Deep-Sea Contourites: Sediments and Cycles

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Introduction

Contourites are defined as all those sediments deposited or substantially reworked by the persistent action of bottom currents (Stow and Lovell, 1979; Stow et al., 2002; Rebesco, et al. 2014). The term "contourite" was originally used specifically for sediments deposited in the deep-sea by contour-parallel (alongslope) bottom currents driven by thermohaline circulation. It has since been widened to embrace a range of sediments affected by different types of current, including those that act in shallower water (Viana et al., 1998)—that is, upper slope and outer shelf depths—as well as in large lakes and inland seas. These are referred to as lacustrine and shallow-water contourites.

Contourites are one of three principal deepwater sediment facies—the others being turbidites, deposited by downslope density currents, and pelagites/hemipelagites, which result from vertical settling through the water column. In fact, there is a continuum between these different processes and facies, which are therefore end-members on a natural spectrum of deposits (Fig. 1). All three types can be closely interbedded, particularly in continental margin sedimentary successions. Strong bottom currents are also capable of winnowing and eroding the sea-floor, and of preventing deposition, thereby causing hiatuses and/or hardgrounds in the sediment record.

Much of the early pioneering work on contourites was carried out along the eastern continental margin of North America, and served to document the strong influence of the deep Western Boundary Undercurrent in shaping the lower continental slope and rise (Heezen et al., 1966). As there are no distinctive, mounded, contourite drifts along much of this margin, the contourite facies are found closely intercalated with turbidites and hemipelagites. This led to early problems with the distinction between these different deep-water facies.

Resolution of these problems has been achieved through the study of contourites from many more drifts worldwide, and especially those of incontrovertible bottom-current construction (Stow and Lovell, 1979; Stow and Faugères, 2008). As many more descriptions of modern contourites emerged in the literature, more reliable facies models were developed for both muddy and sandy contourites, and these were combined into the now standard contourite facies model (Gonthier et al., 1984). A recent expedition of the International Ocean Discovery Program, IODP339, drilled a series of six sites in the Gulf of Cadiz and recovered over 4500 m of contourite cores (Hernandez-Molina et al., 2014). Subsequent research on this material has validated the standard facies model, extended our understanding of sandy contourites (Brackenridge et al., 2018), and elucidated the nature of the depositional processes and controls.

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 the contourite sediment facies, based largely on modern and subrecent data recovered from present-day oceans. 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 larger-scale contourite drifts and bedform morphology, and the nature of bottom currents.

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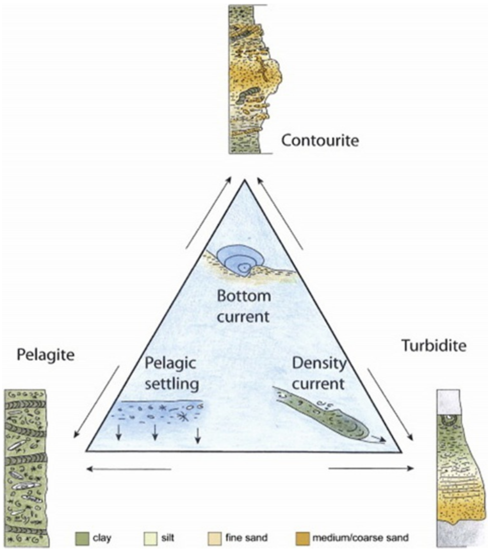

Fig. 1 The three main types of sedimentary processes operating in the deep sea (within the triangle) and the facies models of the respective depositional products. Modified after Rebesco, M., Hernández-Molina, F. J., Van Rooij, D. and Wåhlin, A. (2014). Contourites and associated sediments controlled 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.

Contourite Facies

A wide range of different contourite facies are now recognized, as summarized in Table 1 and illustrated in Fig. 2. These range in grain size from fine muds, through silts and sands, to sand and gravel lag deposits, and are often poorly sorted mixtures of different grain size fractions. In composition they are equally varied, including siliciclastic, bioclastic (calcareous, siliceous), volcaniclastic, and chemogenic (manganiferous) varieties, commonly displaying a mixed composition.

Siliciclastic contourites (Figs. 1 and 2) are well known from a wide range of marine settings, including continental slopes, abyssal plains, shallow-marine and high-latitude settings, and are most easily recognized as part of large-scale contourite drift deposits. They commonly occur as thick featureless units, which are poorly bedded, with a more or less cyclic alternation of muddy, silty and sandy facies, characterized as bi-gradational sequences. In any one location, they tend to show a very uniform, monotonous aspect, in terms of color, texture and composition. They are generally highly bioturbated, often with an indistinct mottled appearance, and may further show distinct burrows of varied (deep-water) ichnofacies (Wetzel et al., 2008). There may be rare primary lamination present (partly destroyed by bioturbation), diffuse and indistinct, in places marked by color change and in places by irregular winnowed concentrations of coarser material.

