EOLIAN–AQUEOUS INTERACTIONS IN THE DEVELOPMENT OF A PROTEROZOIC SAND SHEET: SHIKAODA FORMATION, HOSANGABAD, INDIA

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ABSTRACT: A 40-m-thick eolian sand sheet deposit characterizes the upper part of the Proterozoic Shikaoda Formation near Hosangabad. It sharply overlies shoreface deposits and comprises wind-ripple strata (~ 50%), adhesion strata (~ 17%) and subaqueous strata (~ 33%). Each stratification type defines stratal packages tens of centimeters thick and few meters wide that are superposed upon one another in a nearly random fashion. The eolian facies is inferred to have been deposited in a low-gradient, sandy supratidal setting. The subaqueous deposits of the sand sheet also reflect a tide-affected, westward-opening coastal setting with an approximately north–south shoreline. Abundance of aqueous and adhesion strata coupled with the absence of granule-rich coarse-grained layers, corrugated erosion surfaces and evaporites are the typical features of the Shikaoda eolian sand sheet. These features indicate that in spite of abundant sand supply from the coastal sources and a net aggradational setting, repeated flooding and high surface moisture were the principal factors that inhibited dune-building processes and favored the growth of a flat-bedded eolian sand sheet in the Shikaoda Sandstone.

Numerous subhorizontal, nearly flat bounding surfaces split the sand sheet succession into tabular sediment bodies 50–100 cm thick. Each of the bounding surfaces can be traced for a few tens of meters and can be correlated to an event of aqueous flooding. Vertical stacking of tabular sandstone bodies implies that long-term sediment aggradation rate in the low-lying supratidal region kept pace with that of basin subsidence.

The sedimentological features of the Shikaoda sand sheet facies when compared with known modern and ancient sand-sheet deposits suggest that the Shikaoda sand sheet developed independent of an erg in a comparatively wet climatic setting. The sub-humid coastal eolian sedimentary system of Padre Island, Texas is probably the closest modern analogue of the Shikaoda sand-sheet facies.

INTRODUCTION

Eolian sand sheets are defined as extensive, flat to gently undulating surfaces covered predominantly with wind ripples and marked by the conspicuous paucity of slip-face dunes (Fryberger et al. 1979; Kocurek and Nielson 1986). Modern sand sheets are known to occur in erg-margin settings as well as in coastal areas and sandy alluvial plains of arid regions (Glennie 1970; Fryberger et al. 1979; Fryberger et al. 1983; Hummel and Kocurek 1984). Eolian sand-sheet deposits have also been recognized from the ancient sedimentary record, and their inferred depositional milieu include periglacial, alluvial plain, tidal flat, and erg margin (Ruegg 1983; Loope 1984; Porter 1987; Dott et al. 1986; Schwan 1987; Simpson and Eriksson 1991; Clemmensen and Dam 1993; Chakraborty and Chaudhuri 1993; Trewin 1993). Observations of the modern sand sheets suggest that a number of factors operate singly or in conjunction to suppress dune-building activity and favor formation of flat-lying, ripple-covered areas. The inhibiting factors include presence of vegetation, armoring by coarser grain size, high water table, surface cementation, and repetitive flooding (Fryberger et al. 1979; Kocurek and Nielson 1986; Kocurek 1996).

Modern sand sheets are most abundant in trailing and advancing margins of ergs (Fryberger et al. 1979; Kocurek and Nielson 1986). Vegetation cover and coarse-grain armoring are probably the two most important causal factors influencing their development (Kocurek and Nielson 1986). Ancient low-angle eolian deposits, particularly those deposited before the advent of the land vegetation, however, might have formed in a different way.

This paper reports a 40-m-thick eolian sand sheet deposit from a Neoproterozoic succession of central India that formed in a coastal setting and probably existed independent of an erg. On the basis of a detailed study of the sedimentary structures and internal architecture of the sand sheet we have attempted to identify the factors that might have controlled formation and preservation of the sand sheet.

STRATIGRAPHIC AND SEDIMENTOLGICAL BACKGROUND

The sand-sheet deposit described in this paper belongs to the Shikaoda Formation (previously known as Upper Bhander Sandstone), the uppermost formation of the Bhander Group, the youngest group of the Proterozoic Vindhyan Supergroup in Son Valley (Fig. 1; Bhattacharyya 1996).

The Vindhyan strata in Son Valley define an ENE–WSW trending, broad

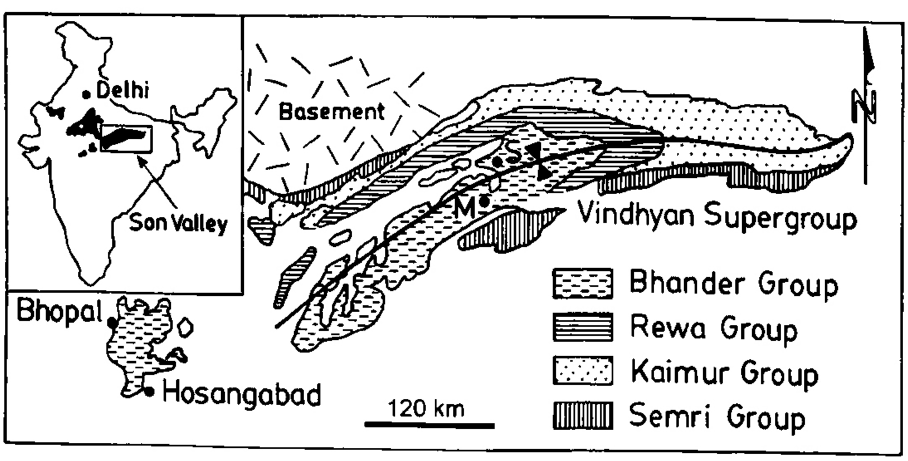


FIG. 1.—Generalized geological map of the Vindhyan Supergroup in Son Valley. Note a detached outcrop of the Bhander Group around Hosangabad. Inset shows the location of the Vindhyan outcrop belt in the Indian subcontinent. M = Maihar, S = Satna.

