EXPERIMENTAL PRODUCTION

OF

SOLE MARKS

by

R. A. PORTER

A Thesis

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SUMMARY

A series of turbidity current experiments were performed in an 8-foot flume. Plaster of Paris was used to record the structures formed on a mud base.

These structures were related to the flow properties, specifically turbulence. The structures formed were pseudo-flutes, longitudinal ridges and furrows, tool marks and triangular markings.

Comparison to other known work is made with varying degrees of agreement or disagreement.

INTRODUCTION

If there are small density differences within a fluid so that gravity produces or maintains a current in the fluid, then that motion is called a density current. When the density difference is caused by suspended sediment the current is known as a turbidity current. (Middleton, 1964).

Relatively large density differences or slopes can, in the small-scale experiment, produce strong turbulence. In nature, the larger scale may not require so great a difference or slope. Such turbulence has been demonstrated to have appreciable erosive force (Kuenen, 1951). This erosion and the subsequent deposition is believed to have produced a wide variety of structures.

The 'classical' turbidity current carries sand over a mud base. This will produce three types of structure: those cut into the mud and preserved as 'negatives' on the sandstone base, the sandstone's internal structures, and upper surface structures. (Dzulynski and Walton, 1965) This paper will deal with the lower surface 'negatives'.

These 'negatives' were first called 'casts' by Hall (1843). They are the hieroglyphs of the European writers (Dzulynski and Sanders, 1962) or sole marks of more recent use. Most of the previous work has been qualitative (Dzulynski, 1965; Dzulynski and Walton, 1963, 1965; Kuenen, 1957). Very little quantitative research has been done, with a few exceptions (Keulegan, 1957, 1958; Middleton, 1966a, 1966b, 1966c, 1967).

The head of a turbidity current is 'probably the locus of bottom erosion' (Middleton, 1966c). As such, it is the area of primary concern for this study. It has been shown that the head has a characteristic, relatively constant shape (Keulegan, 1958). It may, however, vary slightly with Reynolds Number (Middleton, 1966a).

Keulegan's studies (1958) have given empirical laws governing the head. The initial velocity (V_o), immediately after release, is given by:

$$V_o = 0.46 \sqrt{\frac{\Delta\rho}{\rho} gH} \qquad (1)$$

in which ρ represents the density of the ambient fluid, $\Delta\rho$ is the difference in density between the head and the ambient fluid, g is the acceleration due to gravity (980 cm. per second), and the depth of water is given by H.

The important variables governing fluid flow are the two dimensionless groups: the Reynold's Number (Re) and the Froude Number (Fr). Below their mathematical definitions are given.

$$Fr = \frac{V_o}{\sqrt{g d_1}} \qquad (2)$$

where $d_1 = 0.5\ d_2$ (Keulegan, 1957)

and $d_2 = 0.34\ H$ (Middleton, 1966b).

$$Re = \frac{V_o\ d_1}{\nu} \qquad (3)$$

The kinematic viscosity (ν) necessary for equation (3) can be determined from Roscoe's equations (1953)

$$Nr = (1 - C)^{-2.5} \qquad (4a)$$

$$\mu x = Nr \cdot \mu H_2O \qquad (4b)$$

$$\nu = \frac{\mu x}{\rho} \qquad (4c)$$

Thus, determination of the volume concentration of sediment in the head (C) will give Roscoe's Co-efficient (Nr) which in turn will define the absolute viscosity (μx).

Application of the above formula allows a certain degree of quantification of the data in these experiments.

PROCEDURE

A plywood flume constructed by Costello (1968) was used. The flume is 8 feet long, 1 foot wide and 1½ feet deep. At one end there is a compartment with a vertically opening gate. This functioned as a mixing chamber. At the other end is a well 4 feet deep. This was used to prevent any back wash of the current. (figs. 1 and 2)

After it had been crushed to a fine powder, a pleistocene varved clay was allowed to settle in the flume to form a mud base about 3 cm. in thickness. (Costello, 1968, gives a more detailed description of this clay.)

A known volume of Plaster of Paris was mixed with the water in the front chamber by means of a mechanical stirrer. Density and velocity of this slurry were varied by appropriate changes in the water height and the volume ratio of Plaster of Paris to water.

After the Plaster of Paris-water slurry had been thoroughly mixed, the stirrer was stopped and the induced turbulence allowed to die out. (This takes about 10 seconds.) Then the forward gate was suddenly lifted allowing the 'turbidity current' to flow down the flume and into the well. The flume was essentially horizontal (less than ½ degree slope measured). The flow time was noted with a stop watch (usually about 4 seconds).

Table 1 gives the conditions of each run.

In order to determine the density of the turbidity current, both the density and the porosity had to be known. Density was measured by weighing a known volume of Plaster of Paris on a chemical balance. Mixing known volumes of water and Plaster of Paris and then noting the resulting volume gave the porosity. Table 2 shows the results of this work.

Both porosity and density varied quite noticeably from sample to sample. This is probably due to compaction differences. However, compaction would probably cause compensating effects on the final slurry density.

The values used were 0.879 gms/cc and 69% porosity. This compares to Costello's work (1968), 0.959 gms/cc and 52% porosity, quite well as the resulting current densities differ by only 1%.

After the Plaster of Paris had hardened in the flume, the water was siphoned off. Then the Plaster casts were cut into segments with a Plaster knife and removed. After cleaning these sections, the recorded structures were noted and measured.

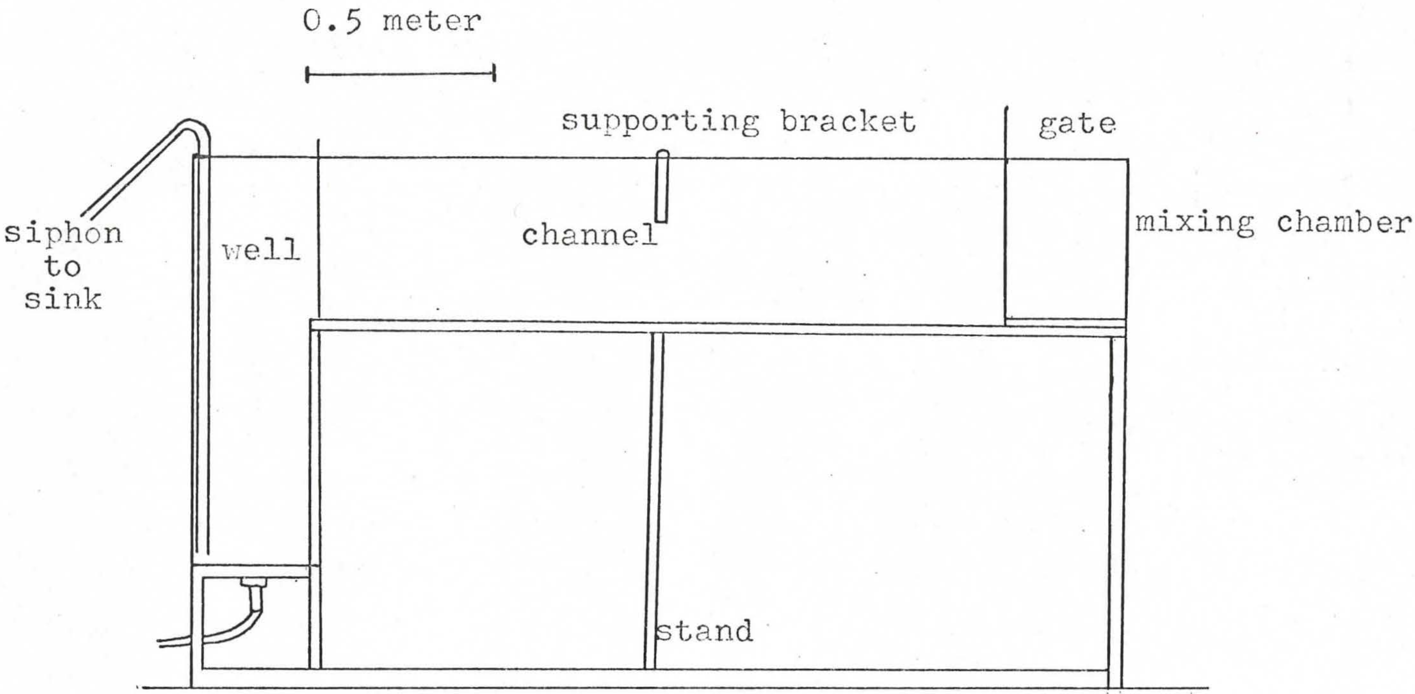

FIG. I. Cross section of the flume (adapted from Costello, 1968).

FIG. 2. Flume.

