DISTINCTIONS AND USES OF STRATIFICATION TYPES IN THE INTERPRETATION OF EOLIAN SAND

GARY KOCUREK AND ROBERT H. DOTT, JR.
Department of Geology and Geophysics
University of Wisconsin
Madison, Wisconsin 53706

ABSTRACT: Eolian and subaqueous cross-strata cannot be distinguished reliably by many commonly cited criteria. They can, however, generally be distinguished by the characteristics of their component types of stratification, which represent processes of sorting and transport of the grain population on dunes. Eolian dune stratification types consist of grainflow cross-strata, grainfall laminae, and wind ripple-generated climbing translatent strata. Some of these types, especially translatent strata, have characteristics unique to the eolian realm. These same stratification types are found to compose some ancient cross-strata, and their occurrence confirms the eolian interpretations of parts of the Entrada (Jurassic), Navajo (Triassic-Jurassic), and Galesville (Cambrian) Formations, as well as revealing emergent islands in the Curtis Formation (Jurassic), previously considered to be totally marine in origin. Stratification types show a characteristic distribution on modern eolian dunes and differ in their relative abundances and structure on dunes of differing size and kind. These same relations allow some estimates of the type, shape, and original height of ancient dune deposits, as well as influencing the occurrences of surface features such as tracks and ripple forms. The geological record of stratification types and other dune features is greatly affected, however, by the extent of the post-depositional truncation of dunes.

INTRODUCTION

The migration of eolian or subaqueous dunes produces cross-stratification that can be very similar in appearance for both cases. This similarity has resulted in debate over the origins of some cross-stratified units (e.g., Marzolf, 1969; Baars and Seager, 1970; Pryor, 1971; Smith, 1971; Stanley and others, 1971; Visher, 1971; Freeman and Visher, 1975; Freeman, 1976; Folk, 1977; Picard, 1977; Ruzyla, 1977; Steidtmann, 1977; Visher and Freeman, 1977). In large part, the controversy was justified and has served to focus attention on the weaknesses of some criteria used to identify eolian deposits, as well as to suggest important parallels between eolian and subaqueous dune fields. The problem of distinguishing between eolian and subaqueous cross-strata becomes especially acute in units that contain both eolian and subaqueous deposits. In such units, needless to say, the level to which interpretations can be made may well rest on the ability to distinguish clearly eolian from subaqueous cross-strata.

We believe that much of the problem in distinguishing eolian from subaqueous cross-strata results from the over-reliance on accessory features, gross aspects of the cross-strata such as size, and often ambiguous grain-size frequency distributions. The actual internal structure of the cross-strata has been largely ignored. Clearly, some fundamental differences in sediment transport and, hence, dune construction in air and water exist. The resulting differences in the internal dune stratification provide the most reliable ways to distinguish eolian from subaqueous cross-strata. Hunter (1976, 1977a, 1977b) has established the foundation for such distinctions by his differentiation of modern eolian dune cross-strata into their component stratification types. Each stratification type described by him is the result of transport of sand on dunes by a particular eolian process. Some of these processes leave telltale characteristics that are uniquely eolian, allowing for definite interpretations of ancient cross-strata.

This paper documents eolian stratification types found in modern dunes as also composing ancient eolian cross-strata. In addition to allowing detailed, bed-by-bed environmental interpretations, eolian stratification types are also tools for the construction of more refined interpretations of ancient eolian dune deposits. Dune type, shape, and estimates of original height are possible additional interpretations that can be made...
from stratification types.

The primary example used here is the eolian Entrada Sandstone (Jurassic), which was studied over its northern extent in Utah and Colorado (Fig. 1). Other formations examined in less detail include the largely subaquously deposited Jurassic Curtis (northeastern Utah and northwestern Colorado) and Sundance Formations (northcentral Colorado), the eolian Triassic-Jurassic Navajo Sandstone (Zion National Park and Dinosaur National Monument, Utah), and the Cambrian Galesville Sandstone (Baraboo, Wisconsin). The Entrada Sandstone is the last of a series of widespread eolian blankets, including the Navajo, deposited over the western North American craton beginning in the Pennsylvanian. The Entrada erg (sand sea) ended with the transgression of the Late Callovian-Oxfordian sea over the region. The Curtis and Sundance Formations represent parts of this transgression. The Galesville Sandstone is one of several enigmatic, widespread Early Paleozoic sandstones on the central craton. These units, used as examples here, are not discussed in detail. The reader is referred to Kocurek (1981a) for more discussion of the western formations.

Modern eolian dune fields were studied at Padre Island (south Texas), Little Sahara (Juab County, Utah), Great Salt Lake Desert (near Knolls, Utah). Active subaqueous dunes were studied at several localities on the Platte River (Nebraska). Detailed documentation of eolian stratification types for some other ancient eolian sandstones in the western United States not considered here is found in Hunter (1981).

