CLASSIFICATION OF LARGE-SCALE SUBAQUEOUS BEDFORMS: A NEW LOOK AT AN OLD PROBLEM[1]

SEPM BEDFORMS AND BEDDING STRUCTURES

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ABSTRACT: A Symposium entitled "Classification of Large-Scale Flow-Transverse Bedforms" was convened at the 1987 Mid-Year Meeting of SEPM in Austin, Texas with the purpose of examining the problems involved in classifying large subaqueous flow-transverse bedforms developed in fluvial, intertidal, and marine environments, and recommending changes in nomenclature.

The consensus of the participants is that despite the wide spectrum of morphologies of large-scale flow-transverse bedforms (excluding antidunes), they all occupy a similar position in the lower-flow-regime sequence between ripples and upper plane bed. The wide variety of forms is a reflection of secondary effects such as channelization, fluctuating water levels, and unsteady and reversing flows. The bedforms appear not to fall into size classes with naturally occurring boundaries but rather form a continuum with spacing from just under 1 m to over 1,000 m. The symposium panel proposes, therefore, that they should have only one name, DUNE. Dune is preferred as it has historical precedence over other terms in use, such as megaripple and sand wave. The term "dune" should be modified by primary descriptors of shape (i.e., 2-D or 3-D) and size based on spacing (small (0.6–5 m), medium (5–10 m), large (10–100 m) or very large (> 100 m)) and the adjective *subaqueous* when it is important to distinguish them from *eolian* dunes. The panel recommends a morphologically based classification that is descriptive, with an underlying genetic rationale. Second order descriptors such a sediment size and bedform superposition may be used to describe more thoroughly the variety of subaqueous dunes in nature.

INTRODUCTION

Large bedforms are ubiquitous in modern sandy environments where water depths are greater than about 1 m, sediment sizes are coarser than about 0.15 mm (very fine sand), and mean current velocities are greater than about 0.4 m/sec. Experimental studies appear to support the generally held contention that large-scale flow-transverse bedforms are a distinct entity separate from the smaller current ripples which have spacings generally less than 0.6 m (Yalin 1964; Allen 1968b; Kennedy 1969; Harms et al. 1982) (Fig. 1). The upper limits for bedform development in sand are not easily established. Active dunes have been observed in water depths to 100 m on the African continental shelf (Flemming 1978), in canyons on the continental slope (Valentine et al. 1984), and are known from deep sea turbidites (Hein 1982).

Research on the morphology, hydrodynamic controls, and internal bedding of bedforms has been conducted by several groups (engineers, physical geographers, geologists, and oceanographers). These studies have included both laboratory and natural environments. Nature, however, exhibits diverse settings ranging from 1) rivers, which are unidirectional and channelized and have a wide range of grain sizes and hydrologic characteristics; to 2) sandy coastal embayments with channelized, unsteady, and reversing (tidal) flows; to 3) relatively deep, unchannelized continental shelves dominated by geostrophic flows, occasional storms, tidal currents and wave-generated currents (which reverse on the order of seconds). As a consequence, several classification schemes have evolved. These schemes are based mainly on differences in bedform morphology, which are now believed to reflect the varying effects of channelization, fluctuating water levels, and unsteady and reversing flows. When sedimentologists began to focus on bedforms in the 1960s, they too invented their own terms. Thus the bedform classification dilemma is analogous to the story of the blind men and the elephant in which interpretation is strongly influenced by the limitations of experience and data. As a result, the existing terminology is confusing and consists of a multiplicity of names with some duplication, overlaps, and conflicts (Tables 1–4). A new look at the problem of subaqueous bedform nomenclature is needed.

A symposium was convened in Austin, Texas at the 1987 Mid-Year Meeting of SEPM for the purpose of examining the problems involved in classifying large-scale flow-transverse subaqueous bedforms (exclusive of antidunes and wave-generated forms) and recommending changes in nomenclature where appropriate. A panel of 27 scientists (listed in the Acknowledgments) representing expertise in experimental and computer-simulation studies, as well as fluvial, intertidal, and subtidal sedimentary environments (modern and ancient) met to focus on and attempt to resolve the terminology problem. The symposium was convened by G. M. Ashley and R. D. Kreisa and sponsored by the SEPM Bedforms and Bedding Structures Research Group. Most of the ideas presented herein evolved from discussions at the symposium and reviews of early versions of this manuscript by J. C. Boothroyd, J. S. Bridge, H. E. Clifton, R. W. Dalrymple, B. W. Flemming, J. C. Harms, P. T. Harris, R. D. Kreisa, N. Lancaster, G. V. Middleton, D. M. Rubin, J. B. Southard, and J. H. J. Terwindt.

The purposes of this paper are to summarize the rec-

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[2] Panel members: G. M. Ashley, J. C. Boothroyd, J. S. Bridge, H. E. Clifton, R. W. Dalrymple, T. Elliott, B. W. Flemming, J. C. Harms, P. T. Harris, R. E. Hunter, R. D. Kreisa, N. Lancaster, G. V. Middleton, C. Paola, D. M. Rubin, J. D. Smith, J. B. Southard, J. H. J. Terwindt and D. C. Twitchell, Jr.

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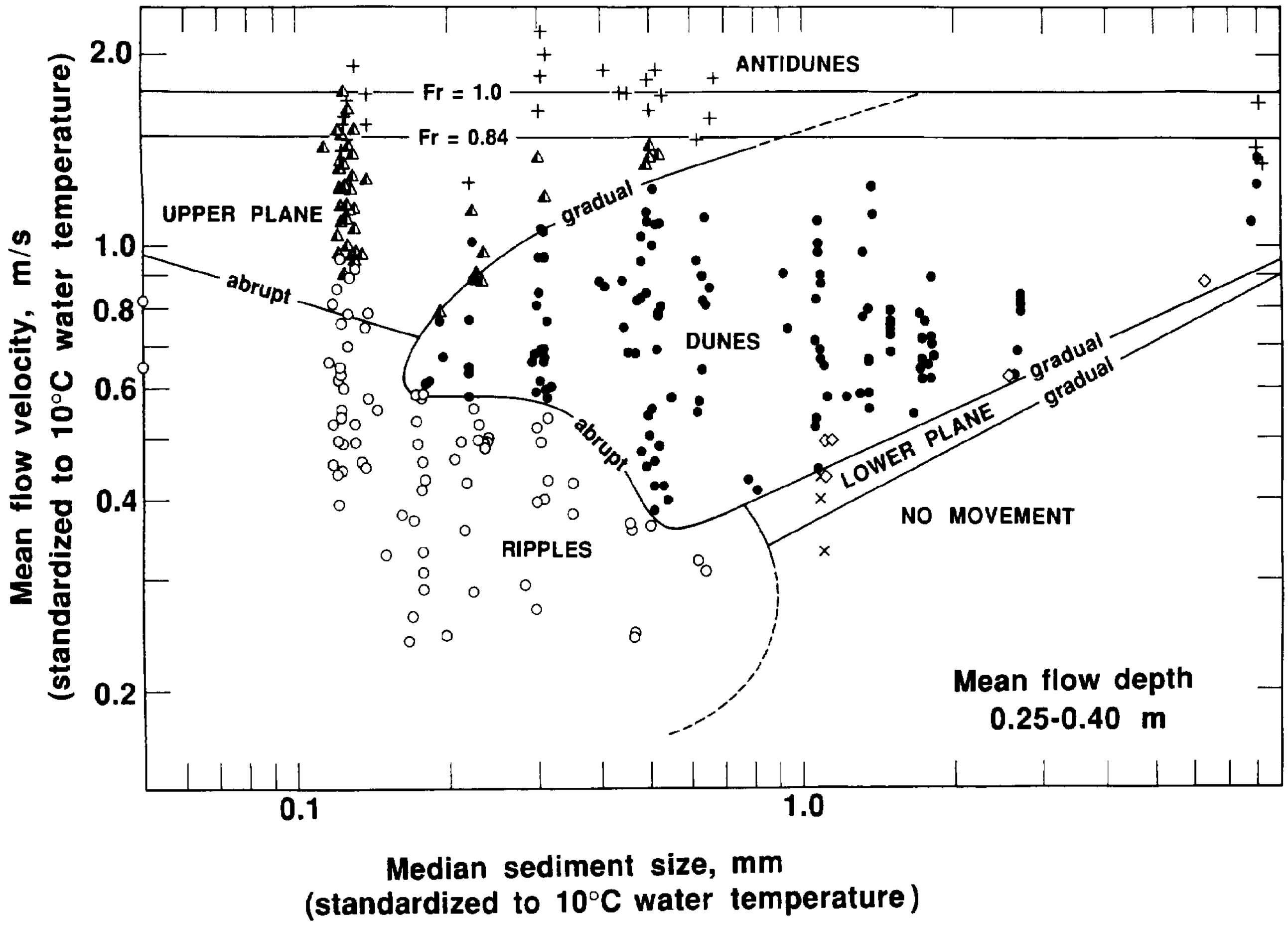

