INTERPRETING DEPOSITIONAL ENVIRONMENTS OF SEDIMENTARY STRUCTURES

By

C. F. Nordin

D. B. Simons

and

E. V. Richardson

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Ripple marks and cross bedding are features common to most sedimentary deposits, and they have received a great deal of attention in Geologic literature. Yet, in spite of the fact that they have been studied for well over a century, remarkably little is known of their dynamic origin or environment. In the great majority of geologic investigations, the only useful information forthcoming from studies of ripple marks and cross bedding has been a qualitative indication of current direction.

Ripple marks are the external form and cross bedding is an internal manifestation of configurations generated at a fluid-sediment interface by a current. In recent years, these configurations have been studied extensively, mostly by engineers concerned with problems of sediment transport, river hydraulics, and stable channel design. Not much has been learned about the dynamic origin of these configurations, but a great amount of information has accumulated about their environment. Some of this information might have useful

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applications in interpreting depositional environments of sedimentary deposits, particularly deposits of fluvial origin. It is the purpose of this paper to summarize briefly the results of recent studies, and to indicate how these results might be used in interpreting environments of sedimentary deposits.

First, consider the bed forms, or configurations, which have been identified in laboratory experiments (Simons and Richardson, 1963a) and verified in field studies (Nordin, 1964a). Commencing with a plane bed prior to sediment motion, with increasing stream power $\tau_0 V$, the following bed forms occur (see fig. 1): ripples, ripples on dunes, dunes, a transition from dunes to a plane bed, a plane bed, antidunes, and chutes-and-pools. Chutes-and-pools ~~have~~ are not ~~been~~ usually observed in natural channels.

Ripples are small elements, triangular shaped in plan with a gentle upstream face and steep downstream slope, and with lengths usually less than [illegible]0 cms and amplitudes less than 3 cms. Ripples form and persist in a limited range of Reynolds numbers

$$3 < \frac{V_* d}{\nu} < 80 \qquad (1)$$

and in a range of velocities such that

$$V_c < V < 1.5\ V_c \qquad (2)$$

where V_* = shear velocity, $\sqrt{gDS}$,

g = gravity constant,

D = flow depth,

S = slope of the energy gradient,

d = particle diameter,

V_c = critical velocity for the initiation of particle motion,

V = mean velocity.

Ripples are observed in flow conditions where the concentration of the bed-material discharge ranges from 0 to 300 ppm (parts per million), and perhaps higher in very shallow flows. The sediment transport rate accompanying ripples is less than 0.14 gms/sec/cm (0.4 tons/day/ft).

Ripple wave length L and amplitude A are independent of flow depth, but dependent on grain size (or more correctly, fall velocity) and size distribution of bed material. As a first approximation for natural river sands, length and amplitude are given by the relations

$$L \sim 1000\, d_{50} \tag{3}$$

$$A \sim 50\, d_{50} \tag{4}$$

Ripples do not form in material with a median diameter greater than about 0.6 mm because at the tractive force required to initiate movement, the critical Reynolds number given above already is surpassed.

Dunes are similar in shape to ripples, but they generally are much larger. They form and persist at Reynolds numbers

$$\frac{V_* d}{\nu} > \overset{20}{\cancel{80}} \qquad (5)$$

and at shear velocities V_* greater than about 4.3 cms/sec. In terms of velocity, they persist in the range

$$1.5\,V_c < V < 3.5\,V_c \qquad (6)$$

Dunes have been observed in flows with concentrations of bed material from 100-2000 ppm (perhaps higher in shallow flows) and at bed material discharges from 0.14 to 8.6 gm/cm/sec (0.4 to 25 tons/day/ft). At low shear stresses and in the range of Reynolds numbers from about 20 to 80, ripples are superposed on the dunes.

The maximum amplitude of dunes is limited by flow depth, and the average amplitude is approximately 1/3D for shallow three-dimensional flow and 1/6 D for two-dimensional flow and perhaps for deeper (greater than 2 meters) three-dimensional flows. As a first approximation, dune wave length is roughly 5D for shallow three-dimensional flow in natural channels with bed material of 0.2 to 0.3 mm in diameter (fig. 2). However, dune wave length is also strongly dependent upon grain size, or fall velocity of bed material, as shown in figure 3.

The ratio of wave length to amplitude L/A for dunes varies widely, and typical distribution curves (fig. 4) show that the dominant mode is less than the average and that the distributions are skewed toward the higher L/A values. The mean value of L/A for dunes is found to be a function of both shear stress and particle size (fig. 5).

Both ripples and dunes are propagated in the downstream direction by the erosion from their upstream face of particles which move to the crest and are deposited on the downstream face at approximately the angle of repose of the bed material. Coarse material segregates in the troughs, and the median diameter of the transported material is generally less than the median diameter of the bed material. For sediment in the sand size range, a suspended load is rarely associated with ripples, but is almost always associated with dunes.

Migrating ripples and dunes commonly form sets of trough cross-stratification, with average lengths of the individual units approximating the average wave-length of the elements forming them (Harms and Fahnestock, 1965). Because of the segregation of material in the troughs, horizontal bedding may also be associated with ripple and dune migration, but usually it occurs when the flow and the bed forms are two-dimensional and the troughs move in a common plane.