**EOLIAN AND SUBAQUEOUS DUNE FIELDS—SIMILARITIES THAT CAUSE AMBIGUOUS INTERPRETATIONS**

One outcome of the growing body of knowledge on eolian ergs and subaqueous dune fields has been recognition of the apparent similarities between the two. It remains to be seen how analogous eolian and subaqueous sand field bedforms really are in the final analysis, but some analogies are bound to occur. Although the transporting fluids are very different, the basic principles of bedform development because of fluid shear stress is the same. Bedform responses to variables such as grain size, sediment availability, and flow conditions also may prove similar. For example, in both eolian and subaqueous dune fields, isolated barchan or simple linear forms characterize areas with thin or incomplete sand cover; more complex transverse forms occur in areas of thick and complete sand cover (Kenyon, 1970; Wilson, 1972, 1973; Werner and Newton, 1975; Tyler, 1979). Both eolian and subaqueous bedforms commonly consist of a hierarchy of superimposed bedforms (e.g., Jordan, 1962; Allen, 1968a; Houbolt, 1968, McCave, 1971; Wilson, 1972; Allen and Collison, 1974). The migration of these superimposed bedforms results in a similar hierarchy of bounding surfaces within their cross-stratified deposits (Allen, 1968b; Banks, 1973; Brookfield, 1977; Rubin and Hunter, 1981; Kocurek, 1981b). Large subaqueous forms up to 20 m high (e.g., Jordan, 1962; Stride, 1963; Houbolt, 1968) are likely composed of superimposed smaller sets of cross-strata (Walker and Middleton, 1977; Doe...
and Dott, 1980) and seem to be analogous to the eolian draa (Wilson, 1972). Differences in scale between the subaqueous ridge and the much larger eolian draa may be a function of differences in depth of flow—the water/air interface versus boundaries in the lower atmosphere. Speculation concerning the origin of linear dunes in both the eolian and subaqueous realm suggests very similar large-scale counter rotating helical vortices (Allen, 1968a; Hanna, 1969; Folk, 1971a; Werner and Newton, 1975).

From the foregoing, it is not surprising that eolian and subaqueous cross-strata should be similar. In many instances, therefore, frequently cited criteria to distinguish the two are very debatable or of limited usefulness. For example, although no subaqueous sets of cross-strata have been found as the largest demonstrably eolian sets in the geological record (e.g., truncated sets up to 35 m thick in the Navajo Sandstone), the theoretical maximum height of subaqueous dunes has not been established. Individual subaqueous sets of cross-strata and modern subaqueous dunes from a few meters to 10 m in height are known (Purdy, 1961; Jordan, 1962; McCave, 1971; Terwindt, 1971; Harms and others, 1974; Swid-Djin, 1976; Bouma and others, 1977; Doe and Dott, 1980). Indeed, except for some extremely large eolian sets of cross-strata, a large degree of overlap in height occurs between eolian and subaqueous sets. Some of the submarine sets of cross-strata in the Curtis and Sundance Formations studied here are as large as or larger than most eolian sets in the Entrada Sandstone (Fig. 2).

Similarly, a broad overlap in foreset dip angle occurs between eolian and subaqueous cross-strata. Modern subaqueous foreset dip angles of 30 degrees are well-known (e.g., Hoyt, 1962, 1967; Smith, 1972). Modern eolian foresets dip at 30 to 35 degrees in dry sand and up to 42 degrees in moist, cohesive sand (Bigarella and others, 1969; Bigarella, 1972; McKee and Bigarella, 1972)—but only in avalanche deposits and mostly near dune crests. Foresets formed by processes other than avalanching (rainfalls and wind ripple migration) are necessarily below the angle of repose. Much of the cross-stratification formed on the lower portions of a dune—that portion of the dune most likely to be preserved—is at angles from less than the angle of repose to near horizontal (Sharp, 1966; Yaalon and Laronne, 1971; Steidtmann, 1974; Hunter, 1977a).

Even the use of valid nonmarine features such as distinct wind ripples, raindrop imprints, single-grain-thick and evenly spaced coarse lag, fulgurites, ventifacts, and vertebrate or freshwater fossils or traces can be misleading when thick units are interpreted on widely scattered features.

**STRATIFICATION TYPES IN EOLIAN DUNES**

Sediment is moved over eolian dunes in three primary ways: avalanching down a slipface, settling of previously saltating grains in zones of flow separation at dune crests, and ripple migration. Hunter (1977a, 1977b) has named the structures produced by these processes respectively sandflow cross-strata, grainfall laminae, and climbing translatent strata. The more general term grainflow cross-strata is used here instead of sandflow cross-strata. The bulk of all eolian dune foresets consists of these three kinds of deposits. Planebed lamination, produced by wind stress too great for ripple formation, is yet another stratification type, but seems to be rare in eolian deposits (Hunter, 1977a, 1981).