Sandy contourites are known to make up thin to thick (5–500 m thick) sheeted drifts, covering extensive areas of the seafloor over the outer shelf/upper slope, across slope terraces, in oceanic gateways and flooring contourite channels. In such areas, the seafloor is typically ornamented by a range of current-induced bedforms (ripples, dunes, furrows) and the underlying sediment may preserve internal sedimentary structures, such as cross-lamination, large-scale cross-bedding and parallel lamination. Structureless and bioturbated sands are also common.

Calcareous bioclastic contourites are prevalent wherever the dominant supply to the bottom current and drift systems is made up of carbonate material. This may be from erosion and downslope reworking of carbonate banks and bioherms, or from pelagic fall-

Table 1 The range of contourite facies

Siliciclastic contourites	Muddy, silty, sandy and gravel-rich variations
Shale-clast/shale-chip contourites	All compositions possible
Volcaniclastic contourites	Muddy, silty, sandy and gravel-rich variations
Calcareous bioclastic contourites	Muddy, silty, sandy and gravel-rich variations, also known as calcilutite, calcisiltite, calcarenite and calcirudite contourites in fossil contourite systems
Siliceous bioclastic contourites	Mainly sand grade recognized
Chemogenic contourites	Mainly occur within mud or calcilutite include manganiferous layers, nodules, pavements
Other contourite-related facies	“Shallow-water” contourites, reworked turbidites, lacustrine contourites

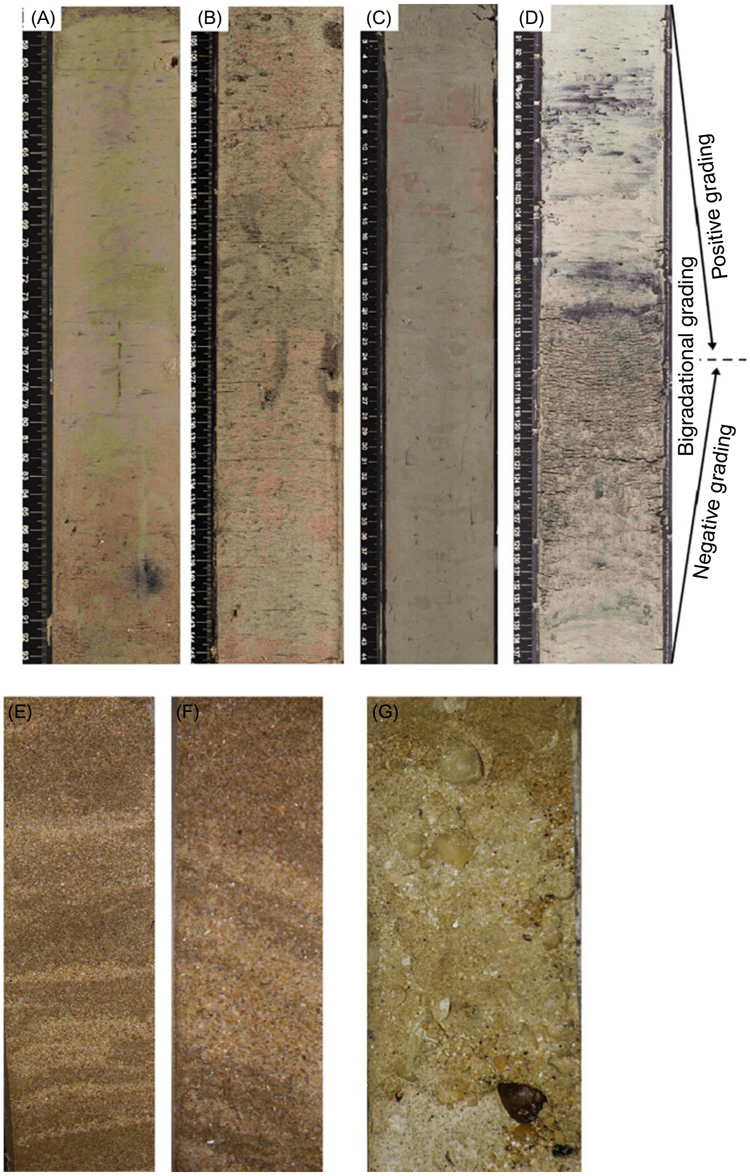

Fig. 2 Examples of contourite facies observed in deep-marine sediment cores: (A–C) structureless and bioturbated muddy and silt-mottled contourite facies, Faro Drift, Gulf of Cadiz. (D) Complete bi-gradational contourite sequence (C1–5), Faro Drift, Gulf of Cadiz. (E and F) Laminated sandy contourite facies, showing parallel and inclined lamination as a result of sand wave migration, Cadiz Contourite Channel. (G) Pebbly sand and gravel-lag contourite facies structureless with irregular concentration of coarse-grained clasts, Faeroe Shetland Channel (gateway), NW UK continental margin. From Stow, D. A. V. and Faugères, J. C. (2008). Contourite facies and the facies model. In: Rebesco, M. and Camerlenghi, A. (eds.) *Contourites*. Amsterdam, the Netherlands: Elsevier (pp. 223–256). https://doi.org/10.1016/S0070-4571(08)10013-9 with permission from The Geological Society, London.

out, especially in regions underlying high primary productivity. Apart from compositional differences, their characteristics are otherwise similar to those of siliciclastic contourites. These calcicontourites are well known from ancient contourite successions exposed on land, which are described in a subsequent section.

