

FORMATION OF SCALLOPED CROSS-BEDDING WITHOUT UNSTEADY FLOWS¹

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ABSTRACT: *Scalloped cross-bedding*—compound cross-bedding with internal bounding surfaces that cyclically scoop into the previously deposited foresets and into the sediment below the set—is a common and distinctive structure in eolian, fluvial, tidal, and nearshore-marine sands. Scalloped cross-bedding in shallow-marine deposits previously has been interpreted to be produced by cyclic flows, such as neap-spring tidal flows, which are known to cause cyclic fluctuations in the depth of scour in the troughs of migrating bedforms, but scalloped cross-bedding also originates by a process that does not require fluctuating flow: migration of small bedforms across the lee slopes or along the troughs of larger bedforms. Intersections of the troughs of the two sets of bedforms form topographically low scour pits, and cyclic passage of these scour pits through the outcrop plane—the plane that later becomes an outcrop surface—causes the lower-set boundary to rise and fall.

Scalloped cross-bedding formed by fluctuating flow superficially resembles that formed by superimposed or intersecting bedforms, but, as illustrated in three-dimensional computer plots, the two kinds of structures commonly can be distinguished by directional properties of the bedding. Scallops deposited by alongslope-migrating, superimposed bedforms have cross-bed and bounding-surface dip patterns that lack bilateral symmetry and have cross-bed dips that are asymmetrically distributed relative to bounding-surface dips. Scallops with dip patterns that are bilaterally symmetrical and with cross-bed dips that are symmetrically distributed relative to the bounding-surface dips can be produced either by fluctuating flow or by downslope or upslope migration of superimposed bedforms.

An example of nearshore-marine scalloped cross-bedding of Pleistocene age was examined in detail in a coastal terrace of Monterey Bay, California. The three-dimensional structure and directional properties of the bedding suggest that the deposit was produced by a series of small bedforms migrating offshore, down a rip channel that was bounded on one side by a migrating oblique bar.

INTRODUCTION

Cyclic cross-bedding is defined as cross-bedding in which the individual cross-beds within a set vary cyclically in structure or texture (Hunter and Rubin 1983). Cyclic cross-bedding can originate by two processes: 1) deposition by bedforms migrating in flows that vary cyclically in velocity or direction, and 2) deposition by trains of small bedforms migrating over the surfaces of larger bedforms. The origin of some cyclic cross-bedding is readily recognizable without considering the complexities discussed later in this paper. For example, some cyclic cross-bedding that forms in tidal flows has cyclically spaced slack-water mud drapes—direct evidence of cyclic variations in flow velocity (Boersma 1969; Visser 1980; Terwindt 1981; de Mowbray and Visser 1984). Many cyclic cross-beds, however, contain no structures that directly indicate cyclic unsteadiness of flow. Lack of these structures is particularly likely to arise in coarse-grained deposits because, as Terwindt (1981) noted, mud drapes cannot form where mud is absent or where “slack-water” current velocities are too high to allow deposition of mud.

Instead of containing direct evidence of cyclic-flow unsteadiness, cross-stratified beds may contain cyclically spaced, inclined bounding surfaces that separate sets of cross-beds. Determining the origin of such structures is difficult, because they can form either by bedforms migrating in cyclically varying flows or by small bedforms superimposed on larger bedforms. One kind of cyclic cross-bedding that can form by either process is *scalloped cross-bedding*—compound cross-bedding with internal bounding surfaces that cyclically scoop into the previously deposited foresets within the set and into the sediment below the set (Rubin and Hunter 1983). The term *scal-*

loped cross-bedding is used for structures produced by fluctuating flow, by migration of superimposed bedforms, or by both processes, because it is often impossible to determine which process generated scalloped cross-beds without detailed three-dimensional analysis of the bedding; inspection of two-dimensional outcrops or photographs would not allow the structures to be named if different names were used for structures produced by the two processes. The purpose of this paper is to show how scalloped cross-bedding can form by fluctuating flow (Figs. 1–3) and by superimposed bedforms (Figs. 4–5) and to show how cross-bedding formed by these two processes can often be distinguished.

