On the dimensional adjustment of subaqueous dunes in response to changing flow conditions: a conceptual process model

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Abstract

Numerous field studies have concerned themselves with the occurrence, dimensions, grain-size characteristics, and the environmental settings of subaqueous dunes. Similarly, laboratory flume studies have mainly looked at the flow conditions producing stable bedforms and the transitions from one bed phase to another as a function of grain size and flow velocity. By contrast, very little is known about the process of dimensional adjustment of dunes to changing flow conditions. Currently, two theories of bedform growth exist, one having dunes grow by the capture of faster migrating smaller dunes by more slowly migrating larger dunes, the other by the stepwise coalescence of smaller dunes into bigger ones scaled to the size of eddies. Both mechanisms are essentially irreversible. The available field evidence clearly contradicts the first theory and supports the second one only in part. The data clearly show bedform amalgamation or coalescence on various scales, both in shallow and deep water, in reversing and unidirectional flows, but also in aeolian dunes, clouds, and snow. Furthermore, there is clear evidence for reversibility of the process. Based on these observations, a conceptual process model is developed which explains the modes of observed dune growth patterns. In this model dune growth proceeds in steps as a function of grain size and flow velocity, the process being inherently reversible. Water depth is a limiting factor, but not otherwise a functional parameter required for bedform generation. Internal sedimentary structures produced in the course of amalgamation or dune splitting is illustrated by theoretical reconstructions and high-resolution seismic profiles.

Introduction

Numerous studies have documented the dimensions, grain-size characteristics, and flow conditions under which subaqueous dunes occur in nature and in laboratory flumes (cf. Ashley, 1990; Southard, 1991). By contrast, very little is known about the processes controlling the dimensional scaling (height/spacing relationships) of dunes, and how such dimensional adjustments are achieved in response to changes in the flow. A general dependence of dune size on grain size, flow velocity and water depth is implicit in the 3-Model of Rubin and McCulloch (1980). However, these authors do not comment on how the dunes adjust their dimensions to changes in flow conditions.

Führböter (1983, 1991) favoured a mechanism by which flow-transverse bed forms (ripples, dunes) are generated from random disturbances which initially produce small, irregular bed features having different dimensions. Since flow-transverse bedforms of different size migrate at different speeds, smaller ones will catch up with and be captured by bigger ones which happen to be in their path downstream. By this mechanism the initially random and irregular features unite to form transversely aligned regular ones, the gradual increase in sediment volume resulting in progressive growth of the bedform.

Yalin (1992) also commences from a random initial disturbance hypothesis, in this case associated with the bursting phenomenon. The bursts generate eddies which grow in size by coalescence, the diameters of the largest ones approximating the flow depth. Since bursting is an ongoing process, eddies are constantly being generated. As a result, there is a coexistence of different eddy sizes stacked vertically in the water column and scaled with the water depth. Linked to this process are concurrent disturbances of the bed which generate small flow-transverse bedforms. Implicit in this model is a stepwise bedform growth scaled with the different eddy hierarchies. In this way a size hierarchy is generated, smaller bedforms coalescing or amalgamating to form the next bigger generation in the hierarchy, the different size classes coexisting at any one time.

Clearly, other than also invoking random disturbances, the Yalin-model has little in common with the Führböter-model. The two models are essentially theoretical, although both make selective use of certain known natural phenomena. Both models can be tested using field evidence, and compliance or non-compliance with the test implications would obviously decide over acceptance or rejection. When applied to dunes, Führböter (1983, 1991) advocates progressive growth through the capture of smaller, faster migrating dunes by larger, more slowly migrating dunes, whereas Yalin (1992) proposes stepwise growth scaled with the size of eddies. Thus, the Führböter-model implies that after initiation, and irrespective of the flow conditions (as long as the flow remains competent), the dunes should continue to grow until they have either all reached the same size, or only one large dune is left because it has trapped all the smaller ones, water depth being a limiting factor in both cases. Furthermore, the process is irreversible unless the bed is levelled by upper plane bed conditions and the bedform generation process commences anew after a drop in flow velocity. In the case of the Yalin-model, dunes relating to different eddy sizes should always coexist and occur superimposed on each other. The larger the hierarchy, the more time must have passed since initiation. Increases in flow speed will generate larger eddies which, in turn, accelerate dune growth, while retaining the superimposition of the different size hierarchies. As in the previous case, the process is essentially irreversible.

