, 1983).

The convex-up wind-ripple strata may record migrating dome dunes (Fig. 20 of Fryberger, Al-Sari & Clisham, 1983) or may represent a transverse section through a cresentic dune complex. Similar convex-up lamination may also be produced by in-phase cresentic dunes (G. Kocurek, 1990, pers. comm.).

Facies 2 (F2): flat-bedded, coarse- to fine-grained sandstone

This facies is characterized by horizontal to subhorizontal, coarse- and fine-grained wind-ripple strata. Locally adhesion laminae, small lenses of aeolian

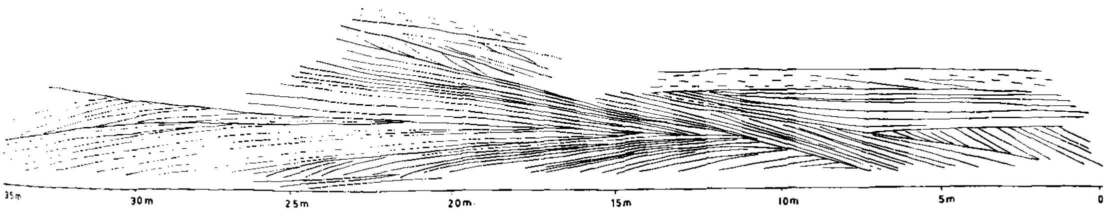

Fig. 8. Field sketch of the railway cutting section, Ramgundam area. Moderate and gently dipping cross-beds consist of 1–2-cm-thick translatent strata. Some of the low-angle strata show a gentle upward curvature over a long distance; adjacent sets have almost a radial dip pattern. Note lateral transition from low-angle to high-angle cross-beds. The sequence may represent a dome dune or a transverse section of barchan dunes or in-phase cresentic dunes. The dashed unit represents a mudstone bed. Section trend 340–160°.

cross-beds or isolated shallow troughs of aqueous origin comprise a minor part of the facies. Individual facies units are 0·1–0·7 m thick, but can reach several metres in thickness. Fairly persistent subhorizontal planar surfaces marked by the concentration of coarse sands or small pebbles occur in this facies. Thicker units of this facies contain low-angle (10–15°) cross-beds varying in thickness from 25 to 40 cm. The individual foresets of these low-angle sets consist of bimodal, coarse-grained wind-ripple strata.

The bulk of the facies developed through the migration of wind ripples on topographically flat, dry depositional areas of either an interdune or sand sheet. Small aeolian dunes developed locally. Wet conditions developed in places or for short periods, giving rise to isolated trough cross-beds, and salt ridge and adhesion laminae. The low-angle cross-beds are interpreted to represent zibars, the low-amplitude aeolian bedforms that lack avalanche slipfaces and generally develop in the marginal parts of dune fields or in sand sheets (Nielson & Kocurek, 1986).

Facies 3 (F3): flat bedded, medium- to fine-grained muddy sandstone

Facies 3 is commonly marked by alternate red and white bands (Fig. 2) and comprises fine to medium sand with a subordinate amount of coarse sand. Some of the red layers are finer grained and muddy. Both fine- and coarse-grained wind-ripple strata are the dominant stratification style of this facies, closely followed by adhesion structures of different types, wave ripples, mudcracks and profuse soft-sediment deformation structures. The deformation, such as irregular, pronounced ridge-like upward flexures (Fig. 9, arrows), collapse structures, water-injection structures and small-scale reverse faults, result in irregular and wavy bedding in places (Fig. 9). The common occurrence of adhesion structures, wave ripples and pervasive deformation differentiates this facies from the flat-bedded sands of F2. Intervals of this facies generally vary from 0·6 to 1·0 m in thickness, but may be up to several metres. Fairly close-spaced, slightly irregular, flat erosional surfaces with microrelief of the order of several centimetres (Figs 10 & 11) occur within the thicker units of this facies and enclose laterally extensive thin sedimentation units (Figs 9 & 11). The basal parts of such units are dominated by red and white bands, abundant ridge-like and other deformational features as well as local occurrences of wave ripples and mudcracks. This is followed upward by adhesion structures and finally by wind-ripple strata and small ($\leqslant 30$ cm) aeolian dune cross-beds (Fig. 11).

The sequences are clearly drying-upward (DU) sequences (cf. Kocurek, 1981a). Collapse structures and reverse faults (Fig. 9) appear to be related to the intrasedimentary growth and dissolution of evaporites

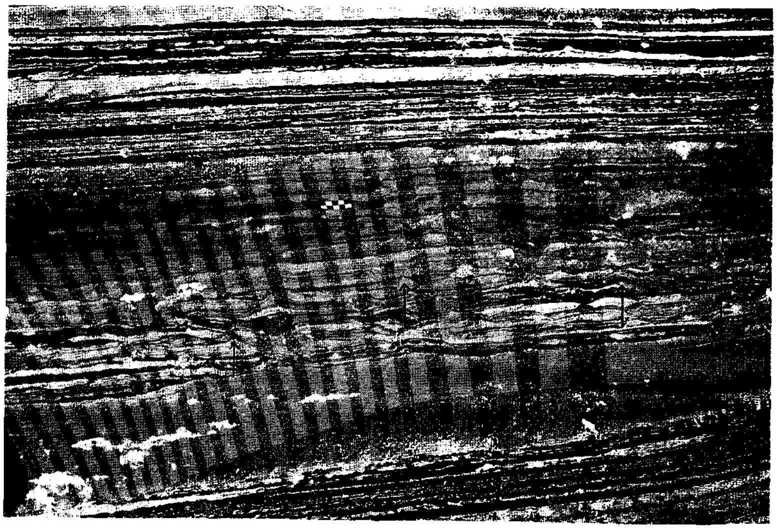

Fig. 9. Close up of the sabkha sequence at Bellampalli. Salt-related deformation has given an irregular and wavy appearance to the beds (unit 'c'). Note pronounced up-arching of beds that represent actual salt-ridge microtopography (arrows). Thin translatent strata, gently dipping to the right, comprise the interval marked 'b'. The bed marked 'a' comprises essentially adhesion cross-laminae. Scale = 5 cm.

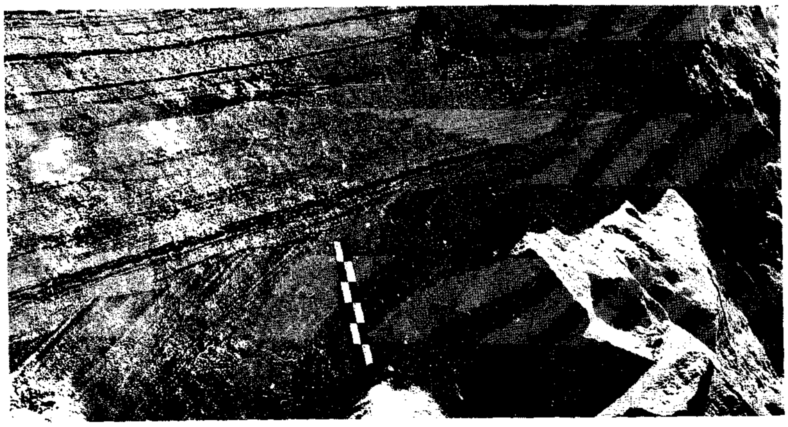

Fig. 10. Undulating microtopography of the upper bounding surface of a dune cross-bed, resulting from early cementation and subsequent differential wind erosion of foresets. The overlying flat-bedded unit is characterized by salt-ridge and related irregular, wavy beds. Such associations are typical of deflation surfaces close to the water-table (Stoke's surface). Scale = 30 cm.