SCALLOPED CROSS-BEDDING FORMED BY FLUCTUATING FLOW

Because the velocities of tidal currents vary cyclically from neap tide to spring tide, tidal bedforms commonly vary cyclically in height from a minimum during or following neap tides to a maximum during or following spring tides (Allen and Friend 1976; Boersma and Terwindt 1981; Dalrymple 1984; Terwindt and Brouwer 1986). As bedforms grow, sand is scoured from troughs and deposited on crests; as bedforms decrease in height sand is transferred from crests to troughs. Boersma and Terwindt (1981) and Terwindt (1981) noted that this process of transferring sand to and from the troughs of the migrating bedforms causes the bounding surfaces scoured by the bedforms alternately to fall (when formed at times when bedforms were growing in height) and rise (when bedforms were diminishing in height). The cyclic deepening of the troughs causes the cyclic scouring of bounding surfaces into previously deposited foresets or underlying sediment, thereby creating scalloped cross-bedding (Figs. 1–3).

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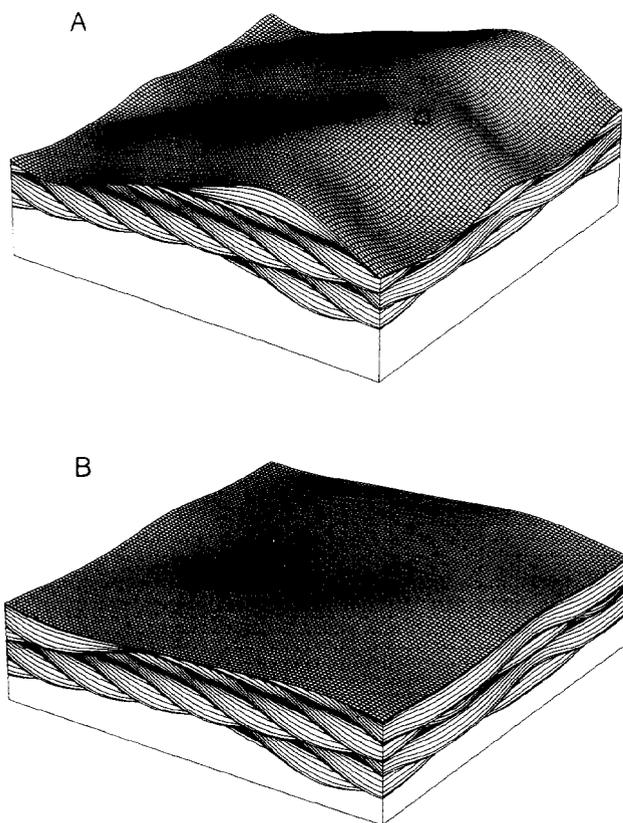


FIG. 1.—Scalloped cross-bedding formed by fluctuating flow. The bedform that is illustrated was generated by computer and programmed to vary cyclically from a maximum height to 20% of that height, while migrating from left to right. Bedform surfaces that were buried, rather than eroded, are displayed in vertical sections. Like real bedding, the illustrated internal structures define intersections of previous bedform surfaces with the outcrop plane. Cross-beds represent the positions of the surfaces of the bedforms, migrated backwards through time and space and displayed at equal intervals of time. The rate of deposition in this example was arbitrarily selected to be 8% of the rate of migration, thereby producing an angle of climb that preserves cross-stratified beds with thicknesses equal to approximately half of the bedform height. A horizontal section through this structure is shown in Figure 2, and plots of cross-bed and bounding-surface poles are shown in Figure 3. A) Bed morphology at a time when bedform height was a maximum. B) Bed morphology at a later time when bedform height was a minimum.

SCALLOPED CROSS-BEDDING FORMED BY SUPERIMPOSED BEDFORMS

Not all cyclic cross-bedding originates in fluctuating flows. Cyclic cross-bedding also originates by the migration of small bedforms or other regularly spaced topographic features over the lee slopes or along the troughs of larger bedforms. Even when this process is steady, the resulting cross-bedding is cyclic because of the cyclic migration of the superimposed bedforms through the outcrop plane (Figs. 4–6). Intersections of troughs of the two sets of bedforms form topographically low features that geometrically behave like scour pits. Passage of such scour pits through the outcrop plane causes the lower boundary of the set locally to fall as the erosional (leading) surface of each scour pit passes through the outcrop plane; the