TABLE 1

Run Number	Type of Plaster used	Settling Time (hrs)	$\Delta\rho$ gm/cc	H cm	$\bar{V}$ cm/sec	V_o cm/sec	Re	Fr	μx $\frac{gm}{sec \cdot cm}$	ν $\frac{cm^2}{sec}$	C %
1	slow set (s)	24 ± ¼	0.18	28.5	32.7	34.5	14,000	0.48	0.013	0.011	10
2	S	24	0.18	28.5	35.2	34.5	14,000	0.48	0.013	0.011	10
3	S	24	0.18	28.5	33.3	34.5	14,000	0.48	0.013	0.011	10
4	fast set (F)	24	0.49	28.5	39.8	53.8	18,000	0.78	0.022	0.015	27
5	S	24	0.42	38.5	- [1]	57.9	27,000	0.75	0.019	0.014	23
6	S	24	0.44	22.1	38.2	45.8	13,000	0.76	0.020	0.014	24
7	S	24	0.39	15.0	32.7	34.8	7,000	0.70	0.018	0.013	22
8	F	12	0.39	24.1	38.1	44.9	14,000	0.71	0.018	0.013	22
9	F	24	0.34	28.0	40.7	44.5	18,000	0.65	0.016	0.011	19
10	S	24	0.34	35.5	38.1	50.0	24,000	0.65	0.017	0.013	19
11	S	24	0.39	25.7	46.9	45.6	16,000	0.70	0.018	0.013	21

[1] a strong surge made the water too turbid to observe the head

TABLE 2

Porosity Determination

Run	Type of Plaster	Vol. Plaster cc	Vol. Water cc	Total cc	Total Observed cc	Diff. cc	Porosity %
1	F	350	570	920	680	240	68.6
2	F	500	606	1106	780	326	65.2
3	F	300	575	875	660	215	71.6
4	F	155	253	408	300	108	69.7
5	F	225	249	474	320	154	68.5
6	S	290	820	1110	950	160	55.2
7	S	360	525	885	630	255	70.9
8	S	220	720	940	775	165	75.1
9	S	300	620	920	690	330	76.7
10	S	200	250	450	300	150	75.0

average porosity fast set = 68.7%

average porosity slow set = 70.6%

overall average = 69.6%

RESULTS

Several different structures were found. These are described in the following pages. For a clear discussion of these markings it is necessary to classify each type; however, it must be made clear that not all structures belong in one set class. They often have transitional types. The scheme used is shown below.

I	Flute-like structures	a.	proximal	F
		b.	associated with tools	Ft
II	Longitudinal Ridges and Furrows			
		a.	in long, narrow, straight groups	Rs
		b.	in short, wide, curved, groups	Rc
		c.	not grouped or only slightly grouped.	
			i. deep and clear	Rd
			ii. shallow and less distinct	R
III	Tool Marks	a.	Tools	T
		b.	Grooves	G
		c.	Brush and Skip Marks	S
		d.	Associated Chevron Marks	C
IV	Triangular Markings			Tr
V	Others			

Table 3 shows a breakdown of the occurrence of the above marks. The runs have been placed in order of ascending Reynolds Number.

Table 3

Run Number	Δρ	Re	Ridges	Flutes	Tools	Plaster Type	Notes
7	0.39	7,000	R	F	-	S	
6	0.44	13,000	R	-	T,G[1]	S	vertical eddy recorded?
8	0.39	14,000	R	-	T,G[2]	F	
1	0.18	14,000	Rs	-	T,G[1]	S	
2	0.18	14,000	Rs	-	-	S	
3	0.18	14,000	Rs	-	-	S	
11	0.39	16,000	-	?	T,G,S[2]	S	
4	0.49	18,000	-	Ft	T,G,C,S[2]	F	
9	0.34	18,000	Rc	?	-	F	
10	0.34	24,000	Rc	F	-	S	
5	0.42	27,000	Rc	F	-	S	arching up of ridges

[1] tools rare (less than 5 for whole run)

[2] numerous tools

I Flute-like Structures

Flute-like structures were found in several runs (4,5,7,10). These are the pseudo-flutes of Costello (1968). Since there were differences between the experimental results and natural flutes, it was suggested that the term pseudo-flutes should be used (Walker in Costello, 1968). Thus it would emphasize their similarity yet distinguish between natural flutes and experimental flute-like structures. The above usage will be continued in this paper.

Generally, the pseudo-flutes have the same morphological features as flutes. They have a narrow, concave up beak which shallows and broadens down stream. The average size was about 1.0 to 1.5 cm. long by 0.5 to 1.0 cm. wide. The depth in the beak was never greater than 0.2 cm. Both triangular and linguiform shapes were seen in the proximal end of the flume. With one exception, discussed below, all pseudo-flutes were found in the first 40 cm. of the flume.

Triangular forms were found on run 5 (see fig. 3a and 3b). They were found between 15 and 30 cm. from the gate. The average size was 1 cm. wide by 1.5 cm. long with a depth of 0.2 cm. These were all very uniform in size and shape.

The association with some ridges is shown (fig. 3b). In this run it appears that a stream has moved diagonally

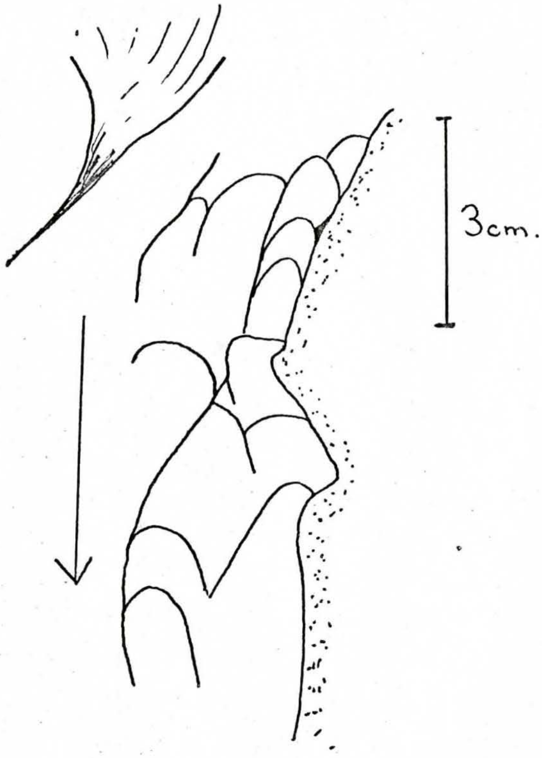

FIG. 3a. Triangular Pseudo-flutes. Run 5.

FIG. 3b. Triangular Pseudo-flutes, association with ridges. Run. 5.

to the wall and then been deflected off it. After the deflection, both deep ridges and triangular flutes were formed. This suggests that a boundary effect may have importance. The induced turbulence from the wall may have increased the local shear forces sufficiently to cut these flutes. Dzulynski and Simpson (1966) have suggested that tools in such a current might lag behind the current. This would produce local velocity gradients and thus cause an increased "turbulence of flow". It is suggested that in the special case of this meandering current the wall may have had the same effect.

Linguiform pseudo-flutes were found on runs 4, 7 and 10. These tend to have a larger length-to-width ratio. In runs 7 and 10 they were found between 10 and 40 cm. from the gate. Run 4 will be discussed later. The average size was about 1.0 cm. long by 0.5 cm. wide with a depth of between 0.1 and 0.2 cm. However, there was a tendency to change shape down current (see fig. 4).

This tendency might indicate a lateral change into longitudinal ridges and furrows (see next section). These intermediate forms were also postulated by Costello (1968).

These pseudo-flutes were more randomly placed than the triangular ones. Fig. 5 shows their spacial arrangement.

