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Experiments on Rapid Deposition of Sand from High-velocity Flows

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Article abstract

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Much of the coarser, structureles slower most parts of thick turbidites might have been emplaced by processes not unlike those described here. Our results suggest that the entire turbidity current need not be of extremely high density for an initial deposit to be formed rapidly from extremely high near-bed sediment concentrations.

Experiments on Rapid Deposition of Sand from High-velocity Flows

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SUMMARY

Observations of sand transport and rapid deposition by strong sand-laden surges in an open channel, by means of high-speed motion pictures, revealed that the dominant effect is a process by which a laminar sheared layer, with sand concentrations approaching the threshold for immobilization by grain interlocking, develops as suspended sand becomes concentrated near the base of the flow. The laminar sheared layer climbs vertically with time as sediment is progressively immobilized at the base of the layer and added at the top from the overlying turbulent flow. The mobility of the laminar sheared layer is probably enhanced by continuous upward flow of interstitial water that is trapped within the layer as the layer accumulates. As the flow weakens and the concentration of suspended sand in the flow decreases, the laminar sheared layer thins and/or becomes immobilized, giving way to the familiar weak traction transport on a well-defined immobile sand bed. Particles reside in the laminar sheared layer only briefly, and move only a short distance before immobilization; the laminar sheared layers seem not to share essential features with traction carpets.

Much of the coarser, structureless lowermost parts of thick turbidites might have been emplaced by processes not unlike those described here. Our results suggest that the entire turbidity current need not be of extremely high density for an initial deposit to be formed rapidly from extremely high near-bed sediment concentrations.

RÉSUMÉ

Des observations réalisées à l'aide de caméras à hautes vitesses sur le transport et la sédimentation rapide provoqués par de forts courants déferlants et à fortes charges de sables en écoulement chenalisé, ont montré que l'effet dominant est le développement, à la base de la coulée, d'une couche laminaire cisaillée ayant une concentration de particules à la limite du seuil de l'immobilisation par congestion des particules. Avec le temps, cette couche cisaillée se déplace verticalement vers le haut, au fur et à mesure que les sédiments s'immobilisent à la base de la couche et que d'autres s'y ajoutent à partir de la couche turbulente du dessus. L'expurgation incessante de l'eau interstitielle par le tassement des sédiments du fond augmente probablement la mobilité de la couche laminaire cisaillée. Lorsque le courant s'affaiblit et que la concentration du sable en suspension diminue, la couche laminaire cisaillée s'amincit et/ou s'immobilise et est remplacée par une couche de transport plus faible caractérisée par la traction sur un fond sableux immobile bien défini. Les particules ne font que transiter brièvement dans la couche laminaire cisaillée et ne se déplacent que sur de faibles distances avant de s'immobiliser ; les couches laminaires cisaillées et les couches de traction ne semblent partager aucune caractéristiques communes essentielles.

Il est possible qu'une bonne portion des couches basales non-structurées des turbidites aient été mises en place par un processus de ce genre. Les résultats de nos études montrent qu'il n'est pas nécessaire que la charge sédimentaire de l'ensemble d'un courant de turbidité soit d'une très grande densité pour entraîner rapidement la formation d'un premier dépôt à partir d'une couche à forte densité longeant le fond.

INTRODUCTION

Understanding of the depositional processes associated with large-scale turbidity currents carrying high concentrations of coarse sediment has been controversial. Because of the great difficulty of observing the depositional surface beneath large-scale sediment gravity flows either in the field or in the laboratory, most of our understanding of these deposits is based on deduction. The same is true for the broader class of deposits that result from rapid deposition from sediment-charged and overloaded unidirectional flows in which subsequent traction does little to modify the fabric or structure of the deposit; for example, washover deposits from sand-charged surges flowing across barriers during major storms (Leatherman, 1977; Schwartz, 1982). The motivation for our study was the idea (*cf.* Middleton, 1967, 1993) that deposition of the unstratified lowermost parts of thick and coarse-grained turbidites results from extremely rapid deposition from concentrated sediment-water mixtures as suspended sediment accumulates near the base of the flow.

In a phenomenon as complex as unsteady and nonuniform two-phase turbulent channel flow, direct observation of flow and deposition, even if only qualitative, is an essential guide to theory and deduction. Direct observations of sediment deposition from experimental small-scale turbidity currents have had a long history (see review by Middleton, 1993), but they have been dishearteningly few. The usefulness of such experiments in understanding local depositional processes in giant flows carrying coarse sediment is limited by the flow strengths and rates of deposition practicably attainable in a laboratory turbidity current. We attempted a different approach: mimic local near-bed processes rather than attempt to reproduce the entire flow. We arranged small-scale open-channel surges whose velocities, near-bed sediment concentrations, and deposition rates were broadly representative of near-bed flow and deposition in much larger turbidity currents (although admittedly we are only narrowing, rather than closing, the gap between experiment and nature).

We took as our starting point the experiments on turbidity-current deposition by Middleton (1967) and attempted to take such experiments a large step further, toward larger scale and more powerful flows, greater rates of deposition, and thicker deposits. Since the time of our experiments (Vrolijk, 1981), Postma *et al.* (1988) have very profitably conducted somewhat similar experiments, although using actual turbidity currents rather than open-channel surges, with somewhat different objectives.

Our assumption is that the essential aspects of the deposit of a large-scale turbidity current as seen at a point along the flow path are governed to a great extent by flow speed, near-bed concentration of sediment in the flow, and rate of deposition. These characteristics, when viewed as proximate rather than ultimate, can be reproduced in at least a qualitative way in a manageably small-scale sediment-charged surge in an open channel. It is much less demanding to attain given values of flow strength, sediment concentration, and deposition rate in an open-channel surge than in a turbidity current, basically because the driving force can be so much greater, other factors (scale, sediment concentration, slope) being the same. We make no pretence that conditions at the bed are identically reproduced, and of course we sacrifice understanding of the overall or ultimate controls on deposition, but useful insights can be gained even if conditions are only crudely similar.