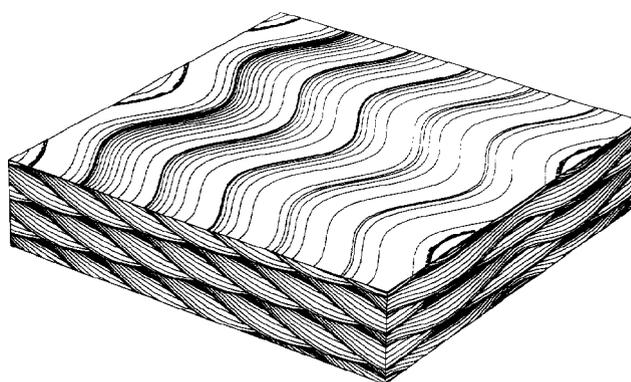


FIG. 2.—Block diagram with a horizontal section through the fluctuating-flow scallops in Figure 1.

set boundary rises as the depositional (trailing) surface of each scour pit passes through the outcrop plane. Passage of curved depositional surfaces through the outcrop plane also causes cross-beds in the outcrop plane to vary cyclically in dip azimuth and inclination and causes traces of the foresets on the outcrop surface to vary cyclically in spacing, even when the foresets have identical shapes and equal thicknesses, as in the computer-generated example in Figure 4.

The depositional situation modeled in Figure 4 shows two sets of bedforms that appear to be simultaneously migrating in different directions. Although such behavior might seem unlikely—if not impossible—deposits produced by bedforms with this kind of behavior are not uncommon in the geologic record, and at least three processes can be imagined that would cause this behavior. First, fluctuations in flow direction might alternately maintain two sets of bedforms. If the individual flow fluctuations transport small enough amounts of sediment

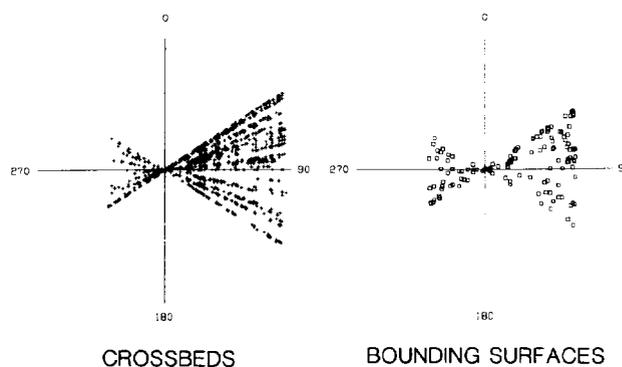


FIG. 3.—Plots of cross-bed and bounding-surface poles of the fluctuating-flow scallops in Figure 1. The plot is oriented relative to Figure 1 such that the right-front vertical section in that figure faces toward 90° and the left-front section toward 180°. Inclination of the planes is proportional to the distance from the center of the plot, but the inclinations have not been quantified because the computer model has not been programmed to incorporate avalanching processes. Dip patterns of the cross-beds and bounding surfaces are bilaterally symmetrical (relative to the horizontal axis), and the cross-bed poles are symmetrically distributed relative to the mean dip direction of the bounding surfaces.