Contourite Characteristics

Sedimentary Structures

Contourites recovered from drift systems beneath extant contour currents are characterized by a notable absence of clear, distinct lamination and by the presence of common to abundant, pervasive bioturbation. In some cases, they appear completely homogeneous, whereas in other cases, they show indistinct and discontinuous parallel lamination, partial grain alignment, subhorizontal to irregular erosion surfaces, thin layers and lenses of coarser material. Cross-lamination is only rarely present in silts and fine sands.

Based on the many observations of regular bedforms (ripples, dunes, etc.) on the sea-floor beneath bottom currents, we might expect contourite sediments to show extensive parallel lamination as a result of fluid flow processes, as well as cross-lamination at different scales as a result of bedload traction. However, the presence of pervasive bioturbation rather than lamination might be explained by relatively low rates of contourite accumulation, which is continuous rather than episodic, so that bioturbation is able to keep pace with deposition and effectively destroy most primary lamination, leaving only remnants as indistinct lamination. For muddy contourites, the low current velocities and sediment concentrations are insufficient to result in primary lamination through the depositional sorting mechanism that develops silt/mud lamination in fine-grained turbidites. The minor erosion/nondepositional surfaces as well as coarser lens and layers within muddy contourites provide evidence of repeated and alternating phases of erosion, winnowing and deposition.

Laminated and cross-laminated sandy contourites are known from beneath higher-velocity bottom currents with large-scale bedforms (e.g., dunes) evident on the sea-floor. The lamination is distinct, typically diffuse and widely-spaced, and may be associated with bioturbation. The presence of such structures clearly indicates bedload tractional movement of granular sediments by the bottom current. Preservation of the primary lamination is probably due either to intermittently rapid sedimentation or to the high current velocity and dearth of organic matter inhibiting extensive bioturbation.

Bioturbation

Bioturbation has long been recognized as a distinctive feature of contourites, but detailed work on their ichnology is still sparse. Wetzel et al. (2008) have compiled the most comprehensive summary of this work to date, in which they demonstrate a clear link between ichnofacies assemblage and a combination of current strength and organic matter supply.

Strong bottom currents deposit sand-rich contourites, relatively poor in organic matter and with common erosional surfaces, omission surfaces and hiatuses. Long term omission yields indurated discontinuity surfaces marked by a stiff- to hardground ichnofauna; where overlain by sand, a typical *Glossifungites* ichnofacies is present and, where covered by mud a sharp-walled piped zone results. The upper parts of sandy contourite layers contain biodeformational structures resulting from ploughers and passively ventilated tube systems. These burrows become overprinted by the deeper penetrating ones like *Skolithos*, *Scolicia* and *Planolites*, in addition to the U-shaped *Teichichnus* deep-dwelling crustacean burrows such as *Thalassinoides* and *Gyrolithes.*

Weak bottom currents deposit mud-rich contourites that are generally richer in organic matter. Within such organic-rich muds, oxygen consumption by benthic animals and bacteria may lead the anoxia of pore water at shallow burial depths. The ichnofauna is both small in size of individuals and low in diversity (including monospecific populations). *Chondrites* and *Trichichnus* are often dominant, together with *Phycosiphon*, *Planolites* and less specific "mycellia" traces. Pyritization is common. Where omission surfaces occur vertical tubes and *Glossifungites* ichnofacies are evident.

Contourite bi-gradational sequences (see below) show a distinctive variation in ichnofacies linked to current strength, through the sandy (larger and more diverse assemblage), silt-mottled, and muddy sequence divisions (smaller and less diverse assemblage).

Sedimentary Texture

The dominant grain size of mud-rich contourite drift deposits is clayey silt and silty clay, generally ranging between 3 and 11 ϕ (125–0.5 μm). They commonly show poor sorting (1.4–2.5 ϕ, bimodal or polymodal grain-size distribution, and may contain significant (up to 15%) sand-size material (>63 μm). Sand-sized material in muddy contourites is typically made up of biogenic tests (calcareous or siliceous), which may either be hydrodynamically light and so be transported within the ambient current suspended load, or represent the direct fall of pelagic material through the current. At higher latitudes ice-rafted material is a common addition, which almost certainly represents glaciomarine hemipelagic fallout.

Sandy contourites are mostly fine to medium-grained, more rarely coarse-grained or pebbly. In many cases, they are only moderately to poorly sorted (0.8–2 ϕ), partly as a result of bioturbational mixing with mud grade material, whereas the laminated sands may be moderately well sorted (0.5–0.7 ϕ). Grain-size distribution spectra are more or less unimodal and, on cumulative frequency plots, commonly show a tripartite subdivision into a coarser-grained bedload fraction moved by traction, an intermediate fraction moved as saltation load, and a finer-grained fraction transported wholly in suspension. Still coarser grained contourites (coarse sand and gravel-rich) are moved wholly and intermittently as bedload.

