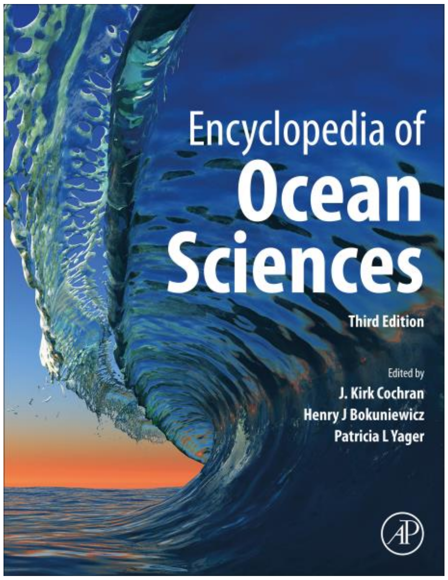

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Deep-Sea Contourites Drifts, Erosional Features and Bedforms

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Introduction

Contourite drifts are identified as the large-scale morphological expression of contourite deposition. They comprise thick to very thick (10 to >1000 m) accumulations of mainly contourite sediments. At the present day, they are found covering large areas of the deep seafloor beneath modern bottom current systems and range in scale from 10^2 to $>10^6$ km^2 (Faugères and Stow, 2008). In the ancient record on land, they are more difficult to recognize, due to their large size and subtle geometry. *Contourites* are sediments that have been deposited, or significantly affected, by the persistent action of bottom currents.

At the still larger scale, Contourite Depositional Systems comprise several related drifts and associated erosional elements. They commonly develop along continental margins that have been under the influence of bottom currents for relatively long periods of time (>2–3 My). Interbedded (mixed) sequences of contourites and other deep-water facies are not uncommon where the influence of the downslope and alongslope processes are equally effective.

Not only do bottom currents transport and deposit sediment but they may also erode the seafloor. Contourite erosional elements are nondepositional zones and erosional features on the seafloor that have been caused by the action of bottom currents. They are often closely associated with and adjacent to contourite drift deposits. They occur where the bottom current velocity is sufficiently strong to prevent deposition or cause substrate erosion.

Contourite bedforms are the small-scale seafloor sedimentary features, such as waves, dunes, ripples, and scours. They result from the erosional, transport, and depositional action of bottom currents at the seafloor. These are very common features that are found covering drifts and erosive surfaces beneath active bottom current systems at the present day. However, many of the internal sedimentary structures due to these bedforms are only rarely preserved in the contourite sediment record, largely because they are destroyed by the action of burrowing organisms.

It was the many observations of such bedforms on the seafloor during pioneering oceanographic surveys of the 1950s and 1960s that, in part, led marine scientists to first propose the significant effects of bottom currents in shaping sedimentation on the deep

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continental rise off eastern North America. The term "contourite drift" was first used in the 1970s by (Hollister and Heezen, 1972), since which time there has been an explosion of research into the nature and effects of bottom currents and their deposits (Stow et al., 2002; Rebesco and Camerlenghi, 2008). Significant major discoveries in the contourite research field were facilitated through the international deep-sea drilling program in its various guises (DSDP, IPOD, ODP, IODP), which specifically targeted drift systems in many parts of the world, and hence provided direct access to the contourite sediments of which they are composed (Hernandez-Molina et al., 2014).

This contribution in the *Encyclopedia of Ocean Sciences* is one of three on deep-sea bottom currents and their deposits. The focus here is on contourite drifts and erosional features, and on the numerous bedforms that are found covering the seafloor over these larger-scale features. It is necessarily based largely on modern and subrecent data recovered from present-day oceans, and draws heavily on a recent synthesis by (Esentia et al., 2018). It also includes reference to current work on ancient contourites exposed on land, and to the broader relevance of contourites to paleoclimate studies, ocean hazards and hydrocarbon prospectivity. The other two contributions outline the contourite sediments themselves, and the nature of bottom currents.

Contourite Drifts

Classification and Terminology

The classification and terminology of contourite drifts has been investigated by many researchers and mostly focuses on deep-water drifts (i.e. >300 m water depth) (Faugères et al., 1993, 1999; Stow et al., 2002; Stow and Faugères, 2008). Based on their geometry, drifts are classified into four principal types (Fig. 1): sheeted drifts, mounded-elongate drifts, patch drifts, and channel-related drifts. Several other drift types are recognized, which are all variations of the principal types, but determined in relation to their specific topographic or sediment supply controls (Esentia et al., 2018). These include (Fig. 1): confined drifts, infill drifts, fault-controlled drifts, and mixed drift systems.

We have further separated out for description those drifts formed in relatively shallow water (<300 m) and those that are wholly carbonate in composition. Selected examples of all these drifts are given in Table 1.

The development of the contourite system, hence their geometry, is controlled largely by a combination of factors, namely: the nature and style of bottom current flow (e.g. tabular vs. multicore flow); the slope gradient and other topographic features; and the sediment supply. Overlap and interdigitation between the various types of drift is quite common, so that the specific types identified should be considered as end-members on a continuous spectrum of deposits.

Sheeted Drifts

Sheeted drifts, ranging from 10^3 to $>10^6$ km^3 in area, represent relatively uniform rates of deposition over a large area of seafloor. They show only very slight seafloor relief, but can build up thicknesses in excess of 1 km. The deposition of mainly fine-grained contourites under low-velocity currents results in mud-rich sheeted drifts, characterized by a low mean accumulation rate (<20 cm kyr^{-1}). By contrast, sand-rich sheeted drifts develop as a depositional-erosional body linked with zones of higher velocity flow. Based on their occurrence, sheeted drifts can be differentiated into: abyssal sheeted drifts, slope sheeted (plastered) drifts, slope-terrace sheeted drifts, and channel sheeted drifts.

Mounded-Elongate Drifts

Mounded-elongate drifts represent relatively enhanced rates of deposition (typically 20–60 cm kyr^{-1}), commonly focused into slope-parallel, elongate sediment bodies over moderate to large areas of seafloor (10^3–10^6 km^2). Where they have continued to grow in the same location for several millions of years, they can build up thicknesses in excess of 1 km. They typically develop adjacent to one or more focused cores of high velocity bottom current, and so become flanked by a contourite moat created by bottom current erosion and nondeposition.

Mounded drifts can be subdivided according to their morphological relationship with the slope on which they occur, yielding detached drifts, which extend outwards from the continental margin, and separated drifts, which are completely separated from the margin by a distinct contourite moat.

Channel-Related Drifts

Channel-related drifts are those associated with deep-water channels, passageways or gateways through which bottom circulation is constrained, therefore leading to an increase in flow intensity and velocity. Such features range from relatively shallower sills between basins, such as the Gibraltar Gateway (>300 m water depth), to those at oceanic depths, such as the Vema Channel (>4000 m water depth).