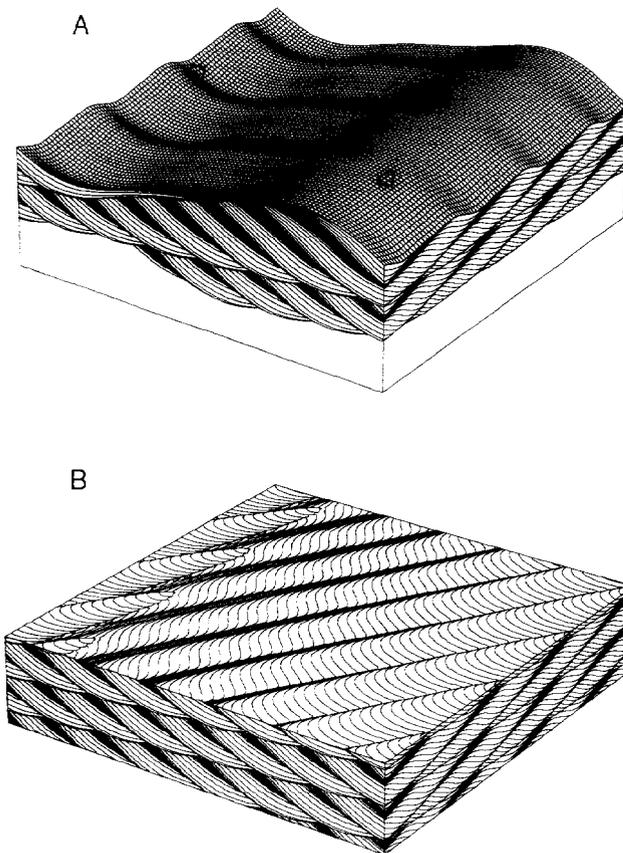


FIG. 4.—Scalloped cross-bedding formed by superimposed bedforms. A) Computer-generated example of a bedform migrating toward the right while superimposed bedforms migrate into the page. Migration speed of the superimposed bedforms is twice that of the main bedform. Scour pits are simulated by the intersections of the bedform troughs, and cyclic migration of these scour pits through the outcrop plane produces scallops. When viewed in an outcrop plane that parallels the trend of the small bedforms, the sedimentary structures that result from deposition by this bedform assemblage are virtually indistinguishable from fluctuating-flow cycles. The angle of climb is the same as in Figure 1. B) Horizontal section through the structure shown in A. The section shows the effect of the three components of migration of the scour pits. Migration of the main bedform causes the scour pits to migrate left to right; migration of the superimposed bedforms causes the scour pits to migrate away from the viewer; and deposition causes the scour pits to migrate upward through the horizontal section.

across the bedform crestlines, then the bedforms will not migrate appreciably during the individual flow fluctuations, and the bedforms will have the appearance of migrating simultaneously. Second, large bedforms interfere with a flow, locally creating flow conditions in which small bedforms can exist (Rubin and McCulloch 1980). Where the large bedforms are oblique to the main flow, lee-side flow commonly takes the form of a helix with an axis parallel to the bedform crestline (Allen 1968); bedforms created within such a flow will develop in response to those local flow conditions and would therefore be expected to have a different trend, migration direction, and spacing from the main bedforms (Boersma et al. 1968). Third, in addition to the two previously listed processes which can maintain two sets of bedforms for relatively

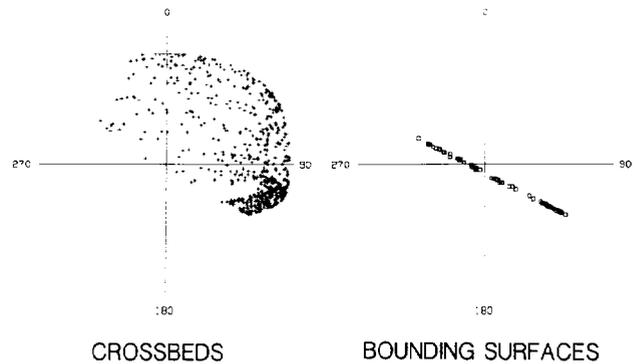


FIG. 5.—Plots of cross-bed and bounding-surface poles of the superimposed bedform scallops shown in Figure 4. Dip patterns of the crossbeds and bounding surfaces both lack bilateral symmetry, and the crossbeds are asymmetrically distributed relative to the mean dip direction of the bounding surfaces.

long periods of time, two sets of bedforms can also exist temporarily at a site where flow conditions are changing and one set of bedforms is being replaced by another.

Although superimposed bedform cycles cannot be used to determine cyclicity in paleoflow velocities (as tidal bundles can be used), the structures have another use. On a main bedform that is not perfectly transverse to the resultant transport direction, the component of transport parallel to the crestline will cause superimposed bedforms to migrate with a preferred alongcrest direction (in other words, the superimposed bedforms will have a mean migration direction that is to the right or to the left of the migration direction of the main bedform). As a result of the differing migration directions of the two sets of bedforms, cross-beds and bounding surfaces produced by the superimposed bedforms dip toward differing directions (Beutner et al. 1967; Rubin and Hunter 1983, 1985). This divergence in the dip directions of cross-beds and bounding surfaces is visible in horizontal sections (Fig. 4B) and in plots of cross-bed and bounding-surface poles (Fig. 5). In polar plots of such structures, cross-beds are asymmetrically distributed relative to bounding surfaces.

Establishing that superimposed bedforms migrated in a different direction from the main bedforms is useful for the determination of paleocurrent directions. With a single set of straight-crested bedforms, the transport direction cannot be determined more accurately than approximately 180 degrees (within 90° of the migration direction of the main bedforms); transport toward any direction within this range will cause lateral displacement of the bedforms. In contrast, where superimposed bedforms are present and are migrating in a different direction from the main bedform, the transport direction can be limited to a single quadrant (limited to one hemisphere by the migration of the main bedforms and limited to one-half of that hemisphere by the rightward or leftward migration of the superimposed bedforms).

