PALEOCURRENT ANALYSIS IN LIGHT OF TROUGH CROSS-STRATIFICATION GEOMETRY[1]

RUDY L. SLINGERLAND AND EUGENE G. WILLIAMS
The Pennsylvania State University, University Park, Pennsylvania 16802

ABSTRACT

Random trough cross-strata dip directions may have a mean direction quite different from the trough axis, and therefore may not give an accurate paleocurrent direction. If trough plunge can be measured, a single measurement on a trough side can be corrected to give the trough axial azimuth. On perfectly two dimensional vertical surfaces it is still possible to estimate trough axial azimuths by measuring the face azimuth and two apparent dips on opposite sides of a trough, and applying a correction established by a theoretical geometric analysis of troughs.

INTRODUCTION

Paleocurrent directions are difficult to determine from cross-stratification because of the complex relationship between currents and bedforms and because of certain interactions between outcrop orientation and bed geometry. Planar cross-stratification, accounting for approximately 25% by volume of the cross-stratification in at least one study (Williams 1971), is most reliably measured in the field (cf. Meckel 1967; Bhattacharya 1969; Potter and Olsen 1954), but its interpretation is difficult. True accretionary planar cross-strata (epsilon type of Allen 1963*a*), have dip azimuths (true dip unless otherwise labeled) up to 90° to the current direction and are thus unreliable for most paleocurrent studies unless their nature is understood. Harms et al. (1963), Frazier and Osanik (1961), Harms and Fahnestock (1965), McGowen and Garner (1970), and Williams (1971) all describe planar (tabular) cross-strata derived from the migration of large-scale channel bars in which the cross-strata are at significant angles to the current direction at that point.

Trough cross-stratification, accounting for at least 50–60% of all cross-strata (Dott 1970; Williams 1971; Harms et al., 1963), has axes with a much stronger correlation with flow direction than the dip azimuths of planar cross-strata (Ray 1976; High and Picard 1974; Williams 1971; and Bhattacharya 1969), but is much harder to measure and interpret correctly. Problems include:

1. Asymmetrical bed filling by migration of swept catenary ripples or by a more random process may produce a paleocurrent direction error of up to 90° if bed dip directions are measured.

2. Even if bed filling is symmetrical with respect to the trough axes, measuring bed dip azimuths on two sides of a trough and determining the bisectrix as the true current direction theoretically only works for the zy and xy coordinate planes (x and y are the two horizontal axis with x parallel to the trough axis, and z is the vertical axis).

(a) Oblique cuts will produce bimodal histograms of dip azimuths, the bisectrix of which is greater than 30° from the true axial direction.

(b) The frequency of bed dip azimuths for both sides of a trough in oblique cuts is a function not only of the obliqueness of the cut, but also of the amount of curvature of the bed traces in the xy plane.

3. Cuts subparallel to the axial direction but off-centered will produce planar cross-stratification traces with dip azimuths which may be up to 180° in error from the true trough axial direction.

4. Theoretical reasoning demonstrates that measuring many bed dip directions from different troughs on a vertical face may lead to a precise paleocurrent estimate but usually not an accurate one.

5. The use of trough axial plunge azimuths as

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suggested by Dott (1970), Dott and Roshardt (1972), Dott (1973), and High and Picard (1974) alleviates these problems when outcrops provide sufficiently three-dimensional views, but in the other more common cases, such direct reading of trough axes is not possible. On quasi-two-dimensional vertical outcrop surfaces it is usually impossible to measure strikes on the erosional sides of troughs because they are not planar or have low dips.

We review here the geometries of trough cross-strata observed in nature and classify cross-strata forms as seen in all possible transections. Based on this classification and information from troughs in a Virginia Pleistocene marine sand, we show that it is impossible to determine an accurate paleocurrent direction from infilling bed traces or from bed dip directions on vertical faces unless the face happens to be perpendicular to the mean trough axial direction. Trough axes determined from trough erosional sides are shown to be better, but for two-dimensional vertical outcrop faces they cannot be measured. Under certain assumptions, however, we show that trough axial azimuths can be calculated for this latter case from apparent dips of trough erosional sides and the azimuth of the transect.

GENERAL OBSERVATIONS

Trough Forms Observed in the Field

Based on field evidence of Allen (1963*a*; 1963*b*; 1968), Stewart (1961), Frazier and Osanik (1961), Hamblin (1961), Williams (1968; 1971) and Slingerland (1977), we assume that most trough cross-strata are formed from migrating three-dimensional ripples or dunes.