EXPERIMENTS

The experiments were made in an apparatus consisting of a horizontal open channel, about 10 m long and with a 0.6 m x 0.6 m cross section, leading from a vertical reservoir tank 2.5 m in height, also with a 0.6 m x 0.6 m cross section (Fig. 1). The reservoir tank opened directly into the channel by way of a watertight gate, hinged above, for sudden release of a large volume of sediment-water mixture into the channel to form a strong surge whose passage down the channel resulted in deposition of a sand layer. The channel emptied *via* an overfall into a large collection box at the downstream end to catch all the water and the remaining sediment.

To generate a surge, the reservoir tank was filled to the desired level with water, and a hopper mounted above the tank was filled with the mass of sediment needed to produce the desired volume concentration in the tank. The charge of sediment, thoroughly homogenized from the previous run, was placed carefully in the hopper so as to minimize spatial segregation by particle size. At the start of a run the contents of the hopper were discharged into the reservoir during a brief period lasting a few seconds, and the gate at the head of the channel was opened almost immediately afterward, just before any of the sand reached the floor of the reservoir tank. Lack of a sufficiently powerful pump and/or stirring device precluded maintenance of a suspension known to be uniform in the reservoir tank prior to a run, but our technique seemed satisfactory: little or no deposit was left on the floor of the reservoir tank, and the depth-averaged sediment concentration in the flow at a viewing station about 5 m down the channel showed no signs of inheritance of non-uniformity from the upstream reservoir tank.

Flow velocity was set in a very approximate way by adjusting the height of the column of water in the reservoir tank: a column of water 2.4 m deep produced a maximum velocity of approximately 3.5 $m \cdot s^{-1}$, and a column approximately 1.7 m deep produced a maximum velocity of about 2.5 $m \cdot s^{-1}$. Two initial volume concentrations were used: 40% (in one case, 50%) and 20%. These were set by adjusting the mass of sediment in the hopper.

The most valuable data came from high-speed motion pictures of sediment transport and deposition at a viewing station 4.85 m downstream of the reservoir tank. The viewing arrangement consisted of two parts (Fig. 1B): 1) a thin, hollow, air-filled, transparent vertical hydrofoil-like flow splitter, about half a metre long in the streamwise direction, placed along the centerline of the flow, with one surface planar and the other concavo-convex, and with knife-edge leading and trailing edges; and 2) an air-filled viewing tunnel with its base coincident with the channel floor and with streamlined upper surface, extending across the flow from a transparent window in the channel sidewall to the medial bulge of the flow divider. The rectangular viewing window extended for 12 cm in the flow direction and 10 cm vertically upward from a level slightly above the floor of the channel. Because the newly developing boundary layer on the planar surface of the flow divider was thin, the flow as seen through the viewing tunnel and flow divider was fairly representative of the deep interior of the flow just upstream of the viewing arrangement. (That was the rationale for such a viewing arrangement in the first place.) A strong beam of light was directed downward at an angle into the flow divider to illuminate the transparent planar wall through which the flow was photographed. Preliminary tests showed that distortion and diversion of flow caused by the presence of the viewing tunnel on the side of the channel opposite to the flow being photographed were not great.

Ten of the 12 runs were photographed at the viewing station with a 16 mm Bolex motion-picture camera at 64 frames per second, and two runs (C-3 and C-4) were photographed with a 16 mm Phototec IV motion-picture camera at 500 frames per second. An additional motion-picture

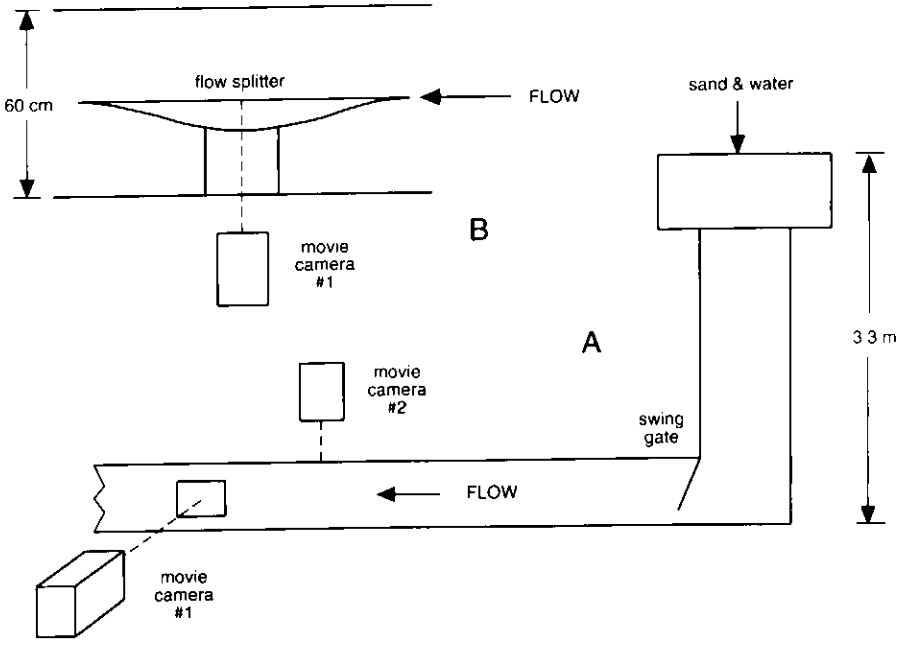

Figure 1 *Diagram of the experimental apparatus.* (**A**) *Overall side view.* (**B**) *Detail of viewing station, from above.*

camera just upstream of the flow divider recorded 1) flow depth, measured on a grid painted on the opposite channel wall, and 2) flow velocity, measured crudely by timing the passage of styrofoam balls floating on the free surface of the surge between two reference lines on the wall. The motion pictures captured the phenomena of flow, transport and deposition well, but still pictures from individual frames of the motion pictures, which do not distinguish between sediment in motion and sediment at rest, are uninformative and so are not presented here.

About an hour after each run, three sediment cores 5 cm in diameter and aligned across the flow 5-10 cm apart were taken with rigid polyethylene tubes at each of two sections, one just upstream of the viewing station and the other 2.5 m downstream. These cores were cut into transverse slices 5 mm thick, and the particle-size distribution of the sediment in each slice was measured by conventional sieving techniques.