(see also Hunter, 1981; Kocurek, 1981a,b; Fryberger *et al.*, 1983, 1984; Fryberger, Schenk & Krystinik, 1988) and the pronounced convex-up laminae are possible salt-ridge structures (cf. Glennie, 1970; Collinson, 1978; Fryberger *et al.*, 1983, 1984). The subhorizontal erosional surfaces (Figs 10 & 11) with microtopography may be deflation surfaces close to the ground water-table, where smooth deflation is impaired because of the presence of water, salt or early calcite cement (McKee, 1979; Kocurek, 1981a,b; Simpson & Loope, 1985; Fryberger *et al.*, 1988). As reported from both recent and ancient sequences,

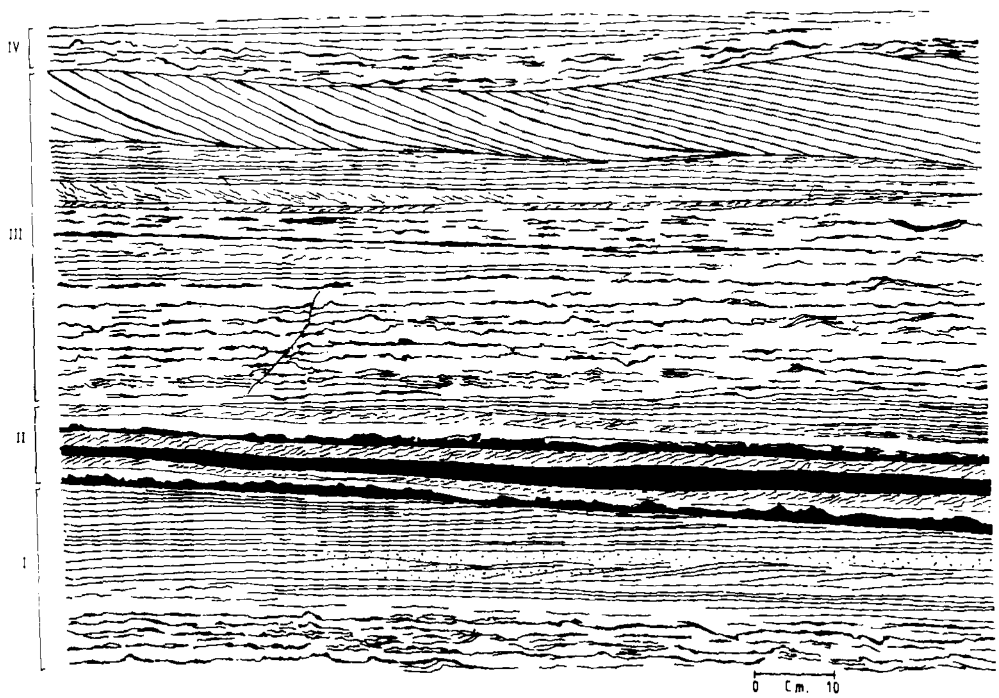

Fig. 11. Field sketch of stacked DU sequences of F4 at Bellampalli. Salt-ridge structures, deformed strata and adhesion cross-laminae constitute the lower part and wind-ripple strata the upper part of each sequence. Note low-angle discordances between each DU sequence and broad undulation of the contact between sequences III and IV.

interdune areas that experience periodic flooding by rain or seawater or inland sabkhas or coastal sand flats are potential geomorphological sites for accumulation of this type of sediment (Kocurek, 1981a,b; Kocurek & Fielder, 1982; Fryberger *et al.*, 1983, 1988; Hummel & Kocurek, 1984; Pulvertaft, 1985; Kocurek & Nielson, 1986; Porter, 1987; Kerr & Dott, 1988).

Facies 4 (F4): mudstone facies

This facies consists of thinly bedded mudstone to fine-grained muddy sandstone. It occurs closely associated with the aeolian facies, either laterally interfingering or sharply overlying the latter (Fig. 8). The maximum observed thickness of a facies unit is about 1·5 m. The facies was deposited in a quiet subaqueous environment such as a shallow pool or lake within the sand sea.

Facies 5 (F5): lenticular units of apparently massive sandstone

Facies 5 consists of poor to moderately sorted fine- to coarse-grained sandstone with mudclasts, organized in single or superposed multiple lens-shaped bodies (Fig. 12; Fig. 17 at 22 and 51 m). Individual lenses vary from 0·35 to 1·5 m in thickness, have erosional lower bounding surfaces and show a well-defined fining-upward trend. The size range and roundness of the sand grains of this facies is the same as the associated aeolian sediments.

The sandbodies evidently formed as aqueous channel-fill deposits. The absence of coarse extraformational gravels distinguishes these channels from typical wadis, and points to their intradune field origin. Preserved channel forms suggest that the channels did not migrate significantly and developed as ephemeral streams as a result of intense localized surface runoff (see also Glennie, 1987).

Facies 6 (F6): cross-bedded mudclast conglomerate and medium- to coarse-grained sandstone

This facies is made up of mudclast conglomerate and medium- to coarse-grained feldspathic sandstone, organized mainly in 10–40-cm-thick trough cross-sets. Few centimetre-long mudclasts generally lie parallel to foresets. Locally, large symmetrical wavy bedforms, about 1·3 m in wavelength, occur in association with the trough cross-beds. The bedforms have form-discordant, mud-draped, low-angle internal lamination (Fig. 13). The facies units show well-defined fining-upward (FU) trends in terms of grain size, cross-set thickness and clast frequency. They have sharp bases and grade upward into F7.

Trough cross-bedded mudclast conglomerate and sandstone, wavy bedforms with form-discordant internal lamination, mud-drapes on foresets and close association with F7 are collectively interpreted to imply a current- and wave-influenced shallow-marine environment of deposition for F6 rocks.

Facies 7 (F7): wave-rippled, muddy, fine-grained sandstone

Fine-grained sandstones of this facies show excellent development of wave ripples (cf. Raaf *et al.*, 1977) at various scales and orientation, and are locally superposed on one another producing a dimpled pattern (Fig. 13, foreground). Rippled surfaces are often veneered by mud. A wave-agitated shallow-marine environment is interpreted for this facies.

