TERMINOLOGY OF CROSS-STRATIFIED SEDIMENTARY LAYERS AND CLIMBING-Ripple STRUCTURES

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ABSTRACT: Cross-stratified sedimentary layers have been referred to as cross-stratified beds or strata by some geologists. The term "bed," when applied to cross-stratified layers produced by climbing bedforms, is in conflict with the term "pseudobed," which has also been applied to such layers. It is proposed that this conflict be resolved by excluding any necessary isochronism from the terms for sedimentary layers and for their bounding surfaces. The sedimentological definition of "bed" is thus made essentially the same as its rock-stratigraphic definition, and a cross-stratified layer produced by the climbing of a bedform can then be properly called a cross-stratified bed or stratum.

A new name, "translational stratum," is proposed for a stratum that is generated by the dominantly translational movement of a depositional surface and whose bounding surfaces are generated wholly or in major part by the dominantly translational movement of linear features on or bounding the depositional surface. The most useful characteristic for recognizing a translational stratum is that the former depositional surfaces within the stratum meet both bounding surfaces of the stratum. Translational strata may be classified as laterally translational and climbing translational, depending on whether the direction of translation is parallel to or at an angle to the generalized depositional surface; a climbing translational stratum is what has previously been called a pseudobed.

Climbing-ripple structure is composed potentially of climbing translational strata and of wavy laminae or crosslaminae whose bounding surfaces are former rippled depositional surfaces. The wavy laminae are here called "rippleform laminae." Rippleform laminae are not detectable in some climbing-ripple structures, especially those formed by wind ripples. The characters of climbing translational strata and of rippleform laminae vary with the angle of ripple climb and change abruptly at the critical angle of climb, which is defined here as the angle at which the vector of ripple climb is parallel to the steepest part of the ripple stoss slope.

INTRODUCTION

Many geologists refer to any cross-stratified sedimentary layer as a bed or stratum. However, this usage is in conflict with one aspect of the generally accepted definition of "bedding surface" or "stratification surface," as is shown in the next part of this paper. A resolution of this conflict is proposed, and concepts arising from the proposed resolution are then applied to the terminology of structures produced by climbing ripples or by other climbing bedforms.

The term "stratum" will be used in preference to "bed" through most of this paper except where cited writers themselves use the term "bed." Most authorities on stratification agree that strata include beds and laminae, but they disagree on whether beds should be distinguished from laminae on the basis of thickness (McKee and Weir, 1953) or on the basis of the presence or absence of stratification within the stratum (Bokman, 1956; Campbell, 1967). This disagreement is not addressed in this paper. Until an answer is given to the question of whether any cross-stratified layer can properly be called a stratum, the term "sedimentary layer" is used for any relatively tabular body of sedimentary material.

THE PROBLEM

It is now agreed by many geologists that much cross-stratification is produced by climbing ripples and by climbing bedforms of larger size that have been referred to variously as large-scale ripples, megaripples, dunes, and sand waves (see, for example, Allen, 1963a, 1968). In the terminology followed by Pettijohn (see, for example, Pettijohn, Potter, and Siever, 1972, p. 107), the deposit of a single climbing ripple or similar bedform is a "cross-laminated bed," provided that the ripple climbs

1 Manuscript received February 24, 1976; revised October 25, 1976.
at an angle low enough that sediment is not permanently deposited on its stoss side (Fig. 1). McKee (1939, 1965), on the other hand, considers the deposit of a single climbing ripple to be not a true bed but rather a "pseudobed." The difference in terminology for cross-stratified layers thus represents a real but generally ignored conflict in the definition of "bed" or, in a more general sense, "stratum."

A rationale for considering the layers formed by individual climbing ripples to be other than true beds is that their bounding surfaces are not bedding surfaces by the generally accepted genetic definition, which states that a bedding surface is an original surface of deposition (Gary, McAtee, and Wolf, 1972) or, in other words, a former sediment-fluid interface or formerly exposed surface. Small parts of the bounding surfaces of layers formed by climbing ripples may have been exposed surfaces at a given moment, but it is not necessary for even small parts of the bounding surfaces to be formerly exposed surfaces. A bounding surface of a pseudobed is, rather, in geometric concept the locus of a moving line, specifically a line close to the ripple trough line on a ripple that was migrating during net deposition. As such, a bounding surface crosses and is crossed by successive depositional surfaces (Fig. 1). In other words, a bounding surface is diachronous, not isochronous.