The main channel region is characterized by erosion, nondeposition and coarse-grained *sheeted* contourites, together with deposition of finer-grained contourites in localized *patch* drifts (either mounded or sheet-form) while the channel exit shows a sheet-like contourite-fan, due to flow broadening and deceleration.

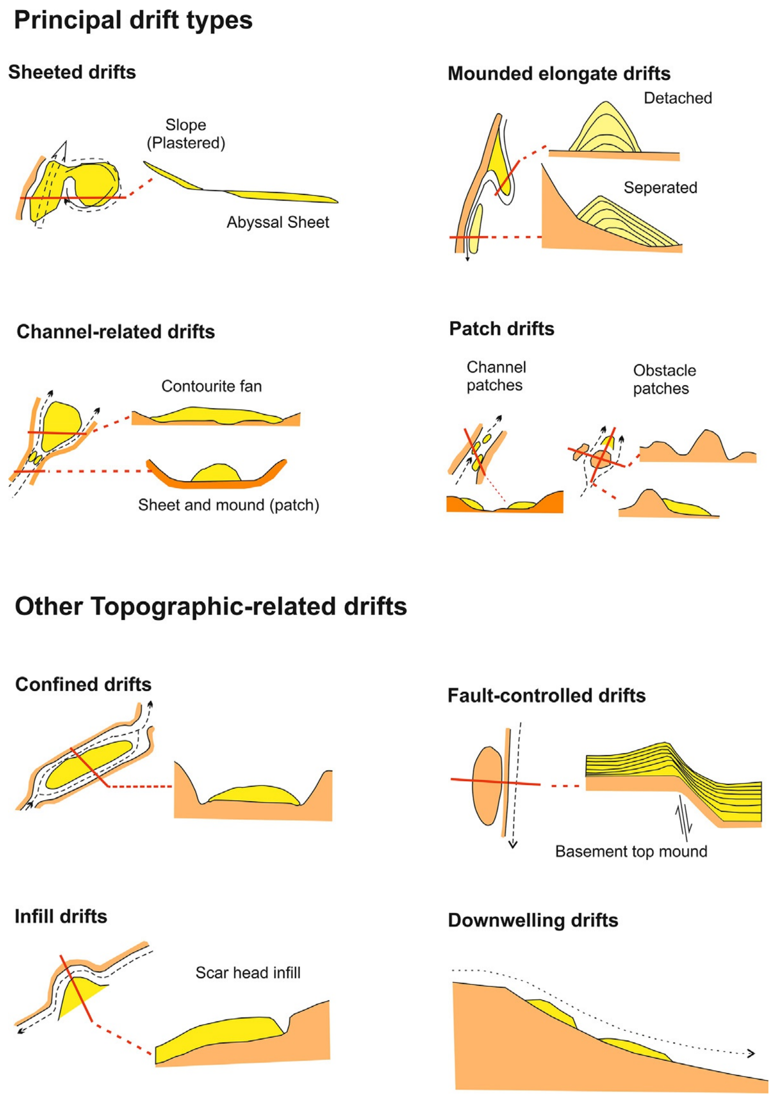

Fig. 1 Summary of principal contourite drift types showing sketches of both plane view and cross-section. Examples are provided for each type in the text and in Table 1. Modified by Esentia, I., Stow, D. and Smillie, Z. (2018). Contourite drifts and associated bedforms. In Micallef, A. & Krastel, S. S. A. (eds.) *Submarine geomorphology*, pp. 301–331. Cham, Switzerland: Springer. doi: 10.1007/978-3-319-57852-1_16 based on the work of Rebesco, M. and Stow, D. (2001). Seismic expression of contourites and related deposits: A preface. *Marine Geophysical Researches* **22**(5/6), 303–308. doi:10.1023/a:1016316913639; Stow, D. A. V., Faugères, J.-C., Howe, J. A., Pudsey, C. J., and Viana. A. R. (2002). Bottom currents, contourites and deep-sea sediment drifts: Current state-of-the-art. *Geological Society* **22**(1), 7–20. doi:10.1144/GSL.MEM.2002.022.01.02, Faugères, J.-C., and Stow, D. A. V. (2008). Contourite drifts: Nature, evolution and controls. In Rebesco, M. & Camerlenghi, A. (eds.) *Contourites*, pp. 257–288. Amsterdam, the Netherlands: Elsevier. doi:10.1016/S0070-4571(08)10014-0, and Rebesco, M., Hernández-Molina, F. J., Van Rooij, D., and Wåhlin, A. (2014). Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations. *Marine Geology* **352**, 111–154. https://doi.org/10.1016/j.margeo.2014.03.011.

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 10^3 km^2 for channel patch drifts to 10^3–10^6 km^2 for contourite fans.

Patch Drifts

Patch drifts include a wide range of small-scale sediment bodies, 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 above); (b) on slope systems associated with the generation and downwelling of bottom water masses; and (c) anywhere that contourite drifts occur, representing the earlier (younger) precursor of a larger-scale mounded-elongate, sheeted or other drift type. They may also represent the break-up of a former larger drift due to increased bottom current activity and localized erosion. The size (10–10^3 km^2), rates of accumulation and occurrence are very variable.

Table 1 Principal morphogenetic types of contourite systems—depositional drifts and erosional elements

	Subdivisions	*Size (km^2)*	*Examples*
Depositional drifts			
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
Carbonate contourites			Many of the examples described before in this table are carbonate drifts. Recent focus are the Great Bahama Bank drifts, carbonate (delta) drift in Maldives and the
Shallow-water contourites			Kwazulu-Natal shelf deposits, west Africa
The Andvord Drift, west Antarctic Peninsula			
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			
Erosional elements			
Depositional hiatuses		10^3–10^6	Vema Contourite fan; Cadiz CDS
Regional erosional surfaces (also known as *areal erosional features*)	(a) Contourite terraces	10^3–10^5	Argentine margin; Uruguayan margin; Iberian margin
	(b) Abraded surfaces	10^3–10^4	Iberian margin; Argentine margin; Uruguayan margin
	(c) Subcircular scour	10^2–10^3	Iberian margin; Antarctic margin
Linear erosional features	(a) Contourite channels	10^2–10^3	The Cadiz Contourite Channel in the middle slope of the Gulf of Cadiz is well-studied example, originated from the distal end of the Cadiz Terrace and is then deflected when it encounters a diapiric ridge as an obstacle to flow.
	(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).

Modified after Esentia, I., Stow, D. and Smillie, Z. (2018) Contourite drifts and associated bedforms. In Micallef, A., & Krastel, S. S. A. (eds.) *Submarine geomorphology*, pp. 301–331. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-57852-1_16.