Grainflow cross-strata arise from the over-steepening of a dune lee slope and subsequent avalanching down a slipface. In dry sand, grainflow deposits are roughly tongue-shaped bodies up to several centimeters thick. They commonly truncate underlying foresets at low angles and necessarily are at or near the angle of repose. Internally, dry eolian grainflow cross-strata are loosely packed and generally lack structure except for a two-fold grain segregation. Coarser

![Fig. 2.—Subaqueous set of cross-strata, very comparable in size to large-scale eolian sets. This set contains glauconite grains and burrows throughout. (Sundance Formation, Seminole Dam, Wyoming).](image-url)
Grains mantel the upper surface as a result of dispersive pressure during flow (Bagnold, 1954; Sallenger, 1979), as well as collect at the toe of the flow as a result of their outrunning the finer ones. In moist, cohesive sand, avalanche deposits are more likely to consist of slumped, coherent blocks along well-defined shear surfaces. Grainflow and slump blocks or breccias have been long recognized in the modern and, to a lesser extent, distinguished in the ancient (Bagnold, 1941, p. 127, 236-241; McKee, 1945, 1957a, 1966; McKee and Tibbitts, 1964; Inman and others, 1966; Sharp, 1966; McKee and Bigarella, 1972; Hunter, 1976, 1977a, 1981; Doe and Dott, 1980).

Grainflows also commonly occur on subaqueous dune slipfaces (e.g., McKee, 1957b; Jopling, 1964, 1965, 1966; Allen, 1965; Boersma, 1967). The distinction between eolian and subaqueous grainflow cross-strata can be difficult as some overlap in the characteristics of this stratification type occurs with varying flow conditions and dune size. In small eolian dunes, grainflow cross-strata are narrow (width < length), tongue-shaped bodies that wedge-out upward on the slipface, have well-defined edges, and are most commonly separated by grainfall deposits (Hunter, 1976, 1977a, 1981). These grainflow cross-strata on small eolian dunes are distinct from most subaqueous grainflow cross-strata, which tend to be wide (width > length), extend to near the top of the slipface, and have diffused lateral boundaries (Hunter, 1976). Allen (1965), however, notes that subaqueous grainflow cross-strata formed at low flow velocities tend to be narrow tongues as well. Hunter (1981) indicates that grainflow cross-strata in larger eolian dunes are wide (commonly several meters) and are not separated by grainfall deposits, hence closely resemble subaqueous grainflow cross-strata.

Grainflow cross-strata in the Entrada Sandstone are most commonly wide, in some cases extending much of the width of the set of cross-strata. Entrada grainflow cross-strata are also generally not separated by grain-fall laminae, hence large dunes are indicated. The development of such wide grainflow cross-strata in large dunes appears to be the result of the coalescing of individual, narrow grainflows. On the larger dunes on Padre Island and at Little Sahara, the avalanching of a slipface usually began as a single, narrow grainflow, as on small dunes. A single grainflow would, however, trigger other grainflows on the slipface. Soon the entire slipface would be affected and individual grainflows coalesced into wide sheets. The wide grainflow cross-strata seen in Entrada and other ancient dune deposits probably formed in a similar manner.

One feature that may serve to distinguish eolian from subaqueous grainflow cross-strata is the alteration of coarse and fine laminae in subaqueous grainflows formed by continuous avalanching on dunes with superimposed ripples. As initially described by Smith (1972) on the Platte River and observed again during this study, ripples with coarse grains segregated in troughs act essentially as “conveyor belts” to transport sediment to the dune brink. Where avalanching is relatively continuous, coarse laminae originate when ripple troughs debouch their sediment on the slipface and fine laminae form as ripple crests spill their sediment. In the Jurassic Curtis Formation studied here, submarine sandflow cross-strata commonly show fine-grained sand grainflows separated by medium-to-coarse-grained laminae. The upper surfaces of the individual sets of cross-strata nearly universally show well-developed water ripples. These water ripples conform in their distribution to the shape of individual sets of cross-strata, thereby indicating that individual sets of cross-strata originated by the migration of subaqueous dunes with ripples superimposed. The structure of the Curtis grainflow cross-strata, therefore, seems to be by the same process as that on modern small dunes in the Platte River. This same process is unlikely to operate on eolian dunes where avalanching is rarely continuous and the coarser grains segregated on ripple crests rarely constitute single grainflow laminae because of the smaller volume of material composing an eolian ripple crest.

Grainfall laminae are initiated at tongues of flow separation at the brink of the slipface where grains in saltation lose momentum and fall onto the dune lee slope. The deposits are concordant, lapping over pre-existing dune lee-side topography. The top surface of grainfall deposits, therefore, is remarkably smooth. Internally, grainfall laminae are indistinct and grains have a packing intermediate between the loosely packed grainflow cross-strata and the more tightly packed translafent strata. Grainfall deposits appear to be the same as “suspension settling” deposits of McKee and others (1971); similar deposits have been described by Gripp (1961).