FIG. 1.—Plot of mean flow velocity against median sediment size showing stability fields of bed phases. The velocities and sediment sizes have been standardized to 10°C water temperature. Bed-phase symbols: × = no movement on plane bed; ● = ripples; ○ = dunes; ◇ = lower-regime plane bed; ▲ = upper-regime plane bed; + = antidunes. Fr = mean velocity Froude number. (Modified from Boguchwal and Southard 1989.)

ommendations of the panel regarding classification of large-scale flow-transverse subaqueous bedforms, and to review the relevant background information supporting these opinions. The classification adopted is a consensus that most panelists (with varying degrees of enthusiasm) thought was workable. There was less agreement when it came to discussing cause-and-effect relationships of fluid flow and bedform morphology. The background review in this paper represents the author's personal viewpoint.

Clarification and simplification of the nomenclatural nightmare is more than a challenge in taxonomy. It is hoped that the classification scheme presented herein is a critical first step in improving communication among the various scientific and engineering communities that study bedforms to interpret the hydrodynamics of modern and ancient environments.

CLASSIFICATION—GENERAL CONSIDERATIONS

The need to classify is an inherent tendency in people to make order out of chaos. Classification leads to improved communication, increased understanding of the interrelationships among and within classes, and the creation of new insights into the various elements being classified, thus aiding in their interpretation. Bridge (1987) notes that the desirable attributes of a bedform classification are that:

1) "descriptive parameters should be objectively defined, easily measured and carry a clear genetic implication,
2) classes of bedforms based on these descriptive parameters should be mutually exclusive and the boundaries should be defined quantitatively based on natural groupings defined statistically from a large sample,
3) names of classes should unambiguously suggest the nature of the bedform to the student, although established well-defined terms should have precedence, and introduction of new terms should be avoided."

A bedform classification scheme based on objective criteria, such as one formulated strictly on morphological descriptors, appears ideal. It is critical that genetically-significant morphological characteristics are chosen as the

TABLE 1.—*Nomenclature for bed forms in alluvial channels (directly from A.S.C.E. Task Force, 1966) graphically depicts the redundancy existing in the literature*

1. Bed Configuration:
   - bed geometry
   - forms of bed roughness
   - bed form
   - bed regime
   - bed phase
   - bed irregularities
   - sand waves
   - bed material forms
   - bed shape
2. Flat Bed:
   - smooth bed
   - plane bed
3. Bed form:
   - bed irregularity
   - bed wave
   - bed feature
   - dune
   - ripple
   - sand bar
   - gravel bar:
   - sand wave
4. Ripples:
   - dunes
   - sand waves
   - ripple marks
   - current ripples
5. Bars:
   - sand waves
   - banks
   - sand banks
   - deltas
   - slipoff points
6. Dunes:
   - ripples
   - sand waves
   - sand bars
7. Transition:
   - sand waves
   - washed-out dunes
8. Antidunes:
   - standing waves
   - antiripples
   - sand waves
9. Chutes and Pools:
   - violent antidunes

basis for the classification. In order to have a classification scheme that is useful to people studying ancient facies (where bedform morphology is rarely preserved) as well as to those working in modern environments, these descriptors must be hydraulically significant so that a link can be made between internal structure, morphology and the flow that created the bedform.

BEDFORMS IN NATURE

For purposes of discussion, flow-transverse bedforms are repetitive structures that develop on a sediment bed under a unidirectional current. Large-scale bedforms, depicted in Figure 1 as "dunes," fall into two groups: two-dimensional (2-D) forms which occur at lower speeds, and three-dimensional (3-D) forms, which occur at higher speeds for a given grain size (Figs. 2, 3) (Middleton and Southard 1986). The distinction between them is that the geometry of 2-D forms can be adequately described by one transect parallel to flow, whereas 3-D forms must be defined in three dimensions. In addition, 3-D forms are characterized by scour pits and curved lee faces (Dalrymple et al. 1978; Elliott and Gardiner 1981).

Environments in which water movement is fast enough and deep enough to develop large-scale bedforms fall into three natural groupings: rivers, tide-dominated coastal embayments, and marine settings. Although there are many similarities in the physical processes characteristic of these high energy environments, the differences among them are sufficient to produce distinctive varieties of large-scale flow-transverse bedforms. As a consequence, researchers have developed a different suite of bedform terms for each environment. Poor communication among scientists and engineers has perpetuated the multiplicity of terms.

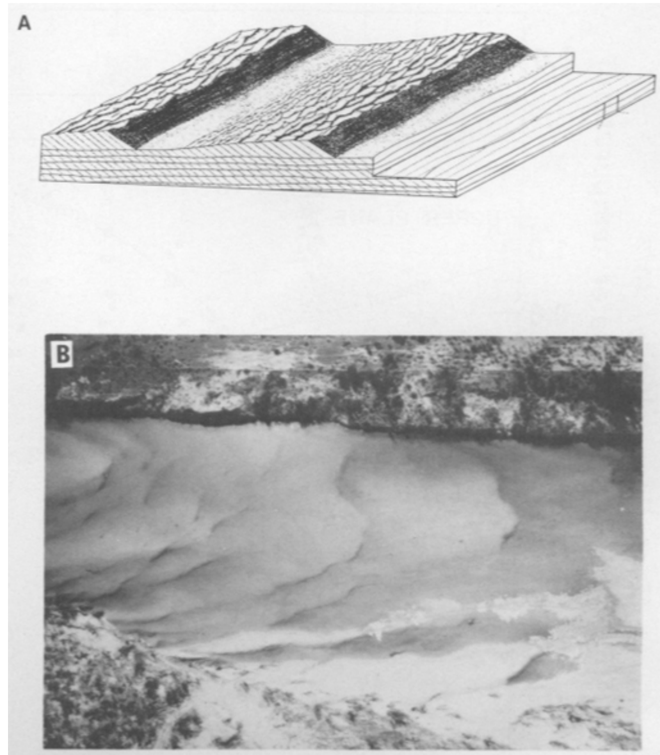

FIG. 2.—A) Block diagram showing large-scale tabular cross-stratification formed by migration of two-dimensional dunes. Flow is from left to right. The length of the sides of the block could range from a few meters to as much as a few hundred meters (from Harms et al. 1982). B) Large 2-D subaqueous dunes in the coarse-grained (gravel) Nueces River. Dune spacing approximately 10 m (photo by T. C. Gustavson).

