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Classification and characterisation of deep-water sediment waves

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Abstract

Deep-water sediment waves can be classified using a combination of grain size and wave-forming process, although in some cases one or other of these criteria may be indeterminable. Sediment waves are generated beneath currents flowing across the seabed, in the form of either downslope-flowing turbidity currents or alongslope-flowing bottom currents. Waves formed by either process show varying characteristics, depending on whether they are constructed of coarse- or fine-grained sediments. Sediment wave studies over the last five decades are reviewed, and clear trends can be discerned. Early descriptive studies in the 1950s and 1960s relied almost exclusively on seismic reflection profiles, and the wave-forming process was often a subject of much debate. In the 1970s and 1980s the quality of sediment wave datasets increased, with sidescan sonar, deep-sea drilling and numerical modelling all applied to sediment wave studies. Consequently, the wave-forming process became more easily identifiable, and models for the growth of bottom current and turbidity current sediment waves were introduced. Most studies from the 1990s onwards have focussed on turbidity current sediment waves, in response to the increasing demand for data from turbidite systems from the hydrocarbon exploration and production industry. Studies of bottom current sediment waves during this period have focussed on the applications to palaeoceanography, in response to the recent boom in climate change studies. The main focus of this paper is the characterisation of both fine- and coarse-grained, turbidity and bottom current sediment waves, including the depositional environment, wave morphology, wave sediments and migration, and the wave-forming process. In addition, criteria for distinguishing between fine-grained bottom current and turbidity current waves are discussed, and also for identifying other wave-like features formed by different processes, such as creep folds. Although in many sediment wave studies the dominant wave-forming process is easy to determine, in others it is likely that a more complex combination of processes has occurred. Further studies should concentrate on methods for identifying these processes and how they interact, and also investigate the exact mechanisms for the initiation and evolution of sediment wave fields.

Keywords: sediment waves; turbidity currents; bottom currents; sedimentary processes

1. Introduction

The mechanisms responsible for generating deep-water sediment waves have intrigued and puzzled marine geologists for many decades, yet

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sediment wave studies have also provided valuable insights into our understanding of turbidity current and bottom current processes. Sediment waves occur in a variety of environments and water depths, and display a wide range of morphologies, dimensions and sediment types. However, it is possible to classify and characterise different types of wave, according to their environment/process of formation and grain size. This paper will attempt to provide a working classification of all wave types, and will also review existing sediment wave studies and describe our current state of knowledge with respect to wave-forming processes.

2. Sediment wave classification

This paper will follow the definition of Wynn et al. (2000c), where a sediment wave is defined as "a large-scale (generally tens of metres to a few kilometres wavelength and several metres high), undulating, depositional bedform that is generated beneath a current flowing at, or close to, the seafloor". For the purposes of this paper (and the accompanying special issue) a simple classification scheme has been constructed for the types of sediment waves that are most commonly described. Many of the terms used in previous studies, i.e. gravel-, sand- and mudwaves, are potentially misleading, especially when applied to areas where there is no direct evidence of the sediment grain size. In addition, they are not always accurate, for example 'mudwaves' can contain a relatively high percentage of thin beds comprising silt-sized sediment. We therefore propose that, where possible, sediment waves are classified as follows:

(1) *Bottom current origin = Bottom current sediment waves*
Mud and silt dominated = Fine-grained bottom current sediment waves
Sand and gravel dominated = Coarse-grained bottom current sediment waves

(2) *Turbidity current origin = Turbidity current sediment waves*
Mud and silt dominated = Fine-grained turbidity current sediment waves
Sand and gravel dominated = Coarse-grained turbidity current sediment waves

(3) *Wave origin unknown = Sediment waves*
Mud and silt dominated = Fine-grained sediment waves
Sand and gravel dominated = Coarse-grained sediment waves

Although it is not always possible to identify the specific sediment type, i.e. with core or grab data, most geophysical data allow some interpretation of seafloor sediment grain size. Normally, this is sufficient to identify whether the wave sediments are mud/silt dominated or sand/gravel dominated. However, if the data available give no clear indication of the grain size then this should be left unspecified. Some of the key characteristics of fine-grained bottom current and turbidity current sediment waves are shown in Table 1, as well as the key characteristics of similar deep-water features such as creep folds.

3. A review of sediment wave studies (1950 to the present day)

This section will attempt to review the history of sediment wave studies in the last 50 years. It is interesting to note that most early studies relied heavily on 3.5-kHz profiles, and the presence of sediment waves was generally assumed to indicate the presence of bottom currents. At the present day the pendulum has swung markedly in the other direction, and there is a much greater emphasis on sediment waves in well-defined turbidite systems, with a whole variety of geophysical and sedimentological techniques being employed to image and sample the waves.

1950s: The first documented examples of deep-water sediment waves began to appear, such as the 'lower continental rise hills' of the eastern US continental rise described by Heezen et al. (1959).