Grainfall also occurs on subaqueous dunes (e.g., Jopling, 1964, 1966; Allen, 1965), and the
distinction between eolian and subaqueous grainfall deposits is usually impossible. One might suspect that grainfall deposits are more abundant in subaqueous cross-strata, owing to the greater buoyancy of grains in water than air, thereby allowing more grains to be swept over the dune crest to be distributed on the lee slopes. This hypothesis, however, has not been confirmed. In addition, grainfall deposits are very common on the small eolian dunes on Padre Island, although they are rather uncommon in the Jurassic Entrada as well as on dunes at Little Sahara.

Climbing translatent strata are formed by the migration of wind ripples under conditions of net sedimentation. A continuous lamina is generated with the translation of each ripple under this condition (Hunter, 1977a, 1977b). The very even, thinly laminated type of eolian deposit has long been noted (some "accretion deposits" of Bagnold, 1941; Sharp, 1966), but only slowly has it been associated with wind ripples (Rim, 1951, 1953; "saltation deposits" of McKee and Tibbits, 1964; "ripple lamination" of Inman and others, 1966; Yaalon, 1967; McKee and Douglass, 1971; McKee and others, 1971; Yaalon and Laronne, 1971; Goldsmith, 1973). Hunter (1977a, 1977b) was the first to emphasize its abundance and to document its mode of formation by climbing wind ripples.

Depending upon the relative rate of ripple migration and the rate of net sedimentation, the angle of ripple climb can vary greatly. Hunter (1977a, 1977b) has erected three groups of climbing translatent strata depending upon whether the angle of ripple climb (A) is less than, equal to, or greater than the angle between the ripple stoss slope and the generalized depositional surface (B). These three groups are: subcritical where (A) < (B), critical where (A) = (B), and supercritical where (A) > (B). This grouping is analogous to that of Allen (1970) for subaqueous climbing ripples.

Subcritically climbing translatent strata are by far the most common of these groups, and they are the most useful structures to distinguish eolian from subaqueous cross-strata. Their distinctiveness is the result of inherent characteristics of wind ripples and serves to distinguish eolian translatent strata from other structures, such as subaqueous climbing ripple structures (Fig. 3).

DISTRIBUTION OF STRATIFICATION TYPES ON DUNES

As a result of their modes of formation, the three primary stratification types show a characteristic and consistent distribution on modern dunes (Fig. 4). The distributions described below are based on observations of dunes at Padre Island, Little Sahara, and Great Salt Lake Desert, and agree well with distributions documented earlier by Hunter (1977a). All the dunes studies here and by Hunter are simple crescentic dunes (barchanoid), but to some degree, the distribution of stratification types on other kinds of dunes can be deduced through an understanding of their modes of formation. Stratification types, therefore, can be used as interpretive tools in deducing original dune type and shape from ancient eolian cross-strata.

Grainflow cross-strata develop on the active slipfaces of dunes. Grainfall deposits originate at the zone of flow separation at the brink of the dune lee face and commonly are broader in their distribution on the lee face than grainflow cross-strata. Preservation of grainfall laminae occurs,
however, only where the lee face slope is less than the angle of repose and where wind stress is insufficient to rework grainfall deposits into wind ripples, generally on the lower part of the central slipface and in a lateral position on the lee slope on either side of the central slipface (Hunter, 1977a). The primary occurrences of wind ripples on dunes are 1) on the stoss slope of dunes, 2) on the lateral edges or horns of crescentic dunes, and 3) on aprons at the bases of lee sides of dunes deposited by winds across the lee face. Also common and a function of winds across the dune lee face are 4) wind ripples on the actual slipface oriented with their crests parallel to slipface dip direction. Most preserved climbing translatent strata occur in the latter three positions because dune stoss slope deposits are almost never preserved.

It became apparent during this study that, where a wide grain-size distribution occurs, such as at the Little Sahara dune field and in the ancient dune deposits of the Galesville Formation, a significant segregation of different grain subpopulations occurs in the different stratification types. The processes forming the different stratification types appear to sort the incoming grain population into subpopulations for transport over the dunes. Grains transported up the stoss slope to the dune crest by wind ripples consist of the creep and saltation populations and represent the widest grain-sized distribution. At the crest, the finer grains in saltation tend to overrun the dune crest and form the grainfall deposits. Grainfall laminae, therefore, tend to consist of the finer fraction of the total grain population on the dune. The creep population and the coarser fraction of the saltation population, collected at the dune crest, tend to remain until over-steepening occurs. The resultant grainflow cross-strata tend to be the coarsest of the three stratification types. This sorting process on dunes apparently has resulted in the marked grain size contrast seen between grainflow cross-strata and grainfall laminae as seen, for example, in the Galesville Formation (Fig. 5).