Not all cross-bedding produced by superimposed bedforms has a scalloped lower bounding surface. Where superimposed bedforms have less relief on lower parts of the lee slopes of the main bedforms than on the upper

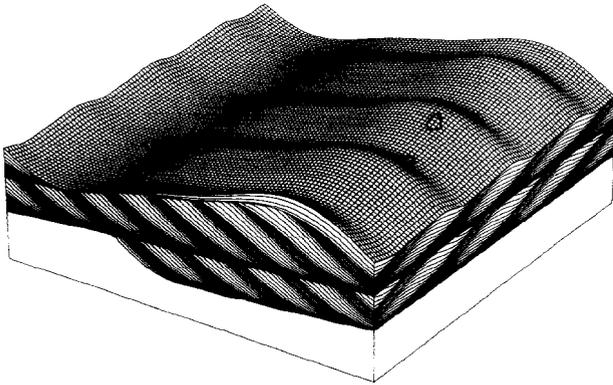


FIG. 6.—The depositional situation modeled here is identical to the one shown in Figure 4, except that in this example the superimposed bedforms have low relief on the lower parts of the main bedform. As a result, scour pits are poorly developed, and the cross-bedding is simple rather than compound.

parts of lee slopes, scour pits are poorly developed, and the discordance of the resulting cross-bedding diminishes toward the base of the set (Fig. 6).

DETERMINING THE ORIGIN OF CYCLIC CROSS-BEDDING

On outcrops that are well exposed in all orientations, the origin of scalloped cross-bedding can be determined by visual inspection. Deposits produced by fluctuating flow have cross-beds and bounding surfaces that have the same generalized strike, a characteristic which is visible in horizontal sections (Fig. 2) and in vertical sections that parallel the bedform crestline (vertical sections on the right-facing sides of the block diagrams in Figure 1A and B). On such vertical sections, the outcrop is normal to trough axes, and the trough-shaped sets of cross-beds are symmetrical. In contrast, alongcrest-migrating superimposed bedforms deposit climbing-ripple structures that are visible in sections that parallel the crestline of the main bedform (Figs. 4 and 6). In vertical sections that are normal to trough axes, trough-shaped sets of cross-beds are preferentially truncated and therefore appear to have been asymmetrically filled.

Without horizontal sections, these criteria are difficult to apply in the field because the orientation of a vertical section relative to the bedform crestline is generally unknown until after the deposit has been interpreted. On a typical outcrop, where not all vertical and horizontal sections are exposed or where the trend of the bedform crestline has not yet been determined, the origin of scalloped cross-bedding cannot be determined by visual inspection but instead must be determined from directional properties of the bedding (strikes and dips of cross-beds and bounding surfaces). Bedforms that fluctuate in height (or that uniformly reverse direction of migration) generate bounding surfaces that roughly parallel the foresets. As a result, the dip patterns of the bounding surfaces resemble those of the cross-beds (Fig. 3). In addition, on bedforms where the superimposed topographic features or crestline sinuosities do not migrate alongcrest, the dip patterns of



FIG. 7.—Example of scalloped cross-bedding (Pleistocene, marine) from a coastal terrace, Monterey Bay, California. The photograph shows details from two scallops in a 20-cm-thick bed; the scalloped bed contains a lateral sequence of approximately a dozen similar scallops. The view is toward the north; the main sandy bedform migrated toward the southeast (apparent migration is left-to-right in the outcrop plane); the superimposed gravel bedforms migrated along the trough of the main bedform, toward the southwest (apparent migration is right-to-left in the outcrop plane); scour pits that formed by intersections of the bedform troughs migrated out of the outcrop, toward the viewer (not apparent in this plane, but determined from the true dip of cross-beds). Variations in dip and grain size within the scalloped bed are due to spatial variations in dip and grain size on the bedform surface. Temporal changes in flow may also have occurred, but are neither necessary nor sufficient to produce the observed structure. Underlying the scalloped set is a gravel bed (contact indicated by arrow) that was exposed at the bottoms of the scour pits. This gravel bed was probably the source of gravel within the bedforms that migrated along the trough of the sandy bedform. Stratigraphy and depositional environments of these near-shore deposits are discussed by Dupre, Clifton, and Hunter (1980).