RESULTS

General Aspects of Flow and Deposition

Twelve runs (Table 1) were made with three sizes of moderately sorted sand, with median size 0.25 mm, 0.44 mm, and 0.54 mm. For each sand size, two different average volume concentrations were used: high (~40%) and low (~20%). For each volume concentration, two different values of initial water level in the reservoir tank were used, to produce two ranges of flow velocity in the channel: high (~3.5 $m \cdot s^{-1}$) and low (~2.5 $m \cdot s^{-1}$).

The flow in each run could best be described as a surge, with a highly turbulent head with a steep front, followed by a body and a tail. The surge attenuated little over the length of the channel, and the thickness of deposited sediment was nearly uniform along the channel. The frothy, roiling head eroded the preexisting bed, marked by a thin surface layer of blackened sand, by as much as 2 cm in no more than a few tenths of a second. After passage of the head, flow depth decreased rapidly at first and then more slowly from a maximum of 10-20 cm. Flow velocity at the viewing station decreased slowly as well, although we could observe this only qualitatively, because the velocity measurements with the styrofoam balls could be made only immediately after passage of the head. The surges were strongly turbulent, in both the head and the following body.

In all but one of the runs, there was net aggradation of the bed during passage of the surge (Table 1). The exception was Run C-1, for which the combination of sediment size, sediment concentration, and flow velocity was such that there was no net deposition. In most of the runs, deposition began soon after passage of the head. The surges took about 3 seconds to pass the viewing station, and in the Series A and B runs the bulk of the deposit at that station was emplaced within 1-2 seconds. Average rates of bed aggradation in those runs were thus of the order of a few centimetres per second. This estimate is not applicable to the Series C runs, in which the deposit formed and became immobilized in a very short time near the end of the surge (see later subsection). In most runs the greater part of the sediment charge from the hopper was deposited in the channel rather than passing with the water into the catch basin.

Of the three imposed variables (sand size, sand concentration, and reservoir head, which in turn acts to set flow velocity in the channel), differences in sand size clearly had the greatest effect on the phenomena of transport and deposition: these varied in important ways (see following subsections) between the coarser sands (Series A and B) and the finer sand (Series C) but not greatly as a function of either sand concentration or flow velocity. Of course, we presumably would have observed greater differences if we had used a wider range of concentrations and ve-

Table 1 Experimental data.

Run no.	Median sediment size (mm)	Sediment concentration (vol. %)	Water temperature (°C)	Reservoir tank head (m)	Greatest surface velocity (m $^{-1}$)†	Greatest flow depth (m)[1]	Deposit thickness (mm)[1]	Grading[2]
A-1	0.44	20	26	2.4	*	**	25	
A-2	0.44	20	25	1.7	*	**	26	IN
A-3	0.44	40	23	2.4	3.2	0.17	33	IN
A-4	0.44	40	23	2.4	3.2	0.17	33	IN
B-1	0.54	40	26	1.7	2.8	0.11	38	N
B-3	0.54	20	25	2.4	3.7	0.20	39	IN
B-4	0.54	20	30	1.7	*	0.16	26	IN
B-5	0.54	40	34	2.4	3.7	0.18	46	U
C-1	0.25	20	25	2.4	3.7	0.18	†	—
C-2	0.25	20	24	1.7	2.8	0.15	18	I
C-3	0.25	50	32	2.4	3.2	0.19	51	U
C-4	0.25	40	30	1.7	2.6	0.09	31	IN

* No measurement possible because no styrofoam balls passed the field of view.

** Not measured.

† There was net erosion of the bed at the viewing station.

[1] Measured at viewing station.

[2] I, inversely graded; N, normally graded; IN, inversely to normally graded; U, ungraded.

locities.

As might have been expected, deposit thickness at the viewing station depended on initial sediment concentration: for both the coarser sands (0.44 mm and 0.54 mm) and the finer sand (0.25 mm) the higher concentrations produced the thicker deposits (Fig. 2). The effect of flow velocity on deposit thickness is less clear but was not as strong as that of concentration (Fig. 2).

Processes of Deposition

We observed two distinctive depositional processes. The first, minor in these experiments, is the familiar particle-by-particle deposition onto an existing sediment bed, with or without subsequent traction transport. This style of deposition was associated only with the very end of each of the runs, when the concentration of residual sediment passing with the tail of the surge was small and flow velocity had fallen below the transport threshold, and it accounted for only a tiny fraction of the resulting deposit.

The bulk of the deposit in each of the runs resulted from upward freezing of a well-defined high-concentration, nonturbulent, sheared layer intermediate between the underlying immobile bed and the overlying turbulent flow. In the following we refer to this layer as the *laminar sheared layer.* We appreciate the desirability of avoiding unneeded proliferation of terminology in sedimentology, but we feel the need for a suitable purely descriptive term, unburdened by interpretation or deduction, and none of the terms that exist in the literature seem entirely applicable or appropriate. A more complete description of the laminar sheared layer might be "a collapsing, sheared, high-concentration, nonturbulent, near-bed layer."

The laminar sheared layer was continuously immobilized, from its base upward, to become part of the permanent deposit. Until near the end of a run, it was continuously replenished by downward transfer of sediment from the overlying turbulent flow. In all cases its thickness was at least an order of magnitude greater than the particle diameter. Whether it should be considered part of the flow or part of the bed is not germane to its significance for the resulting deposit. In the descriptions and discussion below we concentrate on the nature of deposition from the laminar sheared layer, because that carries by far the most important implications for deposition by turbidity currents and other large-scale overloaded flows.

Deposition in Series A and B Runs (Coarser Sand)

Early in the depositional phase of each of the Series A and B runs there was rapid development of a thick (up to 2 cm) laminar sheared layer, which was susceptible to irregular "bowl of jelly" shaking or oscillation in addition to general shearing, seemingly in response to passage of strong turbulent eddies in the overlying flow (Fig. 3). The sheared layer maintained coherence during such shaking; there was no mixing of sediment on either local scales or larger scales.

As time went on, the laminar sheared layer thinned slowly and irregularly to less than a centimetre as it "climbed" by immobilization at its base and addition of new sediment from above. It was by no means a steady and uniform phenomenon: addition of new sediment from above tended to occur in pulses, as large eddies with higher-than-average sand concentration swept along the top of the layer. During its existence the layer was often briefly and locally thinned by impingement of strong eddies from above, and in some such instances it became largely or even entirely collapsed along most or all of the 12 cm field of view, between pulses of sediment addition. Despite these disturbances, however, the laminar sheared layer could clearly be seen in the motion pictures to maintain its identity as it developed.

