FLUME STUDIES OF LARGE-SCALE CROSS-STRATIFICATION PRODUCED BY MIGRATING BED FORMS

by

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Submitted to the Department of Earth and Planetary Sciences on June 18, 1981, in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

ABSTRACT

A technique, demonstrated previously by the writer, for synthesizing sedimentary structures (by combining a time series of bed-surface-height profiles taken at equal intervals into a synthetic vertical section of the bed) is applied to large-scale dune bed forms produced by equilibrium unidirectional flows in an experimental channel 60 m long, 2.25 m wide and 1.5 m deep. Three subphases of the dune bed phase and the sedimentary structures created by each of them are examined.

Two-dimensional dunes, characterized by straight crests and the lack of deep erosional scours in front of lee faces, produce planar cross-laminated structures but show irregularities in spacing, migration rate, and depth of erosion in troughs. Three-dimensional dunes have sinuous crests and erosional scours in front of their lee faces and more regular spacing and migration rate, but the trough cross-stratification they generate is more complex because of curvature of erosional and depositional surfaces. Higher-velocity dunes (a provisional term for bed forms that resemble sand waves -- long, low bed forms with sinuous crests and without scours -- observed in shallow fluvial and tidal environments) commonly deposit large thicknesses of angle-of-repose foreset bedding that is modified by migration of smaller bed forms over the backs of the larger dunes.

The synthesis technique is also used to simulate bed aggradation by deposition by fallout of material from suspension. Examination of synthetically aggraded sections for two-dimensional and three-dimensional dunes shows that depositional-stoss stratification can be created for dunes at very low angles of climb, primarily because of the low angles of stoss (upstream) faces of dunes.

Structures generated by the synthesis technique match

those observed in the field, demonstrating the utility and applicability of the technique.

Thesis Supervisor: John B. Southard

Title: Associate Professor of Geology

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CHAPTER 1

INTRODUCTION

One of the most important areas of sedimentology has been the interpretation of primary sedimentary structures. Many studies of such structures have been made, but there are still a number of difficult questions that have not been well answered. One of these questions involves the relationship between the structures and the conditions under which they were generated. An important example is the analysis of large-scale cross-stratification, and the depositional conditions that generate such stratification. Field studies have had some success in relating large-scale cross-stratification to the migration of large sedimentary bed forms. However, these studies have been hindered by difficulties and uncertainties in the methods of data acquisition. Study of large bed forms in the laboratory has mainly been concerned with the general morphology of the bed forms themselves, and such experimental studies have been restricted by problems involving the size of the bed forms.

Because of the problems with both field and laboratory studies, a clear picture of the generation of large-scale cross-stratification has not yet been assembled. A method for studying the structures generated by migration of large-scale bed forms in very large open channels in the laboratory would be a major advance in sedimentology. Such a method

would also be helpful if it could be applied to field studies as they become more precise and detailed in their measurement of the many variables of sediment transport.

A simple technique for generating sedimentary structures from migrating bed forms under controlled conditions has already been proposed, demonstrated, and tested on a small scale (Corea, 1978). This technique works by combining a series of successive profiles of bed-surface height, taken at equal time intervals, into synthetic sedimentary structures. The need for laborious draining and trenching of the sediment bed is thus circumvented. Availability of experimental apparatus for generation of large-scale bed forms under controlled conditions has now permitted an extension of the earlier study. This dissertation presents the results of the application of this method for synthesizing sedimentary structures. Since large-scale bed forms could be produced in the available equipment, the sedimentary structures were also large. In fact, the structures generated are among the largest ever created in the laboratory.

The relations between structures and bed forms derived from the application of the method are similar to those defined in field studies, but they are not hindered by the same data-acquisition problems. Sedimentary structures were observed during their development, not at some later time. Because the studies were all made under conditions of equilibrium flow and sediment transport, all effects due to varying

flow conditions have been removed. Such variations have been the nemesis of all field studies, and the ability to neutralize them makes this technique an important contribution. Variability of factors that control the development of sedimentary structures is an important aspect of how such structures are generated in nature, but temporal and spatial variations in flow conditions create confusion in relating bed forms to structures. If flow variations occur, they may alter the bed forms and therefore also the structures the bed forms are generating. If flow conditions are varying disequilibrium effects on the structures cannot be ruled out. The important complexities created by variations in the flow can best be analyzed by comparison with equilibrium conditions. Therefore, by eliminating variations it is possible to determine their effects.

The study of large bed forms in the laboratory seems to have reached an upper bound, in that the apparatus in which this study was performed seems to be about as large as any practical laboratory system can become. It is therefore important that the new technique can be applied to any flow environment. As sedimentologists extend their studies to examine very large bed forms seen in natural environments, this new method can go with them. This widespread applicability is an additional benefit of this new technique.

CHAPTER 2

BACKGROUND TO THE STUDY OF SEDIMENTARY STRUCTURES

History

Since the beginning of the study of sedimentary rocks, it has been realized that the rocks themselves hold important information about their history. Much of this information is in the form of the primary sedimentary structures observed in the rocks. These structures are the record of the conditions that existed at the time of deposition of the sediments. In any kind of analysis of sedimentary rocks, the ability to define the depositional conditions precisely is an important asset. To this end, a number of studies have been made, with the object of relating assemblages of sedimentary structures to depositional environments.

The study of sedimentary structures dates back to 1908, when Henry Clifton Sorby, in an examination of experimental information and modern sediments, derived a sequence of flow phenomena, bed forms, and structures (Sorby, 1908). The sequence of structures he derived was: massive sandstones, flat-bedded sandstones, small-scale cross-stratification, and lastly large-scale cross-stratification. These were related to increasing flow strengths, from less than 15 cm/sec to more than 30 cm/sec (Allen, 1963). This first attempt at relating flow to structures is the foundation on which almost all subsequent work has been built. In another early study,

G. K. Gilbert (1914) expanded Sorby's work. Gilbert used five flumes ranging up to 45 m long, 50 cm high, and 30 cm wide. These allowed him to examine bed forms larger than ripples. That Sorby's and Gilbert's observationally derived data could produce a system that coincides with the present state of knowledge demonstrates that the problem of relating flow characteristics to primary sedimentary structures can be approached with simple techniques, based on careful observation and reliable data-taking. It also shows that the state of the art has not progressed rapidly in this area, because meaningful data are hard to acquire from field work, and problems with experimental techniques have proved difficult to overcome.

The detailed study of sedimentary structures is a relatively recent development. Most of the large body of data collected under the name of "sedimentology" has been assembled within the last thirty years. Twenty years ago, Jopling (1960) wrote a thesis that examined, in some detail, the reasons for the production of bedding structures in sedimentary deposits. At about the same time, Simons and Richardson (1961) systematized the concept of the flow regime by relating the strength of a fluid flow to a specific type of sedimentary bed configuration through a series of experiments in laboratory open channels. These experiments have been expanded by a number of others (e.g. Pratt, 1971; Williams, 1967, 1970; Hill, Srinivasan, and Unny, 1969; Southard and Boguchwal, 1973; Costello, 1974;

Nordin, 1976; Costello and Southard, 1981), to provide a more complete catalog of the variables that affect the relations between bed forms and flow conditions.

In trying to define flow characteristics, dimensional analysis has been applied to help simplify the proper characterization of the flow conditions. Many variables can be used to characterize the relationship between sediment bed and fluid flow, and several different concepts have arisen around the question of which variables are the most important. Simons and Richardson (1963) suggest the use of the acceleration of gravity, g; fluid density ρ and dynamic viscosity μ; sediment density ρ_s and grain size D; and flow power τU and mean bed shear stress τ_o. Vanoni (1974) used most of the same variables, but added a measure of the sediment sorting, σ, and replaced flow power and mean bed shear stress with mean flow depth d and mean bed shear stress τ_o as variables defining the flow. Since Brooks (1958) determined that certain values of τ_o can represent more than one bed configuration, Southard (1971) removed flow power and shear stress from the list of flow variables. Replacing τ_o by the mean flow velocity U produces the following set of variables: d, U, ρ_s, D, ρ, μ, and g (Southard, 1971). In this case, the seven variables that characterize flow and sediment transport can be reduced to four dimensionless variables. These can be a Reynolds number $\rho Ud/\mu$, a Froude number $U/\sqrt{gL}$, a size ratio D/d, and a density ratio ρ_s/ρ (Middleton and Southard, 1977).

Measurement or control of d, U, D, ρ_s, ρ, and μ is important because they define a specific relationship between a fluid flow and the bed over which the flow is moving. The result of this relationship is that on the average, a specific flow should create a specific bed configuration. This allows the comparison of known relationships between flow and bed configuration with cases where only the bed configuration is preserved.

Other workers (e.g., Harms and Fahnestock, 1965; Coleman and Gagliano, 1965) have attempted to define the relationship between bed forms and sedimentary structures. Almost all of these studies have been in natural environments because of the difficulties of producing sedimentary structures with thickness greater than the height of a single large-scale bed form in flume experiments.

Bed-Form Sequence

In the course of the study of sedimentary bed forms a bed-form sequence based on size and geometry has been defined. Because there is some disagreement on terminology, it might be helpful to give consistent definitions of the various bed-form types. This sequence, based on experimental data from flume studies (e.g. Simons and Richardson, 1960, 1961, 1963) and from field observations (Knight and Dalrymple, 1975; Dalrymple et al., 1975, 1978; Reineck and Singh, 1980), is:

Ripples -- Small-scale bed forms with spacings less than a few tens of centimeters and heights less than a few centimeters. They have gentle stoss

(upstream) slopes and steeper lee (downstream) slopes, which are generally avalanche slopes. The height-to-spacing ratio is about 1:10.

Dunes -- large-scale bed forms with spacings of a meter to many meters. Dune heights range from 10 to 20 cm in small flume experiments to 50 to 60 cm or more in the field. In cross section, dunes are roughly triangular in shape, with height-to-spacing ratios similar to ripples, about 1:10.

Sand waves -- large-scale bed forms with spacings of tens to hundreds of meters. Sand-wave heights range from 10 cm to several meters. This produces long, low bed forms with height-to-spacing ratios up to 1:200.

Previous Studies of Sedimentary Structures

Studies seeking to relate structures to depositional environments have taken two basic forms: field studies and laboratory studies. Both of these have limitations. Field studies of modern environments give excellent representations of the types of flow phenomena, but are constrained by the lack of controls on the important flow variables. Simultaneous observation of the flow and the bed forms produced by the flow is difficult. The presence of water makes the bed inaccessible,

and turbidity of the water often obscures the bed, hindering direct observation of the bed forms produced. Because of this, a number of studies in natural environments have been made in areas where the bed becomes exposed either naturally or because of man-made interference.

CHAPTER 3

FIELD STUDIES

In spite of their limitations, field studies in fluvial and tidal environments have been a major source of information on the relationship between bed forms and sedimentary structures. Probably the most important relationship worked out so far is that between migrating dunes and large-scale trough cross-stratification. Several studies (Harms and Fahnestock, 1965; Collinson, 1970; Williams, 1971) have involved excavation of trenches in dry or drained river beds; all have demonstrated a clear connection between the presence of trough (or festoon) cross-stratification and the presence of dunes as the dominant bed form. Another group of studies in estuarine environments has shown that this relationship between dunes and large-scale trough cross-stratification cuts across environmental lines (Boothroyd, 1969; Reineck and Singh, 1967; Boersma, 1969; Davidson-Arnott and Greenwood, 1974).

Studies in Fluvial Environments

In the fluvial studies, several approaches have been taken in studying the relationship between bed forms and structures. The study of the Rio Grande by Harms and Fahnestock (1965) was an attempt to examine the relationship between flow and bed forms. Two segments of the Rio Grande,

each about 500 m long, were examined. Because the river upstream of the study area was controlled by an irrigation dam, it was possible to measure the flow characteristics of the river while the water was flowing and then examine the bed after the dam had been closed and the flow stopped. This study showed that flows of moderate velocity (65-86 cm/sec) generated dunes. At higher velocities (1.5 m/sec), the dunes were washed out and replaced by plane-bed transport. In an intermediate range of velocities (about 95 cm/sec), a combination of dunes and washed-out bed were formed. While this is a useful correlation, only four flow velocities were observed, and the bed forms generated by the high flow stages could not be directly observed. The bed forms actually seen in the channel after removal of the flow were altered by late stages of the waning flow, as the channel drained. An added objective of that study was an attempt to draw comparisons between the flow conditions and the sedimentary structures produced. The technique involved waiting for the river bed to dry out and then digging trenches. Wells were dug, and the bed of the river was drained by pumping, so that a trench about 1.2 m deep, 7.6 m wide, and 10.6 m long could be dug to expose the sedimentary structures produced by the migrating bed forms. These trenches revealed the nature of the structures generated by the bed forms exposed on the bed surface.

The overall relationship between flow and structure was derived in the following way. At maximum flow, all of the

variables were measured. After the river had stopped flowing, the bed left behind was examined. When the bed had dried, trenches were dug, and the structures revealed were examined. There are some problems in relating the measured flow velocity with bed forms not observed until six months later and structures generated by bed forms that were not observed while migrating. Specifically, these problems center on the fact that, as the channel drains, sediment transport continues, and bed forms continue to migrate. The bed forms and structures preserved on the dry river bed are therefore not truly representative of the structures that would be formed by a river system that flows continuously.

A different procedure was used by Williams (1971), who examined flood-deposited sediments in the Lake Eyre Basin in Australia. After an especially severe seasonal flood, otherwise dry stream beds carried flows 2-6 m deep. After the flood subsided, the beds were exposed for observation. Williams found a direct relationship between the presence of dunes and the presence of large-scale trough cross-stratification. This conclusion was based on observations of the dry stream beds, along with some observations of the flow at the time of the flood. Velocities and flow characteristics were measured in another river in the same alluvial system. In that case, the bed forms ranged from ripples to plane beds, indicating a wide range of flow velocities. In the measurements taken, however, the velocities ranged from 0.67 to 1.96 m/sec. The major thrust

of Williams' work was in the area of sedimentary structures. By examining a number of troughs dug in the dry river beds, he was able to draw genetic relations between certain types of bed forms and certain sedimentary structures. The main relations connected lobate (three-dimensional) ripples with small-scale trough cross-stratification, dunes with large-scale trough cross-stratification, and sand waves with tabular cross-stratified sets. This is an expansion of the relationships seen by Harms and Fahnestock, but it lacks the direct correlation between flow and bed forms which the work of Harms and Fahnestock had.

This same general pattern runs through several studies in natural environments. In studies of the Tana River in Norway by Collinson (1970), and of the Brahmaputra in East Pakistan by Coleman (1969), techniques similar to those of Harms and Fahnestock were used, with similar results.

Collinson (1970) was able to assign three classes of sedimentary structures to three scales of observed bed form. He attributed small-scale and large-scale trough cross-stratification to ripples and dunes, respectively. He also noted the presence of large "linguoid bars," which he related to the production of planar-tabular cross-stratification. His "linguoid bars" are sand waves, as defined earlier. An important observation by Collinson was the formation of reactivation surfaces in linguoid bars. He saw these as "low-angle erosion surfaces, truncating underlying foresets

and succeeded by normally dipping foresets." He attributed the formation of these surfaces to a change in stage of the river. As the stage fell, the linguoid bars stopped migrating and were eroded along their lee faces. When the stage rose again, the bars were "reactivated," and their continued movement buried the old erosion surface. In this way, a cross-cutting surface was emplaced across the foresets.

Coleman (1969) noted that the rate of deposition was much higher in the Brahmaputra than in other rivers that had been studied. This resulted in formation of very large bed forms and fuller preservation of internal structures. Flow in the Brahmaputra can generate sand waves 7.5 to 15 m high, with spacings of 185 to 900 m. In some cases these were observed to migrate 640 m in a single day (Coleman, 1969). The higher rate of aggradation assured rapid and complete burial of structures, preserving them from reworking by the passage of subsequent bed forms.

In summary, studies in modern fluvial environments have produced a picture of a three-stage progression. As flow strength increases, bed-form size increases. Ripples produce small-scale trough cross-stratification, whereas dunes produce large-scale trough cross-stratification. Sand waves produce large-scale planar-tabular cross-stratification. The available data concentrate mostly on the smaller-scale features, both on the bed surface and in the sedimentary record.

Studies in Tidal Environments and Estuaries

In addition to studies made in streams and rivers, there have been a number of attempts to examine relationships between bed forms and structures in areas of tidal currents. In several cases, intertidal areas were studied where the tidal range is sufficient to expose the sediment bed for several hours. This permits the examination of bed forms and the sedimentary structures generated by them in some detail. In addition to this regular, short-period bed exposure, these areas are often very wide in comparison to rivers. This allows the formation of many more features of broad areal extent, such as sand waves.

Reineck and Singh (1967) showed that in areas of high current velocity and coarse sediment, the major sedimentary structure is large-scale cross-stratification, which they attributed to dune migration. In this case, the structures were revealed in box cores from the bed of a tidal channel. Reineck (1963) showed that internal structure of large sand waves was often generated by the action of smaller bed forms. Boothroyd (1969), in a study of bed forms and sedimentary structures in an estuary in northeastern Massachusetts, noted that two different types of dunes produced two different types of stratification. Whereas three-dimensional dunes form typical trough cross-stratification, two-dimensional dunes produce large-scale planar cross-stratification. The two-dimensional features are formed at lower flow strengths than

the three-dimensional features (Boothroyd, 1969). Boersma (1969), examining a similar environment in the Netherlands, found that large linear dunes generated large-scale cross-stratified sets.

Dalrymple, Knight, and Lambiase (1978), working in a part of the Bay of Fundy, looked at the development of very large bed forms (dunes and sand waves) on sand bars exposed to strong, asymmetrical tidal currents. In the examination of the structures, however, their interpretation of the structures was limited somewhat by the effects of flow reversals. During each tidal cycle, the flow reaches $\tau_{o\ crit}$ (the minimum bed shear stress necessary for sediment transport) in two directions. This results in modification of the bed forms by flow reversal.

Other studies made in tidal environments (e.g. Reineck and Singh, 1980; Hayes, 1975; Nio et al., 1980) have drawn similar pictures of the relationship between bed forms and structures. In each case, a measurement of flow velocity in an area is made. After the bed becomes exposed, bed forms are examined at the same location (or as near as possible) and trenches or box cores are made for examination of structure. In most cases, the highest velocity measured, or some type of time-averaged mean velocity, is correlated with the bed forms observed. In each of these studies, the flow velocities are related to bed forms actually observed.

In some recent studies (Tarasov, 1977; Rubin and McCulloch,

1980) flow velocities have been related to bed forms observed on side-scan sonar or echo-sounder records. In these cases, there was no attempt to examine the types of structures produced, largely because the water depths were in the range of 20 to 85 m. Some problems in resolution of small-scale bed forms exist (Bouma et al., 1980), but large-scale forms are relatively clear on side-scan records. In situations where the bed is not seen, some precautions must be taken to ensure the validity of sonar-based data. Bed photographs or other independent data-taking techniques can serve this purpose.

Studies of Recent Sediments

A third kind of field study that deserves mention is the examination of recent sediments in areas where they are not in direct contact with the depositing flow. The work of Frazier and Osanik (1961) is an example. In this situation, trenches being excavated for the construction of a lock on the Mississippi River were examined. The suite of structures observed (primarily large-scale trough cross-bedding) could be related to the environment of deposition. Since the only significant sedimentological agent in the area was the river, the structures could be assumed to have been created by the river. The only factors missing were the details of the flow, e.g. velocity and flow depth. While a general picture of the type of flow responsible for the structures could be obtained, the details of development of the structures could not be determined.

Developing the relationship between a particular environment and the assemblage of sedimentary structures therein is a common theme in recent sediment studies. Wherever the major agent in sediment transport and deposition can be determined (river, lake, estuary, etc.), a study of the overall suite of structures as exposed in cores and trenches can yield a fair representation of the environment of deposition. For example, Coleman, Gagliano, and Webb (1964) examined inter-channel deposits in the Mississippi delta, and Hayes (1975, 1980)

examined estuaries and barrier-island environments.

The work of Jones (1979) is an attempt to examine an even older group of sediments. In a study of fluvial channel deposits preserved from the Upper Carboniferous, Jones found a well-preserved collection of sedimentary structures. Because the structures were especially well exposed, he was able to speculate in some detail about the type of flow processes which prevailed at the time of deposition. Specifically, he saw evidence for the modification of large structures by smaller ones. This implies modification of large bed forms by smaller ones.

All of these studies in preserved sediments produced models of depositional environment based on collections of sedimentary structures and lithologies. While such models are excellent for the purpose of reconstructing overall depositional environments, they are unable to provide information about the exact nature of the fluid flows involved. This would mean that a general model could be developed, but it might be limited in its applicability because certain flow conditions may exist that did not exist in the area from which the "general" model was derived. A method for examining the generation of sedimentary structures under controlled conditions would therefore seem useful.

CHAPTER 4

EXPERIMENTAL STUDIES

In experimental physical sedimentology, "under controlled conditions" usually means in a flume, channel, or tank of some sort. There have been numerous flume studies, whose object has been to derive a relationship between flow conditions and bed forms. Although limited in scale, laboratory studies offer a means of studying migration of bed forms under equilibrium conditions with good control and good observability.

Relationships between Flow and Bed Configuration

Simons and Richardson and their coworkers (Simons and Richardson, 1960, 1961, 1962; Simons, Richardson and Albertson, 1961; Simons, Richardson, and Nordin, 1965; Guy, Simons, and Richardson, 1966) at the U.S. Geological Survey have generated the major portion of the existing data on the relationship between flow characteristics and bed forms in shallow flows. In their data analysis, they recognized a relation between stream power $\tau_o U$ and median fall diameter of the sediment grains. This produced a two-dimensional graph that shows fields in which specific types of bed forms would be generated (Simons, Richardson, and Nordin, 1965). A given stream power combined with a given fall diameter should produce a specific type of bed form. Unfortunately, the use of stream power leads to

some ambiguity, since as many as three different values of flow velocity can be associated with a single value of shear stress (Middleton and Southard, 1977). The U.S. Geological Survey data have been used as the basis for several attempts to relate combinations of flow and sediment variables to specific bed phases. Allen (1968) used flow power to generate a diagram similar to that of Simons et al. (1965), mentioned above. Vanoni (1974) generated a three-dimensional graph with axes defined by the Froude number $\mu/\sqrt{gd}$, dimensionless flow depth $\rho^2 gd^3/\mu^2$, and the ratio of flow depth to grain size d/D. Southard (1971) used the same dimensionless depth $(\rho^2 gd^3)/\mu^2$, with dimensionless velocity $(\rho\mu^3)/\mu g$, dimensionless grain size $(\rho^2 gD^3)/\mu^2$, and density ratio ρ_s/ρ. If the fluid and sediment are taken to be water and quartz sand and temperature is reasonably constant, the variables in Southard's diagram become flow depth, velocity, and grain size. This produces a three-dimensional graph which draws one-to-one relations between bed forms and combinations of depth, velocity, and sediment size. The result of this is that a known combination of the first three variables will produce a specific bed configuration, i.e., a bed covered with a group of bed forms of the same gross morphology (Harms et al., 1975). The depth-velocity-size diagram has been expanded by later workers to include coarser sediments (Costello, 1974; Southard and Costello, 1981) and larger flow depths under modelling conditions (Boguchwal, 1977; Bohacs, 1981). All of these experimental programs were

devised to study the bed forms; the structures generated were largely unexamined.

Experimental Studies on Generation of Structures

Flume experiments have been run to study the relationship between bed forms and sedimentary structures under laboratory conditions. These experiments have involved running the flume until an unchanging bed state is created, examining the bed forms present, draining the flume, and then drying and sectioning the bed (McKee, 1957). This is a slow process, requiring long waiting periods for the sand to dry sufficiently to permit sectioning. Other studies, using side-wall photographs (Jopling and Walker, 1968; Middleton, 1965), have been restricted to a longitudinal profile along the wall of the flume. Most flume studies have been made at a zero aggradation rate -- meaning that there is no net buildup of the bed. In the absence of net aggradation, most sedimentary structures are erased by reworking of the sediment by passage of later bed forms. The only structures preserved, and visible in section cuts made after the flume run is completed, are those in very deep troughs and those created by the last bed form to pass the sampling station. In the studies that have involved aggradation, either climbing ripples were produced (e.g. Ashley, Southard and Boothroyd, 1981; Allen, 1971, 1973; Jopling and Walker, 1968; McKee, 1965) or artificial deltas were construct-

ed (Jopling, 1960; McKee, 1957). The climbing-ripple studies produce structures similar to those found in low-energy, high-sediment environments such as river flood plains and areas of overbank flow (McKee, 1966), or areas of glacial sedimentation (Jopling and Walker, 1968). While these are indeed natural environments, they represent only a small subset of all the environments in which cross-stratification is produced by migrating bed forms. The studies of artificial deltas have been largely concerned with the description of how stratification originates (Jopling, 1960, 1965; McKee, 1957). These have determined what processes lead to the inhomogeneity of sediment that we see as stratification, but they have little applicability to the determination of diagnostic flow phenomena present when the strata were deposited.

Limitations of Previous Experiments

All of the laboratory studies cited above examined small-scale features and processes. Study of the generation of sedimentary structures on a large scale has not been approached in the laboratory. The reasons for this are quite simple and understandable. As mentioned above, most flume experiments involve almost total reworking of the sediment bed. If a flume is allowed to run for a very long time, all the structures created in the early part of the run are erased. This is a situation similar to a natural case in which a flow is operating under conditions of nondeposition. In such a case, most of the structure preserved

is that generated near the end of a period of flow. Structures can be more nearly completely preserved for study only if there is net aggradation of the bed. In a flume, preservation of structure is difficult because of the size limitations of the channel. Bed aggradation by addition of sediment can be used for small bed forms, such as ripples. As the scale of bed forms increases, however, the practical problems increase. If an experiment to produce climbing dunes were to be attempted, the scale of all dimensions would have to be increased dramatically.

The physical size of most recirculating open channels places limits on the quantity of sediment that can be added. If, for example, a channel is 50 cm deep, adding 20 cm of sediment and 25 cm of water leaves only 5 cm for added sediment to build up the bed. Obviously this is not enough to allow substantial preservation of structures. If a large flume is built with the idea of simulating shallow alluvial and estuarine flows, the bed forms generated will approach half a meter in height. Adding enough sediment to preserve structures in this case is beyond the ability of all but the most ambitious research operations.

From the preceding discussion a few basic concepts emerge: (1) the best information, to date, relating depositional environments to sedimentary structures has come from field work; (2) field work is limited by the inability to control, and often even to measure, precisely, the flow and sediment transport variables; (3) flume studies permit control and measurement of those variables, but size limitations restrict in their usefulness in

studying the generation of sedimentary structures. Both field and laboratory studies on the relationship between bed forms and stratification involve substantial difficulties that have hindered progress. Field studies require a setting in which the bed can be examined in detail; this means either trenching when water levels are low at some time after the generating flow has ceased, or subaqueous coring soon after the flow event. In addition, flow and bed forms must be monitored during the generating event. In any case, appropriate correlation between the past history of the flow and the present picture of stratification is typically ill-defined or uncertain.

In flume studies it is simpler to monitor flow and observe structures, and the past history of the flow is well known and controllable. However, flume studies suffer from unrealistically small scale, and the quantities of sand needed to generate a deposit more than one bed-form height thick exceed the capacity of most flumes. It therefore seems apparent that sedimentology can benefit from the development of a technique that allows the generation of sedimentary structures under the controlled conditions generally associated with flume studies. The remainder of this dissertation is concerned with the exposition, description, and demonstration of such a technique as applied to large-scale bed forms.

CHAPTER 5

THE NATURE OF AGGRADATION

As discussed in the following chapter, the technique for synthetic reconstruction of sedimentary structures developed in this dissertation can be used to simulate structures produced under conditions of net aggradation as well as under equilibrium conditions of zero aggradation. In order to evaluate the applicability and limitations of this technique in the aggradation case, some discussion of the nature of aggradation is necessary at this point.

Aggradation in Terms of Sediment Conservation Equation

The main controls on bed-material sediment transport rate per unit width, q_s, in steady uniform flow are flow velocity U, flow depth d, and sediment grain size D. Increasing U increases q_s, but decreasing d or D increases q_s (Williams, 1967). Depth and velocity can change readily in a given natural flow system, but grain size is fixed by the sediment available. In flume experiments, all of these controlling factors can be changed readily.