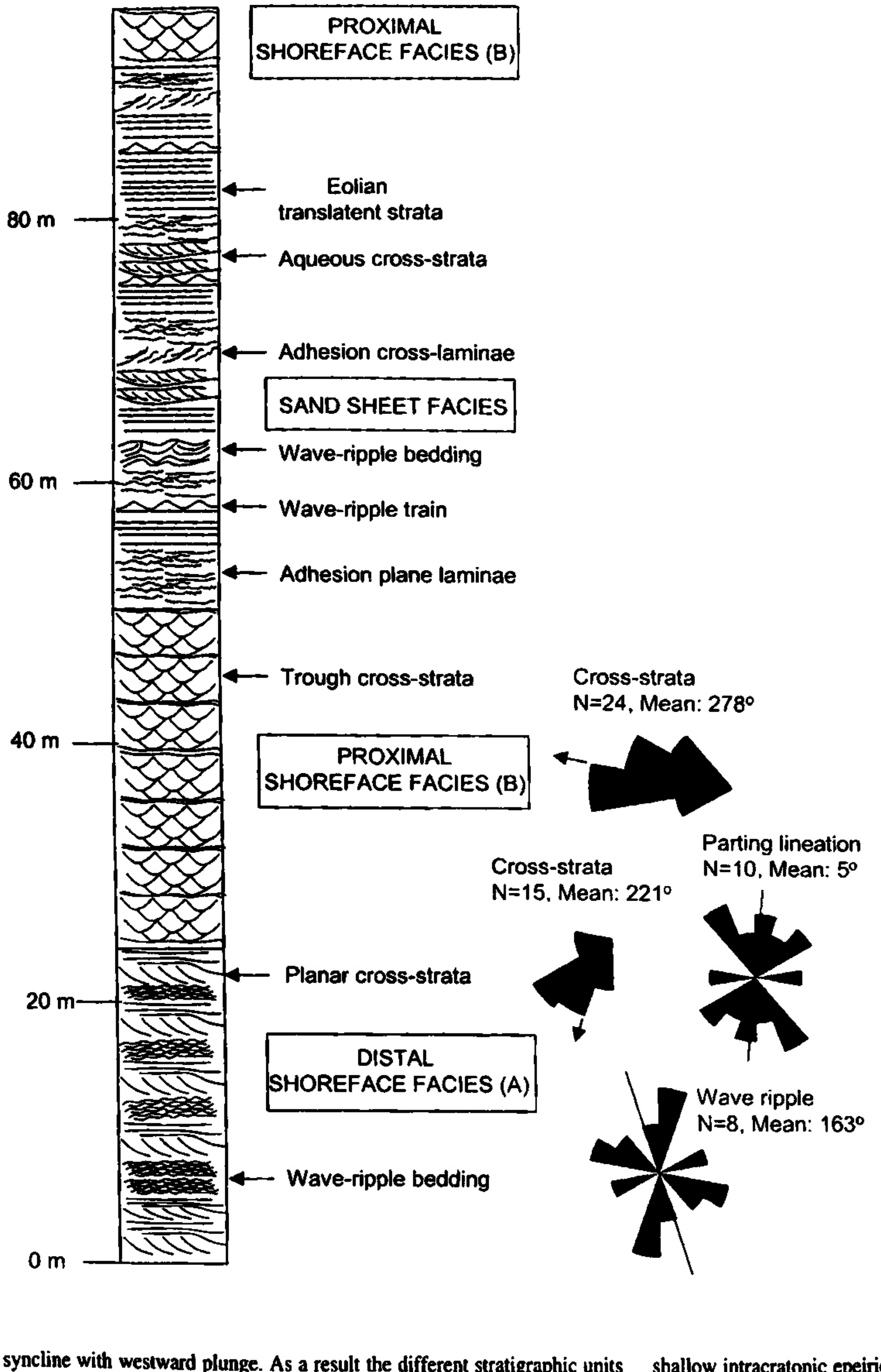


FIG. 2.—Vertical log of the sedimentary succession of the Shikaoda Formation exposed south of Hosangabad. Different sedimentary features present in different facies are schematically represented with specific symbols and are not to scale and position. Paleocurrents of the shallow marine deposits underlying the sand sheet-facies are also shown.

syncline with westward plunge. As a result the different stratigraphic units are exposed as parabolic bands with eastward closure (Fig. 1). At the southwestern extremity of the outcrop belt, around Hosangabad, Madhya Pradesh, a detached outcrop of the Shikaoda Formation occurs as an inlier within the Deccan Trap (Fig. 1; Sastry and Moitra 1984). The eolian sandsheet deposit described in this paper occurs within the 100-m-thick succession of the Shikaoda Formation exposed south of Hosangabad (Fig. 1).

The Vindhyan succession in Son Valley represents deposits of a variety of depositional systems ranging from continental to marine shelf. The features of the Vindhyan succession clearly indicate existence of a vast, very shallow intracratonic epeiric basin (Naqvi and Rogers 1987) throughout its depositional history.

A coastal-plain depositional setting has commonly been inferred for the Shikaoda Formation (Singh 1973, 1976). Recently Bose et al. (1999) have identified an eolian unit comprising a small longitudinal dune deposit within the Shikaoda Formation occurring around Maihar (Fig. 1).

The succession of the Shikaoda Formation exposed at Hosangabad is dominated by fine- to medium-grained sandstones with minor shale interbeds and comprises four sheet-like packages (Fig. 2). The lowermost package (Facies A) is characterised by a regular, meter-scale alternation of

FIG. 3.—Thin persistent wind-ripple (translatent) stratification in the sand-sheet facies. Note low-angle foresets (arrows).

cross-stratified and wave-rippled units. The cross-strata are concave-up and sigmoidal in flow-parallel sections. The thickness of the cross-sets varies from 30 cm to 1 m. Cross-stratification may grade laterally and vertically into parallel lamination bearing parting lineation. The intervening wave-rippled units contain mud flasers and drapes. Individual rippled strata have thicknesses on the order of a few millimeters and in places define low amplitude hummocky macroforms (Arnott 1992).

The proportion of the ripple-bedded unit in Facies A gradually decreases upwards and the facies grades into a medium-grained, dominantly trough-cross-stratified sandstone facies (Facies B, Fig. 2). In Facies B the thickness of the cross-sets range from 10 to 30 cm and in flow-parallel sections individual sets can be traced up to 1.5 m. The eolian sand sheet unit sharply overlies Facies B and is also capped by the same facies (Fig. 2).

Absence of subaerial exposure features, dominance of dune-scale cross-stratification, and presence of wave-rippled, hummocky macroforms together suggest that Facies A and B largely represent a shallow marine shoreface environment. Lack of mud, absence of hummocky bedforms, coarser grain size, and lower thickness of cross-sets in Facies B are collectively inferred to indicate a more proximal shoreface position of the Facies B compared to Facies A. The paleocurrent directions of these facies reveal a mean trend towards the west or southwest (Fig. 2).

SAND-SHEET FACIES

The sedimentary features observed in the Shikaoda sand sheet facies can be broadly categorized into three groups: dry eolian features, damp eolian features, and subaqueous features (Table 1).

Dry Eolian Features

The dominant dry eolian feature in the sand-sheet facies is wind-ripple strata. The strata comprise thin, subhorizontal to gently dipping ($< 10°$) laminae within very fine to medium-grained, well-sorted sandstone (Fig. 3). Laminae vary in thickness from less than a millimeter to several millimeters and laterally persist for several decimeters to more than a meter. Many of the individual laminae, in low-angle sections or in thin sections, show inverse grading (Fig. 4). Gently inclined foreset laminae are rarely visible within the wind-ripple strata of the Shikaoda Formation (Fig. 3) as observed in experimentally produced wind-ripple strata (Fryberger and Schenk 1981). Wind ripples exposed in plan surfaces have low amplitude, straight to sinuous crest lines and show concentration of coarser grains in the crestal region. Wind-ripple laminasets range in thickness from several centimeters to few tens of centimeters.

A few solitary sets of eolian cross-strata have also been observed in the sand-sheet facies (Fig. 5) that occur sandwiched between sets of wind-ripple strata and range in thickness from 1 to 8.5 cm with an average of 4 cm. The sets can be traced laterally for up to a few meters. Within a cross-set, steeply ($\approx 22°$) dipping, comparatively coarser-grained grainflow wedges occur irregularly interspersed within wind-ripple or grainfall foreset laminae (Fig. 5). Irregular spacing of sandflow wedges within grainfall or wind-ripple strata are typical of eolian dunes in contrast to aqueous dune cross-strata that are mostly made up of grainflow deposits (Hunter and Kocurek 1985; Kocurek 1991). In some cases dip of the foreset layers decrease in the downcurrent direction as alternating grainflow and grainfall/wind ripple strata are replaced by gently dipping wind-ripple strata.

