1971) in areas occasionally experiencing considerable current velocities, as witnessed by small- and large-scale ripple deposits above and below the flaser beds. Flaser bedding normally shows some kind of alternation in the number and thickness of the clay layers in a vertical sense (Terwindt, 1981). This means that flaser beds having only thin clay and thicker sand layers merge vertically into flaser beds with increasingly thick clay lenses and thinner sand layers, and vice versa. Such alternation may be explained by variations in $U_{0.5\ \max}$ as occurs in the neap-spring tide cycle, but it is hard to imagine how such systematic variations can be explained by the unsystematic occurrences of storms.

Thus we think that storm activity cannot explain the wide occurrence of flaser beds, even in channel deposits, over all depths and the remarkable vertical alternations in character in flaser beds. Furthermore, Reineck & Wunderlich (1967) demonstrated with tracers the deposition and preservation of mud layers on tidal flats in the course of a tidal cycle without storm waves.

Similar observations were made by one of the present authors (Terwindt) on an intertidal shoal. During neap tide, with no relevant wave action, a centimetre-thick mud layer was deposited on the highest part of the shoal, subject to rather low current velocities. From neap to spring tide the bed was remodelled into current ripples having mud drapes in the trough when exposed at low water. Sectioning revealed the existence of flaser beds. Towards the top of the spring tide the flaser bedding vanishes and ripple drift cross-laminated sets, without mud drapes are formed. The whole succession was deposited by current action without any appreciable wave effects. Thus we conclude that there is much field evidence against Hawley's alternative mechanism and we are still convinced that flaser bedding in the tidal setting is primarily a bedding type governed by tidal current action.

(*Manuscript received 22 March 1982*)

REPLY

NATHAN HAWLEY*

Department of Atmospheric and Oceanic Sciences, University of Michigan, Ann Arbor, Michigan 48104, U.S.A.

The discussion by Terwindt & Breusers raises several points which need to be addressed. First, I thank them for pointing out the typographical errors in my equations (4) and (5) (Hawley, 1981). The forms given by them are correct and are the ones that were used to calculate the values presented in my table 4. It should also be noted that since equation 2 (my equation 5) is not dimensionally homogeneous, it can only be used if the elevation is in meters and the velocities in m sec^{-1}. In the following comments the equation numbers are those that appear in Terwindt & Breusers' discussion.

Their main objection is the use of equation (2) to calculate values of $U_{0.5}$ above a rippled bed which is at least partly covered by mud. I have no quarrel with the use of equation 1 when the ripples are completely immersed in a layer of heavy fluid (see my Fig. 6d) but this fluid is dispersed at low flow velocities (less than 0.16 m sec^{-1} in the flume), leaving a thin mud layer draped over the rippled sand (Fig. 6e). The question is, what formula can be used to calculate $U_{0.5}$ over an undulating bed of this sort? The formula proposed by Terwindt & Breusers (equation 3) is not applicable since it describes the flow over a hydraulically rough but planar bed, while what we have is a hydraulically smooth (at least initially) rippled bed. Later, as some of the mud is eroded and the underlying sand is exposed, the situation becomes even more complicated since the bed is hydraulically smooth in some places and hydraulically rough in others. As far as I know, there are no formulas which deal with this situation. I have chosen to use equation (2), which was empirically derived from flume measurements made over rippled beds, because it includes both the

*Currently at The Great Lakes Environmental Research Laboratory, NOAA, 2300 Washtenaw Avenue, Ann Arbor, Michigan 48104, U.S.A.

surface and form drags (due to the grain and bed form roughness respectively). As Terwindt & Breusers point out, the diminution of ripple amplitude due to the mud in the troughs may decrease the form drag, but it is also possible that equation (2) will overestimate the surface drag. In any event, since the form drag accounts for the bulk of the total drag (see examples in Simons & Senturk, 1977) it seems to me more realistic to use a formula which accounts for it, rather than use an equation applicable to a plane bed.