Near the end of deposition from the laminar sheared layer, there was a tendency for transitory internal waves to develop (*cf.*, Middleton, 1967). These internal waves affected the whole of the layer, as well as the immediately overlying flow, which, by this stage, carried a greatly reduced concentration of suspended sand. These waves had amplitudes of about a centimetre and spacings of several centimetres, and propagated downstream at a speed slower than that of the overlying flow. They existed for only a fraction of a second at most and were not nearly as prominent as the waves that developed in the final stages of the Series C runs (see following subsection).

The upper boundary of the laminar sheared layer was diffuse and gradual, over a vertical distance of a few millimetres, but the layer was distinctive and easily perceptible in the motion pictures by virtue of absence of turbulence (except for disturbances occasioned by passage of turbulent eddies in the overlying flow), higher sand concentration, and much slower velocities than in the flow above. Owing to the rapidity of climb of the laminar sheared layer, particles remained in the layer for only an extremely short time: a fraction of a second. De-

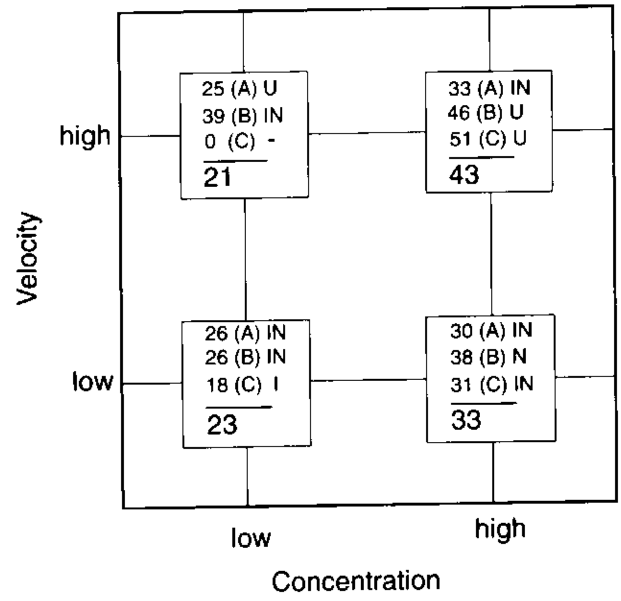

Figure 2 *Deposit thickness (from Table 1), in millimeters, at the viewing station as a function of flow velocity and sediment concentration. Letters A, B, and C refer to run series (Table 1). The values below the horizontal bars are average deposit thickness for each of the four groups of runs shown. Nature of vertical grading is also given (IN, inversely to normally graded; I, inversely graded; N, normally graded; U, approximately ungraded).*

spite the shearing, they moved only a short distance — no more than 10 to 20 particle diameters — in that time as the layer climbed.

Although we could not observe it directly from the films, we assume that sediment is added to the laminar sheared layer from above faster than the excess interstitial water that is thereby being trapped can escape upward. This must enhance the mobility of the laminar sheared layer. The basal immobilization of the laminar sheared layer probably results from upward dewatering until the packing of particles becomes sufficient to resist the shear stress exerted by the overlying flow (although still loose enough to be susceptible to occasional shaking after immobilization).

Deposition in Series C Runs (Finer Sand)

The style of deposition from the laminar sheared layer in the runs with the finer sand (Series C, 0.25 mm) was rather different from that in the coarser sands: the layer was thicker, and remained thick even after the overlying flow had become almost clear of suspended sand.