1960s: More sediment wave studies were published but are generally based upon widely spaced

Table 1
Summary of characteristics for different types of sediment waves and also soft sediment deformation features

Wave-forming process	Turbidity current	Turbidity current	Bottom current	Bottom current	Soft sediment deformation (e.g. creep folds)
Sediment grain size	Fine-grained (mud and silt dominated)	Coarse-grained (sand and gravel dominated)	Fine-grained (mud and silt dominated)	Coarse-grained (sand and gravel dominated)	Varied – usually fine-grained (mud/silt dominated)
Environment	Channel levees, continental slope/rise	Canyons, channels and canyon/channel mouths	Sediment drifts on basin floor/lower slope/rise	Topographic ridges, continental slope, b-c passages	Varied – potentially any submarine slope
Wavelength	Up to 7 km	Usually up to 1 km, rarely larger	Up to 10 km	Up to 200 m	Up to 10 km
Wave height	Up to 80 m	Up to 10 m	Up to 150 m	A few metres	Up to 100 m
Key features	Usually on slopes of 0.1–0.7° Wave dimensions progressively decrease downslope Wave asymmetry usually decreases downslope Crests are roughly parallel to regional slope Waves migrate upslope/upcurrent	Crests aligned perpendicular to flow direction Can show decrease in dimensions at channel margin Morphology is often irregular/disrupted Migration direction variable Often associated with erosional scours	Wave dimensions decrease near edge of wave field Wave symmetry decreases near edge of wave field Waves on slopes are aligned oblique to slope Most waves on slopes migrate upcurrent and upslope Crests are straight or slightly sinuous	Can occur as straight waves or barchans Both types aligned perpendicular to flow Barchans common where sediment supply is poor Barchan migration is downcurrent Ripple patterns show peak flow near barchan crest	Most common on slopes of >2° Oriented perpendicular to maximum slope Do not show true lateral migration Usually show broad crests and narrow troughs Typically random scatter of dimensions
Key examples	Monterey Fan levees (Normark et al., 1980) Bounty Channel levees (Carter et al., 1990) Toyama Channel levees (Nakajima and Satoh, 2001) Var Fan levees (Migeon et al., 2000, 2001) Canary Islands slopes (Wynn et al., 2000b,c)	Var Canyon (Malinverno et al., 1988) Stromboli Canyon (Kidd et al., 1998) Valencia Channel mouth (Morris et al., 1998) Canary Islands (Wynn et al., 2000b) Laurentian Fan (Piper et al., 1985)	Argentine Basin (Flood et al., 1993) Rockall Trough (Howe, 1996) Blake-Bahama Ridge (Flood, 1994) Gardar Drift (Manley and Caress, 1994) Falkland Trough (Cunningham and Barker, 1996)	NW European slope (Kenyon, 1986) Iceland–Faroe Ridge (Dorn and Werner, 1993) Carnegie Ridge (Lonsdale and Malfait, 1974) Gulf of Cadiz (Kenyon and Belderson, 1973) Various sites (Lonsdale and Speiss, 1977)	South Korea Plateau (Lee and Chough, 2001) Beaufort Sea (Hill et al., 1982) Tingin Fjord (Syvitski et al., 1987) Landes Marginal Plateau (Kenyon et al., 1978) New England slope (O'Leary and Laine, 1996)
Examples in this volume	Normark et al., 2002 Ercilla et al., 2002a,b Gonthier et al., 2002 Lewis and Pantin, 2002 Lee et al., 2002	Wynn et al., 2002b Lewis and Pantin, 2002	Flood and Giosan, 2002 von Lom-Keil et al., 2002 Masson et al., 2002 Lewis and Pantin, 2002 Ediger et al., 2002	Wynn et al., 2002a Kenyon et al., 2002	

seismic profiles and sediment cores. As a consequence firm identification of the wave-forming process was often impossible, or instead became a subject of much debate; for example the sediment waves on the north-east US continental rise were initially linked to gravitational sliding (Ballard, 1966) before being re-interpreted as bottom current bedforms (Fox et al., 1968). A wide variety of terms were used to describe the observed features, including 'abyssal antidunes' (Fox et al., 1968), 'giant ripples' (Ewing et al., 1968, 1971), 'ocean basin hills' (Johnson and Schneider, 1969) and 'lower continental rise hills' (Rona, 1969).

1970s: One of the first examples of sediment waves to be imaged by sidescan sonar was presented by Kenyon and Belderson (1973). They showed a series of coarse- and fine-grained bottom current waves that are generated beneath Mediterranean Outflow Water. Lonsdale and Malfait (1974) then produced a detailed study of a series of coarse-grained bottom current barchan dunes on the Carnegie Ridge, and used a combination of sidescan sonar and bottom photographs to map the distribution of current ripples across the dune surface. More sediment wave studies based largely on seismic profiles and sediment cores were published, with both bottom current and turbidity current origins being recognised (Asquith, 1979; Bouma and Treadwell, 1975; Damuth, 1975; Damuth and Hayes, 1977; Embley and Langseth, 1977; Hollister et al., 1974; Jacobi et al., 1975; Johnson and Damuth, 1979; Kolla et al., 1976; Roberts and Kidd, 1979; Tucholke, 1977). Embley and Langseth (1977) summarised existing knowledge at the time by recognising that sediment waves occur in two main settings: turbidity current channels and their levees, and deep basins with sediment drifts shaped by bottom currents. However, certain authors still discuss the possibility that gravitational processes such as downslope slumping are responsible for the origin of some wave fields on the continental slope (e.g. Bouma and Treadwell, 1975). Hollister et al. (1974) observed that some bottom current sediment waves are aligned oblique to the regional contours, and that current flow along the wave crests may have been important in wave generation. Lonsdale and Hollister (1979) provided the first quantification of wave migration rates in their study of bottom current sediment waves on the Feni Drift, and also suggested a simple mechanism for the observed upslope migration. Damuth (1979) introduced the idea that extensive sediment wave fields on the continental rise are not always related to bottom currents, but can also be generated by turbidity currents. Nevertheless, despite these advances in knowledge, many published examples still lacked detailed oceanographic data and information on the plan view morphology of the waves, often preventing detailed analysis of the wave-forming process.