Erosional surfaces.—The trough bottom has been described as a "scoop-shaped erosional hollow" (Allen 1968, p. 118), an elongate ellipsoid (Pick 1964), or a spoon-shaped depression (Harms et al. 1963). This erosional surface plunges steeply at the upcurrent end of the trough and then flattens out to a straight line downcurrent (Pick 1964; Williams 1971; van Beek and Koster 1972; Allen 1968). Pick (1964) found maximum plunges of less than 10° in 64% of 395 cases although plunges of 10° and 20° accounted for 25% of the cases. Pick's percentages may reflect the probability of transecting a trough at a given place along the x axis. An average thickness/length ratio of troughs (Harms et al. 1963; Harms and Fahnestock 1965; Hamblin 1961, Stewart 1961) is 0.13. From Allen (1968, p. 118) the "usual" thickness of sets of large-scale cross-strata is from 0.25 to 0.75 m, and by the above, the "usual" lengths would range from 1.93 to 5.8 m. If the plunge of the back slope averages 25°, then about 12% of the length of a trough can be expected to have a high plunge. Although it is only fortuitous that precisely 12% of Pick's (1964) 395 measurements had trough axial plunges of more than 21°, the similarity between values is encouraging. Thus, from the data at hand, we might expect with a random cut to transect the more steeply plunging upstream trough erosional surface only 1 or 2 times out of 10.

The general plunge of trough axes is not as well known if trough ends are excluded. Allen (1963*a*, 1963*b*, 1968) argued that if the cross-strata are to be preserved, trough axes must rise downstream in response to net deposition. But Pick (1964), Ray (1976) and Coleman (1969), among others, presented field data showing trough erosional bottoms continue to plunge gently ($\approx 5°$) downcurrent. On the other hand, doubly plunging trough bottoms, although scarce, are known from ancient sediments (Dott 1973) as well as recent (Harms et al. 1963). But these are always small-scale troughs. Therefore we conclude that a random vertical cut of a large-scale trough should expose the trace of an elongate semi-hemispherical scour, plunging gently ($< 10°$) downstream 8 out of 10 times.

Infilling beds.—Infilling cross-strata vary in placement with respect to trough erosional axis, in dip angle, and in amount of curvature. A review of the literature (Pick 1964; Harms et al. 1963; Williams 1971; McGowen and Garner 1970; Wurster 1958; and others) shows that, in general, 50–70% of infilling cross-strata are disposed symmetrically about the trough axis. This percentage probably reflects the relative numbers of swept catenary ripple trains compared with other types, as well as the amount of troughs filled from the side by random processes.

Most dips in infilling beds range between 20° and 30° although the range can be from 1° to 36° depending upon grain size and the position of measurement along the z and y axes. Data from Wurster (1958, table 11) show a significant increase of bed dip with distance up the z axis for beds at any one location within the trough, i.e., some beds are curvilinear with asymptotic bases. Also, bed dips decrease as one travels laterally away from the trough axis.

The amount of curvature or swing angle is here defined as the angle subtended from trough edge to edge by the arc of the bed trace in the xy plane. It is highly variable, most likely reflecting the type of ripples that produced the cross-strata and the level at which the cross-strata were beheaded. Wurster (1958, p. 340, fig. 4) gives an example of the latter dependency. Some sets average 33° of curvature (Pick 1964), but those of Harms et al. (1963) averaged 180°. The swing angle as well as the thickness/width ratio should increase through the progression: quasi-three dimensional straight, sinuous, transverse, catenary, to lunate ripple trains, given the same z level (Allen 1968), but no data are available to test this hypothesis.

Measurement of Paleocurrent Direction from a Quasi-Three-Dimensional Vertical Outcrop Face

Infilling beds.—As discussed above the cross-strata of a trough can be assumed to be 50–70% symmetrically infilled but can have highly variable swing angles and dips. There are five important types of transects through an infilled trough (fig. 1).

Case 1 (fig. 1*a*): Plane of transection is perpendicular to the trough axis. The beds are symmetrically disposed about the plane of the axis but may have various degrees of curvature in this yz plane depending upon their dip and swing angle. True dip equals the apparent dip only where the swing angle is 180° and then only for the beds near the upper trough sides. Only one dip azimuth, that taken from beds at the exact center of the trough, is the trough axial (paleocurrent) direction.

Case 2 (fig. 1*b*): Plane of transection is coincident with the trough axial plane. Apparent dip equals the true dip and dip azimuth equals the paleocurrent direction. Both the cross-stratification and bounding surface may appear planar.