Sediment packages made up of dry eolian features (dry eolian packages) constitute 50% of the measured sections. The maximum observed thickness of the dry eolian packages is 40 cm whereas modal thickness ranges between 15 and 20 cm. Lateral extent of the packages is less than a few meters. Flat to gently undulating erosional surfaces, in places overlain by subaqueous strata, frequently occur within the dry eolian packages (Fig. 6).

Damp Eolian Features

Adhesion structures comprising thin, crinkly laminae of variable dip are abundant in the sand-sheet facies. These structures form when dry wind-blown sands stick to a wet or damp substrate (Kocurek and Fielder 1982). Adhesion cross-laminae of the Shikaoda sand sheet occur in sets less than a centimeter to several centimeters thick (Fig. 7). Many of the exhumed bedding planes are covered with adhesion ripples that appear as rhythmic, small surface undulations with discontinuous crest lines (Fig. 8). Foreset azimuths of the adhesion cross-laminae vary considerably and in places show bipolar arrangement in successive sets (Fig. 9). Adhesion laminae are subhorizontal and occur in sets a few millimeters to 7 centimeters thick (Fig. 10). Most of the sets, however, range between 3.5 and 4 cm. Commonly, within a set of adhesion planar laminae thickness of individual laminae decreases upward (Fig. 10). Lateral and vertical gradation of adhesion cross-lamination to adhesion planar lamination and vice versa is common. Adhesion warts are found less commonly. In places adhesion ripples are found to mantle wave-rippled surfaces. Sand-filled desiccation cracks have also been noted.

The sediment packages formed by the adhesion structures (damp eolian packages) are up to 15 cm thick, modal thickness being 5–7 cm. Lateral extent of the packages does not exceed few meters as they grade into or are erosively replaced by subaqueous or wind-ripple strata. In the measured sections damp eolian deposits constitute 17% of the sand sheet facies.

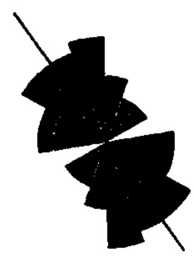
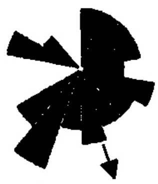
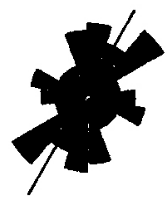
Formation of adhesion ripples and adhesion cross-lamination requires high substrate moisture ($> 80\%$ of the pore spaces filled with water). Lower moisture content and high wind speed, on the other hand, favor formation of adhesion plane lamination. Adhesion warts probably form because of the irregular, bumpy nature of the substrate or because of frequent changes in the wind direction (Kocurek and Fielder 1982).

Aqueous Features

Four types of aqueous sedimentary features have been noted in the sand sheet facies: (1) wave ripple, (2) trough cross-strata, (3) channel scour, and (4) massive sandstone.

The most abundant aqueous structure in the sand-sheet facies is wave ripples. Trains of wave ripples occur within exhumed shallow scour channels or cover flat pavements (Fig. 11). The wave-ripple strata may occur as single form sets or cosets varying in thickness from a few centimeters to 15 centimeters (Fig. 6). Ripples are nearly symmetrical to asymmetrical, have straight and bifurcated crestlines. The ripple lamination in profile shows symmetrical waveform, and bundled upbuilding of laminae with offshoots (Fig. 12). Bedding-plane exposures also show isolated patches of wave ripples with irregular to elliptical margins (Fig. 13). These isolated ripple patches probably represent small scour pools subsequently filled by

TABLE 1.—*Summary of the Shikaoda sand sheet facies.*

Sedimentary Features	Brief Description	Paleocurrent	Volumetric proportion
Wind-ripple (translatent) stratification	Horizontal or low-angle, persistent laminae, few mm to 2 cm thick; inverse grading within laminae; rarely preserved low-angle foresets	**Eolian Regime** *Crestal trends of wind and adhesion ripples* N = 21, Mean: 144° 	>45%
Adhesion cross-lamination	Crinkly, inclined laminae forming cross-sets less than 1 cm to 5 cm thick that show variable inclination and may grade laterally into adhesion plane laminae; adjacent sets often show bipolar orientation		Combined proportion of all types of adhesion strata: 17%
Adhesion plane-lamination	Thin, crinkly, subhorizontal laminae that occur in sets a few mm to 7 cm thick; lamina thickness decreases upward within a set; may grade laterally or vertically into adhesion cross-laminae		
Wind ripple	Low-amplitude, straight- to sinuous-crested ripples showing concentration of coarser grains in the crestal region; occur on exhumed bedding planes	*Azimuths of dune cross-strata, adhesion cross-laminae and gentler slope of asymmetric adhesion ripples* N = 34, Mean: 164° 	
Adhesion ripple	Rhythmic, small (few mm), surface undulations with discontinuous crest lines; often asymmetric; may occur on top of adhesion plane-/cross-laminated sets; may mantle wave-rippled surfaces		
Small eolian dune cross-stratification	Small cross-sets with irregularly spaced wedge-shaped grainflow foreset strata alternating with grainfall/wind ripple strata; sets 1–8.5 cm (ave. 4 cm) thick; may grade laterally into low-angle wind-ripple strata		<5%
Wave ripple	Symmetric to asymmetric, bifurcating, straight-crested ripples; amplitude in mm; wavelength 1.5–4 cm; in profile show bundled upbuilding and offshoots; ripple stratification up to 15 cm thick; single rippleform layers common	**Aqueous Regime** *Crestal trends* N = 27, Mean: 27° 	
Trough cross-stratification	Regular alternation of coarse- and fine-grained foresets; sets up to 10 cm and cosets up to 30 cm thick; laterally grades into concordant, scour-fill strata; herringbone structures common	*Azimuths* N = 32, Mean: 232° 	Combined proportion of all types of aqueous strata: 33%
Subaqueous scour channel	Elongate to slightly sinuous in plan view; few cm to 20 cm deep, less than a meter wide; mostly filled up with wave-ripple or trough cross-strata, but may be filled with concordant laminae or massive sandstones	*Trends* N = 16, Mean: 80° 	

wave- ripple strata. Alternatively, they may denote stabilization of the surrounding flats by microbial mats (Schieber 1999).

Sets and cosets of trough cross-strata commonly occur with erosional, undulating lower bounding surfaces. Individual sets are up to 10 cm thick and are characterized by regular alternation of coarse- and fine-grained foreset layers. Cosets of trough cross-strata may be as thick as 30 cm. Cross-strata in successive sets often show reversal of foreset azimuths (Fig. 14).

The scours frequently encountered in the sand sheet facies are typically elongate, a few centimeters to 20 cm deep (Fig. 11) and in places show slightly sinuous margins in bedding-plane exposures. The scours are filled with either wave-ripple stratification or sets of small-scale trough cross-stratification. The trough cross-stratification often grades into concave-up lamination that conforms to the scour geometry. Less commonly, massive sandstones containing intraformational clasts at the base overlie irregular scour surfaces. The massive sandstones may denote rapid aqueous sedimentation or may represent fluidized eolian sediments where stratification was destroyed because of rising water table (Chakraborty and Chaudhuri 1993). Scours denote shallow channeled flow in the sand-sheet facies.