The purpose of this paper is to compare available field evidence with the test implications of the two models outlined above. This could lead a) to the acceptance of the one and the rejection of the other, b) to the rejection of both, c) to the adaptation or modification of the one or the other, or d) to the formulation of a completely new model.

1. Evidence for dune growth

To recognize and document the process of dune growth the morphology of a bedform sequence should ideally be monitored over a time span in the course of which the flow increases or decreases from one velocity level to another and maintains the new level long enough to let the dunes adjust their dimensions to the new flow conditions. In practice this is not easily accomplished because in most natural flows such changes are difficult to predict. In the case of tidal flows, the velocity changes are predictable but, at the same time, are so rapid that the bedforms are unable to fully adjust in the course of individual tidal cycles, thereby producing the well-known time-lag effects (e.g. Allen, 1976). Nevertheless, Davis and Flemming (1991) and Flemming and Davis (1992) were able to document the dimensional adjustment of subtidal dunes in the course of a spring-neap semicycle, in the course of which the peak surface velocity decreased by about 10%. Repeated echo-sounder and side-scan sonar profiles revealed that at spring tide the bedform sequence comprised dunes with an average spacing and height of L = 28 m and H = 1.0 m, respectively. The dune backs were relatively smooth and mostly devoid of smaller superimposed dunes (Fig. 1A). At neap tide, by contrast, the dunes had an average spacing and height of L = 11 m and H = 0.6 m, respectively (Fig. 1B). Thus, in the course of the flow reduction from spring to neap tide the large dunes evidently split up into several smaller ones. The bathymetric track at neap tide (Fig. 1B) reveals that the larger spring-tide dune bodies are still discernible at neap tide, indicating that the duration of the reduced flow at neap tide was not sufficiently long to completely adjust the bed to the new condition before reversing the trend towards the next spring tide.

