

Bedform-velocity matrix: The estimation of bottom current velocity from bedform observations

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ABSTRACT

A wide variety of bedforms, both depositional and erosional in origin, has been recognized on the deep seafloor and attributed to the influence of bottom currents. These range in scale from those visible in bottom photographs (centimeter to decimeter), to those recorded with seafloor bathymetric imaging (meter to kilometer). In many cases it has been possible to provide some quantification of substrate grain size and flow velocity responsible for each bedform type. We have synthesized both our own and published data in order to present a bedform-velocity matrix, which facilitates the estimation of bottom current velocity based on bedform type. Despite imperfections, we believe this to be a valuable model for assessing strength and variability of bottom currents that can have a significant influence on the siting of submarine cables, pipelines, and other seafloor installations.

INTRODUCTION

The impact of bottom (contour) currents in shaping the deep seafloor is well known. Long-term erosion creates widespread hiatuses and other erosive features, whereas extensive deposition leads to the construction of contourite drifts. The seafloor beneath deep-water bottom currents is characterized by a wealth of erosional and depositional bedforms that can provide valuable information about flow direction, strength, variability, and continuity (Hollister and Heezen, 1972; Kenyon and Belderson, 1973; Tucholke et al., 1985; Nelson et al., 1993; Wynn and Stow, 2002; Mulder et al., 2003; Masson et al., 2004; Hanquiez et al., 2007). However, few attempts have been made to synthesize this extensive database (Hollister and McCave, 1984; McCave and Tucholke, 1986). This paper aims to provide (1) a preliminary database of deep-water bedforms; (2) quantification of the associated flow velocity; and (3) a new bedform-velocity matrix for application to bottom current systems. We also comment on some of the implications for understanding the fundamental processes involved.

QUANTIFICATION OF BOTTOM CURRENT VELOCITY

Many publications that document the influence of bottom currents in the development of bedforms report only the relative current intensity (weak, moderate, strong) and/or flow direction. In other cases, one or more of the following methods has been used to directly measure or infer current velocity, directly above the bottom boundary layer where it is unimpeded by edge effects.

1. Short-term deployment of current meters and Doppler systems (days or weeks) provides a direct, instantaneous measure.

2. Long-term deployment of current meters, landers, and seafloor laboratories provides direct data on velocity and its variability over a period of months to years.

3. Derived bottom current transport from hydrographic measurements provides important constraints on mean flow velocity for fixed two-dimensional (2-D) transects.

4. Bottom current compilations based on a combination of these methods for any one region can then be related to the range of bedforms observed.

5. Inference based on sediment grain size of bedforms uses empirical and experimental data to relate this to shear velocity.

6. Direct comparison with the bedform field diagram is based mainly on flume experiments, in which flow velocity is plotted against grain size (Southard and Boguchwal, 1990).

7. Direct comparison can be made with observed flow velocity and/or bedform relationships in shallow marine systems.

BEDFORM DATA SET

We have compiled data from 69 separate publications, noting details of bedform, location, substrate, and current velocity. We have selected for use only those that demonstrate a robust link between bedform and flow velocity, and that together provide representative coverage of the range of bedforms observed in deep water beneath active bottom current systems. The full database and reference details have been placed in the GSA Data Repository¹. Brief definitions of terms are included in the following.

Linear Bedforms

Bedforms that are elongated parallel to flow direction arise either from mainly depositional processes at lower current velocities, or from mainly erosional processes at relatively higher velocities. They occur at a range of scales, characterized by the bedform length, spacing, and height, or depth of erosive feature.

Surface lineation refers to a relatively smooth sediment surface with low-relief linear streaks, parallel to subparallel in planform, and separate to merging laterally. It is a common bedform, ranging from small-scale (spacing of millimeters) silt lineation on a muddy substrate, through well-defined sand lineation on a sandy substrate, to gravel stringers (or streaks) on a mixed substrate (spacing of decimeters). Current velocity ranges from 0.1 to 0.2 m s⁻¹ on mud, up to 0.3 m s⁻¹ on sand, and 0.5 m s⁻¹ on sand and/or gravel.

Groove and ridge is the term used for linear features in a cohesive muddy substrate, where the grooves have a distinctly erosive origin between ridges that are typically narrower and sharp crested. Ridges may be remnant forms between erosive grooves or mainly depositional in origin (also known as longitudinal [triangular] ripples). Grooves may be straight to sinuous in planform; the smaller-scale features (decimeter spacing), require flow velocities of 0.15–0.3 m s⁻¹, whereas the larger-scale bedforms (spacing 1–5 m) have been linked with velocities >0.4 m s⁻¹.