1980s: Normark et al. (1980) published a comprehensive study of fine-grained turbidity current sediment waves on channel levees. They reviewed previous studies and described a sediment wave field on the levees of the Monterey Fan channel. They then compared the bedforms to antidunes, and used a two-layer physical model to estimate the flow characteristics of turbidity currents responsible for wave formation. In summary, they suggested that the sediment waves are formed by thick, low-velocity, low-concentration flows that overtop the levee crest. Kolla et al. (1980) also proposed the antidune mechanism for development of fine-grained bottom current sediment waves in the Mozambique Basin. Piper et al. (1985, 1988) presented detailed data from an area of coarse-grained turbidity current waves in the Laurentian Fan valley, and discussed how bedforms composed of coarse gravel and boulders can be generated. Trincardi and Normark (1988) discussed the discrimination of outer shelf sediment waves from mass movement features such as slumps and growth faults. Kenyon (1986) used a series of bedforms, including barchan dunes, to estimate bottom current directions and velocities on the upper continental slope of north-west Europe. A series of important publications on bottom current sediment waves in the Argentine Basin were presented (e.g. Klaus and Ledbetter, 1988), including a detailed description of the lee wave model (Flood, 1988; Blumsack and Weatherly, 1989) which is used to explain the generation of sediment waves beneath steady, weakly stratified, sediment-laden bottom currents. In addition, Flood and Shor (1988) revealed that fine-grained bottom current waves can require up to hundreds of thousands of years to develop, and therefore reflect a long-term response to environmental conditions. The first deep-sea drilling cruise to specifically target a sediment wave field was DSDP Leg 94 to the Feni and Gardar Drifts in the north-east Atlantic Ocean (Kidd and Hill, 1986).

1990s: An increase in the number of papers published on turbidite systems sees a predictable increase in documented examples of turbidity current sediment waves, and a brief overview of existing studies was included in Normark and Piper (1991). There was a new focus on coarse-grained turbidity current waves in both modern (Shor et al., 1990; Piper and Savoye, 1993; Masson et al., 1995; Kidd et al., 1998; Lewis et al., 1998; Morris et al., 1998) and ancient (Piper and Kontopoulos, 1994) turbidite systems, while new examples of fine-grained turbidity current waves also continued to appear (Carter et al., 1990; Droz et al., 1996; Howe, 1996; Nakajima et al., 1998). However, the exact mechanism of both fine- and coarse-grained turbidity current wave generation was still a subject of much debate. An interesting account detailing the internal architecture of turbidity current sediment waves on channel levees was presented by Flood et al. (1995). Their study, based on ODP drilling results, showed that the upslope wave flank has (1) a greater overall thickness, (2) a higher number of silt/sand beds, and (3) almost 10 times as many beds with sand as the downslope wave flank. More results from the extensive project on fine-grained bottom current waves in the Argentine Basin were published (Manley and Flood, 1993a,b; Flood et al., 1993), and the controls on wave crest orientation with respect to flow direction were investigated (Blumsack, 1993; Weatherly, 1993). Other studies of bottom current sediment waves discussed how sediment wave morphology can be used to interpret both the present-day and palaeoflow conditions (e.g. Dorn and Werner, 1993; Flood, 1994; Manley and Caress, 1994; Cunningham and Barker, 1996; Howe, 1996; McCave and Carter, 1997). In their review of seismic features diagnostic of contourite drifts, Faugeres et al. (1999) recognised the difficulties in distinguishing sediment waves formed by turbidity currents and bottom currents, and also similar features related to gravitational processes such as creep. They attempted to summarise sediment wave characteristics, and also concluded that an interaction of two or three wave-forming processes is likely for many continental slope wave fields.

2000–2002: A series of papers examining turbidity current sediment waves and their mode of formation were published. Wynn et al. (2000b,c) concluded that the antidune model is the most suitable explanation for the observed pattern of turbidity current sediment waves, and they discussed the use of numerical modelling to infer turbidity current flow characteristics. Meanwhile, Migeon et al. (2000, 2001) presented a detailed description of wave evolution on the Var Sedimentary Ridge, while Nakajima and Satoh (2001) described a turbidity current sediment wave field on the levees of the Toyama Channel, and presented data showing that fine-grained, upslope-migrating, sediment waves can develop on top of coarse-grained, downslope-migrating dunes. They suggested that generation of turbidity current sediment waves does not require internal waves within the flow, but instead that they form as a flow response to pre-existing dune topography. Wynn et al. (2000a) investigated the application of modern sediment wave analogues to subsurface hydrocarbon exploration and production. Finally, Hopfauf et al. (2001) refined the lee wave model for bottom current sediment waves by taking into account additional factors controlling wave development, such as the three-dimensional Coriolis vector.

4. Characteristics and mode of formation of fine-grained turbidity current sediment waves

4.1. Environment and morphology

Fine-grained turbidity current sediment waves are found in areas swept by unconfined turbidity currents, including the backslopes of channel levees (Normark et al., 1980, 2002; Carter et al., 1990; Jacobi and Hayes, 1992; Droz et al., 1996; Lewis et al., 1998; Nakajima et al., 1998; McHugh and Ryan, 2000; Migeon et al., 2000, 2001; Nakajima and Satoh, 2001), sections of the continental slope and rise (Jacobi et al., 1975; Damuth, 1979; Wynn et al., 2000c; Ercilla et al., 2002a,b; Gonthier et al., 2002; Lee et al., 2002), and the slopes of volcanic islands (Wynn et al., 2000b). The largest turbidity current wave fields cover areas of several thousand km^2 (Damuth, 1979; Carter et al., 1990; Ercilla et al., 2002a,b). Where fine-grained turbidity current sediment waves occur on channel levees, the waves are often better developed on one side of the channel than the other due to the effects of Coriolis force. As a result, in the northern hemisphere sediment wave fields are best developed on the right-hand levee (looking down-channel) (e.g. Normark and Gutmacher, 1985; Nakajima et al., 1998), while in the southern hemisphere the opposite occurs (Tucholke, 1977; Carter et al., 1990; Lewis, 1994; Lewis and Pantin, 2002). Waves developed on the levees of meandering channels are also usually concentrated on the outside of meander bands, where centrifugal forces affecting turbidity currents lead to concentrated flow overspill (e.g. Normark et al., 2002).