I note that Terwindt & Breusers have decreased their value of the shear velocity necessary to initiate erosion. This diminished value ($U_* = 0.0176$ m sec^{-1}) when plugged into equation (2) gives $U_{0.5}$ equal to 0.26 m sec^{-1}. I may have overstated the rarity of peak flow measurements less than 0.6 m sec^{-1}, although their statement (Terwindt & Breusers, 1972)—'The maximum current velocity at 0.5 m above the bottom ($U_{0.5\ max}$) is normally considerably higher than 0.6 m sec^{-1} in the Dutch tidal waters. Then no preservation of mud layers can occur. However at some places values of $U_{0.5\ max} <$ 0.6 m sec^{-1} are occasionally measured'—seems to me to imply that they were not very frequent, but if the mud erodes at velocities of 0.26 m sec^{-1}, then the likelihood of centimetre-thick layers resulting from the accumulation of several thinner layers is much diminished. Only if the total accumulation is much thicker than 10 mm will the basal portion consolidate sufficiently to withstand subsequent current action. In my previous paper I suggested that suspended sediment concentrations of 3 kg m^{-3} were needed to form a mud layer 0.11 m thick. Recent work by Chase (1979) and Hawley (1982) suggests that natural aggregates fall considerably more quickly than Stokes' Law (which was used in the original calculation) predicts. This means that the suspended sediment concentration necessary to produce a 0.11 m thick mud layer is about an order of magnitude less than previously supposed. Such concentrations are not rare in tidal settings and could account for the formation of flaser beds in these areas, eliminating (or at least reducing) the need for some mechanism (such as storm action) which produces higher concentrations. I believe that my original suggestion—that storm activity is the main cause of flaser beds in tidal areas—is incorrect and that my alternative mechanism—that they form as the result of basal consolidation of thick deposits formed in a single slack water period—is more likely to be the main cause of flaser beds.

REFERENCES

ALLEN, G.P., SALOMON, J.C., BASSOULLET, P., DU PENHOAT, Y & DE GRANDPRÉ, C. (1980) Effects of tides on mixing and suspended sediment transport in macrotidal estuaries. *Sedim. Geol.* **26**, 69–90.

CHASE, R.R.P. (1979) Settling behaviour of natural aquatic particles. *Limnol. Oceangr.* **24**, 417–426.

DELFT HYDRAULICS LABORATORY (1962) *Report on the siltation of Demarara Bar channel and coastal erosion in British Guiana.* Delft. 237 pp.

HAWLEY, N. (1981) Flume experiments on the origin of flaser bedding. *Sedimentology*, **28**, 699–712.

HAWLEY, N. (1982) Settling velocity distributions of natural aggregates. *J. geophys. Res.* (in press).

KRONE, R.B. (1962) Flume studies of the transport of sediment in estuarial shoaling processes. *Bull. Hydr. Eng. Lab. Un. Calif. Techn.* **19**, 62 pp.

KRONE, R.B. (1976) Engineering interest in the benthic boundary layer. In: *The Benthic Boundary Layer* (Ed. by I. N. McCave), pp. 143–156. Plenum Press, New York.

METHA, A.J. & PARTHENIADES, E. (1975) An investigation of the depositional properties of flocculated fine sediments. *J. Hydraul. Res.* **13**, 361–382.

MIGNIOT, C. (1968) Etude des propriétés physiques de differents sediments trés fins et de leur comportement sous des actions hydrodynamiques. *Houille blanche,* **23**, 591–620.

POSTMA, H. (1967) Sediment transport and sedimentation in the estuarine environment. In: *Estuaries* (Ed by G. H. Lauff), pp. 158–179. American Association for the Advancement of Sciences, Washington, D.C.

REINECK, H.E. & WUNDERLICH, F. (1967) Zeitmessungen an Gezeitenschichten. *Natur Mus., Frankf.* **97**, 193–197.

RICHARDSON, E.V. & SIMONS, D.B. (1967) Resistance to flow in alluvial channels. *Proc. 12th Congr. int. Ass. Hydr. Res.* **1**, 141–150.

SIMONS, D.B. & SENTURK, F. (1977) *Sediment Transport Technology*, Water Resources Publication, Ft Collins, Co., U.S.A., 807 pp.

TERWINDT, J.H.J. (1971) Lithofacies of inshore estuarine and tidal inlet deposits. *Geologie Mijnb*, **50**, 515–526.

TERWINDT, J.H.J. (1977) Deposition, transportation and erosion of mud. *Proc. Symp. Interactions between sediments and Water* (Ed by H. L. Golterman), pp. 19–24. Junk, the Hague.

TERWINDT, J.H.J. (1981) Origin and sequences of sedimentary structures in inshore mesotidal deposits of the North Sea. In: *Holocene Marine Sedimentation in the North Sea Basin* (Ed by S.-D. Nio, R.T.E. Schüttenhelm and T.C.E. van Weering). *Spec. Publs int. Ass. Sediment.* **5**, 4–26. Blackwell Scientific Publications, Oxford.

TERWINDT, J.H.J. & BREUSERS, H.N.C. (1972) Experiments on the origin of flaser, lenticular and sand-clay alternating bedding. *Sedimentology,* **19**, 85–98.

(*Manuscript received 22 March 1982*)