In nonuniform flow, unit rate of transport of suspended bed material, q_{ss}, typically adjusts by increasing or decreasing in the downstream direction at spatial scales greater (and usually much greater) than bed-form spacing; unit rate

of transport of bed load, q_{sb}, typically adjusts faster, at scales less than one bed-form spacing. Similarily, in unsteady flow, q_{ss} (and therefore c_s, average volume concentration of suspended bed material above a unit area of the bed) typically adjusts less rapidly than q_{sb} (and therefore c_b, volume of bed load in transport above a unit bed area divided by flow depth). Effects involving wash load (suspended sediment whose grain sizes are not present in the bed) need not be considered here.

Deposition or erosion of sediment at some point on the bed is associated with changes in q_s and in c, the average volume concentration of sediment in transport above a unit area of the bed, according to the well-known sediment conservation equation

$$\frac{\partial h}{\partial t} = - \frac{1}{1-\lambda} \left(\frac{\partial q_s}{\partial x} + d \frac{\partial c}{\partial t} \right)$$

where h is height of the bed at a given location (when the bed is aggrading, $\partial h/\partial t$ is positive), λ is porosity, t is time, and x is distance downstream. Thus, aggradation is associated with streamwise change in transport rate of either suspended bed-material load or bed load, or temporal change in volume concentration of sediment (again, either suspended bed-material load or bed load) in transport. Since, if wash load is disregarded, $q_s = q_{ss} + q_{sb}$ and $c = c_s + c_b$, in analyzing the possibilities for aggradation, four distinct rate-of-change terms must therefore be considered (Table 1). Aggradation of the bed by spatial change in bed-load transport rate may have effects on bed forms and structures that differ from those produced by spatial change in suspended-sediment concentration

TABLE 1

Rate-of-change terms in sediment conservation equation associated with net aggradation of the bed.
See text for definition of symbols.

MODE OF TRANSPORT	NATURE OF CHANGE: SPATIAL		NATURE OF CHANGE: TEMPORAL
Suspended-bed-material transport	$-\frac{\partial q_{ss}}{\partial x}$	Suspended-load fallout	$-\frac{\partial c_s}{\partial t}$
Bed-load transport	$-\frac{\partial q_{sb}}{\partial x}$	Bed-load slowdown	$-\frac{\partial c_b}{\partial t}$

or by temporal change in volume concentration of sediment in transport (bed load or suspended load), because migration of bed forms is governed in an essential way by bed-load transport but not by suspended-load transport. Temporal change in volume of bed-load in transport, proportional to $\partial c_b/\partial t$, will not be considered further because it cannot lead to aggradation of large thicknesses of sediment.

Temporal Change in Suspended-Sediment Concentration

In cases where suspended-sediment concentration is changing, either spatially or temporally, the bed forms migrate over a constantly rising base level. As sediment is showered out of suspension, it builds up each bed form, which then climbs up the elevated stoss slope of the next bed form downstream. The depositional structure created by this aggrading process is low-angle or high-angle climbing-bed-form structure. The bed forms migrate under relatively constant flow conditions and act in a certain sense as sediment traps.

Spatial change in suspended load is more important in fast processes, such as the deposition of climbing-ripple structure. The availability of large amounts of suspended sediment and rapid deposition from suspension can generate structures with high angles of climb. Deposition from suspension due to downstream change in sediment concentration is the only way to generate very high angles of climb because it is the only depositional process that can operate fast enough

over moving bed forms (Ashley et al., 1981).

Temporal change in suspended sediment concentration is likely to occur as a result of a slow change in flow conditions at a given location that reduces the ability of the flow to keep material in suspension. As flow conditions change, the bed forms under the flow will react to the changes. A typical deposit created by a slowly decelerating flow might consist of a vertical series of beds, each containing thinner cross-laminations. The series would be the product of a decrease in bed-form size with decreasing flow velocity, and would be produced only under a deep flow containing a high concentration of bed material in suspension. The structures would be preserved by aggradation of the bed, caused by fallout of material from suspension.

In all cases of bed-form climbing by temporal or downstream decrease in suspended-sediment concentration, the bed forms effectively lose no sediment as they migrate; the rate at which sediment is permanently locked up in the bed by bed-form climbing is just matched by addition of sediment onto the bed forms by fallout from suspension.

In an experiment designed to generate climbing-ripple structure, Ashley et al. (1981) simulated downstream change in suspended-sediment concentration. They did this by showering sediment into a flume over a reach of migrating bed forms. Under these circumstances, sediment was deposited evenly, over the entire bed. As shown by comparison

of an aggrading run with an equilibrium run, there was little modification of bed forms caused by aggradation. The major effect of increased sediment input was to increase climb angle of the bed form. This is expected, since $\tan \theta = V_y/V_x$, where θ is the angle of climb and V_y and V_x are aggradation rate and migration rate of the bed forms, respectively. The limited degree of modification of bed forms indicates that the ripples were able to adjust dynamically to the flow conditions, in spite of the large sediment influx.

The experiments by Ashley et al. (1981) showed that typical climbing-ripple stratification is produced in a very short time. Aggradation rates were typically high, on the order of 10-15 cm/hr. These rates were possible since bed aggradation was occurring by deposition from suspension. As the ripples migrated under the constant sediment fallout, they moved vertically as well as down the channel. When sedimentation rate was high enough relative to migration rate, the entire profile of each ripple was preserved as depositional-stoss stratification. Each ripple was able to migrate on a constantly aggrading bed surface, and it therefore behaved like a ripple migrating up a sloping average bed surface under equilibrium conditions. At lower aggradation rates, less of each bed form was preserved, and the structure involved erosional-stoss climbing-ripple stratification.

Downstream Change in Bed-Load Transport Rate

Climbing-bed-form structure produced by downstream decrease in unit bed-load transport rate q_{sb} is limited to relatively low angles of climb, by the following line of reasoning. For a fairly long train of climbing bed forms to exist in the first place, flow conditions appropriate for the existence of the given kind of bed form must prevail along a reach of flow many bed-form spacings long, so that the percentage change in q_{sb} over a distance of one bed-form spacing must be small (and thus also $\partial h/\partial t$, by the sediment conservation equation) relative to the migration rate of the bed forms. Angle of climb Θ is related to aggradation rate $V_y = \partial h/\partial t$ and bed-form migration rate V_x by the equation $\tan \Theta = V_y/V_x$. Assuming two-dimensional triangular bed forms, $V_x = 2\, q_s/H$ (where H is bed-form height) and so $V_x \propto q_{sb}/H$. Since as argued below, bed-form shape remains unchanged as the bed forms migrate and shrink, $H \propto L$ (where L is bed-form spacing), so $V_x \propto q_{sb}/L$. Since $V_y = \partial h/\partial t \propto \partial q_s/\partial x >> q_{sb}/L$ under the assumed conditions, $\tan \Theta = V_y/V_x$ is small.

If q_{sb} decreases rapidly in the downstream direction, sediment is deposited in delta-foreset deposits, similar to those created by Jopling (1960). Rapid change in q_{sb} has to be due to a fairly rapid change in flow velocity. Over a short distance, a large decrease in flow velocity means that the flow is strongly nonuniform. Under such conditions of strongly

nonuniform flow, it is likely that bed forms will decay into small delta-like bodies, depositing angle-of-repose bedding as they grow shorter and smaller and ultimately merging to form a single large delta. Under such conditions, climbing of bed forms would occur only as one delta front moved out over another, as simulated by Jopling (1960). The flow velocity would have to drop nearly to the threshold velocity for sediment movement over a relatively short distance to produce large negative values of $\partial q_s/\partial x$. If q_{sb} changes at a slower rate, the bed forms will react in a different way, based on the rate of deposition (or angle of climb).

In the case of downstream change in q_{sb}, two distinct processes -- one kinematic and one dynamic -- affect the bed forms simultaneously. Due to aggradation under conditions of negative $\partial q_{sb}/\partial x$, the migrating bed forms must continuously lose sediment to the bed. This is in striking contrast to the $\partial c/\partial t$ case. This adjustment must occur as a decrease in either migration rate or size of the bed forms, if the bed forms maintain their individual identity. Decrease in q_{sb} is most readily caused by decrease in the flow velocity; at constant discharge this can happen if the flow depth and/or width increases. Decrease in velocity also causes dynamic adjustments in bed forms, in that the bed forms tend to adjust toward a new equilibrium geometry and migration rate in response to the changing flow conditions. For ripples, this adjustment occurs largely as deceleration of the bed forms, with bed-form size remaining

approximately constant. In certain cases, large-scale bed forms such as dunes adjust not only by decelerating but also by becoming smaller (Williams, 1967). Rubin and Hunter (1981) note this coincidence between kinematic and dynamic shrinkage of large-scale bed forms when $\partial q_{sb}/\partial x$ is negative.

In examining natural environments, it is difficult to imagine a case in which the two different processes would not operate simultaneously. Flow velocity is the major controlling factor in both processes, and it is the most likely factor to vary rapidly in a natural case. Slower flows generate smaller, slower-moving bed forms.

Rubin and Hunter (1981), in their model for deposition by climbing bed forms, assume that the bed forms maintain equilibrium shapes as they lose sediment by climbing, but they do not fully justify this assumption. A possible way to provide a rationalization for this assumption is to construct a hypothetical experiment to examine possible changes in shape of bed forms depositing sediment by downstream decrease in sediment transport. These possibilities are:

Case I: bed forms deposit sediment while decreasing angles of stoss face and/or slip face to zero;

Case II: bed forms deposit sediment while increasing angles of stoss face and/or slip face;

Case III: bed forms deposit sediment but maintain equilibrium shape.

Both Case I and Case II ignore the control exerted on bed-form shape by dynamics. On a bed-form-by-bed-form basis, shape is controlled by the dynamic relation between the bed form and the flow, involving such effects as flow separation and reattachment. These effects operate to give each bed form its characteristic shape. The normal bed-form profile is maintained by the effects of dynamics on each bed form. Since both cases I and II require that the bed forms be deformed from normal shapes, they cannot be valid. This leaves only Case III, meaning that the bed forms maintain their equilibrium shapes as deposition occurs.

Bed forms must also tend to readjust in size to counteract the tendency to shrink to a size smaller than that dictated by equilibrium with the locally prevailing flow conditions. The model developed by Rubin and Hunter (1981) does not take into account this mode of bed-form readjustment during deposition. This process must operate, since as deposition occurs, the amount of sediment in the bed forms must decrease, and the bed forms have to sort themselves out to account for this decrease. If the entire train of bed forms is considered, the size of the bed forms is controlled by the dynamics of the relationship between flow and bed forms. Net aggradation forces the bed forms to become smaller, since each bed form leaves sediment behind in the bed as it migrates. As the bed forms become smaller than the size dictated by dynamic controls, they will tend by other processes to grow so as to re-establish equilibrium size. Presumably, for smaller and smaller rates of

change, as $\partial q_s/\partial x$ approaches zero, bed forms approach their equilibrium shapes and sizes asymptotically.

At present there are no data on average bed-form height and spacing as a function of $\partial q_{sb}/\partial x$ for given mean flow velocity (even for ripples, let along large-scale bed forms) to reveal where the balance is struck between the shrinkage effect during climb and the tendency for the bed forms to re-equilibrate in average size. However, some indirect idea can be gained by comparing bed-form shrinkage at given values of $\partial q_{sb}/\partial x$ with the rates at which bed forms in an equilibrium train undergo random change in height and spacing, on the reasonable supposition that the rate of re-equilibration is strongly correlated with the underlying extent of variability in bed-form size. Specifically, at low values of $\partial q_{sb}/\partial x$ it seems likely that rates of random change in bed-form shape at equilibrium are larger than rates of change due to depositional effects, so that bed-form adjustability is high. To test this possibility, variations in bed-form size at equilibrium were examined using data gathered in the present study (see Chapter 8). For a run with two-dimensional dunes, instantaneous values of bed-form spacing were measured at the end of ten equal time intervals for several bed forms as they migrated over a distance about equal to one bed-form spacing, and from these, an RMS value of rate of change in spacing due to random variations around the equilibrium average was computed. Comparison of this value with the rate of shrinkage due

to deposition, for various degrees of flow nonuniformity (Table 2), shows that for low aggradation rates, expressed as small climb angles, the rate of bed-form variation at equilibrium is as large as or larger than the rate of bed-form variation due to shrinkage caused by deposition. At angles of climb up to about 5°, the rate of bed-form variation is larger than the rate of bed-form shrinkage. Therefore, at such rates of bed aggradation, it can be assumed that the bed forms can adjust to maintain not only their equilibrium shapes but also approximately their equilibrium average size. It will be shown in Chapter 10 that such low angles of climb may be responsible for the preservation of a major portion of the sedimentary structure observed in the field.

Preservation of Sedimentary Structures by Aggradation

In examining the types of structures that might be preserved by bed aggradation, it might be useful to examine what effects the different mechanisms could have on preserved structure. Downstream decrease in q_{sb} causes deceleration of bed forms if the bed forms maintain constant size. This is an effect that probably would not leave a distinct sedimentary record. A set of cross beds usually cannot be used to determine migration rate since no independent evidence of bed-form celerity is preserved.

The three different circumstances in which sediment is

TABLE 2

Comparison of rate of random change of bed-form spacing at equilibrium to rates of change of bed-form spacing due to aggradation.

RMS value of rate of random variation in bed-form spacing at equilibrium (ℓ_{RMS}) for Run K-1, calculated by graphic differentiation of spacing/time plot, measured at 10 equal intervals for four bed forms.

Rate of change in spacing due to aggradation (ℓ) calculated at several angles of climb (Θ) for mean spacing/height ratio for the four bed forms examined.

Mean bed-form migration rate = 197 cm/hr
Mean spacing/height ratio for four bed forms = 6.78
ℓ = 6.78 (197) tan Θ

Θ	ℓ (cm/hr)	ℓ/ℓ_{RMS}
1.0	23.3	0.19
1.5	35.0	0.29
2.0	46.6	0.39
2.5	58.3	0.49
3.0	70.0	0.58
3.5	81.7	0.68
4.0	93.4	0.78
4.5	105.	0.88
5.0	117.	0.98
5.13	119.9	1.00
5.5	129.	1.08

ℓ_{RMS} = 119.9 cm/hr

added to the bed, manifested in the three terms $\partial c_s/\partial t$, $\partial q_{ss}/\partial x$, and $\partial q_{sb}/\partial x$, should tend to produce different types of structure. Temporal decrease in c_s or spatial decrease in q_{ss} causes sediment to fall evenly over the whole bed over some local area, building it up everywhere at the same time. A small downstream rate of decrease in q_{sb} will cause each bed form to leave part of itself behind, so that each bed form becomes smaller as it migrates downstream. Both of these cases result in deposition of climbing-bed-form structure. The main differences can lie in angle of climb, duration of the depositional episode and hence thickness of sediment, vertical variation in structure, and any effects of shrinkage of bed forms due to change in q_{sb}. The term $\partial q_{sb}/\partial x$ cannot be large if nonuniformity of flow is to be mild enough for a train of bed forms to exist in the first place so climb angles produced by decreasing q_{sb} will be relatively small. On the other hand, change in q_{ss} can produce either low or high climb angles. In the case of $\partial c_s/\partial t$ the amount of sediment available for deposition, and therefore the thickness of the deposit, is limited by the amount of bed material in suspension above the bed, and some vertical variation in structures is inevitable. These differences provide a means for gauging the likelihood that one or another of the three effects was involved in deposition of a given bed showing climbing-bed-form structure, as summarized in Table 3. Deposition by $\partial q_{ss}/\partial x$ can account for all possible combinations of angle of climb, thickness of deposit, and degree of vertical uniformity of structure.

TABLE 3

Relationships between features of a cross-stratified deposit and likely depositional mechanism

Vertical extent	Uniformity of structure	Angle of Climb θ	
		high	low
thick	vertically uniform	Likely $\partial q_{ss}/\partial x$	Likely $\partial q_{ss}/\partial x$
	vertically nonuniform	Likely $\partial q_{ss}/\partial x$	$\partial q_{ss}/\partial x$ and/or $\partial q_{ss}/\partial x$
thin	vertically uniform	Likely $\partial q_{ss}/\partial x$	$\partial q_{ss}/\partial x$ and/or $\partial q_{sb}/\partial x$
	vertically nonuniform	$\partial q_{ss}/\partial x$ and/or $\partial c_s/\partial t$	$\partial q_{ss}/\partial x$, $\partial c_s/\partial t$, and/or $\partial q_{sb}/\partial x$

If deposition is by $\partial c_s/\partial t$, the type of deposit produced cannot be thick but must be vertically nonuniform, although any angle of climb is possible. Deposition by $\partial q_{sb}/\partial x$ is limited to low angles of climb; $\partial q_{sb}/\partial x$ can produce a vertically nonuniform deposit of any thickness, but it cannot produce a thick vertically uniform deposit.

At small rates of aggradation, all three of these processes produce similar although not necessarily identical types of structure, e.g. because of differing effects of local deposition on temporarily stalled bed forms. As the rate of aggradation increases, modification of bed forms in reaction to lower q_{sb} will begin to alter both shape and size. The only type of modification that will be obvious in the sedimentary record is decrease in size (especially height). For low angles of climb, however, this effect may not be noticeable, because the full height of the bed form is not preserved. Therefore, at low climb angles, the structure will be similar, but not identical.

CHAPTER 6

SYNTHETIC GENERATION OF SEDIMENTARY STRUCTURES

Description of the Technique

Many primary sedimentary structures, like cross-stratification, observed in rocks and recent sediments are the record of the position of the bed surface at a succession of times. The formation of distinct laminae as the result of hydraulic sorting processes that operate during migration of the bed form has been well studied and documented (Jopling, 1960, 1963, 1965, 1967). In nature, this record of bed-form position is expressed as concentrations of mineral grains, grain-size segregations, or other markers that form laminae on the surface of a migrating bed form. These laminae make up what are seen as sedimentary structures in rocks and modern sediments. In trying to model the generation of structures in experimental studies, this concept of laminae as records of position can be applied in another way. Instead of being recorded by mineral-grain concentrations or the like, the position of the bed can be recorded externally, as with a depth recorder or point gauge. Combining a series of such records produces exactly the same result as burying the laminae: sedimentary structures are generated. Any record of the position of the bed surface becomes part of a sedimentary structure, if it is not eroded by passage of successive bed forms.

In all flume studies, until now, the thickness of large-

scale structure has been limited to the height of a single bed form. In earlier experimental work, the generation of thicker structures required that sediment be added to the flume, to allow the bed to build up. To eliminate this need to add great volumes of sediment to the system to produce thick large-scale structures, a synthesis technique has been developed and tested (Corea, 1978). The common system of drying and sectioning the bed to examine structures can then be replaced by a synthesized profile. The simulation of addition of sediment to the system uses a transformation, or reconstruction, of profiles of bed-surface height taken in the course of ordinary flume runs in which no aggradation has occurred. In this way, bed aggradation can be simulated without actually adding sediment to the flume.

In a zero-aggradation case, structures generated by one bed form are partly or largely erased by reworking of the sediment by passage of successive bed forms, but progressively more complicated structure develops in a layer about one bed-form height below the surface, in the path of migrating troughs, until eventually an approximate balance between production and destruction of structures is reached. The technique described here can also be used to generate zero-aggradation structures in equilibrium flume runs under conditions of no aggradation.

Synthesis of sedimentary structures by this technique operates on the principle that for any cross-stratified deposit produced by migrating bed forms, it should be possible to

duplicate graphically the actual pattern of cross-stratification, as seen in any vertical section through the deposit, by plotting the succession of bed-surface profiles at the location of that section as a time series. In order for this plot to reproduce the cross-stratification, the following conditions must be observed: 1) wherever the given bed profile is higher than the preceding profile, a new lamina is considered to have been deposited; 2) wherever the given profile is lower than the preceding profile, erosion of sediment is assumed to have taken place. Plotting of an entire succession of profiles in this way generates a pattern of cross-stratification consisting of sets of synthetic depositional laminae bounded by surfaces of synthetic erosional truncation. This pattern should coincide with the actual cross-stratification observed in a section through the deposit. The only differences might be in the detailed nature of the laminae, because they are not generated as layers of material falling over the face of the bed form, but, rather, as synthetic time lines. Their overall orientation in any region would, however, be the same.

Figure 1 is a cartoon showing the sequence of steps involved in synthetic generation of cross-stratification. First the profiles are taken individually. Next, they are stacked, to produce an equilibrium, zero-aggradation profile. This is the profile that would be seen if no aggradation had occurred. Finally, synthetic aggradation can be added, thus modifying the equilibrium profile to simulate deposition of a bed thicker than the height

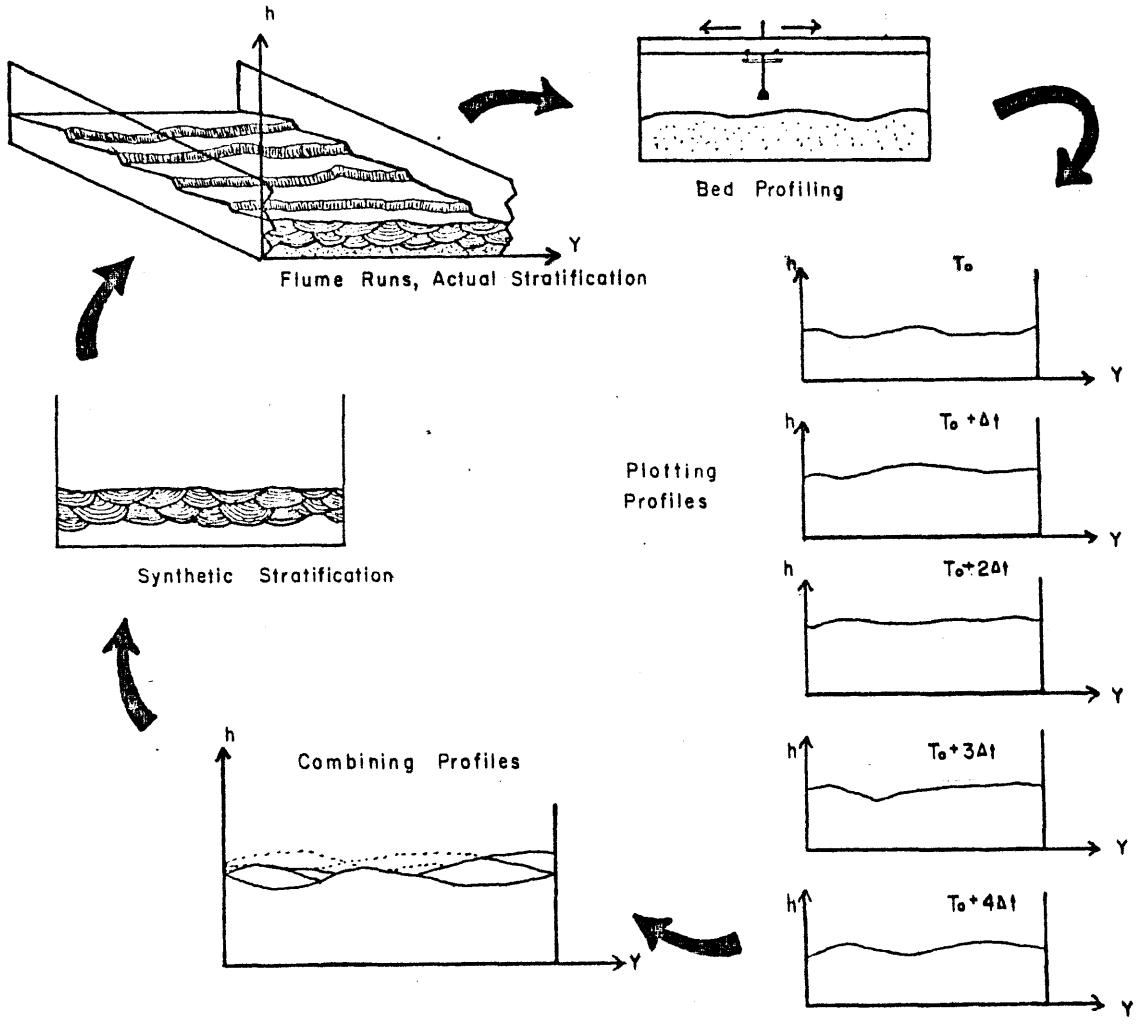


Figure 1 -- Cartoon of the synthesis technique.

of the shifting bed forms. Any number of cases of cross-stratification, each for a different rate of net aggradation of the bed, can be generated from a series of bed-profile measurements made during a single zero-aggradation flume run. To do this it is necessary only to superimpose a constant net aggradation rate on the profile measurements. In practice this means raising each profile by a small uniform increment over the last, as each is plotted, to generate the cross-stratified sections. A series of such sections, each for a different net aggradation rate, can show the range of structures possible from a given set of migrating bed forms. Differences in structures would depend on the conditions of aggradation. In an equilibrium flume run each set of profile measurements would lead to a cross-stratified pattern that differs in detail from all others.

Restrictions on Application

For zero aggradation, the synthetic technique described above should be expected to reproduce very closely the structures produced by migration of bed forms. That this is indeed the case was demonstrated earlier by the writer (Corea, 1978) for small-scale current ripples. Streamwise and transverse profiles of bed-surface elevation were taken while ripples developed to equilibrium from a flat sand bed, and the synthetic structures produced by application of the technique were virtually identical to the actual structures revealed by direct sectioning of the bed.

There is one important qualification to applying the technique to cases of nonzero aggradation. If the existence of net aggradation changes the characteristics of the migrating bed forms in any way relative to the case of no aggradation but the same local mean flow depth and mean flow velocity, then the synthetic cross-stratified section generated from the zero-aggradation run would differ from the actual cross-stratified section that would be found by sectioning a deposit produced under conditions of actual aggradation. As discussed in the last chapter, deposition by downstream and/or temporal decrease in concentration of suspended bed-material load ($\partial q_{ss}/\partial x$, $\partial c_s/\partial t$) should lead to no substantial changes in geometry or migration of the ripples simply by virtue of the existence of a nonzero aggradation rate. (Possible changes in ripples caused by high suspended-sediment concentrations

are not considered here.) Therefore, the synthetic technique should reproduce well the nature of the structures generated in this case. However, it was also shown in the last chapter that deposition by downstream decrease in bed-load transport rate ($\partial q_{sb}/\partial x$) should be expected to cause modification of bed-form size at moderately negative values of $\partial q_{sb}/\partial x$. For these values of $\partial q_{sb}/\partial x$, the synthesis technique does not account for such modifications.

An examination of typical angles of climb in cross-stratified deposits produced by bed-form migration indicates that angles of climb are very small, so that the bed forms have time to adjust to the rate of sediment influx as they migrate. In this way, they maintain approximately their equilibrium profiles, even though some aggradation is taking place. An examination of natural environments in which deposited large-scale bed forms have been studied (Harms and Fahnestock, 1965, Frazier and Osanik, 1961) shows that low angles of climb are very common for large-scale sedimentary structures. It therefore seems justified to apply the synthetic technique to cases of slow aggradation by small negative $\partial q_{sb}/\partial x$ in the expectation that important natural cases will be modelled without serious distortions. However, changes also occur in cases of local climb, in which one bed form climbs over another. On a bed-form-by-bed-form basis angle of climb should not exceed a few degrees if the synthetic technique is to produce reasonable results.

In summary, the technique is best applied to synthesis of conditions of aggradation by small to moderate negative values of $\partial c_s/\partial t$ or $\partial q_{ss}/\partial x$ and should not be used to simulate bed aggradation by downstream decrease in q_{sb}, except at near-zero rates of bed aggradation at which bed form shrinkage due to deposition is negligible; see also the discussion in the section on climbing dunes in Chapter 10.

CHAPTER 7

EXPERIMENTAL ARRANGEMENT

Flume

The runs were made in a very large flume constructed especially for the modelling of large-scale bed forms (Figs. 2 and 3). The flume consisted of two wooden channels side by side, 60 m long, 2.25 m wide, and 1.5 m deep, connected at the ends to form a closed circuit. The walls of the flume were multi-layered. The inner face was a sheet of 1/4" plywood faced with several layers of glass fiber cloth, impregnated with polyester resin. The outer face was a sheet of 3/4" plywood. Between the faces was a 1" (2.54 cm) polystyrene bead-foam sheet for thermal insulation. A frame of 2 x 4 studs spaced at one-foot intervals braced the wall vertically. The wall was held vertically by 4 x 4 braces spaced at four-foot intervals. The wall was modified in one section after a catastrophic failure in which a 30 m long section of the wall collapsed outward. At that time 4 x 4 braces were augmented by 1/2" steel rods placed across the top of the channel at four-foot intervals to hold the walls in place.