the cross-beds and the bounding surfaces are similar; both patterns are bilaterally symmetrical; and the cross-bed dips are symmetrically distributed relative to the mean dip direction of the bounding surfaces (Fig. 3). In contrast, bedforms with alongcrest-migrating, superimposed bedforms scour bounding surfaces and deposit cross-beds that have differing dip patterns; neither is bilaterally symmetrical; bounding-surface poles plot along a single line (if the scour pits all migrated in the same direction); and cross-bed dips are asymmetrically distributed relative to the mean dip direction of the bounding surfaces (Fig. 5). These criteria for recognizing the origin of scalloped cross-bedding are based on the assumption that the depositional surface across which the bedforms migrated was horizontal except for the bedforms. If this was not the case, the inclination of the depositional surface can contribute a rotation to the dips, as was recognized in the field example discussed below (Figs. 8–9).

Distinguishing fluctuating-flow cycles from superimposed bedform cycles has an additional complication because superimposed bedforms that migrate directly down the lee slope of the main bedform produce structures that are very similar to those produced by fluctuating flow, particularly where the crestlines of the superimposed bedforms exactly parallel the crestline of the main bedform. Downslope migration of such parallel bedforms, like fluctuating flow, produces deposits with two characteristics:

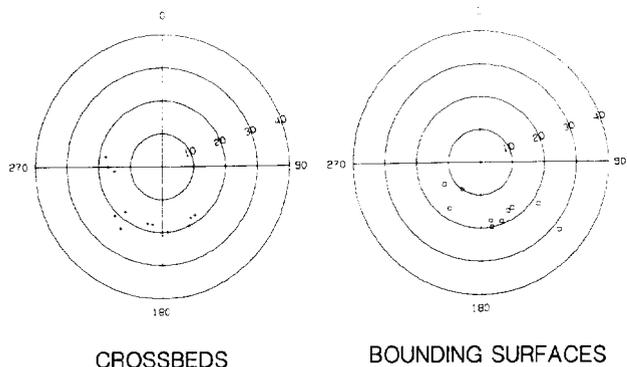


FIG. 8.—Plots of cross-bed and bounding-surface poles in the field example of scalloped cross-bedding. The patterns are similar to those formed by the computer-simulated superimposed bedforms, although these real beds show more scatter. The scatter is probably due in part to measurement error and in part to irregularities in behavior and morphology of the real bedforms. Trough axes trend approximately 015° – 195° , normal to the line of plotted bounding-surface poles.

1) great lateral continuity of sets of cross-beds relative to the coset, in a direction measured parallel to strike (McCabe and Jones 1977; Hunter and Rubin 1983), and 2) parallel strikes of cross-beds and bounding surfaces and, hence, an apparent conformity of cross-beds and bounding surfaces in horizontal sections (Hunter and Rubin 1983). In general, exact parallelism of the superimposed bedforms to the main crestline is atypical, and these two characteristics can be used to infer an origin by fluctuating flow.

De Mowbray and Visser (1984) also discuss the complicated problem of distinguishing the bounding surfaces scoured by superimposed bedforms from those scoured by fluctuating flow. They emphasize that “the development of tidal reactivation surfaces will show a regular periodicity.” However, as shown above, regular periodicity of bounding surfaces also arises from superimposed bedforms. De Mowbray and Visser apparently do not consider this possibility because they consider bedform superpositioning to arise from the relatively random interaction of individual bedforms of a single population (Allen 1973) rather than from systematic superpositioning of one population on another (Rubin and McCulloch 1980; Dalrymple 1984). However, superpositioning of populations of small dunes or sand waves on larger ones occurs even in steady flows. For example, in controlled steady flows in flumes that are on the order of one meter deep, the flows are deep enough that large bedforms can develop, and the resulting superimposed bedforms are large enough to be recognizable as large-scale dunes or sand waves (Bohacs 1981). In most flumes, however, flows are not deep enough, and the resulting bedforms are so small that superimposed dunes or sand waves are the size of ripples (Davies 1982).