Sandstone packages composed exclusively of aqueous strata (aqueous packages) may be up to 30 cm thick and extend laterally for more than several meters. Calculations from eleven measured sections from four profiles show that aqueous packages constitute about 33% of the sand-sheet deposit.

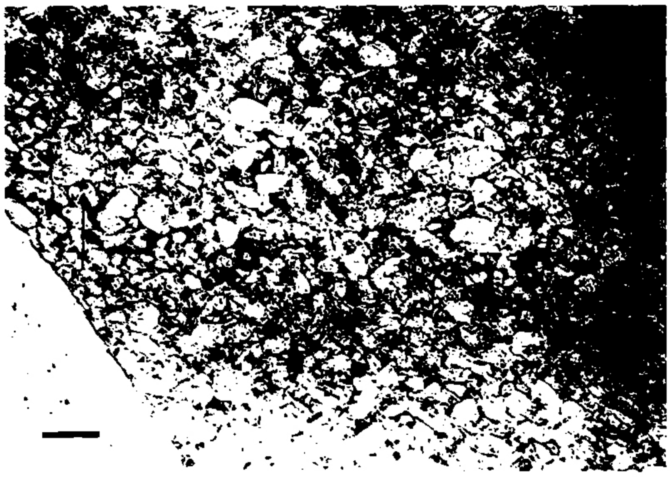


FIG. 4.—Thin-section photomicrograph of thinly laminated wind rippled sandstone. Note inverse size grading within laminae (arrow). Stratigraphic top is towards the top of the photograph. Bar scale represents 720 μm.

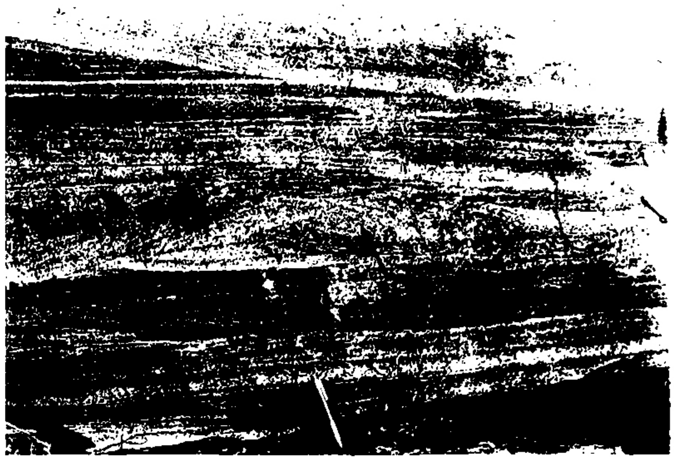


FIG. 6.—Large-scale wave-generated stratification (arrow) encased between eolian packages. Note distinct chevron arrangement of laminae and slightly irregular lower bounding surface of the aqueous unit.

ARCHITECTURE OF THE SAND-SHEET FACIES

The 40-m-thick eolian sand-sheet facies of the Shikaoda Formation is characterized by the occurrence of numerous subhorizontal, planar surfaces that split the succession into thinner (50–100 cm), tabular sandstone bodies (Fig. 15). Exhumed bounding surfaces are marked by wave ripples, adhesion ripples, or shallow channeled scours (Figs. 8, 11).

Individual thin sandstone bodies are internally made up of approximately 50% dry eolian, 17% damp eolian, and 33% aqueous packages described in the previous section. The different types of package are superposed somewhat randomly within individual thin sandstone bodies (Figs. 16, 17). The boundaries between the dry eolian packages and the vertically or laterally adjacent damp eolian packages are commonly gradational, although in places sharp erosion surfaces separate them. The aqueous packages commonly have an erosional base and gradationally pass upward into dry or damp eolian packages. Lateral transition from aqueous packages to damp eolian packages is very common (Fig. 17).

Abrupt transitions between dry eolian, damp eolian, and aqueous strata appear to be very common in the Shikaoda sandstone sheet facies (Figs. 16, 17). However, aqueous cross strata at places are found to be successively overlain by adhesion cross-lamination, adhesion plane-lamination, and finally by wind-ripple stratification (Fig. 17). The reverse is also observed where wind-ripple strata are succeeded upward first by adhesion strata and then by aqueous strata.

Paleocurrent data measured from the different groups of sedimentary features of the sand sheet facies are shown in Table 1. Abundant scour structures show a consistent east–west trend, whereas the azimuths of aqueous cross-strata show a much greater dispersion with a dominant mode towards the southwest with a few minor bipolar modes. Trends of the wave-ripple crestlines also show a high dispersion with a NE-SW vector mean. The trends of the adhesion-ripple and wind-ripple crests on the bedding plane also record a wide variation with a NW–SE dominant mode. Wind directions measured from adhesion ripples and wind ripples (both in sections and in bedding-plane exposures) show variable directions with bipolar modes and a southward vector mean.

PALEOGEOGRAPHY OF THE SHIKAODA SAND SHEET

Occurrences of wind-ripple and adhesion stratification throughout the succession indicate deposition in a near emergent setting—either in an al-

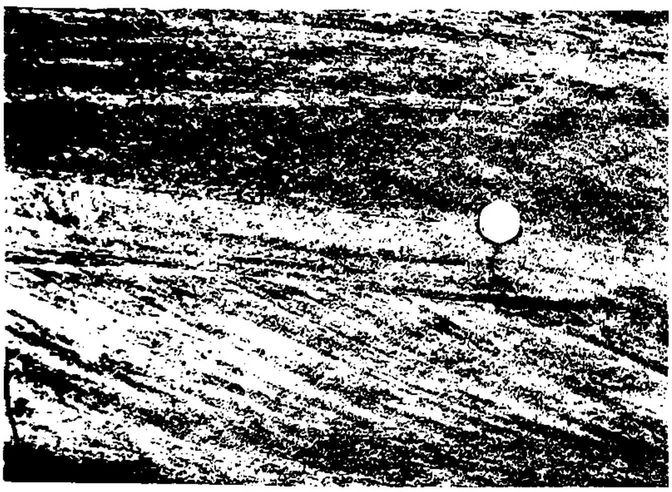


FIG. 5.—Small eolian dune cross-stratification in the sand-sheet facies. Note wedge-shaped, high-angle, coarser-grained foresets (lighter), irregularly alternating and interfingering with finer-grained grainfall layers (darker). The cross-set is sharply overlain by gently inclined wind-ripple strata. Diameter of the coin is ~ 2.5 cm.

FIG. 7.—Adhesion cross-laminated set (arrow) encased between wind-ripple strata. Note crinkled nature of the cross-laminae.

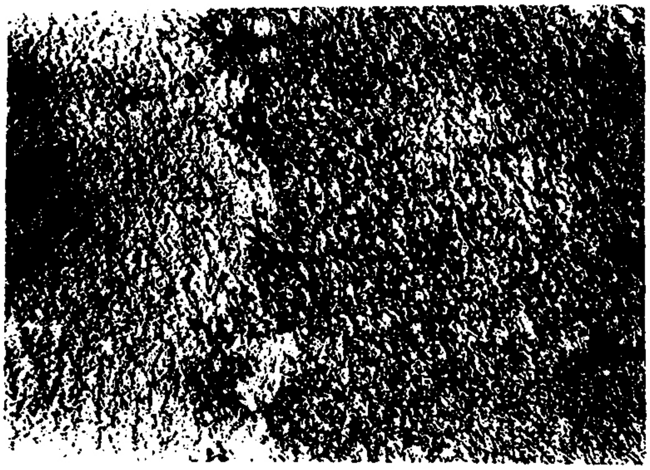


FIG. 8.—Bedding-plane view of adhesion ripples. Note impersistent and irregular nature of the crests and low amplitude of the ripples. Coin for scale (circled).