Clearly, the grain-size populations transported by creep, saltation, and suspension and, hence, incorporated into the different stratification types will vary with wind velocity and even position on the dune. For example, the finer fraction of the saltation load carried over the crest as grainfalls may be re-sorted into creep and saltation populations by wind ripples forming under the weak lee-slope eddies. Similarly, coarser grains in creep may be put into saltation by strong winds. Stratification types, however, may bear inherent textural imprints, especially where a particular wind regime prevails. Presumably, attempts to establish textural parameters of eolian deposits (e.g., Ahlbrandt, 1979), grain-size differences over various parts of dunes (see review by Folk, 1971b), and the sorting of the total incoming grain population into various eolian bedforms (e.g., Warren, 1971, 1972) should take into account the sorting processes active on dunes. In many published examples, sampling appears to have been done without regard to stratification types and, hence, to different processes; clearly mixing of populations has occurred as a result.

ILLUSTRATION OF USES OF STRATIFICATION TYPES IN THE INTERPRETATION OF ANCIENT CROSS-STRATA

Distinguishing Eolian From Subaqueous Cross-Strata

Recognition of the distinctive characteristics of eolian stratification types is a powerful tool in distinguishing eolian from subaqueous cross-strata. The advantage of using stratification types is that they allow centimeter-by-centimeter field
interpretations based directly on the cross-strata rather than gross-scaled features, accessory structures, or procedures confined to the laboratory. The three primary eolian stratification types were readily recognized in the Entrada, Navajo, and Galesville Sandstones. No definite planebed lamination was seen in any of these formations. As in all rock units, however, some stratification in these formations could not be clearly identified. Within the Entrada Sandstone, grainflow cross-strata is the predominant stratification type. Grainfall laminae are relatively uncommon (Fig. 6). Climbing translatent strata are common. Of these, the subcritically climbing type, the most diagnostic eolian feature, is by far the most typical form of wind ripple deposit in the Entrada (Fig. 7,8). This type is most common along the edges of sets of cross-strata, as viewed in outcrops perpendicular to the paleo-wind direction. Also present are thin zones of subcritically climbing translatent strata in the centers of sets of cross-strata, sandwiched between grainflow cross-strata. These wind ripple deposits show a pronounced along-slope migration direction and are interpreted as having been deposited by lee face ripples oriented with their crests parallel to the slipface dip direction. Rare in the Entrada, as well as in the other eolian deposits studied here, are critically to supercritically climbing translatent strata (Fig. 9).

Stratification types proved especially useful in the western and northern margins of the Entrada (Section 4, 5, 6, 7, 19, 21, Fig. 1). At these sections, identification of eolian deposits, based on recognition of eolian stratification types, indicates interbedded eolian and marine deposits (Fig. 10). This interbedding is interpreted as resulting from an oscillating shoreline during de-
was found at one locality (Section 19, Fig. 1) to contain zones of eolian deposits. Mapping showed that these eolian zones form lenticular bodies that thin laterally and terminate in marine deposits. These lenticular eolian bodies are interpreted as emergent islands in the Oxfordian sea (Fig. 11). Without recognition of clear eolian features in these cross-stratified sand bodies, they would almost surely have been interpreted as submarine bodies. Needless to say, recognition of such features can significantly alter paleoenvironmental reconstructions.

**Interpretation of Dune Type and Shape**

The original dune type and shape are usually far from obvious from ancient, truncated cross-strata. Original dune structure has previously been interpreted from analyzing the overall structure of the cross-strata (e.g., McKee, 1966), foreset dip-direction dispersion (McKee, 1979), and geometric relationships between bounding surfaces in the cross-stratified unit (Brookfield, 1977; Rubin and Hunter, 1981; Kocurek, 1981a,b). The distribution and relative percentages of stratification types in ancient dune deposits also can be utilized in interpreting dune type and shape. Clear relations cannot yet be stated, however, as a large data base of the abundances and distributions of stratification types in different kinds of dunes has yet to be gathered.

As already discussed, crescentic dunes show a symmetrical distribution of stratification types (Fig. 4). These dunes may have a high percentage of grainflow cross-strata (see examples in McKee, 1957a; Inman and others, 1966; Yaalon and Laronne, 1971), but grainfall deposits and climbing translatent strata are also abundant on parts of the lee slopes of many crescentic dunes. McKee and Tibbitts (1964) report primarily oppositely dipping grainflow cross-strata in linear dunes in Libya, but also note some "saltation" deposits (probably climbing translatent strata) at the bases of these dunes as well as within the major dune structure. These linear dunes in Libya are subject to diurnal opposing winds and show high, peaked summits with steep slipfaces. This structure is very different from linear dunes in the Simpson Desert, Australia, and those on the Moenkopi Plateau, Arizona. Breed and Breed (1979) describe the latter linear dunes as having only rare slipfaces and an internal structure consisting of low-angle "accretion laminae" (probably translatent strata). Still other
linear dunes show very complex shapes and the distributions of stratification types in these is not known. Similarly, the distribution of stratification types in star dunes is not known. Almost certainly, however, grainflow cross-strata, grainfall laminae, and climbing translatent strata make up most dune deposits. Although it still remains to be documented, the relative abundances of the different stratification types from dune to dune generally can be predicted from knowledge of how each stratification type forms and from the overall structure of dunes. Dunes with abundant slipfaces will be characterized by high percentages of grainflow cross-strata and grainfall laminae. Dunes without slipfaces will be characterized by climbing translatent strata.