The depth of scour is a function of both intensity and time of the stress applied. Since for both types of

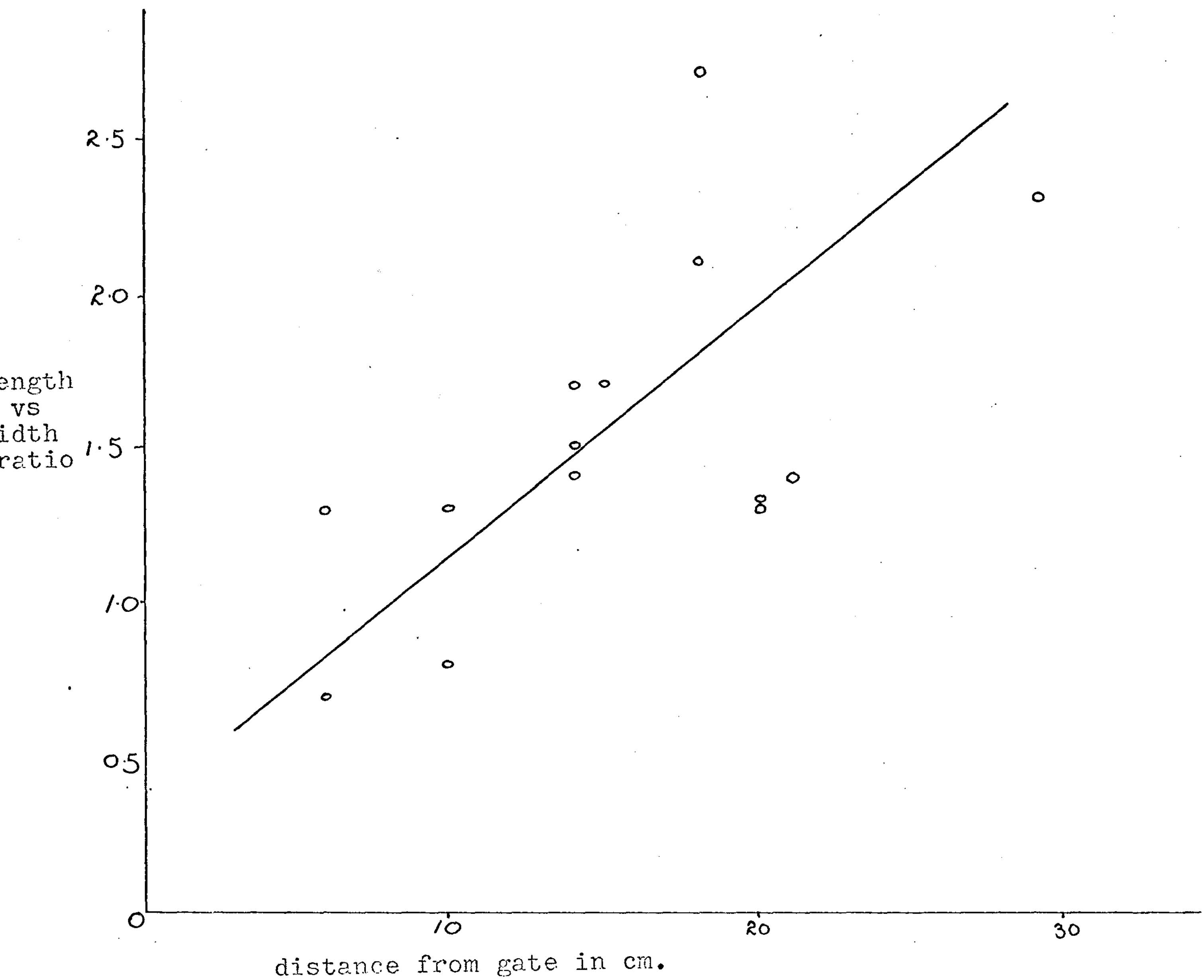

FIG. 4. Graph of length to width ratio vs distance from gate.

pseudo-flute the time is probably the same, then the intensity of scouring must be less strong for the linguiform than the triangular forms. If, as postulated above, induced increasing "turbulence of flow" was responsible for the latter, then it would be logical that they be more deeply cut.

A third mode of occurrence of pseudo-flutes was seen in run 4. Immediately before a cluster of large tools several pseudo-flutes were found. These were linguiform (fig. 6). Dzulinski and Simpson (1966) noted this same effect in their experiments. However, Costello (1968) found no such association.

In these experiments, run 4 was the only one to show such an occurrence. Several runs contained many tools yet had no associated pseudo-flutes. However, in this case the association seems quite clear. Thus, it is suggested (Dzulynski and Simpson, 1966) that tools will increase velocity gradients in a current by their lagging nature. This will increase the magnitude of velocity gradients. A greater turbulence will result which may or may not create pseudo-flutes. That pseudo-flute formation is facilitated by secondary induced turbulence is indicated by (1) their association with tools (run 4), (2) their association with wall currents (run 5), and (3) the deeper flutes were those associated with these tools and wall currents.

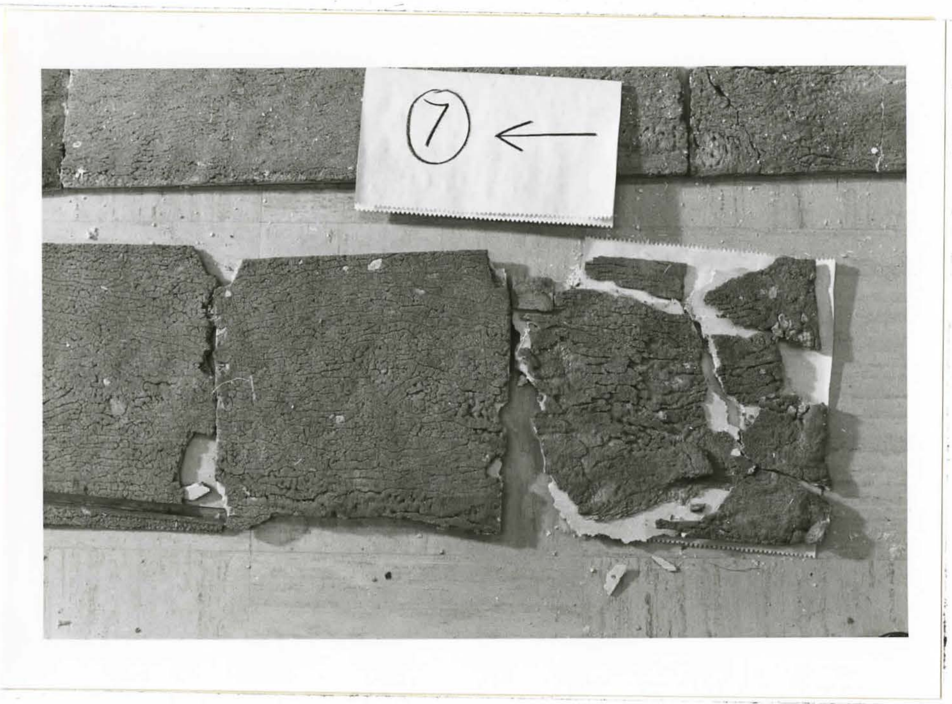

FIG. 5. Linguiform Pseudo-flutes. Run 7.

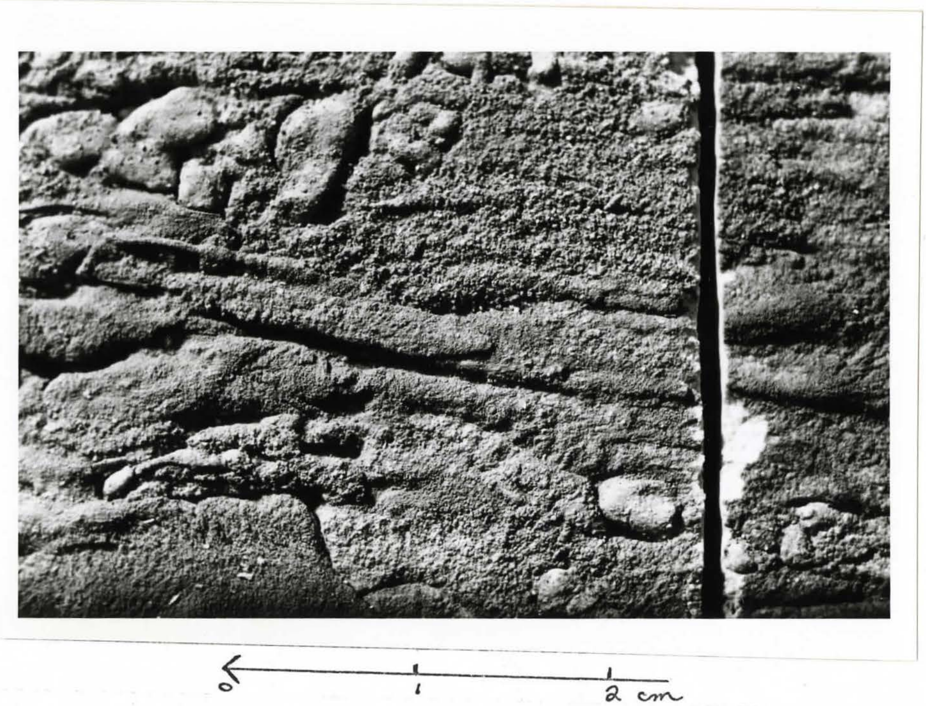

FIG. 6. Pseudo-flutes associated with tools. Run 4.

II Longitudinal Ridges and Furrows

These ridges and furrows were found over the complete range of Reynold's numbers studied. However, there were distinct types produced, based upon their grouping and deviation from the flume direction.

The ridges are found along the whole length of the flume; however, they are deeper and more clearly seen in the first 60 cm. than at the distal end.