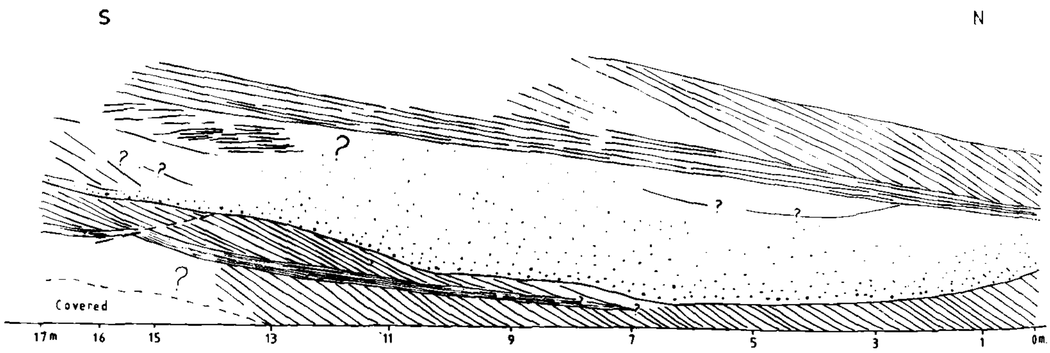

Fig. 12. Field sketch showing a view to the west of a lenticular channel-fill body in the road cutting section, Ramgundam. The channel-fill unit cuts into the underlying dune–interdune sequence.

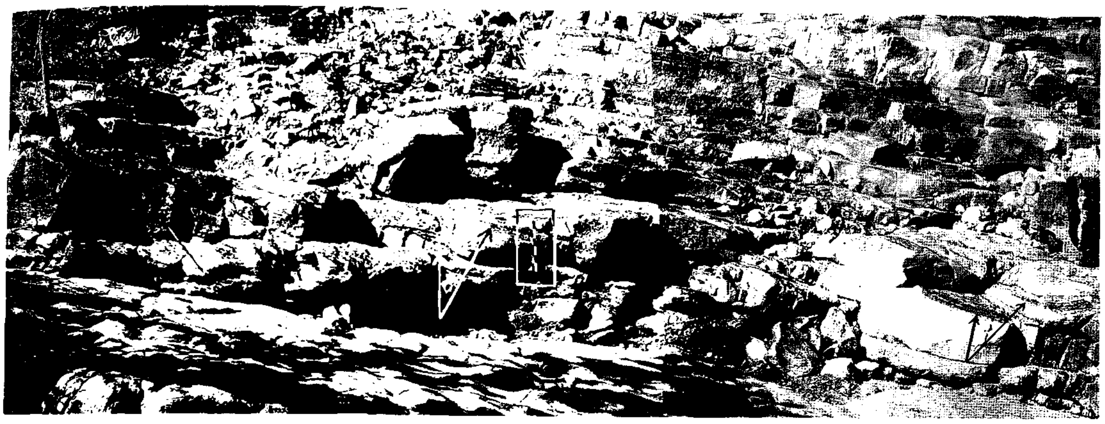

Fig. 13. Large wavy bedforms of F6 showing form-discordant internal accretionary surfaces (arrows). Note the F7 wave ripples in the foreground. Scale = 30 cm.

Facies 8 (F8): fine-grained sandstone with climbing-ripple cross-lamination

This facies consists of fine-grained sandstone with subordinate silt and mud and is characterized by climbing-ripple cross-lamination. The thickness of the pseudobeds in the range of 2–6 cm, well-preserved foreset lamination and absence of reverse grading suggest that the structures formed in a subaqueous environment. F8 always occurs intimately associated with the parallel beds of F9.

Facies 9 (F9): parallel-laminated fine- to medium-grained sandstone

Parallel-laminated fine- to medium-grained sandstones with well-developed parting lineations occur as 10–50-cm-thick, laterally extensive, tabular units. It commonly underlies the climbing-ripple-laminated rocks of F8.

Parting lineation has been reported from some aeolian deposits (Meinster & Tickell, 1976; Porter, 1987), but alternation of parting-lineated sandstone with climbing ripples of F8 clearly indicates an aqueous origin for the F9 rocks.

FACIES SEQUENCE

Bellampalli section

Details of a quarry section of the Venkatpur Sandstone near Bellampalli Railway Station (19°03′, 79°29′) are shown in Fig. 14. The lowest 4 m consists of dune cross-beds of F1. The cross-stratified unit is truncated by a knife-edge erosion surface and is overlain by a 5-m-thick, laterally extensive, sheet-like unit of F4. Signatures of evaporite and aqueous deposition abound in this unit. It consists of a number of stacked DU sequences (e.g. I–IV in Fig. 11). Each DU sequence is separated from the other, or the basal DU sequence from the underlying F1 unit, by a subhorizontal erosional surface with microtopography (Fig. 10) implying deflation close to the water-table. The erosional surfaces resemble in all their essential details the 'Stoke's surfaces' as described from different modern sand seas (Fryberger *et al.*, 1988). Sheet-like geometry and the thickness of the flat-bedded unit (≈ 5 m) exceeding those of the associated cross-bedded units preclude a dune-confined, i.e. interdune, origin. Evidence of deposition on the deflation surfaces, ubiquitous presence of salt and the absence of marine beds suggest an inland sabkha origin for the flat-beds (Kinsman, 1969). The sabkha sequence grades into a sequence of wind-ripple lamination and small cross-beds of F2 reflecting a comparatively dry, sand-saturated condition. The 3-m-thick sequence dominated by coarse-grained wind-ripple strata resembles deposits of aeolian sand sheets (cf. Fryberger *et al.*, 1979, 1983; Kocurek & Nielson, 1986).

The succeeding 8 m is dominated by large (≈ 3 m) cross-beds (Fig. 14). The cross-beds occur in single sets alternating with thin units of wind-ripple flat-beds (F2). The topmost part of the section consists of large superposed cross-beds. Superposed cross-beds represent either a compound aeolian bedform (see Havholm & Kocurek, 1988) or dune complexes, whereas the wedges or thin sheets of wind-ripple strata are the interdune deposits. The coset of large cross-

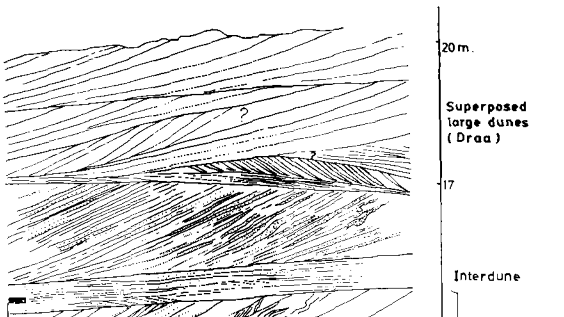

Fig. 14. Field sketch showing details of the stratification exposed in the cliffs of Bellampalli quarry.

beds in the basal and uppermost part of the section represents the net deposit left by the migrating dune complexes in the Venkatpur sand sea.

Godavari River section

The section measured in the south bank of the Godavari River, 2 km south of Mancheral (18°52′, 79°28′, Fig. 1) is about 17 m thick and predominantly finer grained than the other sections. Dune cross-beds and interlayered thin flat-beds, between 1·5–6·0 m and 14–17 m (Fig. 15), represent migrating dune–interdune complexes. Subhorizontal wind-ripple strata dominate the rest of the sequence. Small- to medium-sized dune cross-beds, aqueous trough cross-beds, sediment collapse and water-injection structures, rare adhesion laminae and salt-crust layers occur at different levels in the flat-bedded unit. The sequence represents sedimentation in wide low-lying sand sheets, dissected by small channels.