A very interesting cross-plot of mean grain-size and sorting has been compiled by Brackenridge et al. (2018). This shows three distinct trends (Fig. 3): (a) a decrease in sorting from 1 to 20 μm, which reflects the greater range of grain size particles carried as bottom current velocity increases; (b) an increase in sorting from 20 to 200 μm, which reflects the progressive winnowing of finer fraction with increasing velocity; and (c) a decrease in sorting (and a less well-defined trend) for contourite sands over 200 μm in grain size, which reflects an increase in winnowing, erosion, traction and bedload.

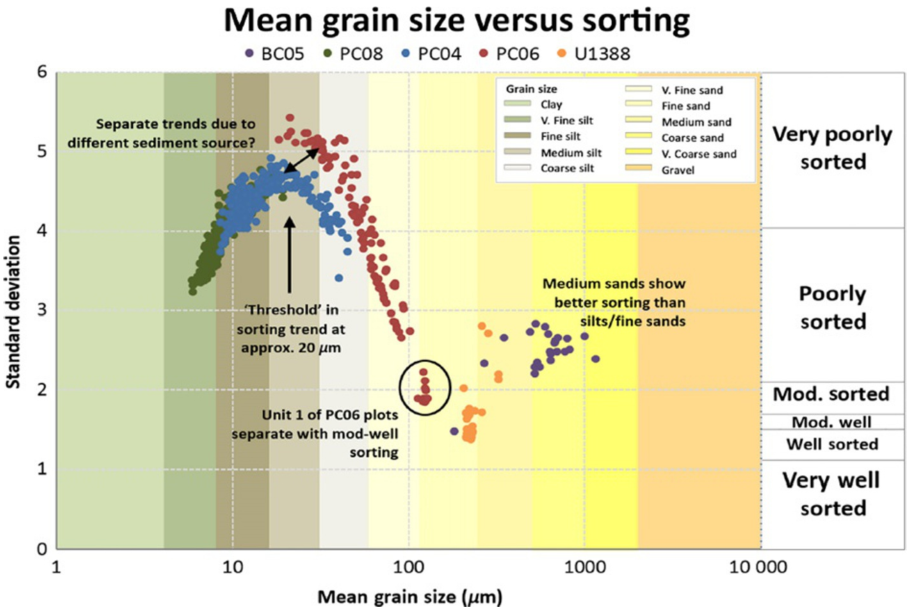

Fig. 3 Cross-plot of sorting against mean grain-size. Clay and fine silt show a negative relationship with sorting, whereas medium silt to fine sand have a positive relationship with sorting. Medium to coarse sands return to poorer sorting. After Brackenridge, R. E., Stow, D. and Hernandez, F.J. (2018). Textural characteristics and facies of sand-rich contourite depositional systems. *Sedimentology*. https://doi.org/10.1111/sed.12463.

Sedimentary Fabric

The sedimentary fabric or microfabric of contourites is still poorly known, and some conflicting results have been published. There is some evidence that grain alignment of silts and fine magnetic particles (using anisotropy of magnetic susceptibility measurements) shows flow-parallel trends. However, other data indicates a more chaotic grain orientation. A recent detailed study using scanning electron microscopy, with automated image analysis, has revealed that both silt and clay microfabrics show a combination of preferred bed-parallel alignment, semirandom/preferred, and wholly random grain orientation. This is interpreted as the result of flow shear during deposition creating a weak to strong fabric, depending on current strength, and pervasive bioturbation tending to disrupt that fabric.

Contourite Composition

Contourites display a wide range of composition, as evidenced by the different facies types—for example, siliciclastic, calcareous, volcaniclastic, and others (see above). Quite commonly, they display a mixed terrigenous-biogenic composition. As proposed by Stow et al. (2008), this indicates a range of sources and supply routes, as well as depositional mixing of components. These include: (a) the vertical settling of pelagic material from the surface, (b) slow horizontal advection and suspension cascading of hemipelagic material, (c) downslope input from turbidity currents and hyperpycnal plumes, (d) downslope flux via spillover processes, and (e) alongslope supply via the bottom current, from material that has been eroded, winnowed, and re-suspended from the seafloor upstream from or adjacent to the site of deposition.

Certain processes and hence component inputs will dominate in different contourite settings. In most cases, the sand-sized fraction will show partial fragmentation, rounding and iron-staining, which is all indicative of bottom current transport as saltation load and bedload.