Case 3 (fig. 1*c*): Plane of transection is at a low angle to the trough axial plane. The swing angle is such that the apparent dip equals true dip on the extreme right side where the section is perpendicular to strike of beds; apparent dip progressively decreases toward the left but with no reversal of apparent dip direction. Mean bed dip azimuth $= f$ (swing angle, obliquity of cut).

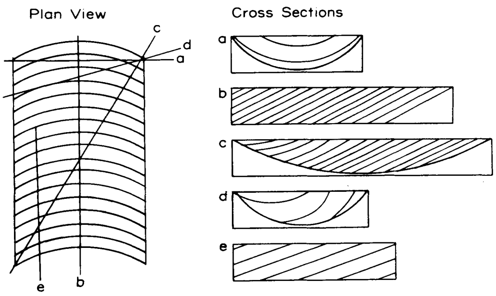

FIG. 1.—Schematic of a non-plunging trough showing traces of infilling beds in plan view and various cross sections. True dip directions measured randomly on faces *a* and *b* would approximate trough axial direction, but on *c*, *d*, and *e* would not.

Case 4 (fig. 1*d*): Plane of transection is at a higher angle to the trough axial plane than in Case 3. The beds show an apparent dip direction reversal and the axial plane of curvature is displaced towards the downcurrent side of the trough and dips inward. Mean bed dip azimuth $= f$ (swing angle, obliquity of cut).

Case 5 (fig. 1*e*): Plane of transection is parallel to the axial plane of the trough but not coincident. Bed dips are all equal but less than the true dip. Mean bed dip azimuth $= f$ (swing angle, distance of offset of section from trough axial plane). The cross-stratification may appear planar.

Can a trough axial azimuth be calculated from dip directions of beds infilling a single trough? Theoretically no, because the relative frequencies of bed dip azimuths are a function of the swing angle of the infilling beds and the orientation of the transect relative to the trough axis.

Consider the xy plane of a trough with axis plunging due south and measure bed dip directions in this plane along a line of section at 33° to the trough axis. The true paleocurrent azimuth is 180°. This analysis is similar to that of Niehoff (1958), reported in German.

As the swing angle increases, and all other variables such as trough width are held constant, mean bed dip direction is increasingly displaced from the true direction of 180° to 163°, an error of 17° to the east. Also, the angular deviation (analogous to the standard deviation in that 67% of the values in a normal or circular normal distribution should lie within ±1 angular deviation from the mean), increases from a spread of ±16° to ±50°. Therefore without knowing the swing angle of beds in a trough, no systematic correction can be made to bed dip directions to account for errors inherent in their measurement.

Furthermore, even if an *average* swing angle is assumed, no statistical manipulation can give the true trough axis direction for oblique cuts, because of an interaction between the number of beds exposed on each side of the trough axis and the orientation of the section. Each different section orientation would need a different scheme to weight the number of bed dips taken on each side of the trough. Thus, one can not measure infilling beds of a single trough and derive a true axis direction from a statistical manipulation of the data.

Trough erosion surfaces.—Can the strike of a trough side be used to estimate the trough axial azimuth?

As discussed previously, in a random vertical cut of a trough one most likely will transect an elongate ellipsoidal or semi-hemispherical erosional scour with a downstream axial plunge of less than 10°. The trace of the trough on the *yz* face will be symmetrical and on oblique vertical cuts, asymmetrical, because of plunge.

The deviation of strike of the trough side from trough axial azimuth is a function of the true dip of the side as well as the plunge. Assume a triangular element of variable plunge α, with an initial side dip of 30° (average angle of repose of sand). By trigonometry this angle of deviation, β, varies with the amount of plunge of the trough, α, as (Jeffrey Levine, personal comm.):

$$\beta = \arctan\left(\frac{\cos\alpha\tan\alpha}{\tan 30°}\right). \qquad (1)$$

Thus, with the data of Pick (1964) where plunges were $< 10°$, measuring the strike of the side of a trough erosional surface can be expected to yield a direction within less than 7° of the true trough axial direction, in 69% of the cases. (The appropriate azimuth is deduced from the line of strike by noting the direction of dip of the infilling beds).