Compared to the Bellampalli section, the dune cross-beds in this section are much thinner. The mean thickness of 10 dune cross-beds at Bellampalli is 1·3 m, whereas that at Godavari is only 0·6 m. The presence of a sand sheet, comprising about 40% of the sequence, and decreased height of the dune bedforms are consistent with a setting marginal to the central erg. The absence of any extra-erg, non-aeolian facies either enclosing or intercalated with the aeolian unit, on the other hand, precludes an erg-margin environment. The sequence should correctly be termed an 'extra-dunefield deposit' as used by Fryberger *et al.* (1979, Fig. 12, p. 745) and is analogous to the 'zone of transportation' in the Jafurah Sand Sea (Fryberger *et al.*, 1983).

Ramgundam section

At Ramgundam (18°45′, 79°26′) several kilometres of road cuttings were examined. The section is marked by rapid facies variation, both laterally and vertically, and compared to the Bellampalli or Godavari sections, the sandstone here is more coarsely grained.

Cross-beds ranging in thickness from 0·3 to 2·8 m with angular foresets are common throughout the section and alternate with thin ($\leqslant$ 40 cm) wind-ripple strata (Fig. 16). The sequence represents a migrating dune–interdune complex. The dune–interdune sequence is interrupted at different levels by (i) thicker units of coarse-grained wind-ripple strata and zibar cross-beds (7–9 m, 11·5–13·5 m, 25–28 m, Fig. 16) that are interpreted to represent sand sheets; (ii) wavy and irregular-bedded (F3) sabkha sequences (19, 27 and 30 m) and (iii) apparently massive channel-fill deposits (0–2·5 m, 16–19 m, 38–39 m, Fig. 16). About 2 km ESE of the road section a railway cutting exposes a thin sequence of mudstone (F4) that overlies and partly interfingers with convex-up wind ripple strata (Fig. 8). The mudstone sequence suggests development of shallow ephemeral lakes within the sand sea. The aggregate thickness of the flat-bedded strata comprising 35% of the sequence, frequent interlayers of sand sheet, sabkha and fluvio-lacustrine deposits and large amount of facies variation is thought to reflect the organization and architecture of the extra-dune field

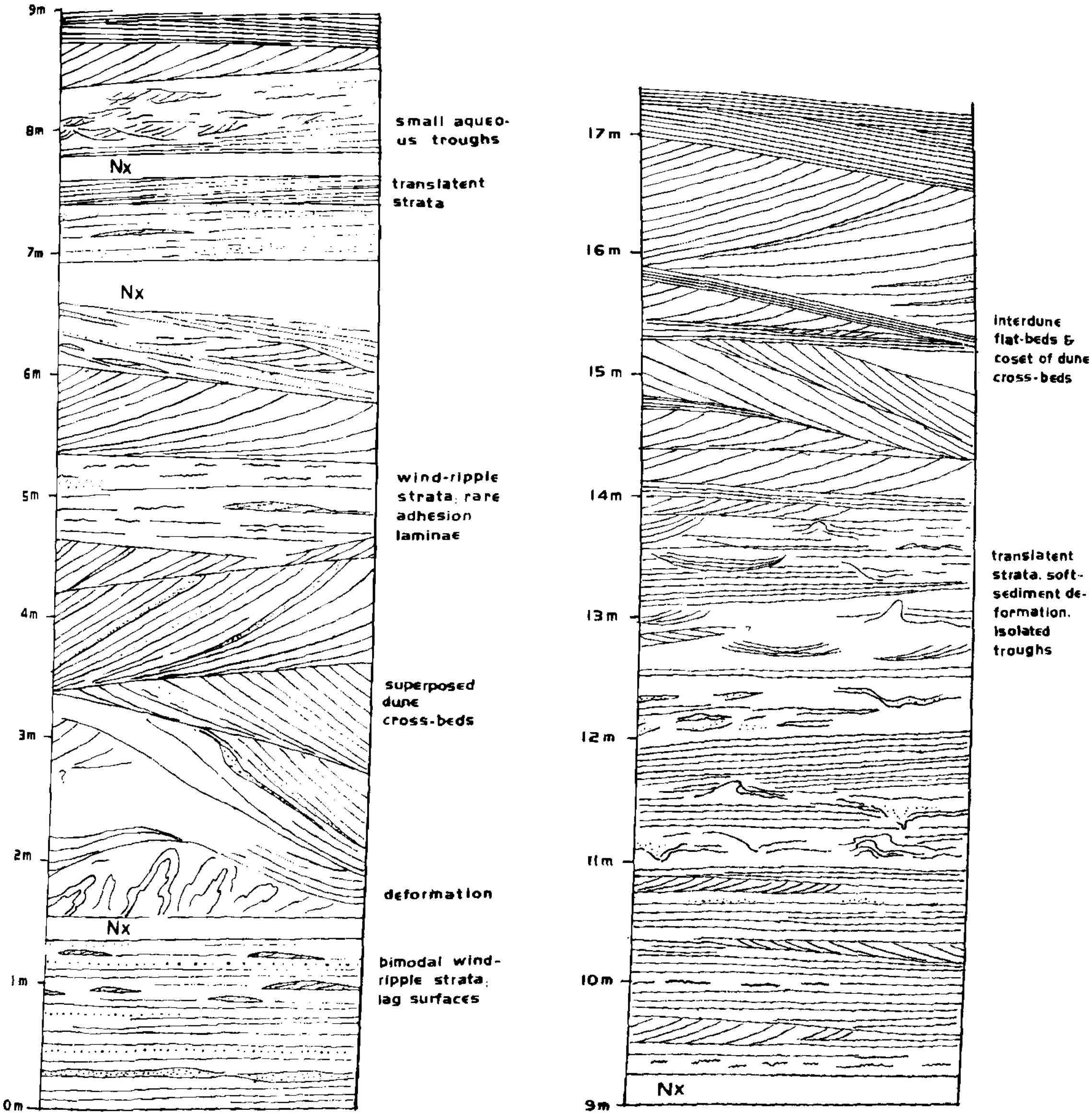

Fig. 15. Sequence of sedimentary structures in the Godavari River section.

sand-sheet-dominated environment. Fairly large isolated dune cross-sets averaging 1·17 m (cf. Bellampalli and Godavari River sections) throughout the sequence, however, suggest the opposite. The fluvio-lacustrine deposits are interpreted as part of the erg system and the absence of extra-erg facies indicates that Ramgundam does not represent the margin of the Venkatpur sand sea. It appears that the sand saturation level at Ramgundam was enough to initiate the dune-building processes repeatedly in time and space, but the dunes failed to develop into trains of compound complex bedforms. Coarse grain size, frequent development of small sabkhas and fluvio-lacustrine processes are some of the identifiable factors that inhibited dune growth and a low-lying sandy plain with scattered dune complexes resulted instead.

