

Contourite Drifts and Associated Bedforms

Ibimina Esentia, Dorrik Stow and Zeinab Smillie

Abstract Contourites, also known as alongslope deposits, are sediments that have been deposited or significantly affected by the persistent action of contour (bottom) currents. Contourite drifts are the large-scale morphological expression of contourite deposition, up to 10^6 km² in area and >1 km in thickness. They are a common feature in some parts of the ocean basins and are found covering large areas of the present-day seafloor beneath modern bottom current systems. They typically co-occur with erosional features caused by bottom currents in very large-scale contourite depositional systems. Contourite drifts are classified into four principal types—sheeted drifts, mounded-elongate drifts, patch drifts, and channel-related drifts—and four specific types linked to their mode or location of formation, including confined drifts, infill drifts, fault-controlled drifts, and mixed-drift systems. The principal erosional elements include: depositional hiatuses; regional erosive surfaces—erosional terraces, abrasive surfaces, channel scour and sub-circular scour; and linear erosion—contourite channels, moats, marginal valleys and isolated furrows. Seismic criteria for the identification of drifts and erosional elements must be applied carefully at three scales of observation—whole drift, seismic element and seismic facies. Bottom-current bedforms are common over drifts and erosive features and provide important insights into the flow characteristics and depositional mechanisms. The wide range of longitudinal and transverse bedforms can be linked to flow velocity and sediment grain-size in a bedform-velocity matrix. The principal controls on contourite systems are: the nature and style of bottom current flow; the slope gradient and other topographic features; and the sediment supply.

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1 Introduction

1.1 Scope and Terminology

Contourites are sediments that have been deposited, or significantly affected, by the persistent action of contour (bottom) currents (Stow et al. 2002, 2008; Rebesco 2005; Rebesco et al. 2008, 2014; Stow and Faugères 2008). They are a group of closely related deepwater facies, deposited under the influence of semi-permanent current action, and are commonly referred to as alongslope deposits resulting from semi-continuous depositional processes. This distinguishes them from other deepwater facies that have been deposited either by episodic downslope processes or events (turbidites, debrites, hybrid deposits, slides and hyperpycnites), or from continuous vertical settling—the so-called background processes (pelagites and hemipelagites).

Several different bottom current processes can be recognised as operating in deep water settings (Shanmugam 2003, 2006; Rebesco et al. 2014) (a) thermohaline bottom currents, (b) wind-driven bottom currents, (c) deepwater tidal bottom currents, and (d) internal waves and tides (baroclinic currents). Types (a) and (b) are both *contour currents* capable of depositing contourites and contourite drifts. Types (c) and (d) can both influence contour currents, and so contribute to contourite deposition, and can also act independently, both on the open slope and where focussed in deep-water channels and passageways. Bottom current velocity is also affected by intermittent processes, such as giant eddies, benthic storms and tsunamis.

Contourite drifts are the large-scale morphological expression of contourite deposition (Faugères and Stow 2008). They are a very common feature in some parts of the ocean basins and are found covering large areas of the present-day seafloor beneath modern bottom current systems. In some regions they are expressed as the build-up of large contourite mounds or drifts through semi-continuous deposition over a period of millions of years (Rebesco and Stow 2001; Faugères and Stow 2008). They also occur as less morphologically distinct sheet-like deposits, which may be closely interbedded with the other deepwater facies.

Contourite erosional elements are the non-depositional zones and erosional features on the seafloor often closely associated with and adjacent to contourite drift deposition. They occur where the bottom current velocity is sufficiently strong to prevent deposition or cause substrate erosion (Hernández-Molina et al. 2008; Rebesco and Camerlenghi 2008; García et al. 2009).

Contourite bedforms are the small-scale seafloor sedimentary features (waves, dunes, ripples, scours, etc.) that result from the depositional and erosional processes that form contourites (Wynn and Masson 2008; Stow et al. 2009; Casas et al. 2015). They are visible on the present-day seafloor under the influence of contour currents. Their external form and internal structures may then be preserved in the sediment record.

Contourite facies range from very fine-grained (mud and silt) to relatively coarse-grained (sand and gravel) contourite deposits, and include siliciclastic, bioclastic, volcanoclastic and chemogenic compositional varieties, so that contourite drifts and contourite bedforms are equally varied in composition and grain size (Stow et al. 2002; Stow and Faugères 2008).

Based on the large amount of information gleaned from modern contourite systems, it is possible to construct a fairly accurate picture of just how, where and when contourite deposition occurs and contourite drifts are formed. An associated picture emerges of when and where deposition gives way to non-deposition and erosion by bottom currents, and how long-term accumulation of contourites can result from the alternation of deposition and erosion in time and space. Following a brief history of past research on the topic, this chapter aims to provide a state-of-the-art review of contourite drifts, contourite erosional elements and contourite bedforms. In each case, we will address: (a) the types, examples and occurrence, (b) the processes/mode of formation, and (c) their recognition and implications. We then briefly highlight key research questions for the future.

1.2 *Brief History of Study*

Early work by the German physical oceanographer Georg Wüst (1933) initially proposed that bottom currents driven by thermohaline circulation might be sufficiently strong to influence sediment flux in the deep ocean basins. But his work was largely ignored until the early 1960s when Bruce Heezen of Woods Hole Oceanographic Institute took up the challenge from a marine geological perspective. In their now seminal paper of 1966, Heezen et al. (1966) demonstrated the very significant effects of contour following bottom currents or contour currents in shaping sedimentation on the deep continental rise off eastern North America. The deposits of these semi-permanent alongslope currents soon became known as contourites, clearly distinguishing them from the deposits of downslope event processes known as turbidites. The ensuing decade saw a profusion of research on contourites and bottom currents in and beneath the present-day oceans, and the demarcation of slope-parallel, elongate, mounded sediment bodies made up largely of contourites that became known as contourite drifts (Hollister and Heezen 1972; McCave and Tucholke 1986). Their initial identification in ancient rocks exposed on land, however, proved mostly inaccurate. Subsequent work has greatly improved on these earlier interpretations (Stow and Lovell 1979; Stow et al. 1998; Hueneke and Stow 2008) although controversy still exists (Shanmugam 2000, 2012).

Standard sedimentary facies models for contourites were developed from detailed observations on modern systems (Stow 1979, 1982; Stow and Piper 1984; Faugères et al. 1984; Gonthier et al. 1984). The direct link between bottom current strength and nature of the contourite facies, especially grain size, was demonstrated (Stow et al. 1986). This has been taken forward through the work by Nick McCave and associates (Robinson and McCave 1994; McCave et al. 1995) in decoding the

often very subtle signatures captured in contourites in terms of variation in deep-sea paleocirculation. Discrimination was made between contourites and other deep-sea facies, such as turbidites deposited by catastrophic downslope flows and hemipelagites that result from continuous vertical settling in the open ocean (Stow and Lovell 1979; Stow and Tabrez 1998). Much progress has been made on the types and distribution of sediment drifts (McCave et al. 1980; Faugères and Stow 1993, 2008; Howe et al. 1994; Stoker et al. 1998), as well as on their seismic characteristics (Faugères et al. 1999; Nielsen et al. 2008).

For the most part, physical oceanographers have worked independently of geologists on the nature and variability of bottom currents, so that much integration is still required between these disciplines. Important contributions that to some extent bridge this divide have come from the HEBBLE project on the Nova Scotian Rise (Hollister and McCave 1984; Nowell and Hollister 1985; McCave et al. 1988), work along the Brazilian continental margin (Viana et al. 1998a, b), and an extensive programme of research in the Gulf of Cadiz (Maldonado and Nelson 1999), culminating in IODP Expedition 339 (Stow et al. 2013a; Hernández-Molina et al. 2014a, b). Prior to this latest mission, the international deep-sea drilling programme in its various guises (DSDP, IPOD, ODP, IODP) has contributed enormously to contourite research—the paleoceanographic context and study of oceanic gateways remain primary targets at present (Knutz 2008). Several edited volumes of papers dealing in part or wholly with contourite systems serve to synthesise much of the knowledge up to the end of the last century. These include: Nowell and Hollister (1985), McCave et al. (1988), Stow and Faugères (1993, 1998), Gao et al. (1998), Stoker et al. (1998), Mienert (1998), Stow and Mayall (1999), Wynn and Stow (2002), Rebesco and Stow (2001), and Stow et al. (2002).