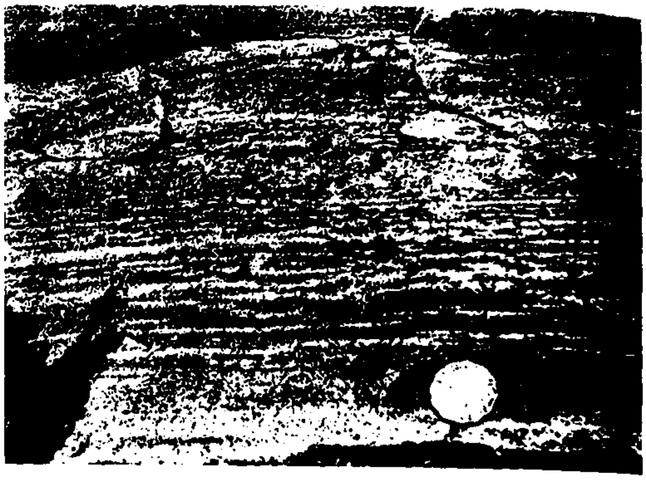


FIG. 10.—Adhesion plane lamination overlying wind-ripple strata. Note crinkly nature of the laminae and upward decrease in lamina thickness. Diameter of the coin is ~ 2 cm.

luvial plain or a coastal plain. The small size of aqueous cross-strata sets and ubiquitous shallow, aqueous scours in the sand-sheet succession indicate shallow depth of aqueous flow that intermittently invaded the wind-rippled sand flat. Abundant wave ripples are inferred to indicate marine influence, and a tidal influence is indicated by the presence of herringbone cross-strata. Absence of typical beach stratification rules out a high-energy foreshore environment. The occurrence of shoreface deposits in the facies succession (Facies A and B) implies a low-gradient supratidal setting for the sandstone sheet facies. Frequent lateral transition of aqueous packages to eolian packages, absence of large-scale bedforms or deep erosional features, and wide directional spread of aqueous cross-strata further point towards a low-gradient, supratidal flat where both eolian and aqueous processes could interplay.

Adhesion structures and eolian ripples are also common in many sandy shoreline systems (Schenk 1990; Reading and Collinson 1996). However, their preservation potential in a shoreface–supratidal systems tract is doubtful and, even if present, the features occur mostly as thin units (Frey and Howard 1988). In the Shikaoda sand-sheet facies, nearly 70% of the 40-m-thick succession comprises low-angle dry and damp eolian strata indicating the importance of eolian processes in the development of this unit and identifying this facies unit as eolian sand sheet rather than the normal sandy shoreline deposits. Low-angle eolian strata are reportedly common in many isolated eolian bedforms in the coastal erg setting (Fryberger et al, 1983; Ahlbrandt et. al. 1994). However, lack of radial dip pattern and/or lateral intertonguing with high-angle slip-face deposits (cf. Ahlbrandt et. al. 1994) indicate that Shikaoda eolian sands do not represent dome or other types of isolated dune bedforms found in modern coastal erg settings. Absence of stacked, multiple, subhorizontal wind-formed erosion surfaces as well as absence of coarse-grained wind ripples (Fryberger et al. 1979; Fryberger et al. 1988; Fryberger et al. 1992) also indicate that the succession is not analogous to the eolian deposits associated with deflation surfaces close to near-surface groundwater table (Stokes surface).

Paucity of fine-grained deposits in the peritidal setting appears peculiar when compared with many modern coastal flats (Ginsburg 1975); but such mud-deficient successions are well documented from Precambrian and early Paleozoic deposits (Aspler et al. 1994; Dott et al. 1986; Eriksson and Simpson 1998). Presence of mud in the underlying shoreface deposit (Facies A), however, implies that the finer clastics were probably removed from the coastal domain by eolian and marine agents (Dalrymple et al. 1985), resulting in the extremely mature and clean quartz arenite deposit of the sand-sheet facies. Absence of mud even within isolated pools filled with wave-ripple strata or massive aqueous strata probably implies flooding of these depressions through rising water table or surface precipitation rather than through direct input from an open marine system.

The dominantly E-W to WNW-ESE trend of the scour and a west to southwest direction of the aqueous cross-strata are taken to indicate a paleoslope to the west. The mean NNE orientation of the wave-ripple crests

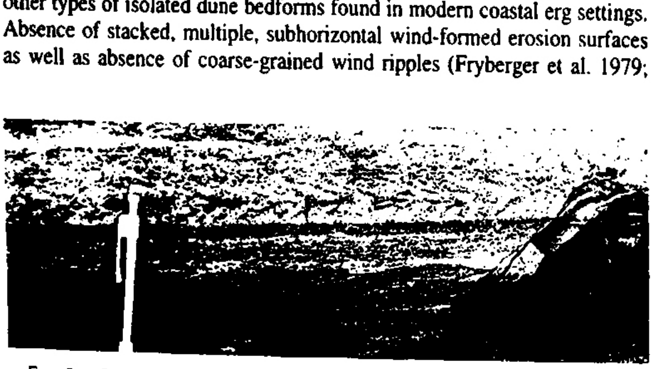


FIG. 9.—Oppositely oriented adhesion cross-lamina sets sharply overlying an aqueous package.

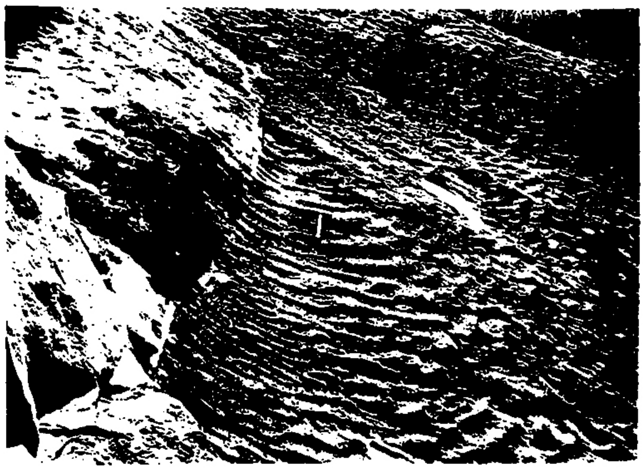


FIG. 11.—An exhumed scour channel associated with the sand-sheet facies. Note wave ripples on the floor of the channel and their termination against the channel margin. Note also the flat pavement mantled with wave ripples at the top right of the photograph.