The plane bed occurs under flow and transport conditions such that any artificial disturbance of the bed is unstable and can only decrease in amplitude (Kennedy, 1963). Contrary to what is reported by many investigators, the plane bed does not require a Froude number, $\mathbb{F} = V/\sqrt{gD}$, of unity; it can, in fact, form at practically any Froude number provided the sediment transport rate is sufficiently great. Generally, the plane bed occurs at sediment transport rates greater than 10 gms/sec/cm (about 30 tons/day/ft) and at velocities greater than approximately 4.5 V_c. Material is transported continuously close to the bed, there is also an appreciable suspended load. There is little or no segregation of the particles; the size distribution of the transported sediment is the same as the size distribution of the bed material. Stratification associated with the plane bed is horizontal bedding, with little or no evidence of segregation.

Antidunes are wave-like configurations of the channel bed which are coupled with and strongly interact with water-surface gravity waves (Kennedy, 1963). Thus, they are related to Froude number. Theoretically, they occur at Froude numbers greater than 0.84; in natural channels they are observed at Froude numbers, based on local mean depth and velocity, of from about 0.7 up (Nordin, 1964a). Antidunes occur in trains which are cyclic in period and which migrate downstream. The water-surface waves accompanying antidunes may build up and fade without breaking, or may build up and culminate in breaking. Breaking water-surface waves have a wavelength of about 4.3D and an amplitude of 0.6D, and the accompanying antidunes have the same wavelength but smaller amplitudes. Antidunes are propogated by material eroding from their downstream face and depositing on their upstream face. Antidunes usually move upstream, but they may remain stationary or move downstream.. They generally are accompanied by high sediment transport rates, and when the water-surface waves break, large quantities of bed material are thrown temporarily into suspension.

Stratification accompanying antidunes is poorly defined, and remnants of antidunes either are not found or not recognized in ancient deposits. Harms and Fahnestock (1965) mention sinusoidal shaped forms with low-angle faces in recent sediments, presumably from antidunes, and Allen (1964) described winnowing parallel to the direction of flow of bed material due to antidune action. In general, however, it can be assumed that antidunes occur during changes in stage, usually accompanying degradation, and that remnants are obliterated by later flows.

Knowing the bed configurations which form in alluvial channels, the range of flow conditions and sediment transport rates under which they exist, and the stratification accompanying them, it is now possible to consider the question of interpreting depositional environments. For this purpose, two additional relations are useful. The first is figure 6, presented previously by Simons and Richardson (1963b), which gives bed configuration as a function of stream power and median diameter of bed material. If particle size and bed configuration for a particular sedimentary unit can be determined, say from ripple marks or cross stratification, a range of stream power is defined. This reduces to a range of unit discharge if the paleoslope of the deposit is known because stream power contains the product of velocity, depth, and slope.

The second important relation is the sediment transport relations developed recently by B. R. Colby (1964). Colby defined the rate of sediment discharge per unit width of channel for sand-size material as a function of depth, velocity, water temperature, and particle size. For a given particle size and water temperature, either sediment concentration or unit sediment discharge may be defined (fig. 7) as a unique function of velocity and depth (Nordin, 1964b). For interpretive purposes, the left-hand graph showing unit sediment discharge is the most useful. The area of the velocity-depth field where either ripples or dunes exist can be defined in terms of transport rates. The Froude number above which antidunes form can be superimposed on the figure as a line with the slope of two, and unit water discharge can be superimposed as a line running downward from left to right with a slope of minus one. Thus, if bed form and slope associated with a particular sedimentary unit are known, the range in velocity and depth of flow associated with the unit may be determined.

Finally, consider a simplified example shown schematically in figure 8. Knowing particle size and bed form, a range of stream power is defined. If paleoslope is determined, a range of unit discharge is defined. If the bed configuration is ripples, the range of velocity and depth can be established. If the bed configuration is dunes, a range in velocity and depth is defined, and the range in total discharge of the channel might be defined[2/], because both

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[2/] The relation of depth to discharge in figure 8 is for stable regime canals, and represents dunes in fine sand at low shear stresses and for two-dimensional flows with low sediment transport rates and unit water discharges less than 40 cfs/ft. Similar relations can be developed for flow in natural channels for either a dune bed or a plane bed.

velocity and depth can be given as exponential functions of discharge (Leopold and Maddock, 1953). Finally, if the L/A ratio of dunes can be determined and if particle size is such that the relation of L/A to shear stress is defined, it should be possible to fix velocity, depth, and discharge with some degree of certainty.

Summarizing, some of the results from studies of bed configurations and of flow and sediment transport in alluvial channels have been presented, and relations developed are suggested as aids to interpreting depositional environments of sedimentary units, particularly units of fluvial origin. It is recognized that sedimentary processes are extremely complex and that the applications considered were oversimplified and somewhat idealized. Nevertheless, the basic approach is sound and when the empirical relations are refined and extended to a wider range of conditions, they should provide quantitative answers to questions which heretofore have been answered only qualitatively.