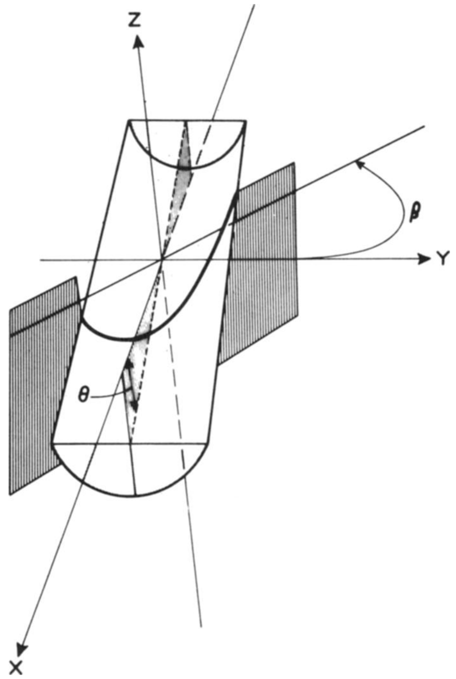

FIG. 2.—Definition diagram of right-circular half cylinder plunging $\theta°$ along a line in the *xz* plane and cut by a vertical oblique plane, $\beta°$ from the *yz* plane.

This error may be acceptable but a better method is to use the bisector of two strike azimuths, one taken on each side of the trough erosional bottom at the same elevation (relative to the trough bottom). For a symmetrical trough this should be the true trough axis direction. These conclusions are tested with field data in a following section.

Perfectly two-dimensional vertical cuts.—Thus far we have assumed a vertical outcrop face that is sufficiently three-dimensional that bed dip directions and strikes on trough sides can be taken. We now show that for a perfectly two-dimensional vertical transect it is still possible to estimate the trough axial azimuth under certain assumptions.

Consider a plunging right circular half cylinder in a coordinate system where the $z'y'$ plane is vertical and cuts the half cylinder at an angle β to its plunge direction (fig. 2). The trace of the half cylinder bottom is generated through solid analytic geometry by solving for the line of intersection of the plunging half cylinder and plane.

The equation describing this trace is:

$$\begin{aligned}&(1 + \tan^2 \theta)z'^2 \\ &+ y'(-2 \tan^3 \theta \sin \beta - 2 \tan \theta \sin \beta)z' \\ &+ y'^2(\tan^4 \theta + \tan^2 \theta + \tan^2 \theta \cos^2 \beta + \cos^2 \beta) \\ &- r^2(1 + \tan^2 \theta)^2 = 0. \qquad (2)\end{aligned}$$

where θ and β are defined in figure 2 and r is the radius of the half cylinder. z' and y' are the coordinates in the plane of cut, i.e., $z' = z$ and $y' = y \cos \beta - x \sin \beta$.

Equation 2 may be solved by the quadratic formula for $z' = f(\theta, \beta, y', r)$. Then the apparent dip angle of the trace at a point is simply the arctan of the slope, dz'/dy' at that point. As figure 3 shows, when a plunging trough is cut at angles increasingly oblique to the trough axis, the trough on the oblique face becomes increasingly asymmetrical. For a constant trough plunge there is a relationship between the difference in apparent dip angles at equal elevations on each side of a trough and the difference in azimuths of the outcrop face and trough (fig. 4). Thus, by assuming an erosional semicircular trough with a bottom plunging a known amount, one can calculate the direction of axial plunge by measuring, at equal elevations, the apparent dips of the trace of the trough bottom and applying a correction to the face azimuth. As discussed in the first section, it is not unrealistic to assume cylindrical troughs plunging 5 to 10°. However, figure 4 shows the relationship depends on the elevation above the trough base, d, (measured in multiples of trough radius) at which the angles are measured. We argue in the next section that, from analyses of field data, one can assume d equals $r/2$ to $r/4$.

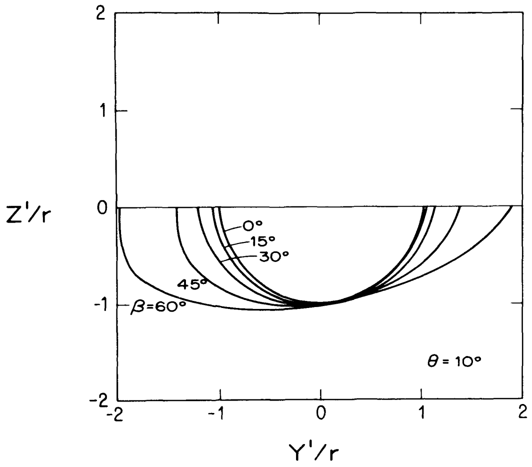

FIG. 3.—Traces on vertical sections of a half cylinder plunging 10° towards the reader as generated by equation 2. Y' and Z' are the horizontal and vertical transformed coordinate directions and r is the cylinder radius. Each plane section is at an angle, β, to the trough axial plane. As the plane of section cuts the trough at increasingly oblique angles, the traces become increasingly asymmetrical.