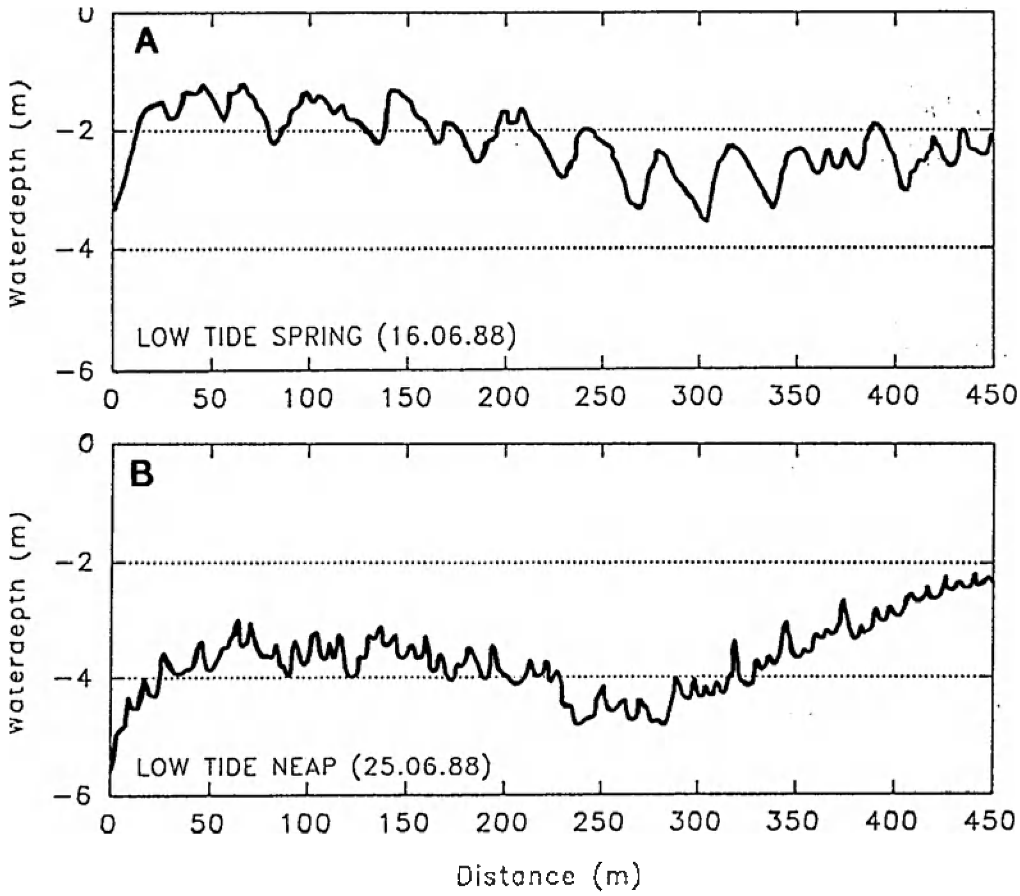

Fig. 1. Almost identical echo-sounder tracks revealing dimensional bedform adjustment from large dunes at spring tide (A) to smaller dunes at neap tide (B) in response to a 10% reduction in the peak flow velocity.

An analysis of side-scan sonar records from a variety of submarine environments (both tidal and non-tidal) shows that dimensional adjustment of dunes not only manifests itself on time-series data in the course of changing flow conditions, but that different size hierarchies may actually exist side by side in situations where the flow is apparently characterized by lateral, i.e. cross-flow velocity gradients. Typical examples are illustrated in Figs. 2 and 3. The sonograph of Fig. 2 was recorded on the south-east African continental shelf at a water depth of ca. 100 m (Flemming, 1980), the flow being essentially unidirectional (Agulhas Current). It depicts a cross-section of a large sand ribbon that is sculptured into parallel bands of symmetrically arranged dune size hierarchies. The flow is from the bottom towards the top of the picture. The strongest flow parcel is evidently located in the centre region of the ribbon, each successively smaller dune hierarchy on either side being associated with progressively weaker flow parcels. Water depth is clearly not a controlling factor. The large dunes observed in the centre of the picture have a spacing of about 40 m, the next smaller hierarchy 20 m, followed by a hierarchy spaced at 10 m, and another one at 5 m. Yet smaller hierarchies may have existed but were not been resolved by the survey equipment. Also note the relatively sharp boundaries between adjacent dune trains and that smaller hierarchies are not superimposed on the larger ones. Numerous other examples have been documented from the wider region.

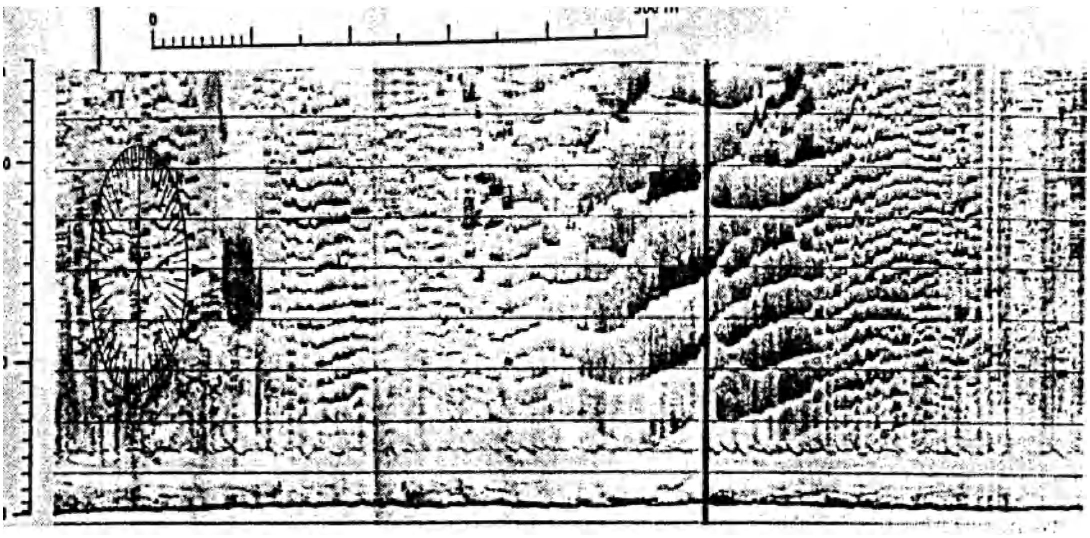

Fig. 2.
Coexistence of different dune size hierarchies along lateral, cross-flow velocity gradients. Note the quasi-symmetrical arrangement of individual size hierarchies, the relatively sharp boundaries between adjacent dune trains, and the absence of smaller superimposed dunes in each case (flow direction from bottom to top).