Both the recent IODP expedition (Stow et al. 2002; Hernández-Molina et al. 2014a, b) and the recognition of the economic potential of contourites by the oil industry has seen a renewed explosion of research (Viana and Rebesco 2007; Rebesco and Camerlenghi 2008). Key synthesis papers and edited volumes on contourites and related research that have appeared in the past few years include those by Rebesco et al. (2014), Pickering and Hiscott (2016), Acosta et al. (2015) and Hernández-Molina et al. (2014a, b, 2016a, b). The following synthesis draws together findings from all of this prior research.

2 Contourite Drifts

At the large scale, contourite deposition is focused in contourite drifts, which range in scale from around 0.5×10^2 to $>10^6$ km², and in larger *contourite depositional systems* that comprise several related drifts and associated erosional elements (Faugères et al. 1993; Stow et al. 2002; Hernández-Molina et al. 2008; Rebesco 2005). Contourite depositional systems develop along continental margins that have been under the influence of bottom currents for relatively long periods of time (>2 – 3 My). They show the development of mounded, elongate, sheeted and patch

drifts, as well as contourite moats and channels. The long-term action of bottom currents generally occurs in association with other deepwater processes, including both downslope and pelagic processes. The larger drifts clearly demonstrate long-term continuity of deposition over several millions of years that allows the accumulation of several hundreds of metres of contourite sediment.

The four principal types of contourite drift that have been identified include (Fig. 1): sheeted drifts, mounded-elongate drifts, patch drifts, and channel-related drifts. Several other drift types have been recognised, which are all variations of the principal types, but determined in relation to their specific topographic or sediment supply controls. These include (Fig. 1): confined drifts, infill drifts, fault-controlled drifts, and mixed drift systems (McCave and Tucholke 1986; Faugères et al. 1993; Rebesco and Stow 2001; Rebesco 2005; Faugères and Stow 2008; Rebesco et al. 2014). These different types of contourite system are controlled largely by a combination of factors: the nature and style of bottom current flow (e.g. tabular vs. multicore flow of Hernández-Molina et al. 2008); the slope gradient and other topographic features; and the sediment supply. There is also a distinct overlap between the drift types identified, such that they form a continuous spectrum of deposits.

Selected examples of these drifts, together with typical range of sizes and key reference, are provided in Table 1.

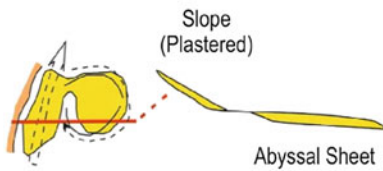
2.1 *Sheeted Drifts*

Sheeted drifts (Fig. 1; Table 1) typically represent relatively slow rates of deposition of fine-grained contourites over a large area of seafloor (slope plastered drifts and abyssal sheet drifts). They can be very extensive in area from 10^3 to $>10^6$ km². The flow is mostly simple and tabular, broad and regionally stable, although it may also include strands of more intense flow and giant eddy circulation. For *mud-rich sheeted drifts*, contourite deposition appears to take place directly from suspension more or less evenly across the whole flow width, with a mean accumulation rate of <20 cm/ky. *Sand-rich sheeted drifts*, however, are a depositional-erosional body linked with more localised zones of higher energy flow, as found in erosive terraces and abrasive surfaces below very active bottom currents. Erosion, winnowing and deposition as bedload alternate continuously such that localised higher rates of accumulation (>60 cm/ky) may give way to longer periods of non-deposition or erosion.

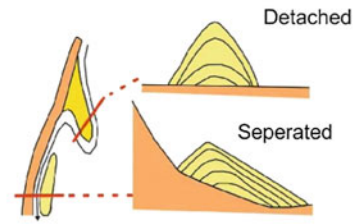
Sheeted drifts can also be distinguished on the basis of their occurrence, yielding: *abyssal sheeted drifts*, *slope sheeted drifts* and *channel sheeted drifts*. Slope sheeted drifts are also referred to as *plastered drifts*. Many examples are known, especially from the Atlantic Ocean, as summarised in Faugères et al. (1999), Stow et al. (2002), Rebesco and Camerlenghi (2008) and Rebesco et al. (2014).

Principal Drift Types

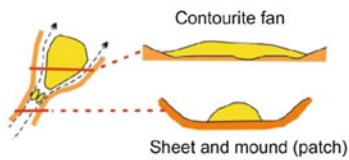
Sheeted Drifts



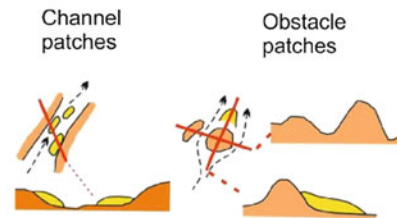
Mounded Elongate Drifts



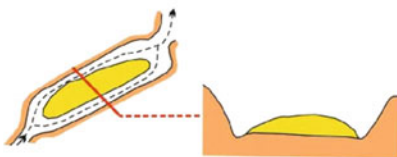
Channel-Related Drifts



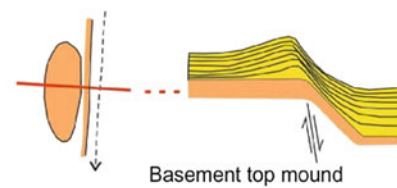
Patch Drifts



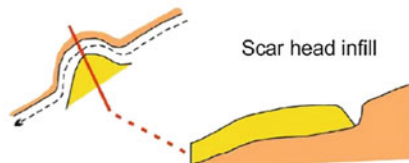
Confined Drifts



Fault-Controlled Drifts



Infill Drifts



Downwelling Drifts

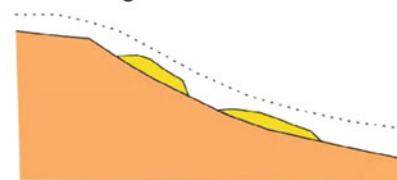


Fig. 1 Summary of principal contourite drift types showing sketches of both plan view and cross-section. Examples are provided for each type in the text and in Table 1. Modified from Rebesco and Stow (2001), Stow et al. (2002), Faugères and Stow (2008) and Rebesco et al. (2014)

There is probably a complete gradation in depositional style between sheeted drifts (with very low mounded geometry), and mixed drifts in which thinner sheets (or beds) of contourites closely interbedded with other deepwater facies (hemipelagites, turbidites, etc.).