The ridges start with a flute-like nose. Indeed, if just the nose is examined, it becomes impossible to differentiate between pseudo-flutes and furrows (see also Costello, 1968). They tend, however, to be far more elongate. The furrow has an average width of 3 mm. and have depths of up to 3 mm., but more commonly 1 mm. This contrasts quite strongly with Costello's shallow, maximum depth of 1 mm. However, this depth of erosion decreases down current to very shall indentations (figs. 7 and 8). Individual furrows had a length of about 15 cm. with maximums of 30 cm. noted. The furrow was often undercut giving it a fragile appearance (see fig. 7).

The grouping of these furrows and ridges allows a classification that appears to be related to Reynold's Number. The low Reynold's Number ridges (R) tend to be roughly parallel to the walls of the flume and no groups

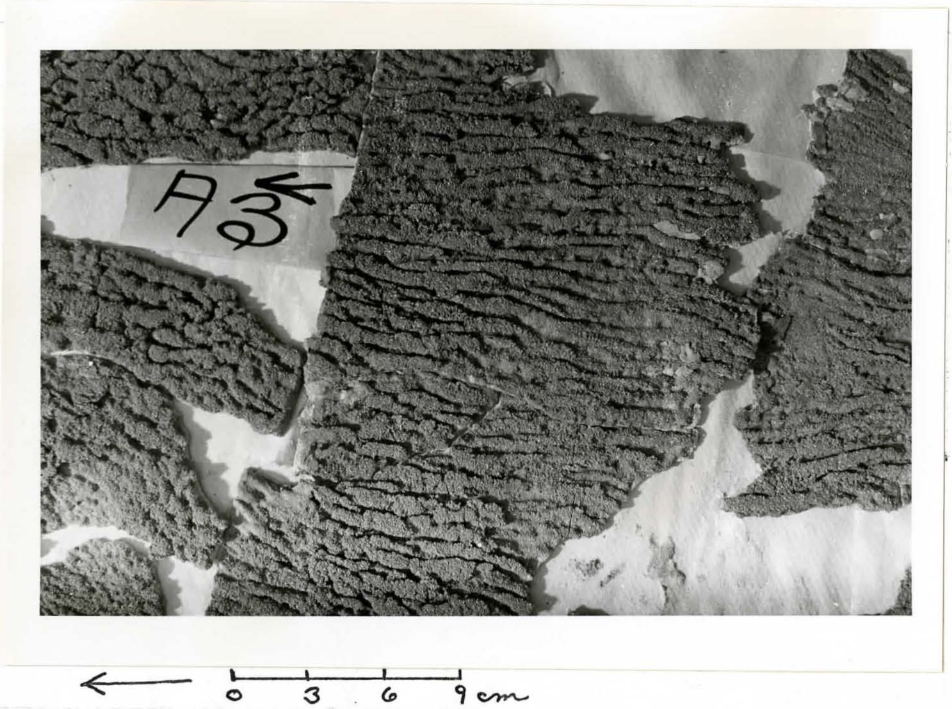

FIG. 7. Proximal Ridges. Run 3.

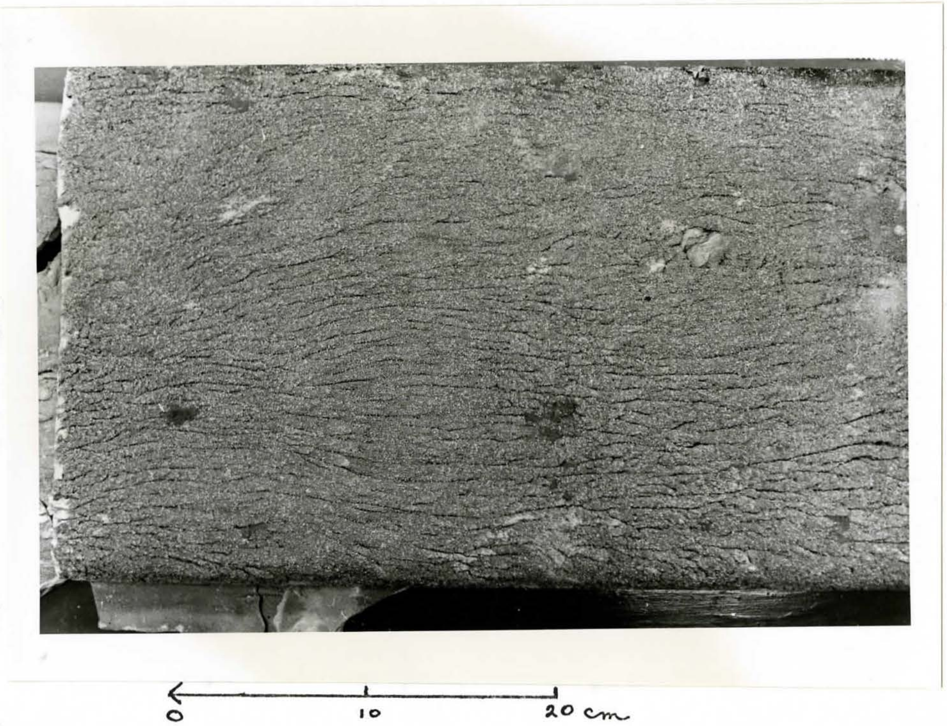

FIG. 8. Distal Ridges. Run 8.

or sets (Costello, 1968) can be discerned. They rarely deviate more than 10° from the wall direction. (fig. 11)

As Reynold's number increases, the ridges tend to group in small sets. These sets are only 3 - 5 cm. across on an average, but may be up to 60 cm. long without break. The ridges tend to be very fine and densly grouped. These sets develop only after the first 40 - 60 cm. of the run, but once formed are characterized by their persistence and strong unidirectional nature (fig. 9).

The next system, that of no ridges at all, is forshadowed by the appearance between these sets of wide areas of totally plane beds (occasionally showing Chevron like markings)

There was a short range of Reynold's Numbers in which no ridges were seen. Then in the higher Reynold's Number they again appear. Here they are again in sets; however, these sets are much wider and shorter (typically 30 cm. by 10 to 30 cm. wide). They are extremely variable in direction, differing by up to 45°. These are more deeply cut than the preceding ones (fig. 10).

Costello (1968) could find "no apparent morphological differences....between those formed at higher Reynolds numbers and those formed at lower ones". However, he did infer that "there is some relationship between Reynolds Number and the production of longitudinal ridges" since he found a region of non-development of ridges in his lower

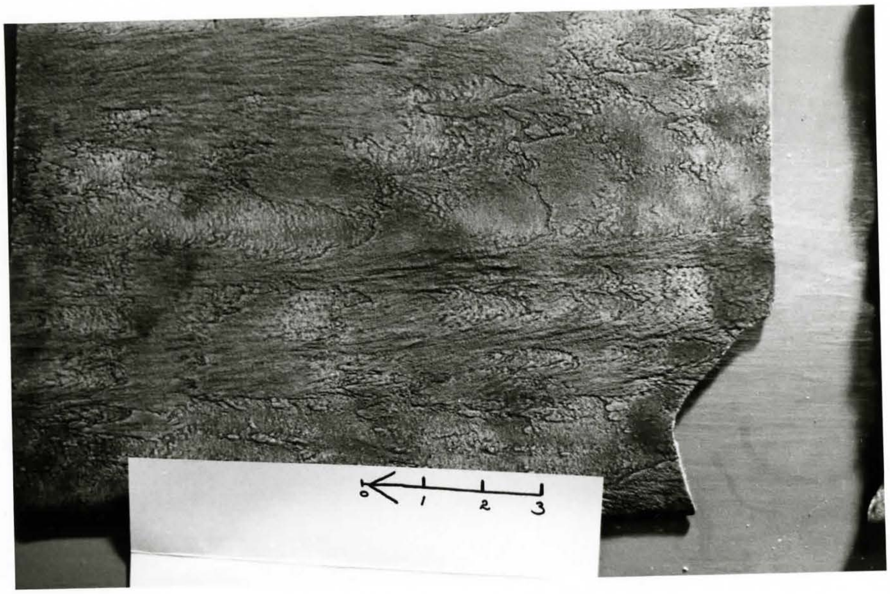

FIG. 9. Long narrow straight ridges. Run I.