A rationale for considering any cross-stratified layer to be a true bed or stratum can be based on the proposition that a bed in the sedimentologic sense must be of the same nature as a bed in the sense of a rock-stratigraphic unit; a bed in this sense has no necessary relation to time (American Commission on Stratigraphic Nomenclature, 1970). By this rationale, the definitions of "bed," "bedding surface," "stratum," and "stratification surface" should be purely descriptive except for the genetic restriction that a bed or stratum must be produced by depositional processes, perhaps supplemented by the penecontemporaneous reorganization of grains by processes such as bioturbation.

Although the ambiguity in the usage of the terms "bed" and "stratum" could be ignored by referring to cross-stratified layers solely as sets of cross-strata, an ambiguity so close to the heart of sedimentology is undesirable. Moreover, a name other than "set" becomes essential when one is faced with describing layers that are produced by the climbing of ripples but that have no visible ripple-foreset cross-stratification. Layers of this type are formed by some subaqueous current ripples or similar bedforms that climb at low angles (Jopling, 1964; Wunderlich, 1967; Smith, 1971; McBride, Shepherd, and Crawley, 1975), by some wave ripples that climb at low angles (Newton, 1968), and by almost all wind ripples that climb at low angles (Rim, 1951, 1953;
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Yaalon, 1967; Yaalon and Laronne, 1971; Hunter and others, 1972; Goldsmith, 1973; Hunter, in press). In a typical layer deposited by a single climbing wind ripple, cross-stratification can not be seen in the best natural exposures, in peels, or in X-radiographs. Is such a layer a pseudostratum or a kind of true stratum?

A PROPOSED RESOLUTION

Definitions of "Stratum" and "Stratification Surface"

The viewpoint is taken here that a classification of primary sedimentary layers into strata and pseudostrata in McKee's (1939, 1945) sense is not practicable, even if it were considered desirable, because it is in essence a first-stage classification that requires an especially difficult interpretation. To determine whether a layer is a pseudostratum or a stratum, one must determine whether former depositional surfaces cross or do not cross the contacts of the layer. The determination of a crossing relation is commonly difficult, as was recognized by McKee (1965, p. 80), and the determination becomes more and more difficult as the generalized angle of crossing becomes smaller and smaller. This difficulty is evident from the controversy that has surrounded the question of whether large-scale cross-stratification is produced most commonly by climbing bedforms or by bedforms that migrate without climbing (Hemingway and Clarke, 1963; Allen, 1963b; Stride, 1965).

Following the alternative rationale that leads to classifying any cross-stratified layer as a true stratum, it is advocated here that a stratum be defined as "a layer that (1) was produced by deposition or by the penecontemporaneous reorganization of deposited grains by processes associated with the depositional surface and (2) is separated from adjacent rocks by visually or physically well-defined bounding surfaces or, if these are absent, by bounding surfaces placed arbitrarily within lithologic transition zones." Some degree of lithologic homogeneity is required of a stratum according to many authorities, but this requirement can be construed so broadly that it may just as well be omitted (Campbell, 1967). A stratification surface can obviously be defined as "the bounding surface of a stratum," but nothing in the above definition of "stratum" requires the additional restriction that the bounding surfaces be former depositional surfaces. In fact, the genetic requirement of isochronous exposure must be removed from the definition of "stratification surface" if the above definition of "stratum" is considered adequate. The terms "bed" and "bedding surface" can be defined similarly to "stratum" and "stratification surface," with the qualification that a bed is a type of stratum.

The proposed removal of any necessary isochronism from the definitions of sedimentary layers and of their bounding surfaces can be justified by analogy to rock-stratigraphic terminology. When it came to be recognized that the contacts of rock-stratigraphic units are not necessarily isochronous, the terminology was not changed but chronological significance was excluded from the definitions of the terms. It is now time to face the fact that all strata cannot be safely assumed to be small-scale, time-stratigraphic units. In my experience, as strata are examined in finer and finer detail, more and more are found to climb, and the possibility of climbing can seldom be eliminated.

By the definition advocated here, the layers that McKee (1939, 1965) called pseudobeds are true strata. However, McKee's terminology has served the valuable purpose of calling attention to the existence of several distinct kinds of layering, and it remains desirable to have a name for the kind of layering that bears an angular relation to former depositional surfaces.