Crag and tail refers to the elongate mound (tail or shadow) deposited immediately downstream of an obstacle (crag) in the path of flow (tail

¹GSA Data Repository item 2009085, Table DR1 (bedform vs. velocity), and Figures DR1 and DR2 (bedform vs. velocity), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

length centimeter to decimeter). They begin to appear on muddy and sandy substrates in association with surface lineation ($0.1\text{--}0.3\text{ m s}^{-1}$). They become more prominent and widespread, and occur in association with comet scour and erosional pluck marks, at slightly higher velocities ($<0.4\text{ m s}^{-1}$). Mound and tail is the term used for similar structures where the obstacle is a biogenic (or other) mud mound. There may also be a genetic link with rhomboid ripples or rill marks, which develop on generally planar beds at flow velocities slightly greater than those required for surface lineation.

Obstacle and comet scour refer to the crescentic to elongate scour marks around and extending downstream from an obstacle in the path of flow. Although these may include depositional tails, they occur at relatively high flow velocities ($0.4\text{ to }>1\text{ m s}^{-1}$) and are principally erosional in origin. Scour length varies from meters to hundreds of meters. Forms transitional to crag and tail structures with small-sized obstacles and less well-developed scour marks (decimeter scale) occur at the lower end of this velocity spectrum. Erosional scour crescents, irregular pluck marks, and tool marks may all occur without an associated obstacle.

Ribbon marks are elongate mounded filaments of sand (and/or gravel), mostly regularly spaced, with parallel to slightly sinuous planform. They may show gentle curvature in parallel with the flow pattern, and merge into or diverge from broad sand sheets. Most of those reported are large-scale bedforms (width $10\text{--}100\text{ m}$, length $5\text{--}50\text{ km}$), although smaller-scale features (width of a few meters) have been referred to as narrow ribbons, sand streamers and sand streaks. They are high-velocity bedforms (generally $0.7\text{--}1.5\text{ m s}^{-1}$) that involve winnowing and erosion of a sand or sand and gravel substrate coupled with redeposition of the material into elongate ribbon mounds.

Furrows are elongate, primarily erosional features, with regular to irregular spacing and a parallel to slightly sinuous planform. They are characterized by incision into the seafloor (rather than by mound-like deposition) and are relatively large scale features (width $5\text{--}150\text{ m}$, length $1\text{--}10\text{ km}$), with subdivision of types based on scale and morphology. Once established, they may develop coarse-grained lag deposits and ripple or dune bedforms within the furrow, contrasted with finer-grained deposition between furrows. They are generally the highest-velocity bedform recognized, with flow velocities estimated as $>0.3\text{ m s}^{-1}$ for mud furrows, $0.6\text{--}1.5\text{ m s}^{-1}$ for sand furrows, and $>0.75\text{ m s}^{-1}$ for sand and gravel furrows.

Other bedforms created at still higher velocities ($>0.8\text{ m s}^{-1}$), or where the seafloor and flow pattern are less uniform, include elongate to irregularly shaped erosional scour hollows, linear scours, extensive gravel-lag winnowed deposits, and exposed bedrock surfaces.

Transverse Bedforms

More or less regular undulations that are oriented transverse to flow direction are among the most commonly occurring depositional bedforms beneath bottom currents. Wide ranges of scales and morphologies are represented, generally characterized by their wavelength (crest to crest distance), amplitude (trough to crest height), symmetry, and planform. Under persistent unidirectional flow, they tend to be asymmetrical in cross section with a steeper, shorter lee side (downstream) and more gentle, longer stoss side (facing upstream).

Ripples are the smallest-scale transverse bedforms (wavelength $0.1\text{--}0.6\text{ m}$, height $0.02\text{--}0.1\text{ m}$), representing lower flow velocity ($0.1\text{--}0.6\text{ m s}^{-1}$) over a fine to medium sandy substrate. In planform, there are straight-crested, undulatory (sinuous crested), and linguoid (3-D) types. In profile, most are asymmetrical with sharp to rounded crestlines.