A literature survey has revealed the existence of similar hierarchical patterns in different types of environments, diverse geographic locations, and a wide range of grain sizes and particle densities. The documentation includes intertidal environments (McCave and Geiser, 1978), subtidal environments (e.g. Bouma et al., 1980; Knebel et al., 1999), and fluvial environments relating to catastrophic glacial outflow events (Bretz, 1969; Carling, 1996; cf. Fig. 3). Analogous patterns have also been observed in aeolian sands, snow, and cloud formations (Flemming, unpubl.). The fact that hierarchically structured bedform patterns of the types illustrated and described above are observed in practically every conceivable flow system suggests that it reflects a fundamental underlying principle which appears to control the growth of flow-transverse bedforms in nature.

On the basis of the observations, this principle suggests a mechanism by which flow-transverse bedforms grow in size by the amalgamation of two or more smaller individuals to form a larger one. Amalgamation proceeds in response to increases in flow velocity, flow depth being a limiting factor. Successive size hierarchies can only evolve if sufficient time is available to accomplish full (or nearly full) adjustment. The larger the amalgamating bedforms, the more time is needed for full development. The process is inherently reversible, a drop in flow velocity resulting in the splitting up of larger bedforms into two or more smaller ones. There is some evidence to suggest that downscaling proceeds at a lower speed than upscaling, a feature probably associated with a more pronounced time-lag resulting from the decelerating flow. As a result, the bed is partially or completely restructured as a function of the size of the bedform and the time span available for re-adjustment.

Hierarchical bedform evolution may be obscured in flows characterised by rapidly fluctuating velocities and other limiting factors (shoaling water depths, wave action) because time-lag effects prevent the evolution of equlibrium forms. The dimensional scaling of bedform hierarchies does not appear to be exclusively dependent on flow parameters alone but also on sediment type, especially grain size, grain shape and grain density. It is important to note that the same flow conditions will not produce the same bedform size in different sediment types.

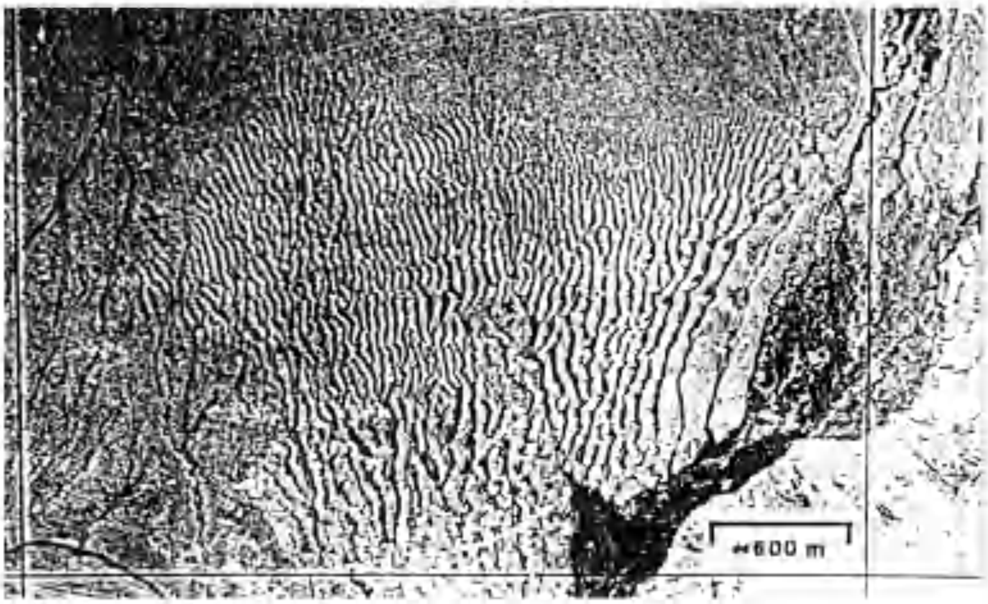

Fig. 3. Air photo of large gravel dunes produced by a catastrophic glacial outflow event in the Altai Mountains of Siberia (from Carling, 1996). The flow is from right to left. Note the hierarchical pattern of different dune sizes in both the downstream and cross-flow directions.