FIELD OBSERVATIONS

To investigate the geometry and modes of formation of trough cross-stratification and test the preceding conclusions, we collected information in two studies from a sand pit located 0.8 km east of route 679 at Persimmon Point, Virginia. The pit is in unconsolidated fine to coarse sands and gravels of Pleistocene age which are thought to be tidal channel or tidal delta deposits. One pit face, 54 m wide by 6 m high, striking 115° east of north, exposed sets of trough cross-stratification.

First Experimental Design

The objectives of the first study were to determine the form, dimensions, and mode of infilling of troughs at this location, to determine trough erosional bottom strike directions and their relationship to the direction of the bisectrix of the infilling beds as measured in the xy plane, and to determine the relationship of bed dip directions to these directions. Four locations along the 56 m length of the face were chosen with a random number table. At each location three blocks of sand were excavated, all evenly spaced vertically and seven feet long, three feet deep, and two feet thick. Strikes on the trough erosional surfaces and azimuths of infilling bed bisectrices were measured as well as five bed dip directions evenly spaced laterally over the xy face.

Forms.—Out of 22 troughs, 19 of the trough erosional bottoms appeared to be symmetrical scoop-shaped hollows with downcurrent

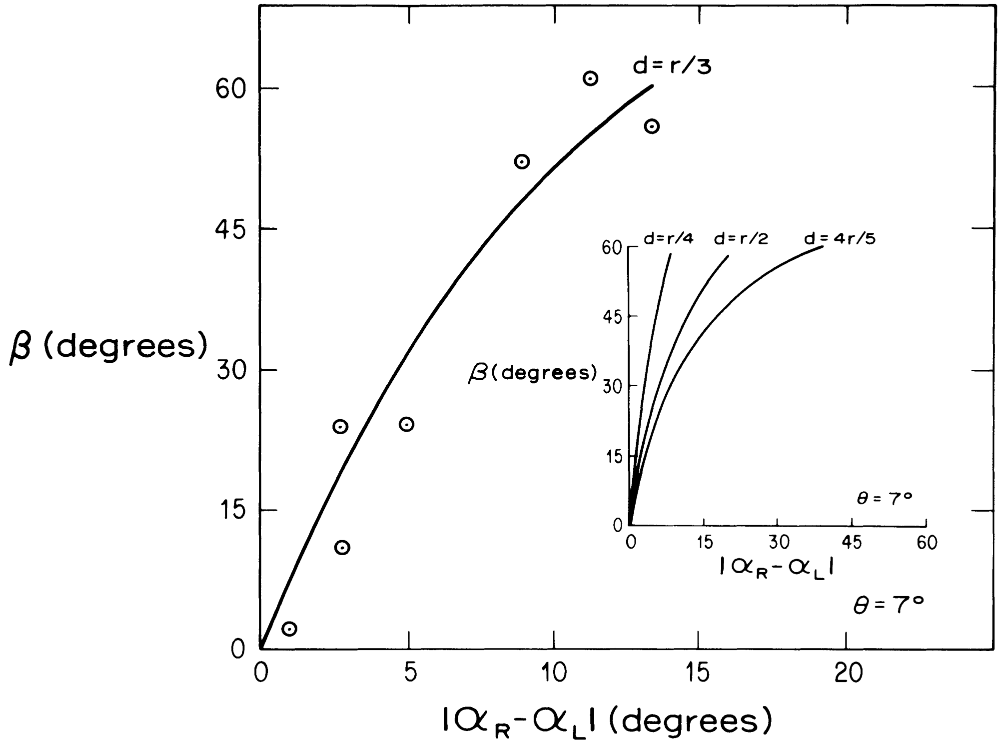

FIG. 4.—Theoretical relationship between obliquity of cut, β, and absolute difference in apparent dip angles, $|\alpha_R - \alpha_L|$, as measured on traces of a half cylinder plunging 7°. Angles α are measured, one on each side of the cylinder trace, at a height d above the trough bottom; r is cylinder radius. Field data for troughs plotted as 0's. See text for details.

plunges of 5° to 15° and mean plunge equal to 7°. One trough was canoe-shaped with the cross-strata infilling up-plunge at the downstream end, and the remaining two had highly irregular bottoms. On the xy plane of large-scale troughs the edges of erosional hollows were approximately linear and sub-parallel to each other. Small-scale troughs, however, usually exhibited the scoop-shaped upstream end.