Table 1 Principal morpho-genetic types of contourite systems—depositional drifts and erosional elements

	Subdivisions	Size (km ²)	Examples
<i>Depositional drifts</i>			
Contourite sheet drift	(a) Abyssal sheet	10 ⁵ –10 ⁶	(a) Ewing drift; Gloria drift, Rockall basin
	(b) Slope (plastered) sheet	10 ³ –10 ⁴	(b) Gulf of Cadiz CDS; Campos margin; Chatham drift; Gardar drift
	(c) Channel (patch) sheet	<10 ³	(c) Within Vema channel: Cadiz channel
Mounded-elongate drift	(a) Detached drift	10 ³ –10 ⁵	(a) Eirik drift; Blake drift (many other examples of mounded drifts worldwide)
	(b) Separated drift	10 ³ –10 ⁴	(b) Feni drift; Faro drift; Flemish drift; Agulhas drift
Channel-related drift	(a) Sheeted patch-drift	10–10 ³	(a) NE Rockall trough; Vema channel; Cadiz channel
	(b) Mounded patch-drift	10–10 ³	(b) Alavarez-Cabral moat; Vema channel
	(c) Contourite-fan	10 ³ –10 ⁵	(c) Vema channel exit
Patch drift	(a) Channel patch-drifts	10–10 ³	Many different examples worldwide, but most are not specifically named
	(b) Slope patch-drifts	10–10 ³	
	(c) Downwelling patch-drifts	10–10 ³	
Confined drift		10 ³ –10 ⁵	Sumba drift; Davies drift; Sicilian channel drift; Louisville drift; Lake Baikal drifts
Infill drift	(a) Slide scar infill	10 ³ –10 ⁴	Many small examples exist; some larger drifts (e.g. Feni, Lofoten) are generally known as plastered drifts that have evolved from infill drifts
	(b) Irregular relief infill	10 ² –10 ³	
	(c) Channel infill	10 ² –10 ³	
Fault-controlled drift		10–10 ³	Examples known from Gulf of Cadiz and Antarctic margin

(continued)

Table 1 (continued)

	Subdivisions	Size (km ²)	Examples
Mixed drifts turbidite-contourite systems	(a) Extended turbidite bodies	10 ³ –10 ⁴	(a) Columbia levee, S Brazil basin; Hikurangi fan-drift, New Zealand margin
	(b) Sculptured turbidite bodies	10 ³ –10 ⁴	(b) Antarctic margins; SE Weddell sea
	(c) Intercalated turbidites-contourites-hemipelagites	Can be very extensive	(c) Hatteras rise; East North American margins; Hebridean margin
<i>Erosional elements</i>			
Depositional hiatuses		10 ³ –10 ⁶	Standard features of very many CDS systems; see especially Gulf of Cadiz CDS
Regional erosional surfaces	(a) Contourite terraces	10 ³ –10 ⁵	Argentine margin; Uruguayan margin; Iberian margin
	(b) Abraded surfaces	10 ³ –10 ⁴	Argentine margin; Uruguayan margin; Iberian margin
	(c) Subcircular scour	10 ² –10 ³	Iberian margin; Antarctic margin
Linear erosional features	(a) Contourite channels	10 ² –10 ³	Linear erosional features are well studied from the Gulf of Cadiz, but also occur in many other areas of contourite deposition and erosion
	(b) Contourite moats	10 ² –10 ³	
	(c) Contourite marginal valleys	10–10 ²	
	(d) Large isolated contourite furrows	10–10 ²	

The table shows approximate size ranges for each type and selected examples only. Further examples and bibliographic references are given in the text and in previous synthesis publications by Faugères et al. (1999), Rebesco and Stow (2001), Stow et al. (2002), Faugères and Stow (2008), and Rebesco et al. (2014)

2.2 Mounded-Elongate Drifts

Mounded-elongate drifts (Fig. 1; Table 1) represent relatively enhanced rates of deposition (typically 20–60 cm/ky) of fine-to-medium-grained contourites, commonly focused into slope-parallel, elongate sediment bodies over moderate to large areas of seafloor (10³–10⁶ km²). The flow may be either simple (as above) or part of multiple current pathways (multicore flow), and tends to be markedly intensified at

drift margins, in some cases causing narrow erosional zones—contourite channels, moats and marginal valleys. Slower flow and large eddies dominate over the drift itself and lead to enhanced deposition and hence to gradual build-up of the drift mound. It remains somewhat unclear on which side of the current core drift build-up is most likely to occur, and whether or not this is primarily a result of Coriolis deflection. There are a number of apparently contrasting examples in the literature (e.g. Faro-Albufeira drift, Stow et al. 2002; Eirik drift, Hunter et al. 2007), so that we consider it more likely that drift deposition is focused in-between different strands of a multicore flow pattern, whereas erosion, non-deposition and coarse-grained contourite facies occur directly beneath the high velocity cores. Over time, and in response to sea-level, climate or other forcing factors, the flow pattern varies both spatially and in intensity, so that individual drifts build up by differential aggradation, progradation, and erosion (Hernández-Molina et al. 2007; Llave et al. 2001, 2006, 2007).

Mounded drifts can be subdivided according to their morphological relationship with the slope on which they occur, yielding *detached drifts* and *separated drifts*. The former are those drifts that extend outwards from the continental margin, whereas the latter are completely separated from the margin by a distinct contourite moat. More examples are provided in compilations by Faugères et al. (1999), Stow et al. (2002), Rebesco and Camerlenghi (2008) and Rebesco et al. (2014).

2.3 Channel-Related Drifts

Channel-related drifts (Fig. 1; Table 1) are those associated with deepwater channels, passageways or gateways through which bottom circulation is constrained, therefore leading to an increase in flow intensity and velocity. Such features range from those that are relatively shallower sills between basins, such as the Gibraltar Gateway (>300 m), to those at oceanic depths, such as the Vema Channel (>4000 m). Where channels are broad, they are typified by multicore flow pathways that may result from topographic interaction and channel margin effects. Smaller channels, by contrast, may show simple flow, although flow meandering and edge effects are also common. The channel region is characterised by erosion, non-deposition and coarse-grained *sheeted contourites*, together with deposition of finer-grained contourites in localised *patch drifts* (either mounded or sheet-form). The channel exit region experiences flow broadening and deceleration, together with re-combination of distinct current strands. Deposition occurs as a sheet-like *contourite-fan*, typically with down-flow decrease in contourite grain size (Faugères et al. 1998, 2002; Masse et al. 1998).

There is not sufficient data on channel-related drifts to provide an average accumulation rate. It is also likely that deposition and erosion will both be evident and show temporal and lateral variation across the channel system. Typical sizes range from 10 to 10³ km² for channel patch drifts to 10³–10⁶ km² for contourite fans.

2.4 Patch Drifts

Patch drifts (Fig. 1; Table 1) include a wide range of smaller-scale contourite depositional bodies that may be mounded or sheet-like in geometry and with either an elongate or more irregular shape. They occur in different settings including: (a) within channels or gateways (as in 2.3 above); (b) slope systems associated with the generation and downwelling of bottom water masses; and (c) anywhere that contourite drifts occur, where they represent the earlier (younger) precursor of a larger-scale mounded-elongate, sheeted or other drift type.

The size ($10\text{--}10^3\text{ km}^2$), rates of accumulation and occurrence are very variable.

2.5 Confined Drifts

Confined drifts (Fig. 1; Table 1) are lesser known systems which, to some extent, appear similar to the broad channel systems (above). They are probably affected by multicore flow pathways and typified by zones of both erosion and deposition. A clear example has been described from the Sumba Gateway in the Indonesian archipelago (Reed et al. 1987). Data from the Sicilian gateway in the central Mediterranean have suggested an interesting aspect of flow behaviour and contourite deposition (Reeder et al. 2002). There are a number of confined basins through which the Levantine Sea bottom water flows and in one of these the nature of sediments and high rate of sedimentation suggest that a process of bottom current flow lofting has occurred. The result is one of a mixed contourite-hemipelagite sheet-like deposit.

2.6 Infill Drifts

Infill drifts (Fig. 1; Table 1) occur directly in response to the excavation of topographic lows or scours, which can be the result of downslope mass transport processes, such as slides and slumps. Along such slump-scarred continental margins that are swept by bottom currents, the portion of slope that has been excavated may become progressively back-filled by contourite drift deposits. These are referred to as infill drifts and their size relates to the size of the scour feature being filled and the length of time over which deposition has occurred.

Downslope turbidity current channels crossing bottom-current pathways may also receive infill drift deposition, although such contourite material will be subject to erosion by the normal downslope processes. Complete drift infill of a channel of unknown origin is observed within the Faro-Albufeira drift in the Gulf of Cadiz (Stow et al. 2002).

2.7 *Fault-Controlled Drifts*

Fault-controlled drifts (Fig. 1; Table 1) are characterised by the direct influence of faulting on their location and nature of growth. The fault activity creates a change in seafloor relief, either instantaneously or as a result of continuing fault movement, and this then causes a perturbation in the bottom-current flow pathway. Drift development may occur either at the base or top of the fault-controlled relief.