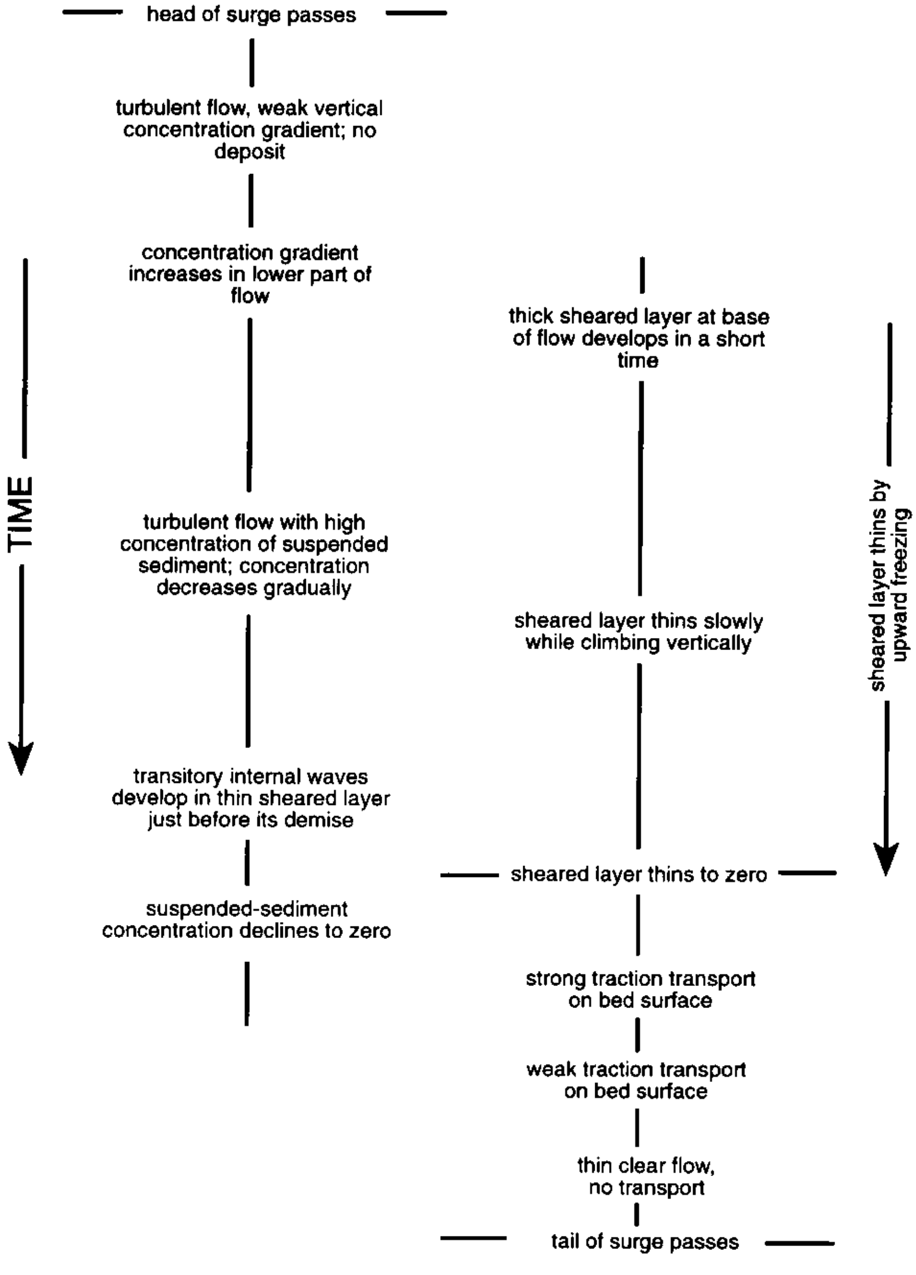

Figure 3 *Schematic time history of flow, sediment transport, and deposition in the Series A and B runs, with time running vertically downward along the two columns. The left column shows the evolution of the flow, and the right column shows the evolution of the sediment bed. The timing of the various stages is shown only approximately.*

Figure 4 (compare with Fig. 3) and this paragraph is our attempt to capture the more varied time history of the various processes observed in the Series C runs. The vertical gradient of suspended-sediment concentration was weak immediately after passage of the head but increased with time until the concentration in the upper part of the flow was small. By this stage, at the intermediate levels in the flow the concentration gradient was strong, and a nonturbulent sheared layer with a sediment concentration only slightly less than the threshold for grain interlocking developed at the base of the flow and thickened rapidly upward. As the concentration gradient in the flow continued to be compressed into the intermediate levels, turbulence both in the lower, high-concentration part of the flow and in the intermediate, high-gradient part of the flow was damped and a well-defined interface developed between an almost clear flow above and a laminar sheared layer below. At this point, in contrast to the Series A and B runs, the laminar sheared layer not only was thick but also extended from the immobile bed below to a clear turbulent flow above. While the laminar sheared layer continued to be immobilized upward from its base, prominent and distinctive internal waves developed within it. The amplitude of the waves (1-2 cm) was greatest at the upper boundary of the layer and decreased downward into the layer (and presumably upward into the clear flow, although we had no way of observing that). They travelled downstream at speeds noticeably less than that of the flow, and they were clearly independent of the rather irregular waves on the free surface of the flow above. The waves died out concurrently with thinning of the laminar sheared layer by basal immobilization, until shearing ceased entirely and an immobile bed was established beneath the clear flow. The event ended with weak traction transport on the bed surface as the tail of the surge passed.

Only in Run C-3 was this complete sequence observed: in Run C-1 the particular combination of sand size, initial concentration, and reservoir head resulted in no deposit being left at the viewing station, and in Runs C-2 and C-4 the combination was such that the deposit was thinner and no deposit was formed before an interface developed between the laminar sheared layer and the almost clear overlying flow.

We remind the reader that this entire varied sequence of events took place in an interval of no more than a few seconds; only by means of high-speed cinematography of the flow interior could it be apprehended.

Grading

The measurements of particle size distributions in the cores taken after the runs reveal clear but varied patterns of vertical grading (Fig. 5). Of the 11 depositional runs, six showed inverse grading in the lower part of the deposit and normal grading in the upper part, three showed almost no grading, one was normally graded, and one was inversely graded (Fig. 2, Table 1). Despite the clear trends in Figure 5, however, we are unable to correlate the observed grading with sand size, suspended-sediment concentration, or flow velocity, and because we made no repeat runs, we do not know whether the results on grading are reproducible.

In general, vertical size grading can be produced by either or both of two effects: temporal variations in sediment supply from upstream, or local vertical segregation of sediment already "deposited" (in the sense of already having been delivered to a local area above the substrate) but not yet permanently immobilized. For two reasons noted below, it is clear that the grading observed in our experiments must have been the consequence of certain unknown effects of fractionation either during mixing of sand and water in the reservoir tank or during suspension transport in the reach of channel upstream of the viewing station (perhaps in a way similar to that proposed for the origin of inverse grading in turbidites by Hand, 1997) rather than of local effects of fractionation within the sheared layer. 1) In the Series A and B runs, the sand particles were sufficiently large relative to the resolution of the motion pictures that the positions of individual sand grains could be followed between the time they became part of the laminar sheared layer and the time they came permanently to rest as the layer was immobilized. Vertical movement of particles while in the laminar sheared layer was minor, as might be expected in view of their observed short mean free paths and brief residence times in the layer. 2) The vertical extent of grading produced by processes within the laminar sheared layer could have been no greater than the thickness of the layer itself, whereas the observed grading included the entire thickness of the deposit produced by climb of the relatively thin laminar sheared layer.

DISCUSSION

The reader should attach less significance to the particular details of time history of sediment transport and deposition reported in these experiments than to the phenomenon of deposition from laminar sheared layers itself, because such details are an artifact of how the flows were created or arranged. If we had been able to maintain the flow longer with a continuing but lesser supply of suspended sediment, we probably would have observed a less abrupt cessation of sheared-layer deposition, a longer transition to traction transport, and more protracted traction transport during slow aggradation of the bed (as is commonly thought to be the case in large turbidity currents).

Here we address three questions that have arisen in our minds from the results of the experiments.