AN EXAMPLE OF CYCLIC CROSS-BEDDING FORMED BY SUPERIMPOSED BEDFORMS

An example of nearshore-marine scalloped cross-bedding is shown in Figure 7. Although it is impossible to

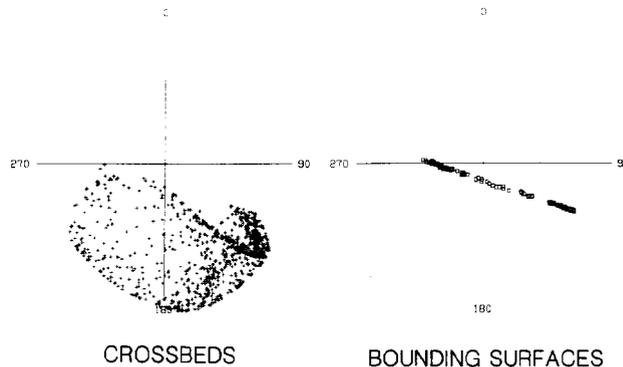


FIG. 9.—Plots of poles of the bedding generated by the computer model of the field example; note the similarity to Figure 8.

determine the origin of this structure from a two-dimensional outcrop, plots of the cross-bed and bounding-surface poles (Fig. 8) indicate that the scallops were produced by superimposed bedforms rather than by fluctuating flow (the polar-plot patterns are similar to those in Figure 5 and different from those in Figure 3).

The trend of the axes of the trough- or scallop-shaped sets of cross-beds is 015° – 195° (normal to the line of bounding-surface poles that are plotted in Figure 8). The southward dip of the cross-beds indicates that scour pits, which were formed by the intersections of the troughs of the two sets of bedforms, migrated toward 195° rather than 015° . Systematic truncation of the right sides of the trough-shaped sets indicates that the scour pits were migrating along a depositional surface that was advancing from left to right across the outcrop plane.

Grain size within the foresets varies with dip direction. Sandy beds at the upper left of each scallop dip toward the southeast, whereas gravel-rich beds at the lower right of each scallop dip toward the west. This characteristic suggests that the sandy beds within the scallops were deposited on the lee slope of a single sand bedform that migrated toward the southeast, and the gravel-rich beds were deposited by separate gravel-rich bedforms that migrated southwest along the trough and lee slope of the sand bedform. Scour pits that were defined by the intersecting bedform troughs migrated southward (as a result of the migration of the two sets of bedforms); the southward-migrating scour pits scoured the north-south-striking bounding surfaces that separate the individual scallops.

This model for the origin of these beds was arrived at by inspection of the outcrop and by inspection of the dip pattern of the cross-beds and bounding surfaces. To test this interpretation and to improve the precision of the reconstructed bedform morphology, a computer was used to create the bedforms, to migrate the bedforms backwards through time and space, to display the resulting cross-bedding, and to plot the dips of the resulting cross-beds and bounding surfaces. Using such computer experiments, the morphology and behavior of the bedforms that deposited the field example were determined by creating cross-bedding that was most similar in appearance and directional properties to the observed cross-stratifi-

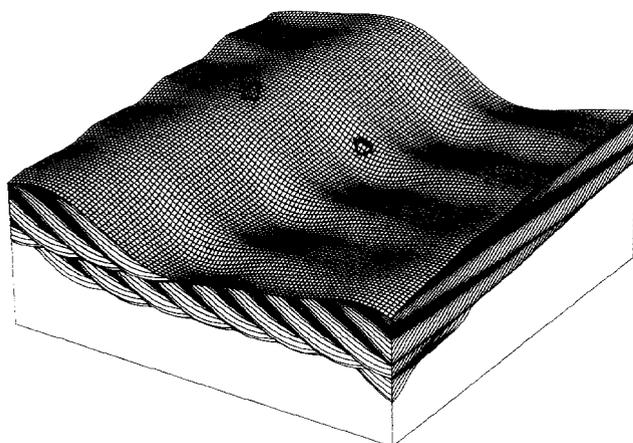


FIG. 10.—Morphology and internal structure generated by the computer model of the field example; note the similarity of left-facing vertical section to Figure 7. The migration speed of the small bedforms is twice that of the large bedforms. The angle of climb is the same as in Figure 1.

cation (Figs. 7–10). In these computer experiments, trends and migration speeds of the main bedform and the superimposed bedforms were selected so that the path of the scour pits formed by intersecting bedform troughs would be toward the observed direction of 195° . The computer-generated stratification was found to be most similar to the real stratification when the superimposed bedforms were programmed to be three-tenths as large as the main bedform and to migrate twice as fast as the main bedform; the main bedform was programmed to migrate toward 135° and the superimposed bedforms toward 225° (Fig. 9).