If these are hemispherical scours, and the complete hemispherical form is preserved, the thickness/width ratio would be one-half. The average ratio from these and others reported in the literature is 0.23, which corresponds to the thickness/width ratio of a hemispherical trough beheaded a little less than halfway up from its base. Thus, in fig. 4, the distance, d, at which apparent dips should be taken would on average fall between $d = r/2$ to $r/4$. Other field data from this study (discussed later) agree.

Mode of infilling.—The infilling beds were highly variable in form and displacement with respect to the trough erosional bottom. No troughs could be found in which filling was truly symmetrical about the trough axis and of constant form in the x direction. In over half the cases, the beds apparently began filling from the trough side, and then through time swung around and filled forward from the rear as well as accreted vertically.

Swing angles were also highly variable, ranging from nearly 0° to 180°, with the majority greater than 40°. This supports a previous conclusion that histograms of bed dip direction can *not* be expected to give true paleocurrent directions.

Relationship among various direction measurements.—Trough erosional bottom strike directions (side strikes), directions of bisectrices of infilling beds measured in the xy plane (swing directions), and bed dip directions from each location and level were each subjected to a Raleigh test to determine if a concentration towards a preferred direction existed. If the directions were unimodal, then the vector mean and angular deviation were calculated. Comparisons among mean directions of the three types of measurement were conducted using an F test as modified by Watson and Williams (1956) for circular normal data under the assumption that two circular normal samples of homogeneous dispersion were given.

Trough side strikes and bed swing directions in any one location and level have similar small variances and mean directions. In the four cases where enough values are available the Raleigh test shows that when the two types of measurements are pooled, directions are clustered and unimodal. The infilled beds apparently are not too asymmetrical, and it appears that measuring the strike on one side of a trough erosional bottom approximates directions taken on bed traces in the xy plane (the method of Dott and others). F tests on means of these pooled directions among the various locations and levels are, with one exception, all significant, indicating groups of troughs throughout the pit have directions to the northeast, southwest, and northwest.

In comparison, eight out of the twelve bed dip direction samples are highly variable and show no statistically significant clustering, an expected outcome because of the interacting factors controlling their orientation. The four bed dip direction sets with a preferred orientation have mean directions in the southwest and southeast quadrants which are quite different from the pooled strike and swing directions. At location 3, level 2, the mean bed dip direction is 146°, whereas the mean side and swing direction is 38°. These results support a conclusion reached in the first section; a few bed dip directions at a location will not adequately represent the paleocurrents estimated by the strike of trough erosional bottoms or bisectrix azimuth of infilling beds.

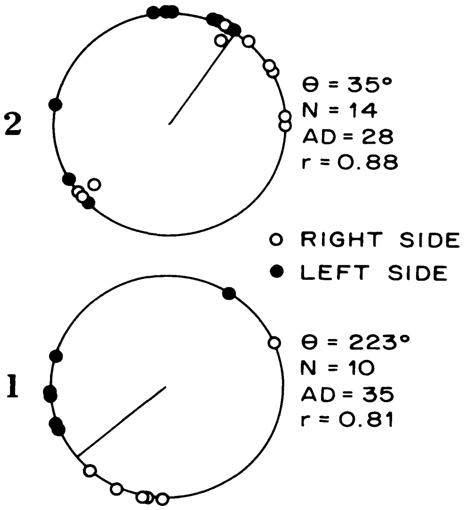

FIG. 5.—Strikes (in the direction of dip of infilling beds) on the sides of troughs at Persimmon Point, Va. Mean strike direction approximately bisects sets of strikes from two different sides, suggesting troughs are symmetrical. Unit 1 is a coarse to pebbly sand and unit 2 is a fine to medium sand.

Second Experimental Design

The objectives of the second sampling program were to determine the validity of bisecting strikes taken on trough sides and to test the method for determination of trough axial azimuth from apparent dips on a two-dimensional transect.

To fulfill these objectives we cleared a section of highwall 3 m long by 2 m high, which constituted the available population. The upper 1 m was predominantly coarse to pebbly sand (unit 1) and the lower 1 m was fine to medium sand (unit 2). We measured all troughs that had a well defined erosional bottom. Erosional bottom dip directions on opposite sides of each trough were converted to strikes with the sense in the direction of trough plunge (fig. 5).

Of 10 troughs measured in unit 2, seven were plunging to the northeast and three to the southwest. Only the northeast plunging troughs are analyzed here. Comparing strikes from each side of the seven troughs shows that the strike directions are statistically different. The troughs are opening to the northeast, as would be expected with a northeast plunge. Equation 1 shows that with plunges from 5° to 15°, side strikes should be corrected 9° to 25° to estimate trough axial plunge direction. This definitely reduces the angular deviation and makes each measurement better converge on the bisector of the two side strikes, taken to be the true trough axial azimuth. Thus, if a plunge can be assumed, it is probably acceptable to measure the strike on a trough erosional side and make the appropriate correction (equation 1).