FIG. 12.—Wave-ripple stratification associated with the sand-sheet facies, sharply overlying a package of wind-ripple strata. Note symmetrical profile of the wave ripples, bundled upbuilding and offshooting laminae. Ignore superficial dark patches.

in the sand-sheet facies as well as in the underlying shoreface facies (Fig. 2, Table 1) is consistent with a broadly north–south orientation of the shoreline. Much greater spread of the wave ripple crests probably reflects influence of local topographic undulations (including that of the scour channels) in the low-lying coastal plain. Mean wind transport direction revealed by adhesion, wind-ripple, and small eolian dune cross-strata is at a low angle to the inferred shoreline and is consistent with the coastal source for the eolian sand (Table 1). Bimodal wind directions indicated by the bidirectional adhesion-ripple strata (Fig. 9), evidently reflect diurnal offshore and onshore wind pattern in the coastal region.

DYNAMICS OF THE SHIKAODA SAND SHEET

The Shikaoda sand-sheet succession is much thicker (~ 40 m) than most of the documented sand-sheet deposits (Fryberger et al. 1979; Kocurek and Nielson 1986) and consists entirely of medium to very fine-grained, well-sorted sandstone. This implies a system favorable for net eolian sand accumulation for the Shikaoda sand sheet rather than a sand-bypassing setting associated with many examples of ancient and modern sand-sheet environments (Fryberger et al. 1979; Fryberger et al.1983; Fryberger et al. 1992; Simpson and Loope 1985; Kocurek and Nielson 1986; Porter 1987; Clemmensen and Dam 1993; Lancaster 1993). Evidently, coarse-grained armoring did not develop in the Shikaoda sand-sheet facies.

Abundance of aqueous strata indicates that eolian processes were frequently interrupted because of flooding. Limited vertical and lateral dimensions of the aqueous packages, and their common occurrence as shallow scour fills attest to the fact that the flooding, either by tides or surface precipitation, led to the formation of shallow channels within the extensive flat-lying wind-rippled area. Elongate, slightly sinuous scours probably represent the drainage pathways of tidal water or accumulated rainwater (cf. Kocurek and Fielder 1982).

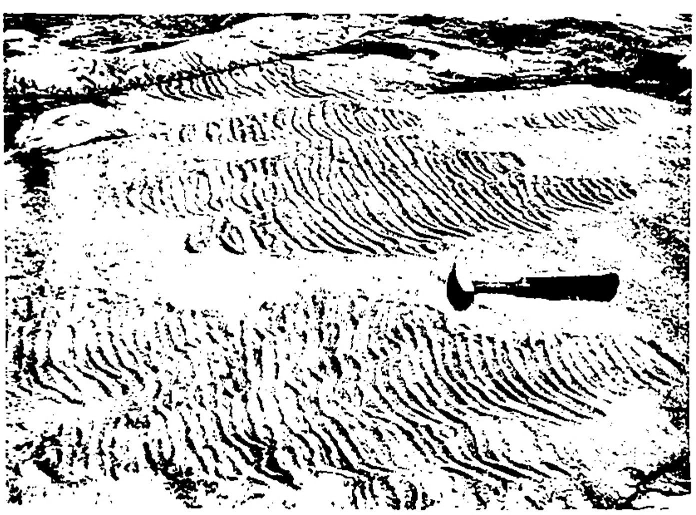


FIG. 13.—Isolated patches of wave ripples exhumed on bedding-plane exposure. Note straight to slightly sinuous, bifurcating crest lines and their deflection at the margin.

FIG. 14.—Aqueous cross-strata showing herringbone pattern (arrow). Diameter of the coin is ~ 2.5 cm.

The sequential vertical disposition of aqueous, adhesion, and wind-ripple strata and vice versa represents either drying-upward or wetting-upward successions (Kocurek and Fielder 1982). Upward decrease of lamina thickness within a set of adhesion plane laminae (Fig. 10) may also be due to subtle decrease of capillary moisture within a single package of aggrading adhesion laminae (Chakraborty and Chaudhuri 1993).

Deviation from the idealized drying-upward or wetting-upward succession is the rule rather than an exception in the Shikaoda sand-sheet facies as manifested in the random superposition of dry eolian, damp eolian and aqueous packages (Figs. 16, 17). In the absence of impervious muddy layers, water seepage through porous sand from a channel or localized pool of water can moisten a considerable stretch of adjacent sand flat, which in turn would favor formation of adhesion structures in areas laterally adjacent to the flooded areas. Similarly, rapid seepage of water through sandy substrate and a time lag between aqueous invasion and renewed eolian sand transportation may result in vertical juxtaposition of aqueous and dry eolian strata. Alternatively, wind deflation may remove a part of a drying-upward succession, leading to juxtaposition of aqueous and wind-rippled strata.

Compared to modern midlatitude sand sheets (Hummel and Kocurek

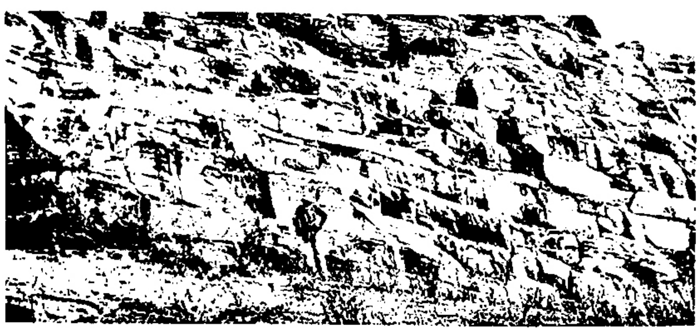


FIG. 15.—Architecture of the sand-sheet facies. Note subparallel, laterally extensive bounding surfaces dividing the succession into thinner sheetlike units. Each individual thinner unit contains randomly superposed eolian and aqueous packages, as described in the text and shown in Figure 16. Tectonic tilt (~ 10°) of the section is to the right. The view represents about 10 m of the sand-sheet succession.