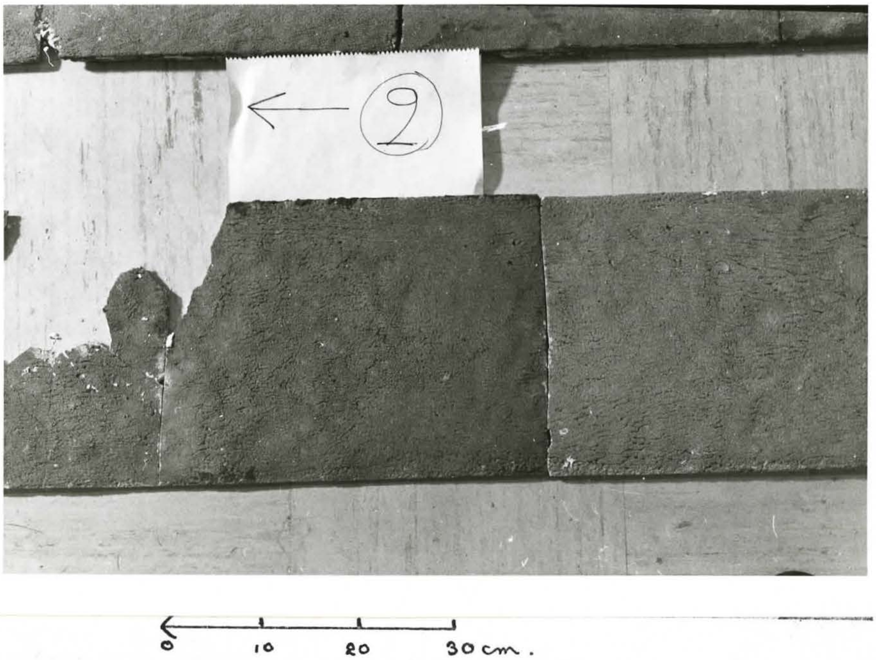

FIG. IO. Short wide curved ridges. Run 9.

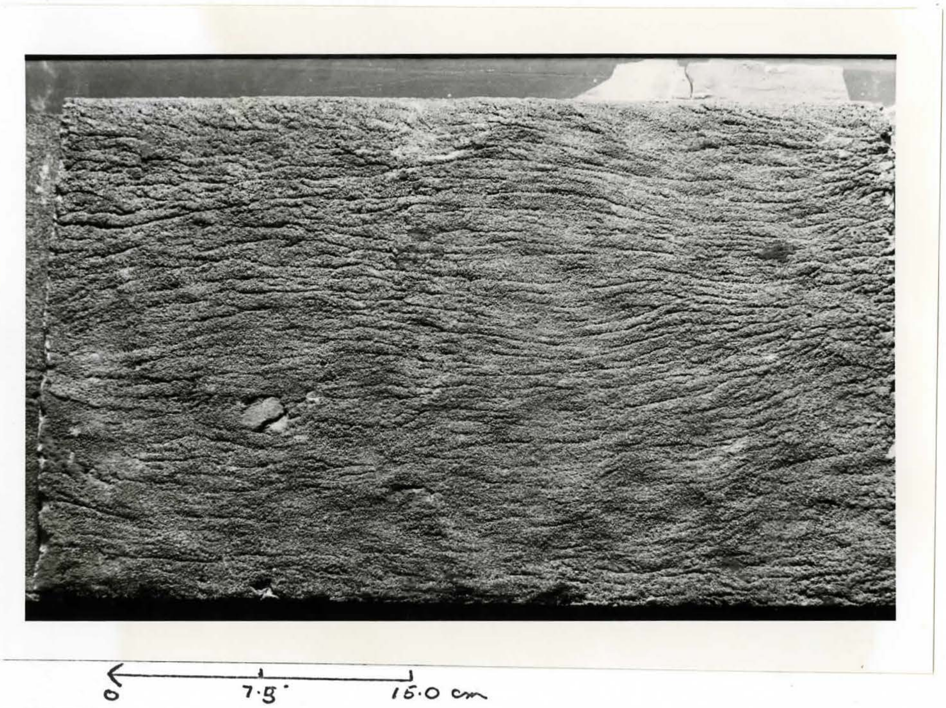

FIG. II. Non-grouped Ridges. Run 8.

Reynold's numbers.

If the above classification has validity, it may indicate that he worked only in the upper regimes, so that his ridges were all of the type b (Rc).

Costello (1968) has given a good summary of the different possible mechanisms for the formation of longitudinal ridges and furrows. Allen (1969) gives more recent work on these ridges. He found that with increasing severity of flow the following sequence of structures formed.

1. longitudinal rectilinear grooves[1]
2. longitudinal meandering grooves
3. flute markings
4. transverse erosional markings

↓ increasing flow severity

For the grooves (ridges and furrows) the sequence is the same as in this series of experiments in that straight ridges give way to curved meandering ridges.

If, as is suggested, the type of ridge depends upon flow severity (Reynold's Number) then it would be logical that the higher flow forms be more deeply cut. This is the case (see description of ridges above).

Allen noted in his experiments that the clay was moved first in fine streaks which divide and rejoin in, characteristically, 5 to 10 cm. These were separated by 0.5 to 2.0 cm. This corresponds to his erosive mode I,

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[1] Note Allen's use of "groove" for this report's "ridge".

"upper layer erosion at low velocity". These fine streaks would arch upwards and suddenly disperse into the higher velocity flow above, during which there was a sudden inflow of water to the area vacated by the streak (also Kline et. al., 1967).

In his mode II, erosion of the upper and lower layers at high flow velocity, violent eddies would drag up (plasticly deform) the clay into ridges. These were shorter in length (1 - 3 cm.) and cut to depths of 3 mm. If the eddies were violent enough, the ridges might even be torn away (compare to fig. 7, proximal ridges).

Run 5 may have recorded some evidence for this mode of erosion. As mentioned before, the flutes of this run were associated with ridges. These ridges are about 20 cm. long. They tend to gradually deep down current. Then quite suddenly two of them arch up and straighten through about 2 cm. of Plaster of Paris. These structures would seem to be records of Allen's system (fig. 3b, 12a, and 12b).

Ridges have been found in different forms. The change of directional type seems to parallel those studied by Allen (1969). That they change in depth of erosion further supports the theory invoking increasing shear stress. The sudden up-turned wisps of run 5 are particularly strong evidence.

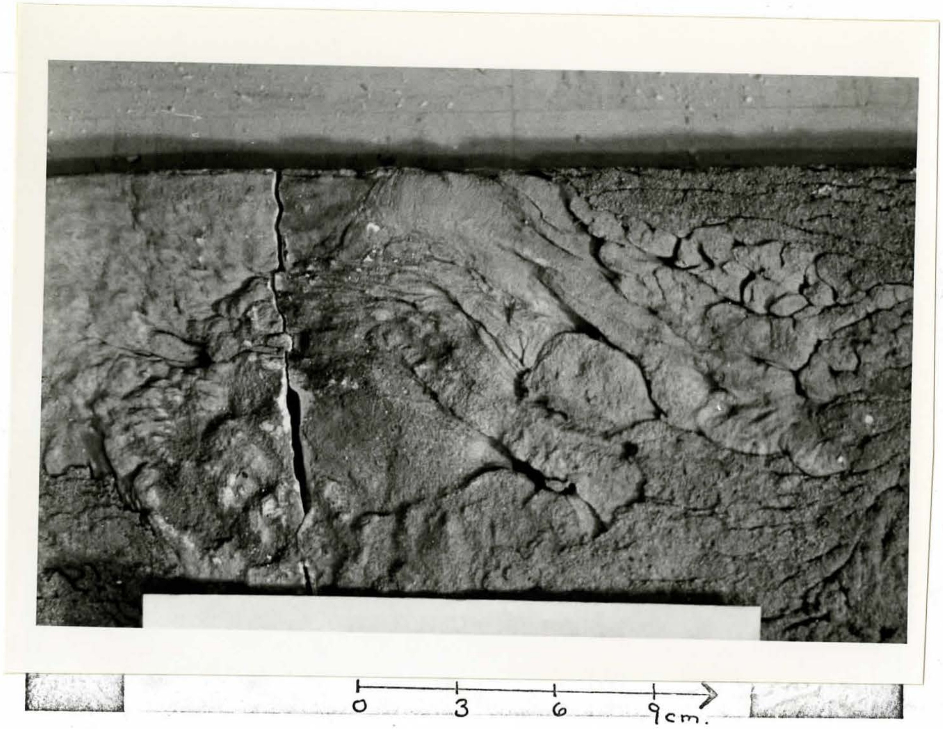


FIG. I2a. Ridges Arching up. Run 5.