Rivers

Rivers are channelized bodies of water in which flow characteristics are generally dictated by climate (precipitation, snow and ice melt, etc.) and gradient. Discharge variations measured on a variety of time scales can change water depth, speed and competence. Some rivers can be characterized by a predictable, seasonally-controlled hydrograph reflecting snow melt or rainy season, whereas others are dominated by diurnal variations characteristic of alpine glacier runoff or random storm events which produce a "flashy" discharge. Few rivers have a long-term record of steady flow.

It is the combination of fluctuating discharge and channelization of flow (producing boundary effects) which has led to the nomenclature proliferation for fluvial bars and bedforms. Smith (1978) addressed this problem with respect to braided rivers ten years ago (Table 2), and more recently Allen (1983) pointed to the paucity of empirical

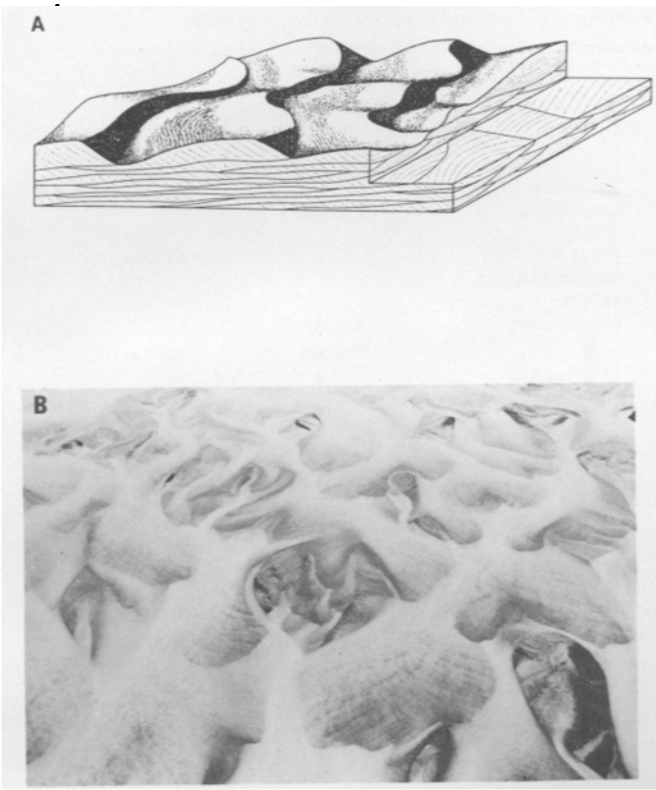

FIG. 3.—A) Block diagram showing large-scale trough cross-stratification formed by migration of three-dimensional dunes. Flow is from left to right. The length of the sides of the block could range from a few meters to a few tens of meters (from Harms et al. 1982). B) Large 3-D subaqueous dunes (liguoid bars) in an Icelandic river. Flow is from top to bottom. Photo width is approximately 0.5 km (photo by J. C. Boothroyd).

TABLE 2.—*Bar terms (Smith 1978)*

alternating	lateral	sheet
braid	linguoid	side
channel	lobate	spool
channel-junction	longitudinal	transverse
chute	meander	transverse-lobate
compound	medial	transverse-lunate
cross-channel	mid-channel	transverse-riffle
diagonal	point	triangular
diamond	remnant	tributary
foreset	riffle	unit
horseshoe	scroll	

studies on disequilibrium flow conditions (and non-uniformity) as an underlying cause of the confusion in terminology for fluvial bars and bedforms.

River systems transport both water, which moves through quickly, and sediment, which is "stored" for intervals ranging from weeks to centuries. These sediment storage elements are of three fundamental types (bedforms, channel forms and unit bars; Table 3), as well as an infinite variety of amalgamations of the three types (braid bar complexes). The "lumping" of the basic elements in various combinations has led to the present confusion regarding terminology in the fluvial literature. Utilizing concepts of bedform hierarchy expressed by Allen (1968a), Coleman (1969), Jackson (1975), Cant and Walker (1978), Smith (1978), Crowley (1983), and Bridge (1985), the following types of sediment storage bodies are identified:

1. *Bedforms* are relatively dynamic sediment storage bodies with response times that are short relative to major changes in flow characteristics. Large-scale bedforms are periodic and occur *in the channel* (scaled to depth). Their presence and morphologic variability have been related to flow strength expressed as mean velocity or shear stress (i.e., the flow regime concept) (Yalin 1964; Raudkivi 1966; Southard 1971). They occur as both 2-D (Fig. 2) and 3-D (Fig. 3) forms. Smaller bedforms have been called dunes or megaripples, and the larger bedforms have been called transverse bars and/or linguoid bars (Carey and Keller 1957; Harms and Fahnestock 1965; Coleman 1969; Collinson 1970; Smith 1974; Boothroyd and Ashley 1975; Gustavson 1978; Crowley 1983). Jackson (1975) referred to them all as "mesoforms."

2. *Channel forms* are also periodic but are an order of magnitude larger than the bedforms in the same channel (Fig. 4A). Jackson (1975) identified these as "macroforms." Channel forms have response times that are long relative to major changes in flow characteristics and are *part of the channel* (scaled to width). Their periodicity is related to the planform geometry of the meandering thalweg, which in turn appears to be scaled to the channel forming discharge (bankfull) (Leopold and Wolman 1963). Channel form elements (e.g., point bar, side bar, diagonal bar) commonly serve as the substrate for migrating superposed bedforms (Allen 1965; Jackson 1976b; Ashley 1978; Bridge 1985).

3. *Unit bars* are quasi-periodic or solitary storage bodies that occur *in the channel* (scaled to depth) (Smith 1974). Jackson (1975) referred to them as "mesoforms." They have simple depositional histories controlled by "local" hydraulic conditions such as changes in water depth and flow competence, and they have been given a variety of names: longitudinal bar, tributary bar, scroll bar, chute bar, lobe, etc. (Smith 1974; Hein and Walker 1977; Cant and Walker 1978) (Table 3; Fig. 4B).

4. *Braid bar complexes* are relatively large solitary or quasi-periodic sediment storage bodies that may persist for years. They may consist of an amalgamation of types 1, 2, and 3 and are usually the product of a history of depositional and erosional events (Williams and Rust 1969; Collinson 1970; Boothroyd and Ashley 1975; Cant and Walker 1978) (Fig. 4C).