Some Geometric Considerations

Before arriving at a new name for what McKee (1939, 1965) called pseudobeds, some geometric aspects of the generation of stratification are considered. Any stratum can be thought of abstractly as a solid geometric figure, specifically as a three-dimensional locus that is generated by the movement of a two-dimensional geometric figure, the depositional surface. A surface must move outward from its initial position for the surface to be depositional. Movements or transformations of a figure can be classified as translations, rotations, distortions, and combinations of these three basic kinds of transformation. Translation is an especially simple kind of transformation in which all points of the figure move a given distance in a given direction defined by a vector of translation, so that the figure moves without change in shape and without rotation.
Commonly, the transformation of a depositional surface in nature can be described as largely a translational movement with a subordinate distortional component of movement. If a depositional surface that undergoes translational movement has edges that separate it from adjacent nondepositional or erosional surfaces, or if the surface is marked by textural, compositional, or morphologic features that persist through time, the direction of translation is uniquely defined as the direction of movement of these features.

Just as a stratum can be thought of as a solid geometric figure generated by the movement of a depositional surface, some stratification surfaces can be thought of as two-dimensional geometric figures that are generated by the movement of linear features during deposition. The linear features may be either the edges of depositional surfaces or the boundaries between depositional areas of significantly different sediment texture, composition, or morphology. Not all stratification surfaces are of this type, of course; many are former depositional surfaces.

**Translant Strata**

With the foregoing geometric considerations, a class of strata can be defined that includes most cross-stratified strata, including as a subclass the kind that McKee (1939, 1965) called pseudostrata. A stratum of this class is here called a “translant stratum,” defined as a stratum that is generated by the dominantly translational movement of a depositional surface and whose bounding surfaces are generated wholly or in major part by the dominantly translational movement of linear features on or bounding the depositional surface. Because the direction of movement of the depositional surface is defined by the movement of features on or bounding the surface, it follows that at least the major parts of the bounding surfaces are parallel or nearly parallel to the translational path of the depositional surface as a whole. It seems reasonable to specify that the destruction of the original upper bounding surface by erosion does not remove a stratum from the translant class.

Some examples of translant strata are shown in Fig. 2. It can be seen that the most important characteristic for recognizing a translant stratum is that the former depositional surfaces within the stratum meet both bounding surfaces of the stratum. The observation of this relation is not conclusive proof that a stratum is of translant type, for a stratum having this character could be produced by the partial erosion of a stratum that did not originally have this character. However, the partial erosion would have to be of very fortuitous extent, and the likelihood of such erosion can probably be estimated easily by observations at the outcrop. To recognize the meeting relation between former depositional surfaces and the bounding surfaces, it is necessary that the
former depositional surfaces be defined by visible stratification within the stratum. In the absence of such stratification, the recognition that a stratum is of translatent type is most difficult.

The relation between translatent strata defined here, and pseudostrata, in the sense can now be seen. The former depositional surfaces within a translatent stratum meet the bounding surfaces of the stratum, whereas the former depositional surfaces within a pseudostratum cross as well as meet the bounding surfaces. Although the term "pseudostratum" is not appropriate here because these layers are considered to be a type of translatent strata, and hence a type of true strata, it remains desirable to have a special name for such strata.

Translatable strata are therefore further classified as laterally translatable strata and climbing translatable strata, the latter being equivalent to pseudostrata in the terminology of McKee (1939, 1945). A laterally translatable stratum is formed by translation of the depositional surface in a direction parallel to the generalized depositional surface; the former depositional surfaces within a stratum of this kind meet but do not cross the bounding surfaces (Fig. 2a). A climbing translatable stratum is formed by translation of the depositional surface in a direction at an angle to the generalized depositional surface; the former depositional surfaces within a stratum of this kind cross as well as meet the bounding surfaces (Fig. 2b).

The classification of sedimentary layering presented here has the desirable hierarchical quality that easier interpretations precede more difficult interpretations. Any layer that can be identified as having been produced by deposition can be referred to as a stratum. By a somewhat more difficult interpretation, some strata can be identified as translatable strata. By a still more difficult interpretation, some translatable strata can be identified as laterally translatable strata or as climbing translatable strata. It is beyond the scope of this paper to propose a complete classification of stratification; probably several classes of strata could be defined at the hierarchical level of what are here called translatable strata.

Terminology of Cross-stratified Layers

Returning to the question of the terminology of cross-stratified layers, it can be seen that all such layers are properly called strata by the definition of "stratum" advocated here. All such layers may be referred to either as cross-stratified strata or as sets of cross-strata. Most cross-stratified strata are translatable strata, but some belong to a class of strata in which former depositional surfaces within the stratum meet the upper but not the lower contact of the stratum, and some belong to a class in which the former depositional surfaces meet both contacts but in which the meeting relation with the upper contact was produced fortuitously by erosion. Of the cross-stratified strata that are of translatable type, most are probably climbing translatable strata, but some are laterally translatable strata.