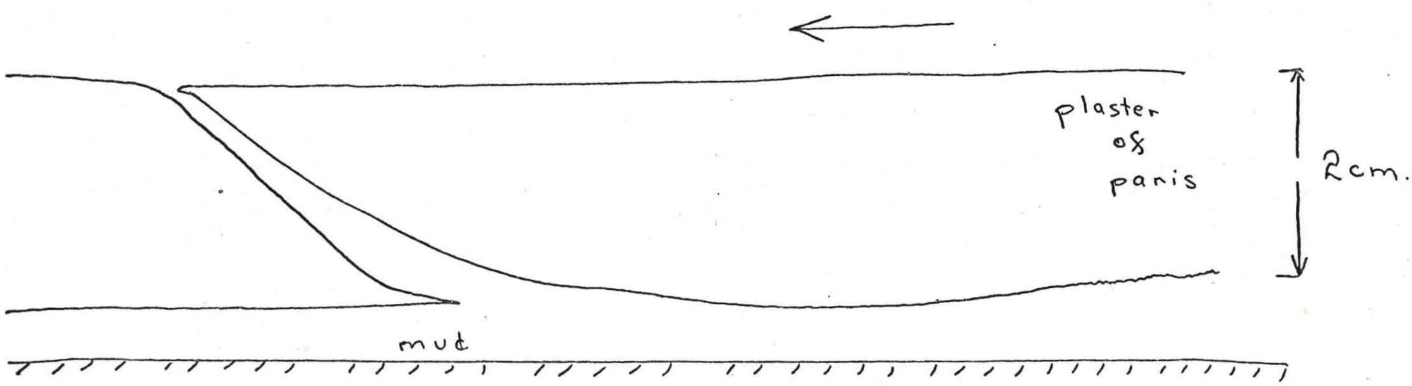


FIG. I2b. Cross Section of Ridges in FIG. I2a.

III Tool Marks

Tools formed in the mixing chamber when the slurry was inadequately mixed or when slightly damp (and therefore lumpy) Plaster of Paris was used. They were far more common in the runs with fast set than with slow set. The tools usually were semi-plastic lumps and occasionally partially hollow. This later property greatly increased their buoyancy and thus they may travel further down the flume than would ordinarily occur. Careful study indicated that no hollow tools were found in run 8. For this, then, graphs of number of tools and size of tools was plotted. Run 11 contained several hollow tools, so similar plots were made for comparison (figs. 13 to 16).

For both types, a logarithmic decrease is noted for the number of tools with distance. However, the hollow tools show a slight irregularity by the appearance of 12 tools between 90 and 110 cm. This could be due to their extra buoyancy carrying them further and probably has little relation to the natural system.

Unexpectedly, however, both runs show a general increase in tool size with distance. The graphs do show a wide scatter of points; however, this trend is real. The trend appears to show a division line at about 50 cm. before which tools tend to be about 1.0 cm. and after which a wide

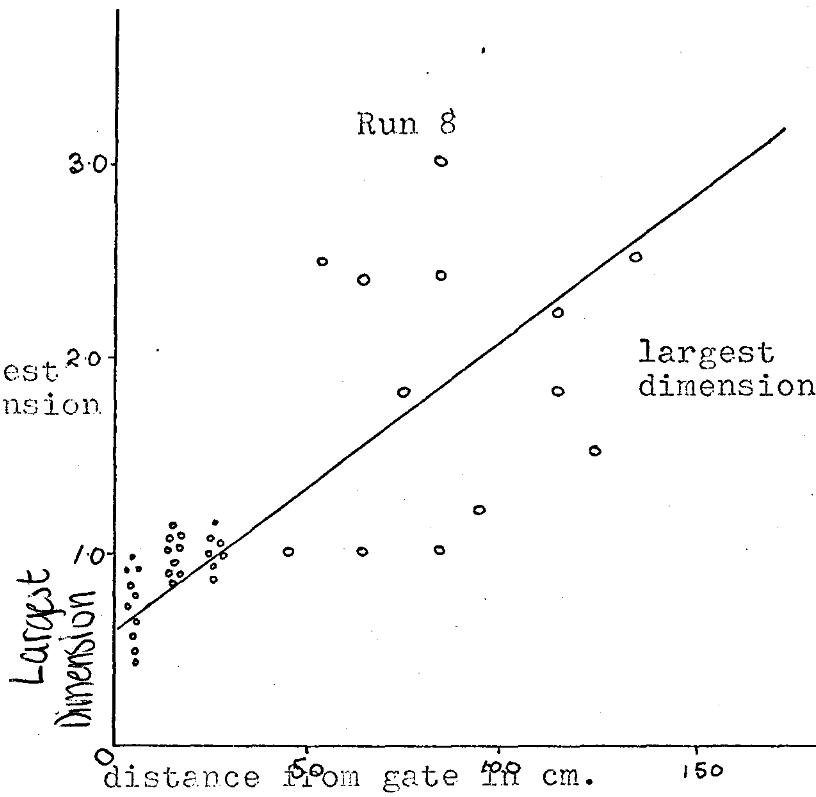


FIG. I3.

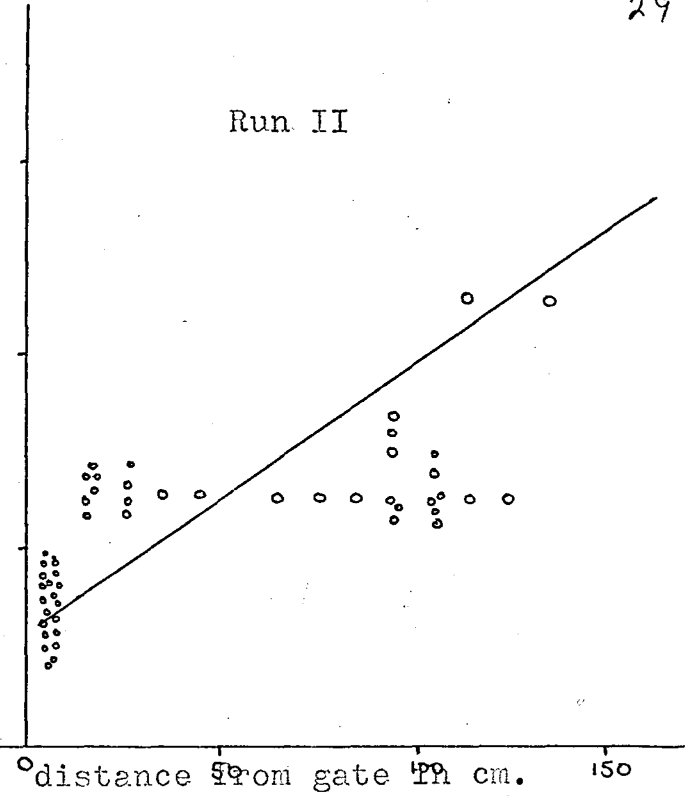


FIG. I4.

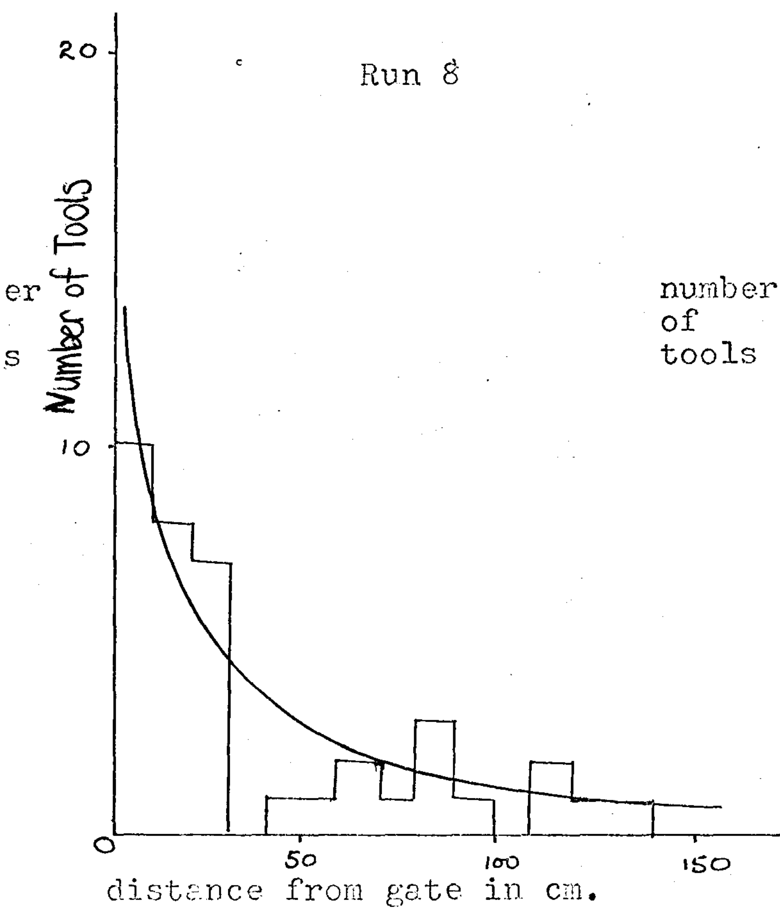


FIG. I5.