In summary, many "forms" of sediment storage occur in rivers, but only one of these, bedforms (those features scaled to depth), is affected by the new terminology (Table 3). It should be pointed out that in the past some bedforms have been called "bars" (Figs. 2B, 3B).

TABLE 3.—*Commonly used terms for sediment storage elements (i.e., bars and bedforms) in fluvial systems*

Sediment Storage Bodies		Commonly Used Term	Illustration	Jackson (1975)
Ripples				
Periodic Forms	ripples	ripples	—	Microform
Large-Scale Bedforms				
Periodic Forms	(1) bedforms*	transverse bar linguoid bar dunes	Fig. 2B Fig. 3B	Mesoform
	(2) channel forms	point bar diagonal bar side bar alternate bar	 Fig. 4A	Macroform
Quasi-periodic or Solitary Forms	(3) unit bars	lobe longitudinal bar chute bar scroll bar tributary bar	Fig. 4B	Mesoform
	(4) braid bar complexes	longitudinal bar	Fig. 4C	Macroform

* Under the new terminology proposed in this paper, all bedforms are dunes.

Tide-dominated Coastal Embayments

Coastal water bodies that are partially enclosed by topography yet have a free connection to the sea are usually tide-dominated on coastlines with greater than 1 m tidal range or where fresh water run-off volume is low relative to the tidal volume. In general, the greater the tidal range the greater the maximum flow strength. Current speeds (mean velocity < 2.0 m/sec) vary through the daily tidal cycle and through the lunar spring-neap cycle.

Tidal currents are inherently unsteady; they accelerate and decelerate as water floods into and ebbs out of the embayment. Although the flow direction reverses regularly, the flow patterns of flood and ebb currents commonly do not coincide. Consequently, the water and transported sediment may follow a circuitous route in and out of the estuary. This leads to spatially varied systems where some parts of the estuary are flood-dominated and other parts ebb-dominated. The temporal and spatial variability of flow and sediment transport, coupled with regularly fluctuating water levels creates a variety of bedform morphologies that has led to an extensive nomenclature (Table 4).

TABLE 4.—*Commonly used terms for estuarine bedforms*

Commonly Used Term	Spacing	Illustration
—2-D megaripple —2-D large ripple —Linear megaripple —Type I megaripple —Dune	1–25 m	Fig. 5A
—3-D megaripple —3-D large ripple —Type II megaripple —Dune	1–15 m	Fig. 5B
—Sandwave or sand wave (may have superposed bedforms) —Rippled sandwave —Low energy sandwave —Megarippled sandwave —High energy sandwave	10–100 m	Fig. 6A
—Transverse bar (may have superposed bedforms) —Alternate bars	100–300 m	Fig. 6B

Large-scale bedforms occur in a wide range of sizes from 1 to over 300 m spacing; superposed bedforms commonly occur on the larger forms (Table 4). Small forms (spacings of a few meters) with small storage capacity may continuously change their orientations during the tidal cycle (Fig. 5). The short tidal cycle does not allow sufficient time for the entire volume of sediment stored in the larger bedforms (spacing > 10 m) to be entirely reworked. Instead, the bedform profile is continually modified by the opposing currents and the overall shape represents a state of quasi-equilibrium adjustment to the relative strengths of the opposing flows. Sediment transport is by way of the migration of small forms (ripples or "small" large-scale bedforms) that are superposed on them. The larger forms commonly act as platforms for the migration of the smaller forms (Figs. 6A, 6B), and thus the bulk of the sedimentary structures composing a large bedform consists of crossbedding left by the smaller more dynamic bedforms (Allen 1980; Dalrymple 1984). Very large, 2-D bedforms (spacing = 100–300 m) occasionally occur in estuaries (Fig. 6B) (Dalrymple et al. 1978; Aliotta and Perillo, 1987; Boothroyd, 1985, 1987). The combination of both spatially varied flow (different flow paths for ebb and flood) and temporally varied flow (daily and spring-neap tidal cycles) creates recognizable signatures in the sedimentary record left by migrating bedforms: herringbone crossbedding, reactivation surfaces (Klein 1970; Boersma and Terwindt 1981), and tidal bundles (Boersma 1969; Visser 1980; Terwindt 1971; Terwindt and Brouwer 1986), all of which retain valuable information on paleohydraulics and paleotides for geologists.

Shallow Marine

Large-scale bedforms occur on shallow, terrigenous or carbonate clastic continental shelves and epicontinental

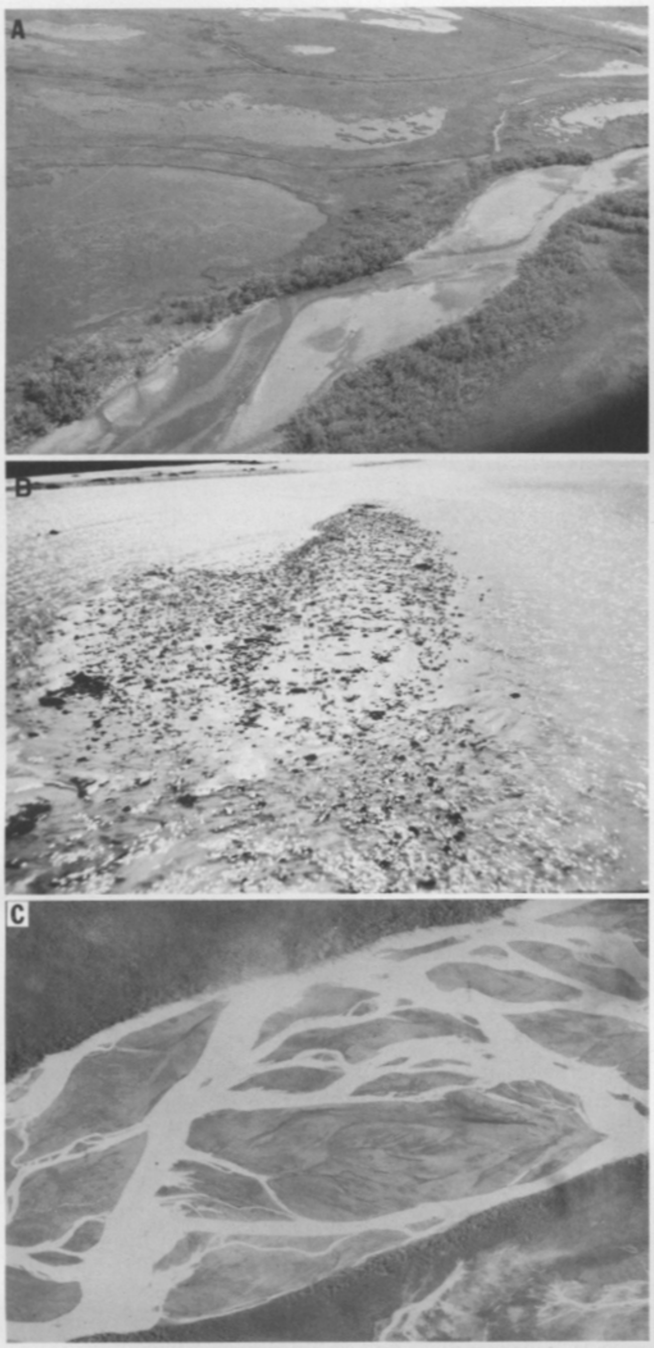

FIG. 4.—A) Channel Form—Scott River, Alaska. Channel width = 50 m. Flow from upper right to lower left (photo by G. M. Ashley). B) Unit Bar—A longitudinal bar, a quasi-periodic (or solitary) sediment storage body; Kicking Horse River, Alberta, Canada. Photo width is 5 m (photo by N. D. Smith). C) Braid Bar Complexes—Matanuska River, Alaska. Channel width = 100 m. Flow from left to right (photo by G. M. Ashley).