The channel was constructed directly on the concrete floor of the laboratory. A seal between the floor and the wall was maintained by a layer of stiff grease emplaced along the base of the wall. A sheet of fiberglass and a sheet of plastic lapped onto the grease seal from the wall. The seal

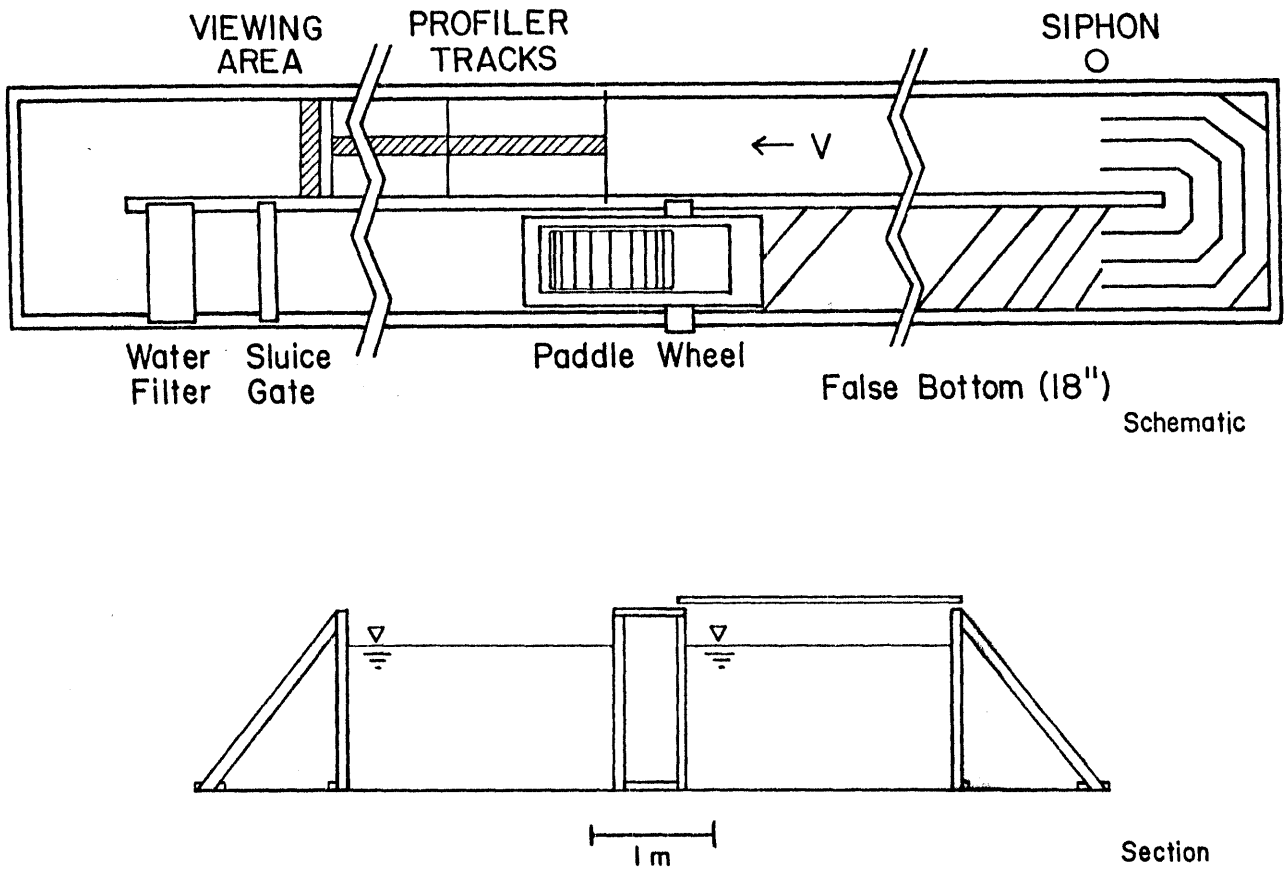


Figure 2 -- Diagram of the 60 m flume

FIGURE 3

Photograph of the 60 m flume



was secured by sandbags and concrete blocks to maintain firm pressure.

To permit the flume to operate at the high water temperatures necessary for dynamic scale modelling, the channel was covered. The covers were constructed of 4' x 8' sheets of 1/4" plywood backed by a 2 x 3 stud frame covered with polyethylene sheeting and were insulated with a sheet of 1" polystyrene beadfoam.

An observation window was installed at a point 50 m downstream along the working section by replacing an eight-foot section of the plywood wall with an eight-foot piece of 1" Plexiglas, reinforced with a steel frame. This allowed observation of the flow and the bed through the wall while runs were in progress.

Paddle Wheel and Drive

The pumping mechanism consisted of a paddle wheel 6 m in diameter, driven by a 40 horsepower electric motor. The speed reduction from the 1800 RPM motor to the 10 RPM wheel was accomplished by driving the wheel at its rim, using a friction drive. In addition to reducing the rotational speed, this system also reduced the necessary weight of the frame-work of the wheel itself. Discharge was controlled by changing the depth of immersion of the wheel in the flow; this was accomplished by raising or lowering the wheel on a tiltable frame. Discharge was measured by the use of a drowned-under flow sluice gate

that constricted the flow just upstream of the paddle wheel. Measurements of differential water levels on both sides of the gate yielded the head loss across the gate. The accuracy of these measurements was $\pm$ 2 mm. Combining this with the accuracy of the velocity-area method for calculating discharge yielded a velocity error of $\pm$ 7%. This head loss was compared to standard tables and calibrated against flow velocity with a Price current meter. This calibration gave a direct measurement of flow velocity by measurement of the difference in water height across the sluice gate. This calibration and other details of the hydraulics of the flume are discussed fully in Bohacs (1981).

The flume operated as a recirculating system. The flow was pumped down one channel by the paddle wheel; it flowed around the bend at the downstream end of the return channel through a set of turning vanes that suppressed secondary flow and flow separation at the inner wall of the bend; it flowed the full length of the working channel, and after passing the observing station, it passed around the other bend and returned, through the sluice gate, to the paddle wheel. The flume was designed to minimize generation of any abnormalities in the flow: the paddle wheel fitted into the channel with a clearance of less than 5 cm on each side, and a false bottom under the wheel reduced backflow and improved efficiency. Also, a hydraulic jump usually formed at the upstream end of the working channel, minimizing secondary circulations created by the bend or the pumping system. The effectiveness of this is shown by the

cross-channel uniformity of large-scale bed forms just downstream of the jump. Because the flume recirculated both water and sediment, sediment transport rate was controlled only by the flow conditions and not by regulation of a sediment-feed device. The water-surface slope in the flume was also controlled by the conditions of the flow. The flume was non-tilting since the channel was constructed directly on the concrete floor of the laboratory.

Profiler and Track

The bed profiles were obtained in two ways: photographically and ultrasonically. The sonic depth sounder was custom-built by Locom, Inc., Vista, California. This unit was originally designed for profiling of small bed forms in a shallow marine environment (cf. Dingler, Boylls, and Lowe, 1977). In consists of two separate parts. The main part is an electronics package containing the sonar transmitter and receiver, digital-to-analog converter, and power supply (See schematic diagram in Appendix 1). The second part is the sonar transducer. The profiler uses a digital timer to measure the time taken for a pulse to travel from the transducer tc the bed and back. Using a 4 mHz pulse limits resolution to more than 0.4 cm. A voltage dependent on the travel time is generated by summing the digital time and con-

verting it to an analog value. Therefore, a direct plot can be made of the distance between the transducer head and the sediment bed.

In attempting to apply a transducer designed to measure small bed forms in shallow seawater to the measurement of large-scale bed forms in a hot-water flume, several problems developed. The two most serious were caused by thermal expansion of the transducer head and the limited dynamic range of the sonar receiver. The former was solved by removing the waterproof faceplate of the transducer. This allowed trapped air or mineral oil in the body of the transducer to expand. It also brought the piezoelectric crystal transducer in direct contact with the water, thereby increasing its sensitivity. The latter problem was solved by modifying the electronics of the receiver to alter the listening curve of the digital receiving section. Neither of these modifications was completely successful, but they allowed the unit to produce usable results.

The transducer head was suspended on an aluminum rod from a cart that ran on a 3" aluminum I-beam. The I-beam was suspended across the top of the channel, just below the covers. The cart moved along the track driven by a sprocket-and-chain system. The drive sprocket was attached to a rod that extended outside the flume to an electric motor. In this way the motor and the reduction sprockets could be mounted outside the flume, so that they were not affected by

the high temperature and humidity in the channel above the water surface.

Two tracks were built: one parallel to the flow along the centerline of the channel, and the other transverse to flow. This allowed the measurement of bed-surface profiles either longitudinally or transversely.

The system operated as follows: the motor-sprocket system moved the transducer cart across or along the channel. As the transducer cart reached the end of the track, it activated a switch that shut off the drive motor and tripped a reversing relay. The relay reversed the connections to the motor. The motor was an AC stepping motor, so this reversal caused it to run in reverse. With the motor running in reverse, the drive system operated in reverse, and the cart returned to the starting position. Once back at the starting end, another switch was tripped by the cart. This switch shut off the drive motor. The sonar signal was carried from the transducer by coaxial cable out of the flume into the electronics package. The electronics package generated an analog voltage, dependent on the distance between the transducer and the bed. This voltage was then plotted by a strip-chart recorder.

As the bed height varied under the transducer, the voltage varied. This variation deflected the pen of the strip-chart recorder. The recorder ran at a rate of 25.4 cm/min, and the profiler cart moved at 101.6 cm/min; therefore strip-chart records were, in fact, profiles of bed-surface height

with a 4:1 reduction in horizontal scale. In this way, the profiler system generated real-time profiles of bed height in the channel.

In addition to profiles, 16 mm time-lapse movies were taken at the observing station. The camera operated at a rate of three frames per minute, yielding a time-lapse ratio of 360:1. The movies were useful in examining the small-scale transient features of the bed forms, which occasionally did not show up on the profiler records because of the time interval between profiles.

The general procedure for a run was as follows: The water depth in the flume was adjusted to a still-water depth of 1 meter ($\pm$5 cm). The paddle wheel was started and then lowered to an approximate operating depth. After a few minutes for stabilization of the system, the discharge was measured at the sluice gate. Based on this reading, and the desired velocity for the particular run, the height of the paddle wheel was adjusted to a final operating position. This process was repeated to keep the discharge constant through each run. At this point, the time-lapse camera and run clock were started. As the run progressed, measurements of water slope, head loss across the sluice gate, and water temperature were made at regular intervals.

During each run, bed profiles were taken at regular time intervals. The time between profiles was longer during runs in which longitudinal profiles were made than those in which

transverse profiles were made. Longitudinal profiles required a profiling time of approximately 3 min; transverse profiles required less than 1 1/2 min. Including two-way travel, these times restricted longitudinal profiles to one every ten minutes, while transverse profiles could be made every five minutes.

Specific data for each run are given in Table 4. For each run, the basic data set consisted of the profiles, time-lapse movies, slope measurements, discharge measurements, and water temperatures. This data set allowed the complete characterization of the flow, the bed forms, and, by synthesis, the sedimentary structures.

TABLE 4 -- Summary of Flume Runs

Run	Depth (cm)	Velocity (cm/s)	Temperature (^{o}C.)	Duration (hr)	Bed Form Height	Bed Form Length	Bed State
K-1	147	68.4	64.8	12.45	58 cm	390 cm	2D Dunes
K-2	145	73.4	65.0	12.93	47	289	3D Dunes
K-3	143	74.9	66.6	24.53	52	414	3D Dunes
K-4	133	61.5	61.9	32.06	19	157	2D Dunes
K-5	120	56.7	58.0	30.56	14	207	2D Dunes
K-6	140	98.6	62.0	36.21	--	---	HV Dunes
K-7	143	86.3	62.3	66.70	25	565	3D Dunes
K-8	134	100.8	59.9	14.70	61	783	HV Dunes
K-9	136	78.5	58.5	8.34	30	431	3D Dunes
K-10	129	82.6	56.2	16.40	59	517	3D Dunes
K-11	143	67.6	55.8	12.3	24	262	2D Dunes
K-12	130	99.1	55.1	19.14	35	461	HV Dunes
L-1	115	70.0	42.0	42.24	24	317	3D Dunes
L-2	117	57.5	52.0	9.40	25	240	3D Dunes
L-3	109	83.7	46.7	13.05	33	405	HV Dunes

All measurements are scaled to 10^{o} C.

CHAPTER 8

EXPERIMENTAL RESULTS

Modelling

The flume experiments used the principle of dynamic scale modelling. This standard technique was first demonstrated to be applicable to the study of bed forms by Southard et al. (1980) and first applied by Boguchwal (1977). The basic concept of the method is that, if dynamic and geometric similitude are maintained between two steady uniform flows, both will show identical relations between flow conditions and bed-form characteristics. By keeping the ratios of the four modelling parameters discussed earlier (Reynolds number, Froude number, density ratio, and length ratio) constant between the laboratory model and the natural case it is possible to model the behavior of natural flows in a laboratory setting. Of these four ratios, those of mean flow depth and median sediment diameter are equivalent dimensionally to any length scale, if the modelled and model cases are geometrically similar. With these ratios constant the sediment and fluid in the model are chosen such that $(\rho s/\rho)_r = 1$. Since g does not vary appreciably, if the model is restricted to earth-surface conditions, equality of Froude numbers between the two flows yields:

$$U_r = (d_r)^{1/2}$$

Model fluid viscosity is then set by the Reynolds number:

$$\mu_r = \rho_r \, (d_r)^{3/2}$$

Substituting kinematic viscosity ($\nu = \mu/\rho$) gives:

$$\nu_r = (d_r)^{3/2}$$

or, rearranging:

$$d_r = (\nu_r)^{2/3}.$$

This is the length-scale ratio for dynamic scale modelling in this kind of sediment transport system (Southard et al., 1980). Kinematic viscosity controls velocity scaling by the factor:

$$U_r = (d_r)^{\frac{1}{2}} = \nu_r^{1/3}$$

and discharge scaling by the factor:

$$Q_r = (d_r)^{5/2} = \nu_r^{5/3}$$

As temperature increases, the kinematic viscosity of water decreases, so scale factor increases. This was the reason for constructing and using a high-temperature laboratory open channel. At high water temperatures (55-65 deg.C) the length scale ratio is about 2 relative to a natural flow at 10 deg.C. In the series of flume runs discussed here, the length scale ratio varied from 1.75 to 2.11, and the velocity scale ratio varied from 1.32 to 1.45. In the analysis of sedimentary structures generated by bed forms in these flume experiments, the scale ratio has no effect on the geometry of

the bed forms. Lengths of bed forms scale at the same ratio as heights, and profiles of the bed are not distorted by the modelling technique. The benefit of dynamic scale modelling is that it allows the study of very-large-scale bed forms and sedimentary structures in a laboratory open channel. The flow depths and velocities modelled in the experiment are common in small rivers and shallow tidal currents, and the sedimentary structures are likely to be found in these types of natural environments.

Sand

In order to generalize results of the experiments, two sand sizes were used in the flume runs. The K series used AFS 50 foundry sand with actual mean diameter 0.27 mm and σ = 0.17 mm. The L series sand was 00 blasting sand with mean diameter 0.44 mm and σ = 0.24 mm. Cumulative size curves for the sands are shown in Fig. 4 . Both sands were obtained from the Holliston Sand Company (Holliston, Mass). They were quartz-rich (quartz > 90%), and derived from glacial outwash. The presence of a small percentage of dark mica (biotite) in the sand was helpful in delineating small-scale sedimentary structures in side-wall photographs taken as bed forms passed the observation window.

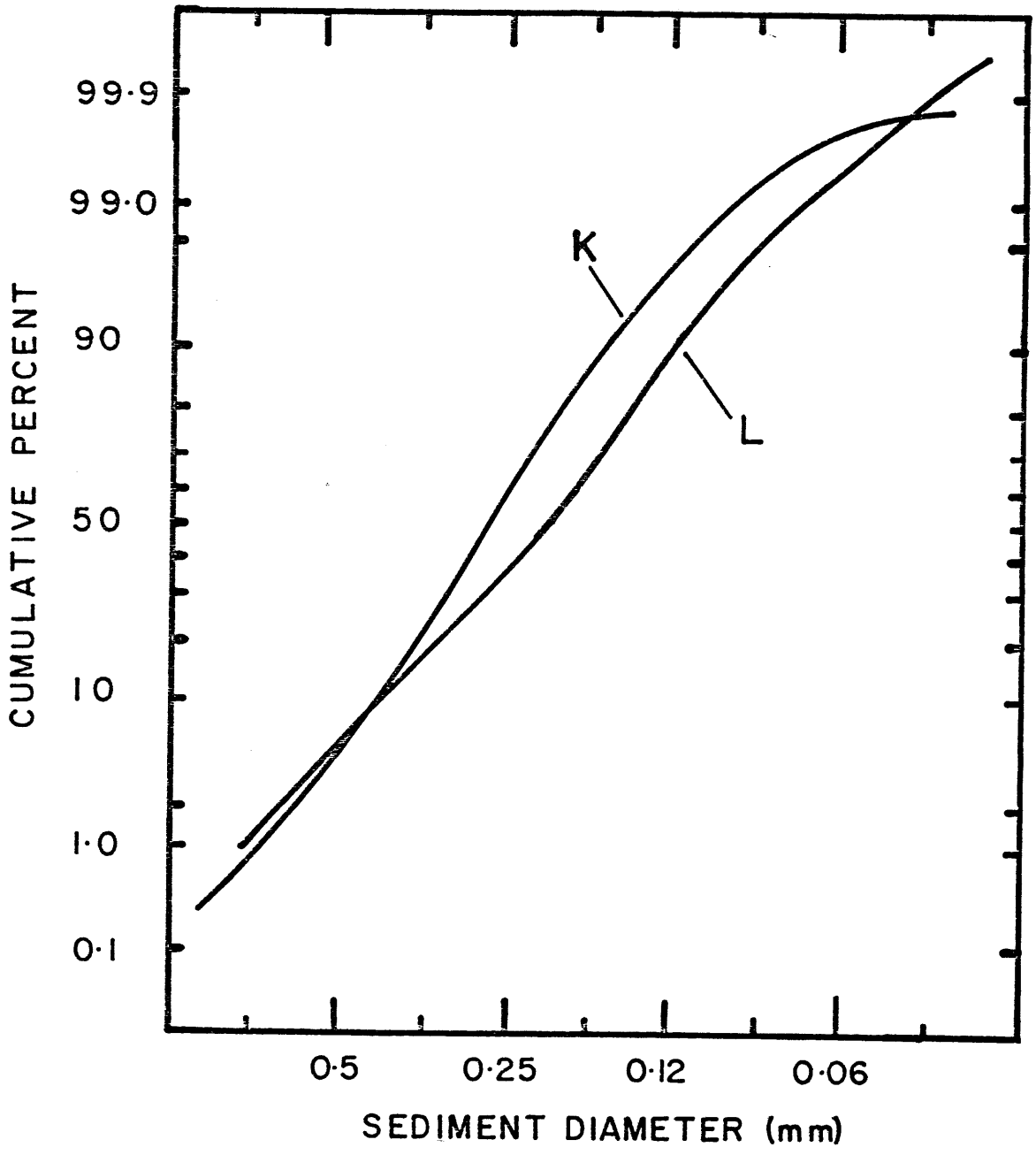


Figure 4 -- Size analyses of sands K and L

Data On Flow and Bed Forms

Data taken from the flume experiments are common to two separate dissertations. This work is concerned with the synthesis of large-scale cross-stratification as generated by the migration of large bed forms. A separate dissertation (Bohacs, 1981) deals with the dynamics and kinematics of these bed forms. While the data set for both theses is, of necessity, identical, the focus of each dissertation, and therefore the way the data are used, is totally different.

The flume experiments produced three types of sedimentary bed forms as flow velocity increased. These were: two-dimensional (2D) dunes and three-dimensional (3D) dunes as defined by Costello and Southard (1981), and higher-velocity (HV) dunes. The term higher-velocity dunes is a provisional term for a subclass of the dune bed phase, which may at least in part be equivalent to sand waves seen in natural flow environments (cf. Bohacs, 1981). The primary differences between these bed-form types lie in spacing, height, and profile shape.

For the runs from the K series for which profiles are available, the scaled average velocities, bed-form heights, bed-form spacings and standard deviations are given in Table 5.

Histograms of heights, spacings and height/spacing ratio for the entire K series are given in Figs. 5, 6, and 7. These show the progressive increase in size from 2D dunes to 3D dunes to HV dunes. There are overlaps in each dimension

TABLE 5

Summary of Data from K Series

	$\bar{V}$ (cm/sec)	σ	$\bar{L}$ (m)	σ	$\bar{H}$ (cm)	σ
2D dunes	68.0	0.57	3.26	0.91	41.0	24.0
3D dunes	80.2	5.54	4.51	1.21	40.25	15.7
HV dunes	99.5	1.15	6.22	2.28	48.0	18.4

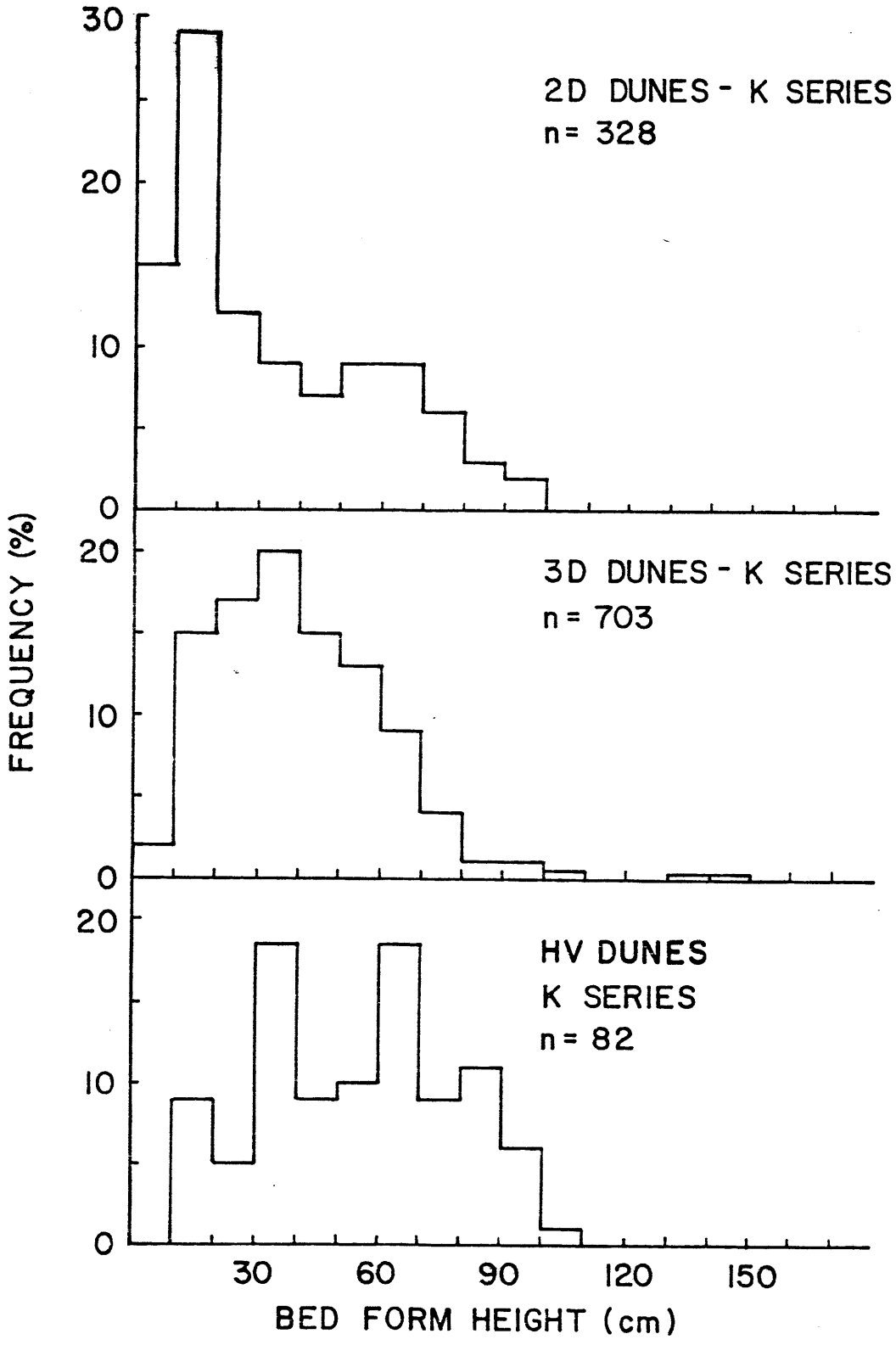


Figure 5 -- Histograms of bed-form height: 2D dunes, 3D dunes, HV dunes

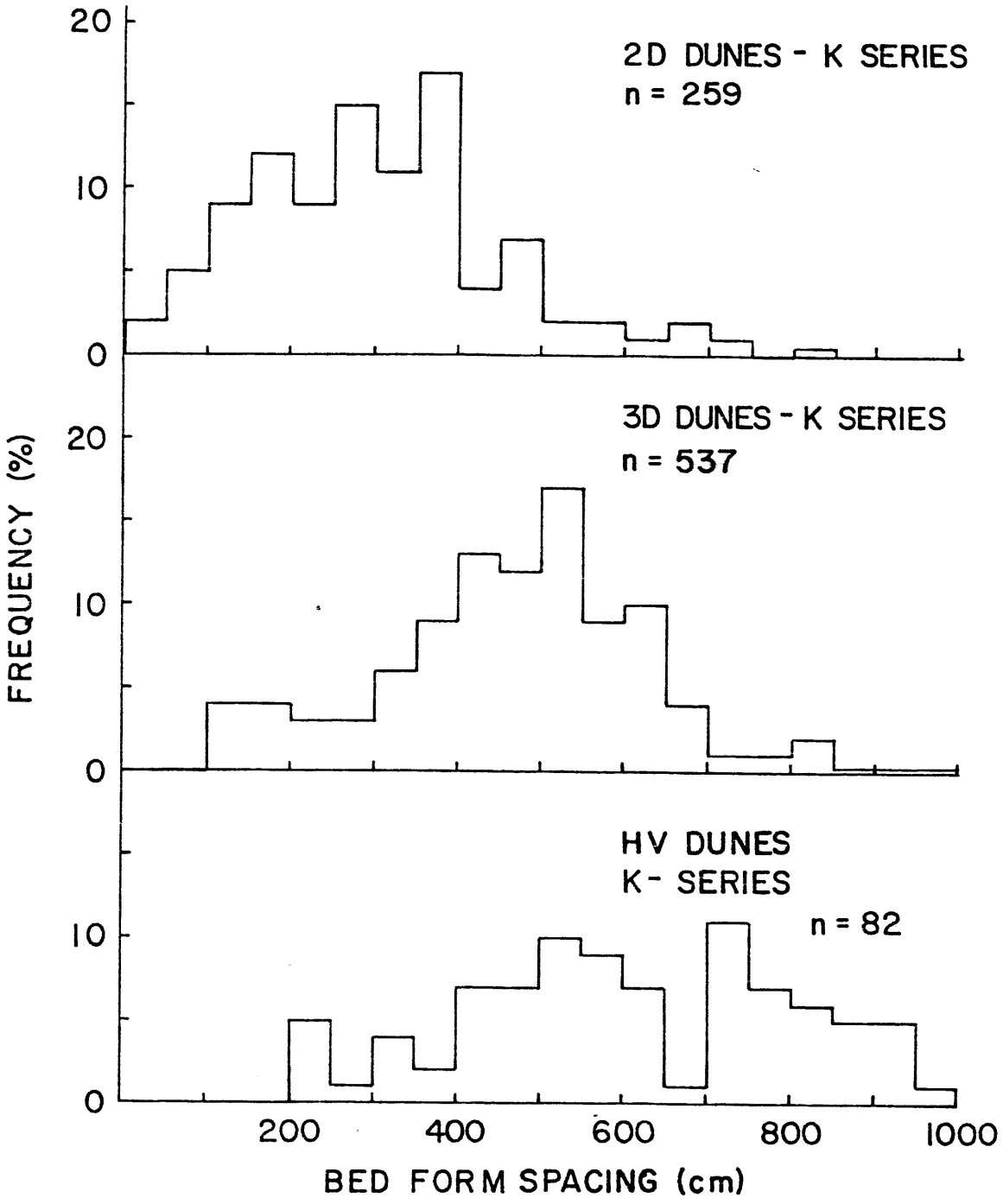


Figure 6 -- Histograms of bed-form spacing: 2D dunes, 3D dunes, HV dunes

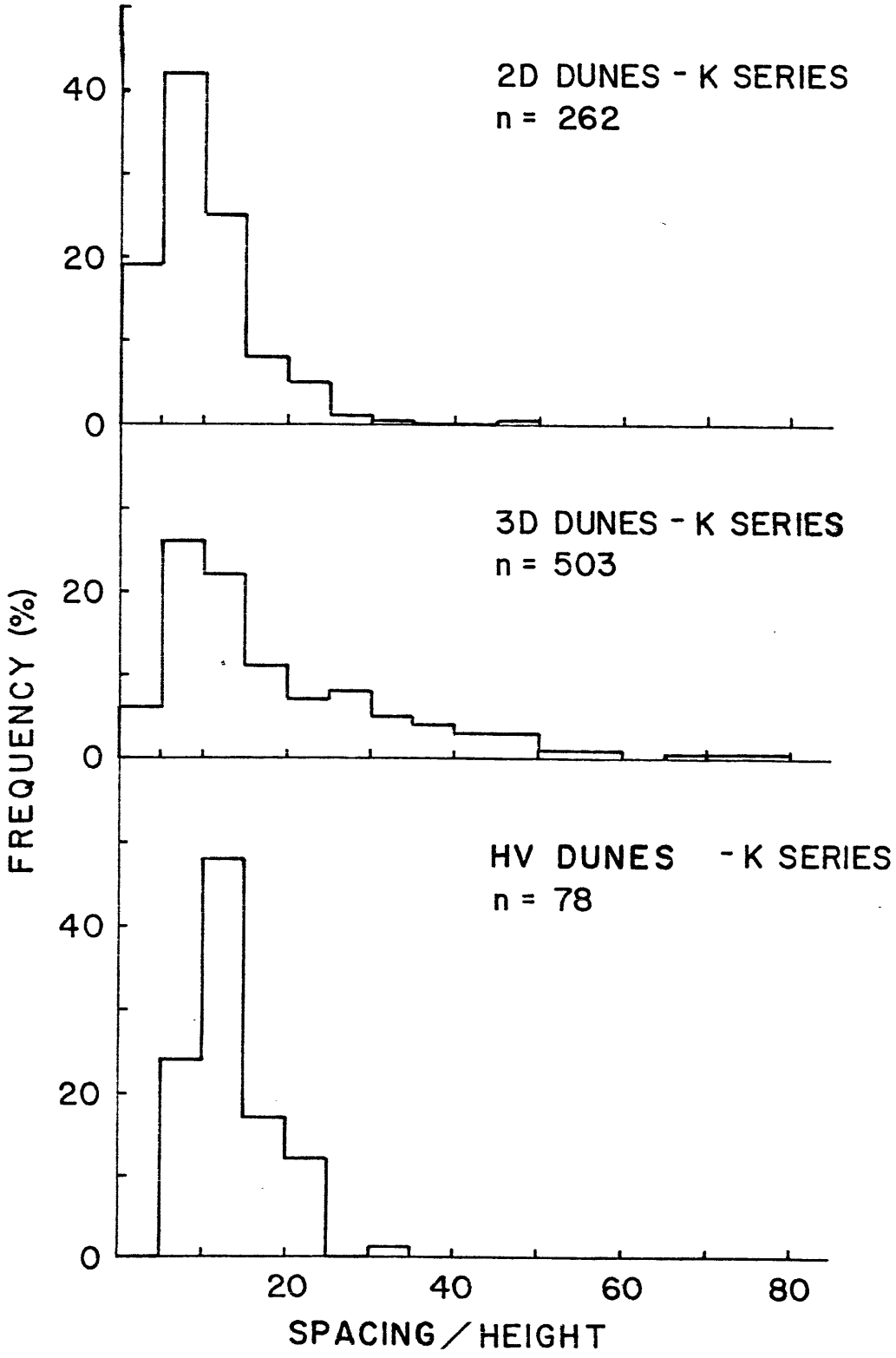


Figure 7 -- Histograms of bed-form spacing: 2D dunes, 3D dunes, HV dunes

between the three bed-form types. The important aspects of the histograms, however, are the modes and the ranges. Two-dimensional dunes show a wide range of lengths and heights, generally skewed toward lower values. Three-dimensional dunes are more symmetrically distributed around the mean. HV dunes have a polymodal distribution and show the greatest ranges of heights and spacings, but have a low standard deviation of height/spacing ratio. This indicates that, while HV dunes exist in many sizes, their geometry is generally more nearly constant than that of 2D and 3D dunes. This constancy of geometry will arise again in the discussion of the structures created by HV dunes.