Laknavaram section

A stream section near Lake Laknavaram Cherevu (18°09′, 80°05′) exposes a 60-m-thick sequence (Fig. 17). The lowest 18 m consists essentially of a number

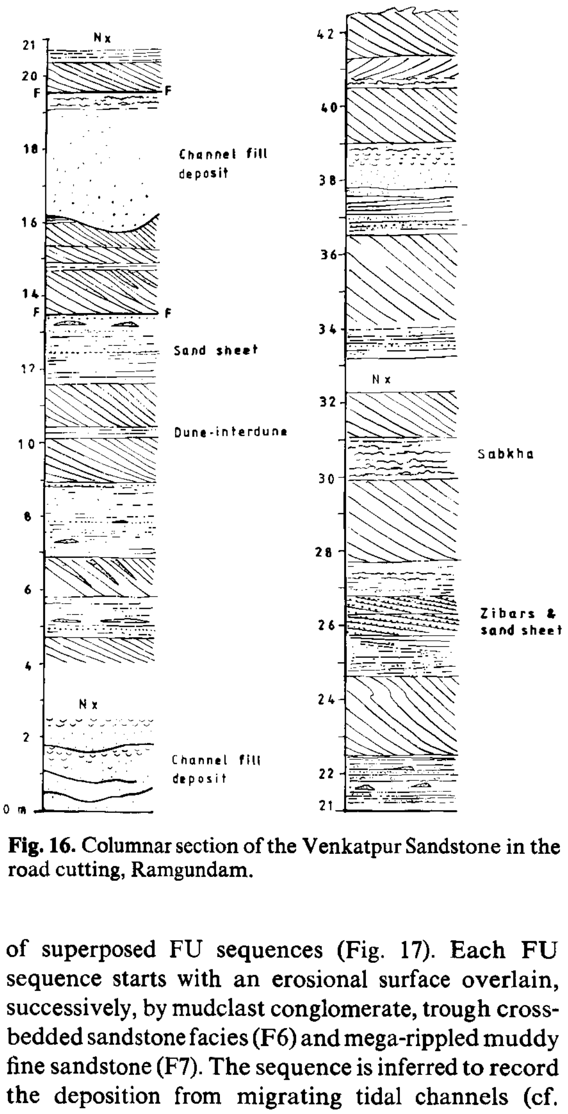

Fig. 16. Columnar section of the Venkatpur Sandstone in the road cutting, Ramgundam.

of superposed FU sequences (Fig. 17). Each FU sequence starts with an erosional surface overlain, successively, by mudclast conglomerate, trough cross-bedded sandstone facies (F6) and mega-rippled muddy fine sandstone (F7). The sequence is inferred to record the deposition from migrating tidal channels (cf. Moslow & Tye, 1985).

The overlying sequence from 19 to 26 m consists of alternating units of aeolian and tidal channel facies. Aeolian facies in this interval consist primarily of wind-ripple strata with subordinate adhesion structures, salt-ridge structures intercalated with rare wave/current ripples and a few small aeolian cross-beds. The assemblage represents coastal sabkha and coastal sand-flat deposits (see Kocurek & Fielder, 1982; Hummel & Kocurek, 1984). The alternation of marine and aeolian environments resulted through intermittent transgression of the shallow sea upon the prograding coastal dunes or coastal sabkhas.

From 34 m upwards, the sequence consists essentially of horizontally stratified wind-ripple strata with a few small dune cross-beds, interspersed with several thin horizons containing wave ripples, desiccation cracks, and adhesion- and salt-related structures. A unit of stacked channel-fill deposits (F5) occurs between 51 and 54 m (Fig. 17). The topmost 4 m shows the development of comparatively larger (≈ 1 m) sets of aeolian cross-beds.

The sequence marks the southeastward marine termination of the Venkatpur erg where a milieu of sand sheets, coastal sabkhas, small isolated dunes and ephemeral channels appeared over an extensive sand flat close to the palaeoshoreline. The transition in the vertical sequence from shallow-marine to aeolian-marine intercalation and finally to dominantly aeolian facies marks the seaward progradation of the aeolian environments.

Machchupuram section

Several kilometres north of Lake Laknavaram, the Venkatpur Sandstone crops out in a few low-lying ridges or is exposed in a few small quarries. The sections are, on average, about 1 m thick, and each comprises a 10–30-cm-thick basal unit of parallel-laminated sandstone with parting lineation (F9) overlain by a 20–60-cm-thick unit of climbing ripples and small cross-beds of F8.

The sequence probably represents overbank sheet-flood deposits of an ephemeral fluvial system (cf. McKee *et al.*, 1967; Tunbridge, 1981) and marks the development of a major non-aeolian sequence within the aeolian regime. Excellent sorting and high grain roundness suggest that ephemeral streams had been reworking the sands of the adjacent dune field or sand sheets.

THE VENKATPUR ERG

The occurrence of different aeolian facies representing different aeolian subenvironments through the 100-km outcrop belt indicates that a well-established aeolian regime, comparable with a well-developed modern erg, dominated the Pranhita–Godavari Valley during the Late Proterozoic. The sedimentary sequences display the following changes from NW to SE: (i) increasing dominance of flat-bedded facies, (ii) corresponding decrease of the cross-bedded facies as well as of superposed large cross-beds and (iii) increase in non-aeolian facies intercalated with the aeolian