platforms which are affected by strong geostrophic currents, occasional storm surges and/or tidal currents (Fig. 7). Near-bottom velocities typically reach 0.5–1.5 m/sec (McCave 1971; Harms et al. 1974; Flemming 1978; Field

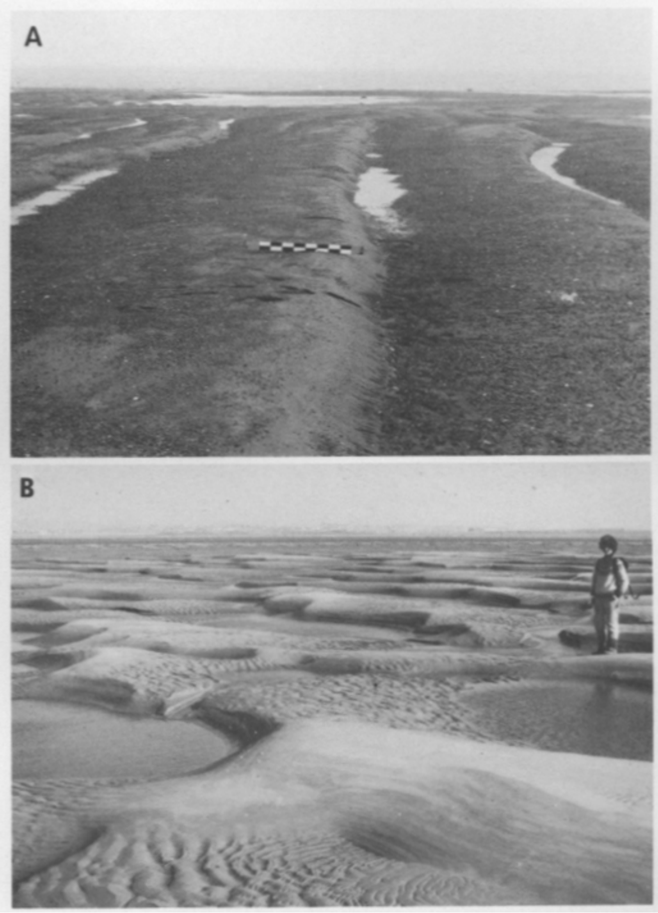

FIG. 5.—A) Small 2-D subaqueous dunes (spacing = 5 m), Bay of Fundy, Canada. Scale = 1 m. Flow from left to right (photo by R. W. Dalrymple). B) Small 3-D subaqueous dunes (spacing = 5 m), Lougher Estuary, Wales, U.K. Flow from right to left (photo by T. Elliott).

et al. 1981). Near the shoreline, shoaling waves generate oscillatory and unidirectional currents that may produce 2-dimensional or 3-dimensional bedforms with a maximum spacing from 1–3 m. The symmetry of the bedform and migration direction reflects the relative dominance of onshore versus offshore currents. The temporal and spatial variability of processes in the nearshore environment typically produces bedforms with complicated internal structures.

The water depths on continental shelves allow development of bedforms of impressive dimensions (Table 5) (Jordan 1962; Flemming 1978; Stride 1982; Harris et al. 1986). The shape of the large bedforms reflects the relative strengths of the dominant and the opposing currents and, in some cases, wave modification. Under strong unidirectional currents, or in reversing tidal currents where opposing flow vectors are strongly asymmetrical, marine bedforms may develop avalanche slipfaces (lee slopes) of 30–35° (Harms et al. 1974; Flemming 1978, 1980, 1982). However, under more nearly symmetrical reversing tidal currents, bedforms typically have more gently dipping

FIG. 6.—A) Medium 2-D subaqueous dunes (spacing = 6–9 m), with superposed ripples, Bay of Fundy, Canada. Flow from upper right to lower left (photo by R. W. Dalrymple). B) Large to very large 2-D subaqueous dunes (spacing 75–125 m), Lougher Estuary, Wales, U.K. Sunlight is reflected off slipfaces. Flow from right to left (photo by G. M. Ashley).

slopes (generally less than 10° but occasionally up to 20°) (Stride 1982; Harris et al. 1986). Because of the volume of sediment stored in them, the gigantic forms are relatively stable on time scales of months or years, whereas the smaller, ubiquitous, superposed forms are more dynamic, responding to daily and/or spring-neap tidal fluctuations (Jones et al. 1965; Bokuniewicz et al. 1977; Allen 1980; Flemming 1980; Langhorne 1982; Stride 1982; Amos and King 1984; Harris and Collins 1985). The internal structures of marine bedforms are poorly known but may consist of large crossbeds (3–10 m high) with moderate dips, or compound crossbedding produced by the migration of small superposed bedforms (Reineck 1963; Flemming 1982; Dalrymple 1984; Walker 1984).

DISCUSSION

The Symposium focused on three key questions pertaining to large-scale subaqueous bedforms which appear to be central to the classification dilemma: 1) do all large-scale bedforms relate to the same hydrodynamic phenomenon, and do they occur in a continuum of sizes or as discrete groups? If they are all related, is there a single acceptable term? 2) what is the significance of bedform superposition? and 3) what descriptors of bedform morphology and behavior are desirable for clear communication amongst scientists working on bedforms or their deposits? Special consideration should be given to linking the sedimentary record to paleoenvironmental indicators of hydraulics and bed configuration. The first two questions are important in modern environments, because they are concerned mainly with process-response mechanisms. The third is particularly critical to those working with the sedimentary record where form and process must be interpreted rather than observed (Harms 1987). These three issues are discussed in detail below.

TABLE 5.—*Commonly used terms for shallow marine large-scale bedforms*

Commonly Used Term	Height (H) meters	Spacing (L) meters	H/L Ratio
Megaripple	0.5–1.5	10–20	1:10–1:25
Sandwave or sand wave	2.0–5.0	Average 100–400	
	12–18	Maximum ≥1,000	1:30–1:100 (or greater)

Bedform Continuum

Are all large-scale flow-transverse bedforms basically the same? Is the wide variety of morphologies simply a reflection of the modifying processes, such as channelization, fluctuating water levels, and reversing flows? Is there a continuum of sizes, or are there discontinuities in their size distributions that should be recognized in a classification?