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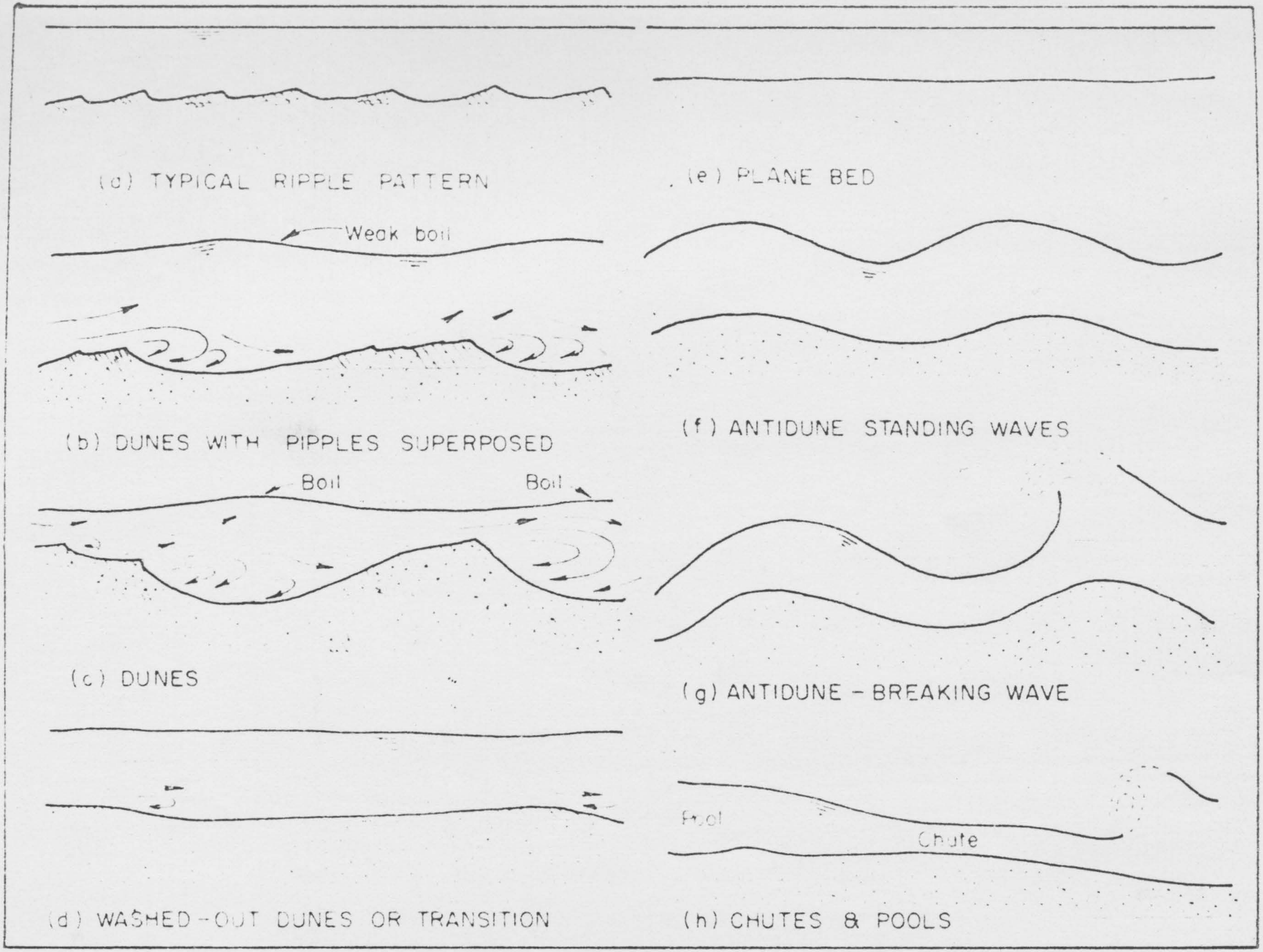


Figure 1.--Bed configurations in alluvial channels.