Most fine-grained turbidity current waves display wave heights up to 80 m and wavelengths up to 7 km, with most waves being developed on slopes of 0.1–0.7°. Overall, wave dimensions appear to be closely related to the slope angle, distance from source and/or sediment supply (e.g. Carter et al., 1990; Migeon et al., 2000; Normark et al., 2002), so that in most cases the wave dimensions progressively decrease downslope (e.g. Nakajima and Satoh, 2001; Ercilla et al., 2002a,b). However, other related factors such as levee height and flow thickness are also thought to control wave dimensions (Normark et al., 2002). Wave asymmetry typically decreases downslope, with more asymmetrical waves occurring in areas with higher sediment supply and steeper slopes, and more symmetrical waves occurring in areas with lower sediment supply and shallower slopes (Normark et al., 1980; Carter et al., 1990; Migeon et al., 2000). Normark et al. (2002) noted that, in general, there is a positive correlation between wavelength and wave height for fine-grained turbidity current waves, but there is no clear relationship between wavelength and channel dimensions or turbidity current initiation process. High-quality multibeam bathymetry data show that the wave crests often display moderate sinuosity and regular bifurcation, and that crest-line morphology is often complex (Wynn et al., 2000b; Ercilla et al., 2002b). Wave crests can be >40 km long, although most are <5–10 km in length. Crests are generally aligned parallel or subparallel to the regional slope, making them roughly perpendicular to a downslope flow direction.

Sections through turbidity current sediment wave fields have revealed how the waves evolve through time. For example, waves sometimes merge together up-section so that younger sections of a wave field have fewer (but larger) individual waves than older sections (Carter et al., 1990; Ercilla et al., 2002b; Lewis and Pantin, 2002). In addition, many wave fields extend further up- or downslope through time (e.g. Lee et al., 2002), while waves on channel levees often become more aggradational up-section (Normark et al., 2002).

4.2. *Wave sediments and wave migration*

Wave sediments typically comprise fine-grained turbidite silts/muds, interbedded with ‘background’ pelagic/hemipelagic sediments. Thin sands a few cm thick are also frequently encountered. Beds are generally thicker and coarser-grained on the upslope (upcurrent) wave flank (Flood et al., 1995; Nakajima and Satoh, 2001; Normark et al., 2002). For example, ODP drilling of sediment waves on the Amazon Fan levees revealed that the overall sediment thickness was higher on the upslope wave flank, and that this flank also had a higher number of silt/sand beds than the downslope flank (Flood et al., 1995; Normark et al., 2002). In addition, geophysical imaging using side-scan sonar (Lewis and Pantin, 2002) or seismic reflection (Ercilla et al., 2002a) has shown that the upslope wave flank displays higher backscatter/reflectivity than the downslope flank, indicating coarser sediments on the upslope flank.

Increased sedimentation rate (up to 40% higher) on the upslope (upcurrent) wave flank leads to active wave migration, which is nearly always upslope/upcurrent and in the opposite direction to the dominant turbidity current flow. Lateral wave migration rates may be as high as 20 m/1000 yr in areas of high sediment supply (Carter et al., 1990; Lewis and Pantin, 2002), and some wave fields have been actively growing for up to 3 million years (Carter et al., 1990; Lewis and Pantin, 2002).

4.3. Wave-forming processes

The large dimensions and temporal persistence of many fine-grained turbidity current sediment wave fields suggest they are in long-term equilibrium with their host turbidite system (Lewis and Pantin, 2002). Several studies of turbidity current waves have concluded that the waves have formed as antidunes, with internal waves generated within the flow being responsible for the sediment wave morphology (Normark et al., 1980; Wynn et al., 2000b,c; Ercilla et al., 2002a,b). Some studies also suggest that the sediment waves may have been generated by internal lee waves (Lewis and Pantin, 2002). This has the disadvantage of imposing a low Froude number and a degree of stability on the flows generating the waves, which is shown to be unlikely in many field examples (e.g. Piper and Savoye, 1993; Nakajima and Satoh, 2001; Wynn et al., 2000c). However, an added complexity is the importance of hemipelagic/hemiturbiditic deposition in wave growth. Slow, dilute, ‘continuous’ gravity flows may contribute to wave migration in some turbidite systems (Wynn et al., 2000c), and these weakly stratified flows would potentially be capable of generating internal lee waves.