For the L series, no separate histograms were produced because of the limited amount of data available. Scaled average values of flow velocity and bed-form spacing and height are given in Table 6.

The values from the K and L series show that as the grain size increases from the K series to the L series, the velocity required to generate a certain bed state decreases. This agrees with the data of Dalrymple et al. (1978; their Fig. 4).

Plotting values for the runs of Series K and L on a depth - velocity - grain-size diagram shows that all of the runs lie in the fields for dunes or sand wave. Figure 8 is a depth-velocity diagram modified from Rubin and McCulloch (1980) on which all of the runs plot in the dune field. On a velocity-size diagram modified from Dalrymple et al. (1978)

TABLE 6

Summary of Data from L Series

	$\overline{V}$ (cm/sec)	$\overline{L}$ (m)	$\overline{H}$ (cm)
3D dunes	63.5	2.79	24.2
HV dunes	83.7	4.05	33.0

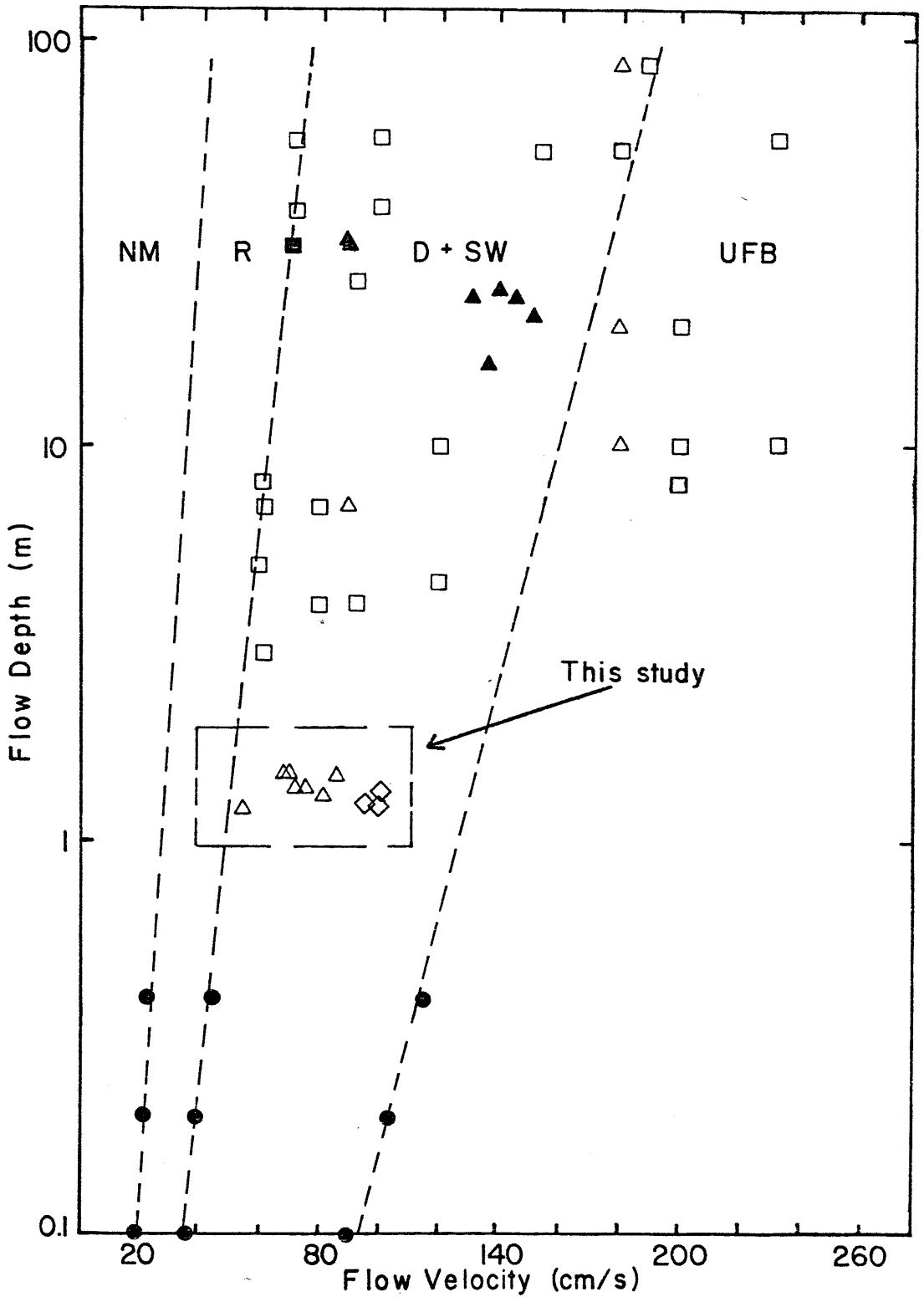
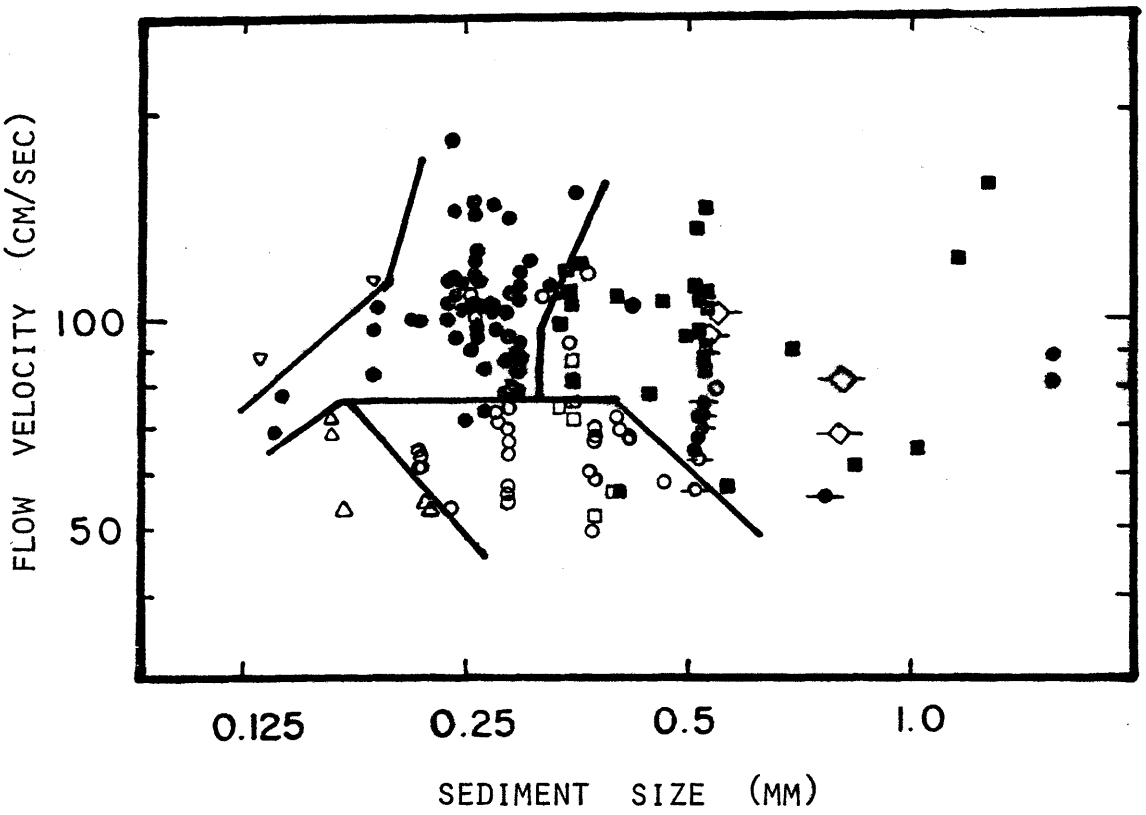


Figure 8 -- Depth-velocity diagram (after Rubin and McCulloch, 1980)

all of the runs plot near the postulated boundary between dunes and sand waves (Fig. 9). From the comparison of these two plots, it appears that stability fields for dunes and sand waves are defined better by velocity and grain size than by velocity and depth. A complete discussion of the classification of the bed forms observed in this study can be found in Bohacs (1981).



Symbols:

△ - ripples

○ - 2D dunes

● - 3D dunes

□ - ripples on sand waves

■ - dunes on sand waves

▽ - upper plane bed

◇ - HV dunes

Figure 9 -- Velocity-size diagram (from Dalrymple et al., 1978) points from this study shown by ticks

CHAPTER 9

SEDIMENTARY STRUCTURES: ZERO AGGRADATION

Features of Zero-Aggradation Synthetic Sections

As a first step in examining the generation of sedimentary structures by migrating bed forms, zero-aggradation sections were constructed using the synthesis technique for each bed-form type. As discussed in Chapter 8, these profiles depict accurately the structures that would have been found if the flume channel had been drained and dried, and the bed had been sectioned.

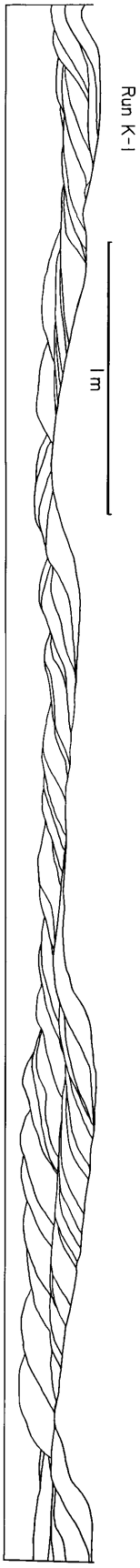
The number of bed forms that pass the observing station affects the amount of detail seen in the lower parts of the synthetic sections. The structure in the upper parts of the zero-aggradation sections is primarily created by the last bed form to pass the observing section. Detail in the lower part of the sections is the product of passage of earlier bed forms. As more bed forms pass through the profiled section, more detail is added to the structure in the lower troughs.

Two-Dimensional Dunes

Fig. 10 is the synthetic zero-aggradation longitudinal section from Run K-1. This section shows four bed forms

FIGURE 10

Synthetic zero-aggradation longitudinal section, Run K-1


Run K-1
1m

and the structure generated as they migrated. The bed forms have scaled spacings of about 3.6 m, and scaled heights of 21 - 31.5 cm. The most notable feature of the section is that it shows the mode of migration of the bed forms. Since individual bed profiles were made at uniform intervals, nonuniform spacing between profile lines in the section indicates the degree of nonuniformity in the rate of migration of the bed forms. In the center of the section, it can be observed that some bed-form climbing has taken place even though there was no net aggradation, either actual or assumed, during the run.

A synthetic zero-aggradation transverse section for the same run (Fig. 11) shows a rather surprising lack of structure. The primary reason for this is that the deepest troughs in the train of bed forms examined all eroded the bed to the same depth. Since the bed was not built up by aggradation, no structures were preserved in the trough. The "climbing" seen in the longitudinal section is merely a depiction of the overtaking of one bed form by another. Because the bed forms had very straight lee faces and crests, in the cross-stream direction the troughs are linear rather than curved, as indicated by the straight trace of the trough on the section.

The bed forms in Run K-1 have several distinctive features. They have fairly regular spacing and straight crests, and show some evidence of bed-form merging, in which one bed form overtakes and coalesces with another. In a transverse section, the bed forms appear very straight. All of these properties are

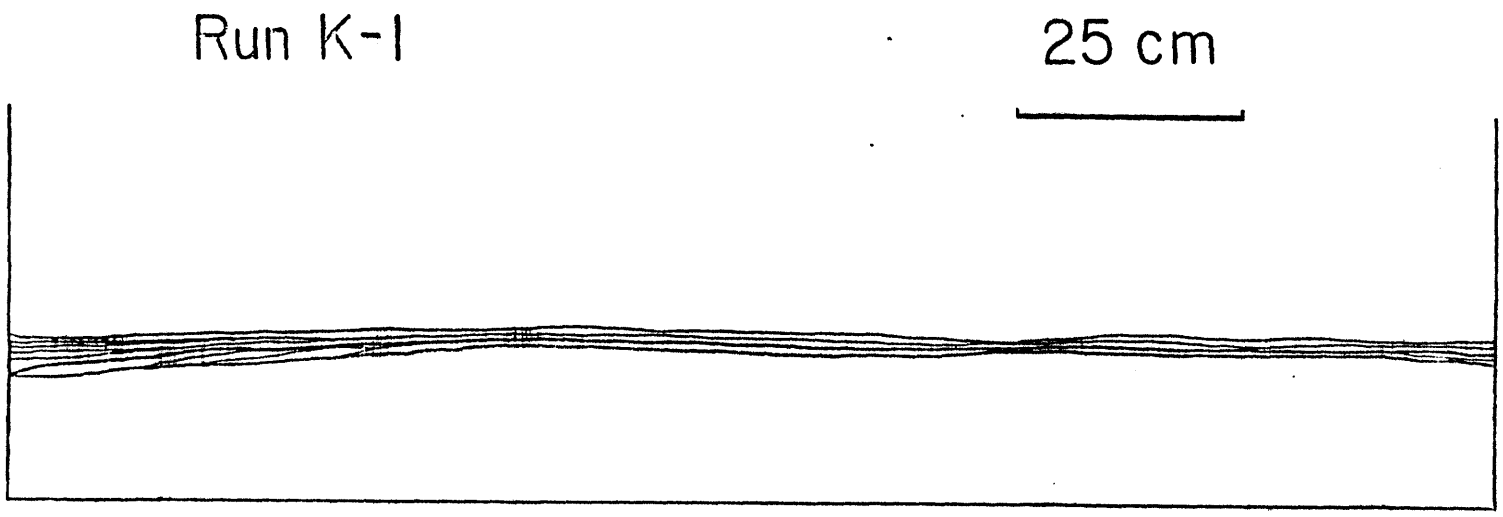


Figure 11 - Synthetic zero-aggradation transverse section, Run K-1

characteristic of two-dimensional dunes.

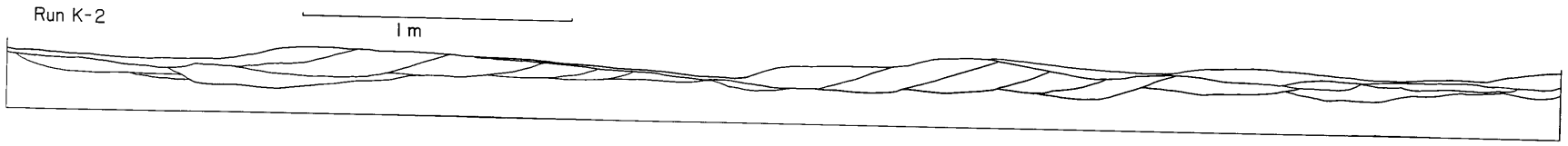
Three-Dimensional Dunes

Figure 12 is a synthetic zero-aggradation longitudinal section from Run K-2 showing three migrating bed forms. This section displays some significant differences from that of Run K-1. The first is the regularity of spacing of the time lines. This is indicative of the regularity with which these bed forms migrate. There is no local climbing of one bed form over another. These bed forms do not migrate by coalescing; they move through the observing section at an even rate, with no overtaking. Another difference is that the K-2 bed forms show some differences between individual bed forms in the train. This is especially noticeable in the second bed form, at about the middle of the profile, which displays a "humpback" shape with a high crest several centimeters upstream of the slip face on the lee side. The scaled lengths of the bed forms in this run are similar to those in K-1, about 3.2 m, but the scaled heights are slightly lower, about 21 cm. The K-2 bed forms also show a variation in trough geometry and depth of erosion.

The synthesized zero-aggradation transverse section for Run K-2 (Fig. 13) with typical 3D dunes, is markedly different from that of Run K-1. The bed forms in Run K-2 show variable trough depths and crest heights, deep erosional scours in troughs, fairly constant migration rate, and curved, concave-up erosional

FIGURE 12

Synthetic zero-aggradation longitudinal section, Run K-2


Run K-2
1 m

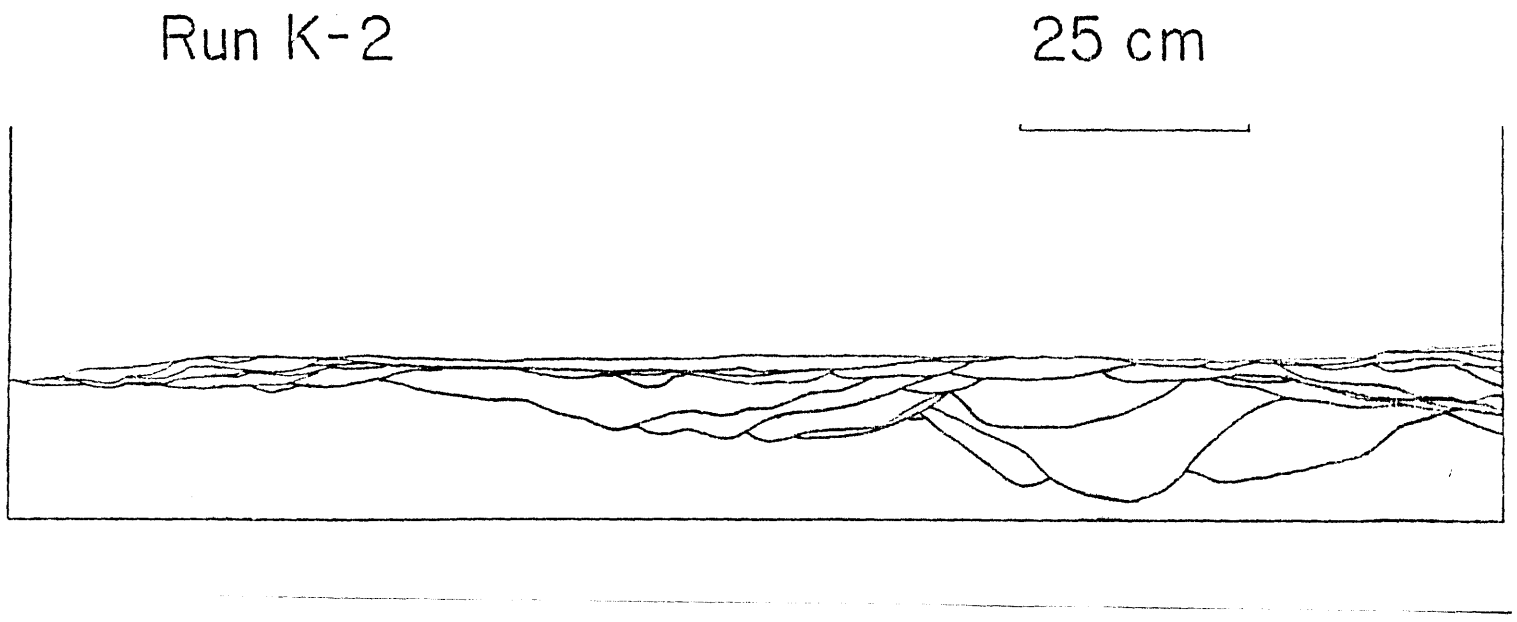


Figure 13 - Synthetic zero-aggradation transverse section, Run K-2

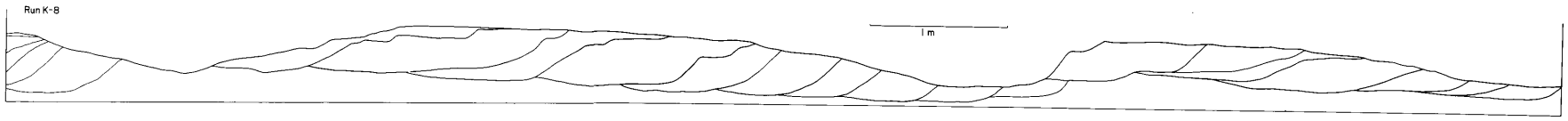
scours. The K-2 section shows concave-up geometry of dune troughs, and considerable variation in depth of trough erosion by successive bed forms. Another aspect of these bed forms is variation in location of the deepest part of the trough. Successive bed forms are not identical, and their erosion troughs do not line up in the streamwise direction. In terms of production of structures, this is an important element of the three-dimensionality of these bed forms, which are three-dimensional dunes.

Higher-Velocity Dunes

The section for Run K-8 (Fig. 14), with HV dunes, shows a different set of characteristics. The bed forms are much longer, with scaled lengths of about 7.0 m and scaled average heights of 0.6 m. The most striking feature of these bed forms is their shape. Instead of the typical dune profiles seen in the sections from Runs K-1 and K-2, these bed forms have long, gently inclined stoss slopes and sharp slip faces that do not extend the full height of the bed form. Instead of rising smoothly, the slip faces are in the form of a series of steps. An examination of the series of profiles indicates that these steps move with the bed form. They are not the result of a series of bed-form overtakings, as was the case with 2D dunes. Rather, these steps on the slip face are smaller bed forms moving down the slip face of the larger bed form. The spacing between the individual profile lines indicates that the bed forms seen here do not move at a constant rate. Since the interval between successive pro-

FIGURE 14

Synthetic zero-aggradation longitudinal section, Run K-8


Run K-8
1 m

files was constant, variations in spacing between profiles indicates variation in bed-form migration rate. The trough depths do appear to be relatively constant, although there are occasional indications of irregularity.