Contourite Facies Models

Classic Bi-Gradational Model

Separate facies models for muddy and sandy contourites were originally proposed in the late 1970s (Stow and Lovell, 1979). Subsequent work demonstrated that these muddy and sandy facies, together with intervening silty contourites, commonly occur in composite sequences or partial sequences a few decimetres in thickness (typical range 0.2–3 m). The complete bi-gradational sequence shows overall negative grading from muddy through silt-mottled to sandy contourites and then positive grading back through silt-mottled to muddy contourite facies (Fig. 4, Gonthier et al., 1984). This bi-gradational sequence is well-reflected in the Zr/Al ratio (Fig. 5), a unique proxy for bottom current speed. Well-defined sedimentary structures are generally absent, in part because they have been thoroughly destroyed by bioturbation. There may be an indistinct and discontinuous parallel lamination and lenses of coarser material. Primary structures, including rare cross-lamination, are more evident in the coarse silts and sands than in finer grained facies. This model can apply to all compositional types.

Components of the sequence are now referred to by notation C1–5, as introduced by Stow et al. (2002), as follows:

C5 = upper muddy contourite division;
C4 = upper mottled silty contourite division;
C3 = middle sandy contourite division;
C2 = lower mottled silty contourite division;
C1 = lower muddy contourite division.

Thus a complete sequence *of any composition* is referred to as C1–5 (Fig. 4). Partial sequences are everywhere common, in which divisions occur in the same order but with the omission of one or more divisions (Fig. 6). Top-cut-out sequences reflect the abrupt truncation of the full sequence as a result of increased bottom-current velocity and subsequent nondeposition. Base-cut-out sequences reflect the gradual onset in deposition after a period of erosion. Partial sequences can also reflect velocity decrease downstream of a narrow gateway or channel, with middle-only sequences deposited proximally and top/base only sequences more distally. Base-only partial sequences are referred to as C1, C1–2 or C1–3, and top-only sequences as C3–5, C4–5 or C5, as appropriate.

Sandy Contourite Models

Contourite sands occur as part of the bi-gradational sequence or partial sequences—the C3 division. These tend to be relatively mud-rich and bioturbated. However, they also occur separately in sand sheets and channel sands, where they are *not* part of a standard contourite sequence. Three different sandy contourite types (or facies models) are recognized: (a) fine-grained bioturbated sandy facies, with some mud; (b) fine to medium-grained, clean (mud-free) sands that are mostly structureless sands with rare bioturbation and lamination; and (c) medium to coarse-grained, laminated and cross-bedded sands that are mud-free, and generally without bioturbation. They may contain pebbly horizons. To date, there is no general agreement on a definitive sandy contourite facies model.

Contourite Cyclicity

The regular variation of different properties through contourite successions is referred to as contourite cyclicity.

Seismic cycles have now been recognized in many different drifts. The smallest scale that can be easily resolved (20–30 ms TWTT) shows an alternation of transparent to weak to strong reflector packages, which are taken to indicate a long-term increase in bottom-current velocity. Such cycles are typically capped by a discontinuity or hiatus in sedimentation, and then revert again to a transparent reflector pattern. Where these have been drilled and dated, in the Gulf of Cadiz, they show more or less regular 100,000 years periodicity, which can be clearly linked to Milankovitch-scale climate oscillation. They also occur grouped into larger-scale seismic cycles.

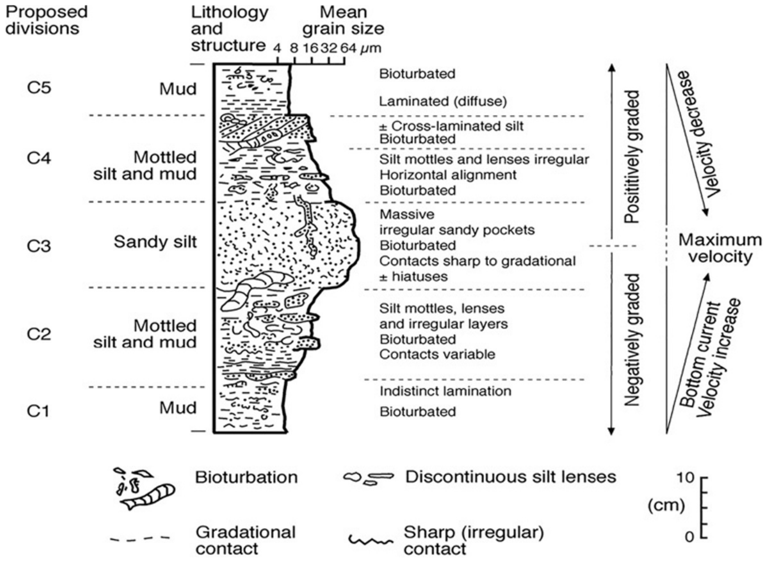

Fig. 4 Composite contourite facies model showing grain-size variation through the standard mud-silt-sand contourite sequence, linked to variation in bottom-current velocity. From Stow, D. A. V., Faugeres, J.-C., Howe, J. A., Pudsey, C. J. and Viana, A. R. (2002). Bottom currents, contourites and deep-sea sediment drifts: current state-of-the-art. *Geological Society, London, Memoirs* **22**(1):7–20. https://doi.org/10.1144/GSL.MEM.2002.022.01.02 with permission from The Geological Society, London.