Recent studies have suggested that the process of wave migration and growth is essentially self-perpetuating once the initial sediment wave topography is established (Nakajima and Satoh, 2001; Kubo and Nakajima, 2002; Lee et al., 2002; Normark et al., 2002). Internal waves are not a prerequisite for wave growth in this case, although it is likely that some form of internal waves would be required for wave initiation to occur. This would imply that the many studies which have assumed that waves at the seafloor are forming as antidunes may be incorrect, and that numerical modelling based upon this assumption is also likely to be inaccurate (e.g. Normark et al., 1980; Piper and Savoye, 1993; Wynn et al., 2000b,c; Ercilla et al., 2002a,b). For example, calculations of flow thickness based upon wave dimensions at the seafloor should be treated with caution, as the waves may not have been growing under antidune conditions at all times. If the antidune model is favoured for wave initiation, then only the waves immediately above the lower bounding surface can be assumed to have formed under antidune conditions. Waves higher in the sequence may not have formed under antidune conditions so equations based upon this assumption are inapplicable.

Numerical/experimental modelling of sediment wave formation by Kubo and Nakajima (2002) and Lee et al. (2002) found that a pre-existing stepped seafloor topography is normally required for wave initiation. However, Kubo and Nakajima (2002) successfully generated sediment waves from a flat bed using numerical modelling, although several thousand individual turbidite beds were required to establish a limited number of waves, which means the results are probably not applicable to most natural systems. The modelling results of Kubo and Nakajima (2002) and Lee et al. (2002) also show that when hemipelagic/pelagic units are deposited between turbidite beds, a sequence of upslope-migrating sediment waves very similar to those seen in natural systems can be created. Without intervening hemipelagic/pelagic units the most proximal waves display erosion on the downslope flank, which gradually changes into non-deposition on the more distal waves. Again, this is also sometimes replicated in natural systems, and suggests a link between turbidity current frequency/intensity and the final deposit character.

5. Characteristics and mode of formation of fine-grained bottom current sediment waves

5.1. Environment and morphology

Fine-grained bottom current sediment waves are generally associated with sediment drifts in basin floor and lower continental rise settings (Ewing et al., 1971; Asquith, 1979; Lonsdale and Hollister, 1979; Kidd and Hill, 1986; Richards et al., 1987; Flood and Shor, 1988; Jacobi and Hayes, 1992; Flood et al., 1993; Manley and Caress, 1994; Manley and Flood, 1993a,b; Marani et al., 1993; Cunningham and Barker, 1996; Howe, 1996; Howe et al., 1998; Flood and Giosan, 2002; Lewis and Pantin, 2002; Masson et al., 2002; von Lom-Keil et al., 2002). They can cover areas of several thousand km^2 and typically display wave heights of 15–50 m, although examples with wave heights up to 150 m have been reported from the Argentine Basin (e.g. Flood et al., 1993). Wavelength is generally in the region of 1–10 km and wave crests can be >10 km long. Wave dimensions typically decrease and wave symmetry increases towards the margins of bottom current wave fields, presumably due to lateral variations in bottom current flow conditions such as velocity or concentration (e.g. Cunningham and Barker, 1996; Flood and Shor, 1988). Wave crests are generally straight or slightly sinuous, with rare bifurcation.

5.2. *Wave sediments*

Most fine-grained bottom current waves are composed of typical contouritic sediments, i.e. mud, silt and fine sand. The sediments are often intensely bioturbated and primary sedimentary structures are usually absent or disrupted as a result (e.g. Ediger et al., 2002; Masson et al., 2002). For example, sediment waves described from mid-ocean sediment drifts are in some cases dominated by thoroughly bioturbated pelagic sediments, with little obvious evidence of bottom current influence (Kidd and Hill, 1986). Sidescan sonar images of bottom current waves with mixed grain size indicate that the lowest backscatter occurs on the upcurrent wave flank, which is interpreted to contain a greater thickness of well-sorted contourite sand than the downcurrent flank (Masson et al., 2002). Actively migrating waves have thicker beds on the upcurrent face, leading to upcurrent wave migration.

5.3. *Wave migration*

Most studies have shown that where fine-grained bottom current waves are developed on slopes, the wave crests are aligned at a low angle (typically 10–50°) to the regional contours. Assuming that the mean bottom current flow is parallel to the slope, most of these oblique waves are seen to migrate upslope *and* upcurrent (e.g. Flood et al., 1993), however, in areas of complex topography around sediment drifts this relationship is not always applicable (e.g. Roberts and Kidd, 1979). Waves developed on flat basin floors tend to have a crest alignment that is more perpendicular to the bottom current flow (e.g. Flood and Shor, 1988). The angle (with respect to the bottom current flow) at which the crests are developed varies between the northern and southern hemisphere, due to the effects of Coriolis force. In the southern hemisphere, waves migrate upslope and upstream to the left of the current (e.g. Kolla et al., 1980; Flood et al., 1993), whereas in the northern hemisphere, waves migrate upslope and upstream to the right of the current flow (e.g. Asquith, 1979; Flood, 1994; Masson et al., 2002). Lateral migration rates of fine-grained bottom current waves on the Feni Ridge were found to be in the order of 0.25 m/1000 yr (Lonsdale and Hollister, 1979), while those in the Rockall Trough are in the region of 0.4–0.9 m/1000 yr (Masson et al., 2002). The observed difference appears to be a function of differing sedimentation rates, which are slightly higher in the Rockall Trough area (Masson et al., 2002).