Most translatable strata are cross-stratified. However, translatable strata are not necessarily cross-stratified, for the inclination of the depositional surfaces relative to the contacts may not be visible or otherwise detectable. Needless to say, the recognition of translatable strata that are not visibly cross-stratified is likely to be very difficult.

Terminology of Climbing-ripple Structures

Structures produced by climbing ripples are composed potentially of wavy laminae or crosslaminae, whose bounding surfaces are former rippled depositional surfaces, and climbing translatable strata, whose bounding surfaces cross former depositional surfaces. As has been noted in the first part of this paper, however, the wavy laminae or crosslaminae whose bounding surfaces are former depositional surfaces are not present, or at least are not visually detectable, within the deposits formed by some climbing ripples, especially climbing wind ripples.

The structure produced by climbing ripples has generally been referred to as "climbing-ripple cross-lamination" (Allen, 1971, 1973), "ripple-drift cross-lamination" (Walker, 1963, 1969; Jopling and Walker, 1968), or "superimposed ripple laminae in rhythm" (McKee, 1965). All of these names imply the presence of wavy laminae or crosslaminae whose bounding surfaces are former depositional surfaces, and the names are therefore not applicable to structures in which only climbing translatable stratification is visible. A more general name, "climbing-ripple structure," which has been used by McKee (1965, p. 80), is here proposed.
for any structure formed by climbing ripples, whether or not wavy laminae or crosslaminae are visible.

The character of climbing-ripple structure varies with the angle of ripple climb, which is defined as the angle between the vector of ripple climb and the generalized depositional surface (Fig. 3). The change in character with changing angle of climb is gradual except for a discontinuity at one particular angle, here called the “critical” angle of climb. The critical angle of climb is the angle above which deposits are formed and preserved on all parts of the ripple surface and below which deposits are eroded from the stoss slope of the ripple; the critical angle is equal to the inclination, measured relatively to the generalized depositional surface, of the steepest part of the stoss side of the ripple. In other words, the critical angle of climb is the angle at which the vector of ripple climb is parallel to the steepest part of the ripple stoss slope. The value of the critical angle differs from ripple to ripple but is generally less than 10°.

Angles of climb that are less than and greater than critical are here called “subcritical” and “supercritical,” respectively. Confusion with subcritical and supercritical flow regimes can be avoided by using terms such as “subcritically climbing ripples”; terms such as “subcritical ripples” must be avoided.

The wavy laminae or crosslaminae produced by deposition on rippled surfaces have been called “ripple laminae” by some geologists (McKee, 1965; Reineck and Singh, 1973, p. 95). In a discussion of eolian sands, however, Inman, Ewing, and Corliss (1966) have used the very similar name “ripple laminae” for thin layers that, from their described character, are probably climbing translatent strata. Because the term “ripple lamina” is ambiguous in that it might be thought to apply either to a wavy layer deposited on a rippled depositional surface or to the tabular depositional product of a single climbing ripple (Jopling and Walker, 1968, p. 971-972), the more explicitly descriptive name “rippleform lamina” is proposed here for the wavy lamination or crosslamination that is parallel to successive positions of the rippled depositional surface. Rippleform lamination is so named because it defines at least part of the form of the ripples.

If the angle of ripple climb is subcritical, rippleform laminae are deposited only on the lee slopes of the ripples or, if deposited on the stoss slopes also, are preserved only on the lee slopes. This incomplete rippleform lamination can be given an alternate name, “ripple-foreset crosslamination” (Fig. 4 and Table 1). Ripple-foreset crosslamination is itself fully preserved only at the critical angle of climb; it is only partially preserved at subcritical angles of
climb. If the angle of ripple climb is supercritical, rippleform laminae are deposited and preserved on both the lee and stoss slopes of the ripples. In the deposits of supercritically climbing ripples, whether of small-scale subaqueous type (Jopling and Walker, 1968) or of eolian type (Hunter and others, 1972, p. 15; Hunter, in press), single rippleform laminae can commonly be traced continuously across many ripple crests and troughs. Rippleform lamination of this type may be called “complete.” If single laminae cannot be traced across ripple crests and troughs, it may be desirable to refer to the lee-side rippleform laminae as “ripple-foreset crosslaminae” and the stoss-side rippleform laminae as “ripple-backset crosslaminae.”