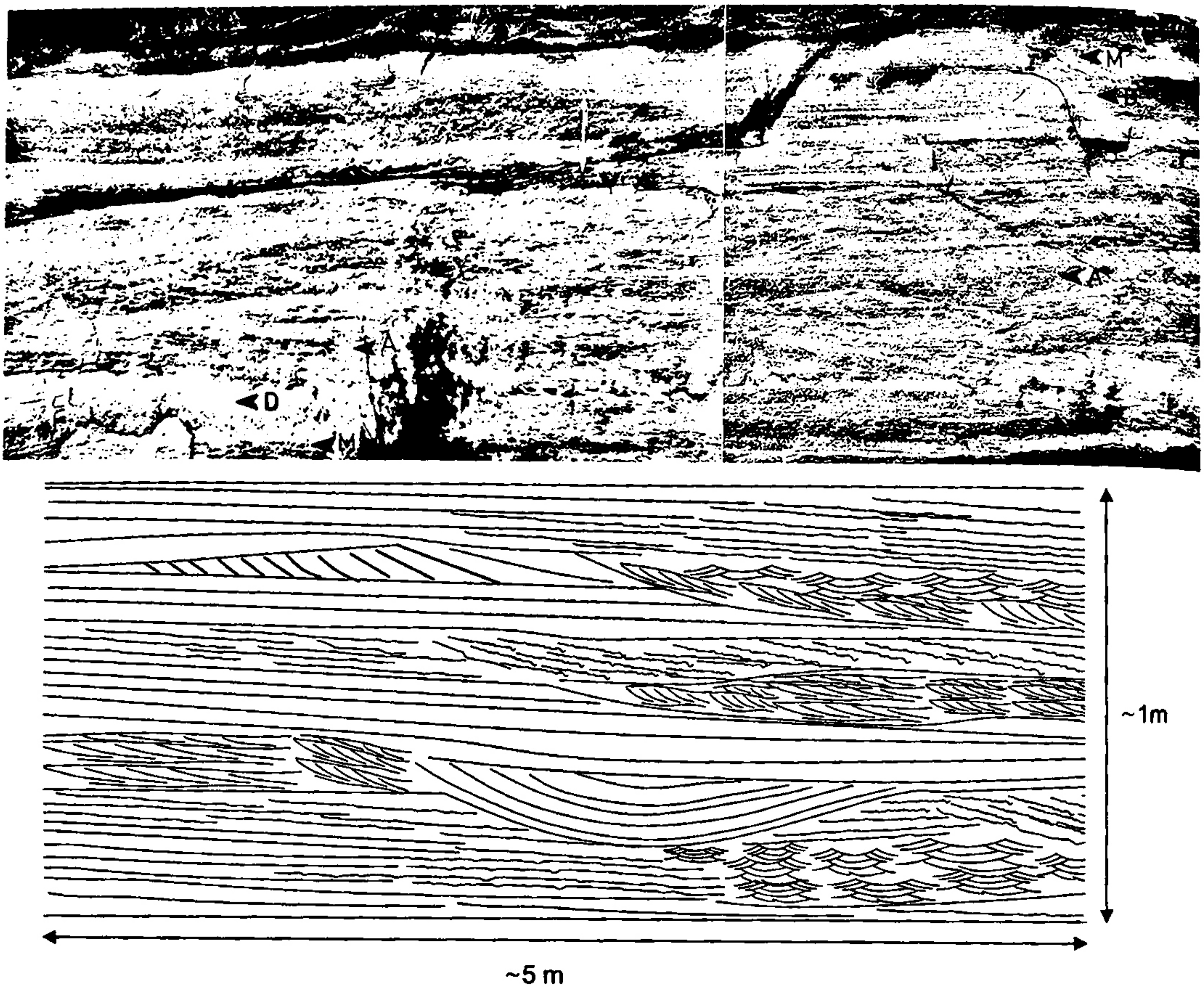


FIG. 16.—A) Photograph and B) idealized sketch showing internal organization of a thinner sandstone sheet lying between successive bounding surfaces. Note random superposition of aqueous (A), dry eolian (D), and damp eolian (M) packages (see text for details). Legends of symbols in the sketch are given in Figure 17.

1984; Kocurek and Nielson 1986) or wet flat-bedded interdune deposits of modern and ancient arid-climate eolian deposits (Ahlbrandt and Fryberger 1981; Simpson and Loope 1985; Fryberger et al. 1988; Chakraborty 1991; Crabaugh and Kocurek 1993), the Proterozoic Shikaoda sand sheet is marked by a remarkable absence of salt pseudomorphs or other salt-related depositional and deformational features. Thus, these are not detrital-dominant siliciclastic sabkha (sensu Fryberger et al. 1983) deposits. Understandably, a balance between precipitation and evaporation inhibited formation of evaporites in the Shikaoda sand sheet and implies a more humid climate for the Shikaoda sand sheet than other known arid climate sand sheets (cf. Kocurek and Nielson 1986). The Cambrian Galesville Sandstone of Wisconsin, characterized by abundance of adhesion structures, is one ancient example of this type of sand sheet. The Galesville Sandstone has been interpreted as a record of sedimentation in a coastal dune field (Kocurek and Fielder 1982).

The sand sheet associated with the Padre Island back-barrier dune field (Hummel and Kocurek 1984; Schenk 1990) appears to be the closest modern analogue for the Shikaoda sand sheet. The points of similarities are (1) a coastal setting in both the cases, (2) high proportion of adhesion and aqueous strata and (3) the lack of evaporitic deposits. However, in contrast to the Padre Island back-barrier dune field and coastal eolian sequence of the Galesville Sandstone, the Shikaoda sand sheet lacks large eolian dune cross-strata altogether and the smaller (< 10 cm) eolian cross-strata are also rather rare. This is even more intriguing because the coastal dune field of Padre Island is currently cut off from the coastal sand sources by a vegetated corridor (Kocurek et al 1992) whereas by all the evidence eolian sand supply was abundant in the Shikaoda supratidal flat due to uninhibited access to the shoreline sand sources.

Starting from a wet, low-lying sandy plain, evolution of dunes in the Padre Island field is controlled by several interrelated factors such as eolian transport, secondary air flow, and sand supply (Schenk 1990; Kocurek et al. 1992). Substrate relief plays a critical role in localization and development of eolian dunes. Initially wind-rippled patches are localized in the lee of the vegetated mounds. Rippled patches grow gradually into "protodunes" with incipient lee-face relief. The relief of the protodunes is again crucial in inducing flow separation, rapid entrapment of sediment, and growth into larger slip-face dune bedforms. It has also been observed that the larger the bedform the greater is its capability to trap sand, and the