5.4. *Wave-forming processes*

Flood (1988) proposed a lee wave model to explain the migration of fine-grained bottom current waves that have their crests aligned perpendicular to the bottom current flow. The model suggests that internal lee waves are generated in weakly stratified bottom currents as they pass over the sediment wave topography. Bottom current flow velocities on the downstream flanks of the waves are higher than those on the upstream flanks, leading to enhanced deposition on the upstream flank and upstream wave migration. The model predicts that wave migration occurs under flow velocities of about 9–30 cm/s. At lower flow velocities, vertical wave aggradation is expected. Where the mean bottom current flow is >16 cm/s some erosion on the downstream wave flank is expected, and at greater flow speeds it is likely that deposition will only occur on the upstream flank. The exact flow velocities necessary for erosion/deposition are expected to vary at different latitudes and wavelengths. Blumsack and Weatherly (1989) expanded upon this simple lee wave model, by explaining the formation of waves with crests aligned oblique to the flow direction. They suggested that in areas where bottom currents show frequent variations in flow direction, a combination of flow over and along the wave crests will produce waves that are aligned at an oblique angle to the flow. In addition, this type of interaction can produce very small wave fields, comprising just one or two waves, as are frequently described in real examples (e.g. Marani et al., 1993; Howe, 1996). The lee wave model was successfully tested against real observations in the Argentine Basin during Project MUDWAVES (Blumsack, 1993; Manley and Flood, 1993a; Flood et al., 1993; Weatherly, 1993), and was further refined by Hopfauf et al. (2001). Other models explaining the growth and migration of fine-grained bottom current waves have been proposed by Lonsdale and Hollister (1979), Kolla et al. (1980) and Kidd and Hill (1986), although these have yet to be comprehensively tested against real examples. No model has yet been devised to comprehensively explain wave initiation, although this is presumably controlled by flow over some sort of pre-existing seafloor irregularity (Howe et al., 1998; von Lom-Keil et al., 2002).

6. Discrimination of fine-grained turbidity current and bottom current sediment waves

Many modern studies of sediment waves and their surrounding sedimentary systems implement a variety of data collection techniques, including vertical seismic profiles, plan view sidescan sonar imagery, 3-D multibeam bathymetry and shallow piston cores. Continued use of such high-quality datasets should allow most sediment wave fields to be assigned to a turbidity current or bottom current origin with confidence. Previous studies have suggested several criteria that can be used for this purpose, and these are listed below as follows:

(1) Regional setting: Most fine-grained turbidity current waves occur in clearly definable turbidite environments, such as channel levees. Most bottom current waves are associated with contourite drifts or deep basins away from turbidity current input. Oceanographic data indicating the presence or absence of bottom currents over a wave field may also be of use.

(2) Wave regularity: Typically bottom current waves are more irregular than turbidity current waves, with no consistent change in wave dimensions up- or downslope (e.g. Cunningham and Barker, 1996). Turbidity current waves usually show a progressive decrease in dimensions downslope.

(3) Sediment type: Bottom current waves typically comprise contourite sediments, often with high levels of bioturbation. Turbidity current waves consist of interbedded turbidites and pelagic/hemipelagic sediments, and bioturbation is less common.

(4) Crest alignment: The crests of turbidity current waves on slopes are normally slope-parallel, whereas bottom current wave crests on slopes are normally oblique to the regional slope. The only exception is for some turbidity current waves on levee backslopes, which may be oblique to the regional slope (although in this case the setting should be obvious). Bottom current waves on flat basin floors can be perpendicular to bottom current flow, but turbidity current waves are scarce in this setting.

(5) Sequence thickness: In turbidity current wave fields, the stratigraphic interval over which the waves occur often shows a progressive downslope decrease in thickness, and the package can actually thin by 40–60% from the top to the bottom of the wave field (e.g. Ercilla et al., 2002b). This indicates that the wave sequence is sourced from upslope, not alongslope as is normally the case for bottom current waves.

It should be noted that not every wave field will fit neatly within the bottom current or turbidity current grouping. Some sediment wave fields are undoubtedly influenced by a combination of steady bottom current flow and sporadic turbidity current input. In some cases this may involve redistribution of the suspended turbidity current load by bottom currents prior to deposition (e.g. Rebesco et al., 1996) or, in areas of stronger bottom currents, the redistribution of previously deposited turbidite sands (e.g. Kenyon et al., 2002). In addition, there may be a more direct interaction between steady bottom currents flowing over a pre-existing turbidity current sediment wave topography, in which case the bottom currents may influence the wave migration direction and rate.

7. Discrimination of fine-grained sediment waves and soft sediment deformation features

Soft sediment deformation is widespread on many submarine slopes, and is especially common where slope gradients are relatively high and sediment accumulation rates are rapid. This deformation can lead to near-surface sediment layers adopting an undulating or 'wrinkled' appearance, which is potentially confusable with fine-grained (current-formed) sediment waves. Fortunately, a number of criteria can be used to distinguish wave-like features related to soft sediment deformation, e.g. creep folds and extensional faults, from fine-grained sediment waves that have formed beneath a current (Kenyon et al., 1978; Hill et al., 1982; Syvitski et al., 1987; Trincardi and Normark, 1988; Mulder and Cochonat, 1996; O'Leary and Laine, 1996; Faugeres et al., 1999; Wynn et al., 2000b,c; Lee and Chough, 2001; Nakajima and Satoh, 2001; Lee et al., 2002; Mosher and Thomson, 2002). However, it should be noted that in many cases good-quality cross-sectional and planform data are required to make this distinction. The main criteria are listed as follows and summarised in Table 1:

(1) Fine-grained (current-formed) sediment waves generally display active migration in the opposite direction to the dominant current, with individual beds generally being thicker on the upcurrent flank, and thinner or even eroded on the downcurrent flank. This variation may also be reflected in the grain size and/or reflectivity across the wave, with the upcurrent flank typically comprising beds containing coarser sediments and/or displaying higher reflectivity. Creep folds do not display lateral migration (e.g. Lee and Chough, 2001) and sediments on either flank of individual folds are expected to be identical.