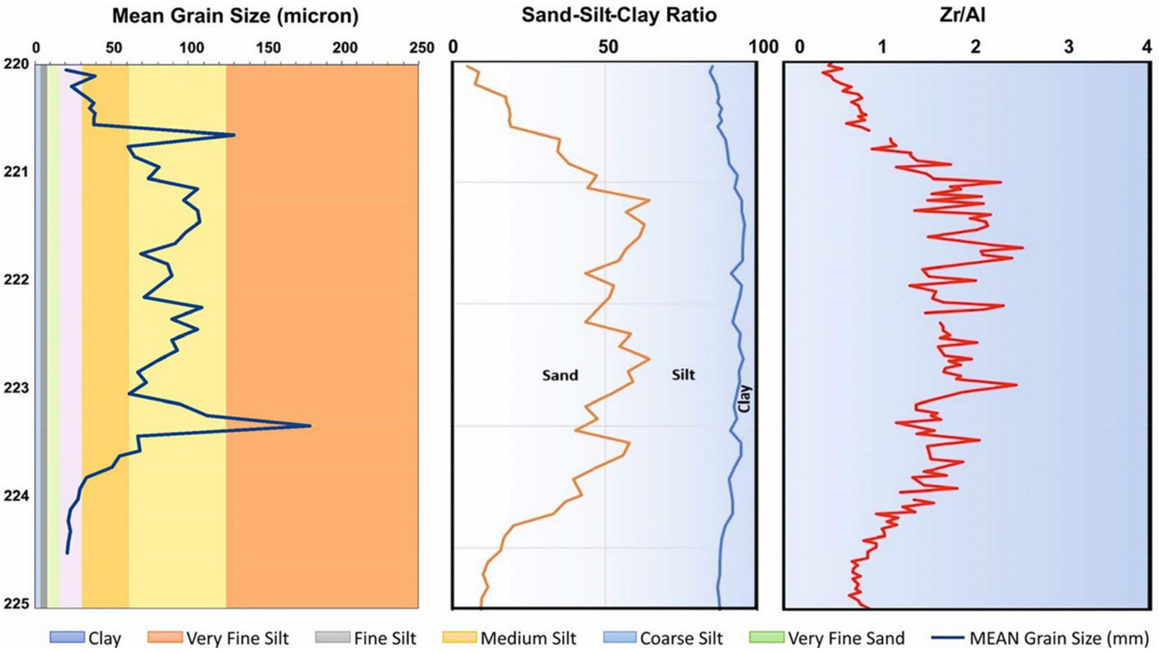

Fig. 5 Variation in the mean grain size and sand percentage in a sediment facies sequence from Gulf of Cadiz. This pattern of change matches the pattern in Zr/Al ratio, a geochemical proxy to the deep-water current strength. Data provided by E Ducassou, S de Castro and A Bahr.