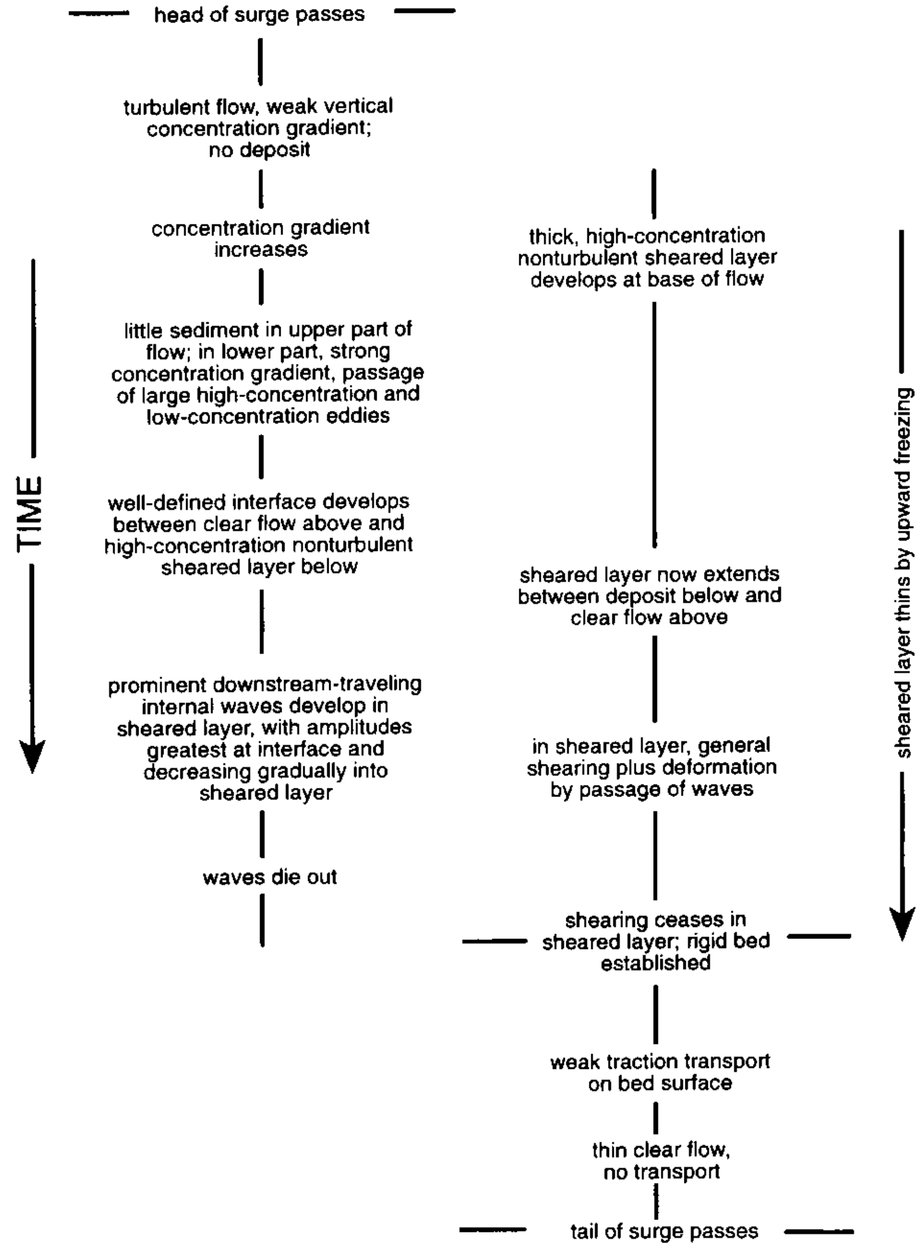

Figure 4 *Schematic time history of flow, sediment transport, and deposition in Run C-3 (0.25 mm sand, high concentration, high velocity), with time running vertically downward along the two columns. The left column shows the evolution of the flow, and the right column shows the evolution of the sediment bed. The timing of the various stages is shown only approximately.*

1) What is the place of deposition from the sheared layers we observed in the experiments in the overall range of processes of sand transport and deposition? We attempt to address that question by means of a qualitative and admittedly rather oversimplified graph of flow strength at the bed *versus* rate of supply of sediment to the bed from suspension (Fig. 6), omitting the effect of sediment size, which in fact is certainly not negligible. Figure 6 shows our experimental conditions as well as those of Arnott and Hand (1989), designed to simulate the deposition of sands of the massive "A" division in turbidites but with rates of deposition an order of magnitude less than in our runs, and those of Postma *et al.* (1988), at shear rates higher than ours.

Sheared-layer deposition, in one or another manifestation, seems likely to operate whenever both flow strength and supply of sand from suspension are high, although we decline to speculate about the effects we would have observed if we could have increased both variables even further. The processes that act when the values of both variables are smaller are better understood, and need no comment here. We are uncertain, however, about what might have been observed if flow strength had been even greater but rate of deposition less: something akin to a traction carpet?