In the superimposed bedform scallops in Figures 4–5, the cross-beds generally dip downcurrent, whereas the bounding surfaces dip upcurrent (because the bedforms climb upward relative to a horizontal, generalized depositional surface). In contrast, cross-beds and bounding surfaces in the field example dip toward the same hemisphere. This characteristic was created in the computer-generated bedding by programming the regional slope to dip toward the south (offshore), thereby rotating the dips of the bounding surfaces into the southern hemisphere.

The assemblage of bedforms that deposited the field example is inferred to have originated within a rip channel that was bordered along its northwest side by a migrating oblique bar (Fig. 11). Transport of sand alongshore caused the bar and rip channel to migrate alongshore (southeast), while offshore transport caused the gravel bedforms to migrate offshore (southwest) down a rip channel that was inclined seaward.

In a previous interpretation of scalloped cross-bedding as neap-spring cycles (Terwindt 1981, fig. 6), the distribution of gravel within foresets conflicted with the inferred flow cycles. Terwindt observed that bedform troughs appeared to have been filled with gravel-rich foresets that were inferred to have been deposited during times of weak currents (because set boundaries were rising). Terwindt (p. 16) stated, "Noteworthy is the astonishing fact that

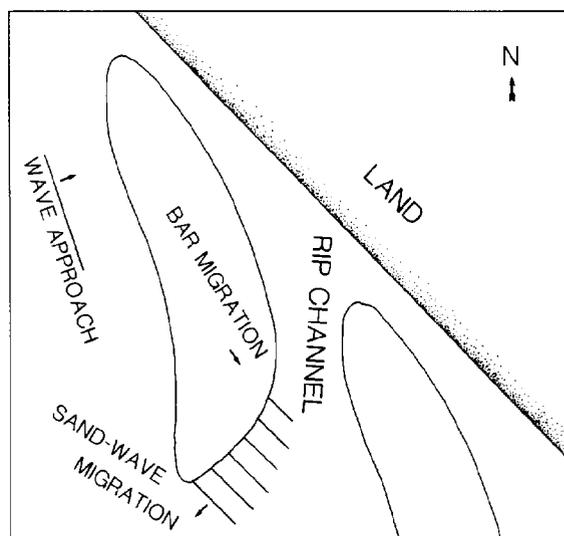


FIG. 11.—Paleogeographic reconstruction of the depositional environment of the field example. The Pleistocene shoreline is inferred to have paralleled the existing shoreline. The trend and migration directions of the bar and rip-channel bedforms are inferred from the trend and migration of the bedforms in Figure 10.

mud pebbles accumulate in the trough during decreasing current intensity. There is no explanation so far as to how the clay pebbles are transported while relatively low current velocities exist." In the scallops in Figure 7, the coarser sediment also overlies set boundaries that rise downcurrent in the outcrop plane, but this cyclic distribution of gravel in the foresets is totally independent of any temporal flow fluctuations. Instead, distribution of gravel within the foresets reflects the spatial distribution of gravel on the depositional surface of the bedform assemblage. Detailed three-dimensional mapping of the bedding in Terwindt's scallops would indicate whether superimposed bedforms may have contributed to the cyclic distribution of gravel in those beds also.

The scallops in Figure 7 occur in marine deposits, but scallops formed by superimposed bedforms have also been found in modern and ancient fluvial and eolian deposits (Rubin and Hunter 1983). Although some eolian scallops have formed as a result of fluctuating (annual) flows, more than half of the scalloped cross-beds that I have analyzed were formed by superimposed bedforms.

CONCLUSIONS

Cyclic cross-bedding can form either by fluctuating flow or by superimposed bedforms. Without direct evidence of cyclic unsteadiness of flow (such as regularly spaced mud drapes) determining the origin of the cyclicity is virtually impossible without considering the three-dimensional structure of the deposit. Some cyclic cross-beds deposited by superimposed bedforms can be identified readily in three-dimensional exposures, in horizontal sections, or in plots of cross-bed and bounding-surface poles by asymmetrical dip patterns of cross-beds and bounding

surfaces and by a divergence between the dip azimuths of cross-beds and bounding surfaces.

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