(2) Individual reflectors can be traced across sediment wave troughs, from one wave to the next. In some cases, seismic inflection patterns in the wave troughs can appear to mimic fault planes, however, closer analysis reveals that these actually represent continuous reflectors (Lee et al., 2002). In contrast, creep folds sometimes show clear evidence of displacement along fault planes, especially in the troughs (Hill et al., 1982; Lee and Chough, 2001).

(3) Sequences of adjacent sediment waves usually show some regularity in terms of their reflector spacing, flank dip angles, crest/trough widths etc. (Lee et al., 2002). Creep folds are more irregular and often display broad crests and tight, narrow troughs (e.g. Lee and Chough, 2001).

(4) Most fine-grained sediment waves show distinct trends in their dimensions, related to the slope angle, sediment supply and/or the flow velocity. For example, most turbidity current sediment waves show a downslope decrease in dimensions, as the slope angle, flow velocity and sediment supply also decrease downslope (Wynn et al., 2000b,c; Lee et al., 2002). Features such as creep folds typically show a more random scatter of dimensions, although a downslope decrease in wavelength related to the transformation from an extensional to a compressional regime has been observed (Lee and Chough, 2001). However, in this case the sequence thickness also increased downslope, which is not typical of a turbidity current sediment wave field (see below).

(5) Many sediment wave sequences decrease in thickness downcurrent, due to a reduction in sediment supply away from the source. Sequences of turbidity current sediment waves almost always decrease in thickness downcurrent *and* downslope. Sequences of similar features that show a downslope increase in sequence thickness, or no signifi-

cant lateral variation in sequence thickness, are more likely to be of a creep fold origin.

(6) In areas with good planform coverage most fine-grained sediment waves appear as linear features with varying degrees of sinuosity and/or bifurcation. Planform images of creep/slump folds are scarce but those available suggest that these features are arcuate in plane view, and do not show bifurcation (e.g. Kenyon et al., 1978).

Certain other processes, in addition to soft sediment deformation, can produce features that may be confusable with current-formed sediment waves. Early compaction effects in thick, fine-grained sedimentary successions can result in large-scale dewatering (or syneresis) and the disruption of intrastratal units by a series of regularly to irregularly spaced faults (e.g. Cartwright and Dewhurst, 1998). When these faults are spaced at intervals of a few hundred metres or even a few kilometres, and display throws of a few tens of metres, they may be confusable with current-formed sediment waves. However, in plan view these features typically display distinctive polygonal patterns that allow them to be distinguished from sediment waves or creep folds. In addition, single-line crossings of slope gullies may also yield seismic reflection profiles with a wave-like pattern (e.g. Field et al., 1999), but again in plan view these features should be easily identifiable.

As in the previous section, it should be noted that some sediment waves or ‘wave-like’ features are probably produced by a complex interaction of processes. In some cases sediment wave morphology may be modified by gravitational processes such as creep, while features such as creep folds could potentially provide the initial topography that allows wave growth to occur.

8. Characteristics and mode of formation of coarse-grained turbidity current sediment waves

8.1. Environment and morphology

Coarse-grained turbidity current sediment waves are found in turbidity current channels (Piper et al., 1985, 1988; Malinverno et al., 1988; Hughes Clarke et al., 1990; Shor et al., 1990; Normark and Piper, 1991; Piper and Kontopoulos, 1994; Masson et al., 1995; Mulder et al., 1997; Kidd et al., 1998; Wynn et al., 2000b; Lewis and Pantin, 2002) and channel–lobe transition zones (Morris et al., 1998; Wynn et al., 2002b). They are normally smaller in size, and less temporally persistent than fine-grained turbidity current waves, suggesting they are only representative of the most recent events in a turbidite system. Wave heights are <10 m and wavelength values are usually in the range of <0.1–1.0 km. Wave crests are aligned roughly perpendicular to the flow direction and channel margins, and wave symmetry is variable. Coarse-grained sediment waves in channels have been shown to decrease in wavelength towards areas where flow velocities are reduced, such as inner channel bends and channel margins (Malinverno et al., 1988; Kidd et al., 1998), suggesting a relationship between flow velocity and wave dimensions. Wave morphology is often irregular, due to disruption by later flows and/or flow phases (Wynn et al., 2002b).

8.2. Wave sediments

Due to their nature, coarse-grained sediment waves are often difficult to sample directly. In cases where samples have been obtained from cores or grabs, the sediment is typically composed of gravels or sands (e.g. Lewis and Pantin, 2002). When seen in cross-section, the waves typically display a thick, massive, gravel or coarse sand unit overlain by a finer-grained, normally graded turbidite unit (Wynn et al., 2002b). On high-resolution sidescan sonar images, coarse-grained sediment waves sometimes show high backscatter lineations running perpendicular to the wave crests (Piper et al., 1988; Kidd et al., 1998; Wynn et al., 2000b), which are interpreted as streaks of coarse sediment transported by bedload traction.

8.3. Wave migration and wave-forming processes

Most coarse-grained turbidity current sediment waves are thought to have formed as dunes or antidunes beneath large-volume, high-concentration turbidity currents (Wynn et al., 2002b), although the exact mechanism is often hard to determine due to reworking. The inability to obtain good-quality cross-sectional images of coarse-grained waves means that the migration direction is also usually indeterminable. Wynn et al. (2000b, 2002b) suggest that the plan view morphology of some waves, with the crest curvature producing an upcurrent convexity, indicates that the waves may be migrating upcurrent (like antidunes) and are migrating most rapidly in the channel axis where flow velocity is highest. Lewis and Pantin (2002) favour their formation as antidunes, based upon the likely characteristics of the flows that formed them (usually near- or supercritical), and also the observation that the upcurrent flanks of the waves are steeper than the downcurrent flanks. However, Lewis and Pantin (2002) and Wynn et al. (2002b) also suggest that some waves that were initially generated as antidunes may be modified by later (subcritical) flow events and could be transformed into dunes. In addition, rare cross-sectional observations of coarse-grained waves in outcrop show clear evidence of downcurrent migration, in a manner more typical of dunes (Piper and Kontopoulos, 1994).