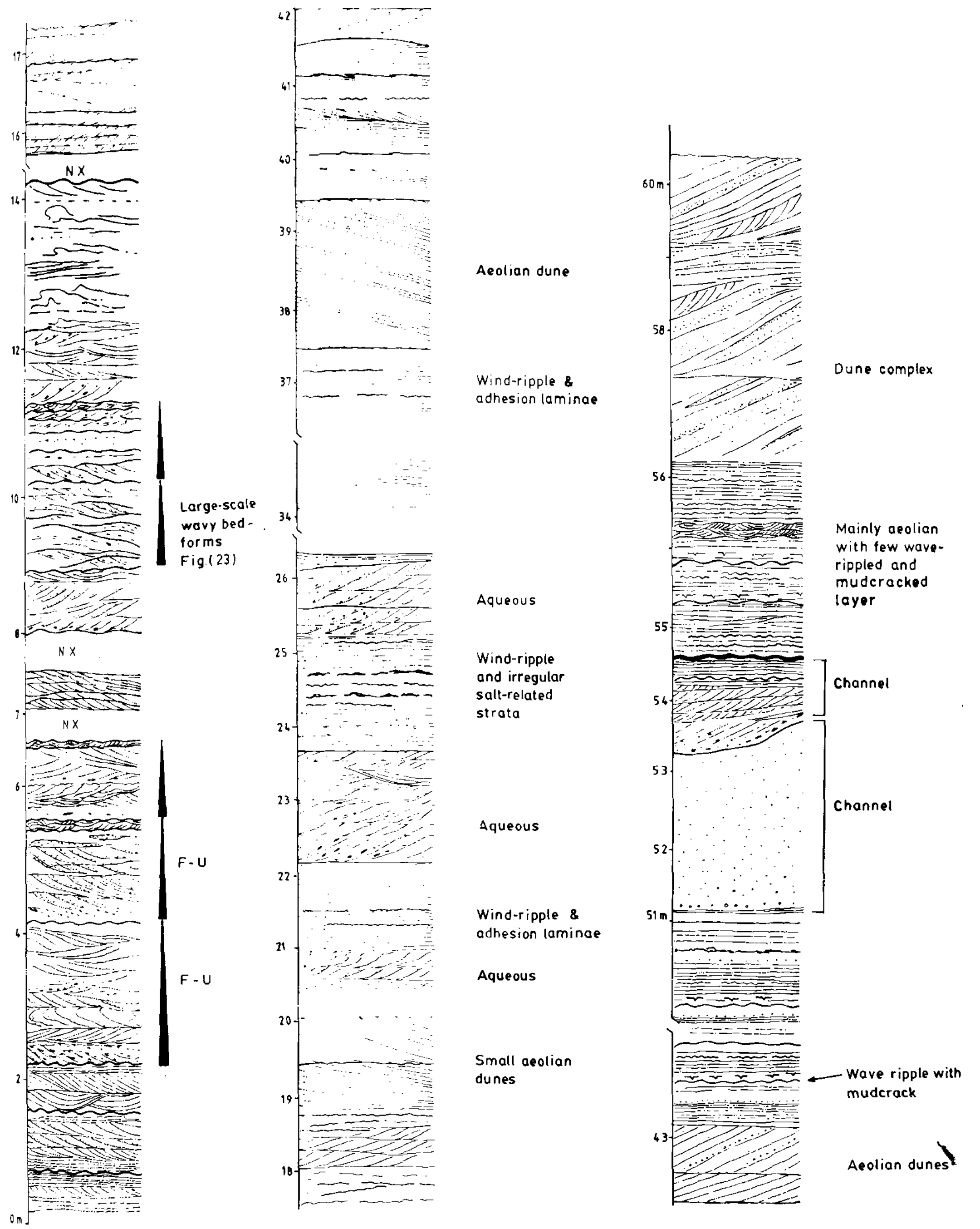

Fig. 17. Stratigraphic section of the coastal erg-margin sequence at Laknavaram.

sediments. The changes can be explained in terms of the changing geomorphology from an erg interior to an erg margin (Fig. 18, see also Breed *et al.*, 1979; Ross, 1983; Porter, 1987). The large dune cross-bedded sequence of the Bellampalli section in the NW extremity of the study area characterizes the well-developed dune fields of the comparatively interior part of the sand sea, whereas the Laknavaram section

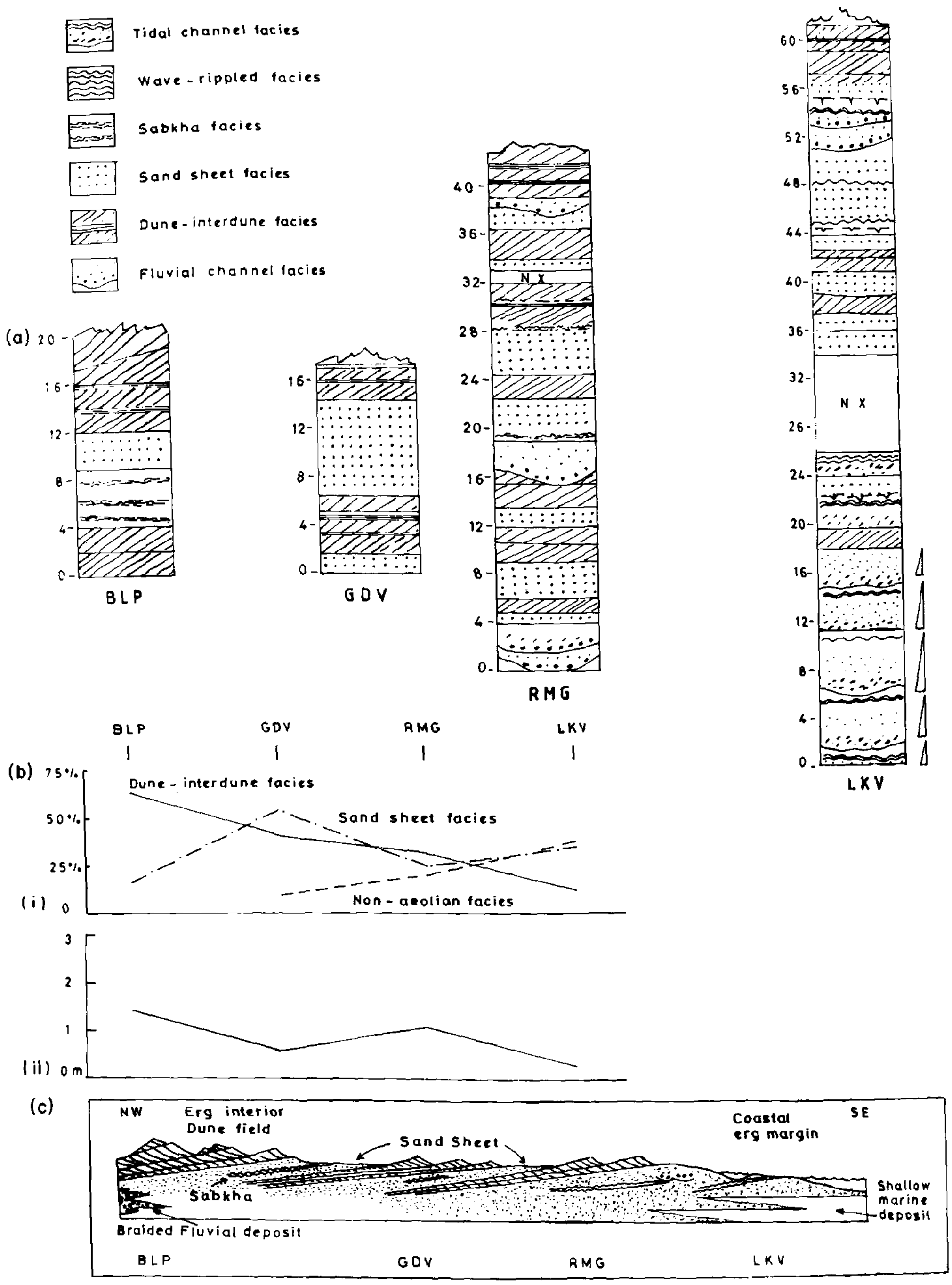

Fig. 18. (a) Generalized logs of the sequences showing lateral facies variation from NW to SE in the Venkatpur Sandstor (i) Graphical representation showing variation in the proportion of different facies along the outcrop belt. BLP = Bellar section; GDV = Godavari River section; RMG = Ramgundam section; LKV = Laknavaram section. (ii) Changir thickness of dune cross-beds in different sections. (c) A NW–SE schematic section through the reconstructed Venkatpu sea.

with the intercalated shallow-marine and aeolian deposits characterizes the coastal erg margin and delineates the SE limit of the sand sea. The Godavari River and Ramgundam sections represent extensive low-lying sand-sheet areas between the interior dune field and the erg margin. Certain departures from the expected have been noted in the changing facies assemblage from NW to SE, and the changes in grain size or set thickness of dune cross-beds (the latter is assumed to be a measure of original bedform height) along the outcrop belt are non-linear. The grain size of the Godavari section is finer than both the Bellampalli and Ramgundam areas and some cross-beds of the Ramgundam section are as large as those of the Bellampalli section. Apparently the major trend of facies variation (Fig. 18) reflects the transition from the erg interior to the erg margin and the departures noted above might have been influenced by local topography, sand transport path, local sand supply sources and a complex lateral arrangement of erg environments with respect to the NW–SE section line.