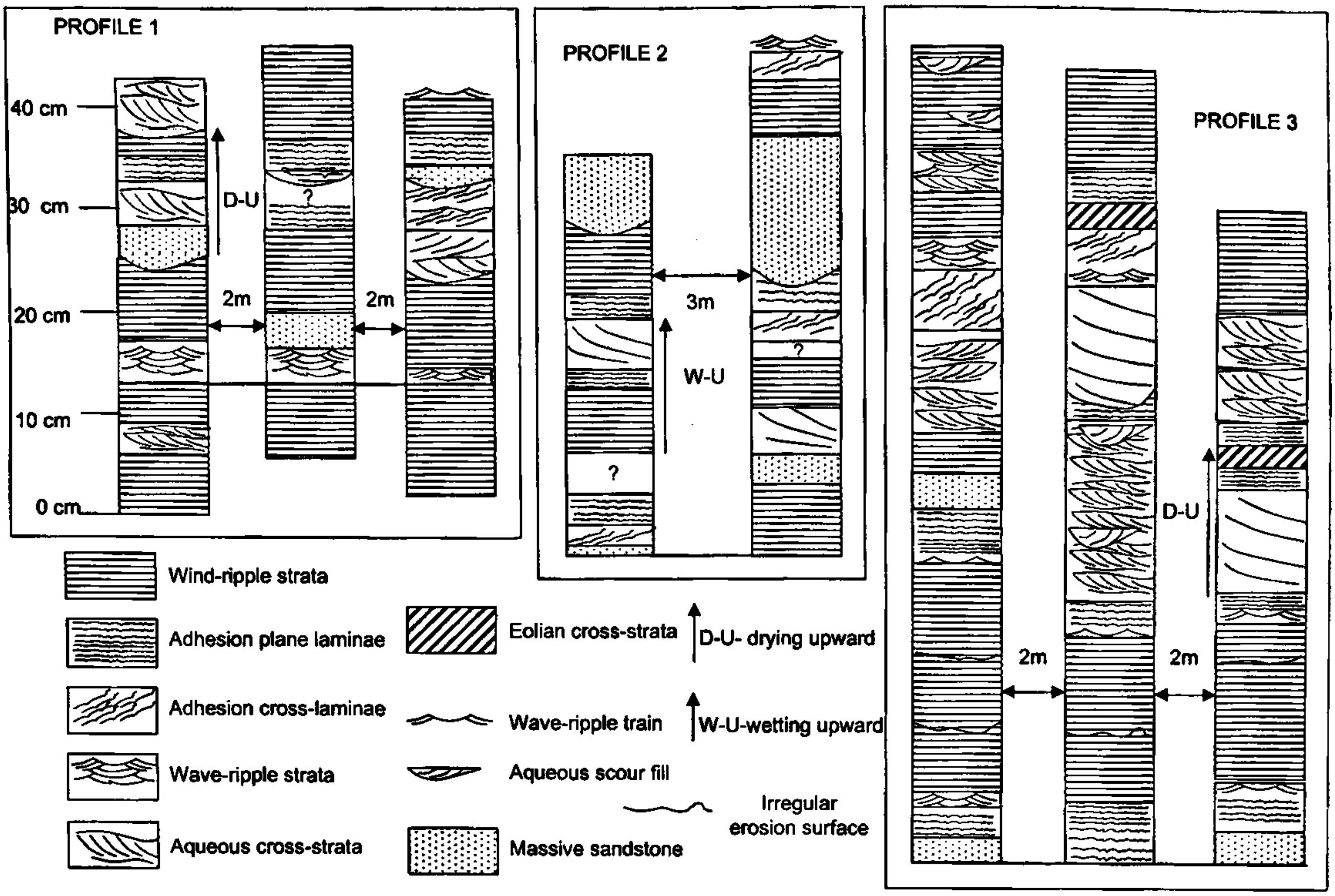


FIG. 17.—Vertical profiles of sand-sheet facies at three different exposures. The distance between individual logs and the correlative surfaces are also shown. Note random superposition of aqueous, dry eolian, and damp eolian packages.

higher is its chance of survival during phases of destruction due to precipitation or change in the direction or speed of the wind (Kocurek et al. 1992).

The absence of vegetation deprived the Proterozoic coastal plain of the relief factor necessary for initiation of the dune-building processes. Wind ripples instead covered extensive flat surfaces. Incipient relief that might have developed in the sand patches were planed off or reworked by repeated aqueous flooding. Further, the water saturation of the sand in the flooded and the adjacent wet areas (sufficiently moistened because of capillary movement of water through a clean, porous sandy substrate) reduced the availability of the sand to the wind. Rising water table, due either to rising tide or surface precipitation, would have the same effect of retarding dune-building processes. It appears that in spite of abundant supply of a suitable grade of sand, the time required for the growth of larger-slip-face dunes was never available in the Shikaoda coastal flat. This is corroborated by the limited lateral and vertical extent of dry eolian packages and their erosive replacement by aqueous packages or gradational juxtaposition against damp eolian packages. To summarize, though other factors like vegetation cover, evaporitic crust, or coarse-grained armoring were absent and sand supply was abundant in the Shikaoda coastal flat, frequent flooding and high substrate moisture inhibited development of dunes and favored development of a sand sheet.

The paleocurrent pattern from both adhesion and wind-ripple strata of the Shikaoda Sandstone indicates a variable and often reversing wind pattern. Changing flow direction in the Padre Island dune field has been identified as one of the key factors that contribute to the destruction of the dunes (Hummel and Kocurek 1984). By analogy, the reversal of wind direction acted as an additional factor in destroying the incipient dunes of the Shikaoda sand sheet.

Lack of evidence of large-scale dune-field deposits in the Shikaoda Formation is inferred to indicate existence of the sand-sheet facies independent of an erg. The high proportion of aqueous strata and lack of evaporite-related features probably indicate that the climatic condition during deposition of the Shikaoda sand sheet was more humid than that of the typical sub-equatorial arid belt in which most of the earth's large sand seas and associated sand sheets are situated today. The Shikaoda sand sheet therefore provides one rare ancient example where repeated flooding alone was the prime causal factor inhibiting dune formation and favoring formation of the sand sheet. Because absence of vegetation in a pre-Silurian land surface was not related to the climatic aridity, we suspect that at that time any subaerial setting with an adequate supply of fine sand should have been the sites of significant eolian accumulation. Low-gradient coastal plains and sandy alluvial plains were likely to be favorable sites and repeated aqueous invasions in both the settings may have resulted in the development of sand sheets. The thick succession of the Shikaoda sand sheet is probably one of many such Precambrian successions (cf. Simpson and Eriksson 1991; Chakraborty and Chaudhuri 1993; Chakraborty 1994; Bose et al. 1999). It is possible that many such deposits have remained unidentified so far.

STRATIGRAPHIC EVOLUTION OF THE SAND SHEET

The Shikaoda sand sheet is composed of a large number of vertically stacked, meter-scale tabular sandstone bodies (Fig. 15). The surfaces that bound the sandstone bodies have been inferred to be related to aqueous events. Parts of these surfaces are the direct products of flooding events, flanked by parts mantled with adhesion ripples reflecting the indirect effects of flooding. Depending on the nature of the flooding event, the surfaces can be slightly scoured or flat and the strata overlying them vary from a single wave-rippled unit to several centimeters of wave- or current-formed aqueous deposits. We propose that the thicker wave-rippled units (Fig. 6) represent storm events whereas the thinner wave-rippled or aqueous cross-stratified units represent normal tidal influxes or surface precipitation. Therefore, the bounding surfaces of the Shikaoda sand-sheet facies neither are "Stokes Surfaces" (Stokes 1968; Loope 1984, 1985) nor do they qualify as regionally extensive sand-drift surfaces that are often associated with flat-bedded eolian strata (Fryberger et al. 1988).

The thickness (~ 40 m) of the sand-sheet facies and the subparallel disposition of the bounding surfaces in the 40-m-thick sand-sheet succession points towards an aggradational setting where sedimentation, though punctuated, kept pace with subsidence in the long term. Such an extensive coastal plain and delicate balance between sedimentation and subsidence over a long period of time is believed to characterize many Precambrian epeiric basins (Sloss 1988a, 1988b). However, surfaces separating the underlying and overlying shoreface deposits from the sand-sheet facies are sharp in nature, appear to be regionally extensive, and therefore, may reflect abrupt changes in relative sea level leading to dislocation of the contiguous facies belts.

SUMMARY AND CONCLUSIONS

The Proterozoic Shikaoda sand sheet represents a low-lying, unvegetated, coastal plain characterized by uninhibited interplay of eolian and aqueous processes. The overall paleogeography is inferred to be an extensive, low-gradient, tide-affected coastal plain with a roughly north–south oriented shoreline and a westward paleoslope. The sand sheet developed in the supratidal region fed by abundant eolian supply of fine- to medium-grained, well-sorted sands from the shoreline. The eolian processes were frequently interrupted by flooding during tidal and storm surges, or surface precipitation that contributed to the suppression of dune-building processes and aided the development of the sand sheet. As a consequence, the resultant deposit virtually lacks large dune strata, evaporites, and deflationary coarse-grained layers. It consists mainly of flat-bedded wind-ripple strata, adhesion strata, and wave or current generated deposits that are frequently superposed on one another in a nearly random fashion.

Autocyclic flooding events formed the numerous, subhorizontal bounding surfaces of the Shikaoda sand sheet. The subhorizontal nature of the bounding surfaces throughout the succession suggests that the sedimentary packages were accumulating in a flat-lying depositional area—a fact corroborated by the facies analysis. It also indicates that the gently dipping coastal plain persisted over time and sedimentation kept pace with basin subsidence.

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