2.8 *Mixed Drift Systems*

The interaction of deepwater depositional processes (downslope, alongslope and pelagic) is the norm along many continental margins, leading to a range of modified or mixed drifts systems (Fig. 1; Table 1). The interaction of pelagic/hemipelagic processes with bottom currents does not result in any morphological effect on the drift morphology, so that the term *mixed drift* generally refers to the interaction of downslope and alongslope flow processes. This may be of several types and different terms have been introduced to describe them. Examples from four different margins are described below:

- (a) Eastern North American Margin: Process interaction is evident from the regular interbedding of thin muddy contourite sheets deposited during interglacial periods and fine-grained turbidites dominant during glacial; and from the marked asymmetry of channel levees on the Laurentian Fan, with the larger levees and extended tail in the direction of the dominant bottom current flow. Along the Cape Hatteras Margin, the complex imbrication of downslope and alongslope deposits on the lower continental rise has been referred to as a *companion drift-fan*.
- (b) The New Zealand Margin: Along the Chatham-Kermadec margin offshore New Zealand, the deep western boundary current scours and erodes the Bounty Fan south of the Chatham Rise and directly incorporates fine-grained material from turbidity currents that have travelled down the Hikurangi Channel. This material, together with hemipelagic sediment, is swept north from the downstream end of the turbidity current channel to form a *fan-drift* deposit. Other mixed drift systems from the region are outlined by Carter and McCave (1994, 2002).
- (c) Antarctic Margins: Eight large sediment mounds off the West Antarctic Peninsula Margin (Rebesco et al. 2002; Camerlenghi et al. 1997) are elongated perpendicular to the margin and separated by turbidity current channels, with an asymmetry that indicates construction by entrainment of the suspended load of down-channel turbidity currents within the ambient southwesterly directed bottom currents and their deposition downcurrent. A complex mix of turbidite and bottom-current controlled sedimentation is evident on the Wilkes Land slope (Escutia et al. 2002).

- (d) Hebridean Margin: This shows a complex pattern of intercalation of downslope (slides, debrites and turbidites), alongslope contourites and glaciomarine hemipelagites in both time and space; the alongslope distribution of these mixed facies types by the northward-directed slope current has led to the term *composite slope-front fan* for the Barra Fan (Knutz et al. 2002).

3 Contourite Erosional Elements

The semi-continuous action of bottom current processes over an extended period of time (e.g. thousands to millions of years) does not only lead to the formation of depositional features (i.e. contourite drifts) but also to the development of non-depositional zones and erosional features on the sea floor. The principal erosional elements identified (Hernández-Molina et al. 2008; Rebesco and Camerlenghi 2008; García et al. 2009; Rebesco et al. 2014) include (Fig. 2; Table 1): (a) depositional hiatuses; (b) regional erosion: erosional terraces, abrasive surfaces, channel scour and sub-circular scour; and (c) linear erosion: contourite channels, contourite moats, marginal valleys and furrows. In general, these areas display erosive winnowing of the seafloor leading to depositional hiatuses and to the accumulation of coarser-grained (sand and gravel) contourites. These features have been relatively less studied than the associated drifts, but we do now have a clear understanding of the importance of erosional elements alongside their depositional counterparts.

3.1 Depositional Hiatuses

A characteristic feature of the seafloor beneath active bottom current systems is that large areas are subject to prolonged periods of non-deposition and/or erosion. Such hiatuses (Fig. 2; Table 1) may extend along a linear channel or moat, across a broad depositional drift or even an entire contourite depositional system. The seafloor beneath the hiatus may be characterised by a hardened substrate (e.g. over-consolidated mud), a coarse-grained lag deposit (e.g. sand or gravel), or a rocky substrate. The overall morphology is either smooth or with an irregular pitted/erosive aspect.

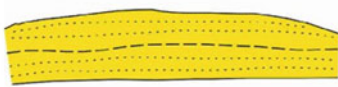
Examples of depositional hiatuses are common to most contourite drifts (Faugères et al. 1999), and have been well described from the Vema Contourite fan in the South Atlantic (Mezerais et al. 1993) and from the Cadiz CDS (Stow et al. 2013a, b; Hernández-Molina et al. 2014a, b). In the case of the Cadiz CDS, IODP drilling results revealed the widespread nature of such hiatuses (10^4 – 10^5 km²) and their variable duration from <10 ky to >1 my.

3.2 Regional Erosive Surface

Relatively large areas of the seafloor (10^2-10^4 km^2) under the influence of bottom currents may undergo substantial erosion. This results in *regional erosive surfaces*, which are also known as *areal erosional features* (Rebesco et al. 2014). Three types have been identified as follows (Fig. 2; Table 1).

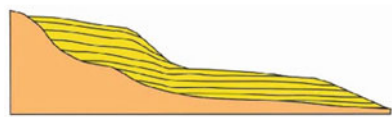
Contourite Erosional Elements

Depositional Hiatus

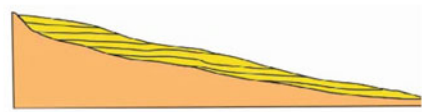


Planar Erosional Surfaces

Contourite Terrace

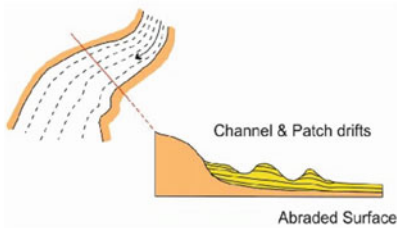


Abraded Surface

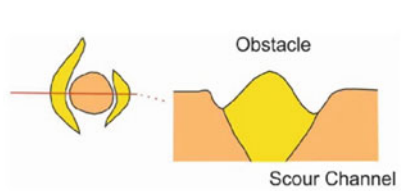


Linear Erosional Features

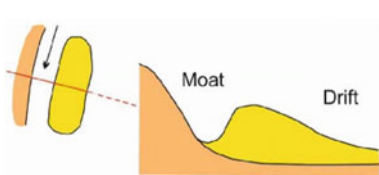
Contourite Channels



Crescentic Scour



Contourite Moat



Marginal Valley

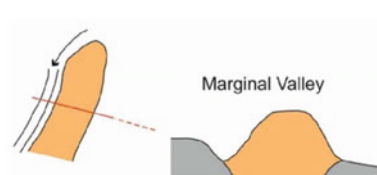


Fig. 2 Summary of the principal contourite erosional elements showing sketches of each type. Examples are provided for each type in the text and in Table 1. Modified from Hernández-Molina et al. (2008), García et al. (2009) and Rebesco et al. (2014)

Contourite terraces have been recognised on several continental slopes. These are extensive scoured surfaces that are cut into the slope topography forming a horizontal to gently seaward-sloping terrace, or series of terraces that are elongated parallel to the margin. They have been described from the Gulf of Cadiz contourite depositional system and from the Argentine margin (Hernández-Molina et al. 2009, 2014a, b). The former is covered with a mixture of coarse-grained lag contourites, intervening mounded contourites (more mud-rich), and a variety of bedforms and larger erosional elements, such as channels. The Argentine terraces are relatively finer-grained in sediment cover and smoother in morphology. Both types represent prolonged erosion and non-deposition associated with bottom currents that impinge on the slope seafloor. They are believed to occur in particular at the interface between different water masses.

Abraded surfaces are very similar to the terraces (above) in terms of morphology and sediment cover, except that they do not form as a slope terrace. They may occur anywhere on the seafloor, and have been documented extensively from the Gulf of Cadiz region (Ercilla et al. 2015). Those that occur within larger-scale channels or oceanic gateways are known as *channel scour surfaces*.