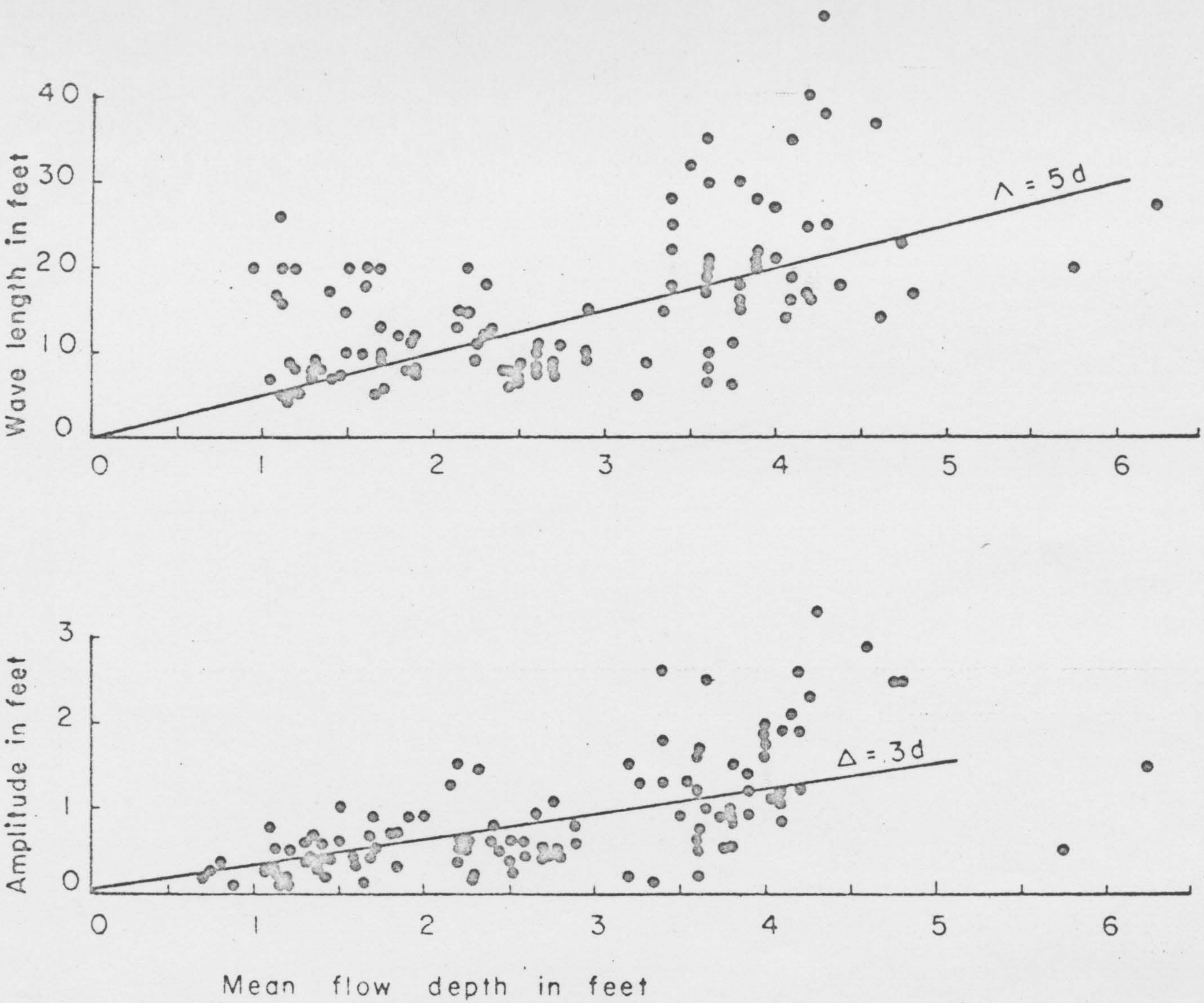


Figure 2.--Relation of dune amplitude and dune wave length to mean flow depth, Rio Grande near El Paso, Texas.