The occurrence of different facies sequences in different parts of the Venkatpur sand sea allows reconstruction of different major erg environments such as (i) dune field, (ii) sand sheet, and (iii) coastal erg margin (Table 3). The facies assemblages are comparable to those in different geomorphological terrains in the modern sand seas (Breed *et al.*, 1983; Sweet *et al.*, 1988), and different erg environments recognized in ancient eolianites (Kocurek, 1981b; Ross, 1983; Dott *et al.*, 1986; Porter, 1987).

Dune field

Dune-field sequences of the Venkatpur Sandstone are characterized by large (2–4 m thick) aeolian cross-beds that comprise about 85–90% of the sequence. Bedforms were either solitary or formed large superposed cross-beds or draas (*sensu* Havholm & Kocurek, 1988), separated by thin interdune sediments. The Bellampalli section, where the sequence is well developed, reveals that water activity was negligible in the dune-field sequence compared to the immediately underlying inland sabkha sequence. This reflects net sedimentation above base level, where influence of ground water is minimal and there is abundant sand for the development of large dunes and dune complexes.

Sand sheet

This facies assemblage dominantly comprises horizontal or low-angle coarse-grained wind-ripple strata in units 0·7–8·0 m thick and is marked by rapid facies variation and intercalated sabkha or fluvio-lacustrine sediments. It represents extensive low-lying sandy

Table 3. Characteristics of different erg environments in the Venkatpur Sandstone.

Erg environments	Distinctive sedimentary features	Occurrence
Dune fields	2–4-m-thick cross-beds constitute 85–90% of the sequence Presence of large superposed cross-beds or draas Sets or cosets of dune cross-beds separated by thin (5–30 cm) wind-rippled flat-beds (interdune deposits) Near absence of aqueous activity	Bellampalli section, 12–20 m
Sand sheets	0·7–7-m-thick, laterally extensive unit of flat-beds which are thicker than or subequal to the thickness of associated cross-beds. Generally reduced height of the cross-beds High facies variation resulting in a complex facies mosaic incorporating different aeolian and fluvio-lacustrine environments Dry sand sheets are dominated by coarse wind-ripple strata with rare zibars and dome dunes	Godavari and Ramgundam sections
	Wet sand sheets are characterized by adhesion- and salt-related features along with wind ripples, abundant soft-sediment deformations and thin DU sequences separated by deflation surfaces close to the water-table	Bellampalli section, 4–9 m
Coastal erg margin	Flat-bedded units of different thickness consisting of wind-ripple strata, adhesion structures, salt-ridge structures, etc., along with a number of wave-rippled and mudcracked intervals Dune cross-beds are rare and when present forms thin units Aeolian units regularly alternate with or laterally and vertically grade into shallow-marine deposits	Laknavaram section

plains with sabkhas, isolated dunes or small dune complexes traversed by small- to medium-scale ephemeral streams. Isolated zibars and possible dome dunes occur in the sequence.

Sabkha facies (F4) are an important constituent of the sand sheets. Sabkhas occur in interior dune-dominated areas, extra-dune field areas or in the coastal areas. Sabkhas occurring in the Venkatpur sand sea are characterized by an abundance of salt-related deformational features, erosional features implying deflation close to the water-table, thin DU sequences and a few muddy beds with aqueous ripples.

Most of the Recent and Phanerozoic sand sheets are characterized, among other things, by an erg-margin setting resulting in a typical architecture of these sandbodies enclosed within or interfingering with the extra-erg facies (Kocurek & Nielson, 1986; Porter, 1987; Sweet *et al.*, 1988). This sandbody architecture is absent in the Vankatpur Sandstone, indicating development of sand sheets as major erg facies that extended over large areas between the erg margin and the well-developed dune fields.

The 'zone of transportation' recognized in parts of the Jafurah sand sea, Saudi Arabia (Fryberger *et al.*, 1984), provides a possible modern analogue for the sand-sheet sequence of the Godavari River section. The zone of transportation in Jafurah fringes the large dune complexes and is characterized by moderate wind energy, 'immature' sand sheets, isolated dunes or small dune complexes and small sabkhas. The sand sheets of the Bellampalli and Ramgundam sections, on the other hand, were essentially a zone of deflation with higher wind energy. Dominance of wind ripples with a coarse, bimodal sand population, common lag surfaces, occurrence of deflation surfaces close to the water-table, sabkhas and zibars characterized these assemblages.

Erg margin

Intercalation of the shallow-marine and aeolian deposits characterizes the erg-margin sequence around Laknavaram. The coastal erg sequence contains very few small dunes and is dominated by low-angle beds consisting of adhesion plane beds, wind ripples, salt deposits and desiccated, wave-rippled muddy sandstone. An overall finer grain size, wet depositional setting and interlayered marine deposits typify the Venkatpur coastal erg-margin sequence.

The complete scenario of Venkatpur sedimentation comprises a very wide sandy plain, essentially a mosaic of small pools, sabkhas, sand sheets interspersed with isolated dunes and small channels. The plain gradually merged with shallow-marine environments through a sandy coastal plain towards the SE, whereas to the NW, it merged with well-developed dune complexes. This scenario appears to be similar to that envisaged for many ancient sand seas (Kocurek, 1981b; Ross, 1983; Dott *et al.*, 1986; Porter, 1987).

SIGNIFICANCE OF THICK FLAT-BEDDED UNITS

In areas dominated by transverse bedforms in most modern erg environments, the length of interdune areas measured perpendicular to the dune crests is much less than the length of the dunes (Breed & Grow, 1979). Migration of such dunes will produce deposits consisting of thick dune cross-beds interstratified with thin interdune horizontal beds. Moreover, the slow rate of deposition in the interdunes results in thin sedimentation units, as is displayed in many ancient dune-field sequences. Flat-bedded units with thicknesses comparable to or exceeding those of the associated dune cross-beds would, on the other hand, imply sedimentation outside the well-developed dune fields. Flat-bedded sequences in the Venkatpur Sandstone occur both as thin sheets wedged between dune cross-beds, and as thick extensive units with signatures of significant water activity and abundant salt deposition. The former represents the interdunes in the dune fields, whereas the latter has been inferred as the product of sedimentation in wide low-lying areas like sand sheets, sabkhas or coastal sand flats.

Horizontally stratified sedimentary units in aeolian deposits may develop in a number of environments: for example interdune, dune apron, sabkha, sand sheet (Fryberger *et al.*, 1983; Kocurek, 1986). Deposits in these environments possess many common attributes, and recognition of a specific depositional regime in the rock record may be problematical. Flat-bedded units in ancient aeolian sequences, however, have been generally interpreted to represent interdune deposits. The study of the Venkatpur Sandstone shows that horizontally stratified units can be inferred to have been deposited both in sand-sheet and/or sabkha environments as well as in interdune areas. This interpretation is based mainly on the association and assemblage of facies as well as stratigraphic considerations, rather than on textural features or stratification styles.