Large-scale *subcircular scour* features have been found in an upper or middle-slope position where strong, dynamic, stratified water masses appear to have formed powerful eddies in the water column that create localised erosion at the seafloor (Hernández-Molina et al. 2008; Rebesco et al. 2014). Little more is known about the nature and genesis of these features.

3.3 *Linear Erosional Features*

Large-scale linear erosional features (Fig. 2; Table 1) are well known from beneath existing and strong bottom current systems. They typically occur in association with seafloor topographic highs, including mounded drifts, ridges, banks, seamount chains, diapirs, mud volcanoes and plateaus (Maldonado et al. 2005; Hernández-Molina et al. 2008; García et al. 2009; Rebesco et al. 2014). According to these authors, they include a variety of types: channels, moats, marginal valleys, and large isolated furrows. However, the distinction between these types is rather subtle in some cases and overlapping in others. The features range in size from 100 m wide and 1–10 km long (large isolated furrows) to 3–10 km wide and >100 km long (channels and moats).

Contourite Channels are elongate erosional depressions that are generated by the erosive action of bottom currents. They can be sinuous, slightly sinuous or straight depending on their position on the slope, the surrounding morphology, type of seafloor obstacle encountered, and the strength of the current acting during their formation or evolution. They are typically orientated alongslope, oblique to slope or around a topographic obstacle, and generally follow the direction of the dominant bottom current flow pathway. The Cadiz Contourite Channel in the middle slope of the Gulf of Cadiz is an example of a well-studied contourite channel that originates

from the distal end of the Cadiz Terrace and is then deflected when it encounters a diapiric ridge as an obstacle to flow. Several other channels in the Gulf of Cadiz are detailed by García et al. (2009).

A *Contourite Marginal Valley* is a particular type of channel that is formed by the interaction of a bottom current with existing seafloor relief such as a seamount, diapiric ridge, diapiric dome, or mud volcano. Erosion occurs around the flank of the structure as the bottom current is accelerated by being constrained by the relief.

A *Contourite Moat* is an erosional channel that occurs specifically along the flank of a mounded-elongate drift, usually taken as the moat that separates a mounded elongate separated drift from the adjacent slope, as a result of non-deposition or localised erosion below the bottom current core.

A *Large Isolated Contourite Furrow* is a relatively small contourite channel, which may be caused by the erosive action of a small flow that has separated from the main bottom current, probably as a result of some topographic feature obstructing and splitting the flow. It could also represent the incipient formation of a larger channel. Since they are commonly small, narrow and with a relatively smaller incision than contourite channels, Rebesco et al. (2014) prefer to classify them as a large bedform.

4 Seismic Characteristics

In many cases, the first means of identification of contourite drifts will be on seismic profiles. However, with growing recognition of the widespread occurrence of drifts in the deep sea, their variety of types, scales and depositional settings, as

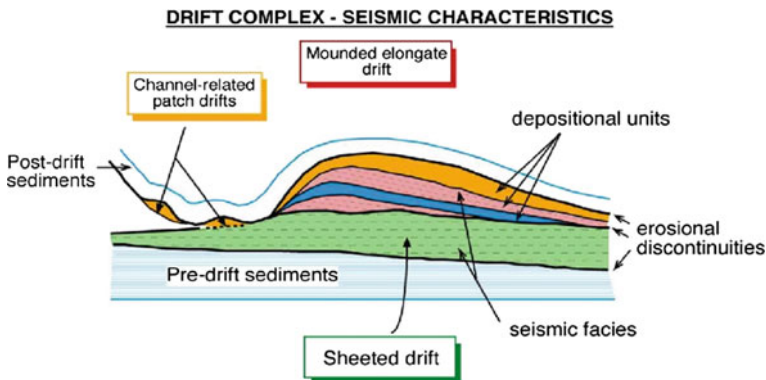


Fig. 3 Conceptual model of the seismic characteristics of contourite drift and adjacent erosional elements. Modified from Stow et al. (2002) and Nielsen et al. (2008). For seismic recognition of contourite systems a threefold approach is required: **a** identify drift type, geometry, elongation and discontinuity surfaces; **b** identify depositional seismic units with a down-current to oblique progradation; and **c** identify typical seismic facies and cyclicity

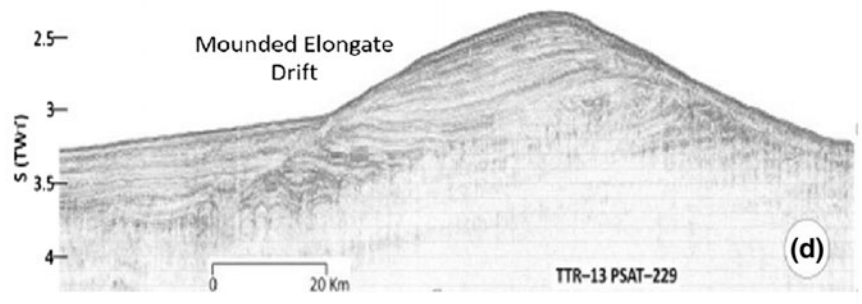
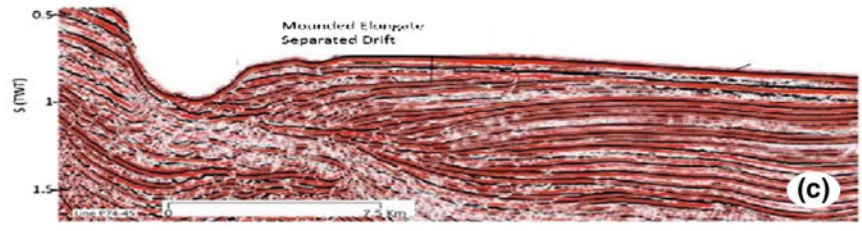
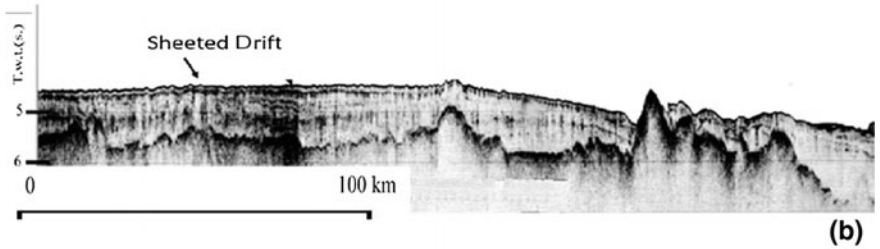
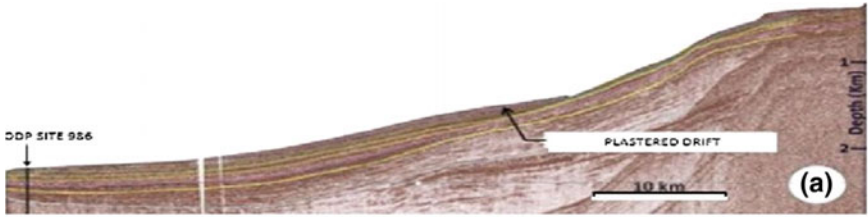
Fig. 4 Examples of seismic profiles across contourite drift depositional systems. **a** Sheeted drift: Isfjorden plastered (slope) drift from West Spitzbergen margin (Reprinted from Deep Sea Research Part I, 79, Rebesco et al., Quaternary contourite drifts of the Western Spitsbergen margin, 2013, with permission from Elsevier). **b** Sheeted drift: Gloria (abyssal) drift from the NW Atlantic Ocean (after Egloff and Johnson 1975). **c** Mounded elongate drift: Faro-Albufeira (separated) drift, Northern Gulf of Cadiz (Reprinted from Marine Geology, 352, Rebesco et al., Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations, 2014, with permission from Elsevier). **d** Mounded elongate drift: Eirik (detached) drift, southern Greenland margin (from Hunter et al. 2007). **e** Confined drift: Louisville (confined) drift, eastern New Zealand margin (after Carter and McCave 1994). **f** Channel-related drift: Vema contourite fan, South Brazilian basin, South Atlantic Ocean (after Faugères et al. 1998). **g** Drift complex: Sheeted drift within NE Rockall Trough passes laterally into a mounded-elongate drift, and patch drifts within the adjacent moat (after Faugères et al. 1999). **h** Infill drift: Faeroe plastered infill (slope) drift, southern margin Norwegian Sea.

well as their similarity to features typical of other deep-sea facies (such as turbidite lobes, levees and fans), it has become necessary to erect a set of seismic criteria that will help distinguish drifts from other similar bodies. This becomes much more difficult, of course, where close interbedding of different facies has occurred as in the mixed drift systems noted above. The current set of seismic criteria for enabling positive identification has been modified from the three-scale approach presented by Faugères et al. (1999), and further developed by Rebesco and Stow (2001), Stow et al. (2002) and Nielsen et al. (2008). The key attributes are shown schematically in Fig. 3 and a range of examples of different drift types in Fig. 4.