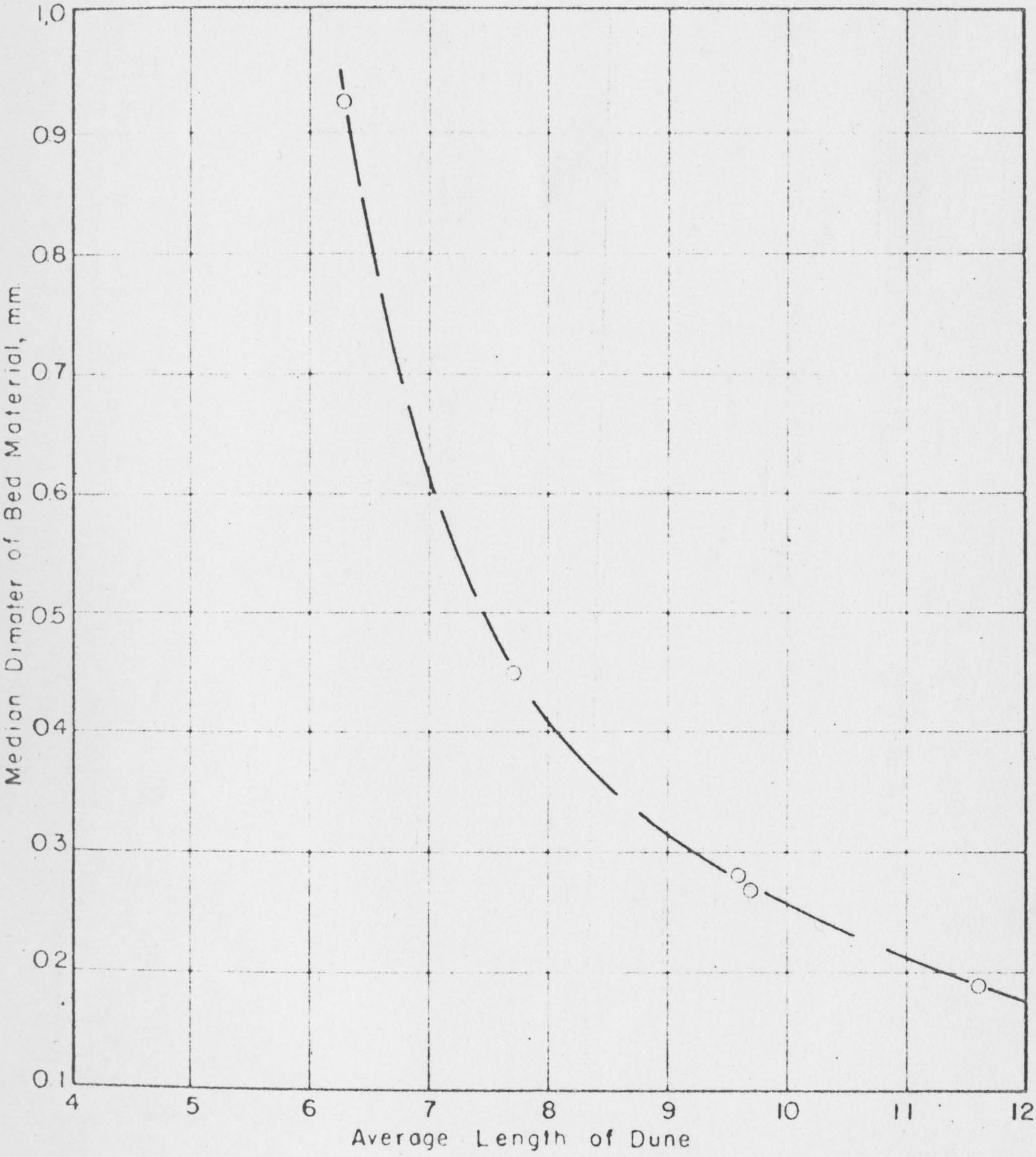
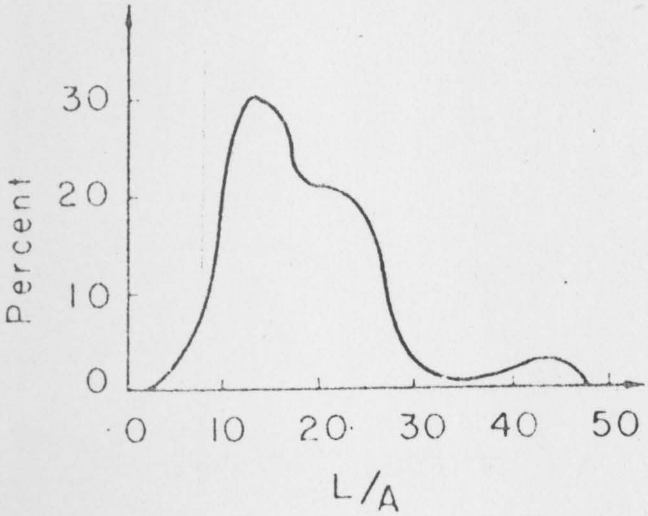
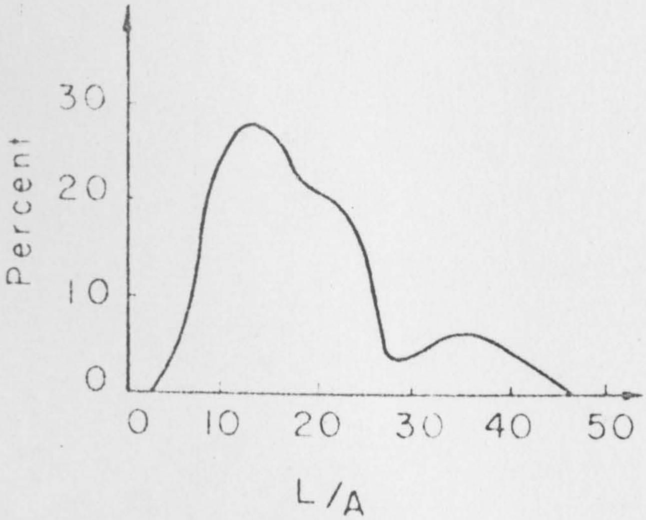


Figure 3.--Relation of dune wave length to median diameter of bed material, for a constant depth (after Simons and Richardson, 1963a).



DISCHARGE	380 cfs
WIDTH	200 ft.
DEPTH	1.10 ft
VELOCITY	1.72 ft/sec
TEMPERATURE	62 °F
MEDIAN DIAMETER	0.22 mm
AVERAGE L/A	16.5



DISCHARGE	953 cfs
WIDTH	103 ft
DEPTH	3.66 ft
VELOCITY	2.53 ft/sec
TEMPERATURE	77 °F
MEDIAN DIAMETER	0.22 mm
AVERAGE L/A	15.7

Figure 4.--Distribution curves of L/A for observations of the Rio Grande near El Paso, Texas.

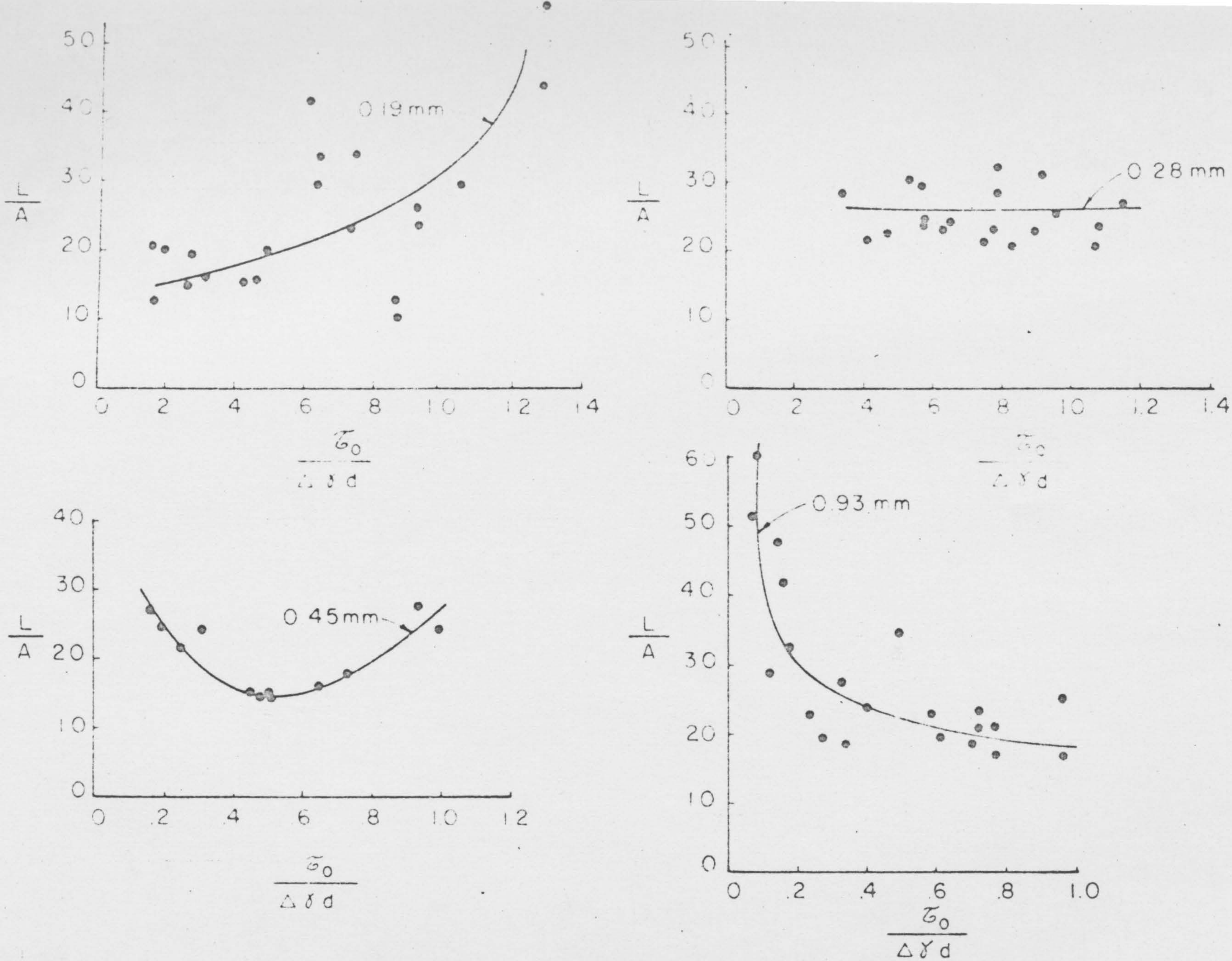


Figure 5.--Relation of L/A to $\tau_0/\Delta\gamma d$.

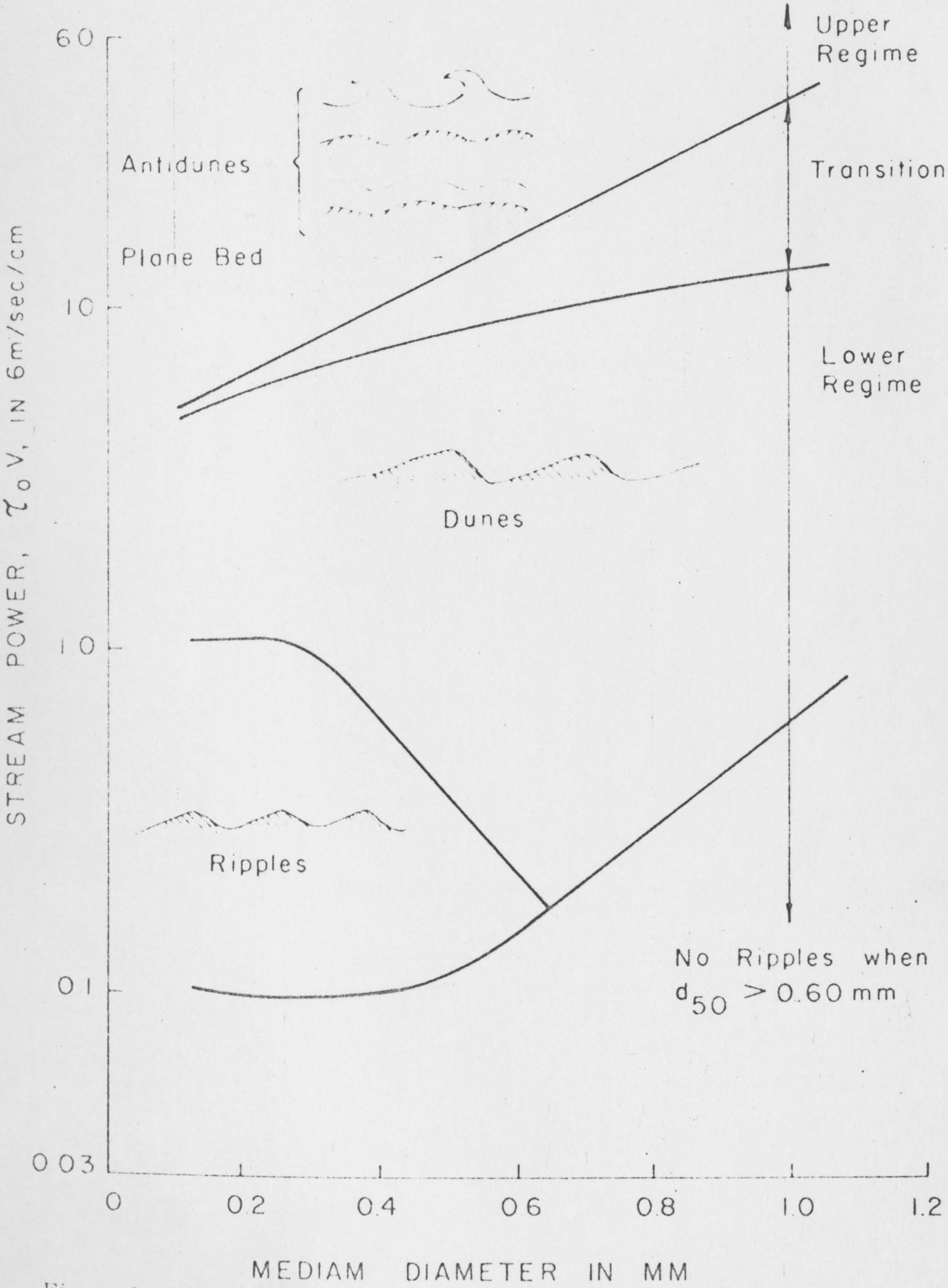


Figure 6.--Bed configuration as a function of stream power and median diameter of bed material (after Simons and Richardson, 1963a).

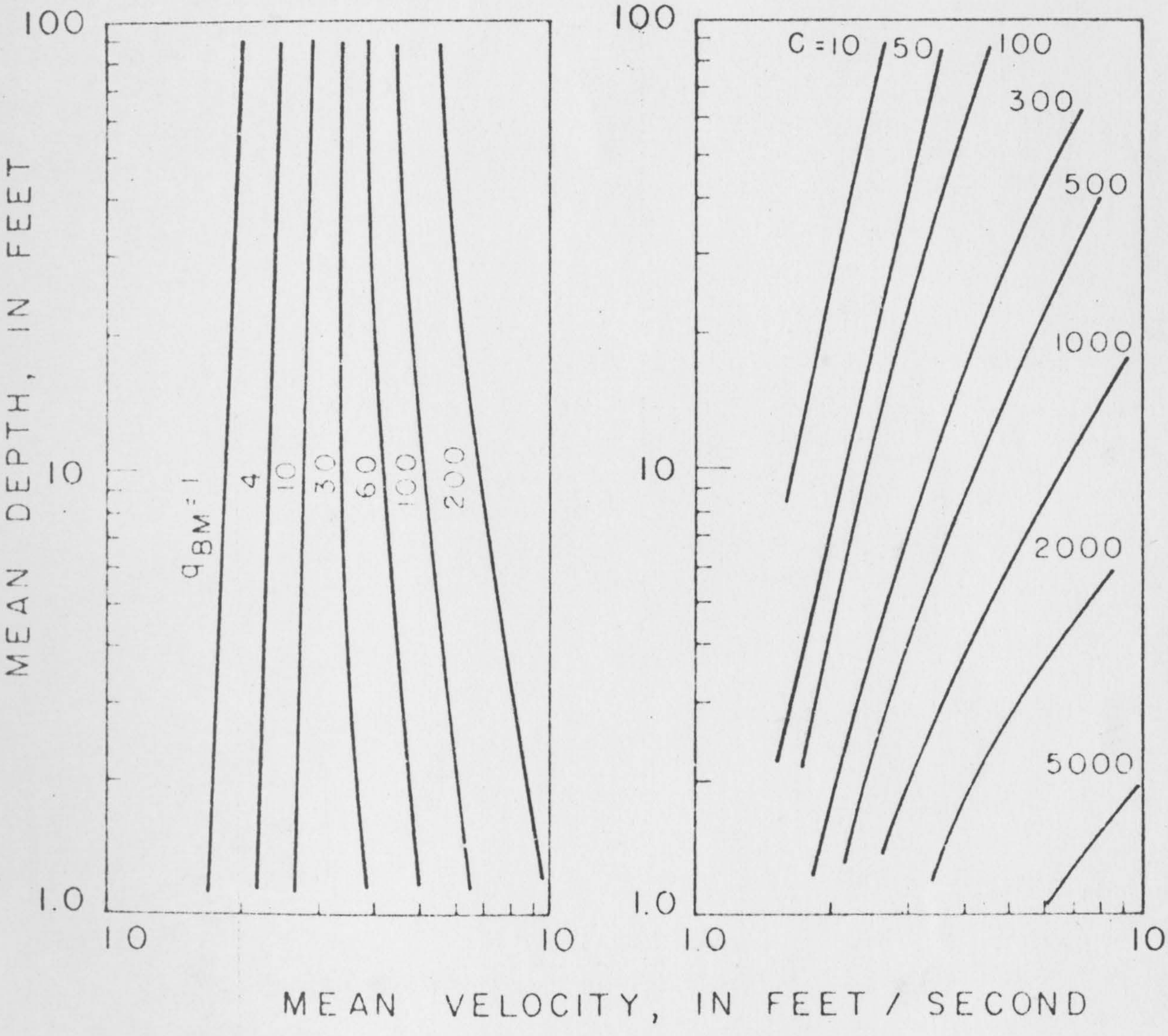


Figure 7.--Relation of unit bed material discharge and bed material concentration to mean velocity and depth, for bed material with a median diameter of 0.3 mm and water temperature 60°F.

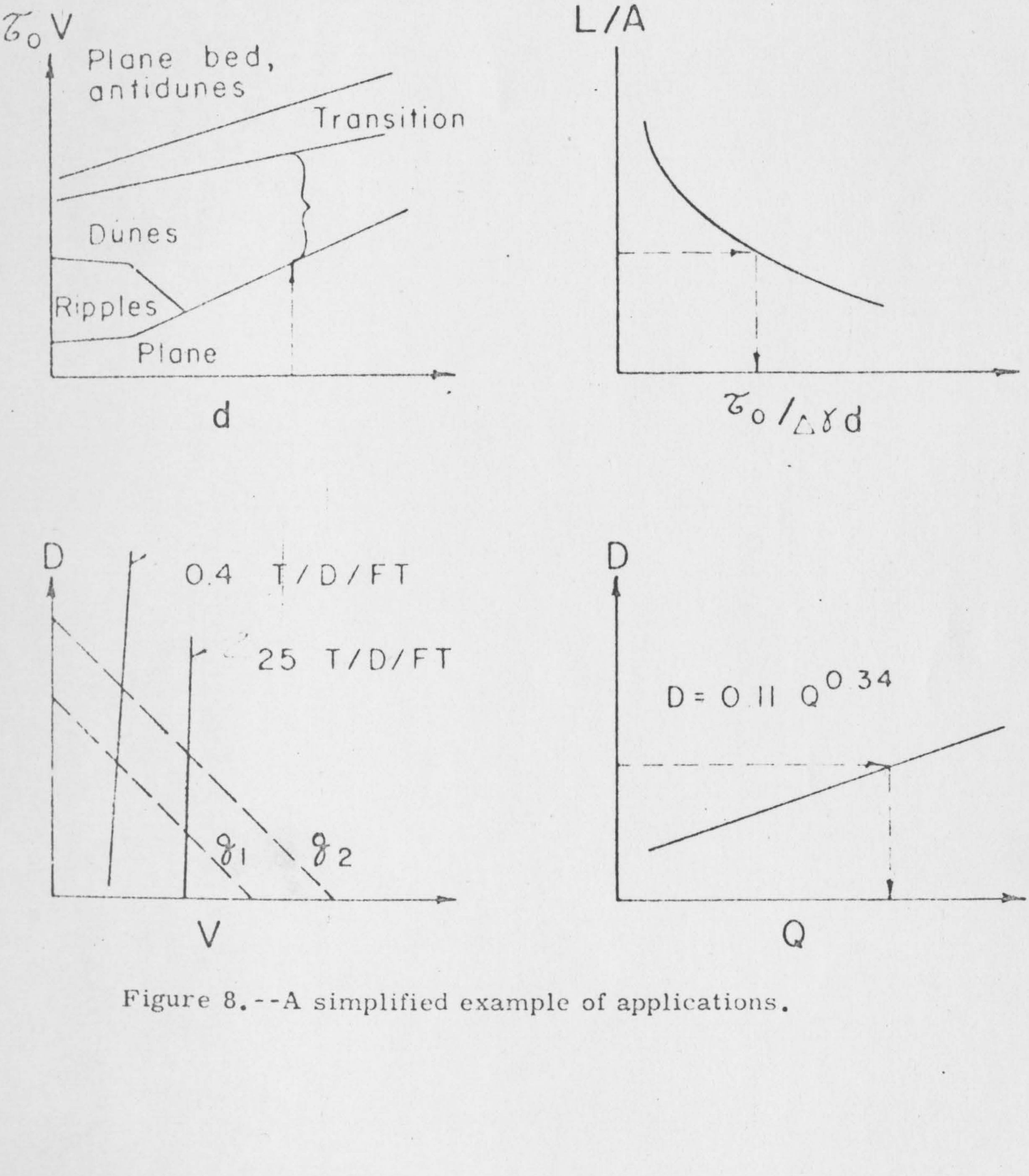


Figure 8.--A simplified example of applications.