The well-documented distribution of stratification types in modern simple crescentic dunes seems certain to have wide application in the rock record, as crescentic dunes are probably
over-represented. Small, isolated barchan dunes and simple linear dunes seem to occur in areas of thin or incomplete sand cover (Wilson, 1972, 1973) and, hence, are unlikely to account for thick accumulations of eolian cross-stratified sandstones in the rock record. Some linear dunes, as in the Sahara, appear to act only as "sand-passing avenues" transporting sand to erg centers where it accumulates, commonly in different dune types (Wilson, 1971; Breed and others, 1979). Star dunes occur in areas of thick sand cover, but appear to be products of converging winds and are either exceedingly slow moving or stationary. Thick geological units deposited by star dunes would call for much vertical accretion in the adjacent interdune areas. Such thick interdune deposits are unknown and subsequent depositional environments, especially transgressive high-energy marine environments, would initially invade these interdune areas and probably obliterate the star dune structures eventually. Crescentic dunes, with the exception of the isolated barchan, are best able to amass thick accumulations of cross-stratified sandstone by virtue of their downwind migration accompanied by climbing (Brookfield, 1977; Rubin and Hunter, 1981; Kocurek, 1981b). With increasing sand cover and time, these crescentic dunes tend to become compound forms or draas (Wilson, 1972). Such compound crescentic dunes are the typical eolian bedforms in closed basin ergs (Breed and others, 1979), the most favorable site for thick eolian deposits to be preserved in the rock record.

The distribution of stratification types on the individual crescentic dunes that occur superimposed on the larger compound dune or draa should show a distribution like that for simple crescentic dunes (Fig. 4). The distribution of stratification types in deposits of ancient compound crescentic dunes becomes important in attempting to deduce the actual original shape of these dunes, which can vary within the crescentic dune family. For example, the central part of the Entrada erg in this study area is interpreted from the geometry of bounding surfaces, foreset dip-direction dispersion, and distribution of stratification types to have been deposited by compound crescentic dunes (Kocurek, 1981a,b). Individual sets of cross-strata, interpreted as having been deposited by crescentic dunes superimposed upon the larger compound dune body, show variations in the distribution of stratification types from symmetrical, as in Figure 4, to
more complicated arrangements. These variations are interpreted as resulting from rather symmetrical crescentic dunes to more curving shapes, respectively. An example of the distribution of stratification types for one of these more curving crescentic dunes is shown in Figure 12.

Crescentic dunes formed under variable winds, such as those at the modern Little Sahara dune field, are characterized by poorly formed, ephemeral slipfaces and an abundance of wind ripples that commonly cover the entire dune structure. Such dunes, where preserved in the geological record, are likely to be represented by low-angle cross-strata consisting predominately of climbing translatent strata. Some Entrada dune deposits (Section 15, Fig. 1) show such a predominance of translatent strata and are interpreted as having been deposited under variable winds. Measured paleowind transport directions show a wide compass spread of 210 degrees. In contrast, Entrada dune deposits consisting predominantly of grainflow cross-strata, such as those at section 11, (Fig. 1), show a narrower dispersion of 135 degrees in foreset dip directions.

![Fig. 11. Cross-section of Curtis Formation showing lenticular cross-stratified sand bodies consisting of eolian stratification types. These bodies are interpreted as emergent islands in an otherwise shallow marine sequence. (Burns, Section 19, Fig. 1) (Fig. 12. Cosets of cross-strata (A) in the Entrada Sandstone. (B) shows the distribution of stratification types in one set of cross-strata (set indicated by arrow in (A)). In (B), translatent strata occupy the left edge of the set and are interpreted as the horns of a crescentic dune; grainflow cross-strata and grainfall laminae occur toward the center of the set, indicating the central slipface with transport direction into the page, as determined by foreset dip direction. The right side of this set of cross-strata, however, also shows grainflow cross-strata and grainfall laminae, indicating an active slipface, but here transport direction was toward the left. Cross-strata from the central and right slipfaces occur intertonguing. The interpreted dune shape (C) shows a crescentic dune with a pronounced curved slipface, which actually turns on itself. (Dinosaur National Monument, Section 11, Fig. 1)
The variability of paleowind directions can also be estimated relatively by the uniformity of the climbing translatent strata. Where a wind regime of particular direction and velocity prevails, individual translatent strata appear to be remarkably similar in thickness and orientation for a given position on the dune. Under more variable wind regimes, as apparently those paleowind conditions represented at section 15 noted above, translatent strata are more irregular (Fig. 13).