PALAEOCURRENTS

A limited number of palaeocurrent data collected from large dune cross-beds indicate a NE palaeowind direction (Fig. 19). More than 200 palaeocurrent data collected by earlier workers around Mancheral (18°53′, 79°26′) and Kistampet (18°51′, 79°45′) (Johnson, 1965) give a NE–ENE mean palaeoflow direction. The mean palaeocurrent direction calculated from 132 measurements from exposures SE of Ramgundam is toward 68° (Chaudhuri, 1970). The consistent orientation of cross-beds over such widely separated areas indicates the existence of a stable regional wind circulation pattern. Notably, the inferred palaeowind direction is nearly perpendicular to the present NE–SE trend of the outcrop belt.

COMPARISON OF THE VENKATPUR SAND SEA WITH KNOWN PHANEROZOIC ERG DEPOSITS

Despite basic similarities, the Venkatpur Sandstone differs from most other documented Proterozoic and Phanerozoic ergs in several important aspects.

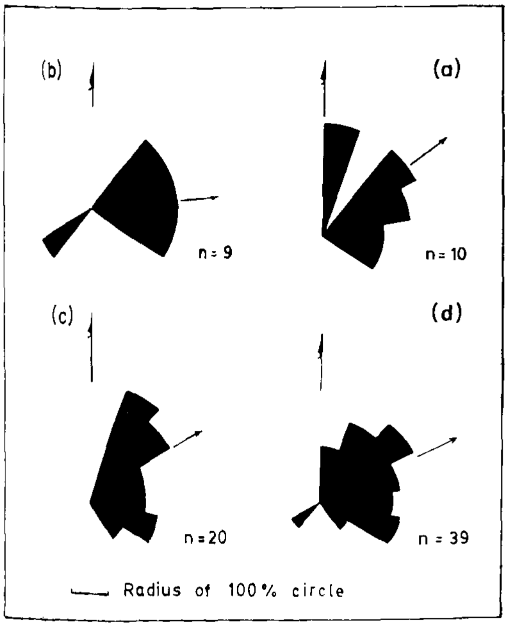

Fig. 19. Palaeocurrent pattern from the Venkatpur Sandstone recorded from large-scale cross-beds. (a) Ramgundam area, (b) Godavari River section and vicinity, (c) Bellampalli area, (d) total Venkatpur Sandstone. Rose diagram construction after the method by Chenney (1983).

First, the sand sea is marked by the common development of sabkhas in its marginal as well as interior parts. Close association of coastal sabkhas and related evaporite facies with the sand seas has been reported by different workers (Kinsman, 1969; Glennie & Evans, 1976; Kocurek, 1981b; Porter, 1987; Fryberger *et al.*, 1988). Marine sabkhas can form tens of kilometres inland through rare storm flooding and capillary processes, but are commonly close to the palaeoshoreline (Chan & Kocurek, 1988). The > 5-m-thick sabkha sequence at Bellampalli is at least 100 km from the recorded coastal sequence, suggesting an inland setting and non-marine sources for the salt. Periodic surface flooding, high water-table even in the interior parts, and an overall deflationary wind regime are some of the factors that might have favoured frequent sabkha development.

Secondly, even though the aeolian regime covered an extensive area, the sequences are marked by an unusual paucity of large compound bedforms. The cross-beds are mostly in the range of 1–2·5 m, which is much less than those of many ancient eolianites (Ross, 1983; Loope, 1984; Porter, 1987; Kerr & Dott, 1988 among many others). The close association and interbedding of the Venkatpur Sandstone with a braided fluvial system (Ramgiri Formation and Mancheral Quartzite, formerly known as Encharani Quartzite; Chakraborty, 1988) attest to the presence of potential source material in the close vicinity. Extensive development of sabkha, fluvio-lacustrine and related wet environments probably caused greater entrapment and/or reworking of sand. This in turn might have retarded sand transportation in the interior areas favouring growth of small dunes and an extensive low-lying sandy plain. A similar role of extensive wet environments has been inferred from the study of recent dune fields as well as ancient sequences (Hummel & Kocurek, 1984; Dott *et al.*, 1986; Kocurek & Nielson, 1986; Chan & Kocurek, 1988; Chan, 1989).

Thirdly, in the Venkatpur Sandstone, the trend of facies transition is not parallel to the resultant palaeowind direction, as has been reported from several ancient aeolian deposits (see Ross, 1983; Dott *et al.*, 1986; Porter, 1987) and modern examples such as the Jafurah Sand Sea (Fryberger *et al.*, 1984). Azimuths of large dune cross-beds collected during the study and earlier (Johnson, 1965; Chaudhuri, 1970, Fig. 18) from widely scattered areas suggest a very persistent palaeotransport direction towards the NE. The exact relationship between flow direction and trend of facies variation has not been resolved.

The relationship is apparently more complex than that for the Aztec or St Peter Sandstone, and may simulate many modern sand seas where the resultant drift direction is oblique to the dune crests (Breed *et al.*, 1979, p. 324, see Figs 201, 206, 235).

Recognition of the Venkatpur Sandstone as an extensive aeolian deposit suggests that many of the mature Proterozoic sheet sandstones that abound in different Proterozoic basins of India, earlier interpreted as shallow-marine deposits (Chaudhuri & Howard, 1985; Singh, 1985; Nagraja Rao *et al.*, 1987 among others), could well be aeolian deposits. In the unvegetated landscape of the Proterozoic traversed by widely fluctuating sandy braided rivers, combined fluvial and aeolian processes may have been more effective in spreading out large sheets of sand than marine processes.

CONCLUSIONS

The Proterozoic Venkatpur Sandstone of the Pranhita–Godavari Valley, interpreted earlier as a shallow-marine deposit, abounds in diagnostic aeolian features such as adhesion laminae and inverse-graded translatent strata. The sandstone sequence developed in an extensive erg that was characterized by a wide sand sheet (Godavari and Ramgundam sections) comprising flat-bedded wind-ripple strata, zibars, sabkhas, ephemeral lakes and channels and scattered small dunes. The sand sheet merged with the cross-bedded dune-field sequence of the erg interior to the northwest (Bellampalli section) whereas to the southeast, it merged with the erg-margin shallow-marine sequence (Laknavaram section). Palaeocurrent measurements denote a very consistent northeasterly palaeoflow direction over the erg which is at a high angle to the present trend of the linear outcrop belt. A shallow water-table, extensive development of salt crusts, reworking by ephemeral channels and coarser grain size are some of the factors that suppressed the development of the dunes and favoured the growth of an extensive sand-sheet environment. This in turn was probably responsible for the small dune cross-beds, even in the interior dune field areas. Abundance of flat-beds, as in the Venkatpur sandstone, is uncommon in many Phanerozoic aeolian deposits; however, similar sequences have been reported from some pre-Silurian aeolian sequences (Dott *et al.*, 1986). Facies assemblages and stratigraphic consideration help in differentiating different subenvironments such as interdune, sabkha, sand sheet or coastal sand flats for the deposition of the flat-bedded units.

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