Dunes represent the next scale upward of transverse bedforms (wavelength $0.6\text{--}10\text{ m}$, height $0.1\text{--}1\text{ m}$), although there appears to be a natural break in scale from ripples, as very few examples occur with wavelengths between 0.3 and 1.0 m . Both sinuous-crested and barchanoid (3-D) dune planforms occur, the former typically at flow velocities of $0.4\text{--}0.7\text{ m s}^{-1}$, whereas the latter appear to be higher-velocity forms ($0.6\text{--}1.2\text{ m s}^{-1}$).

Sandwaves are a longer wavelength ($5\text{--}500\text{ m}$), flatter bedform (height $0.5\text{--}5\text{ m}$) compared with dunes, and generally sinuous crested (2-D) in planform. Many of what are called small sandwaves in the literature are equivalent to dunes in our terminology and some care must be taken to avoid confusion. Average flow velocities for sandwaves range between 0.3 and 0.75 m s^{-1} .

Gravel waves and sand and/or gravel bars have not been documented unequivocally from beneath bottom current systems, although they are well known from turbidity current channels. By analogy with such downslope systems, we should expect to find them within high-energy contourite channels and gateways, in association with current scour and exposed bedrock, being indicative of velocities $>1.5\text{ m s}^{-1}$. Transverse ribs and cells of gravel-sized manganese nodules (to 10 cm diameter, but relatively low density) have been noted beneath bottom current flow at velocities $>0.6\text{--}0.8\text{ m s}^{-1}$.

Giant sediment waves (or mudwaves) are very large scale (wavelength $0.5\text{--}10\text{ km}$, height $10\text{--}80\text{ m}$), regular, transverse to oblique bedforms, exclusive to deep-water systems and comprising only fine-grained (silt and clay) sediment. They are very well known from both turbidity current and bottom current systems, representing deposition under long-term stable current conditions at low flow velocities between 0.05 and 0.25 m s^{-1} .

Seafloor Architectural Elements

Both linear and transverse bedforms are found covering the surfaces of much larger scale seafloor features (architectural elements), from tens to hundreds of kilometers in length and width. Depositional elements are widely referred to as contourite drifts, including broad (plastered) sheets, elongated mounds, irregular-shaped patch drifts, and channel-exit fan-drifts (McCave and Tucholke, 1986; Faugères et al., 1999). They represent prolonged current activity ($>1\text{ m.y.}$) and long-term mean velocities generally $<0.5\text{ m s}^{-1}$. Erosional elements have been classified more recently, and include erosive terraces, abraded surfaces, contourite channels, marginal moats, giant scours, and large-scale furrows (Hernández-Molina et al., 2006). These forms represent prolonged, high-energy current activity, with mean velocity $>0.5\text{ m s}^{-1}$ and considerable flow variability.

DISCUSSION

Bedform-Velocity Matrix

The principal physical parameters that control development of bedforms include flow velocity and depth, fluid density and viscosity, particle density and size, sediment supply, and bed roughness (Allen, 1982; Gardner et al., 1989). To a first approximation, fluid properties in deep-sea bottom currents are more or less constant, and neither the absolute water depth nor the flow thickness is of relevance in this context (Middleton and Southard, 1984). We have therefore synthesized the data presented for both linear and transverse bedforms in a composite model, referred to here as a bedform-velocity matrix for deep-water bottom current systems (Fig. 1). The x-y axes show mean grain size of sediment versus mean flow velocity near the seafloor (but above the benthic boundary layer), and the field is filled with schematic representation of the bedforms present under specific velocity and grain-size conditions. Differences in grain density, such as between foraminifera and quartz-rich sands, may alter slightly the position of boundaries between bedform types, but not the overall schema. Sediment supply effects are also unlikely to alter the matrix fields, whereas bed roughness is a potentially important control for which an independent schema is probably needed.

This matrix is analogous, in part, to the bedform distribution model developed for tidal current transport in shallow marine environments (Belderson et al., 1982). A number of the bedforms are directly comparable to those occurring in shallow water, and the flow velocities at which they are formed are similar to those of tidal currents. However, we include