Confined Drifts

Confined drifts are those that have developed in a restricted setting, and are therefore similar to large patch drifts in broad channel systems. They are possibly influenced by multicore flow pathways and typified by zones of both erosion and deposition. Examples of these drifts are recorded in Sumba Gateway in the Indonesian archipelago and Sicilian gateway in the central Mediterranean.

Infill Drifts

Infill drifts occur directly in response to the excavation of topographic lows or scours, created by downslope mass transport processes or other forms of erosion. The portion of slope that has been excavated may become progressively back-filled by contourite drift deposits. The drift size is controlled by the size of the scour feature being filled and the length of time over which deposition has occurred. Complete drift infill of a channel is observed within the Faro-Albufeira drift in the Gulf of Cadiz.

Fault-Controlled Drifts

Fault-controlled drifts are characterized 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.

Mixed Drift Systems

The interaction of deep-water depositional processes (downslope, alongslope, and pelagic) is common on many continental margins, resulting in a range of modified or mixed drifts systems (Table 1). The term "mixed drift" is generally used to describe the interaction of downslope and alongslope flow processes, which results in the interbedding of turbidites and contourites. It is important to note that contourites may also be deposited as a minor component of other deep-water depositional systems and not, therefore, be expressed at the seafloor by any distinctive drift morphology.

Shallow-Water Drifts

Along upper slopes and outer continental shelves, relatively shallow-water bottom currents affect widespread areas over long periods of time, up to 100,000 years (Verdicchio and Trincardi, 2008). There are four main oceanographic regimes that may result in sustained unidirectional contour-parallel flows over appreciable distances and prolonged intervals: thermohaline contour currents, wind-driven currents under the principal global wind belts; and cascading (or downwelling) currents that develop in areas of bottom water formation; and currents due to internal waves and tides. Under each of these regimes, the prolonged accumulation of shallow-water contourites can lead to the development of contourite drifts (Fig. 2). Under higher energy regimes, erosion may result.

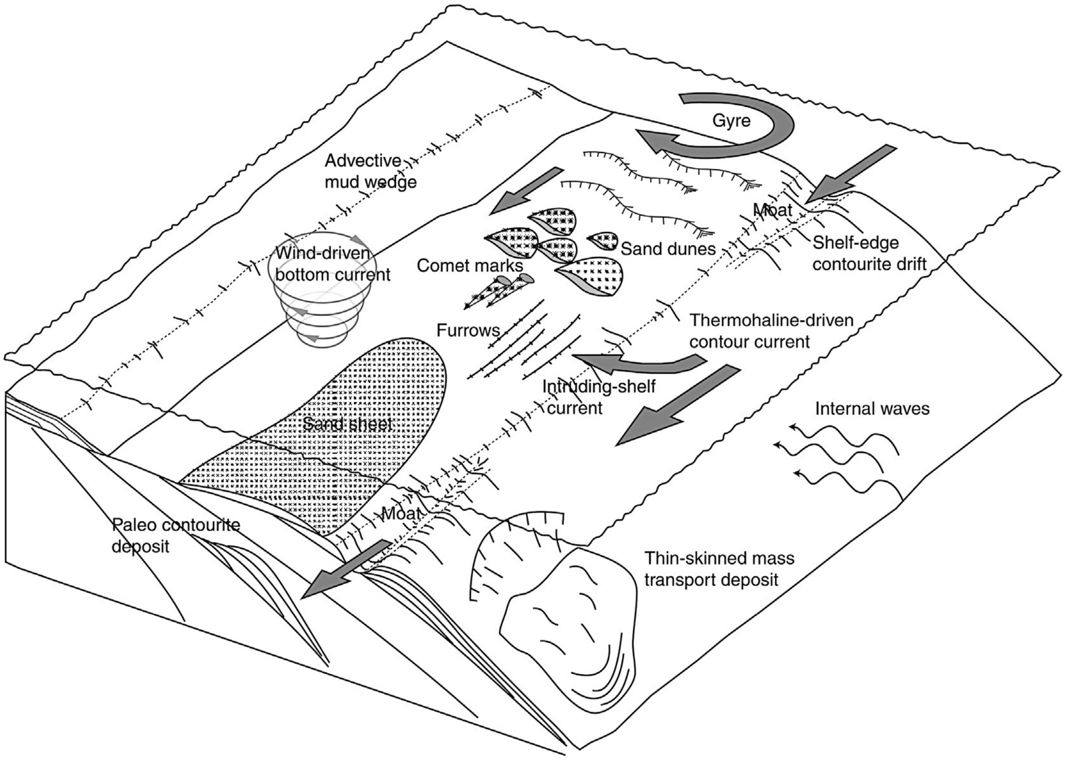

Fig. 2 Schematic representation of the main processes operating in shallow-water contourite settings and their associated deposits. After Verdicchio, G. and Trincardi, F. (2008). Shallow-water contourites. *Developments in Sedimentology* **60**, 409–433 https://doi.org/10.1016/S0070-4571(08)10020-6.

Carbonate Drifts

Contourite drifts that are composed mainly of carbonate material have been recorded from both the deep oceans away from significant terrigenous input (e.g. Gardar and Hatton drifts in the NE Atlantic, or the Zapiola drift in the S Atlantic), and shallow-water to slope systems off carbonate banks and bioherms (e.g. off the Bahama Banks and Maldives). The same principal drift types are recognized for these *carbonate drifts* as for drifts in general—i.e., abyssal sheeted drift (Zapiola), elongate-mounded drift (Hatton), patch-drifts (off the Bahamas), and channel-related drifts (off the Maldives).

Recent work off the Maldives in the Indian Ocean (Lüdmann et al., 2018) has elucidated a potential new drift type—provisionally called a "delta drift." This is a shallow- to deep-water carbonate drift, made up of several stacked lobes, and formed under persistent water through-flow at the exit of two gateways that connect the Inner Sea of the Maldives carbonate platform with the open ocean. The drift onset marks the transition from a sea-level controlled to a progressively current-dominated depositional regime, at around 13 Ma ago.

Most of the ancient contourite sediments now exposed on land, which have been recognized to date, are, in fact, carbonate contourites. These include the Paleogene Lefkara Formation of Cyprus, the Devonian bioclastic contourites in the Central Massif of Morocco, the Lower Ordovician carbonate drifts in Jiuxi, southern China, and the Cretaceous Talme Yafe formation in Israel among others (Hüneke and Stow, 2008). However, only in the case of the Jiuxi drift in China and the Lefkara drift in Cyprus is there sufficient field evidence to infer true drift-like geometry.

Contourite Erosional Elements

The principal erosional elements identified within contourite depositional systems (Rebesco and Camerlenghi, 2008; García et al., 2009; Robesco et al. 2014) include (Fig. 3; Table 1): (a) depositional hiatuses, (b) regional erosion surfaces, and (c) linear erosion features.