To answer this, one must get beyond the smoke screen created by the seemingly infinite variety of sizes and morphological types and examine the fluid dynamics behind the origin and migration of large bedforms. Based on experimental studies and field observations conducted over the last 30 years, flow-transverse bedforms appear to function as a resistance element to the flow and to migrate under shear stress imparted on the bed by the moving fluid. In the plane parallel to flow, a repetitive pattern of converging and diverging flow lines interacts with the cohesionless bed and produces alternating zones of erosion where shear stress increases downstream and deposition where shear stress decreases downstream. If this flow pattern persists relatively unchanged in the third dimension (perpendicular to flow) and there is an absence of strong eddies and vortices, the bedform produced is straight-crested and can be termed 2-dimensional (Figs. 2, 5A, 6). However, if the flow structure varies significantly in the third dimension and vortices capable of scouring depressions are present, then the bedform reflects this and a 3-dimensional shape is produced (Figs. 3, 5B). Thus, it is perceived that the three-dimensionality

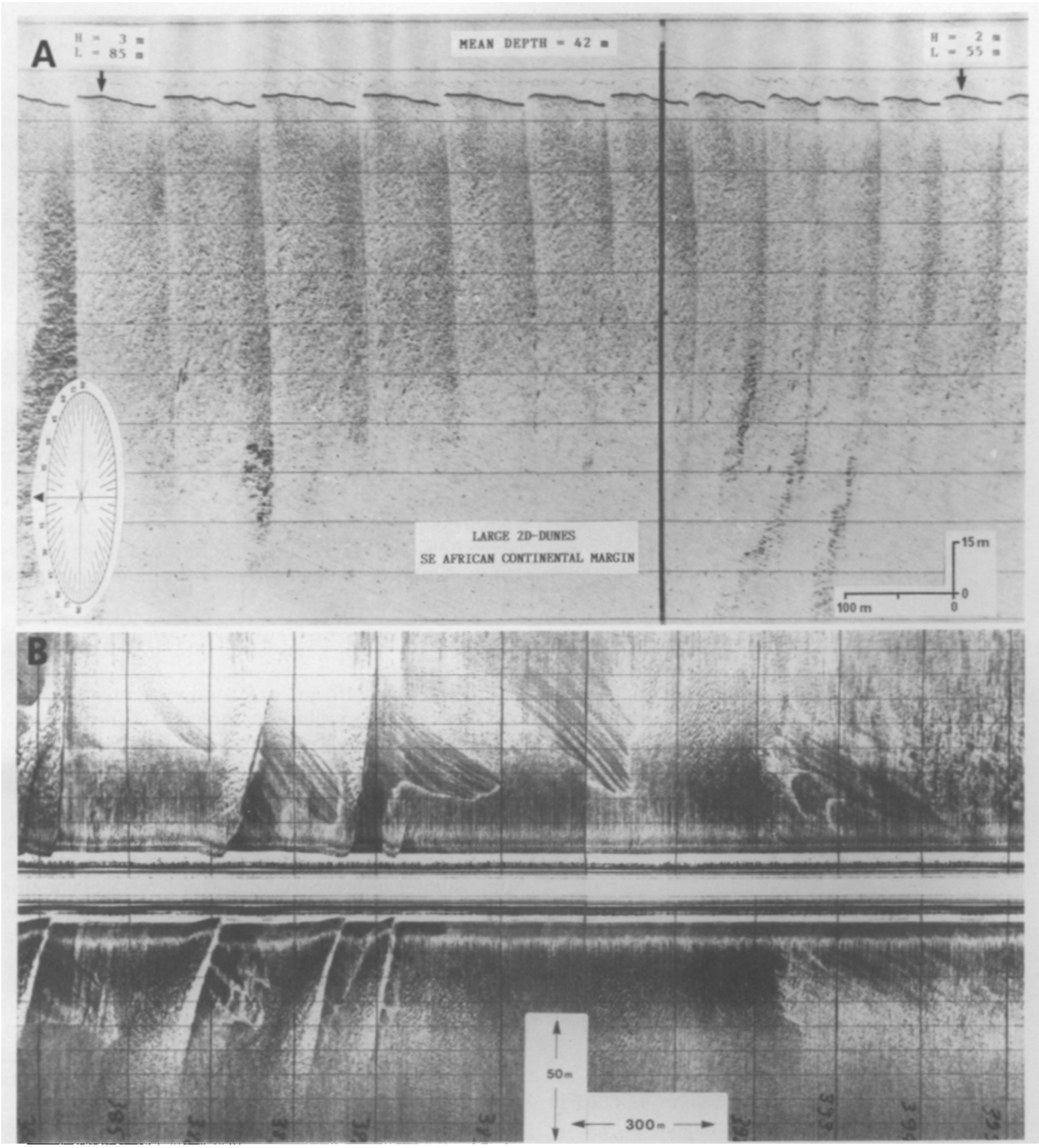

FIG. 7.—A) Large 2-D subaqueous dunes. Side-scan sonograph taken on the southeast African continental shelf in 42 m water depth (L = 55–85 m, H = 2–3 m) (sonargraph by B. W. Flemming). B) Side-scan sonograph showing 2-D large to very large subaqueous dunes, L = 50–300 m H = 4 m with small dunes superimposed, located in Torres Strait, Australian continental shelf at 20 m water depth (Harris 1988). The seabed is scoured clear of sand in places resulting in elongate (flow parallel) sand ribbons which appear to stream away from dune crests.

of the flow and the three-dimensionality of the bed interact. A plot of 2D and 3D bedforms from tide-dominated environments and flumes shows that 2-D forms occur under slower flows than do 3-D forms for a given depth and grain size (Costello and Southard 1981) (Fig. 8). This reflects a change in flow structure at higher velocities.

Although most scientists accept the interpretation of lower energy for 2-D bedforms and higher energy for 3-D bedforms (Harms, 1969), there has been a controversy concerning whether large-scale bedforms fall into natural groupings based on size, specifically height/spacing ratios, etc. (McCave 1971; Boothroyd and Hubbard 1974, 1975; Stride 1982; Amos and King 1984; Harris and Collins

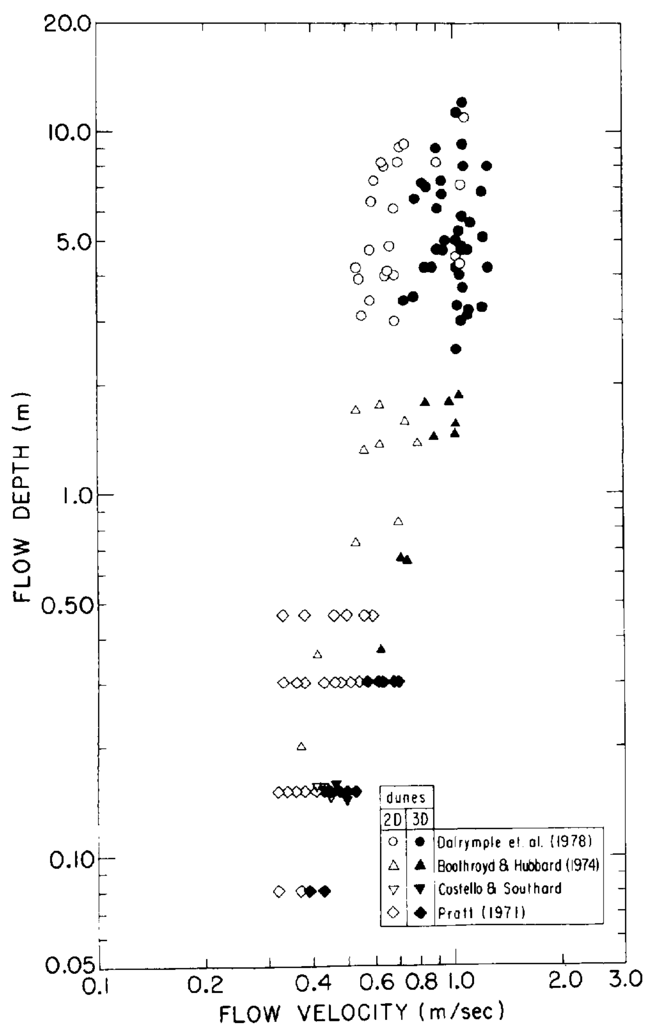

FIG. 8.—Depth-velocity diagram showing comparison of hydraulic relationships of dunes in medium to coarse sands in flumes and deeper tidal-current flows. Open symbols, two-dimensional dunes; solid symbols, three-dimensional dunes. Circles, Dalrymple et al. (1978); triangles, Boothroyd and Hubbard (1974); diamonds, Pratt (1971); inverted triangles, Costello and Southard (1981) (from Costello and Southard 1981).