4.1 *First-Order Seismic Element (i.e. Drift Scale)*

This involves identification of the large-scale elements of the drift such as the overall architecture, the external geometry, the internal reflector character, and the upper and lower bounding surfaces. This first order seismic element of drifts reflects long-lasting (temporally) stable conditions in the bottom-current regime and/or oceanographic setting. The bounding surfaces represent a record of major changes in the depositional environment. The large-scale features observed include:

- (a) *Drift geometry.* The variety of drift geometries now known to exist have been described in the previous section. Those with a more distinctly mounded rather than low-relief sheet-like geometry are most easily identified. This is especially true where the sediment body occurs beneath an existing bottom current system and is clearly isolated from other possible sediment sources (such as downslope supply routes).
- (b) *Drift elongation.* An overall down-current elongation is typical of most drifts. The elongation direction is therefore wholly alongslope or at some small angle of deviation (generally $<30^\circ$) from the slope contours. In order to observe the planform geometry of drifts, it is necessary to obtain either a closely-spaced 2D seismic survey or 3D seismic survey.



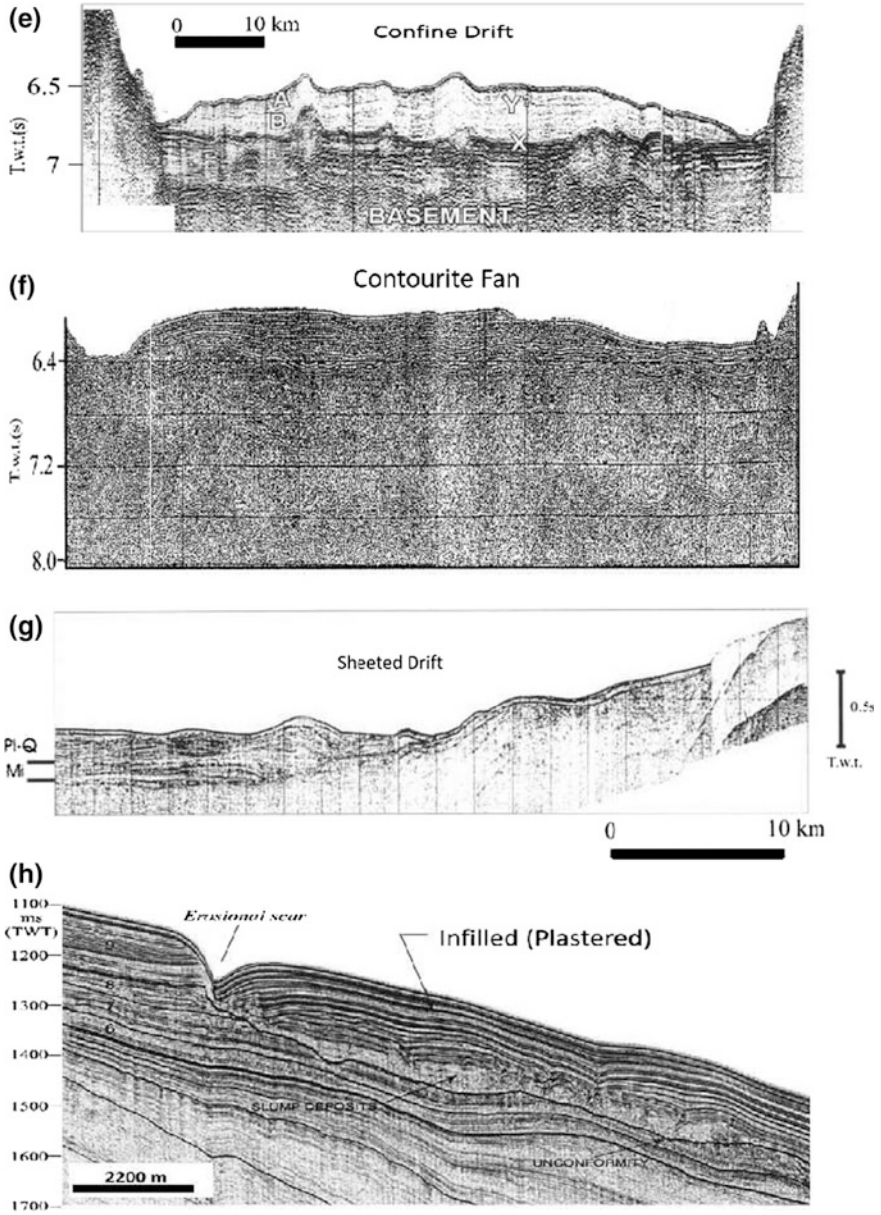


Fig. 4 (continued)

- (c) *Erosional discontinuities*. These are typically widespread discontinuities both at the base and within the drift, extending across the accumulation as a whole. These are commonly marked by continuous high-amplitude reflectors, which may also underline a change in seismic facies. Some of these unconformities will be on a sub-regional scale, beyond the confines of the drift, while others (such as the basal horizon) may even link into ocean-wide discontinuities. These reflect periodic changes in bottom-current conditions.
- (d) *Uniform reflector pattern*. Drifts are commonly represented by extensive, sub-parallel, moderate to low-amplitude reflectors, with mainly gradational changes typical between seismic facies, in addition to the erosional discontinuities noted above. These reflect the long-lasting stable conditions, both laterally and temporally, that are the norm for drift accumulation.

4.2 *Second-Order Seismic Element* (i.e. *Depositional Seismic Units*)

This involves the analysis of the internal architecture of the first-order drift and identification of medium-scale seismic units, their shape and stacking pattern, and reflector terminations. Internal architecture within a drift is generally complex, as a result of local variation in processes and accumulation rates linked to changes in current activity. In many cases, the history of drift construction is marked by an alternation of periods of sedimentation and periods of erosion or non-deposition. Medium and small-scale features reflect these changes.

- (a) *Seismic units*. Most of the larger drifts will comprise a series of broadly lenticular, upwardly-convex, seismic units.
- (b) *Stacking pattern*. Progradational, aggradational and uniform stacking patterns occur in different drift systems. These may change through the history of drift development.
- (c) *Migration direction*. The individual seismic units may show migration in down-current to oblique direction, coincident with the elongation direction of the drift as a whole. Any lateral migration direction is likely to be influenced by the Coriolis Force (to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere), providing the right morphological context, current direction and latitude.
- (d) *Reflector terminations*. Down-lapping and sigmoid progradational reflector patterns are typical, whereas a top-lapping pattern is less common.

4.3 Third-Order Seismic Element (i.e. Seismic Facies)

At the fine-scale of seismic resolution, the nature of individual seismic facies reflects changes in both depositional processes and in sediment types. They are not unique to contourite drifts and also depend very closely on the methods employed for seismic acquisition and processing. However, once a drift origin has been established, using a combination of seismic and other characteristics, much interesting detail can be gleaned from this small-scale approach.