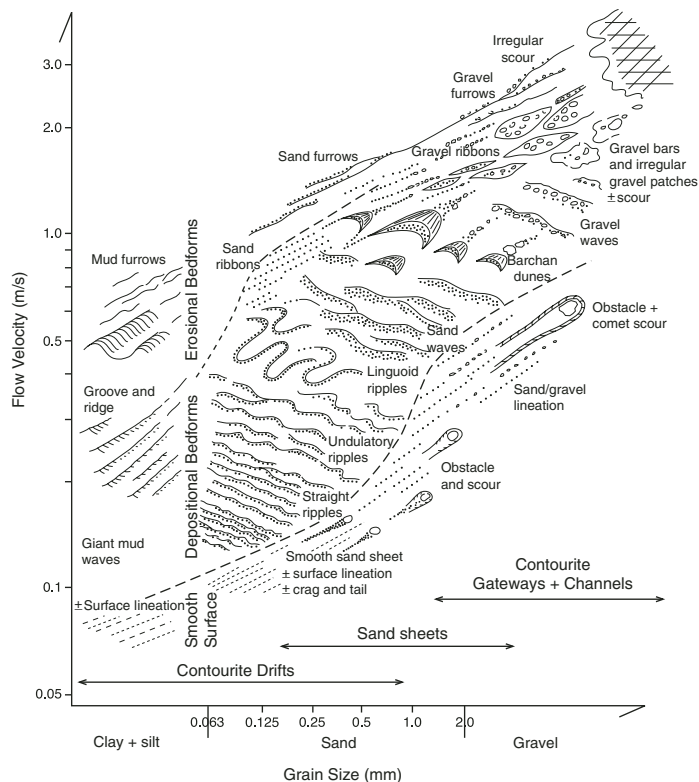


Figure 1. Bedform-velocity matrix for deep-water bottom current systems, showing mean grain size of sediment versus flow velocity at or near seafloor, with schematic representation of bedforms present under specific velocity-grain-size conditions. For bedform scale, refer to text.

a number of additional bedforms and note greater overlap in terms of flow velocity between different bedform fields.

The portion of our matrix that shows depositional bedforms in sand-sized sediment is further analogous to the well-known sedimentary structure matrix showing stability fields for subaqueous bedforms (Allen, 1968; Southard and Boguchwal, 1990). Although this stability field is based largely on experimental flume data beneath shallow flows (0.25–0.5 m), the same relative position of bedform fields is maintained for deep-water bottom currents that may be tens to hundreds of meters thick. In our matrix, the smooth sand sheet with surface lineation and the field of sand ribbons are comparable with the lower and upper plane bed fields, respectively, of Allen's (1968) stability field. Antidunes in bottom current sands have not so far been documented.

Furthermore, we show an evolution of ripple scale (from small to large) and planform, from straight to undulatory to linguoid, with increasing velocity. This is in agreement with earlier work on subaqueous bedforms (Harms, 1969; Allen, 1982), with observations on unrestricted tidal flats where large fields of straight-crested ripples are common (Allen, 1997), and with the bedform field synthesis shown in Stow (2005). It is not supported by recent experimental work in controlled, shallow-flow, flume conditions, which led Baas (1999) to propose that the evolution of ripple planform is controlled by time rather than by velocity. However, the considerable observational data presented here from beneath deep-water bottom currents show the persistence in time and space of large stable fields of a particular ripple type. Straight-crested ripples appear to be more common beneath slow, unrestricted flows, whereas linguoid forms occur under faster restricted flows in channels. In our view, this argues for a velocity rather than time control in the evolution of ripple form under these conditions.

Contourite depositional systems, including drifts and sandsheets, are characterized by a current-smoothed sediment surface, in many cases with low-relief linear bedforms, as well as by fields of transverse bedforms in mud, silt, and sandy material. Higher-energy depositional bedforms are also present in contourite channels and gateways. These latter are typical of erosional bottom current systems, characterized by mainly linear bedforms displaying moderate to large seafloor relief resulting from scour and incision, as well as by irregular scour hollows, subcircular-circular holes, sand-gravel pavements, and bare rock surfaces. The transition between depositional and erosional bedforms is a gradational one, characterized by hybrid bedforms such as groove and ridge (longitudinal ripples, Flood, 1981) and combined sand ribbon and/or sand furrow structures.

The preservation potential of depositional bedforms in Quaternary and more ancient contourite successions, however, appears to be severely limited, especially those of low energy currents and finer grain size. This is because the generally slow accumulation rates allow for continuous and extensive bioturbation, which progressively destroys any primary sedimentary structures. Higher-energy sand and gravel depositional bedforms, by contrast, may undergo less bioturbation and are therefore more likely to be preserved. Erosional bedforms and large-scale depositional bedforms may be preserved, but are at a scale less easily recognized in ancient sedimentary successions. Widespread erosion and regional hiatuses result from prolonged periods of high-energy currents, although these may occur laterally adjacent to and, in some cases, interspersed with areas of marked deposition.