2. Conceptual model for dune growth by amalgamation

The available evidence on bedform amalgamation clearly suggests the existence of a mechanism by which two or more smaller flow-transverse bedforms coalesce to produce a larger bedform. In order to assess the implications of such a process in terms of sediment volume and geometry, a two-dimensional graphic experiment was conducted (Fig. 4). Using the average spacing/height relationship of Flemming (1988), the cross-sectional areas (and hence sediment volumes per unit distance along the crest) of typical dunes were calculated (the procedure was simplified by using a triangular form). Since spacing increases more rapidly than height in the course of dune growth, the sediment volume contained in two smaller dunes is clearly much smaller than that required by a dune having twice the spacing, the deficit amounting to about 40% (Fig. 4A). This means that a larger dune produced by combining the sediment volumes of two smaller dunes (i.e. keeping the same bed level) would not have twice the spacing but rather a spacing corresponding to about L = 1.5 times that of the smaller ones. If a succession of dunes were involved, the resulting dune field would be characterized by sediment free gaps amounting to about 0.25L between each successive dune. Although such gaps are occasionally observed in nature, many dune fields recorded on side-scan sonar show closed forms (cf. the dunes in Fig. 2). Both features therefore occur in nature and hence require consistent explanations.

To produce a closed larger dune sequence from a closed smaller dune sequence by doubling the spacing, a sediment volume amounting to about 40% of the total has to be obtained from somewhere. The easiest way to acquire the missing sediment is to lower the base level in the process of amalgamation. As illustrated in Fig. 3A, most of the additional sediment does initially not even have to be moved as it is simply incorporated at the base of the dune body by scouring a deeper trough. In cross-section, freshly amalgamated dunes should thus show two erosional unconformities in their internal architecture. One is produced along the stoss side of the down-current dune when the up-current dune coalesces with it. The other one is located just above the new base, corresponding to the depth of disturbance, i.e. the trough level of the smaller dunes. Both unconformities will gradually disappear as the larger dune continues to migrate. Amalgamation thus produces a complex internal structure characterized by cross-bedding and bounding surfaces, the latter gradually disappearing as the dune migrates downstream over the distance corresponding to its spacing (Fig. 4B).

In the course of migration a closed dune sequence may detach itself from its former sediment body by moving onto a hard, non-erodable surface (e.g. a planed rock terrace, a gravel sheet). If the flow conditions then change to induce amalgamation, the evolving larger dunes are now unable to compensate the sediment deficit by lowering their base level through trough scouring. As a result, the dune becomes sediment starved, producing an incomplete body. While having the correct spacing, their heights are now much lower than that suggested by the empirical relationship, the hard grounds emerging in the gaps between successive dunes (Fig. 4C).