Original Dune Height

The preserved thickness of a set of cross-strata in the rock record may have little relation to the original dune height. In tracing individual sets of cross-strata in the Entrada Sandstone in the migration direction of the dunes, substantial changes in set thickness occurred, indicating that changes occurred in the net deposit left by a single migrating dune. Migrating dunes may leave no deposit at all or may leave a substantial preserved thickness depending upon a host of factors such as rate of migration, rate of sand supply, and rate of subsidence. Most ancient dune deposits, however, probably record only a small fraction of the original dune height.

Stratification types offer one method of estimating the original dune height. Qualitatively, Hunter (1977a, 1981) notes that grainflow cross-strata predominate in relatively large crescentic dunes. On these large dunes, most grainfall deposits accumulate near the upper part of the lee slope and are later incorporated into grainflow deposits or are lost with later dune truncation. Only on smaller dunes do grainfall deposits reach the dune base, where the chances for preservation are greater. Very small dunes (<1m) and incipient dunes tend to show a predominance of climbing translatent strata (Hunter, 1977a). Where grainflow cross-strata make up only a small, uppermost part of a set of cross-strata, the dune height was probably considerably greater than the set thickness (Hunter, 1981).

Based upon such qualitative relations, some Entrada, Navajo, and Galesville dunes must have been quite large because grainfall laminae are uncommon and grainflow cross-strata predominate. Many of the grainflow cross-strata do not extend to the bases of the sets. Unfortunately, as yet, no numerical values can be set for “larger” and “smaller” dunes.

A possible quantitative factor for determining original dune height may be the thickness of individual grainflow cross-strata to dune slipface height, originally suggested by Hunter (1977a). Observations in the Entrada Sandstone showed that individual grainflow cross-strata within a single dune deposit (a single set of cross-strata) are remarkably constant in thickness, although a wider range of thicknesses in grainflow cross-strata occur from set to set and in different locations across the study area. The thickness of individual grainflow cross-strata and slipface height were measured at the modern Little Sahara dune field. A plot of these measurements (Fig. 14) shows that grainflow cross-strata thickness generally increases with slipface height, but not in a strictly linear fashion. Rather, for a given grainflow cross-strata thickness, a minimum slipface height can be predicted. Data are from only one modern dune field with relatively small dunes and thin grainflow cross-strata. The thickest grainflow cross-stratum seen in the Entrada was 9 cm, presumably indicating dunes much larger than those at Little Sahara.

Penecontemporaneous deformation structures associated with wetted, cohesive dune sands and consisting of slumped, rotated blocks, faults, and breccias (e.g., Bigarella and others, 1969; McKee and others, 1971; Bigarella, 1972) are conspicuously rare in the Entrada Sandstone throughout the study area as well as other ancient eolian deposits studied here. Only a few possible examples were found in Entrada dune deposits along the paleocoastline. Judging from the abun-
Fig. 14.—Plot of the maximum thickness of individual eolian cross-strata versus slipface height for dunes in the Little Sahara dune field. Minimum dune height seems indicated by maximum grainflow cross-strata thickness.

The parting planes upon which tracks and other surface features occur must represent depositional surfaces. Grainfall laminae should show the greatest abundance of surface features as these are gently inclined and parting planes are depositional surfaces between individual grainfall laminae (Fig. 16A). Parting planes between grainflow cross-strata are also depositional surfaces, but are relatively steep and loosely packed, hence, making for less favorable surfaces for the preservation of surface features. Parting planes developed in deposits of climbing-ripple translatent strata are along individual ripple bounding surfaces, which are inclined at low angles.

Implications of Eolian Stratification Types For the Occurrence of Bedding Plane Structures

An additional implication of the different eolian stratification types is in understanding why bedding-plane features such as ripples, raindrop impressions, and animal tracks are conspicuous in some ancient dune sandstones but virtually unknown in others. For example, why should the Lyons and Coconino Sandstones possess all of these surface features whereas they are almost totally lacking in the Navajo and Entrada Sandstones? Part of the answer certainly is fortuitous exposures. An additional explanation seems to us to lie in the relative proportions of the different stratification types in a given formation.

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Fig. 15.—Large-scale and small-scale eolian dunes truncated to differing levels (A,B). Level of dune truncation greatly influences the geological record of the dunes, with features characteristic of the upper slipface being lost.
Fig. 16.—A) Stratification consisting of grainfall deposits. Parting planes developed along laminae are depositional surfaces. B) Pseudoripples formed by the broken edges of low-angle translatent strata. C, D) Stratification consisting of climbing wind ripple-deposited translatent strata. Parting planes do not represent single depositional surfaces. In (C), pseudoripples developed on a single translatent stratum bounding surface. In (D), pseudoripples developed by breakage across translatent strata (after a suggestion by R. E. Hunter).

angles to depositional surfaces. These bounding surfaces are depositional surfaces only momentarily before being buried by the next advancing ripple. These surfaces, therefore, may not be exposed long enough for consequential surface features to form (Fig. 16 C, D). It seems significant that the Lyons Sandstone, for example, consists mostly of grainfall deposits at the famous quarry at Lyons, Colorado (Hunter, 1981) where rare tracks, raindrop impressions, and true ripple forms are relatively common (Walker and Harms, 1972). Conversely, the Navajo and Entrada display much more grainflow cross-strata and climbing-ripple translatent strata and are conspicuously impoverished of bedding surface features in our experience.