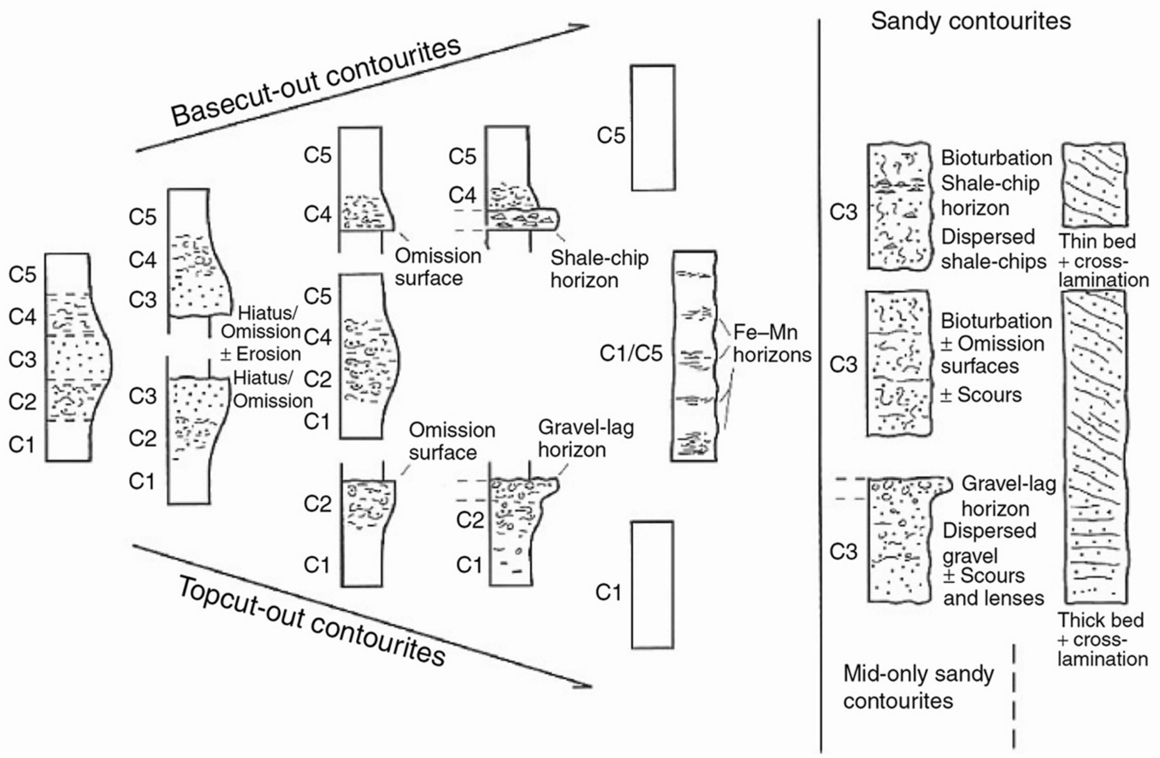

Fig. 6 Variations on the standard contourite facies models showing the range of contourite facies, sequences and partial sequences commonly encountered in contourite successions (Stow and Faugères, 2008).

Sediment cycles refer to the alternation of complete and partial contourite sequences (as described above), which appear to be ubiquitous in most contourite successions. They are somewhat irregular in thickness and duration, with the current best estimate of periodicity for individual cycles being 3000–8000 years. Grouped sequences may show a periodicity up to 20,000 years, and carbonate-rich contourite successions appear to have still longer periodicity (20,000–40,000 years approximately) (Hüneke and

Stow, 2008). Whereas these longer-duration cycles may also be linked with Milankovitch-scale climate oscillation, the cause of the millennial-scale cyclicity is not yet understood.

These sediment cycles are most likely due to sub-Milankovitch climate oscillation, current-related variation or both. In addition, it is not easy to differentiate the relative importance of current velocity versus sediment supply in the development of contourite sequences, so that some of the cycling may be wholly due to supply variability that is not linked with bottom-current fluctuations. Cycle irregularity is likely to result from interaction of sediment supply and current velocity.

Ancient Contourites in Outcrop

Whereas there is a growing body of literature on ancient (or *fossil*) contourites exposed in outcrop, from Cambro-Ordovician to Neogene in age, there is still considerable debate surrounding their accurate identification and characteristics. Indeed, it is both difficult and time-consuming to recognize contourites in the ancient record, so that many erroneous examples have appeared in the literature. It is simply not possible to identify contourites from direct observations in the field or borehole alone. Rather, a careful three-stage approach is required, as put forward in several earlier publications (Stow et al., 1998, 2002; Hüneke and Stow, 2008).

The principal examples for which this three-stage interpretation is most persuasive, to date, are mainly carbonate-rich facies or calci-contourites. These include: (a) Miura slope contourites, Neogene, SE Japan; (b) Lefkara contourite drift, Oligocene, Cyprus; (c) Chalk contourite drifts, late Cretaceous, Danish Basin; (d) carbonate contourites, Devonian, Morocco, Germany and Austria; (e) Jiuxi contourite drift, Ordovician, Hunan, China. Details on each of these are provided in Hüneke and Stow (2008). Two contrasting examples are briefly described below.

The *Lefkara Carbonate Drift* has been put forward as a type example of fossil contourites (Kahler and Stow, 1998) and is currently undergoing further intensive research. The principal characteristics identified include:

Small-scale: Calcilutite, calcisiltite and calcarenite facies occur in bi-gradational sequences (0.5–2.5 m thick), with a distinctive thin-bedded lenticularity of the calcarenite facies. For the most part, they are bioturbated and burrowed throughout. The microfacies are dominantly packed biomicrites, including wackestones and foraminiferal packstones, with the finer beds and pelagites being sparse biomicrites.

Medium-scale: The upper parts of the Lefkara Formation shows notable variation in thickness across southern Cyprus from little more than 10 m to over 200 m, which is consistent with deposition as part of a contourite drift system. Extensive calcarenite horizons, which extend over at least 80 km laterally, may represent a contourite terrace system. A widespread hiatus (or hiatuses) in sedimentation is everywhere present for the Mid-Oligocene interval, consistent with bottom-current erosion and winnowing.

Large-scale: Tectonic reconstruction of the region shows that the Lefkara Formation as a whole was deposited in the closing Tethys Ocean, in a basin plain to distal slope apron setting. Paleo-water depths have been estimated at between 2000 and 3000 m, and land was at least 50–80 km away to the north. The nature of bottom circulation in the closing Tethys during the Oligocene is not well known, but continued constriction of the Tethys at this time may have led to intensification of both surface and bottom current systems, which is reflected in the development of regional hiatuses and contourite drifts.

The *Rifean Sandy Drift* is an example of a siliciclastic contourite system that has recently been identified in the upper Miocene succession of the Rifean Corridor in northern Morocco (Capella et al., 2017). The principal features of this system include:

Small-scale: Encased in a thick succession of silty marls, of hemipelagic or muddy contourite origin, there are several, mainly siliciclastic sand-rich units, from 5 to 50 m thick. These occur as: (a) a series of stacked sandstone beds with large-scale (up to 1.5 m sets), unidirectional cross-bedding; and (b) isolated, tabular sandstone beds (up to 50 cm thick), with parallel lamination, cross-bedding, and bioturbation, which form part of bi-gradational sequences.