Bottom Current Process and Variability

Bedform observations support the knowledge gained from physical oceanography and also permit further insights into flow process. That bottom current systems are semipermanent features of deep ocean circulation is clearly evidenced by their ability to construct and maintain large-scale, complex bedforms associated with major drifts and widespread areas of erosion. They are also known to vary in location and intensity (or velocity) over a range of time scales (Gross and Williams, 1991). This may occur on a scale of 24 h due to diurnal deep-water tidal influence, a few weeks due to episodic benthic storm events, and from tens to thousands of years due to other natural variations in bottom current generation and transport. The observed bedform assemblage will clearly reflect that variability.

Surface lineation, crag and tail structures, and small ripples require only a few hours, at most, to form, but their very common occurrence in bottom photographs and their persistence over repeated photo transects often reflect long-term mean velocity. Larger ripples, dunes, and sand-waves take relatively longer to form, and so reflect persistent higher-velocity currents over a period of several hours to days, or even weeks for larger sandwaves. That these larger bedforms are commonly covered by smaller ripples and lineation suggests that they reflect intermittent high-velocity episodes, perhaps related to tidally enhanced flow (Kenyon and Belderson, 1973), benthic storms (Hollister and McCave, 1984; Culver et al., 1988), or other events of sufficient duration to allow their construction. Still larger-scale depositional bedforms, such as sand and gravel ribbons, and erosional features, including furrows and comet scours, require a longer period of formation, although whether this is days, months, or years is not currently known (Flood, 1983). They almost certainly form in regions prone to persistent high-velocity currents, such as contourite channels and gateways, but the presence of smaller-scale ripples within some furrows indicates intervening periods of relative quiescence. Giant sediment waves form over periods of thousands to a few million years and so reflect the long-term stability of low-velocity bottom currents.

While the vertical superposition of different bedforms indicates alternate response to mean flow and peak flow velocities over variable time scales, the lateral juxtaposition of bedforms is also significant. Regional studies have shown clear trends in bedform style indicating downstream

change from high to low velocity, for example, away from the Gibraltar Gateway (Nelson et al., 1993), as well as in an across-stream sense, for example, for the Faeroe-Shetland Gateway (Wynn et al., 2002; Masson et al., 2004). Some studies of bedform orientation have shown variable flow directions related to two different bottom current filaments (Kenyon and Belderson, 1973), to two distinct opposing currents (Gardner et al., 1989), and to deep-tidal and/or bottom current interaction yielding interference ripples. These observations clearly demonstrate the common existence of narrow (2–5 km wide), higher-velocity, near-bottom flow filaments within a broader, more sluggish water-mass movement. It is significant that they may further allow inferences to be made about other properties (density, viscosity, and thickness) of the mean flow and/or boundary layer conditions that so far remain elusive.

Application and Limitations

As high-resolution seafloor mapping coupled with bottom photographic observation becomes progressively more common, so the recognition and mapping of bedforms under bottom current pathways increases. By using the bedform-velocity matrix presented here, regions of the seafloor can be more accurately assessed in terms of the strength and variability of bottom currents. This, in turn, may have a significant influence on the siting and management of submarine cables, pipelines, and other seafloor installations, which are subject to chaffing, undercutting, or removal by strong current action. It will further contribute to a better understanding of the detailed nature of bottom currents and of how they erode, transport, and deposit sediment. Where possible, the reconstruction of paleo-bottom current intensity (and direction) using sedimentary structures would be of great interest for paleoceanographic studies.

There remain certain limitations in the data set and approach. (1) Although the velocity data presented are for near-bottom flow, the exact height above seafloor is not clearly defined. The variable nature of the benthic boundary layer will also complicate how flow velocity affects seafloor sediment. (2) For most data sets it is impossible to know the precise flow velocity (mean or peak) that created the observed bedform, as we rarely have the opportunity of seeing deep-water bedforms develop in situ. (3) The effects of sediment supply and bed roughness on bedform development have not been considered separately. Notwithstanding these, we believe that it is both important and useful to synthesize our knowledge of bottom current systems in this way, and so present the velocity-bedform matrix as a working model. We look forward to its refinement in detail as more precise data are obtained from beneath bottom current pathways.

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