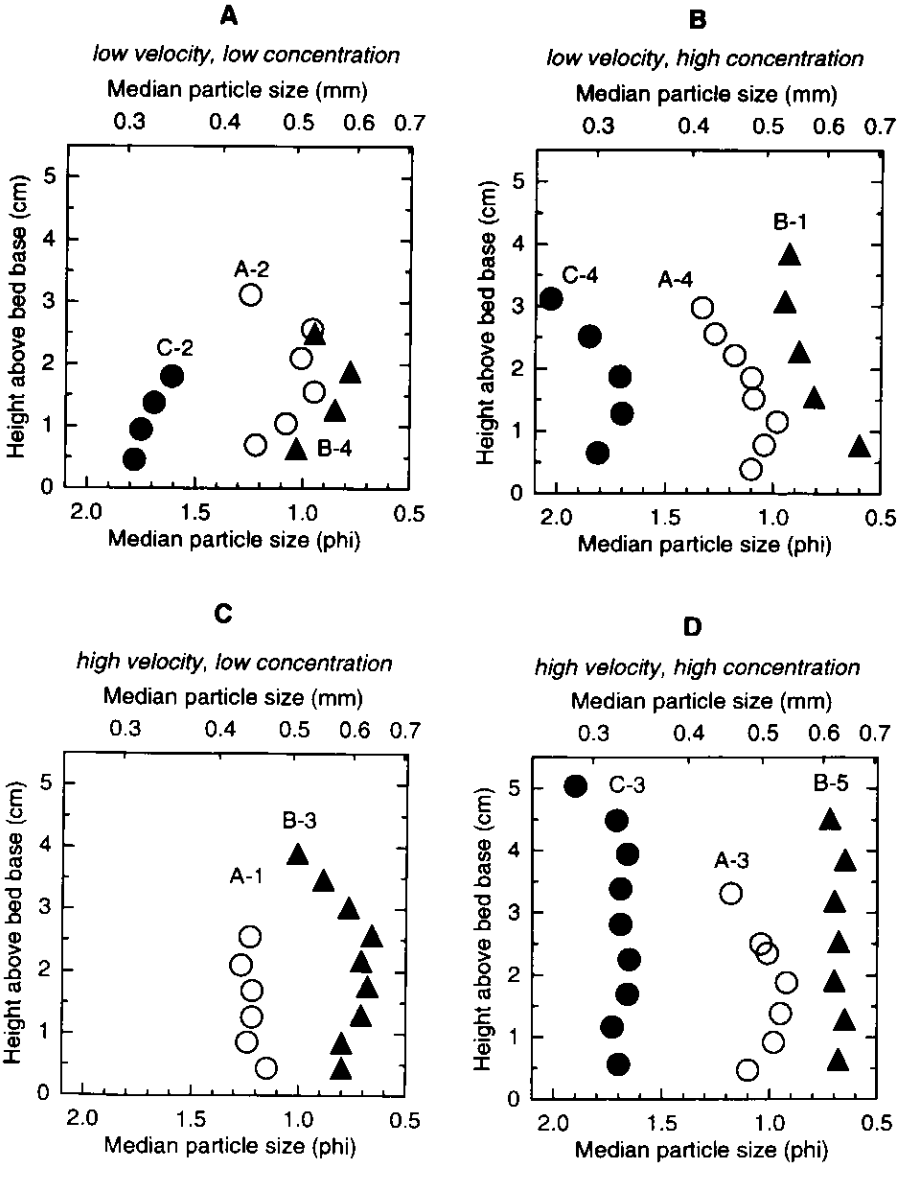

Figure 5 *Vertical grading of sediment size produced in the runs: plots of median particle size versus height above bed base for each of the four combinations of flow velocity and sediment concentration.*

The dashed arrow in Figure 6 shows in a very crude way the time history of processes during one of the runs: sheared-layer deposition gave way to the more familiar fallout with traction, and then finally to clear residual flow over an immobile bed. We note, however, that the rate at which such a parametric curve is traced is strongly uneven: in the context of the Series A and B runs, for example, the sheared layer thinned slowly for a relatively long time but then disappeared abruptly to give way to weak traction.

2) To what extent are our experiments relevant to large-scale natural flows like turbidity currents? In other words, is sheared-layer deposition described on a small scale here important on much larger natural scales?

Deduction has proven dangerous many times over in fields as complex as transport and deposition of sediment by turbulent flows, but we suggest that sheared-layer deposition is indeed likely to be important, inasmuch as time, travel distance, and sediment in suspension are available for development of basal concentrations approaching the upper limit for shearing unimpeded by particle interlocking, and the values of basal shear stress in our runs must lie within the range of many natural turbidity currents. Although we can offer no more than deductive support, it is possible that much of the coarser, structureless lowermost parts of thick sandy turbidites were emplaced by processes similar to those described here, although in many, if not most, cases presumably under the largely unexplored effects of even stronger shearing. We ask only that readers keep such a possibility in mind when examining or interpreting such deposits. Our results add weight to the idea that the entire turbidity current need not be of extremely high density in order for an initial deposit to be formed rapidly from extremely high near-bed concentrations.

The question, which of course we cannot answer from our experiments, remains: how would the depositional processes have differed if the shear at the base of the flow had been much greater during sheared-layer deposition? We did not measure either deceleration or water-surface slope in the experiments, so we can offer only the crudest estimate of bed shear stress for comparison with estimates, from the literature, of bed shear stresses beneath large-scale turbidity currents. If the effects of suspended sediment and flow deceleration are neglected, a flow 0.2 m deep with a surface velocity of 3.5 $m \cdot s^{-1}$ and a bed with sand-grain roughness (values representative of the Series A and B runs) would have a bed shear stress of a few tens of newtons per square metre. This is likely to be well within the range of many large-scale natural turbidity currents that deposit thick sand beds, although it is less than half the values of bed shear stress attained by Postma *et al.* (1988) in their revealing experiments on transport and deposition of sand-gravel mixtures by laboratory turbidity currents.

In our experiments, the rate of sediment loss (percentage extraction per unit distance) was very high, much higher than in natural turbidity currents. That in itself does not automatically make our experiments unrepresentative of deposition by turbidity currents, however, because the reservoir of sediment in a unit vertical column through a turbidity current is so much larger. So even a more modest degree of overloading might produce the same rate of deposition as in our experiments.

(3 To what extent are the laminar sheared layers described here related to traction carpets?

A multitude of terms, based largely upon deductive interpretation, have been proposed over the years to describe phenomena and processes near the beds of large turbidity currents carrying high concentrations of suspended sediment (see Middleton 1970 for a still-relevant review). For example, since its introduction by Dzulynski and Sanders (1962) the concept of the traction carpet has commonly been invoked or discussed in various ways as significant in near-bed transport and deposition of sediment in powerful turbidity currents; for more recent considerations on traction carpets, see Lowe (1982), Hiscott (1994, 1995), and Sohn (1995, 1997). Reconciling the phenomena of transport and deposition observed in our study with the various such terms, and the phenomena they purport to describe, is not a straightforward matter. In part this is because to a great extent the focus has been on steady processes, whereas the laminar sheared layers we observed are clearly short-lived. A "snapshot" of flow and sediment movement near the bed in our Series A and B runs would show a well-defined layer, with a thickness of up to a few centimetres, undergoing shear. Such a snapshot might call to mind a traction carpet. In reality, however, the layer was at most times in the process of rapid collapse, so that it is difficult to make a case that such effects as bed-normal dispersive stress and vertical particle segregation, usually associated with such layers, were of more than negligible importance.