1985) or form a natural continuum (Yalin 1964; Allen 1968b; Kennedy 1969; Allen and Collinson 1974; Jain and Kennedy 1974; Jackson 1976a). This controversy has contributed to the redundancies shown in Tables 1, 2 and 4.

A plot of spacing versus height of 1,491 subaqueous marine bedforms depicts a range of sizes from 0.01 m spacing to over 1,000 m spacing (Fig. 9; Flemming 1988). The data are from shallow (< 1 m) to deep (< 50 m) water and from both unidirectional and reversing flows. A single "discontinuity" in the continuum occurs at slightly less than one meter, providing support for the commonly recognized distinction between current ripples and large-scale bedforms. The data also demonstrate that large-scale bedforms are a single genetic population.

On the basis of the foregoing, panel consensus on the first issue is: 1) all large flow-transverse bedforms are a similar phenomena; the morphologic variety reflects the response to channelization, fluctuating water level, speed, and direction; 2) large bedforms occur as a continuum of sizes, not as discrete groups; and (3) large bedforms should be given one name rather than be split into classes. To reach this consensus, the panel made the assumption that the same mechanisms are involved in producing the spectrum of bedform morphologies under a variety of hydrodynamic conditions.

The term *dune* was recommended as the preferred term (Table 6) because 1) "dune" was used by the earliest researchers documenting the position of large bedforms within the flow regime context (Gilbert 1914; Yalin 1964; Guy et al. 1966; Kennedy 1969), 2) "dune" has not been used for as many different bed configurations as sand wave or megaripple and, 3) there appears to be a genetic affinity (albeit with different fluids) between eolian dunes and large subaqueous bedforms. Eolian dunes also form a height/spacing continuum, but it is clear that eolian bedforms reach greater heights for a given spacing at the large end of the plot (Fig. 9B) (Flemming 1988; Lancaster 1988). This may be due to depth limitations in the subaqueous forms.

Bedform Superposition

Superposed bedforms are common, and next to size and shape, the hierarchical nature of bedforms is the most frequently used attribute for classification. The question is, are superposed bedforms inherently different from simple bedforms in terms of flow and sediment transport?

The common superposition of smaller bedforms on larger bedforms has been a source of confusion for those looking for a simple relationship between flow and form. Some studies of flow structure over large-scale bedforms have indicated that "high" bed shear stress on the stoss side is necessary for the growth and migration of the large forms (Raudkivi 1966), but this conclusion seems to be inconsistent with the simultaneous presence of ripples. Some have argued that only one size may be in equilibrium at a time (Allen 1966; Allen and Collinson 1974; Davies 1982). However, several field-based fluvial studies have documented simultaneous migration of large bedforms and the larger bedforms on which they were superposed (Pretious and Blench 1951; Carey and Keller 1957; Jackson 1976a; Dalyrmple 1984; Bridge 1985). In addition, superposed bedforms have been developed in the laboratory under steady equilibrium conditions (Bohacs 1981) and therefore are not simply an aberration or a "disequilibium in nature" that can be ignored.

Superposition has been used as a means of classifying and pigeonholing bedform types (Dalrymple et al. 1978; Elliott and Gardiner 1981). However, using superposition as a classifying parameter implies that there is a fundamental difference between simple bedforms and those with superposed forms. There have been very few studies in the laboratory or field that specifically address the hydrodynamic nature of compound bedforms (Allen and

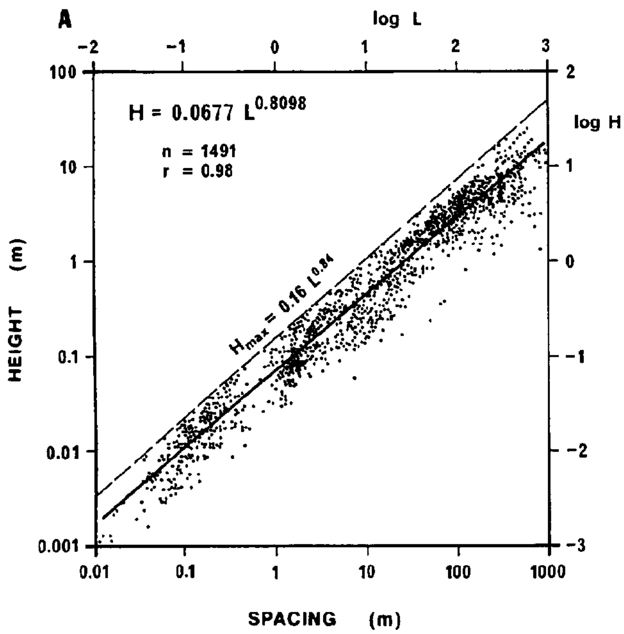

FIG. 9A.—A log-log plot of height (H) versus spacing (L) of 1491 flow transverse subaqueous bedforms (Flemming 1988). The data appear to cluster into 2 populations separated by a paucity of forms at approximately 0.5 m to 1.0 m spacing. The smaller forms are ripples; the larger forms are dunes.

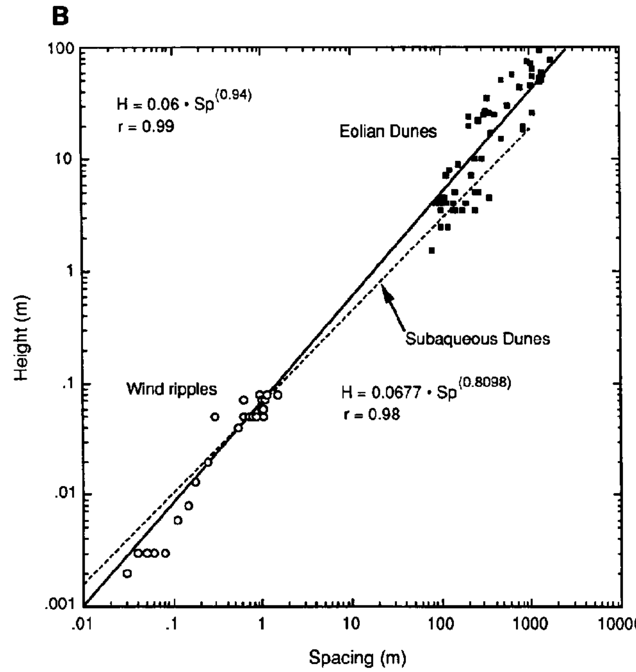

FIG. 9B.—A log-log plot of wind ripples (O) and eolian dunes (■) and the calculated least squares regression line compared to regression line (dotted line) of the subaqueous dune data in Figure 9A. The height/spacing ratio is greater for very large (L = 100 m) eolian dunes than for subaqueous dunes of the same size (after Lancaster 1988).

Collinson 1974; Jackson 1975, 1976a; Rubin and McCulloch 1980; Bohacs 1981; Bridge 1982; Dalrymple 1984). It appears, though, that the presence of more than one size bedform may simply be a matter of available space. Large-scale superposed bedforms will form wherever flow conditions are appropriate and will develop to a size consistent with the reach length. Conceptually the situation might be visualized as "nested" boundary layers, with each successively smaller bedform limited by space available on the substrate between adjacent bedform crests. The larger bedforms generate a boundary layer in which the smaller bedforms are locally stable (Smith and McLean 1977; Rubin and McCulloch 1980). The fact that larger bedforms appear static (even moribund) while smaller superposed forms are active is a func-

TABLE 6.—*Classification scheme recommended by the SEPM Bedforms and Bedding Structures Research Symposium*

Subaqueous Dune				
First Order Descriptors (necessary)				
Size: Spacing =	small 0.6–5 m;	medium 5–10 m;	large 10–100 m;	very large >100 m
Height* =	0.075–0.4 m;	0.4–0.75 m;	0.75–5 m;	>5 m
Shape: 2-Dimensional				
3-Dimensional				
Second Order Descriptors (important)				
— Superposition: simple or compound (sizes and relative orientation)				
— Sediment characteristics (size, sorting)				
Third Order Descriptors (useful)				
— Bedform profile (stoss and lee slope lengths and angles)				
— Fullbeddedness (fraction of bed covered by bedforms)				
— Flow structure (time-velocity characteristics)				
— Relative strengths of opposing flows				
— Dune behavior-migration history (vertical and horizontal accretion)				

* Height calculated using the equation $H = 0.0677L^{0.8098}$ (Flemming 1988).

tion of the relative volumes of sediment composing the two sizes and of the time available for bedform migration.

The consensus of the panel on question #2 (the significance of superposition to bedform classification) is that, although superposed bedforms may be important in terms of the internal structures, superposition appears to be a function of available space and time for growth and migration. Thus, superposition should not form the basis of classification but could be a useful second order descriptor (i.e., simple or compound). This "group opinion" is based on the assumption that superposition reflects complexity of conditions rather than fundamental processes of bedform genesis. Research focused on this specific problem is needed to support or deny this assumption.

Important Bedform Descriptors

The sedimentary structures left by migrating bedforms are of great importance to geologists interpreting the sedimentary record. What physical characteristics are of first order, second order, and third order importance in describing large-scale bedforms? Ideally these descriptors should be linked to flow regime and therefore environmentally significant.

The consensus of the panel is that a morphologically based classification scheme is needed, i.e., one that is descriptive but based on an underlying genetic rationale. The classification scheme should consist of a single term: *dune*. A hierarchy of descriptors should be used where feasible to differentiate the various morphologies of dunes and the modifer *subaqueous* when it is important to distinguish them from *eolian* dunes (Table 6).

The First Order descriptors should effectively subdivide dune bedforms into useful populations. The descriptors should be based on characteristics that can be determined or estimated in both modern and ancient environments. These descriptors (size and shape) should be adjectival modifiers and should be an integral part of the bedform name. Size is measured in terms of spacing. As bedform spacing is a continuum (Fig. 9A), ranging from slightly less than 1 m to greater than 1,000 m, easily-remembered arbitrary divisions at 5, 10 and 100 m are here suggested in order to differentiate "small," "medium," "large" and "very large" forms (Table 6).

Using the height (H)–spacing (L) relationship determined by Flemming (1988) (Fig. 9A):

$$H = 0.0677L^{0.8098} \quad [1]$$

the range of bedform spacing and the (calculated) mean heights for each size grouping are: L = 0.6–5.0 m, H = 0.075–0.4 m, *small*; L = 5.0–10.0 m, H = 0.4–0.75 m, *medium*; L = 10.0–100.0 m, H = 0.75–5.0 m, *large*; L = > 100 m, H = > 5.0 m, *very large*.

Shape is the other First Order descriptor (Table 6). The two main shape categories are 2-dimensional and 3-dimensional. The bounding surfaces of crossbedding produced by 2-D dunes are flat (Fig. 2A), whereas they are scoured or trough-shaped in 3-D dunes (Fig. 3A).

A discussion centered on the Second Order characteristics important in describing bedforms, and the prioritization of these characteristics did not yield a consensus. The following two aspects of bedforms were considered important, but should not be incorporated formally in the bedform name: 1) factors relating to superposition, such as size and mutual orientation of the two bedforms ("compound" bedforms have superposed bedforms; "simple" bedforms do not); and 2) sediment size and sorting.

Third Order descriptors are considered "useful" and should be provided when feasible:

1) A variety of shape factors such as the lee face slope angle, toe of the lee face (tangential/planar contact), symmetry of bedform profile;
2) Dune train characteristics such as fullbeddedness versus sediment starvation; and
3) Hydraulic information reflecting the temporal behavior of bedforms. These descriptors could include flow characteristics, such as flow reversal, the relative strength of the opposing flows, and the migration history of dunes (both horizontal and vertical rates).

CONCLUSIONS

The consensus of the participating symposium members is that, despite the wide spectrum of bedforms in fluvial, coastal, and shallow marine environments, all large-scale flow-transverse bedforms (excluding antidunes) are sufficiently similar in terms of formative processes as to be assigned a single name. The wide variety that occurs in nature is simply a reflection of the effects of modifying processes such as channelization, fluctuating water levels, and unsteady and reversing flows. Thus a single term for them, *dune*, is recommended. "Dune" has precedence as it was used by many of the early workers (Gilbert 1914; Allen 1965; Guy et al. 1966). The modifier *subaqueous* should be used when necessary to signify the affinity of these bedforms with *eolian dunes*, but also to stress the *difference* between water-generated and wind-generated forms.

A morphologically-based classification scheme with an underlying genetic rationale is recommended (Table 6):

1) First Order descriptors of shape and size are deemed critical to describe adequately the widely different morphologies found in nature and should be used as adjectival modifiers to the term *subaqueous dune* (such as, 3-D medium subaqueous dune).
2) Second Order descriptors are important and should be used where feasible; these include superposition (simple or compound bedforms) and sediment type (size and sorting).
3) Third Order descriptors which describe details of bedform morphology, bedform behavior and flow characteristics are useful.

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The success of the Symposium is attributed to the spirit of compromise and cooperation of the participants under the skillful direction of moderator Gerard Middleton. The symposium participants are listed alphabetically below, speakers are designated by * and corresponding members by **.

* Gail Ashley	Ron Kreisa
Richard Beck	** Nick Lancaster
* Jon Boothroyd	Elana Leithold
Jodie Bourgeois	Gerry Middleton
* John Bridge	Chris Paola
Ed Clifton	David Roy
* Bob Dalrymple	* David Rubin
Trevor Elliott	** Rudy Slingerland
* Burg Flemming	Jim Smith
* John Harms	** Norm Smith
Peter Harris	* John Southard
Karen Havholm	* Joost Terwindt
John Hubert	David Twichell
Ralph Hunter	

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