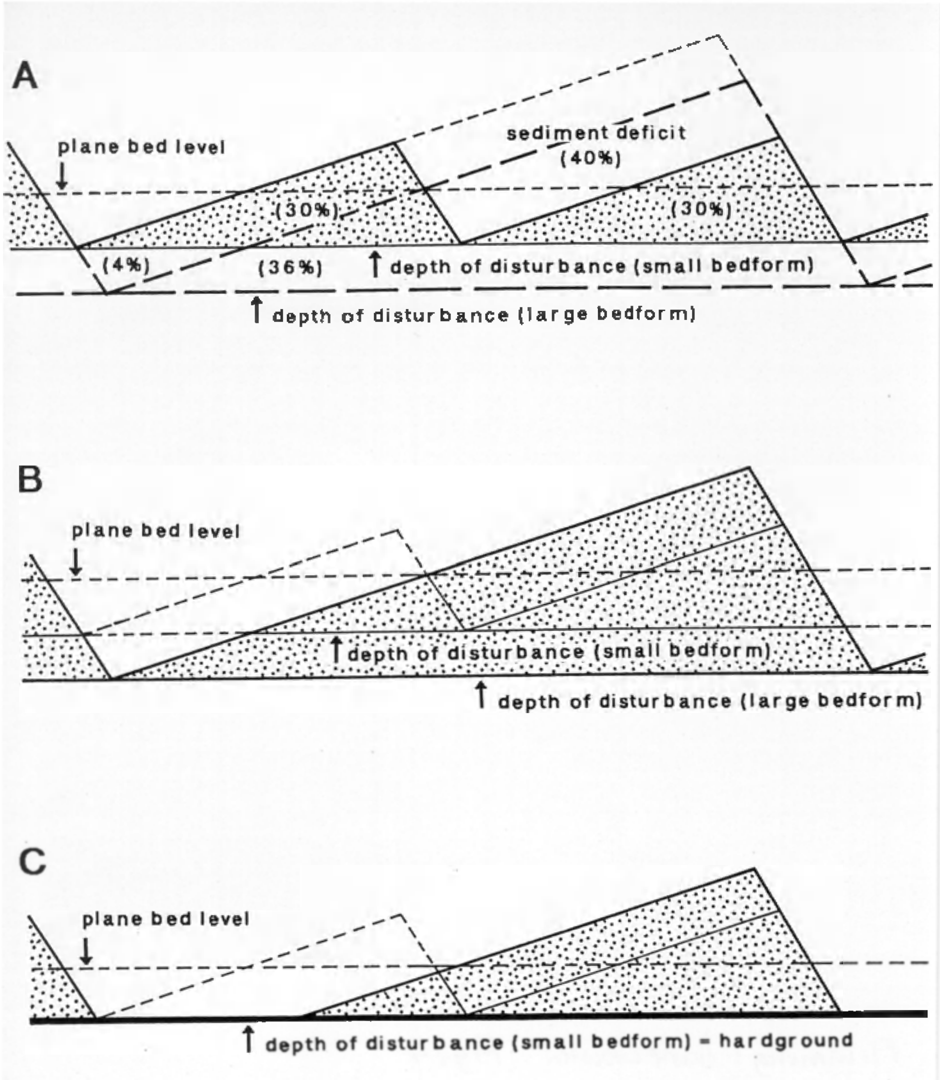

Fig. 4. Schematic diagram illustrating aspects of dune amalgamation (heights are exaggerated but proportionally correctly scaled). A: Sediment budget considerations. Note the ≈ 40% deficit created by the amalgamation of two small dunes into one larger dune having twice the spacing. B: Compensation of the deficit by lowering the base level through scouring in the trough. C: Evolution of sediment starved dunes if lowering of the base level is prevented by hard grounds.

Discussion and conclusions

The available field evidence clearly reveals bedform amalgamation or coalescence on various scales, both in shallow and deep water, in reversing tidal and unidirectional flows, and in different sediment types, but also in aeolian dunes, clouds, and snow. Since equilibrium dunes may evolve on an originally plane sediment surface irrespective of their ultimate size, trough scouring must play a fundamental role in dune growth. Amalgamation also implies that dunes grow or split up in steps corresponding to the increase or decrease in mean flow velocity and as a function of the sediment properties. Furthermore, specific signatures revealing the amalgamation process should be visible in the internal structures of dune cross-sections. Indeed, large asymmetrical dunes often show complex bedding which may at least in part have been generated in the course of amalgamation, split-up processes, or both. Two examples of large complex dunes are illustrated in Fig. 5 (from Berné et al., 1988).

Taken together, the observations and their implications not only contradict the Führböter-model, but also mitigate strongly against certain aspects of the Yalin-model. Thus, there is little evidence in nature favouring the general applicability of the dune capture model. Such a process may be conceivable as a temporary response in the wake of a major disturbance (e.g. a severe storm) that has thrown a dune field into disarray. Furthermore, the frequent absence of superimposed dune hierarchies on sonograph records and the fact that dunes in different sediment types have different sizes under similar flow conditions seriously questions the structuring role of eddy hierarchies. The inherent reversibility of dune growth, in turn, argues against both models.