From the nature of the strike directions it seems reasonable to pool the side strikes and calculate a mean axis direction. For all northeast plunging troughs, the resulting distribution is unimodal with mean direction 35°, and angular dispersion 28. This compares favorably with a trend of 38° for the northeast troughs of the first experimental design. Pooling side strikes is then also probably a justifiable method of obtaining paleocurrent directions. Troughs in unit 1 confirm these conclusions (although their mean direction is 231°, in the opposite quadrant).

Finally, we test the theoretical relationship between apparent dips seen on the trace of a trough-erosional bottom and the obliquity of the section. Apparent dips were recorded from seven separate troughs exposed on the main face. Measurements were taken as far up the trough sides as possible, at a distance of $d = r/2$ to $r/4$. Afterward, the troughs were dissected and trough axial azimuths and plunge were measured. Mean plunge, as already noted, was 7°. The results, plotted in fig. 4, agree remarkably well with the theoretical relationship when $d = r/3$ and confirm a manner of trough azimuth measurement of general use.

CONCLUSIONS

As deduced from geometric considerations, many field studies, and our own field work in Pleistocene marine sands at Persimmon Point, Virginia, measurement of trough orientation, despite its difficulties, is a method of paleocurrent determination superior to measurement of cross-strata dip directions.

Random bed true dip directions measured on the family of coordinate planes cutting a single trough may have a mean direction coincident with trough axial direction, but on all other planes definitely will not. No statistical manipulation of dip directions measured on these oblique planes can correct this error because the amount of correction depends on the bed swing angle, itself highly variable and unknown. Even on the *yz* plane, our field data show that in eight out of 12 trials, five bed dip directions were not clustered.

For quasi-three-dimensional vertical outcrop faces, a single strike measured on the erosional side of a trough (in the direction of dip of infilling beds) can be corrected for the amount of trough plunge to give the trough axial azimuth. If the trough plunge must be assumed, 5–10° is reasonable. But a better estimate of paleocurrent direction is the bisectrix of two strikes, one taken on each side of the trough.

On a perfectly two-dimensional oblique vertical transect of a plunging trough it is still possible to estimate trough axial azimuth by measuring the face azimuth and two apparent dips at equal elevations, one on each side of the trough erosional bottom. It must be assumed that the trough is plunging θ° (shown to be 5° to 10° in this study) and is approximately semi-hemispherical with thickness/width ratio of $\frac{1}{2}$ to $\frac{1}{4}$. These are not too limiting because our data and those of other workers show that randomly oriented vertical transects of trough cross-stratification, whose average thickness/width ratio is $\frac{1}{4}$, should, eight out of 10 times, expose traces of elongate semi-hemispherical scours plunging gently (less than 10°) downstream.

As an example calculation, consider an oblique vertical cut (azimuth = 85°) of a trough whose true axial azimuth is 203°. On this face, and assuming the trough is plunging the average 7°, one should measure apparent dips near the top of the trough of 40° and 36° on the trough left and right erosional sides, respectively. The absolute difference between these angles is 4° which from figure 4 indicates the cut azimuth is $\beta = 28°$ from a perpendicular to the trough axis. Because infilling beds are dipping towards the observer, 28° is *added* to the face azimuth to a give an azimuth perpendicular to the trough axial azimuth of $85° + 28° = 113°$. Therefore, the trough axial azimuth is $113° + 90° = 203°$. Since in many cases it is easier to measure these apparent dips than to measure strikes on trough sides, and since bed dip directions are not accurate paleocurrent indicators this method should have general applicability on vertical faces exposing trough cross-stratification.

REFERENCES CITED

ALLEN, J. R. L., 1963a, The classification of cross-stratified units with notes on their origin: Sedimentology, v. 2, p. 93–114.

———, 1963*b*, Asymmetrical ripple marks and the origin of water-laid cosets of cross-strata: Lpool. Manchr. Geol. Jour., v. 3, pt. 2, p. 187–236.

———, 1968, Current Ripples: Their Relation to Patterns of Water and Sediment Motion: North Holland Pub. Co., Amsterdam, 433 p.

VAN BEEK, J. L., and KOSTER, E. A., 1972, Fluvial and estuarine sediments exposed along the sude moos (The Netherlands): Sedimentology, v. 19, p. 237–256.

BHATTACHARYA, A., 1969, Applicability of cross-beds in determining the paleocurrent direction: Geol. Mining Met. Soc. India, Quart. Jour., v. 41, no. 1, p. 45–49.

COLEMAN, J. M., 1969, Brahmaputra River: channel processes and sedimentation: Sed. Geology, v. 3, p. 129–239.

DOTT, R. H., JR., 1970, Limitations in paleocurrent analysis of trough cross-stratification: Am. Assoc. Pet. Geol. Bull. (abs.), v. 54, no. 5, p. 844.

———, 1973, Paleocurrent analysis of trough cross-stratification: Jour. Sed. Petrology, v. 43, no. 3, p. 779–783.

———, and ROSHARDT, M. A., 1972, Analysis of cross-stratification orientation in the St. Peter Sandstone in southwestern Wisconsin: Geol. Soc. Am. Bull., v. 83, no. 9, p. 2589–2595.

FRAZIER, D. E., and OSANIK, A., 1961, Point-bar deposits, Old River Locksite, Louisiana: Gulf Coast Assoc. of Geol. Soc. Trans., v. 11, p. 121–137.

HAMBLIN, W. K., 1961, Micro-cross-lamination in Upper Keweenawan sediments in northern Michigan: Jour. Sed. Petrology, v. 31, no. 3, p. 390–401.

HARMS, J. C., and FAHNESTOCK, R. K., 1965, Stratification, bedforms, and flow phenomena (with an example from the Rio Grande): *In* G. V. MIDDLETON, ed., Primary sedimentary structures and their hydrodynamic interpretation (Soc. Econ. Paleo. Min., Tulsa, Okla.), Spec. Publ. 12, p. 84–115.

———, MACKENZIE, D. B., and MCCUBBIN, D. G., 1963, Stratification in modern sands of the Red River, Louisiana: Jour. Geol., v. 71, no. 5, p. 566–580.

HIGH, L. R., and PICARD, M. D., 1974, Reliability of cross-stratification types as paleocurrent indicators in fluvial rocks: Jour. Sed. Petrology, v. 44, no. 1, p. 158–168.

LEVINE, JEFFREY, 1978, personal comm.

MCGOWEN, J. H., and GARNER, L. E., 1970, Physiographic features and stratification types of coarse-grained point bars: modern and ancient examples: Sedimentology, v. 14, no. 1–2, p. 77–111.

MECKEL, L. D., 1967, Tabular and trough cross-bedding-comparison of dip azimuth variability: Jour. Sed. Petrology, v. 37, no. 1, p. 80–86.

NIEHOFF, W., 1958, Die Primär gerichteten sedimentstrukturen, insbesondere die schrägschichtung im koblenzquartzit am mittelrhein: Geol. Rund., v. 47, p. 252–321.

PICK, M. C., 1964, The stratigraphy and sedimentary features of the Old Red Sandstone, Portshead coastal section, northeast Somerset: Geologist's Assoc., Lon. Proc., v. 75, pt. 2, p. 199–221.

POTTER, P. E., and OLSEN, J. S., 1954, Variance components of cross-bedding direction in some basal Pennsylvanian sandstones of the eastern interior basin: geological application: Jour. Geol., v. 62, p. 50–73.

RAY, P. K., 1976, Structure and sedimentological history of the overbank deposits of a Mississippi River point bar: Jour. Sed. Petrology, v. 46, no. 4, p. 788–801.

SLINGERLAND, R. L., 1977, Processes, Responses and Resulting Stratigraphic Sequences of Barrier Island Tidal Inlets as Deduced from Assawoman Inlet, Va.: Ph.D. Diss., The Pennsylvania State University, 387 p.

STEWART, J. H., 1961, Origin of cross-strata in fluvial sandstone layers in the Chinle Formation (Upper Triassic) on the Colorado Plateau: U.S. Geol. Surv. PP424-B, p. B127–B129.

WATSON, G. S., and WILLIAMS, E. J., 1956, On the construction of significance tests on the circle and the sphere: Biometrika, vol. 43, pp. 344–352.

WILLIAMS, G. E., 1968, Formation of large-scale trough cross-stratification in a fluvial environment: Jour. Sed. Petrology, v. 38, no. 1, p. 136–140.

———, 1971, Flood deposits of the sand-bed ephemeral streams of central Australia: Sedimentology, v. 17, p. 1–40.

WURSTER, P., 1958, Geometrie and Geologie von Kreutzschichtungskörpern: Geol. Rund., v. 47, p. 322–358.