Climbing translaminar stratification, like rippleform lamination, undergoes a discontinuity in character at the critical angle of climb. The bounding surfaces of climbing translaminar strata are sharp and erosional if the angle of climb is subcritical, are sharp but nonerosional if the angle of climb is critical, and are gradational if the angle of climb is supercritical (Fig. 4). It should be stressed here that climbing translaminar strata are generally made visible even in the absence of coexisting rippleform lamination by variations in grain size or type from bottom to top of each layer. It should also be noted here that some geologists, including Pettijohn and Potter (1964, plate 39), apparently restrict the term “pseudobeds” to what are here termed “supercritically climbing translaminar strata.” McKee (1965), however, extends the term to what are here called “supercritically climbing translaminar strata.” It certainly seems reasonable that the value of the angle of climb relative to the critical angle is not important enough to require that the layer be given a radically different name.

If a subcritically climbing translaminar strata...
stratum is internally crosslaminated, it may be given the alternative designation, "set of ripple-foreset crosslaminae" Table 1). Similarly, a set of subcritically climbing translatent strata may be alternatively designated a "coset of ripple-foreset crosslaminae." These terms are obviously inappropriate if cross-stratification is not visible.

The lack of visible crosslamination in some subaqueous current ripples and wave ripples and in most wind ripples may be due to several reasons (Hunter, in press). At least one reason is

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<th>Table 1.—Terminology of the components of climbing-ripple structure</th>
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<td>Angle of Ripple Climb</td>
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<td>Translatent Stratal Component</td>
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1 The terminology of structures formed at a critical angle of ripple climb is identical to that of structures formed at subcritical angles of ripple climb, except that "subcritically" is replaced by "critically."
the lack of sufficiently large fluctuations in the character of the grains supplied to the depositional surface through time. This lack of contrast inhibits the detectability of crosslamination especially if the climbing translatent strata are very thin and distinctly graded. Another conceivable reason, perhaps only applicable for wind ripples and perhaps not even applicable for them, is the destruction of thin crosslamination due to the jostling of the grain framework in a surficial layer as saltating grains bombard the surface.

APPLICATION OF THE TERMINOLOGY

An example of eolian climbing-ripple structure is shown in Fig. 5, a photograph of a wind-scoured horizontal surface truncating stratification that dips at a low angle toward the top of the photograph. Because the exposed surface is horizontal, only the alongslope component of ripple climb is visible; trenching showed that upslope or downslope components of climb were insignificant in this deposit. Because the exposed surface cuts across the stratification at a low angle, the apparent ratio of ripple height to ripple spacing is exaggerated; the exaggeration has the effect of making this horizontal exposure of climbing wind ripples resemble a vertical exposure of climbing subaqueous current ripples.

Both climbing translatent stratification and rippleform lamination are visible in parts of Fig. 5. The climbing translatent stratification trends diagonally across the photograph from lower left to upper right, whereas the rippleform lamination is approximately parallel to the top and bottom edges of the photograph. Former depositional surfaces are defined, as in all climbing-ripple structures, by the rippleform lamination.

The angle of ripple climb and the character of the climbing-ripple structure change gradually from bottom to top of the photograph. The angle of ripple climb increases from a subcritical value in the lower part of the photograph to 90° near the top of the photograph.

In the lower third of the figure, the climbing-ripple structure is composed of subcritically climbing translatent strata without coexisting ripple foreset crosslaminae. The subcritical value of the angle of climb is indicated by the sharpness of the contacts of the translatent strata, but, in the absence of any feature defining the attitudes of former depositional surfaces, the precise value of the angle of climb can not be determined. It must, of course, be less than the critical value, which for wind ripples is 2° to 6°. Were it not that the strata can be traced into the upper part of the photograph, where climbing is obvious, the assertion that these strata are of translatent type, and moreover are of climbing translatent type, would be unconvincing.

The angle of ripple climb passes the critical value at the level of the pen in Fig. 5. At about this same level, rippleform lamination becomes visible. The climbing-ripple structure in the upper two-thirds of the photograph thus consists of supercritically climbing translatent strata and coexisting rippleform laminae. Note, however, that the angle of climb does not increase monotonically but rather first increases, then decreases to nearly critical, and then increases again to vertical near the top of the photograph.

ACKNOWLEDGMENTS

I wish to thank the many geologists who have given their opinions on these terminological questions; especially extended conversations were held with H. Edward Clifton and Edwin D. Mckee. Thomas S. Ahlbrandt and Russell G. Shepherd reviewed the manuscript. Not all of these workers agree with my conclusions, and they should not be held responsible for any shortcomings of this paper.

REFERENCES


HUNTER, R. E., in press, Basic types of stratification in small eolian dunes: Sedimentology.