An especially notable element of the geometry of these bed forms is the thin layer of deposited sediment that often develops along the upper surface of the stoss slope. A side-wall photograph from Run K-6 (Fig. 15), in which this bed-form type was also observed, shows that upper-regime flat-bed flow conditions exist on this flat, top surface. Bridge (1981) noted that "as development of a plane bed on dune backs is a result of increasing local bed shear stress, this must be dynamically similar to the plane bed existing in the upper flow regime." Therefore, the sedimentary structure created on the upper surface of the HV dunes is generated by conditions similar to upper-flat-bed flow. At times when sediment supply from upstream is unusually great, deposition of sediment on the back of an HV dune produces parallel lamination. This type of structure is common in areas of deposition under upper-flat-bed flow (Harms et al., 1975). As the dune migrates, the erosional hollow in front of the next dune upstream erodes this parallel lamination and replaces it by angle-of-repose cross-bedding deposited at the lee face of the next bed form. No transverse section was obtained for this type of dune in this sand size. A transverse section from Run L-3 (Fig. 16), in which the bed-form type was the same as in Run K-8, shows some

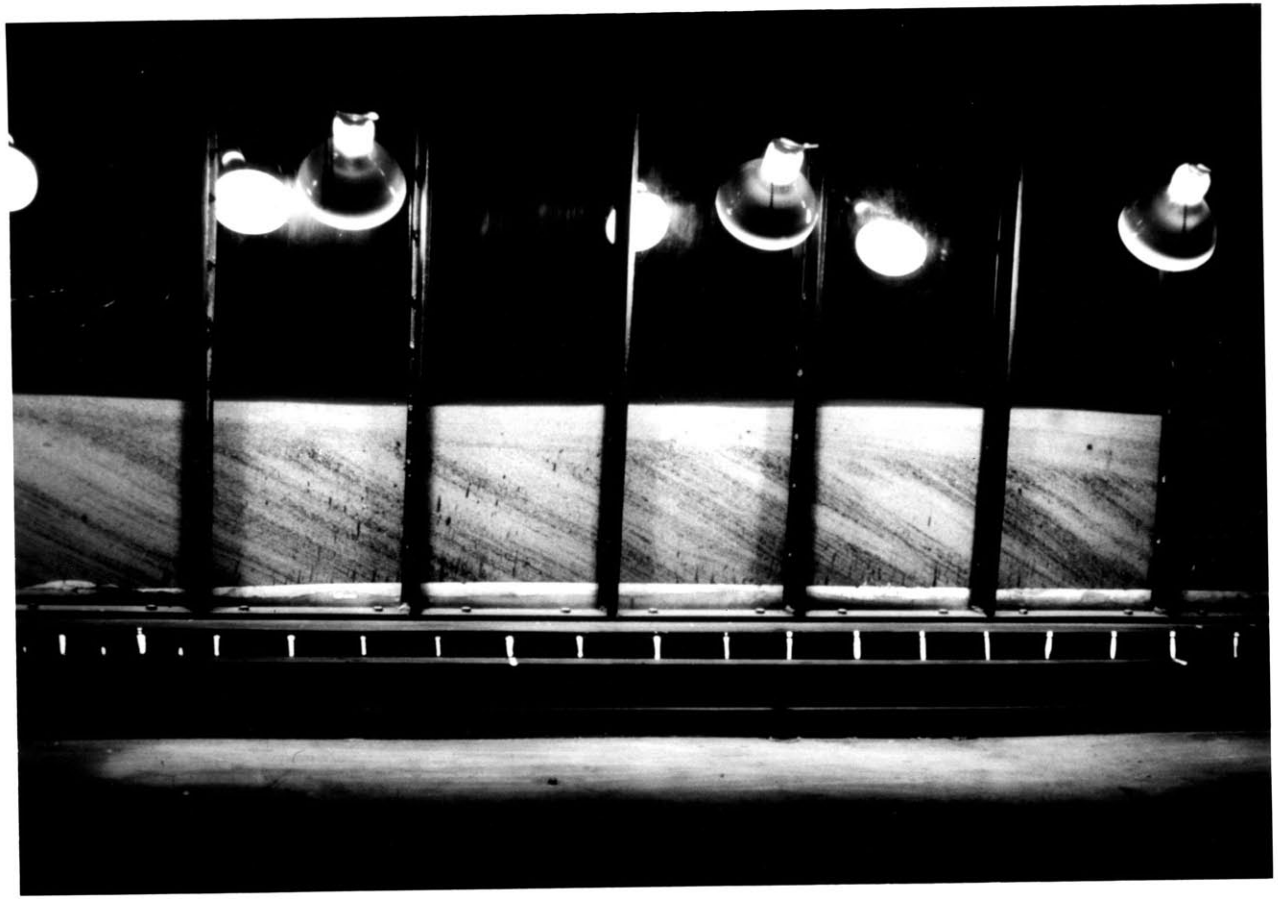


Figure 15 -- Parallel lamination generated under upper-flat-bed conditions on back of HV dune

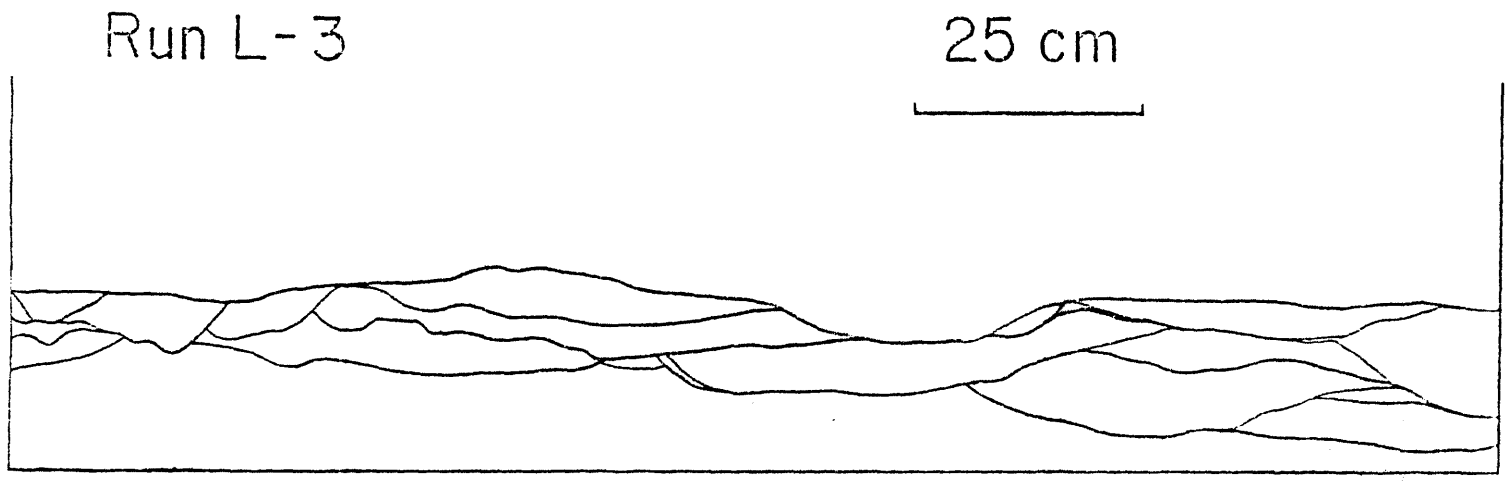


Figure 16 - Synthetic zero-aggradation transverse section, Run L-3

interesting characteristics. In general, individual troughs create linear lower bounding surfaces as seen in longitudinal sections. As the bed form migrates past the transverse profile station the upper parts of the slip face cross the plane of the profiler at different times. This implies a curved slip face. Although the lower surface on which the bed form is migrating has been planed flat, the bed form is depositing somewhat curved laminae by slumping of sediment over a slip face that has an element of curvature normal to the downdip direction on the face.

This type of bed form has a number of distinguishing features. The bed forms are long and low relative to the other dunes that have been described. They have smaller bed forms riding on them and have planed-off stoss slopes. Those slopes are gentle and are truncated by sharp slip faces that are curved in the vertical plane. The bed forms do not migrate by merging, but they have an irregular rate of migration, as shown by the uneven spacing between successive profiles. All of these features are characteristic of higher-velocity dunes.

Relationships Between Bed Forms and Structures

Three subtypes of dunes (2D dunes, 3D dunes, and HV dunes), distinguished by geometry and kinematics, were observed in the flume runs. From the data that were collected it is possible to relate the special characteristics of each type of bed form (size, shape, migration, superimposed bed forms, and temporal variability of all of these) to the internal structures the bed forms generate. The major control on the geometry of large-scale cross-stratification is the geometry of the bed forms that generate it. In general, bed forms with planar lee slopes and linear troughs generate planar structure, and bed forms with curved lee slopes and trough surfaces generate curved structure. While this seems obvious, there are definite causes of the relations between bed forms and structures. The shape of the erosion trough in front of each bed form determines the shape of the lower bounding surface of a set of laminae. The slope of the slip face of the bed form controls the orientation of the laminae as they fill in above the lower bounding surface. What happens on the upper surface of the bed form is not as important as events at the bottom of the erosion trough in front of the bed form and on the slip face, because the stoss slope and the upper part of the slip face are not preserved unless the bed form climbs at an angle steep enough to preserve these upper parts of the bed form.

Two-Dimensional Dunes

The structures generated by 2D dunes are largely controlled by the mode of migration of the dunes and the lack of scour pits in front of the lee faces. As 2D dunes migrate, they tend to move in pulses rather than at a uniform rate. The uneven spacing between successive profiles in the synthesized longitudinal section shows this. As shown in the synthetic section from Run K-1 (Fig. 10), the bed forms tend to move over one another. A cartoon (Fig. 17) illustrates this motion as a frame-by-frame depiction. The first bed form, marked by the arrow at time zero, is partially overtaken by an upstream bed form. As this occurs, the reattachment point associated with flow separation over the upstream bed form moves over the downstream bed form. This causes a reduction in the shear stress over the downstream bed form and hence a reduction in sediment movement over it, so the bed form slows down and stops migrating. The upstream bed form then catches up to and merges with the downstream bed form, producing the erosional-stoss climbing structure seen in the middle of the synthetic longitudinal profile of Run K-1.

Because of the lack of scour pits in 2D dunes, potholing (Simons et al., 1961) does not occur. Potholing is a process for forming climbing-bed-form structure by erosional excavation of a deep hole on the lee side of the bed form. As successive bed forms migrate into and over the pothole, a

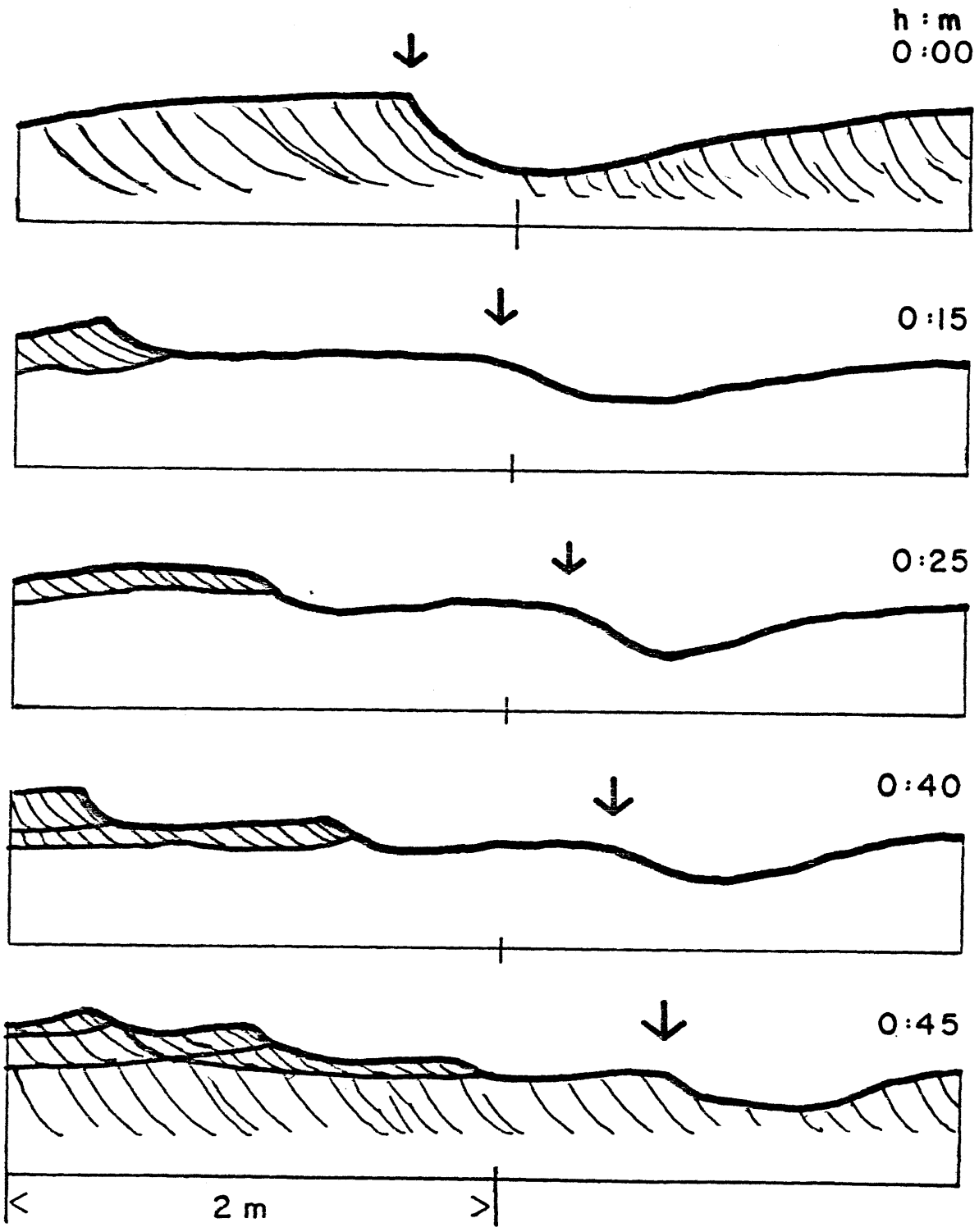


Figure 17 -- Cartoon showing mode of migration of 2D dunes

2D Dune - Migration Behavior (cont.)

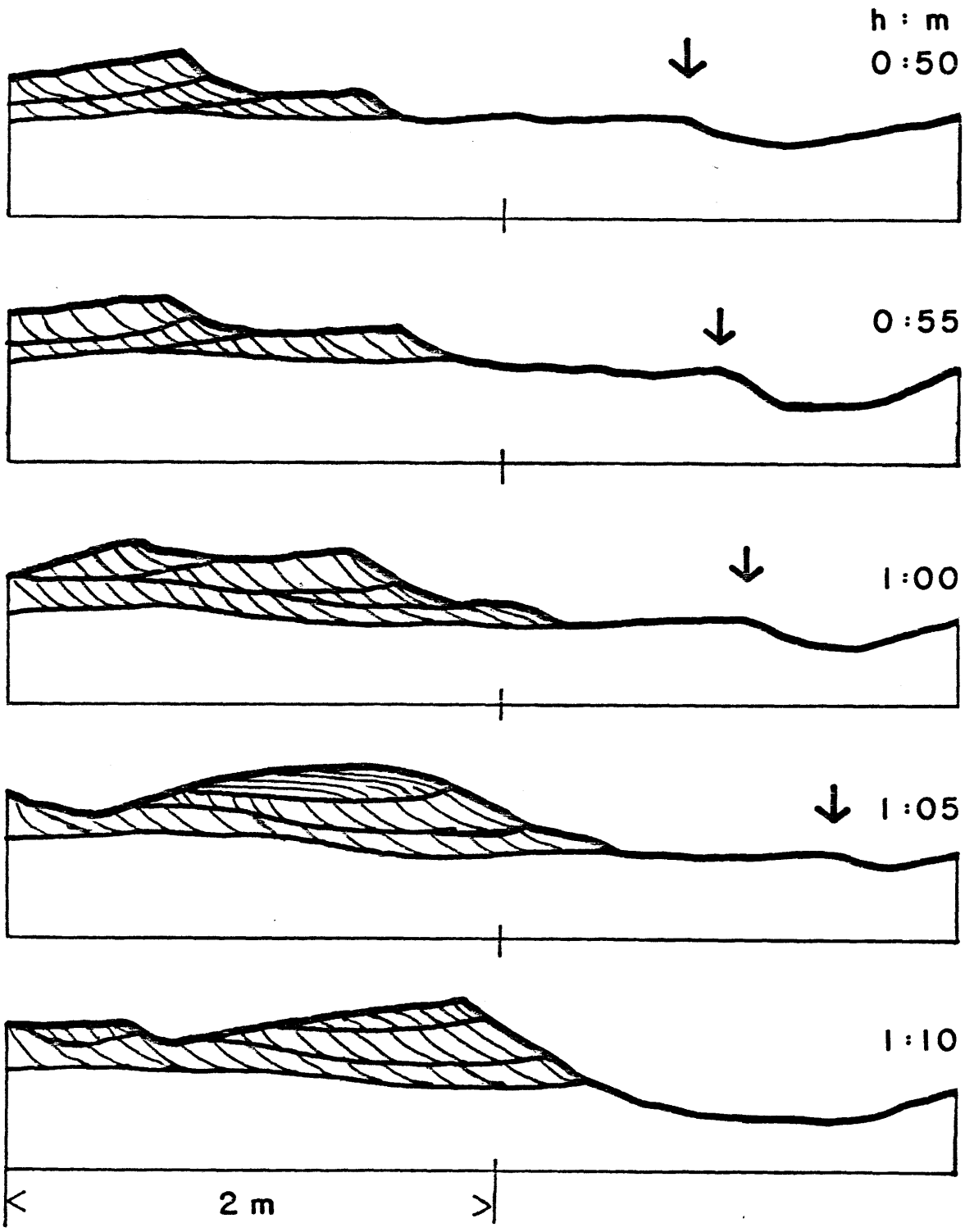


Figure 17 continued

structure similar to climbing-bed-form structure is formed. While common in trains of 3D dunes, it was not observed in 2D dunes. The erosional surface generated in front of each 2D dune has an approximately planar surface that forms a horizontal lower boundard for the deposition of foreset laminae. The foreset laminae deposited by each dune as it moves over this planar surface show an orientation similar to that of the angle-of-repose slip face on the lee side of the bed form. The result is planar-tabular angle-of-repose cross-stratification.

The relation between slip-face geometry and stratification becomes complicated when successive bed forms merge or coalesce, as shown in the cartoon in Fig. 17. In that case, the lower bounding surface is still planar, but the sediment fill consists of several sets of laminae oriented along the slip face of each bed form that merged into the single remaining dune. The structures record the passage of several bed forms, not just the bed form observed as a final product. In some cases, the boundaries between the sets of cross-laminae may not be distinct, since all of the individual sets are deposited by bed forms of the same scale. In a natural environment, a bed form preserved on the surface of a dry river bed or tidal sand flat might be a large 2D dune, while the multiple sets of cross-bedding within the bed form would be cited as evidence that the bed form was not in equilibrium with the flow or that the bed had been reworked by several flow events. In fact,

the bed form might have been produced as a combination of several smaller bed forms in an equilibrium flow. If there are indications of flow reversal (e.g., reversal of cross-bed direction in a known tidal environment), then the structures will indicate the contributions of several bed forms to the observed external geometry of the large bed form.

Three-Dimensional Dunes

Just as the special qualities of the geometry of 2D dunes influence the structures they generate, the distinctive features of 3D dunes have effects on the sedimentary structures they create. The most important features of 3D dunes are scour pits and sinuous, uneven, discontinuous crests. These are the basic elements of the three-dimensionality of these bed forms. Observation of time-lapse movies and comparison of successive profiles show that as the dunes migrate downstream, the depth of erosion is different for each dune in the chain. The lateral position of the deepest scour changes as the bed forms move, and transverse sections show that the position of the deepest scour changes from one bed form to the next. There are also indications that the location of the scour can move across the face of a single dune, but a lack of data does not allow proof of this. These deep scours are a major characteristic of 3D dunes, but attempts to explain the dynamics of their development have usually run into circular discussions (Costello and Southard, 1981).

The exact causes of the change in geometry from 2D dunes to 3D dunes with increasing flow strength are not well known. Costello and Southard (1981) state: "The development of three-dimensional dune geometry would appear to be closely linked with the nature of sediment transport low on the stoss side, in and near the zone of boundary-layer reattachment." The shape of these scours has important effects on the shape of the erosional surfaces they create.

The scours are curved and concave upward but they are filled by linear angle-of-repose or slightly curved laminae that are curved in the cross-stream direction. The shape of the scours is determined by the shape of the stoss slope and "pothole" in front of the dune, and the orientation of the scour fill is determined by the orientation of the slip face, even though the scour and the slip face do not necessarily have the same orientation. As the scour pits migrate and are filled, they create an interfingering of troughs as shown in the transverse section of Run K-2 (Fig. 13). Three-dimensional dunes do not move downstream in an even sequence but, rather, in an alternating pattern that causes each bed form to erode, and deposit, in a position offset laterally from the position of the next bed form in the train. Since the alignment and depth of erosion in successive troughs is not the same, the lenses of concave-upward laminae are deposited in an over-lapping arrangement.

Three-dimensional dunes are not commonly observed to

migrate by overtaking in the profiles or movies, so the internal structure of each bed form tends to be directly related to the surface morphology of that bed form. Each dune migrates into an erosional hollow ahead of it, and the laminae deposited by the dune fill this hollow. The resulting structure is a set of curved laminae extending the full bed-form height. A section of a 3D dune in a natural environment should tend not to have the confusing combination of structures seen in 2D dunes because all of the structure observed in a single bed form will be the result of deposition of that single bed form. A concave-up lower erosional surface is covered and filled with laminae that preserve the shape of the slip face of the bed form.

One modification of this structure produced by 3D dunes occurs as a result of certain nonuniformities in the migration of the bed form. As the 3D dune migrates, the crest occasionally stalls and stops migrating for a brief period of time. Stalling is caused by migration of superimposed bed forms on the dunes that climb up the back of each dune and cut off sediment supply to the slip face. Sediment momentarily stops avalanching down the slip face and builds up on the top surface of the dune. After a few seconds, avalanching resumes, but the dune has built up, and the brinkpoint moves up as the dune continues to migrate. As the dune grows in height, sediment is deposited on the top surface of the dune and also on the slip face. The result of this is the formation of "kinked" laminae, which are horizontal across the back of the bed form but bend down over

the slip face. An example of this kind of structure is shown in Fig. 18. These peculiar structures have a low probability of preservation because the kink in the structure is formed near the top of the bed form. As the next dune migrates down the channel, it will remove this part of the bed form by erosion. Unless the bed is aggrading at a rate high enough to cause the next dune to climb completely over the first, the upper surface of the dune will be eroded away.

Higher-Velocity Dunes

Structures generated by migration of higher-velocity dunes are more complex than the external profile of the bed forms would indicate, mainly because HV dunes deposit several different types of stratification. As pointed out earlier, the slip face of an HV dune can be an angle-of-repose face or it may have a modified structure with several small slip faces. The back of an HV dune is often flat, with upper-flow-regime flat-bed transport occurring on it, although smaller bed forms may be generated in the troughs between HV dunes. This leads to the creation of a suite of structures by the actions of a single major bed form.

The most important type of structure, occupying on the average the largest volume of the bed form, is angle-of-repose cross-laminae deposited at the slip face. A qualitative estimate, based on observations at the window of the flume, analysis of profiles, and an estimate of preservability of structure, is

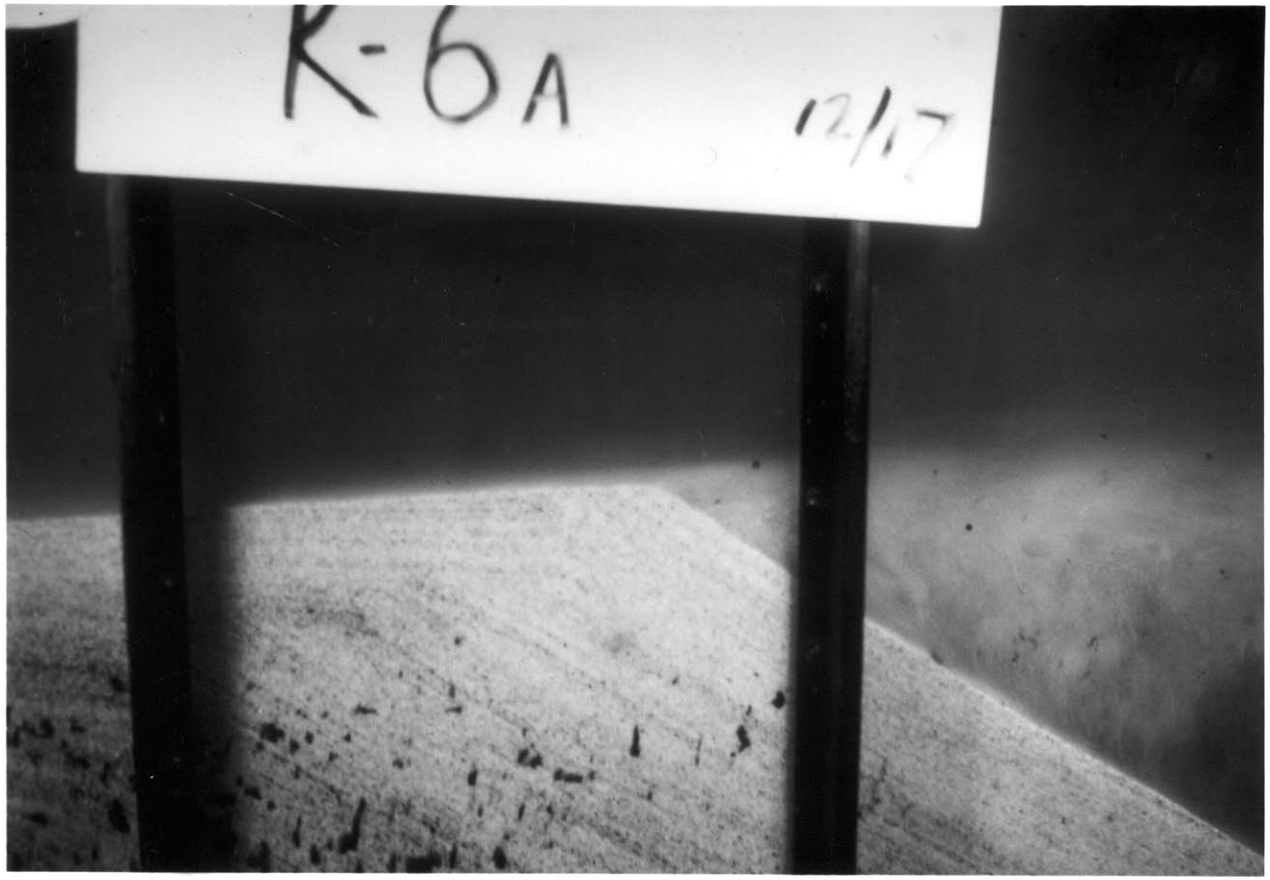


Figure 18 -- Kink in structure caused by stalling of brinkpoint Note also large jet of sediment caused by flow separation

that such cross-bedding will make up 90 to 95 percent of the preserved structure generated by HV dunes. The smaller bed forms and other minor structure on the backs of HV dunes occupy about 20 percent of the height of the bed form as it migrates and are easily removed by erosion resulting from passage of the next bed form. Therefore, they should make up a small (although not insignificant) part of the structure preserved. The general lack of deep, three-dimensional scour pits in front of HV dunes implies that the lower bounding surface of cross-lamina sets are planar. This is seen in the synthetic transverse section from Run L-3. However, the laminae deposited above this surface can show several distinctive features. Because of the variations in flow conditions over the backs of HV dunes, different types of structure may be created there. Flow conditions observed on the backs of HV dunes in the flume ranged from small dunes to upper-regime flat bed. These smaller features generated structure on the upper surfaces of the HV dunes that was not related to the scale of the larger bed forms. While the lower portions of the large bed forms were made of angle-of-repose cross-stratification, the upper few centimenters contained sedimentary structures generated by the smaller bed forms. Figure 19 shows closely similar structure as seen in an intertidal sand wave in the Bay of Fundy.

Height of structure generated by avalanching of material over the slip face does not equal the entire height of the bed form. While this idea has been suggested before (Dalrymple, 1980),



Figure 19 -- Section of sand wave, Big Bar, Bay of Fundy, showing complex internal structure due to activity of smaller bed forms on backs of large bed forms

this set of flume runs represents the first instance in which the process has been observed directly. A photograph from a run in which HV dunes were generated (Fig. 20) shows the development of smaller bed forms on the back of a major bed form. The structure in the upper part of the HV dune was created by the smaller bed forms, which migrated over the top of the HV dune, cut into the upper surface, and deposited cross-laminae whose height was on the order of that of the superimposed bed forms. The train of smaller bed forms reworked the upper few centimeters of the back of the HV dune. This is a direct indication that sedimentary structures deposited by HV dunes do not preserve the total height of the bed form even in a case of perfect preservation. Modification by smaller bed forms erases at least part of the structure generated by migration of the slip face of the HV dune.

An additional element in the creation of structures by these large HV dunes involves changes in the geometry of a dune as it migrates. A common type of midification is a surface of either erosion or nondeposition cutting across the normal, angle-of-repose cross-lamina sets (Fig. 21). This type of structure has been observed in sand waves and transverse bars in the field, where it has been called a "reactivation surface" (Collinson, 1970). McCabe and Jones (1977) generated this structure on a small scale by allowing ripples to migrate over the back and down the slip face of a dune; they attributed it to the erosional activity of superimposed bed forms scouring

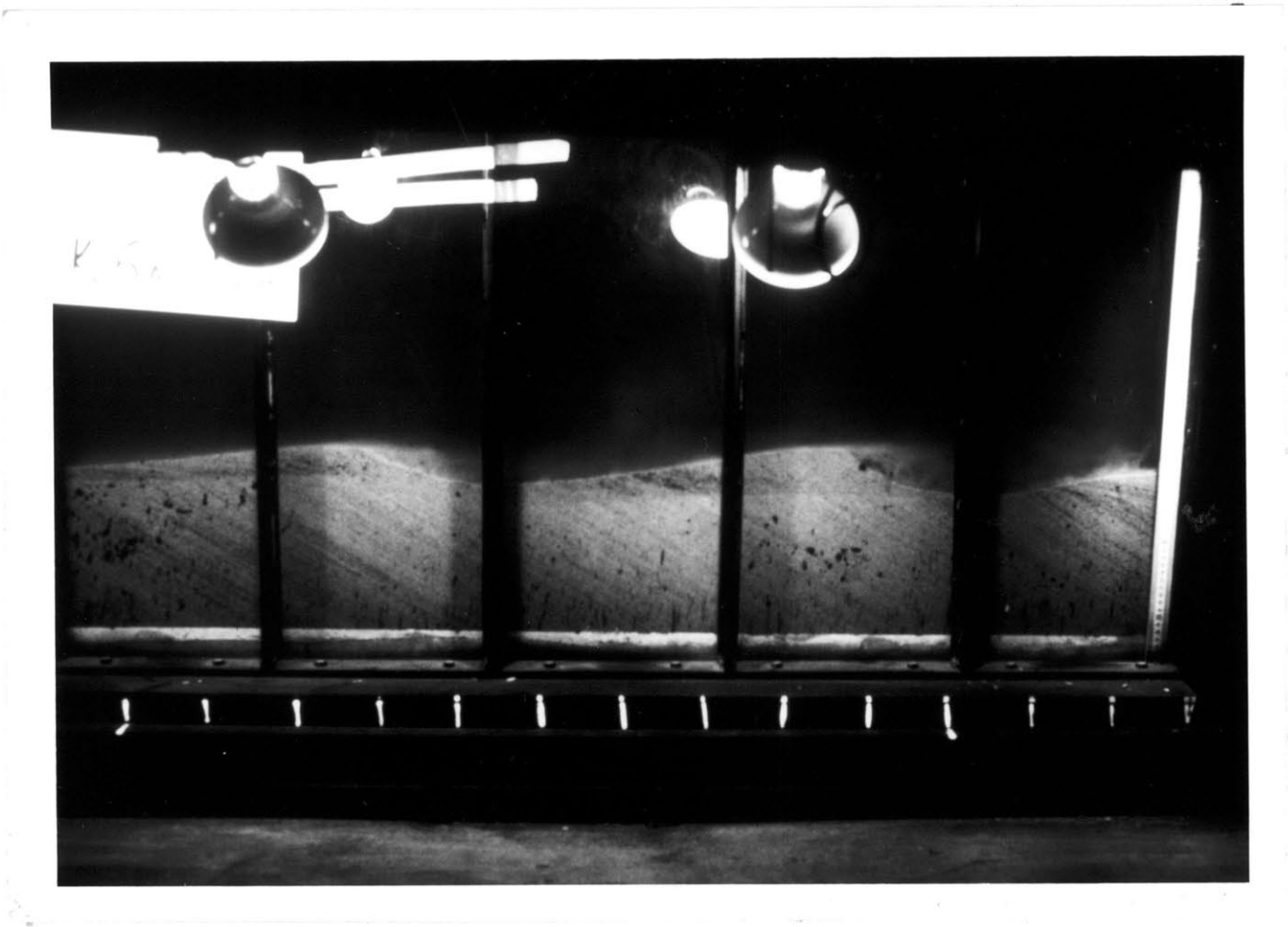


Figure 20 -- Smaller dunes on back of HV dunes

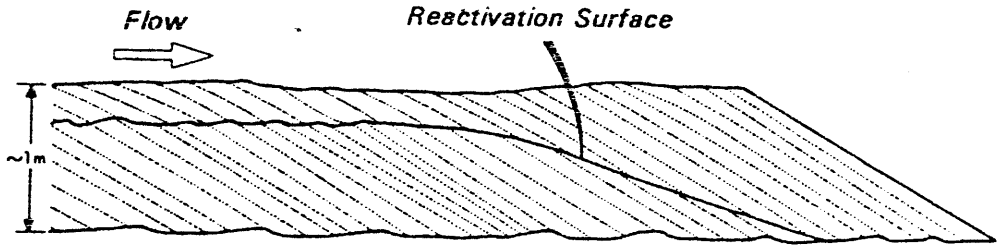


Figure 21 -- Reactivation surface (from Harms et al., 1975)

the slip face. As the smaller forms migrate, they ride up the back of the sand wave, over the crest and brinkpoint, and then down the slip face. This cuts down the slip face and creates the reactivation surface.

While the foregoing mechanism was responsible for much of the rounding of slip faces on HV dunes observed in this study, on occasion there was another cause. At times, a similar sort of rounding developed without the presence of superimposed, smaller bed forms. A common sequence of events is depicted in the series of photographs in Figs. 22, 23, and 24. In the first picture, the brinkpoint has been rounded off and is starting to build back up. Laminae preserved in the bed form show the extend of this rounding. The laminae curve over from the top surface of the bed form and down over the slip face, indicating that flow separation was not strong at the crest or the brinkpoint. Middleton and Southard (1977) attribute this rounding of the crest and upper part of the bed form to streamlining of the bed form at high velocities when flow separation is weak or restricted. As the bed form migrates, the brinkpoint continues to build up (Fig. 23) and flow separation becomes more intense, as shown by the presence of the separation jet at the brinkpoint. The slip face maintains its height, and deposition of angle-of-repose cross-laminae extending the full height of the bed form resumes as the bed form continues to migrate (Fig. 24). Another set of photographs (Figs. 25, 26, and 27) gives a more detailed view of the geometry of the structures.

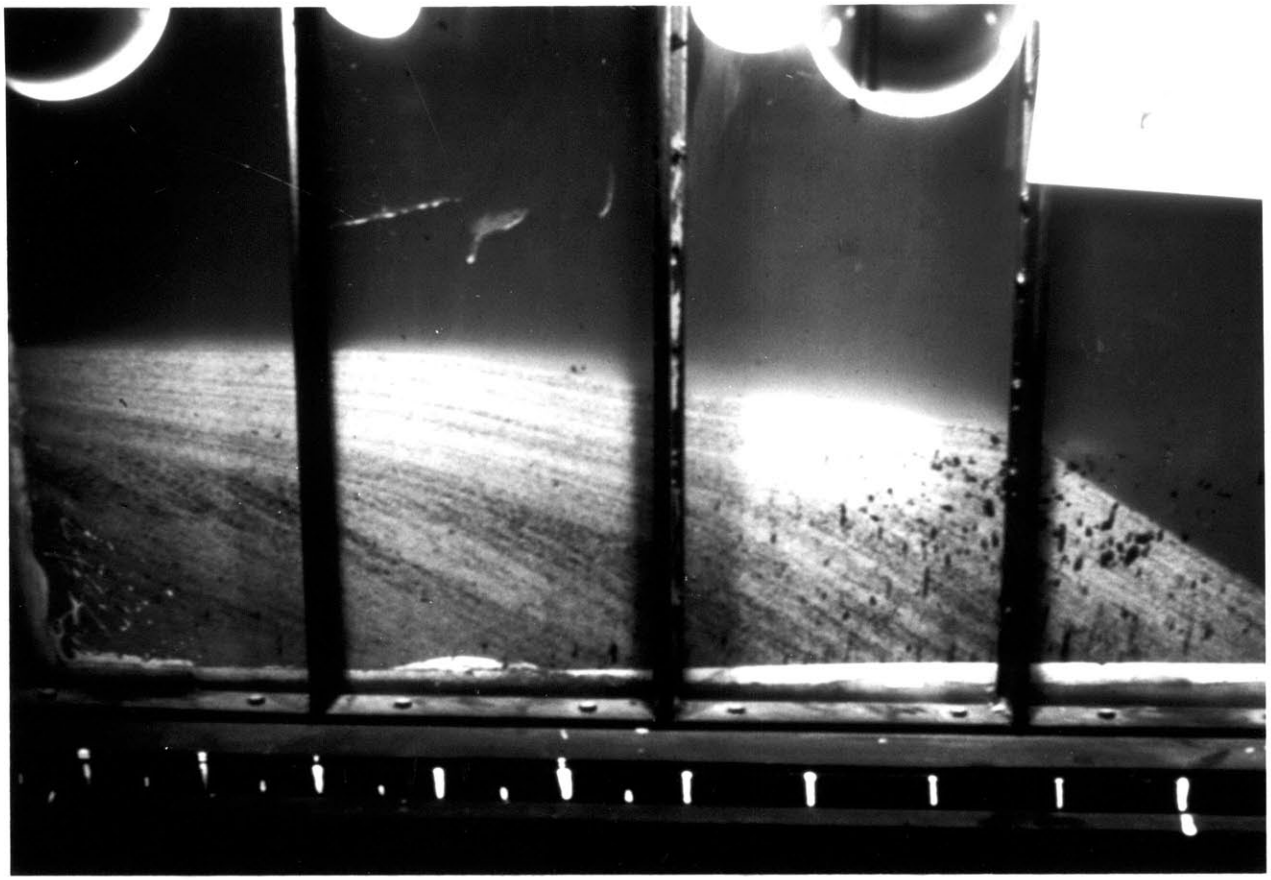


Figure 22 -- HV dune -- internal structure shows effect of bed form stalling and rounding at brinkpoint



Figure 23 -- HV dune -- bed form has built back up, flow separation becoming re-established



Figure 24 -- HV dune -- bed form has regained former size Angle-of-repose bedding is full height of bed form

FIGURE 25

HV dune -- typical profile -- high crest, lower brinkpoint

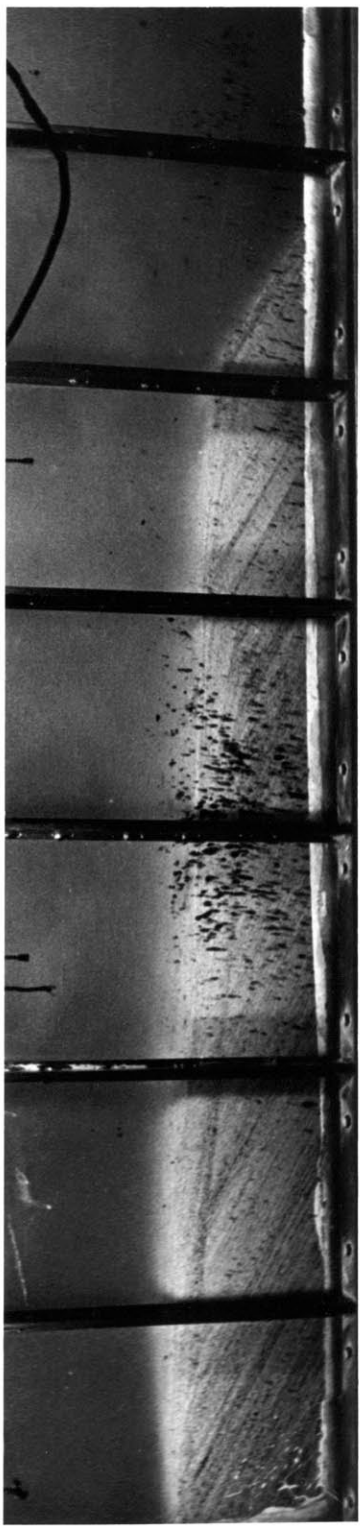


FIGURE 26

Detail of previous photograph Note continuity of preserved laminae over former location of brinkpoint, also this wedge of sediment moving over top of structure

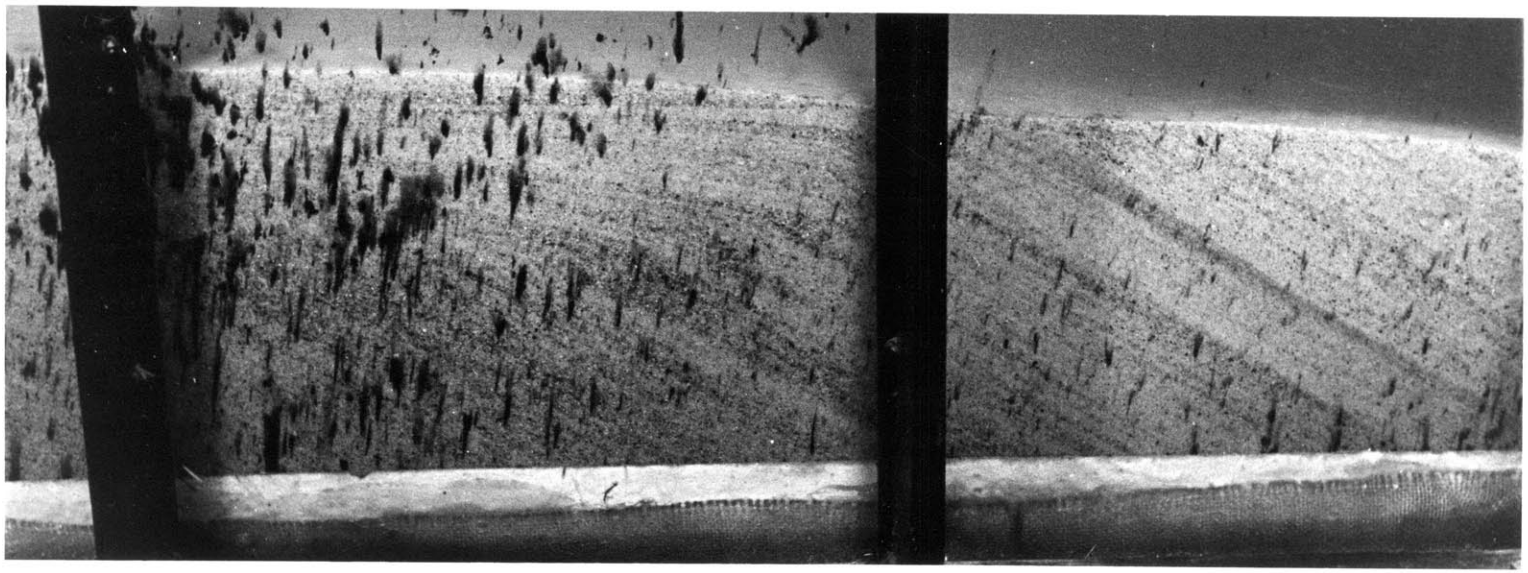


FIGURE 27

Detail of Figure 25 Note truncation of angle-of-repose laminae by parallel lamination

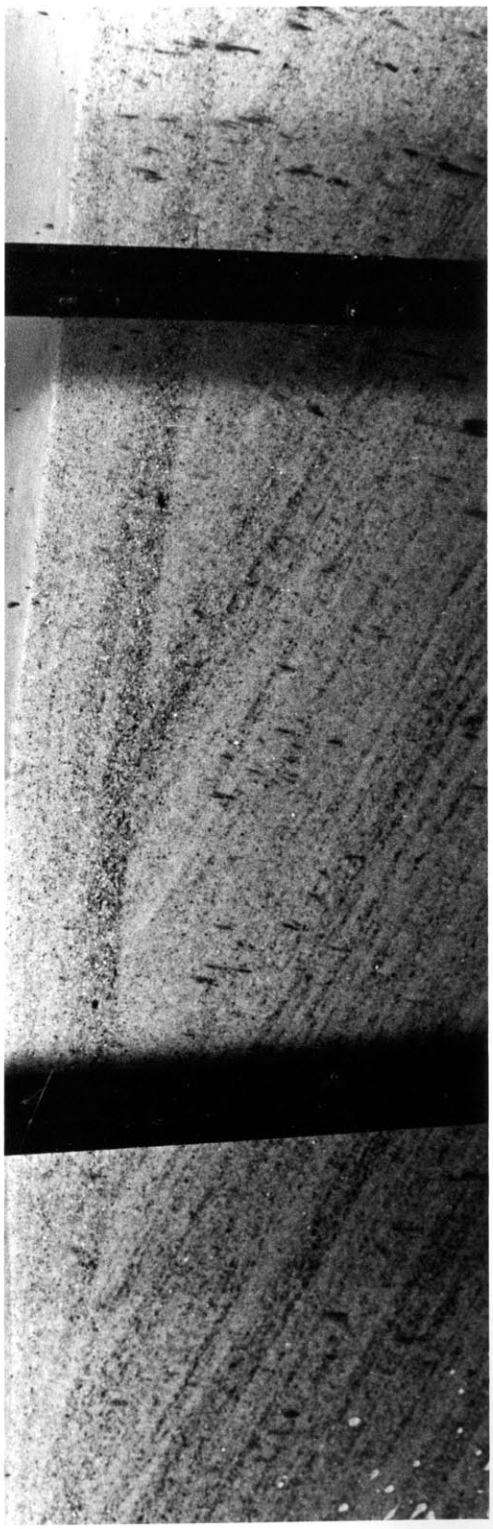


Figure 25 shows an HV dune with the typical modified profile, with a high crest and lower brinkpoint. Figure 26 shows in more detail the continuity of laminae over the top and brinkpoint and the advancing sheet of sediment being deposited on the upper surface of the bed form. Truncation of angle-of-repose laminae by the overlying nearly horizontal "topset" laminae is shown in Fig. 27. The laminae just above the erosional truncation pinch out downstream, just as the thin layer of new sediment pinches out in Fig. 26. At this point on the surface of the bed form the laminae do not show the same continuity over the former position of the brinkpoint, due to the erosional rounding of the top of the slip face as the bed form degraded.

The reasons for this behavior of HV dunes are rather straightforward. The major cause appears to lie in the relationship between successive bed forms, and is similar to a mechanism suggested by Allen (1973). During the flume runs, clouds of sediment were occasionally observed in the flow over HV dunes. These were indications that especially strong sediment-laden eddies were being shed off upstream bed forms. These eddies interfere with sediment supply over downstream bed forms, resulting in modification of the shapes of these downstream bed forms. If the sediment supply is interrupted, the bed form must decrease in height. This process is seen in Fig. 23. As the bed form continues to migrate, the height of the brinkpoint decreases, and flow separation weakens. This weakening allows

the deposition of continuous laminae from the top of the bed form, over the brinkpoint, and down the slip face. After the disruption of the flow and sediment supply ceases, the brinkpoint builds up and resumes its normal position, as seen in Fig. 24. In this way, a "reactivation" structure can be generated even in the absence of superimposed smaller bed forms.

Summary of Relations Between Bed Forms and Structures

The three different types of dunes produced in the series of flume runs all generated different types of equilibrium, zero-aggradation synthetic sections and have geometries different enough to create different types of structures under equilibrium conditions.

Two-dimensional dunes, with their linear crestlines and absence of scour pits generate structures with planar lower boundaries and two-dimensional, angle-of-repose filling. This represents typical planar-tabular cross-stratification as defined by McKee and Weir (1953). Three-dimensional dunes, with their deep scour pits, uneven trough depths, and curved crest lines, generate structures with curved, concave-up lower boundaries and curved filling. This is typical large-scale trough cross-stratification (McKee and Weir, 1953). The HV dunes created in the flume runs generate several different types of sedimentary structure. The basic type is large-scale planar-tabular cross-stratification, similar to that generated

by 2D dunes when no merging of bed forms takes place, but somewhat taller (assuming complete preservation). Modifications of the HV dune structures should be rather common, either through the action of smaller, superimposed bed forms, or by planing off of the top surface and generation of reactivation surfaces. It is important to note that these last two types of modification appear to be mutually exclusive. In observation of the behavior of HV dunes in the flume it became apparent that if the HV dune built up to the point where it became a significant flow contraction, the upper surface would become planed off and parallel lamination would be deposited. If, on the other hand, the HV dune was lower, and the flow velocity over the back remained low enough, small dunes would form. This creates two exclusive cases: either smaller bed forms are superimposed and they generate structure of their own; or the HV dune is planed off and parallel lamination and reactivation surfaces are formed. The implications of this finding are that, if enough of the HV dune structure is preserved, the depth of the flow relative to bed form height can be estimated. Unfortunately, the part of the bed form that must be preserved is the upper portion of the stoss slope. This is the least likely part of the bed form to escape erosion and destruction. Another drawback is that there is a possibility that this flow-depth-indicating mechanism may have been enhanced by the experimental conditions.

In the foregoing, each different type of bed form has been

related to a type of structure created under equilibrium conditions. If these structures are observed, it is now possible to state with certainty the type of bed form and the flow conditions prevailing at the time of deposition. The only condition is that a large portion of the structure must be preserved.

It was stated earlier that studies of equilibrium conditions can provide a means for studying the varying conditions that are common in nature. In this study, each type of bed form has been isolated and examined separately. Obviously, in a natural situation such isolation is not as rigorous; the various dune bed subphases are likely to be closely associated in space or time. Field studies have defined a genetic relation between 3D dunes and large-scale trough cross-stratification, but the type of structure produced in this study by 2D dunes is not nearly as commonly reported. An examination of a bed-phase diagram (in terms of depth, velocity, and grain size) for a given grain size in the dune range indicates that 3D dunes form over a wider range of flow conditions than 2D dunes. It might be expected that 2D dune structure would not be as common as 3D dune structure. An additional effect on the occurrence of 2D dune structure is that, if velocities increase into the 3D dune range in a field area, the 2D dunes will be erased by deeper-cutting and more readily preservable 3D dune structure. Since 3D dunes erode deeper into the bed than 2D dunes, their structure will be preserved even after a train of 2D dunes has migrated over it. Another effect tend-

ing to minimize preservation of 2D dune structure is that even a small degree of three-dimensionality will result in scour troughs and 3D dune stratification. In the sedimentary record, therefore, preservation of characteristic 2D dune structure should be relatively uncommon and indicative of a specialized set of flow conditions in which only 2D dunes were produced for an extended period of time. Presence of this type of structure would be a good indicator of a very specific flow environment.

CHAPTER 10

SEDIMENTARY STRUCTURES: NONZERO AGGRADATION

Construction of Aggraded Sections

A series of aggraded sections was made by raising each time-line profile an amount proportional to the aggradation rate, compared to the zero-aggradation position of the bed form. As discussed in Chapter 6, for nonzero rates of net aggradation of the bed this technique for synthetic generation of sedimentary structures produces an accurate simulation only in the case of aggradation by sediment fallout (temporal or downstream decrease in suspended-sediment concentration). For aggradation by downstream decrease in bed-load sediment transport rate, the technique introduces certain distortions, although these become less serious as average angle of climb approaches zero.

Synthetically aggraded sections were constructed for two-dimensional and three-dimensional dunes seen in this study. An examination of the two available series of profiles from HV dune runs indicated that they were severely constrained by the width of the flume. A synthetic transverse section (Fig. 28) shows that these large bed forms migrated in an alternating fashion down first one side of the flume channel and then the other. This is assumed to be a severe distortion in bed-form geometry brought about by the narrowness of the channel relative to both the spacing and the potential crest length of the

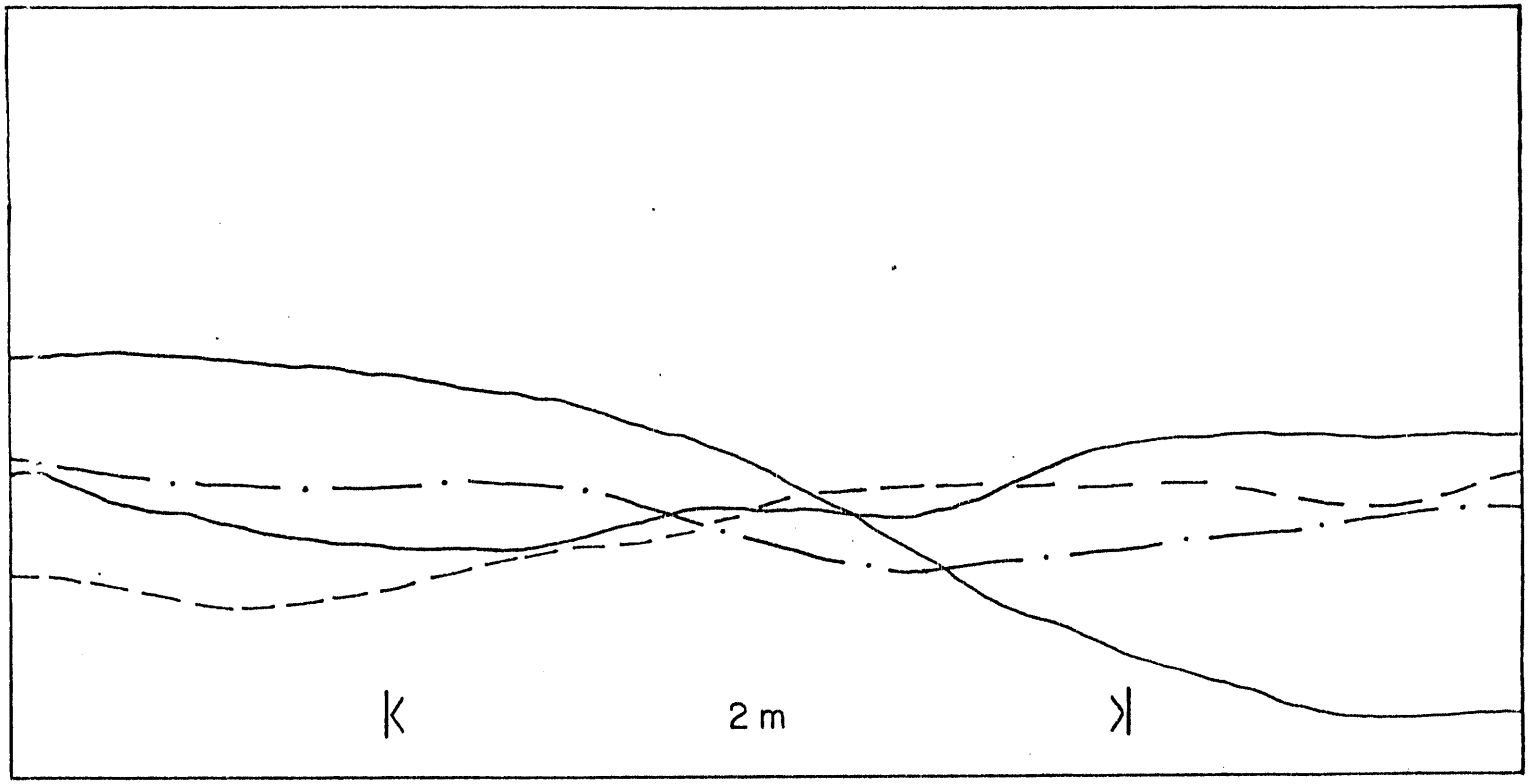


Figure 28 -- Transverse section from Run L-3 superimposing profiles of several sequential bed forms. Figure shows that bed forms migrated alternately down sides of channel, therefore they were constrained by channel size.

bed forms. Since no structure generated by synthetic aggradation could be expected to be representative of real HV dune stratification, no synthetically aggraded sections were made for HV dunes.

Climbing Dunes

All of the structures discussed in Chapter 9 are those generated by equilibrium bed forms under conditions of zero aggradation. A complete analysis of a given deposit showing large-scale cross-stratification should include an estimate of how much of the structure originally generated by migrating bed forms is preserved. As discussed in Chapter 5, under all conditions in which no sediment is being introduced onto the bed from suspension and bed forms are depositing sediment, only a minor portion of the total height of the bed form will be preserved as sedimentary structure. This is also obviously true (and will be shown by the synthetic sections from the present set of experiments) for deposition from suspension if there is only enough deposition to make a bed form climb a fraction of its own height in a migration distance of one bedform spacing.

By comparison of the sedimentary record with the results of observations of structures left by migrating bed forms in flumes and modern natural environments, it is abundantly clear that large-scale cross-stratification can be produced by climb-

ing dunes, although this usually involves very low angles of climb. As discussed in Chapter 5, the necessary aggradation of the bed in such cases comes about most probably by downstream decrease in either suspended bed-material transport rate or bed-load transport rate. Both of these mechanisms must be of non-negligible importance in natural environments, although it seems impossible at this point to summarize their relative importance in the various natural flow environments in which large-scale bed forms can exist. As an example, consider a point bar in a meandering river. The central and downstream reaches of the point bar typically are sites of accretion, while the upstream reach is a locus of degradation, so that the bar extends laterally outward and at the same time migrates downstream. This pattern of aggradation and degradation is consistent with decrease in either q_{sb} or q_{ss} downstream around the point bar, whether sediment is merely recycled within the bar or shifted from an upstream bar to a downstream bar. Climbing-dune cross-stratification beneath that part of the bar over which flow conditions maintain migrating dunes can be produced under conditions of $\partial q_{ss}/\partial x$ or $\partial q_{sb}/\partial x$ or (perhaps most probably) by a combination of both.

When rate of aggradation is large enough relative to rate of bed-form migration, bed forms climb a vertical distance equal to their own height in a migration distance of one bed-form spacing. This produces Type B (depositional-stoss) climbing-bed-form cross-stratification (Jopling and Walker, 1968; Allen, 1971;

Ashley et al., 1981). Although certainly represented in the sedimentary record, distinctive stratification produced by dunes climbing in this way by sediment fallout from suspension is not nearly as common as that produced by ripples. This is presumably a consequence of two effects: grain size and therefore fall velocity of the sediment is larger, and the streamwise extent of the area of fallout must be at least an order of magnitude larger to encompass more than just a single bed form. An example of such structure, from a glacial-lake prodelta environment, is shown in Fig. 29. This example is from the Hadley Delta in glacial Lake Hitchcock (Gustavson, Ashley, and Boothroyd, 1975).

For the erosional-stoss climbing-dune cross-stratification at very low angles of climb, typical of the sedimentary record, there seem to be few criteria by which to distinguish $\partial q_{ss}/\partial x$ and $\partial q_{sb}/\partial x$ effects -- and certainly no criteria applicable to exposures only a few bed-form spacings long in the downstream direction. We are thus faced with the dilemma that the synthetic technique described in Chapter 6 reproduces cross-stratification that is non-negligibly represented in the sedimentary record, but we cannot be sure to which natural deposits or depositional circumstances it applies. Nonetheless it seems worthwhile to describe here, by use of the synthetic technique, the features of cross-stratification that would be produced by migration of dunes in an aggrading regime in which aggradation was by $\partial q_{ss}/\partial x$.

FIGURE 29

Climbing-dune structure in glacial outwash, Connecticut Valley; scale is 30 cm (Photograph courtesy of J. Southard).



Features of Synthetic Aggraded Sections

Three-Dimensional Dunes

Since the structures generated by synthetic aggradation in 3D dune runs show more diversity than those of 2D dunes, 3D dunes are examined first. Figures 30, 31, and 32 are a sequence of three synthetically aggraded transverse profiles from Run K-2. The aggradation rates correspond to angles of climb of 5°, 2.5°, and 1.25°. At lower angles of climb, differences between aggraded sections and equilibrium sections were insubstantial.

All of these aggraded sections show similar trough cross-stratification, but the nature of the troughs changes with increasing aggradation rate. As the angle of climb increases, more of each bed form is preserved, meaning that more than just the lower portion of each trough appears in the section. The more linear upper portion of the slip face and upper stoss slope begin to be preserved and the "laminae" they create are more nearly linear. Their preservation leads to a greater proportion of linear, planar structures. The sections indicate that the higher the angle of climb, the less trough-like the structure, because the trough is created by the lower part of the bed form. This is a way to approach the determination of angle of climb on an exposure of trough cross-bedding when only a transverse face is exposed. As the angle of climb increases, the structure becomes more planar, although still preserving some elements of the lower parts of the troughs.

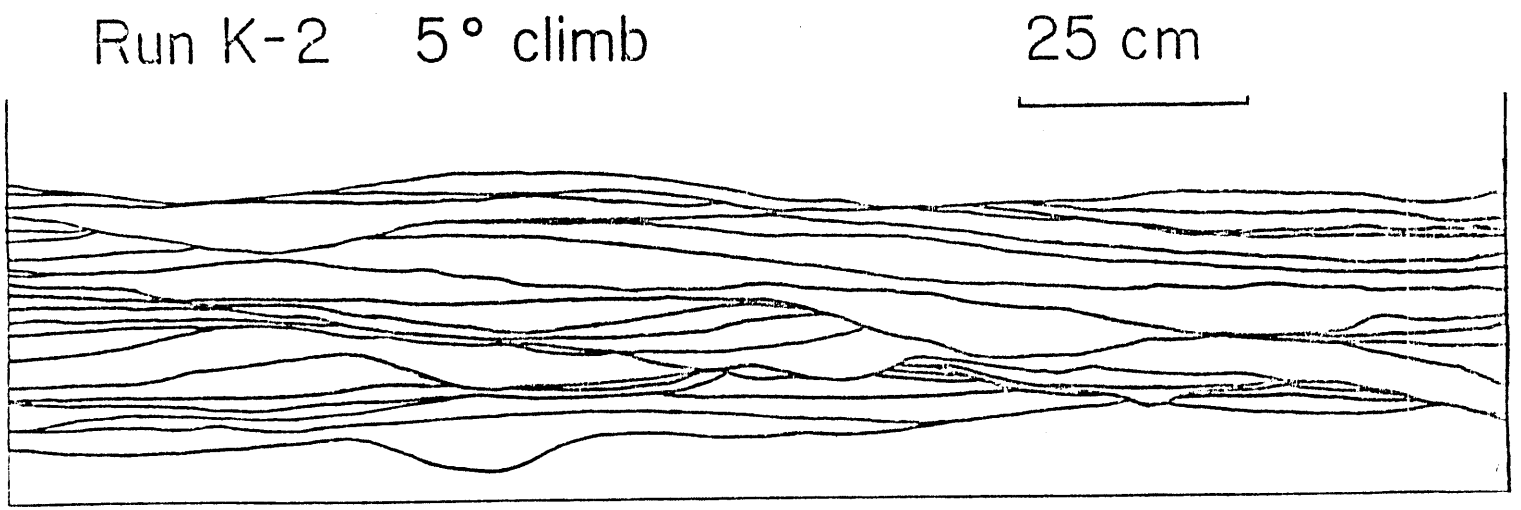


Figure 30 - Synthetically aggraded transverse section -- Run K-2 5° angle of climb

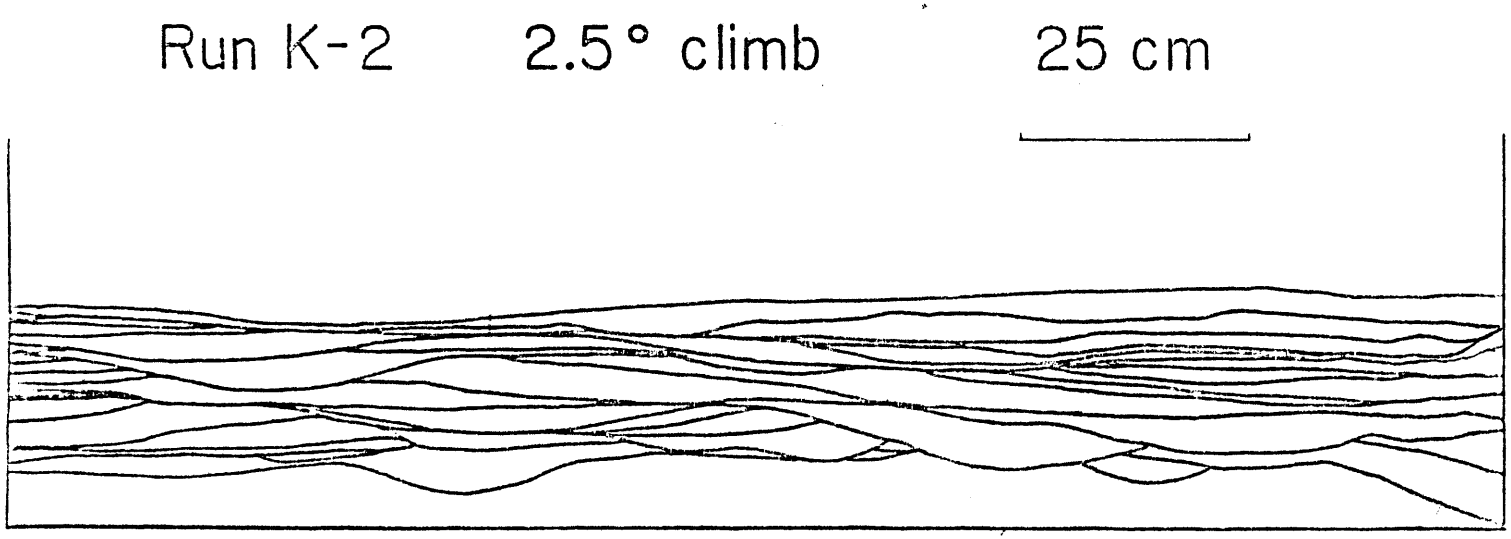


Figure 31 - Synthetically aggraded transverse section -- Run K-2 2.5° angle of climb

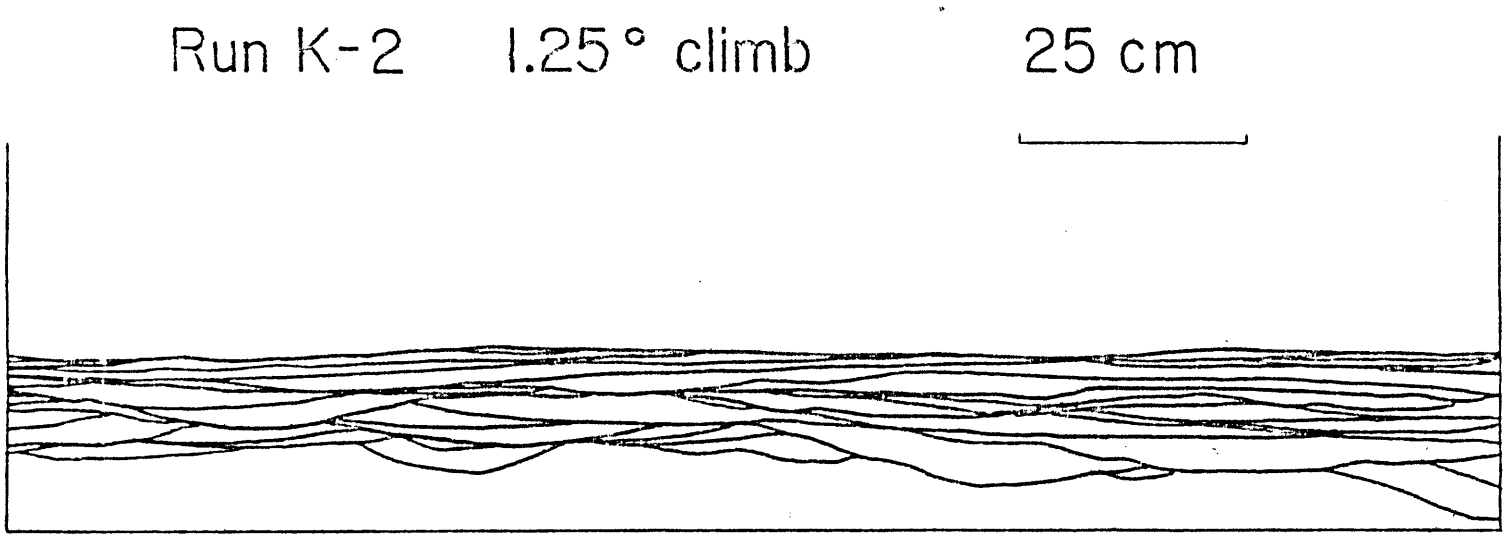


Figure 32 - Synthetically aggraded transverse section -- Run K-2 1.25° angle of climb

Examination of a series of longitudinal profiles from the same run (Fig. 33, 34, and 35) shows that the extent of preservation of each bed form varies as the angle of climb changes from 1.25° to 5°. The 5° profile (Fig. 33) shows preservation of stoss slopes. At a climb rate of 2.5° some erosion of stoss slopes does occur, but there is still some stoss-slope structure retained, as seen in Fig. 34. Only when the angle of climb drops to 1.25° (Fig. 35) are the stoss slopes eroded completely.

For Run K-2, the average migration rate of the bed forms was 2.12 m/hr. To find the aggradation rate for each angle of climb, the relation is $V_x \tan \theta = V_y$, where V_x is the migration rate of the bed forms, θ is the angle of climb, and V_y is the aggradation rate. For climb angles of 1.25°, 2.5°, and 5° these aggradation rates were 4.63, 9.26, and 18.6 cm/hr, respectively. Rates of bed buildup in excess of 5 cm/hr might be expected to be short-lived in natural cases, as this corresponds to an aggradation rate in excess of one meter per day. This is in agreement with the experimental work of Ashley et al. (1981), who found that natural-looking climbing-ripple sequences were deposited in the span of a few hours at most. For a much slower rate of deposition, on the order of 10-15 m/yr, the angle of climb for the same migration rate becomes 0.04°. Under these circumstances, the structures generated would be almost identical to the equilibrium profiles of Figs. 12 and 13.

FIGURE 33

Synthetically aggraded longitudinal section -- Run K-2 5^{o} angle of climb

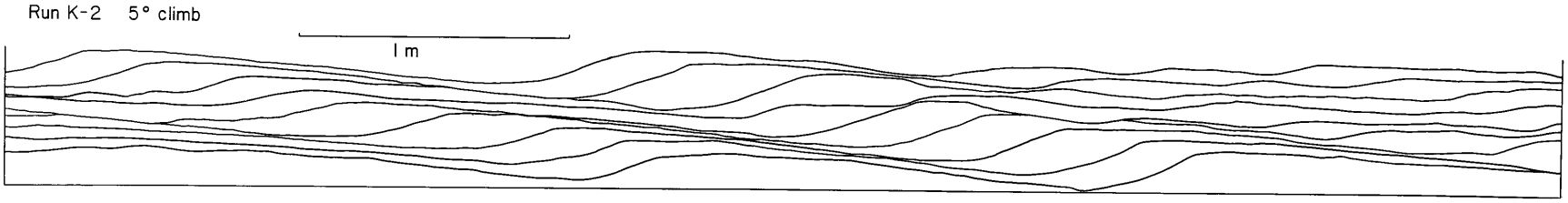

Run K-2 5° climb
1 m

FIGURE 34

Synthetically aggraded longitudinal section -- Run K-2 2.5° angle of climb

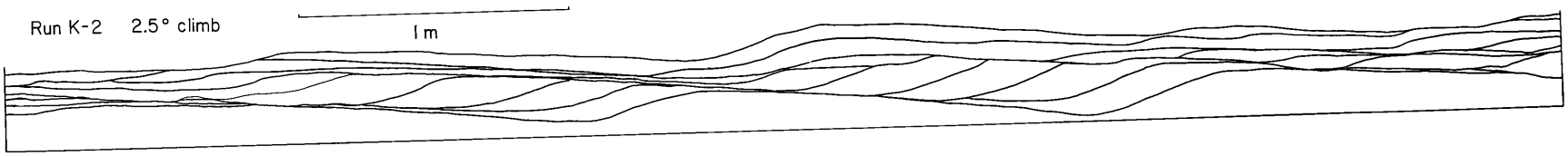
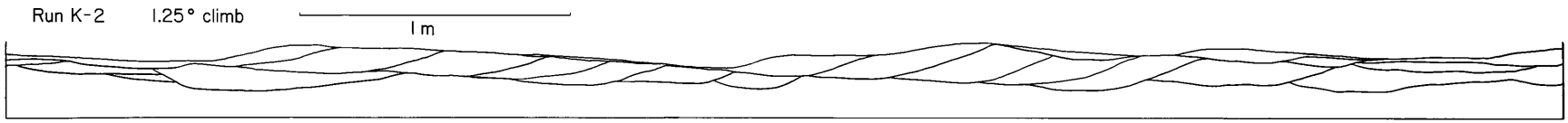

Run K-2 2.5° climb
1 m

FIGURE 35

Synthetically aggraded longitudinal section -- Run K-2 1.25° angle of climb


Run K-2
1.25° climb
1 m

In typical trough cross-stratification, the troughs are arranged in an alternating pattern. This is explained by the nonuniformity of sequential trough locations and depths. Since the bed forms that generated the stratification did not all erode to the same depth in the same location, the troughs are arranged in a random pattern as well. This alternating arrangement of troughs makes possible the preservation of structure without building the bed up more than one or two bed-form heights. From the synthetic structures created in the present study, it is easy to see that such an amount of buildup can be obtained with a very small angle of climb.

Two-Dimensional Dunes

In contrast to the trough cross-stratification seen in the sections of Run K-2, the synthetic sections from Run K-1 show a much simpler structure. Figures 36 and 37 are aggraded transverse profiles generated by the 2D dunes of Run K-1. Because of the strong linearity of the crests of the bed forms, the laminae generated are very straight. As the aggradation transform is added to each time-line profile, the series of straight lines builds up. The only nonuniformity in the structure comes from irregularity of spacing of laminae, which is the result of the nonuniform migration rate of the bed forms. The structure generated by synthetic aggradation for

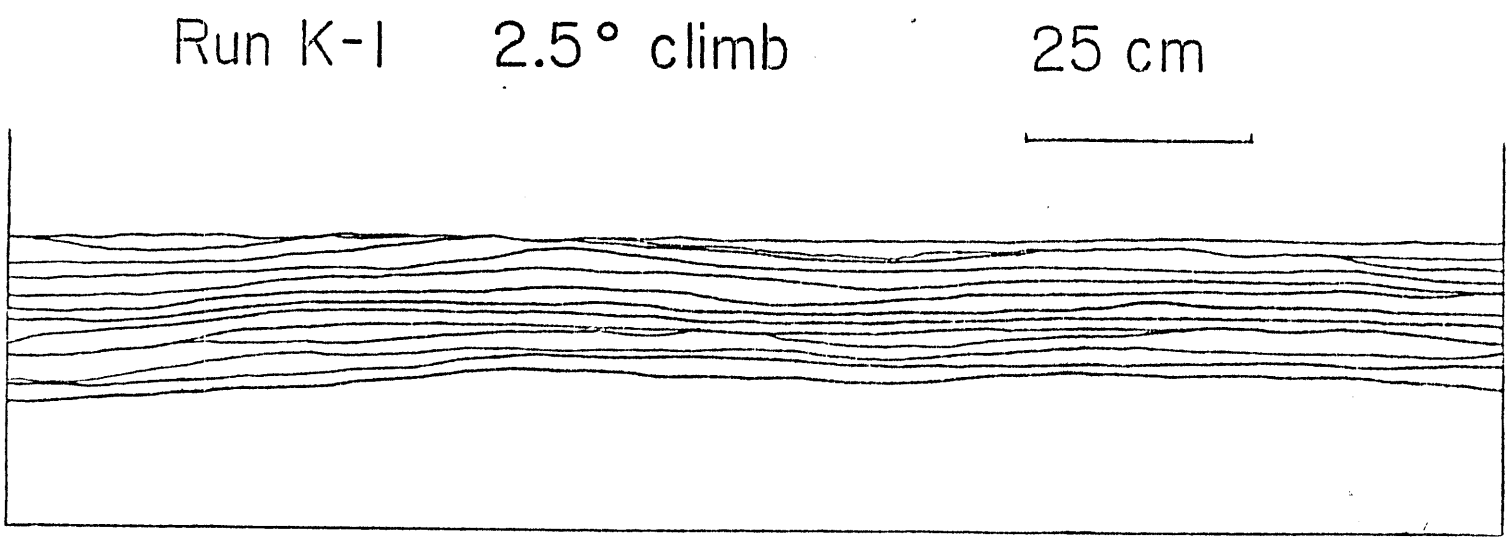


Figure 36 - Synthetically aggraded transverse section -- Run K-1 2.5° angle of climb

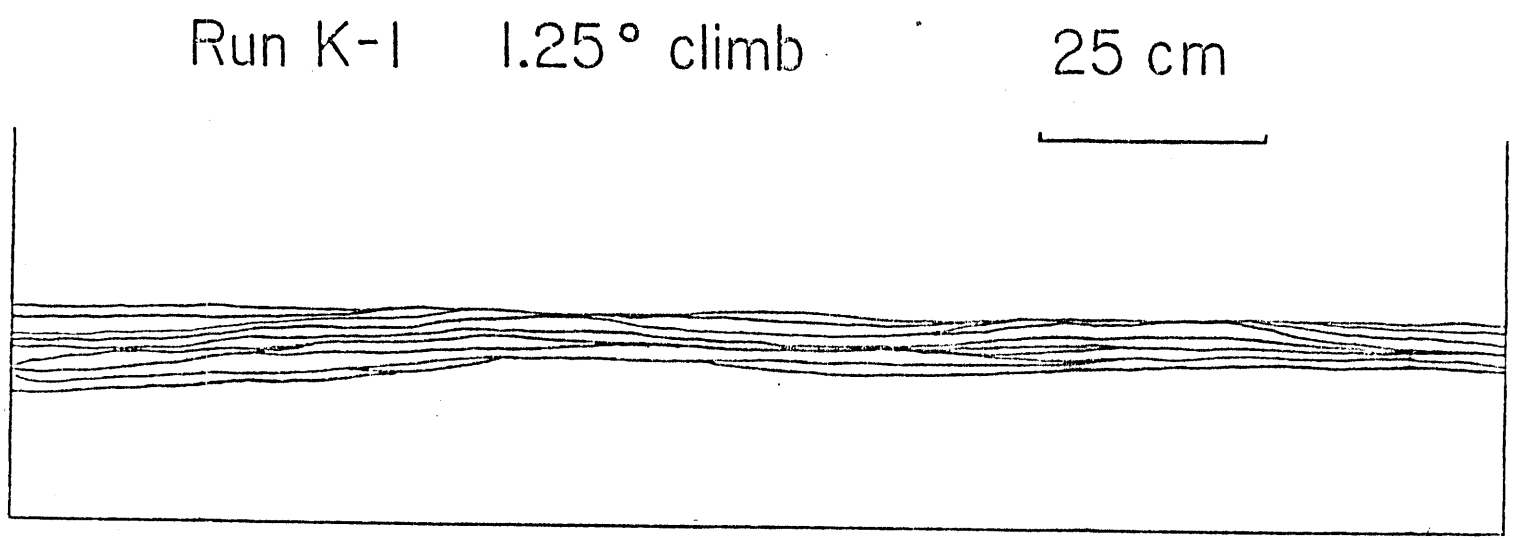


Figure 37 - Synthetically aggraded transverse section -- Run K-1 1.25° angle of climb

the run is planar stratification. Since there are no deep scours in front of the bed forms, the slip faces are relatively straight and even. The structure seen in a transverse section is therefore a series of straight lines. The spacing between the lines depends on the aggradation rate and the angle of climb. For Run K-1, the aggradation rate for a 2.5° angle of climb is 8.6 cm/hr. For a 1.25° climb, the aggradation rate is 4.3 cm/hr.

Examination of two synthetic longitudinal sections with angles of climb of 2.5° and 1.25° (Figs. 38 and 39) shows the effect of aggradation on the overtaking of 2D dunes. The major effect is the almost total preservation of stoss-slope structure and exaggeration of the merging structure seen in the equilibrium section. The linearity of troughs and slip faces creates linear transverse structure, but streamwise variability in migration characteristics makes longitudinal structure more complex. When overtaking occurs, it creates a region of climbing-bed-form structure with a higher angle of climb than that generally preserved in the section. This is apparent from the evidence of bed-form overtaking preserved as tangential toesets, seen in the middle of the 2.5° aggraded section (Fig. 38). As merging occurred, the bed form briefly stopped moving forward and built up vertically. This vertical motion is preserved by the synthetically aggraded section, since the lower parts of the slip face are accentuated by aggradation. In the equilibrium profiles, the lower slip

FIGURE 38

Synthetically aggraded longitudinal section -- Run K-1 2.5° angle of climb

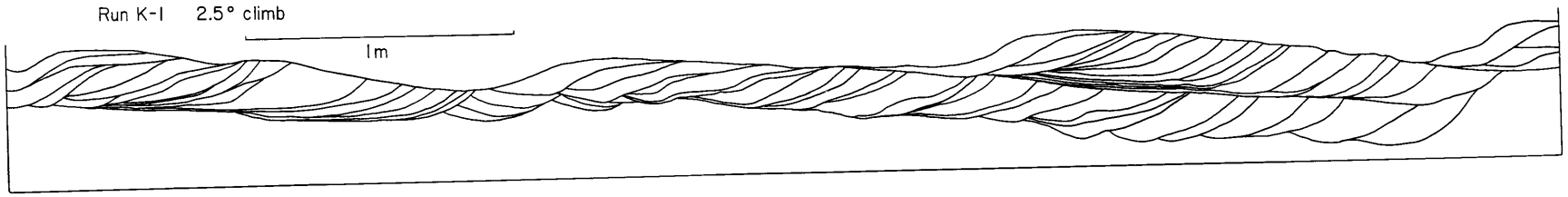
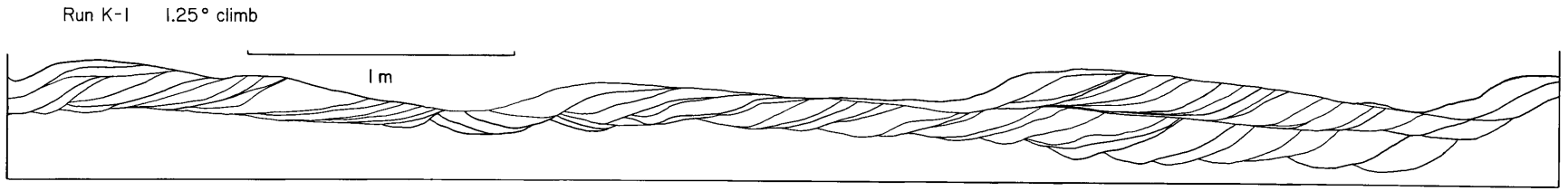

Run K-1 2.5° climb
1m

FIGURE 39

Synthetically aggraded longitudinal section -- Run K-1 1.25° angle of climb


Run K-1 1.25° climb
1 m

face showed no structure because there was little deposition there. When synthetic aggradation was added, thin layers were added at the toesets. The 1.25° section (Fig. 39) does not show this toeset preservation, so a critical angle has been defined at this migration rate for the preservation of toeset laminae. This synthetic structure is realistic only to the extent of aggradation caused by fallout of sediment from suspension. High local angles of climb may not occur in the same way under conditions of real aggradation.

The structure generated by 2D dunes is simpler in transverse sections, but slightly more complicated in longitudinal sections, than structure generated by 3D dunes, because of merging structure. Preservation of distinctive merging structure is dependent on a rather large aggradation rate (more than 8 cm/hr) to produce a large enough angle of climb. While this is not an unreasonably large rate, it might be expected only in depositional environments where sediment is being deposited from suspension, since this is the only mechanism that can produce high aggradation rates under relatively uniform flow conditions.

Summary of Aggraded Sections

Comparison of the synthetically aggraded sections to equilibrium sections and to some field examples (e.g., Harms and Fahnestock, 1965; Harms et al., 1975) indicates that

very low angles of climb are the rule rather than the exception with large-scale bed forms. This is predictable from the large amounts of sediment required to aggrade large-scale bed forms and the long time it takes to develop dunes on a bed (relative to ripples).

If these depositional processes operate on a very short time scale, it is possible that dunes do not have time to develop fully. Another possibility is that, since dunes generally form in coarser sand than ripples, insufficient suspended sediment is available to generate climbing-dune structure.

The very low angles of climb required for depositional-stoss stratification in large-scale bed forms reflect the differences in general shape between dunes and ripples. Ripples have steeper stoss slopes that can be preserved only at high climb angles. The lower-angle stoss slopes of dunes are protected from erosion with angles of climb of 5° or less. Such small climb angles could make recognition of climbing structure difficult (cf. Rubin and Hunter, 1981), except that preservation of any bed-form structure implies that some process operated to raise erosion troughs of successive bed forms, thereby preserving structures. If a vertical sequence of at least two sets of angle-of-repose cross-stratification is found, and it can be shown that the stratification was produced at a bed-form slip face, then the stratification must have been preserved by climbing of successive bed forms.

No other process can preserve structure more than one bed-form height high.

CHAPTER 11

SUMMARY OF THE STUDY

This study has examined structure generated by large-scale sedimentary bed forms and demonstrated a synthesis technique for the study of sedimentary structures and their generation by migrating bed forms. The results are summarized in Figure 40, which shows the relations between the several subphases of dunes produced compared to the structure they generate.

Comparison of synthetic trough cross-stratification produced in this study to actual trough cross-stratification observed in the natural environment shows that the technique accurately synthesizes structure produced by moderate amounts of bed aggradation due to fallout of sediment from suspension. Detailed examination of the synthetic structure shows that there are important geometric differences between structures produced by 2D dunes, 3D dunes, and HV dunes.

The merging structure produced by 2D dunes is unusual and may not be preserved in the field. Three-dimensional dunes generate the classic trough cross-stratification usually associated with "dunes" (= megaripples) by most field sedimentologists. Higher-velocity dunes (≈sand waves?) can produce complicated structure from the passage of a single large bed form. Superimposition of smaller bed forms and modification of the upper surfaces of HV dunes create a set

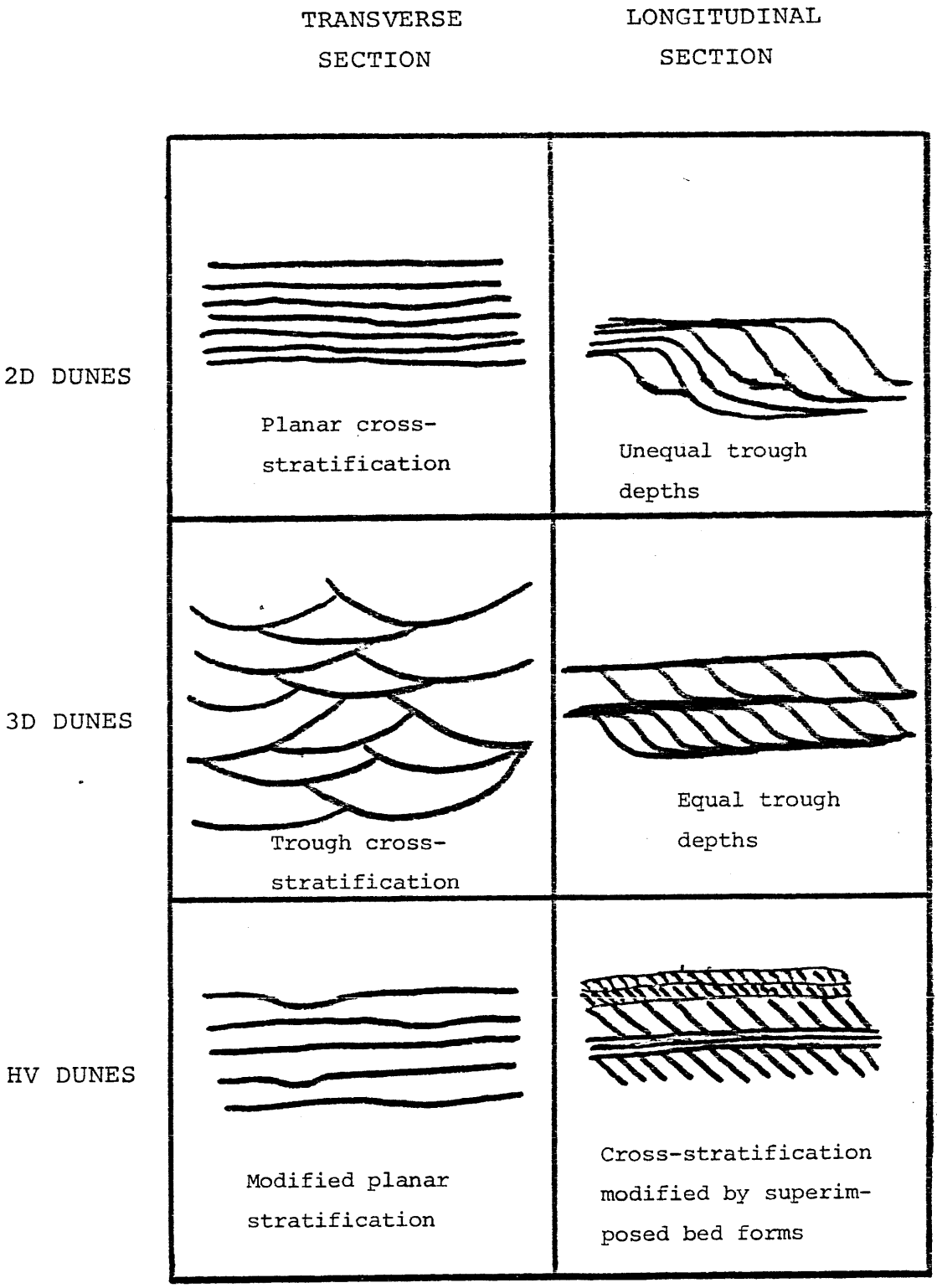


Figure 40 - Cartoon summary of relations between major dune subphases and sedimentary structures as seen in the flume

or suite of structures. Generation of reactivation surfaces on HV dunes under steady uniform flow was demonstrated in this study and observed in side-wall photographs. Deposition of parallel lamination under upper-flat-bed conditions was also observed on the upper surface of HV dunes.

Synthetic bed aggradation for low angles of climb, under conditions simulating deposition by fallout from suspension, has established that depositional-stoss structure can be created by dunes at very low climb angles, primarily because of the low angles of dune stoss slopes. The seeming lack of climbing-dune structure in nature may result from the fact that dunes often form in low-aggradation-rate environments. Synthetic aggradation of 3D dune structure has shown that structure is modified by preservation of the upper parts of bed forms at low angles of climb. This allows estimation of climb angles from transverse sections of trough cross-stratification, and indicates that most natural deposits are formed at very low climb angles and aggradation rates.

The next step in the application of this technique can be either in field studies or laboratory simulations. Construction of a profiler track over an active sand-wave field in an estuary would permit detailed analysis of generation of structure and produce data on bed-form migration and behavior as well. In a laboratory, the technique could be applied to examine other types of bed structures or models, such as channel movement in braided streams or the effects of

variations in ripple geometry on sedimentary structures. All of these are possibilities, since the synthesis of sedimentary structures is a useful technique, newly developed and awaiting further application.

BIOGRAPHICAL SKETCH

William Charles Corea was born at 3:59 p.m., April 15, 1952, the only son of Rev. Peter and Rev. Alicia Corea. Having survived the trauma of 14 years at Milton Academy, and of having both parents be ministers, he matriculated at Harvard College in September 1970. Three years and nine months later he graduated cum laude, with honors in Geological Sciences. As a senior advisee of Raymond Siever, he became acquainted with John Southard of M.I.T. and was bitten by the "flume bug", with which he has been afflicted ever since. Entry into M.I.T. was fairly easy, but getting out has taken a few years longer than expected. Along the way, Bill married Patricia J. Irwin from Nashville, Tenn., and she has proven to be far more tolerant than most wives.

Bill enjoys many facets of life, from serving communion in church, to "ham" radio, to fixing a broken flume. His predominant interest is sedimentary geology, and he earnestly hopes someone will pay him to keep working at it.

Bill is a joiner, so he maintains membership in the American Association for the Advancement of Science, American Association of Petroleum Geologists, American Geophysical Union, Geological Society of America, New York Academy of Sciences, Society of Economic Paleontologists and Mineralogists, and Sigma Xi - The Scientific Research Society of North America.

APPENDIX 1

Manufacturer's description and schematic diagram of sonic bed profiler

Sonic Bed Profiler

To operate the Sonic Bed Profiler, simply plug the unit into a 115 vac outlet. Connect the transducer to the transmitter out via the underwater co-ax cable supplied. Place the unit in the short range and turn unit on. A buzzing sound can be heard from the transducer. This buzzing is produced by the repetitive rate of the 4 Megahertz tone bursts. In the short range mode, the rep-rate is approximately 500 hertz, and is 250 hertz when the long range mode is selected.

Place the transducer in water above the sand bed to be measured. Care must be taken to insure that no air is trapped in the transducer. The minimum distance between the transducer and the bed is approximately 15 cm, while the maximum distance is 1.5 meters, and 3 meters for the short and longe ranges respectively.

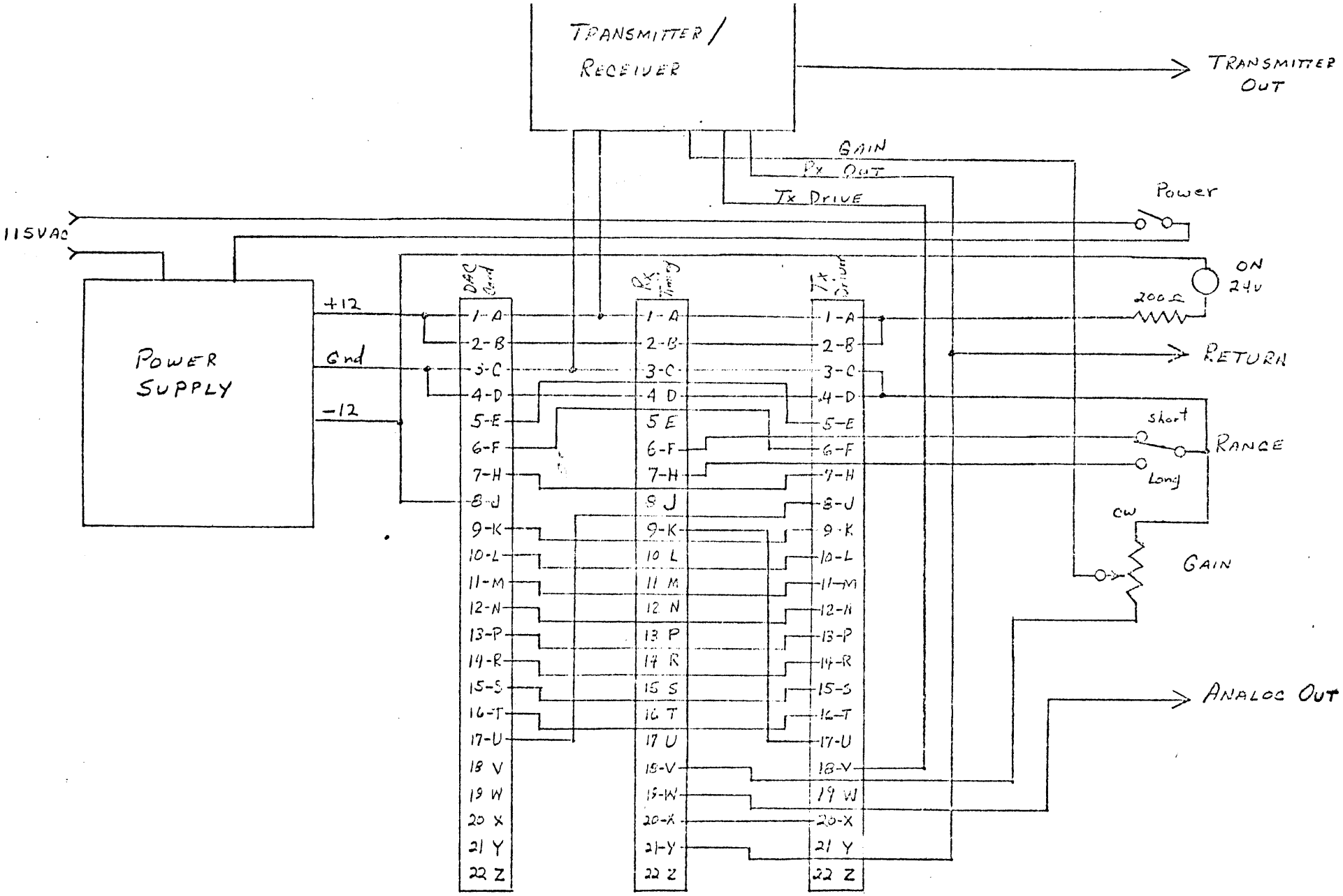
Once the transducer has been appropriately mounted, an oscilloscope should be used to set the gains of the receiver. Turn the Gain Control fully counter-clockwise (minimum gain). Connect the return signal to the vertical input to the scope. Sync the scope to the transmitter output. Adjust the time base of the scope until two pulses appear. These pulses are the transmitted tone bursts. Turn the Gain Control clockwise until a stable pulse appears between the two original pulses; this is the reflected return from the bed. No further adjustment should be necessary.

The unit has been calibrated (short range) by attaching the transducer to a vertical displacement gauge. The gauge was moved 27 cm in 1 cm steps. The accuracy of the step was better than 1 mm. The starting distance about the bed was approximately 75 cm. This distance was decreased using the vertical displacement gauge. The volt output (analog out) changed from +230 mu to + 2.045 volts. A linear fix to the data gives a calibration of:

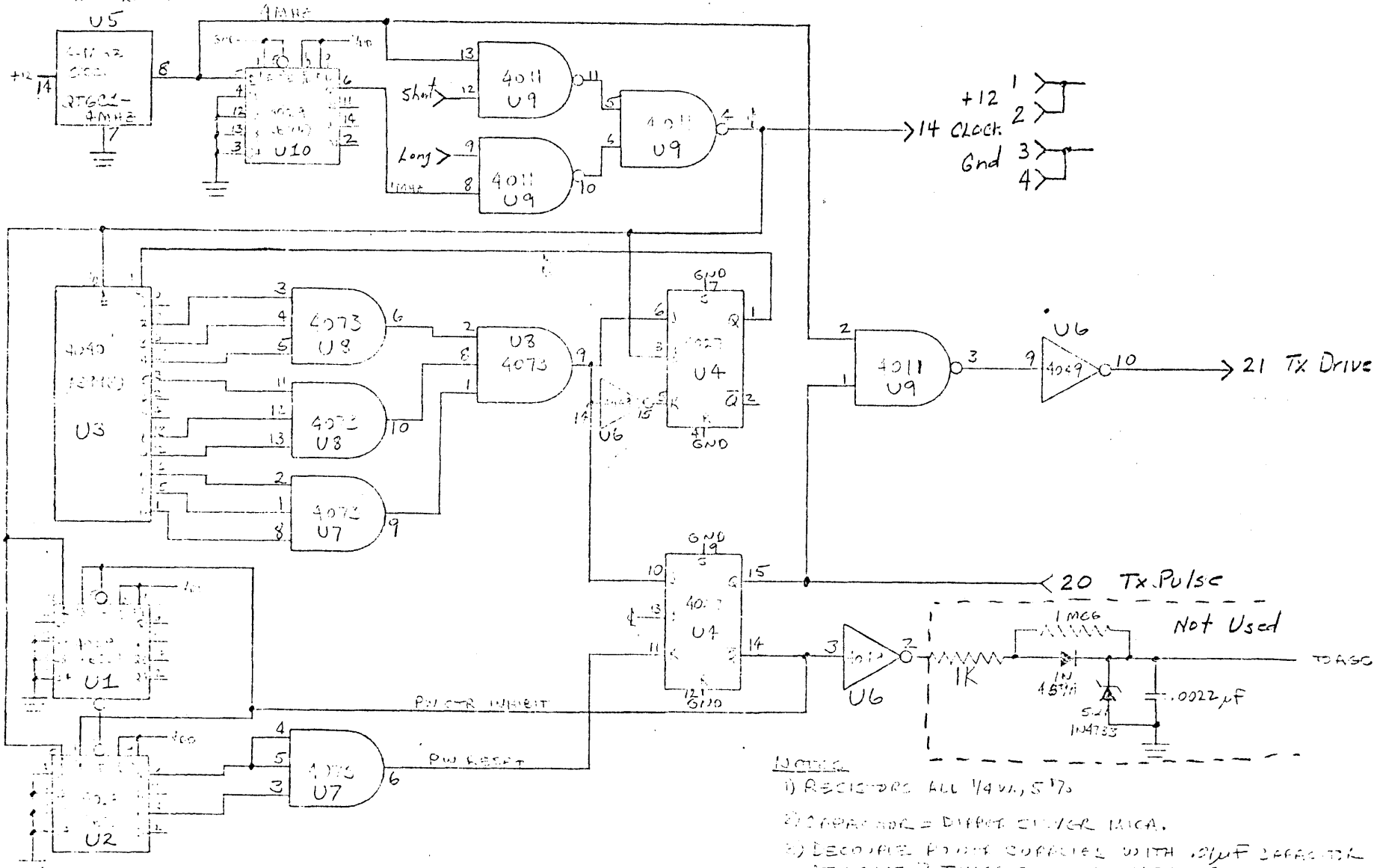
Distance above bed (cm) = V_{out} (mv) x (Cal. Factor) + Offset

Cal. Factor = $- 15.414 \times 10^{-3}$

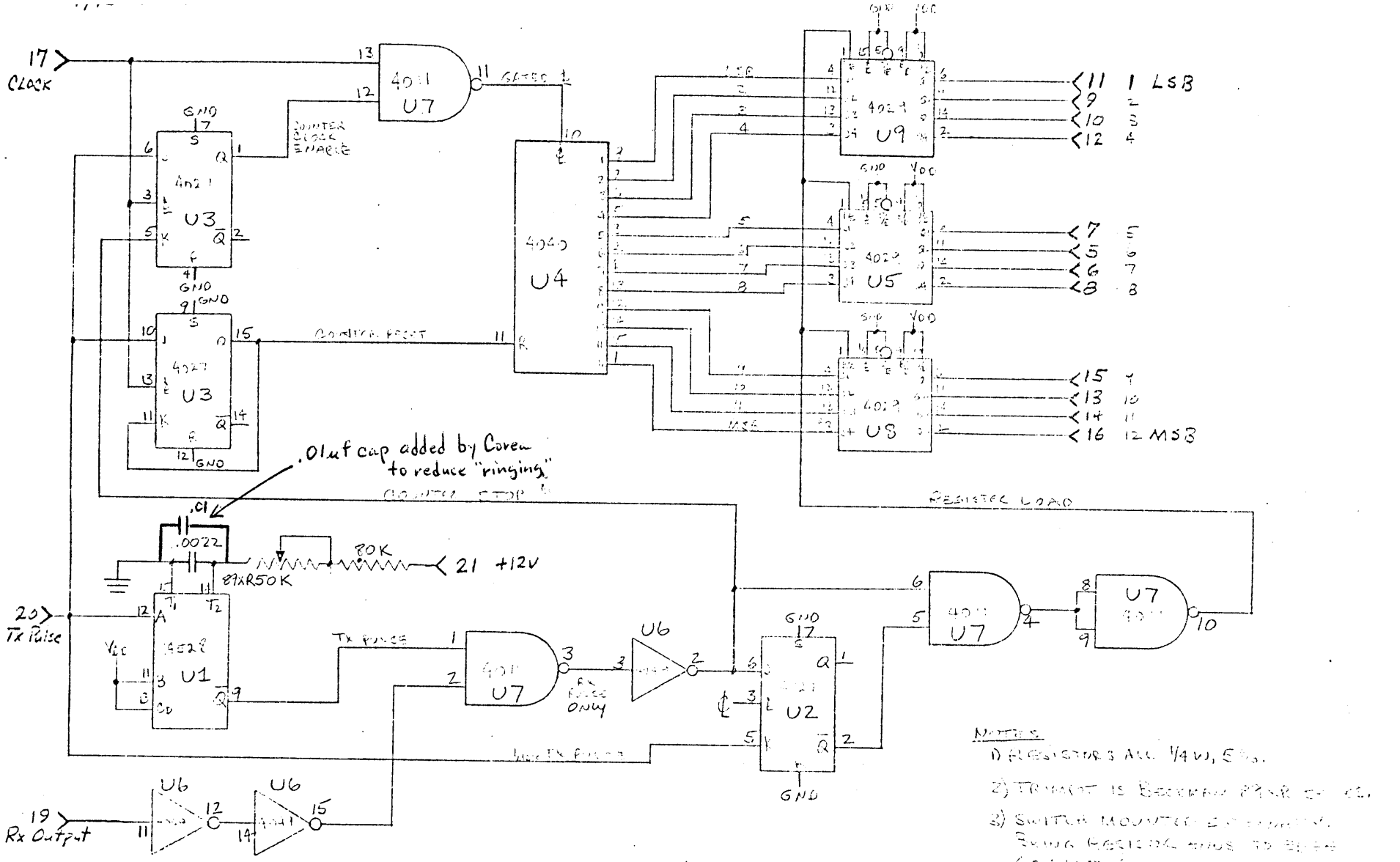
Offset $\sim$ 78.42


TRANSMITTER / RECEIVER
TRANSMITTER OUT
GAIN
Rx OUT
Tx DRIVE
Power
115VAC
ON 24V
200Ω
RETURN
short
RANGE
Long
CW
GAIN
ANALOG OUT
POWER SUPPLY
+12
Gnd
-12
DAC Card
Rx Analog
Tx Driver
1-A
2-B
3-C
4-D
5-E
6-F
7-H
8-J
9-K
10-L
11-M
12-N
13-P
14-R
15-S
16-T
17-U
18-V
19-W
20-X
21-Y
22-Z

BY JCB DATE 6/24/76 SUBJECT COAX → DRIVER SHEET NO. 1 OF
CHKD. BY DATE JOB NO. Model 1276
Corr. 6/77
Mod. 4/78 R.L.L.



NOTES
1) RESISTORS ALL 1/4 W, 5%
2) CAPACITOR = DIPPED SILVER MICA.
3) DECOUPLE POWER SUPPLIES WITH .01μF CAPACITOR AT LEAST 3 TIMES ON BOARD NEAR OSCILLATOR AND OTHER IC'S.



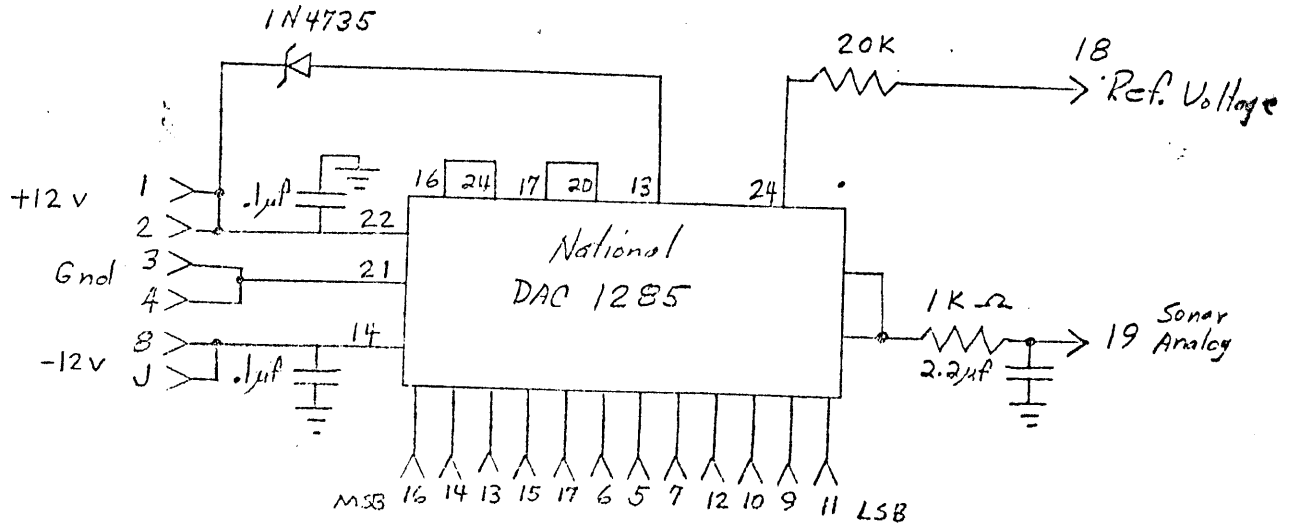
NOTES

1) RESISTORS ALL 1/4 W, 5%.

2) TRANSMIT IS BROADBAND PULSE OF 45 µs.

3) SWITCH MOUNTED ON [illegible]. SHUNT RESISTORS MUST BE ON SWITCH TERMINALS.

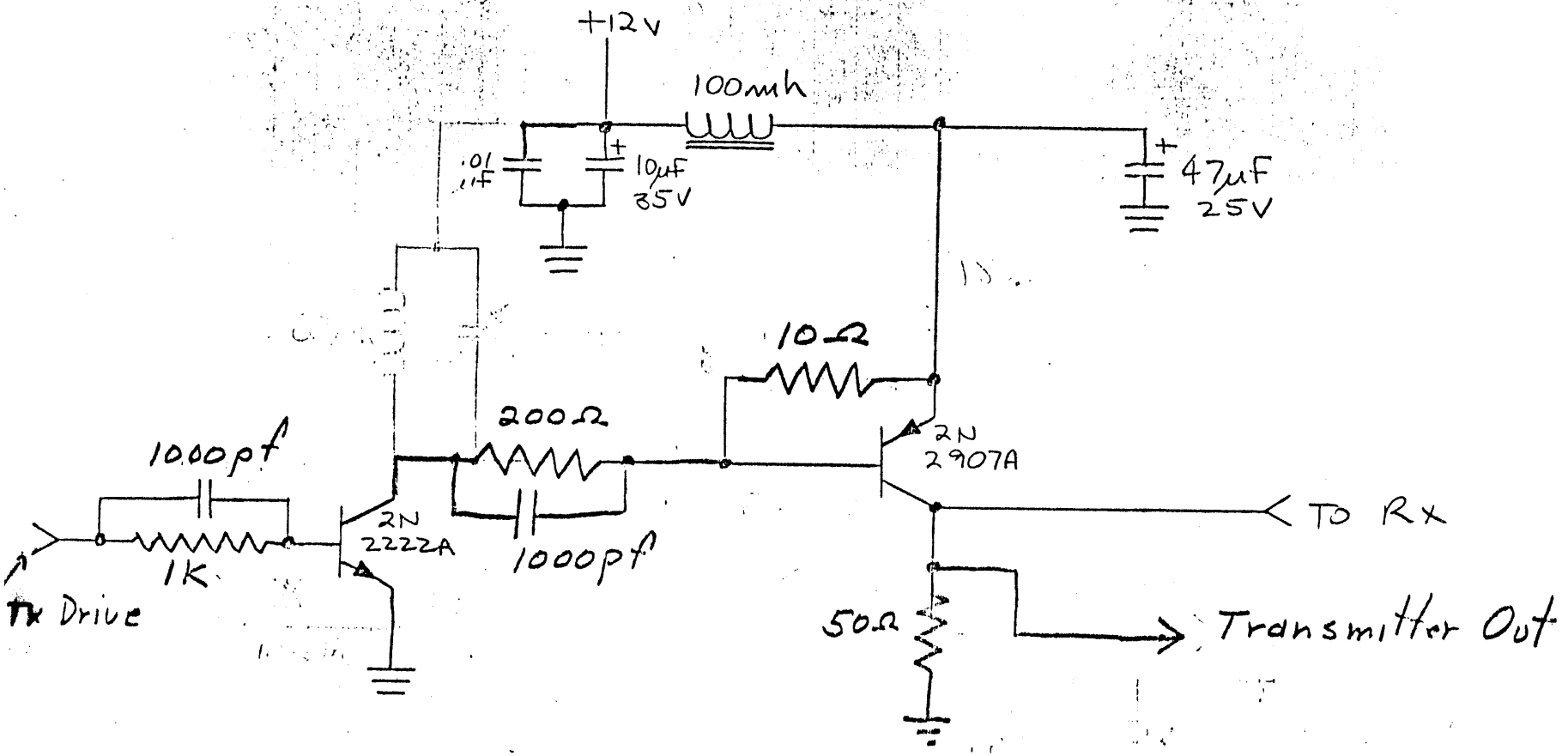
4) POWER SUPPLIES TO BE DECOUPLED WITH 10µF AT EACH 4 TIMES 10 MIL CIRCUIT.

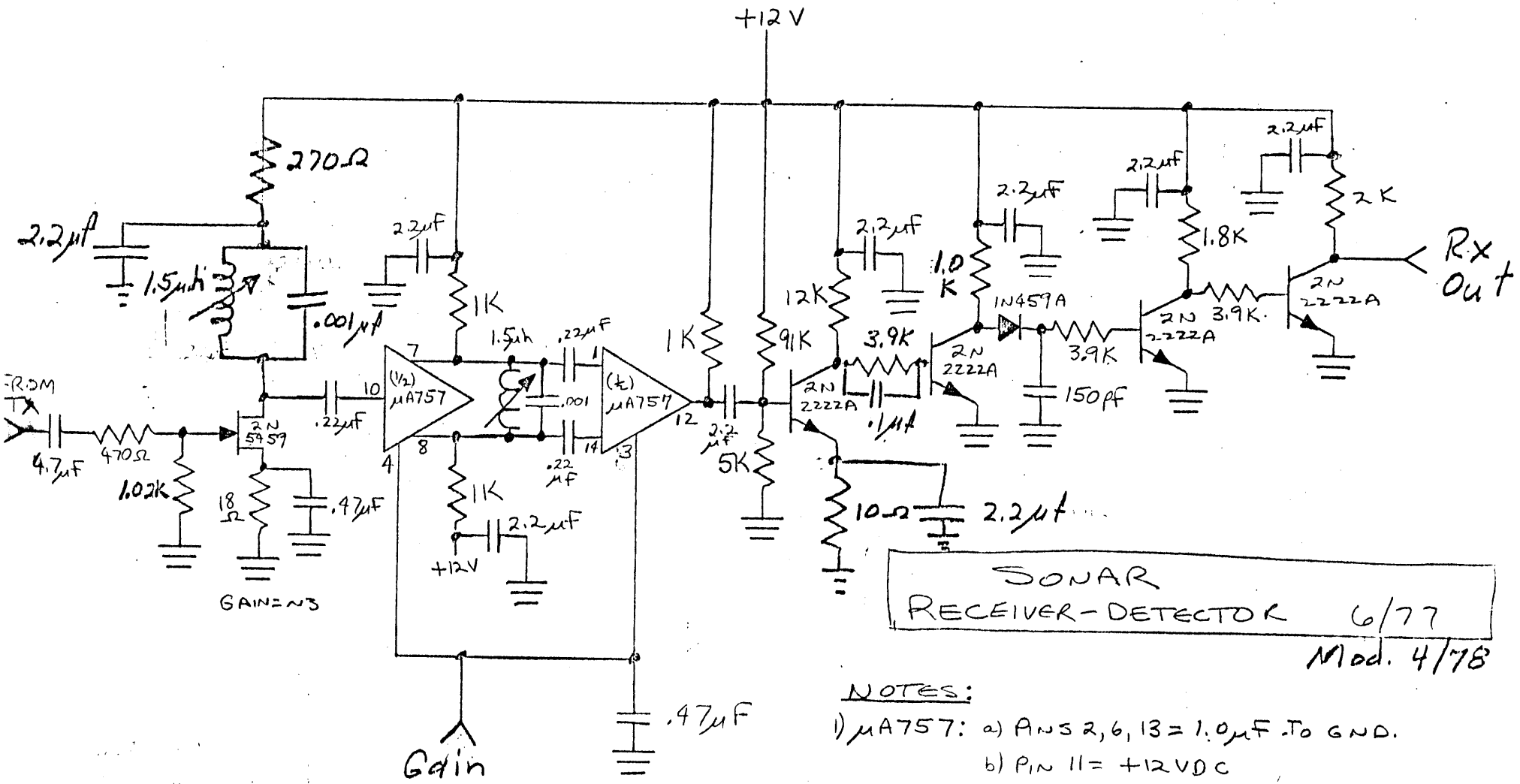


Sonar Digital to Analog Conv.

SONAR TRANSMITTER 6/77
LOCOM CO.

Mod 3/78 R.L.L.





SONAR
RECEIVER-DETECTOR 6/77
Mod. 4/78

NOTES:

1) μA757: a) Pins 2, 6, 13 = 1.0μF To GND.
   b) Pin 11 = +12VDC
   c) Pins 5, 9 = GND
2) Copper shielding can installed around coil and capacitor near μA757.

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