9. Characteristics and mode of formation of coarse-grained bottom current sediment waves

9.1. Environment and morphology

Coarse-grained sediment waves that are generated by deep-water bottom currents (i.e. those that occur downslope of the shelf edge) usually take two main forms. (1) Linear waves or dunes that resemble coarse-grained turbidity current waves have been described from topographic ridges (Dorn and Werner, 1993). The wave crests are aligned roughly perpendicular to the bottom current flow direction, and are spaced at up to 100-m intervals. (2) Submarine barchans have been noted in a variety of slope environments swept by substantial (>40 cm/s) bottom currents, especially in areas where coarse sediment is in relatively short supply (Lonsdale and Malfait, 1974; Lonsdale and Speiss, 1977; Kenyon, 1986; Dorn and Werner, 1993; Kenyon et al., 2002; Wynn et al., 2002a). These may occur as individual bedforms of up to 200 m width and a few metres high, or as laterally amalgamated bedforms that have a characteristic ‘gull-wing’ shape (Dorn and Werner, 1993). Barchans often merge into fields of linear sand streaks in areas where flow velocity increases (Dorn and Werner, 1993).

9.2. Wave sediments

Coarse-grained bottom current waves are typically composed of sand-sized sediment, although the number of published datasets is small and direct observations are rare (e.g. Kenyon et al., 2002; Wynn et al., 2002a). Barchans composed of sand often migrate across gravel or coarse sand substrates (Lonsdale and Malfait, 1974; Wynn et al., 2002a).

9.3. Wave migration and wave-forming processes

Coarse-grained barchans appear to migrate downcurrent in a similar fashion to subaerial barchans. Sediment is transported across the upcurrent flank before ‘avalanching’ down the downcurrent flank and moving along the barchan ‘horns’ towards the tips. Lonsdale and Malfait (1974) and Wynn et al. (2002a) documented the pattern of ripples across the surface of a series of barchans, and found that the highest interpreted flow velocities occurred near the barchan crest, while the lowest flow velocities were immediately downcurrent of the steeper downcurrent barchan flank. Kenyon et al. (2002) show that barchans formed beneath bottom currents in the distal Mississippi Fan are actually composed of reworked turbidite sands.

10. Conclusions

(1) Deep-water sediment waves have been studied by marine geologists for almost 50 years, and over this period there has been a gradual shift in dominance from studies of bottom current waves to studies of turbidity current waves.

(2) Sediment waves can be classified according

to the wave-forming process (i.e. bottom current, turbidity current or unknown) and also their overall grain size (fine-grained = mud and silt dominated; coarse-grained = sand and gravel dominated).

(3) Fine-grained turbidity current sediment waves are found on channel levees, sections of the continental slope and rise, and the flanks of volcanic islands. They can cover huge areas of seafloor and in most cases show upslope migration and a downslope decrease in dimensions and asymmetry. Individual beds are thicker and coarser-grained on the upslope wave flank. The wave-forming process is currently a subject of much debate. Recent studies suggest that wave growth and migration requires a continuous interaction between the flow and the wave topography, but that a specific flow condition (e.g. antidunes or lee waves) is not a prerequisite for wave growth and migration once a wavy topography has become established.

(4) Fine-grained bottom current sediment waves are associated with sediment drifts in basin floor and lower rise settings. They can also cover large areas and usually show a decrease in dimensions and symmetry towards the margins of the wave field. They are dominantly composed of typical contouritic sediments, and those developed on slopes tend to migrate upcurrent and upslope, with the angle with respect to the flow being dependent on Coriolis forces. The wave-forming process is related to internal lee waves that develop within a bottom current flowing over a wavy topography, although the wave initiation process is not well understood. The study of fine-grained bottom current sediment waves has applications in the field of palaeoceanography, as the waves reflect a long-term interaction between seafloor topography and a steady, sediment-laden bottom current.

(5) Fine-grained bottom current and turbidity current waves can be distinguished using several criteria, including regional setting, sediment type, crest alignment, wave regularity and sequence thickness trends. Both wave types can be distinguished from similar features such as creep folds as they show active migration and asymmetry of deposition across the wave crest, individual reflectors that can be traced from one wave to the next, and distinct lateral trends in dimensions related to sediment supply, slope angle etc.

(6) Coarse-grained turbidity current sediment waves are found in channels and channel–lobe transition zones. They are smaller than fine-grained waves and are relatively short-lived. There appears to be a relationship between wave dimensions and flow velocity, but the wave migration direction is less clear, and may even involve both up- and downcurrent migration in a single wave during one or more events.

(7) Coarse-grained bottom current sediment waves typically occur in barchan form on slopes swept by substantial bottom currents. They appear to migrate downcurrent in a similar fashion to subaerial barchans, and are commonly found in areas of hard substrates and low sediment supply.

(8) Future sediment wave studies should attempt to increase our understanding of wave-forming processes, especially the process of wave initiation. The recent trend of using high-quality integrated 2-D and 3-D geophysical datasets, combined with sediment cores recovered from adjacent wave flanks, should be continued.

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