We had no way of measuring or estimating the importance of intergranular dispersive forces in the laminar sheared layer, but the individual moving grains in the sheared layer were clearly distinguishable in the films, and the overwhelming impression is that relative velocities of immediately neighboring particles were small. Even if dispersive stresses were not negligible, their magnitude and their duration of action upon a given volume of sediment-water mixture in the laminar sheared layer were insufficient to cause noticeable vertical segregation of particles; as noted above in the discussion of vertical size grading, motions of particles normal to the planes of shear were minimal. Moreover, the thickness of the observed laminar sheared layers was almost certainly governed not only by the magnitude of the shearing stresses exerted by the overlying turbulent suspension but

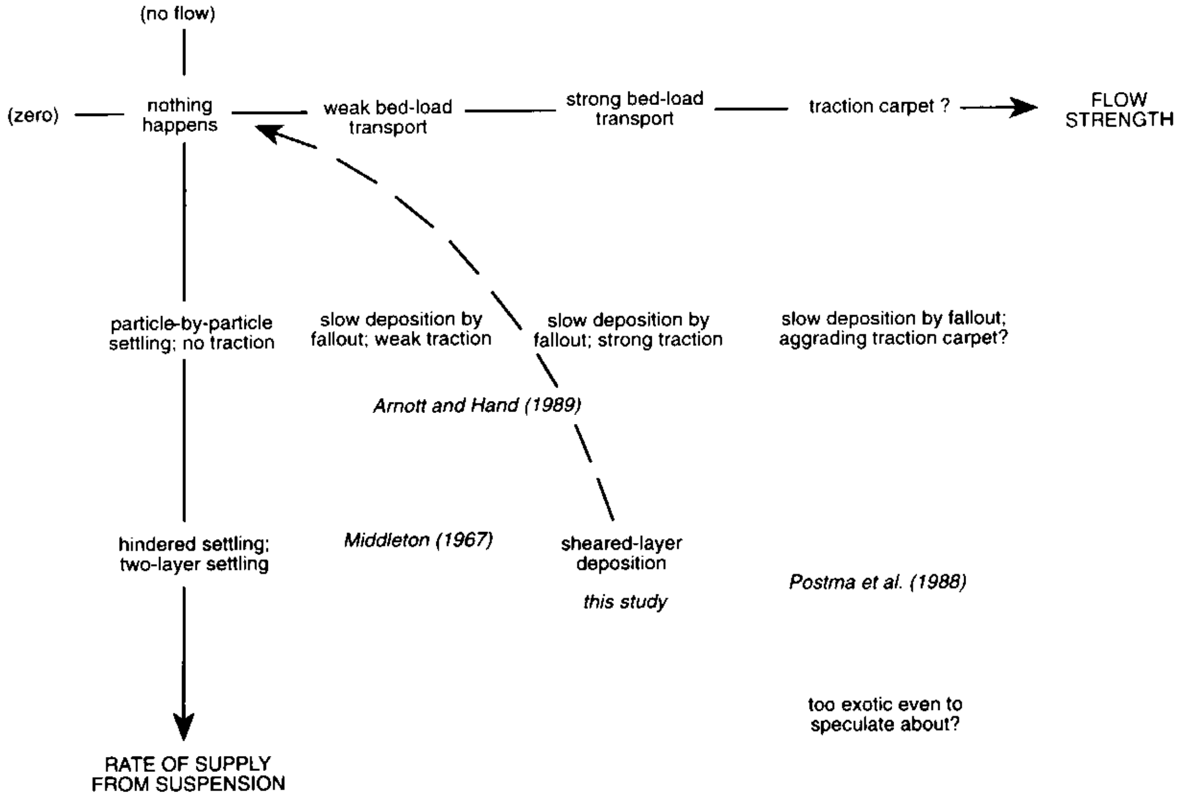

Figure 6 *Conceptual graph of sheared-layer deposition in the range of processes of sediment transport and deposition as a function of flow strength at the bed and rate of supply of sediment to the bed from suspension. The dashed arrow shows qualitatively the time history of processes observed in the experimental runs. There should be a third dimension to this graph: the effect of sediment size is not taken into account.*

also, and perhaps more importantly, by the rate of supply of sediment from above.

We cannot offer more than speculation that with increasing near-bottom shear, other factors being the same, the importance of grain collisions would increase. With decreasing degree of overloading of the surge, the rate of climb of the laminar sheared layer would decrease and the residence time of particles in the layer would increase. Such changes in conditions might make the laminar sheared layers we observed seem much more like traction carpets.

Conclusion

We see the laminar sheared layer as the manifestation or consequence of the tendency toward two-layer segregation in settling of concentrated suspensions, a phenomenon known since at least the work of Coe and Clevenger (1916; *cf.* Been and Sills, 1981, and Middleton and Southard, 1984, Chapter 4), together with shearing by the overlying flow; the material in the sheared layer is passive, in the sense that particle interactions are not an important factor in the dynamics. In our opinion, such passively sheared layers during rapid deposition are likely to be important modes of deposition of the bulk of the lower, coarser part of many thick turbidites, and thereby deserving of greater attention than we have been able to give them on the basis of our small-scale experiments. Our results provide experimental confirmation of the conclusion reached recently by Kneller and Branney (1995), largely by deduction, that massive turbidite sands can be deposited by gradual aggradation by upward migration of a sheared basal high-concentration layer during passage of a turbidity current that is not grossly unsteady.

CONCLUSIONS

The most significant aspect of the experiments was the development of what we call laminar sheared layers: in all but the final stage of passage of a strong sand-laden surge, accumulation of high concentrations of sand near the base of the turbulent flow gives rise to a distinctive non-turbulently sheared layer with sand concentrations close to the maximum possible for pervasive shearing. During passage of the surge, the laminar sheared layer climbs by immobilization of sediment at its base and delivery of additional sediment from the overlying high-concentration turbulent flow. Individual particles reside in the layer for only a short time, and while there, they move only a short distance and seem to experience no strong interaction with neighboring particles. In that respect, the laminar sheared layers observed in the experiments seem not to share essential features with such superficially similar phenomena as traction carpets.

Our experiments were crude and on a small scale, yet we think that they reveal processes that are likely to be of great importance in interpreting deposition by large-scale flows overloaded with sediment, like turbidity currents. We did not even come close to "pushing the envelope": similar experiments on a larger scale would not be unmanageable or outrageously expensive, and they hold the promise of adding much to our understanding of turbidity-current deposition.

We hope that our experiments might serve to stimulate or redirect thought on the part of those who deal with turbidity-current deposition, in the same way as have, for example, the early and seminal work by Middleton (1967) and the more recent and very revealing work by Postma *et al.* (1988). In particular, they might serve as "ground truth" for the numerous deductive or theoretical accounts of deposition from turbidity currents in the literature. (The ratio of deduction to observation in the area of turbidity-current deposition is unusually large.)

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