Depositional Hiatuses

Depositional hiatuses are the result of prolonged periods of nondeposition and/or erosion under the influence of bottom currents. In the deep oceans, they represent the principal means by which the otherwise continuous sedimentary record is interrupted at a regional scale. They are generally related to significant long-term changes in the ocean current and/or climate regime.

Such hiatuses may extend along a linear channel or moat, across a broad depositional drift or even an entire contourite depositional system, and may be characterized by a hardened substrate (e.g. over-consolidated mud), a coarse-grained lag deposit (e.g. sand or gravel), or a rocky substrate. Significant changes in sedimentation style and dominant sedimentary processes were identified in association with widespread depositional hiatuses within the Gulf of Cadiz, some of which mark a significant transition from marine to terrestrial sediment input or vice versa.

Regional Erosive Surfaces

These erosive surfaces result from the influence of strong bottom currents over large areas of the seafloor, spanning 10^2–10^4 km^2. Three types have been identified as follows (Esentia et al., 2018) and (Fig. 3 and Table 1).

1. Contourite terraces are extensive scoured surfaces, described from several continental slopes, which cut into the slope topography and form a horizontal to gently seaward-sloping terrace, or series of terraces, elongated parallel to the margin. They are typically covered by either coarse-grained lag deposits and prominent bedforms (Gulf of Cadiz CDS), or fine-grained contourites with smoother morphology (Argentine margin) Both types represent prolonged erosion and nondeposition associated with strong bottom currents that impinge on the slope seafloor, and are believed to occur in particular at the interface between different water masses.
2. Abraded surfaces are very similar to the terraces (above) in terms of morphology, sediment cover, and mode of origin, except they may occur anywhere on the seafloor. Those that occur within larger-scale channels or oceanic gateways are known as *channel scour surfaces*.
3. Subcircular scour features have been found in both upper and middle-slope locations, often associated with contourite terraces. They may be linked to powerful eddies formed by strong, dynamic, bottom currents, creating localized erosion at the seafloor. Such eddies can, in some cases, be caused by current interaction with seafloor topography.

Linear erosional features

Large-scale linear erosional features include four main 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. Mostly, they can be considered channels of one sort or another.

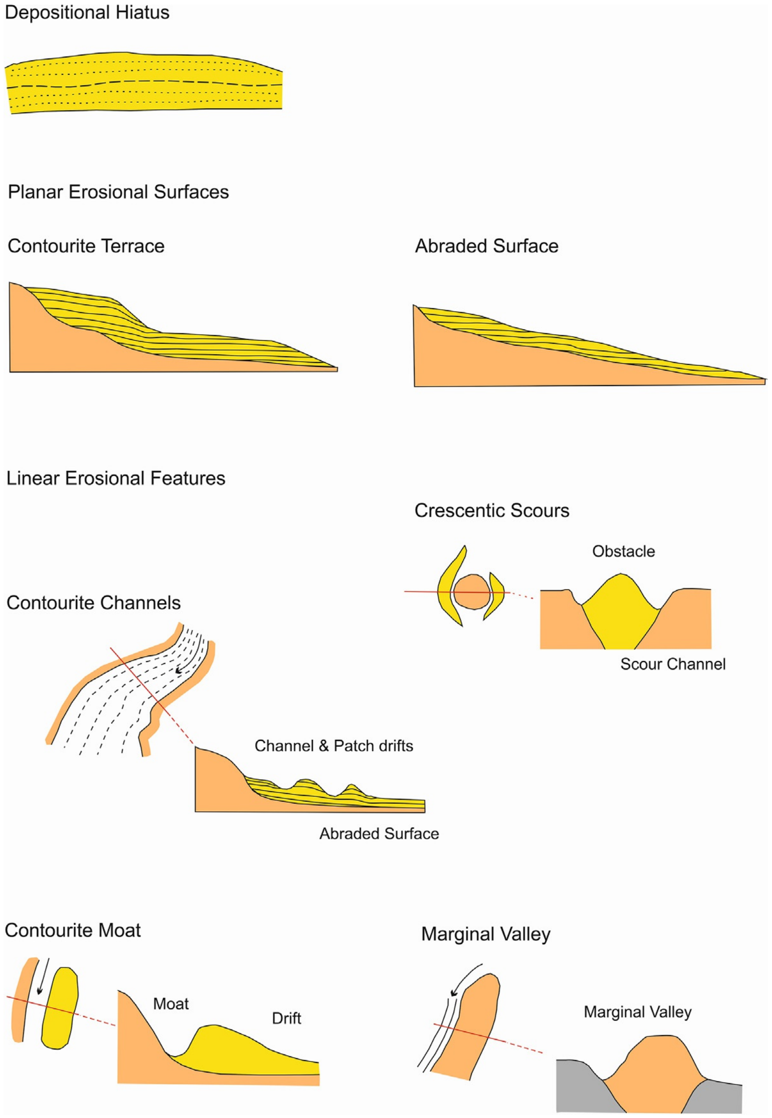

Fig. 3 Summary of the principal contourite erosional elements showing sketches of each type. Examples are provided for each type in the text and in Table 1. Modified by Esentia, I., Stow, D., and Smillie, Z. (2018). Contourite drifts and associated bedforms. In Micallef, A., & Krastel, S. S. A. (eds.) *Submarine geomorphology*, pp. 301–331. Cham, Switzerland: Springer. doi: 10.1007/978-3-319-57852-1_16 from Hernandez-Molina, F. J., Stow, D. A. V., Alvarez-Zarikian, C. A., Acton, G., Bahr, A., Balestra, B., and Ducassou, E. (2014). Onset of Mediterranean outflow into the North Atlantic. *Science* **344**(6189), 1244–1250. doi:10.1126/science.1251306; García, M., Hernandez-Molina, F. J., Llave, E., Stow, D. A. V., Leon, R., Fernandez-Puga, M. C., Diaz del Rio, V., and Somoza, L. (2009). Contourite erosive features caused by the Mediterranean Outflow Water in the Gulf of Cadiz: Quaternary tectonic and oceanographic implications. *Marine Geology* **257**(1–4), 24–40. doi: 10.1016/j.margeo.2008.10.009 and Rebesco, M., Hernández-Molina, F. J., Van Rooij, D., and Wåhlin, A. (2014). Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations. *Marine Geology* **352**, 111–154. https://doi.org/10.1016/j.margeo.2014.03.011.

1. Contourite Channels are elongate erosional depressions. They are sinuous or straight in plan-view, 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 can be orientated alongslope, oblique to slope, or around a topographic obstacle, and generally follow the direction of the dominant bottom current flow pathway.
2. 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 constrained by the relief and hence accelerates.
3. A Contourite Moat is a channel that occurs along the flank of a mounded-elongate drift. In the case of a separated drift, it is the channel that separates the drift from the adjacent slope. Moats form as a result of nondeposition and localized erosion below the bottom current core.