- (a) *Seismic facies*. A wide variety of seismic facies are typical of contourites, most of which are equally present in turbidite and/or hemipelagic systems. These include: (i) semi-transparent, reflector-free intervals, (ii) continuous, sub-parallel, moderate to low-amplitude reflectors, (iii) regular, migrating-wave, moderate to low-amplitude reflectors, (iv) irregular, wavy to discontinuous, moderate-amplitude reflectors, and (v) an irregular, continuous, single high-amplitude reflector. Stow et al. (2002) suggest that this order of seismic facies (i–v) reflects increasing strength in the bottom-current regime. Particular seismic facies associations may be more diagnostic of contourite systems, although this area also needs more work.
- (b) *Seismic facies cyclicity*. There is now much evidence of a cyclic pattern in some drifts between a more transparent facies (T) and a moderate-amplitude continuous reflector seismic facies (R) (Fig. 5). Preliminary interpretation suggests seismic facies R reflects a greater proportion of silt/sand content contourites, more hiatuses and condensed sedimentation sections, due to increased bottom current intensity. Seismic facies T, by contrast, is due to low silt/sand content within a more continuous and homogeneous muddy contourite section, reflecting decreased bottom current intensity. The driver for this cyclic model is most likely bottom-current variation linked to climate change.

5 Bottom Current Bedforms

At a small scale, the seafloor is smoothed and/or sculpted into a wide variety of bedforms at dimensions that range over several orders of magnitude (Heezen and Hollister 1971; Kenyon and Belderson 1973; Wynn and Masson 2008; Masson et al. 2004; Stow et al. 2009, 2013a, b). These provide important insights into both flow characteristics and depositional-erosional mechanisms of bottom currents. Surface lineation and ripples are ubiquitous at the centimetre scale, sand waves and dunes are common metric scale features, mud furrows and sand ribbons occur with a spacing of tens of metres and length up to several kilometres.

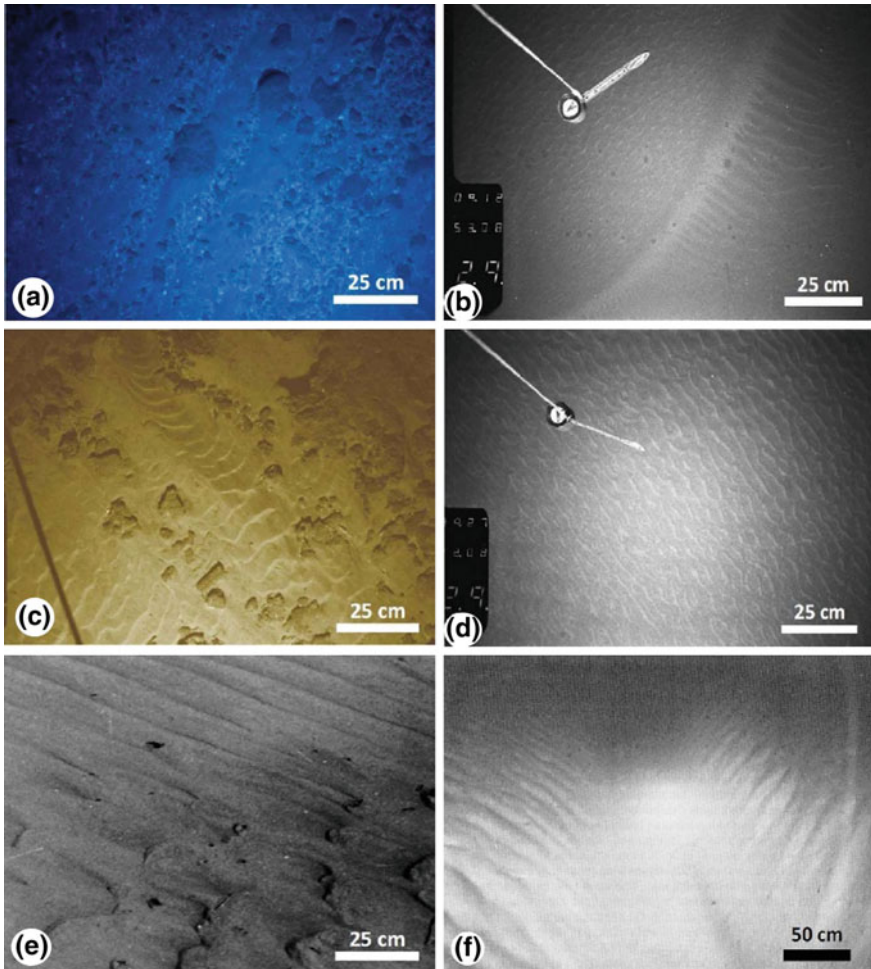


Fig. 6 Examples of bottom photographs showing selected bedforms on the present-day seafloor. **a–f** From Gulf of Cadiz. **a** Lamination in coarse-grained sand-gravel sediment. **b** Sand wave or dune covered in smaller-scale ripples, with curved crest and avalanche stringers down the lee face. **c** Transverse sand ripples between gravel patches and stringers. **d** Small sand ripples, most transverse to flow but with some interference. **e** Lamination in sands (longitudinal ripples), with more linguoid ripples in foreground. **f** Part of longitudinal furrow, deeply erosive into muddy seafloor

5.1 Longitudinal Bedforms

This is a range of bedforms that are all generally elongated parallel to flow direction and that can be developed on mud, sand and gravel substrates. They include four main types:

- Surface lineations of very low relief (mm) and spacing (mm to cm) occur on muddy and silty substrates at low flow speed (<0.15 m/s). They also occur at slightly greater relief (cm) and spacing on sand and gravel substrates at correspondingly higher flow speeds (0.1–0.5 m/s).
- Ribbon marks are large mounded and elongate sand ridges up to metres in height that can run for several kilometres over a sand sheet, in some cases with a more or less anastomosing pattern. Gravel ribbons or stringers are similar features formed on a sand-gravel substrate. Both features require high flow speeds (0.5–1.5 m/s).
- Crag and tail features refer to the elongate depositional mound that forms behind a seafloor obstacle. Comet scours are crescentic to elongate erosional scours that form around the margins of and extend downstream from an obstacle. Both structures occur at all different scales, from centimetres to hundreds of metres, and at flow speeds of 0.1–0.5 m/s.
- Furrows are commonly occurring, regularly-spaced, elongate, sub-parallel and mainly erosive bedforms that occur at a wide range of scales in different substrate types. Those that have been excavated under powerful bottom currents over muddy substrates can reach several metres in depth, tens of metres in width and extend for many kilometres down-current. Equivalent furrows are known from sandy and gravel substrates. All three types probably have an element of deposition on the ridge segments between furrows, and form at flow speeds from 0.5 m/s (mud furrows) to 2 m/s (gravel furrows).

5.2 *Transverse Bedforms*

These bedforms are oriented transverse to the flow direction and form on substrates of fine sand/coarse silt up to gravel-size. They include three main types:

- Ripples are the smallest of the transverse bedforms (wavelength decimetres, height centimetres), and occur in straight, sinuous, and linguoid planform. Flow speed ranges from 0.15 (small straight-crested) to 0.5 m/s (linguoid).
- Dunes and sand waves show similar variations to ripples but with longer wavelengths and heights and are formed under correspondingly higher flow speeds—up to 1.0 m/s for the larger barchan dunes. Gravel waves are relatively less common but do occur under still higher flow speeds up to around 1.3–1.4 m/s.
- Giant mud waves occur in very fine-grained sediments at low flow speeds (0.1–0.2 m/s), with wavelengths of 1–3 km and wave heights up to around 50 m. Whereas the other transverse bedforms are formed under tractional grain movement and show down-flow migration, the giant mud waves mostly show up-stream migration and accumulate from the settling of suspension loads.