There is yet an additional, more subtle implication with respect to the exposure of ripples on parting surfaces. Only if the partings develop along true depositional surfaces would complete, true ripple forms be present. True eolian ripple forms certainly occur on some eolian sandstones partings, but close examination is in order, for if the partings instead represent translatent strata bounding surfaces, then only apparent ripples or pseudo-ripples will be present (Fig. 16B). Pseudoripples are a series of asymmetrical parting ridges rather than complete, smooth ripples; they reflect the ripples but are not the actual ripple forms.

Two cases of pseudoripples may exist. First, pseudoripples may represent the broken edges of the thin, low-angle cross-laminae along a single bounding surface (Fig. 16C)—a situation perfectly analogous to the more familiar, largerscale “washboard-like” broken cross-strata. Al-
TERNATLY, AS SUGGESTED TO US BY R. E. HUNTER (WRITTEN COMMUNICATION), PSEUDORIPPLES MAY FORM BY THE BREAKAGE IN STAIR-STEP FASHION ACROSS BOUNDING SURFACES (FIG. 16D). SEEMINGLY, ONLY AN IDEAL EXAMPLE SHOWING PSEUDORIPPLES, TRANSLATEN STRATA, AND CLEARLY DEFINED DEPOSITORIAL SURFACES COULD RESOLVE THE PRECISE ORIGIN OF PSEUDORIPPLES. THE RECOGNITION OF PSEUDORIPPLES FROM TRUE RIPPLES IS SIGNIFICANT, HOWEVER, IN THAT REGARDLESS OF WHICH ALTERNATE EXPLANATION BEST EXPLAINS PSEUDORIPPLES, ERRONEOUS RIPPLE INDEX VALUES CAN ARISE FROM THE MEASUREMENT OF PSEUDORIPPLES. NEITHER THE HEIGHTS NOR THE WAVELENGTHS OF PSEUDORIPPLES NECESSARILY REFLECT TRUE RIPPLE DIMENSIONS.

CONCLUSIONS

THE STUDY OF EOLIAN SEDIMENTATION HAS EVOLVED TO THE POINT WHERE EOLIAN AND SUBAQUEOUS CROSS-STRATA OFTEN CAN BE POSITIVELY DIFFERENTIATED. THE ATTEMPT HERE IS NOT TO URGE THE ABANDONMENT OF SOME OF THE COMMONLY USED CRITERIA FOR DETERMINING EOLIAN ENVIRONMENTS, AS THESE CAN PROVIDE VERY USEFUL INFORMATION, BUT RATHER TO SUGGEST THAT MORE DETAILED INTERPRETATIONS CAN BE MADE FROM THE CROSS-STRATA THEMSELVES BY ANALYSIS OF THEIR COMPONENT STRATIFICATION TYPES. IN ITSELF, JUST THE DETERMINATION OF AN "EOLIAN ENVIRONMENT" IS NOT A VERY REFINED INTERPRETATION FOR SYSTEMS AS COMPLEX AS EOLIAN ERGS. BY WAY OF ANALOGY, INTERPRETING A BODY OF ROCK AS "TIDAL FLAT" IN ORIGIN WOULD NOWAYS BE INSUFFICIENT. ONE WOULD ROUTINELY DISCRIMINATE BETWEEN SUPERLATIVAL AND INTERTIDAL AREAS AND TIDAL CHANNELS, AND ATTEMPT TO DETERMINE BEDFORM TYPES AND MOVEMENTS, CURRENT FLOW PATTERNS AND EVEN WATER FLOW VELOCITY, AND TIDAL RANGE. SIMILAR REFINEMENTS SHOULD BE MADE FOR INTERPRETATIONS OF EOLIAN ENVIRONMENTS. STRATIFICATION TYPES ARE SOME OF THE TOOLS WITH WHICH THESE MORE REFINED INTERPRETATIONS CAN BE BUILT.

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REFERENCES


—, 1971b, Longitudinal dunes of the northwestern edge of the Simpson Desert, Northern Territory, Australia: geomorphology and grain size relationships: Sedimentology, v. 16, p. 5-54.


—, 1981b, Significance of interdune deposits and bouding surfaces in eolian dune sands: Sedimentology (in press).


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WERNER, F., AND NEWTON, R. S., 1975, The pattern of large-scale bed forms in the Langeland Belt (Baltic Sea): Marine Geol., v. 19, p. 29-59.