4. A Large Isolated Contourite Furrow is a relatively small contourite channel, caused by the erosive action of a small flow that has separated from the main bottom current. This is possibly caused by a topographic feature obstructing and splitting the flow. It could also represent the incipient formation of a larger channel.

Seismic Characteristics

The first stage in identifying contourite drifts and erosional features is on the basis of seismic reflection profiles. However, it is not always easy to distinguish contourites from other deep-sea systems (such as turbidite lobes, levees, and fans), and even more difficult in the mixed drift systems where close interbedding of different facies has occurred. It is therefore important to develop a set of seismic criteria to help with this identification. The current set of seismic criteria for enabling positive identification has been developed from (Faugères et al., 1999; Rebesco and Stow, 2001; Stow et al., 2002; Nielsen et al., 2008). The key attributes are shown schematically in Fig. 4, and a range of examples of different drift types in Fig. 5. The three scales of approach are discussed below.

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

These are the large-scale elements of the drift: the overall architecture, the external geometry, the internal reflector character, and the upper and lower bounding surfaces. They reflect long-lasting, 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:

1. Drift geometry. Those with a more mounded geometry 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).
2. Drift elongation. An overall down-current elongation is typical of most drifts, either wholly alongslope or at some small angle of deviation (generally <30°) from the slope contours.
3. Erosional discontinuities. Laterally extensive discontinuities, both at the base and within the drift, are common. They may be marked by continuous high-amplitude reflectors, evidence for slight erosion or unconformity, and a change in seismic facies. Some of these unconformities will be on a subregional scale, beyond the confines of the drift, while others (such as the basal horizon) may even link into ocean-wide discontinuities.
4. Uniform reflector pattern. Laterally extensive, subparallel sets of moderate to low-amplitude reflectors are typical of many drift systems.

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

This includes the analysis of the internal architecture of the first-order elements and identification of medium-scale seismic units, their shape and stacking pattern, and reflector terminations. Internal architecture within a drift is generally complex, being

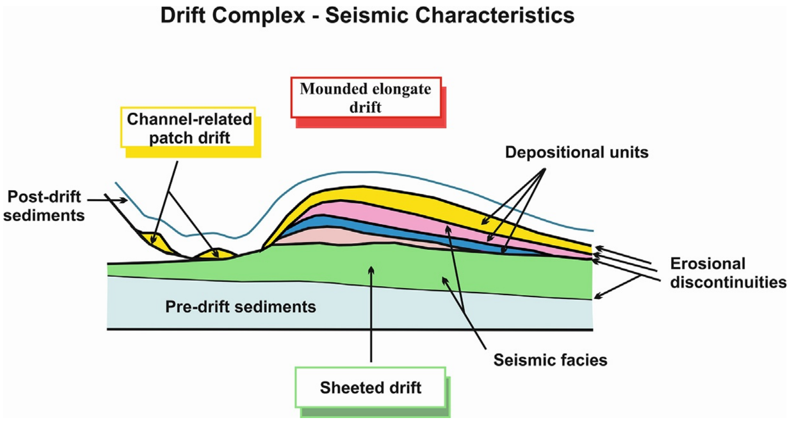

Fig. 4 Conceptual model of the seismic characteristics of contourite drift and adjacent erosional elements. Modified by Esentia, I., Stow, D., and Smillie, Z. (2018) Contourite drifts and associated bedforms. In Micallef, A., & Krastel, S. S. A. (eds.) *Submarine geomorphology*, pp. 301–331. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-57852-1_16 from Stow, D. A. V., Faugères, J. -C., Howe, J. A., Pudsey, C. J., and Viana. A. R. (2002). Bottom currents, contourites and deep-sea sediment drifts: Current state-of-the-art. *Geological Society* **22**(1), 7–20. doi:10.1144/GSL.MEM.2002.022.01.02 and Nielsen, T., Knutz, P. C., and Kuijpers, A. (2008). Seismic expression of contourite depositional systems. *Developments in Sedimentology* **60**, 301–321. doi: 10.1016/S0070-4571(08)10016-4. 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.