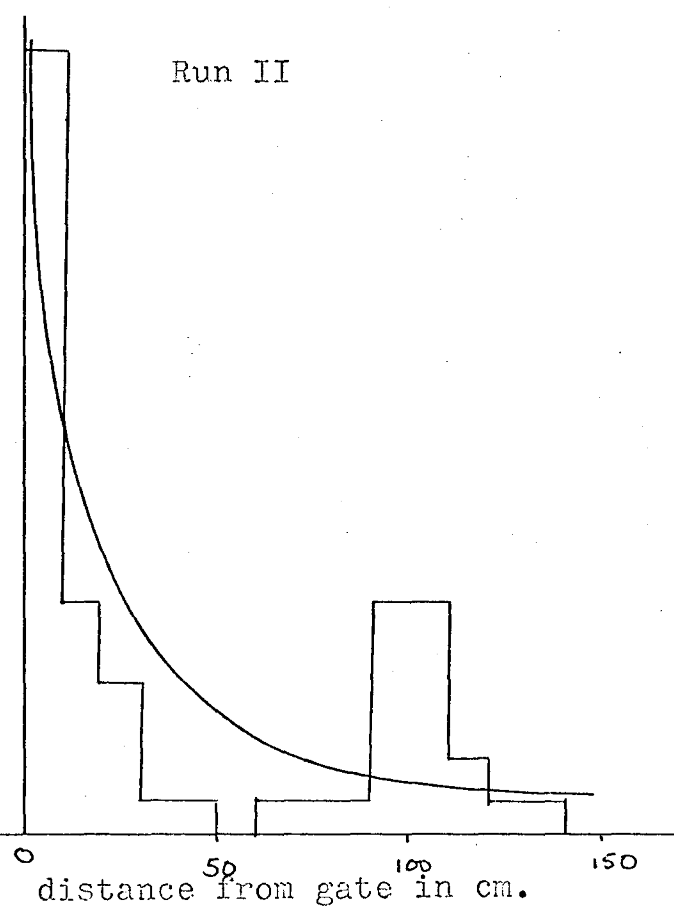


FIG. I6.

spread appears, but points are greater than 1.0 cm. in maximum diameter. The hollow tools of run 11 make that graph the least certain, and perhaps nothing can be said about it with any certainty. However, run 8 definitely does show this trend.

This size distribution is in disagreement with what Costello (1968) found.

Although the greater weight of the larger tools would tend to make them drop earlier, their greater surface area might give them more area for the turbulence to work on. This effect is a square law and the weight is a cube law, so that one cannot totally compensate for the other.

An alternative mechanism has to do with the properties of the Plaster of Paris. When a lump is dropped into water, the water starts to enter it. However, often this starts hardening immediately, forming a protective coat against further absorption. Thus, the tool might have a lighter centre or core. This would tend to increase its buoyancy and thus its distance travelled. This effect would increase with size of the tool and could be quite effective due to the density difference of Plaster of Paris (0.879 gms/cc) with water (1.000 gms/cc).

When the tools hit the clay base they would either bounce back into the flow or else glide to a halt. The former produces brush or skip marks; the latter, grooves.

Costello found a correlation between groove length and tool size. In these experiments no systematic variation could be found. However, as in Costello's work, grooves tended to be straight and rarely much out of line with the flume length (10° maximum deviation). Fine straie indicate that very little, if any, rotation of the tool occurs as it slows down (fig. 17).

Excellent skip or brush marks were found on run 11. These were spaced at 5, 10, 22 and 28 cm. behind the tool. These marks were steeper upstream than downstream, indicating a lower angle of rebound than entry, probably due to friction forces (Costello, 1968). The tool stopped dead with practically no groove before coming to rest. Occasionally in other cases a groove followed the skip marks (fig. 18).

Associated with all these tool structures were chevron markings. These are found both cut and undercut. It is suggested that these are due to a tool passing close to the surface of the mud. As the tool passes over the mud, a suction behind the tool will create an eddy system that will deform the bed into chevron markings. When the tool actually hits the bed, they will be cut by the groove. (Dzulynski and Walton, 1965)(fig. 19).

If a tool passes very close to the surface, not only may chevron marks develop, but also longitudinal

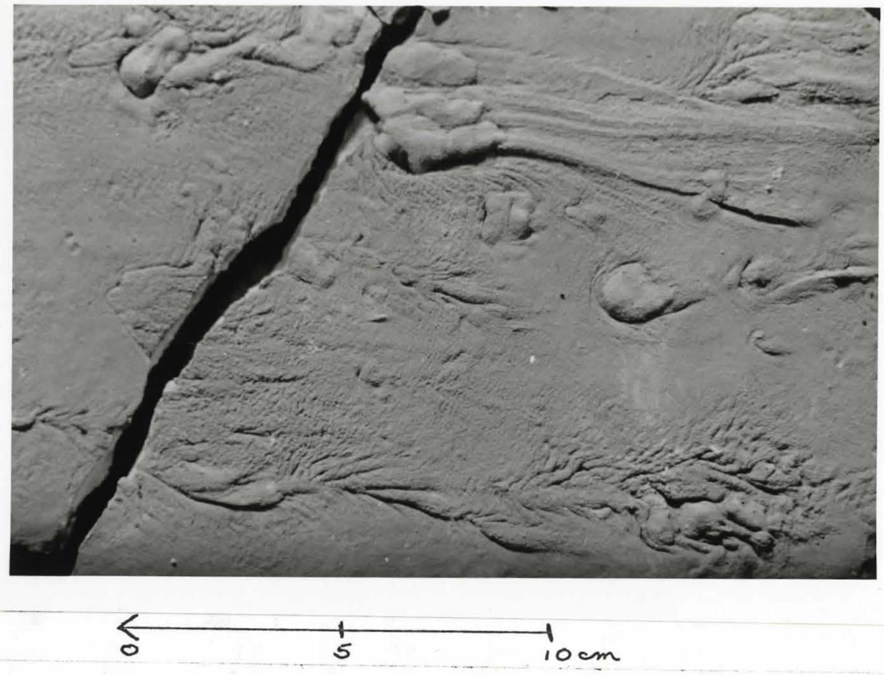


FIG. I7. Grooves. Run 4.

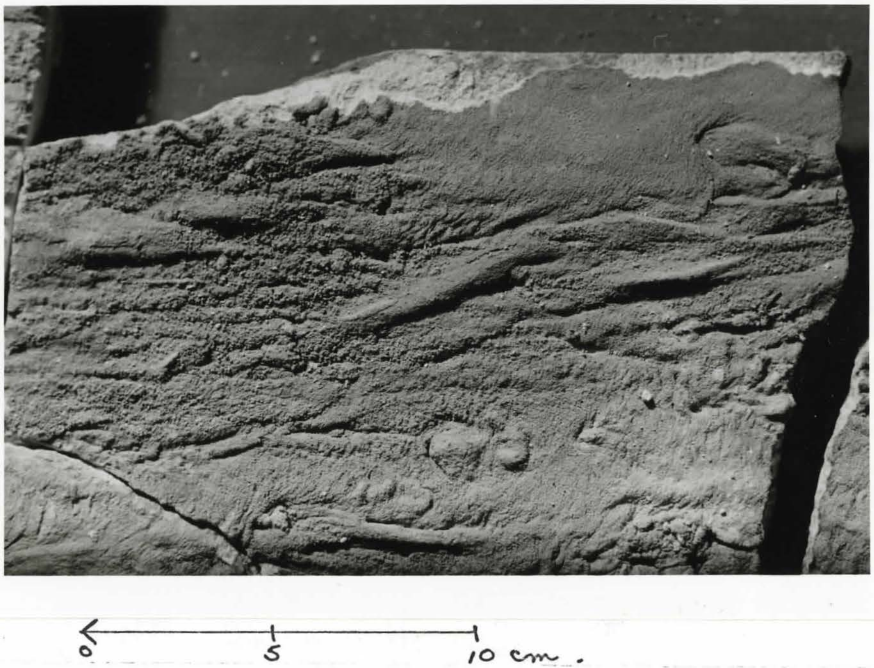


FIG. I8. Bounce & Skip Marks. Run 4.