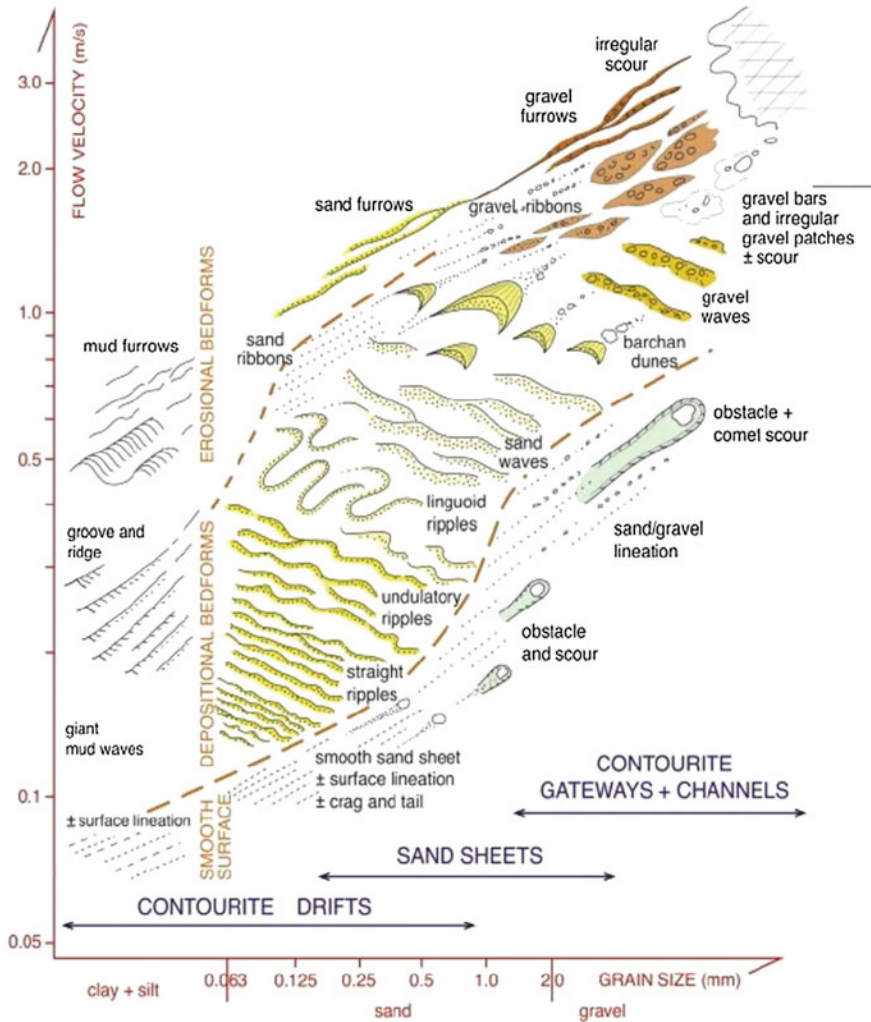


Fig. 7 Bedform-velocity matrix. Modified from Stow et al. (2009) and Rebesco et al. (2014). The plot shows the range of depositional and erosive bedforms commonly associated with bottom currents in deepwater, with an indication of where different bedforms occur (drifts, sand sheets, gateways and channels). The bedforms are controlled in part by flow velocity (y-axis) and in part by grain size of the sediment (x-axis). Both axes are plotted as log scales

Stow et al. (2009) have synthesised a large amount of this data into a bedform-velocity matrix (Fig. 7), from which we can derive information on flow direction, velocity, variability and continuity. The nature and distribution of bedforms also allows comment on various aspects of contourite deposition.

- (1) The widespread fine-grained contourites of many drifts, with smoothed sediment surfaces and/or surface lineation, represent deposition of silt and clay directly from suspension through a laminar boundary layer, which in places is subject to well-ordered small-scale helical flow vortices creating the linear sediment fabric.
- (2) The common presence of ripple bedforms at all scales on silt-sand substrates indicates that tractional movement of bedload at the base of flow is the normal mode of transport and deposition of fine-to-medium grained granular material in bottom currents.
- (3) In zones subjected to higher velocity currents, tractional movement of coarser materials is evidenced by sand waves, barchan dunes and, more rarely, gravel waves and bars. That these bedforms are often covered by smaller-scale ripples is evidence of bottom current variability, probably over timescales of hours (tidal influence) to weeks (benthic storm effects). Periods of intense bedload transport therefore alternate with periods of lesser transport and deposition.
- (4) Some linear bedforms, known as furrows, are formed at relatively higher flow velocities in both mud and sand-gravel substrates. These represent mainly erosive conditions at the base of flow leading to sediment entrainment and transport. Groove and ridge structures (also known as longitudinal triangular ripples) appear to be a smaller scale equivalent of mud furrows, formed at moderate flow velocities over fine substrates and involving both deposition and erosion.
- (5) The lateral juxtaposition of bedform types occurs over a horizontal scale of metres, indicating the variability in velocity of strands of flow (or regions of flow) at this order of magnitude. There is also the larger-scale of variation over hundreds of metres from more dominantly erosive to mainly depositional. This can occur in an across-flow sense, from erosive marginal moat to central depositional drift, and in a down-flow sense, away from a gateway or channel exit.
- (6) The development of large-area fields of giant sediment waves and their persistence in time through the sedimentary record (thousands to a few million years), reflects the broad tabular flow and long-term stability of low-velocity bottom currents in their region of formation. Deposition of the fine clays and silts that make up these bedforms is almost certainly directly from suspension, under the influence of internal lee waves in a weakly stratified bottom current (Flood 1988).

6 Future Research

Amongst many important research topics that remain outstanding with respect to contourite studies, we suggest the following as the most significant:

- (a) *Processes*. (i) Understanding the processes of bottom current flow, how these vary laterally and longitudinally within the current system, and what controls the variability of the flow in both time and space. (ii) Recognition of boundaries between water masses flowing at different velocities and of the effects of these boundaries on sedimentation, seafloor morphology and geotechnical properties of contourites. (iii) Understanding the influence and impact of different processes (e.g. turbidity currents, internal tides and waves) on bottom currents and contourites. (iv) Improvement in knowledge of the link between physical oceanography and contourite deposition/erosion.
- (b) *Deposition and budget*. (i) Understanding the exact mechanisms of how the carrying capacity and deposition is distributed across a current system. (ii) Analysing the sediment budget for different drift systems—how much and what types of sediment are derived from different sources. (iii) Careful consideration of the control of coarser layers on contourites from turbidity current input, increased bottom current velocity and increased primary productivity.
- (c) *Climate change*. (i) Decoding the links between bottom current flow variation, contourite deposits and climate change. Consideration of how different bottom water masses and hence different bottom current systems are affected by climate.
- (d) *Fossil contourites*. (i) Clear characterisation of the criteria for recognition of contourites in the ancient record (subsurface and on land) and their distinction from related deposits in deep water—e.g. turbidites, hemipelagites and the deposits from other bottom current systems. (ii) Establishment of good type examples in the field and in subsurface cores for the different facies types. (iii) Recognition of hybrid facies that have been influenced by one or several processes during sedimentation.
- (e) *Economic significance*. (i) Recognition of the role of contourites as a deepwater play for hydrocarbon reservoirs in deepwater, and the discovery and characterisation of oil/gas in contourite reservoirs. (ii) Documenting and understanding the variation of organic carbon content of contourites. (iii) Recognising the role and impact of both bottom currents and contourite sediments in the field of ocean geohazards. (iv) Detailed study of the role of bottom currents in the development of ferro-manganese nodules.
- (f) *Biological significance*. (i) Detailed study of the ichnofacies characterisation of contourites in terms of the nature, diversity and distribution of trace fossils, and the specific controls of water mass, organic matter supply, and rates of sedimentation. (ii) Clear understanding of the role of bottom currents in deepwater benthic ecosystems, including those of black smoker vents and cold-water corals.

The multidisciplinary research discussed by Howe (2008) and amplified by Rebesco et al. (2014) points towards the most appropriate methodologies that should be employed to address the above questions.

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