Medium-scale: The location and extent of these sand bodies suggest that they were elongate patch drifts within the northern sector of the Rifean Corridor. Lack of outcrop precludes accurate determination of their geometry, but they can be traced laterally up to 10 km. Erosion and hiatuses are also evident. Furthermore, seismic facies representing elongated mounded drifts and associated moats are present at the western mouth of the seaway.

Large-scale: The Rifian Corridor was a seaway between the Atlantic Ocean and the Mediterranean Sea during the late Miocene, through which there was an exchange of Atlantic inflow at the surface, and Mediterranean outflow (bottom current) in the lower part of the water column, analogous to the present-day exchange through the Gibraltar Gateway. As the seaway progressively closed, leading to the Messinian Salinity Crisis in the Mediterranean Sea, bottom current pathways in the South Rifian Corridor intensified.

The planktic and benthic foraminifera indicate a paleo-depth for the encasing marls of 150–300 m, so that the sand bodies can be considered as shallow-water contourites. The geostrophic bottom current was likely strongly influenced by tides.

Significance and Debate

Nature of Deposition

Contourites are the result of continuous rather than episodic deposition under semi-permanent bottom current systems. Average rates of sedimentation typically range from 10 to 100 cm ky^{-1}. However, there is also marked variation within this "continuous" deposition at several different scales, caused by external drivers:

1. Benthic storm events
2. Large-scale current eddies

3. Variation in sediment supply
4. Cyclic fluctuation in bottom-current velocity
5. Long-term change in bottom-currents.

The shorter (subannual) variations resulting from benthic storm events are likely to cause some of the specific features *within* the contourite sequence, such as sharp or erosional contacts, coarse-grained lenses, and nondeposition surfaces. Subtle color banding, ichnofacies changes, and variation in certain proxy measurements (e.g., magnetic-susceptibility characteristics), appear to occur with a mean centennial-to-millennial periodicity. These may be linked to bottom-current changes due to eddy generation and cycling, or to periodic spillover of bottom water through oceanic gateways.

The contourite characteristics documented in a previous section are all commensurate with transport of a very low-concentration suspended load within the bottom current, and a coarser-grained bedload, where the current velocity is higher. The finest material (<10 μm) is most likely carried in the form of larger aggregates, flocs and fecal pellets, which are deposited directly from suspension and broken up during deposition through the benthic boundary layer by a process of flow shear. These are more or less hydrodynamically equivalent to the silt fraction between 10 and 63 μm, which is referred to as sortable silt and used as an indicator of flow velocity (McCave et al., 1995). Deposition of this material forms the muddy and silty contourites, with progressive winnowing and removal of the fine fraction as flow velocity increases. Fine sands are also carried in suspension, whereas medium and coarse sands form part of the bedload and are moved largely by traction along the seafloor.

Contourite Controversies

Contourites have led to much debate and controversy since they were first described over 60 years ago. Although what is presented in the foregoing is now well established and supported by most scientists in the field, there is still some dissent, which we address briefly in order to highlight the continuing debate (Shanmugam, 2000). The particular areas of debate include:

1. *Traction structures*. Some authors claim that traction structures are widespread in all contourite facies. However, we suggest that they are mainly obscured by bioturbation in the finer-grained contourites, and only preserved in medium and coarse sandy contourites. Furthermore, the structures proposed by these authors, we interpret as due to turbidity currents.
2. *Facies model*. Whereas this has been demonstrated and validated from a wide range of drifts worldwide, some authors maintain that it is neither correct nor useful (Shanmugam, 2000). We contest that it is a hugely important signature of contourite sedimentation, but should always be used carefully in conjunction with other scales of observation to ensure accurate interpretation.
3. *Bottom current type*. There are a number of different types of bottom current and some authors propose characteristic deposits for each current type. However, it is not always possible, especially for ancient contourites, to ascertain exactly what type of bottom current system has been responsible for the deposition of a particular sediment. We therefore prefer to leave the interpretation open, unless evidence is conclusive.

Contourite Significance

The scientific and economic significance of contourites has recently been summarized by (Rebesco, et al., 2014), and is more extensively treated in two recently edited volumes (Viana and Rebesco, 2007; Rebesco and Camerlenghi, 2008).

In brief, contourites are one of the three principal sediment types found in the deep oceans. It is therefore essential to document their nature, deposition and distribution, if we are to fully understand the largest part of planet Earth. Furthermore, contourite successions beneath the seafloor hold a very detailed and often expanded record of past ocean circulation and bottom currents, and of how variation in these links with global climate. Their study is therefore a crucial element of paleoceanography and past climate change. The action of strong bottom currents, both by erosion and undercutting of slope sediments, and by rapid deposition of large-scale drifts, can lead to significant slope instability. This is of great significance for the long-term safety and security of submarine cables, pipelines and other seafloor installations. Finally, sandy contourites, in particular, are likely to become one of the most important targets for oil and gas exploration in deepwater in the coming decades.

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