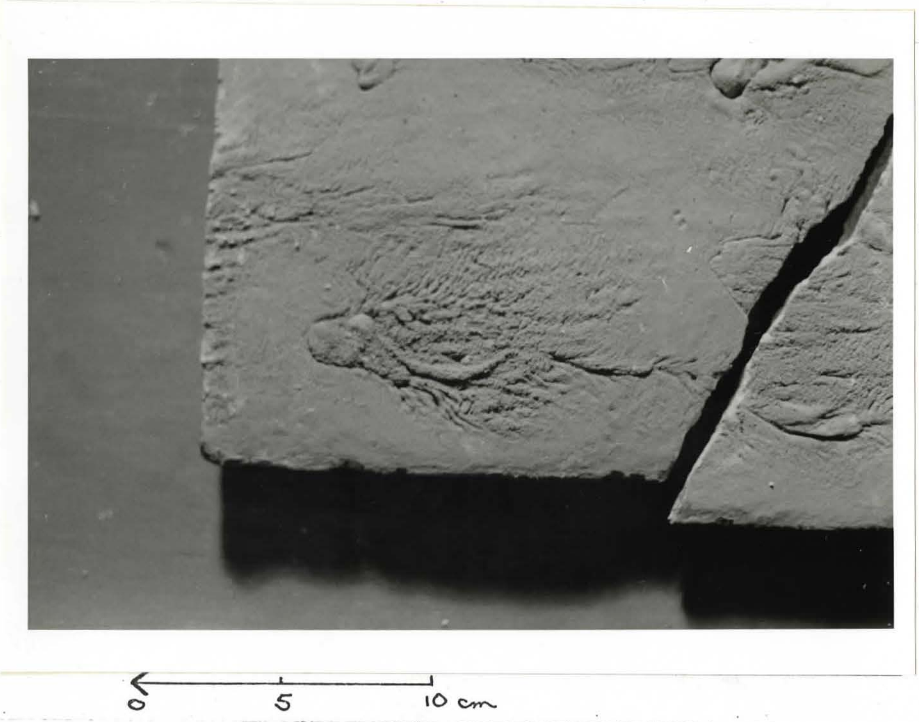


FIG. I9. Chevron Marks. Run 4.

ridges (Dzulynski and Walton, 1965, plate 73). This could be an alternate mode of formation for the Rs ridges. However, in those runs (1,2,3) in which these were seen, no tools were found near or after these ridges. Also, the lower Reynold's number of these runs makes it unlikely that a tool of sufficient size could be carried so far, so uniformly close to the clay interface.

IV Triangular Markings

These were found on only run 1. Fig. 20 shows this structure. They were extremely shallow and at a cursory glance could be mistaken for "wrong way" flutes. They are associated with the longitudinal straight ridges. The impression gained is one of plastic defomation of the mud interface. Thus, the ~~longitudinal ridges~~ these structures may be a result of secondary currents over the bottom which, depending upon strength cut ridges or plastically deform the sediment into the traingular markings. As these marks are found after the ridges, they may indicate lower turbulence (fig. 9). (See also Dzulynski and Walton, 1965, p.77 and 81.)

V Others

In run 6 the record of an eddy of larger size than normal may be preserved. The general spiral shape and deep centre may indicate a vertical eddy of considerable force (fig. 21). The stability of vertical or horizontal eddy systems has been debated, for the formation of flutes. (Rucklin, 1938; Hopkin, 1964; Dzulynski, 1966.) This might tend to show that vertical eddies are capable of deep erosion and may be stable for an adequate time for the erosion of a flute.

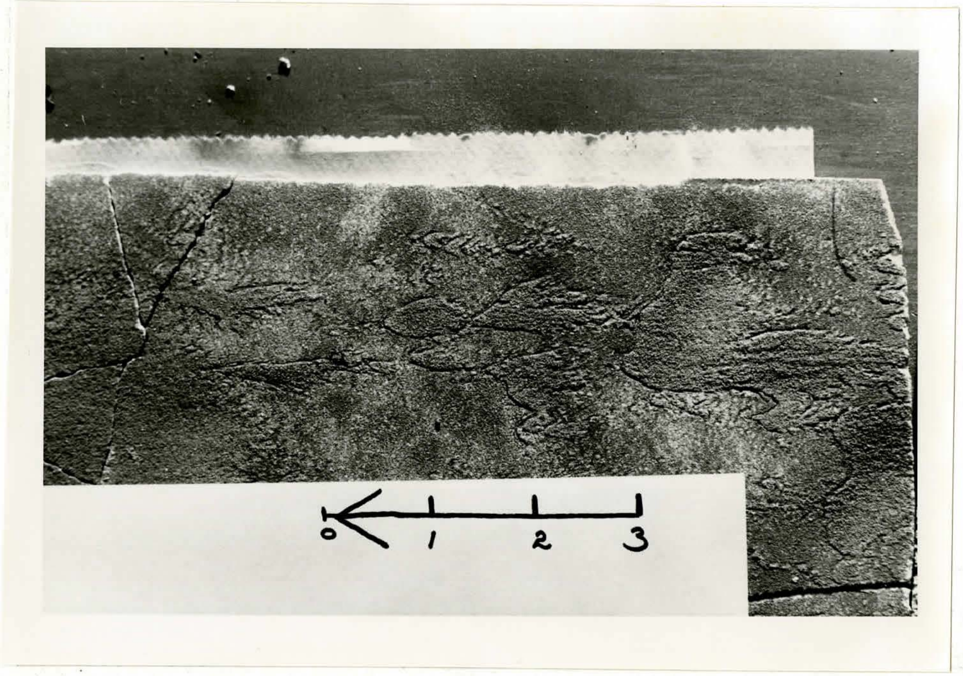
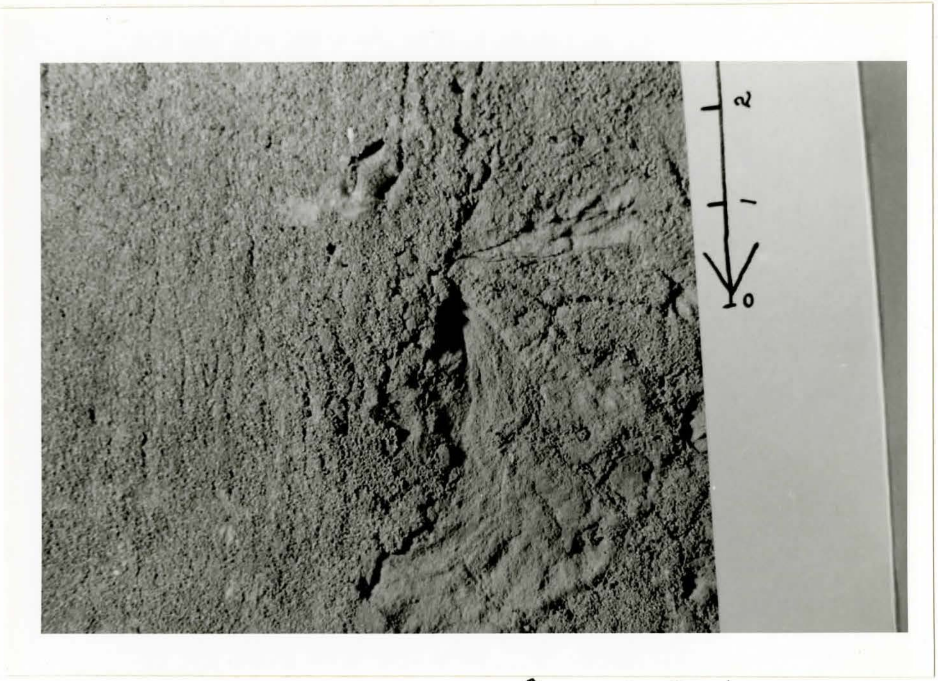


FIG. 20. Triangular Markings. Run I.



Scale in Inches

FIG. 2I. Vertical Eddy. Run 6.

DISCUSSION

Costello (1968) and Middleton (1966) have both discussed the limitations of scale model experiments. Suffice it here to say that since the laws governing such scaling-down experiments have been followed (Froudian similarity, lower suspension settling velocity, etc.) it is felt that, despite the many hazards of extrapolation to the natural large scale system, there is value in such a comparison. Similarity of structures in the experimental and natural system is probably the strongest argument in its favour.

Other problems involved include boundary effects. These were obviously present and when recognized were noted as such. Perhaps a larger flume would reduce this problem.

Similarly, fully turbulent flow takes time to develop. This could explain in part the lateral change in structures. Again, larger scale experiments are necessary.

Also, the cohesion properties of the Plaster of Paris slurry might well be very different for the viscous properties of a natural turbidite.

To these or any other arguments can be reiterated the statement that experimental structures are often remarkably similar to nature structure (Dzulynski and Walton, 1965). Thus, despite the problems there seems to be a real relationship to the natural system.

CONCLUSIONS

1. The pseudo-flutes produced in these experiments were related to the longitudinal ridges and to tools. They were usually found in the proximal end of the flume.
2. Longitudinal ridges are probably formed by secondary currents such as those suggested by Allen (1969) and Kline (1967). The type of ridge is a function of Reynold's Number or erosive force.
3. Grooves, brush and skip marks, and chevron marking are a result of tools, either by direct impingement or by associated eddy systems.
4. Triangular marks were also produced.
5. Vertical eddies are possible in the flume case and are capable of quite deep erosion.

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