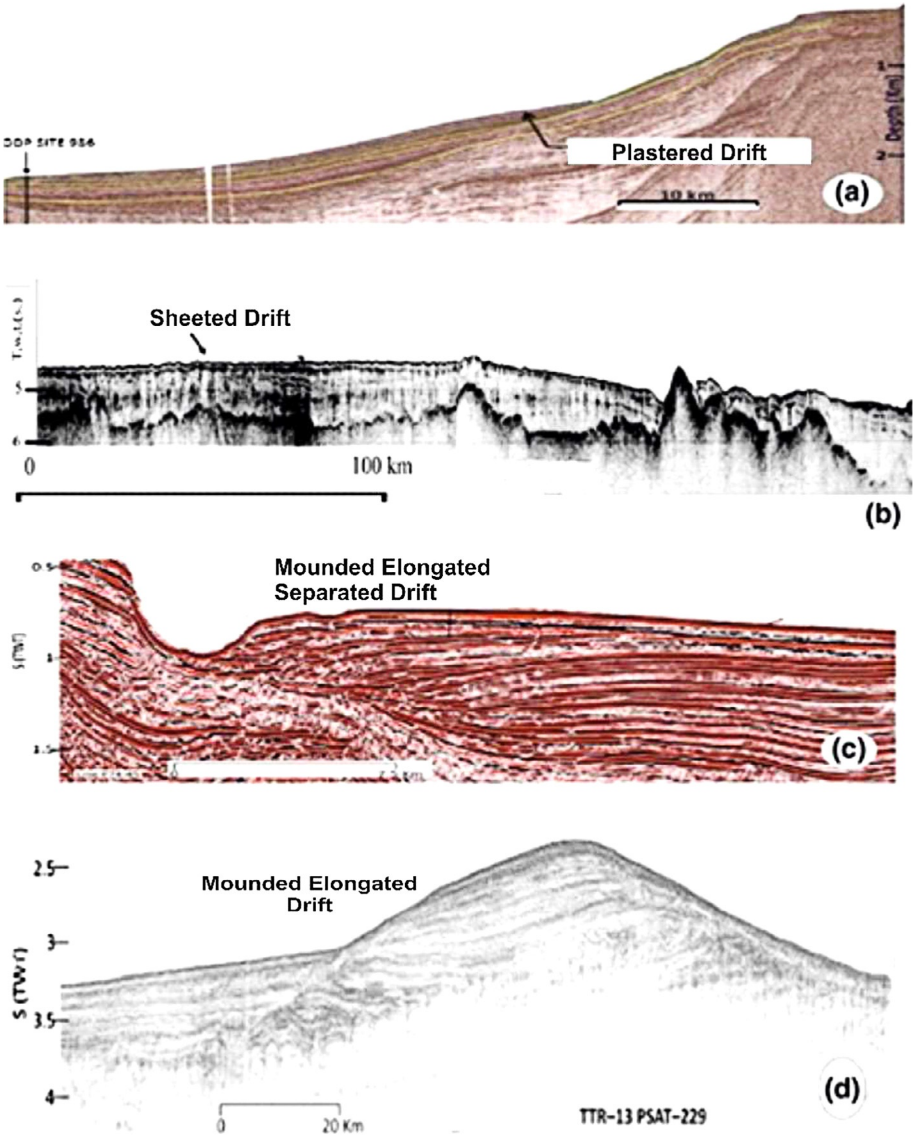

Fig. 5 Examples of seismic profiles across contourite drift depositional systems. (A) Sheeted drift: Isfjorden plastered (slope) drift from West Spitzbergen margin (Reprinted from Rebesco et al. (2013). Quaternary contourite drifts of the Western Spitsbergen margin. *Deep Sea Research Part I*, **79**, with permission from Elsevier). (B) Sheeted drift: Gloria (abyssal) drift from the NW Atlantic Ocean (after Egloff, J. and Johnson, G. L. (1975). Morphology and structure of the southern Labrador Sea. *Canadian Journal of Earth Sciences* **12**, 2111–2133). (C) Mounded elongate drift: Faro-Albufeira (separated) drift, Northern Gulf of Cadiz (Reprinted from Rebesco et al. (2014). Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations. *Marine Geology*, **352**, with permission from Elsevier). (D) Mounded elongate drift: Eirik (detached) drift, southern Greenland margin (from Hunter, S., Wilkinson, D., Louarnb, E., McCave, I.N., Rohling, E., Stow, D.A.V. and Bacon, S. (2007). Deep western boundary current dynamics and associated sedimentation on the Eirik Drift, Southern Greenland Margin. *Deep-Sea Research* **I–54**, 2036–2066).

(Continued)

influenced by the local variation in processes and accumulation rates. Medium and small-scale features reflect changes in the history of drift construction including periods of sedimentation and periods of erosion or nondeposition. Second-order elements include:

1. Seismic units. These typically comprise a series of broadly lenticular, upwardly-convex, seismic units.
2. Stacking pattern. Progradational, aggradational, and uniform stacking patterns occur in different drift systems. These may change through the history of drift development.
3. 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.
4. Reflector terminations. Down-lapping and sigmoid progradational reflector patterns are typical, whereas a top-lapping pattern is less common.

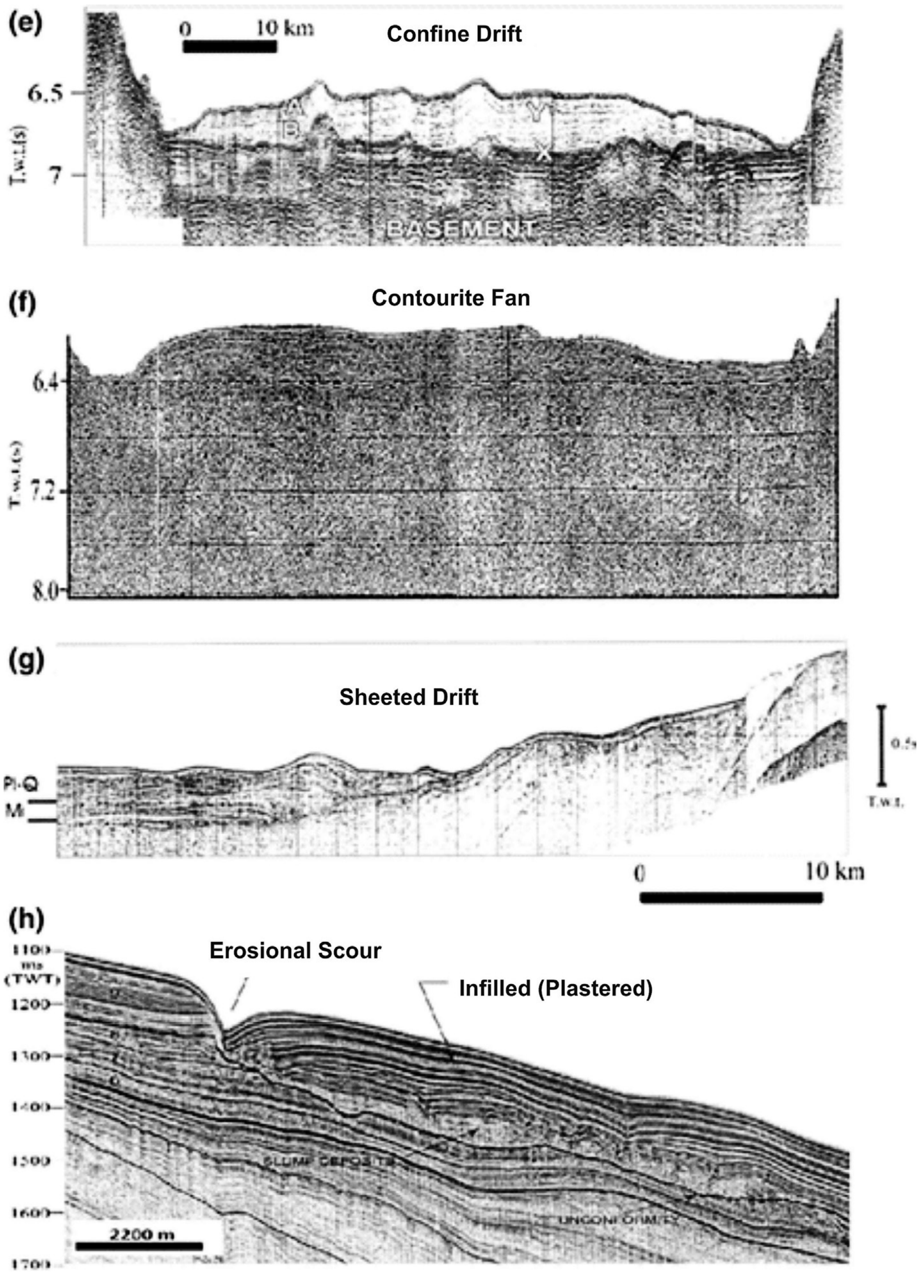

Fig. 5, Cont'd (E) Confined drift: Louisville (confined) drift, eastern New Zealand margin (after Carter, L. and McCave, I. N. (1994). Development of sediment drifts approaching an active plate margin under the SW Pacific deep western boundary current. *Paleoceanography* **9**, 1061–1085). (F) Channel-related drift: Vema contourite fan, South Brazilian basin, South Atlantic Ocean (after Faugères, J. C., Imbert, P., Mézerais, M. L. and Crémer, M. (1998). Seismic patterns of a muddy contourite fan (Vema Channel, South Brazilian Basin) and a sandy distal turbidite deep-sea fan (Cap Ferret system, Bay of Biscay): A comparison. *Sedimentary Geology* **115**(1–4), 81–110. https://doi.org/10.1016/S0037-0738(97)00088-2). (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, J. -C., Stow, D. A. V., Imbert, P., and Viana. A. (1999). Seismic features diagnostic of contourite drifts. *Marine Geology* **162**(1), 1–38. https://doi.org/10.1016/s0025-3227(99)00068-7). (H) Infill drift: Faeroe plastered infill (slope) drift, southern margin Norwegian Sea. Modified by Esentia, I., Stow, D., and Smillie, Z. (2018) Contourite drifts and associated bedforms. In Micallef, A., & Krastel, S. S. A. (eds.) *Submarine geomorphology*, pp. 301–331. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-57852-1_16

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

Small-scale seismic elements reflect changes in both depositional processes and sediment type. These features are not unique to contourite drifts and can depend, in part, on seismic acquisition and processing. However, once a drift origin has been established, these elements can be used, in combination with other characteristics, to document a more detailed history.

1. Seismic facies. Typical seismic facies of contourites include: (i) reflector-free intervals; (ii) low-amplitude, continuous, subparallel reflectors; (iii) moderate-amplitude, regular reflectors; (iv) moderate-amplitude, irregular, wavy and discontinuous reflectors; and (v) high-amplitude, continuous to irregular reflectors. (Stow et al., 2002) suggest that this order of seismic facies (i–v) reflects increasing strength in the bottom-current regime.
2. Seismic facies cyclicity. Some drifts show a cyclic alternation of transparent and more reflective seismic facies. These cycles likely represent lithological changes linked to bottom-current variation and climate change.

Seismic Stratigraphy

In placing contourite systems within a sequence stratigraphic context, it is important to note the correlation between sea level, climate and bottom current velocity. Two end-member models are identified: The first model reveals a contourite system where bottom current activity is markedly more vigorous during times of sea-level highstand, whereas the second model indicates margin evolution where bottom water currents are most vigorous during times of lowstand. It is recognized that there are additional controlling factors that can significantly modify the distribution and development of contourite elements linked to sea level variation, including major paleoceanographic and tectonic events.

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 (Stow et al., 2009, 2013). Such bedforms can provide critical understanding of both flow characteristics and depositional-erosional mechanisms of bottom currents (Wynn and Masson, 2008).

Bedforms can be divided into two main groups: longitudinal and transverse bedforms (Fig. 6, Esentia et al., 2018). It is important to note that none of these bedforms is exclusive to formation under bottom currents, nor do they occur solely in deep-water settings.

Longitudinal Bedforms

These are generally elongated bedforms parallel to flow direction and include five main types: (a) surface lineation—low-relief linear markings on muddy or sandy substrates; (b) ribbon marks—linear ridges up to several meters in height on sand and gravel substrates; (c) crag and tail—elongate depositional mounds that form behind a seafloor obstacle; (d) comet scours—crescentic to elongate erosional features that develop around the margins of and behind an obstacle; and (e) furrows—regularly-spaced, elongate, subparallel, erosive grooves, which occur at a wide range of scales in different substrate types.

Transverse Bedforms

These bedforms are oriented transverse to the flow direction and form on substrates of coarse silt/fine sand and up to gravel-size. They all result from flow re-arrangement of the substrate into a regular pattern of crests and troughs. They occur at very different scales, with a crest to crest wavelength from centimeters to kilometers. Three main types are recognized, with increasing wavelength and wave height: (a) ripples, with straight, sinuous, and linguoid planforms, are the smallest; (b) dunes and sand waves, with a similar variety of planforms, are intermediate; and (c) giant sediment waves, in muds, sands or gravels, are the largest in size.

(Stow et al., 2009) synthesized a large amount of bedform data into a bedform-velocity matrix (Fig. 7), showing information on flow direction, velocity, variability and continuity. Different bedforms are also characteristic of different drift types and erosional features.

Muddy drifts (mounded and sheeted) typically have smoothed sediment surfaces and/or surface lineation, representing deposition of silt and clay directly from suspension through a laminar boundary layer. The common presence of ripple bedforms at all scales on both muddy and sandy drifts 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. As flow velocity increases, so longitudinal bedforms and erosional furrows form.

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.

Sandy drifts and sand-gravel sheets are subjected to higher velocity currents, and the 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. Stronger currents will produce large areas of linear bedforms in both sands and gravels. The lateral juxtaposition of bedform types occurs over a horizontal scale of meters, indicating the variability in velocity of strands of flow (or regions of flow) at this order of magnitude.

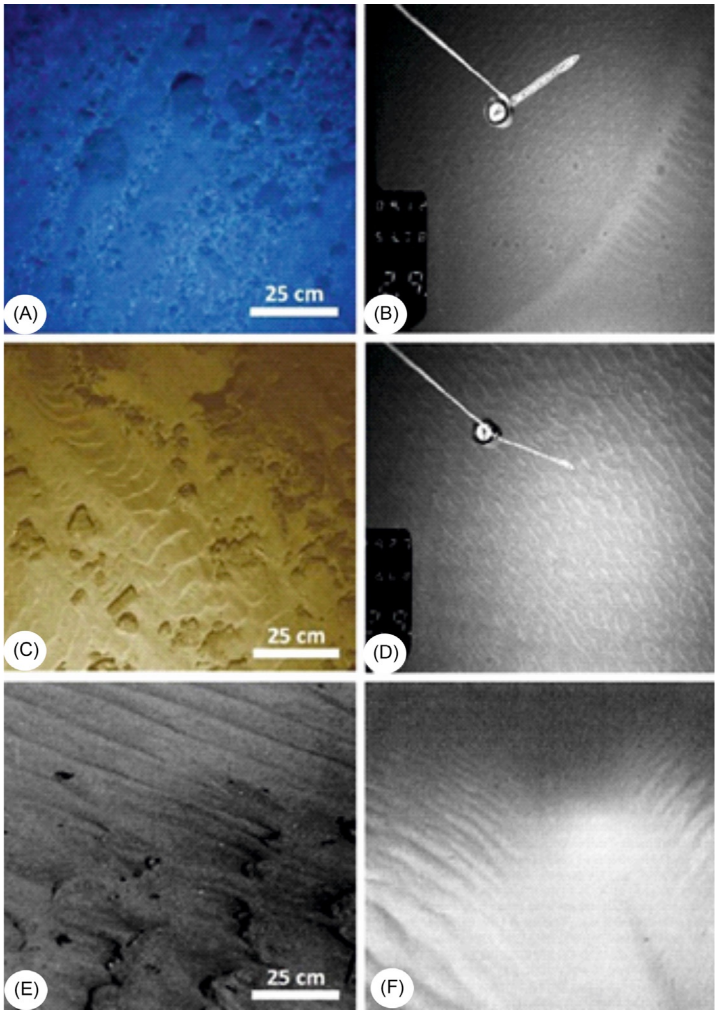

Fig. 6 Examples of bottom photographs showing selected bedforms on the present-day seafloor. (A–F) From Gulf of Cadiz. (A). Lineation in coarse-grained sand-gravel sediment. (B). Sand wave or dune covered in smaller-scale ripples, with curved crest and avalanche stringers down the lee face. (C). Transverse sand ripples between gravel patches and stringers. (D). Small sand ripples, most transverse to flow but with some interference. (E). Lineation in sands (longitudinal ripples), with more linguoid ripples in foreground. (F). Part of longitudinal furrow, deeply erosive into muddy seafloor. Stow, D. A. V., Hernández-Molina, F. J., Llave, E., et al. (2013). The Cadiz contourite channel: Sandy contourites, bedforms and dynamic current interaction. *Marine Geology* **343**, 99–114. https://doi.org/10.1016/j.margeo.2013.06.013.

Contourite Significance

Contourite sediments are very widespread in the present-day oceans and through the sedimentary record. The study of contourite systems is significant in three major respects (Viana and Rebesco, 2007):

(a) Paleoceanography and paleoclimatology: contourite drifts hold a high-resolution, semi-continuous record of past ocean circulation linked to climate change.
(b) Hydrocarbon exploration: sand-rich contourites provide potential reservoir rocks in deep-water, whereas mud-rich contourites can provide both source rocks and seals.
(c) Ocean hazards: vigorous bottom currents are a potential threat to seafloor installations, submarine cables and pipelines. In addition, contourite sediments are prone to failure due to their location, under-consolidation, low shear strength and well-sorted nature. They are therefore a major source of slope instability.

Acknowledgments

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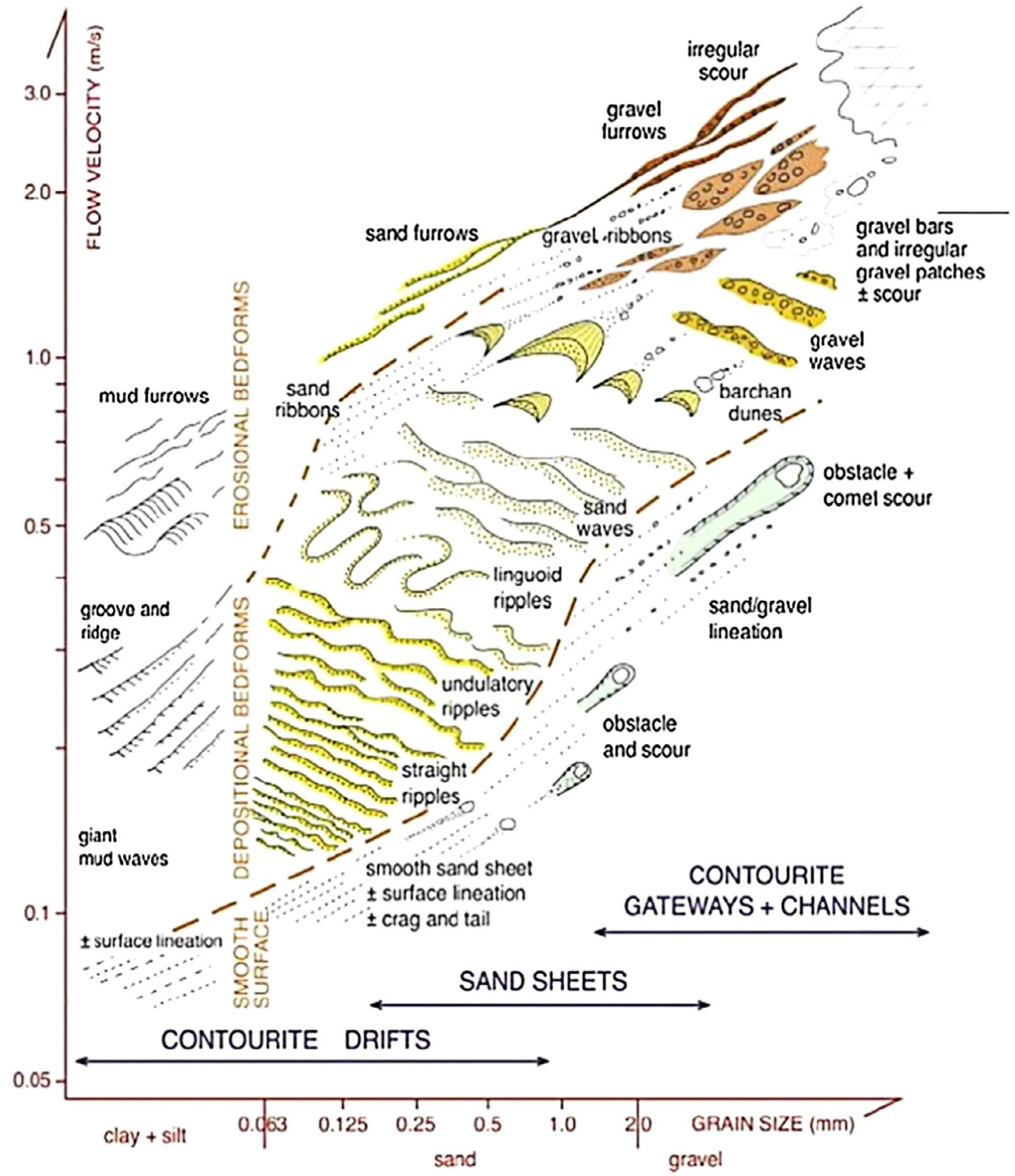

Fig. 7 Bedform-velocity matrix. Modified from Stow, D. A. V., Hernandez-Molina, F. J., Llave, E., Sayago-Gil, M., del Rio, V., and Branson, A. (2009). Bedform-velocity matrix: The estimation of bottom current velocity from bedform observations. *Geology* **37**(4), 327–330. doi:10.1130/g25259a.1 and Rebesco, M., Hernández-Molina, F.J., Van Rooij, D., and Wåhlin, A. (2014). Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations. *Marine Geology* **352**, 111–154. https://doi.org/10.1016/j.margeo.2014.03.011. The plot shows the range of depositional and erosive bedforms commonly associated with bottom currents in deep-water, 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.

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