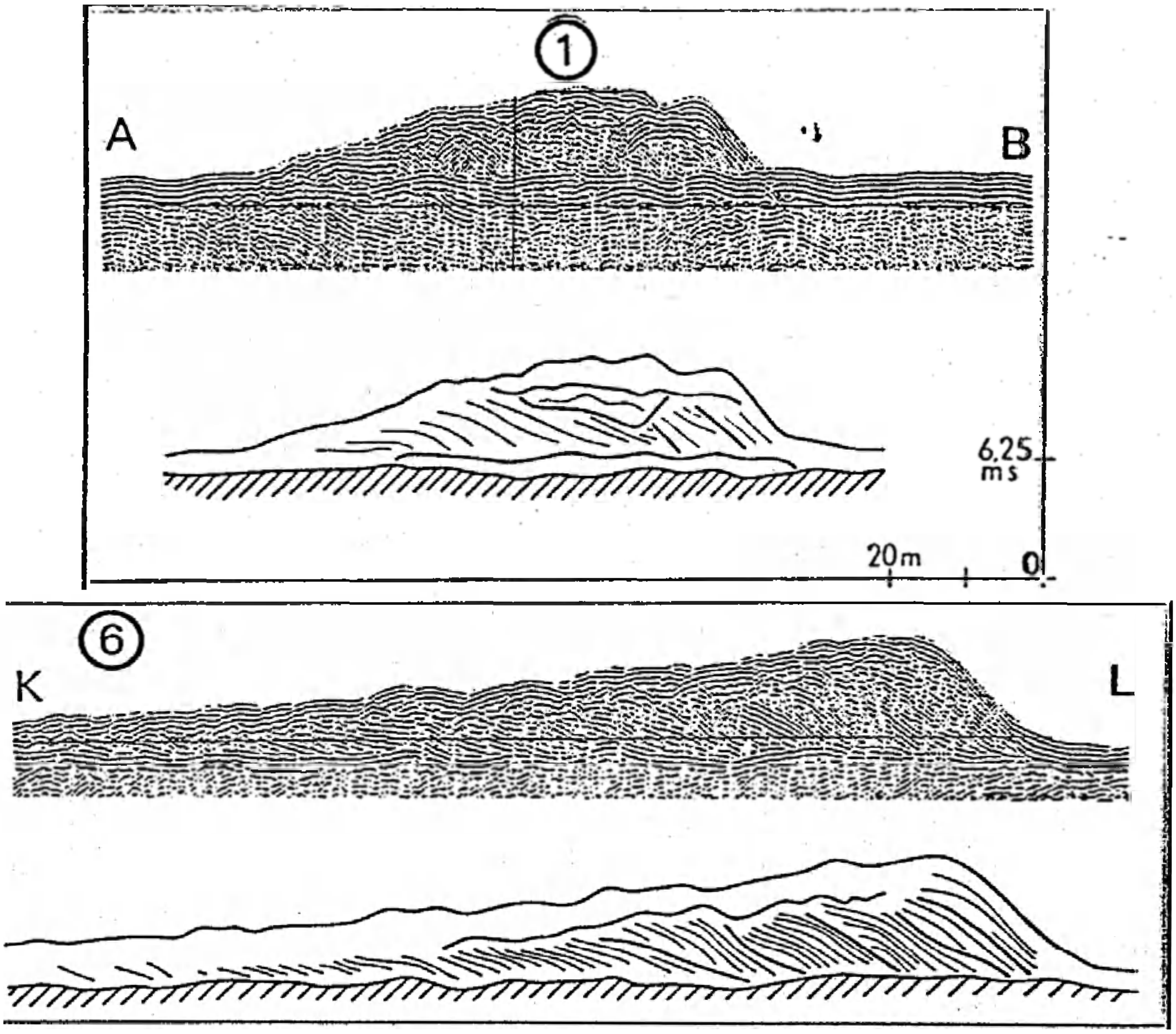

Fig. 5. Examples of large dunes revealing complex internal structures, including erosional unconformities near the surface and near the base (from Berné et al., 1988).

In this study it has been demonstrated that the same basic process-response mechanism can consistently explain the evolution of two important features commonly observed on sonographs, namely the occrrence of closed dune systems on the one hand, and incomplete dunes on the other. The conceptual growth model presented here does not explain why dunes amalgamate in the way described in this paper. The lowering of base levels by trough scouring in the wake of increasing flow velocities evidently plays a central role. However, it is not clear why the trough of the downstream dune is scoured, while that of the amalgamating upstream dune is phased out. Dune spacing is evidently controlled by a flow-related scaling factor which increases in jumps, beginning with a step length defined by the smallest dune size. Since, for a given sediment, the smallest dune size also depends on the sediment properties (grain size, grain shape, grain density), the scaling factor must in some manner be controlled by both the flow structure and sediment properties. Water depth is not a fundamental scaling factor but simply represents the special case of depth-limited flow. The complex interactions between the flow and the bed, as outlined in this study, can probably be better integrated by a kinematic wave theory (e.g. Nelson and Smith, 1989) than by other existing models.

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Sommaire: