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Contourites in the Gulf of Cadiz: a cautionary note on potentially ambiguous indicators of bottom current velocity

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Abstract Facies associations in cores collected in the deep part of the Gulf of Cadiz, which is under the influence of the lower branch of the Mediterranean Outflow Water, are investigated in terms of the classical contourite model using grain-size analyses and thin sections of indurated sediment. Cores include both low-energy (contourite drift) and high-energy (channel) environments. The thin sections and grain-size distributions show that clayey fine silts and sandy coarse silts are the most common facies associations in the studied contourite sequences, while coarse-grained, gravelly contourites are less common. Grain-size distributions are unimodal in the fine-grained and bi- or trimodal in the coarser-grained contourites. This change in grain-size composition is related both to the partial removal of the fine-grained fraction and to the replenishment of the coarser-grained one. In addition, most of the contacts between individual facies are sharp rather than transitional. This suggests that the contourite sequence is only in part related to changes in bottom current velocity and flow competency, but may also be related to the supply of a coarser terrigeneous particle stock, provided by either increased erosion of indurated mud along the flanks of confined contourite channels (mud clasts), or by increased sediment supply by rivers (quartz grains) and downslope mass transport on the continental shelf and upper slope. The classical contourite facies association may therefore not be solely controlled by current velocity, but may be the product of a variety of depositional histories. The classical contourite depositional sequence should therefore be interpreted with greater care and in the light of the regional sedimentological background. In addition, the wisdom of exclusively using mean or modal particle size for the interpretation of depositional contourite processes is questioned. Instead, it is proposed that the vertical evolution of grain-size populations in the facies successions forming contourite sequences be assessed.

Introduction

The classical contourite sequence depicting a model for deposition from deep-marine contour currents (Hollister 1967) was originally proposed by Gonthier et al. (1984) and Faugères et al. (1984) using data on cores collected from the Faro Drift in the Gulf of Cadiz off the SW Iberian Peninsula (Figs. 1 and 2a). It was first defined for deposits related to sediment transport and deposition by thermohaline circulation or geostrophic currents (Stommel 1958) related to deep-water masses of different temperatures and salinities (Heezen et al. 1966) and known as the "conveyor belt" (Broecker 1991). These deposits form most of the sediment drifts. The contourite concept was extended later to deposits reworked by other deep-sea currents including wind-driven currents, internal tides and other loop currents related to cyclones (see related references in Shanmugan 2012). The model was first applied to clay- and silt-dominated (= muddy) contourites (mud contents of up to 95 %) and later extended to sandy contourite facies by Stow (1994) and used to build a conceptual, idealized contourite sequence model (Stow and Faugères 2008).

The classical scheme comprises two superposed units: a basal coarsening-up unit grading from fine homogeneous

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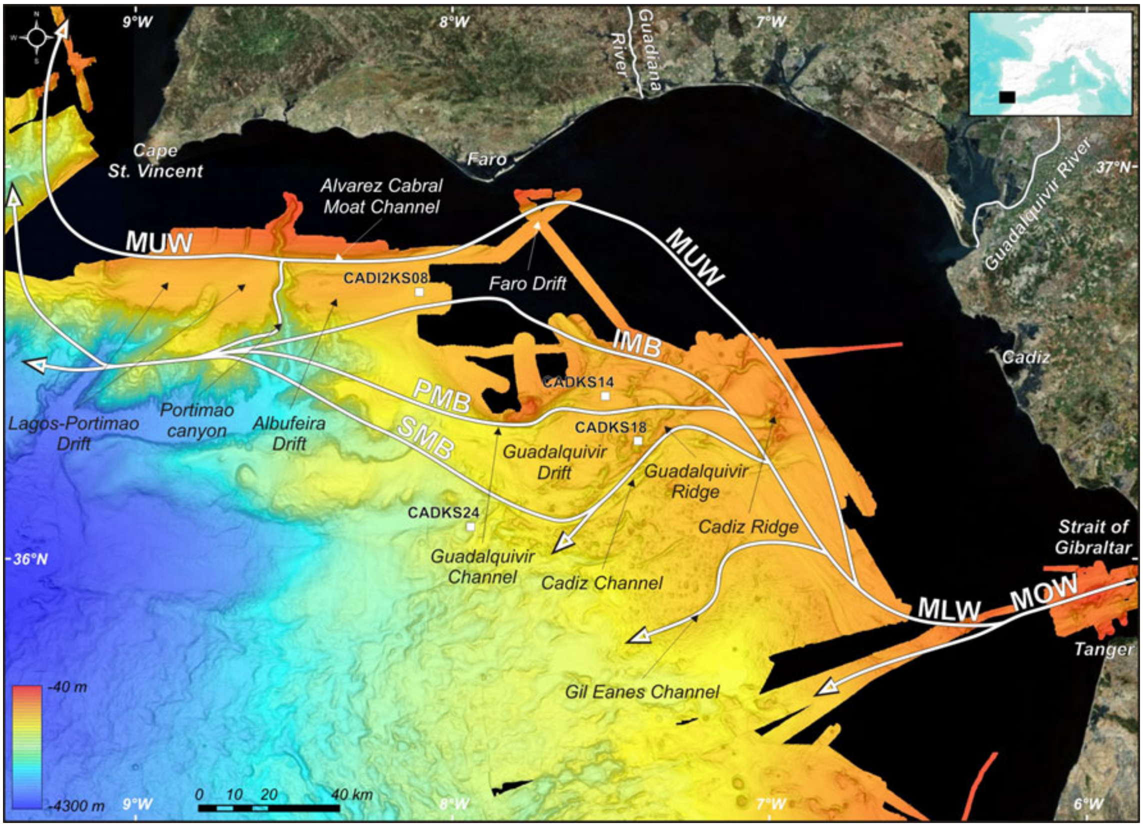

Fig. 1 The study area in the Gulf of Cadiz, with an overview of Mediterranean Outflow Water (*MOW*) circulation, the main morphological features (including the Guadiana and Guadalquivir rivers), and the locations of the four cores selected for the study. The bathymetry (EM 300, Cadisar 1 and 2 cruises) is extracted from Mulder et al. (2003, 2006). *MUW* Mediterranean Upper Water, *MLW* Mediterranean Lower Water, *IMB* Intermediate MOW Branch, *PMB* Principal MOW Branch, *SMB* Southern MOW Branch

mud (clayey fine silt) to mottled coarser silt and finally sandy silt/silty sand, followed by a fining-up unit showing the same facies succession in reverse order (Fig. 2a). This is nicely illustrated in Fig. 2b, which shows a section of a core recovered by T. Mulder and colleagues from the Faro Drift (Cadisar cruise 2, 2004, core CADI2KS08). In the corresponding upcore grain-size distributions (Fig. 2c), curves A and D represent the basal/top mud facies having a typical bimodal shape reflecting the mixing of a subordinate sandy coarse silt and a dominant clayey fine silt population. This bimodal distribution in the terrigeneous silt fraction was already underlined by Robinson and McCave (1994), McCave et al. (1995a, b), and Bianchi and McCave (2000). Curves B and C are also bimodal but with a dominant sandy silt/silty sand and a subordinate clayey fine-silt population. This so-called mottled facies corresponds to a sandy mud facies containing coarse silt lenses resulting from infilled polychaete burrows.

Using mean grain size as indicator, the change in sediment composition has hitherto been interpreted as being associated with a change in bottom current competency and velocity. This idea emerged because, differently to what happens in turbidity currents, contour currents (whatever their origin) act as a winnowing machine generating sediment resuspension by tractive (bed load) transport (Allen 1984) of already deposited particles. The sorting of particles is particularly efficient (Shanmugan 2012). Thus, winnowing intensity and current competency can both be related to current speed, although this concept must be applied with care when dealing with aggregation processes affecting fine-grained cohesive particles. This interpretation is based on the "sortable silt" concept of McCave et al. (1995b), who considered that the non-flocculated fraction can be used as a proxy for current velocity and that the mean (modal) grain size can serve to reconstruct current strength and be interpreted in terms of climate variation (McCave et al. 1995a, b; Bianchi and McCave 1999; Bianchi et al. 2001). This model has been successfully applied to fine-grained sequences examined by Toucanne et al. (2007) in a core collected in the neighbourhood of the present study area, in the low-energy Faro-Cadiz sheeted drift. It shows silt–clay facies (most abundant), clayey silt (mottled) facies and rare clayey sand facies. All the facies have a bimodal grain-size distribution, and are organized into vertical coarsening- and

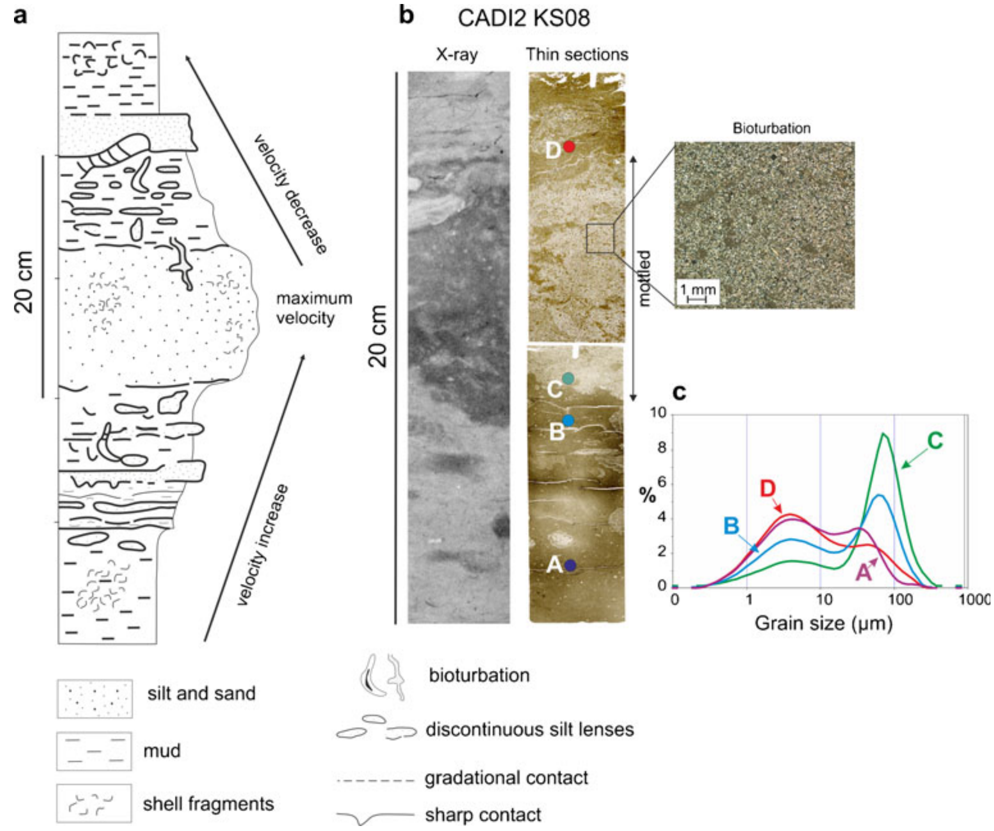

Fig. 2 Classical contourite sequence. **a** Conceptual scheme (extracted from Gonthier et al. 1984). **b** Core CADI2KS08, Faro Drift (see Fig. 1 for core location): X-ray image and indurated thin sections. **c** Typical grain-size distributions

then fining-up sub-sequences bounded by progressive contacts. They have been interpreted as classical contourites deposited by a current with initially steadily increasing velocity, followed by a decrease in velocity. During periods of increasing current velocity, the coarser mode becomes predominant while the finer diminishes, suggesting significant winnowing of fine particles during periods of enhanced bottom current activity (Hernández-Molina et al. 2003, 2006; Llave et al. 2006).

Stow and Faugères (2008) extended the model to sandy contourites and published a generalized composite contourite model consisting of the superposition of a negatively graded lower sub-sequence (mud + mottled silt and mud units), a middle sandy silt unit and an upper positively graded sub-sequence (mottled silt and mud + mud units). They again underlined the destruction of primary sedimentary structures by thorough bioturbation, and the rarity of sand. As emphasized by Shanmugan (2012), Stow and Faugères (2008) also stated that this idealized conceptual sequence is never found in totality in natural depositional environments and that, commonly, only base- and top-cut sequences with respectively sharper base and top contacts are encountered, reflecting the abrupt change in current velocity or the presence of a complex seafloor topography which locally modifies the current speed. Upper contacts related to current intensification are more frequent than lower contacts (Hollister 1967).

Although the entire sequence is fully bioturbated, the grain-size signal has evidently been retained, suggesting that it represents longer-term (5,000–20,000 years) fluctuations (acceleration and deceleration) in mean current velocity (Lovell and Stow 1981; Stow et al. 1986) in most terrigeneous or mixed drifts. The recurrence intervals of these oscillations might be greater (20,000–40,000 years) in bioclastic accumulations (Stow and Faugères 2008). Such long-term oscillating energy conditions are one of the main differences between contour currents and waning turbidity currents moving downslope along continental margins (Shanmugan 2012). In fact, Faugères and Stow (1993), Stow et al. (2002), and Stow and Faugères (2008) suggest that most of the sandy contourites can be interpreted as bottom current-modified turbidites. Shanmugan (2006) underlined that the predominance of mud in the Faro Drift could be misleading when attempting to define a generalized contourite facies model. Other authors (e.g. Dalrymple and Narbonne 1996) criticised the use of bioturbation as a diagnostic feature of contourites, although most contourites do show intense bioturbation given the low sedimentation rate and the loading with oxygen and nutrients by bottom currents (Chough and Hesse 1985). For example, Tucholke et al.

(1985) prefer to relate the intensity of bioturbation to the current intensity along the seafloor. Masson et al. (2010) showed that the muddy sand contourite collected in the Faroe-Shetland Channel could result from the incomplete winnowing of underlying sand and that along slope transport is minor. Other sedimentary sequences related to contour currents are the gravel-lag contourites resulting from the complete winnowing of particles ranging in size from mud to sand by powerful bottom currents (Stow et al. 1996), resulting in the preservation of the base-only sequence of the generalized Stow and Faugères (2008) model and biogenic contourites (Kidd and Hill 1986).

Other studies close to the Gulf of Cadiz—for example, on the Galicia margin (e.g. Bender et al. 2012) or in the Mediterranean (e.g. Verdicchio and Trincardi 2008)—have provided evidence for recent (post-Last Glacial Maximum) sedimentation on continental slopes resulting from increased sediment availability (including variations in detrital input, marine productivity and sea-level stands, as well as current velocities). Contourite deposition, however, has been more strongly affected by climatic and sea-level changes rather than tectonics since the Mid-Pleistocene Revolution (Llave et al. 2011). The formation of coarse-grained contourites in the Gulf of Cadiz over the last 50,000 years is thus interpreted to be the result of an intensification of MOW formation and current velocity during cold periods. Sandy-silt contourites are related to the Younger Dryas, Heinrich events (in particular H1 and H2) and stadial Dansgaard-Oeschger events (Mulder et al. 2002; Hanquiez 2006; Llave et al. 2006; Voelker et al. 2006; Toucanne et al. 2007). Conversely, fine-grained contourites are related to warm periods (Bølling-Allerød and Dansgaard-Oeschger interstadials). Such fluctuations in the MOW and other bottom currents, and their implication for late Quaternary climate forcing on slope sedimentation, have also been recorded in the northernmost areas of MOW activity, i.e. along the Rockall Trough and Porcupine Bank, and off Ireland (Øvrebø et al. 2005, 2006). However, an increase in bottom current velocity during sea-level lowstands is not a general rule, but also depends on regional tectonic activity and the presence of a nearby englaciated continental margin (Brackenridge et al. 2011).

The fact that the Gulf of Cadiz is located close to the outflow of the Strait of Gibraltar (Fig. 1) makes it a prime target for the study of contourites, i.e. sedimentary beds deposited by bottom currents following bathymetric contours. Within this context, the main aim of the present paper is to call for caution in interpreting the classical contourite model characterized by a coarsening- and fining-up depositional sequence solely in terms of changes in current velocity because other factors can also explain changes in the grain-size composition of the sediment. It is also demonstrated that mean grain size alone is insufficient for the reconstruction of contourite formation mechanisms and that the temporal (vertical) evolution of the whole grain-size distributions yields much more information for comprehensive interpretations.

Physical setting

The continental margin of the Gulf of Cadiz is exposed to the action of a strong, warm (13 °C) and saline (>37 g l^{-1}) current called the Mediterranean Outflow Water (MOW), which forms in the Alboran Sea (western Mediterranean) and flows into the North Atlantic Ocean (Fig. 1). In detail, the MOW is formed by the superposition of two major flow systems: the Mediterranean Upper Water (MUW; salinity 36.1 g l^{-1}, temperature 11.5 °C; Ambar 1983), which forms the uppermost core funnelled through the Alvarez Cabral Channel, and the Mediterranean Lower Water (MLW; salinity 37.4 g l^{-1}, temperature 13.6 °C; Ambar 1983), which comprises three branches—the Intermediate Branch (IMB), which flows between 700 and 900 m water depth, the Principal Branch (PMB) between 900 and 1,000 m water depth, and the Southern Branch (SMB) between 1,000 and 1,200 m water depth. Just after the Strait of Gibraltar is passed, part of the MOW is sharply deflected towards the Spanish and Portuguese margins under the effect of the Coriolis force (Madelain 1970). When flowing through the Strait of Gibraltar the velocity of the MOW exceeds 2 m s^{-1} (Fig. 1). Although the mean velocity then rapidly decreases, obstacles can locally accelerate the current along the seabed (García et al. 2009). On average, the velocity reaches only 0.2 m s^{-1} off Cape St. Vincent (southwest Portugal), where the MOW lifts off the seafloor at about 1,400 m water depth.

The bathymetric map (Fig. 1) shows that the seafloor morphology in the eastern part of the Gulf of Cadiz is strongly affected by the MOW. In addition, the regional sedimentation patterns have been controlled by the MOW since Messinian times, and the long depositional history therefore excellently reveals the general sedimentary regime in the Gulf of Cadiz. The resulting sedimentary system has been called the Cadiz contourite depositional system (CDS) by Hernández-Molina et al. (2003, 2011). The MOW captures particles supplied by Spanish rivers and also erodes material from the continental shelf (Grousset et al. 1988). Seafloor morphology strongly influences the circulation pattern of the MOW, as is also known from other contourite depositional systems such as those in the Mediterranean (e.g. Palomino et al. 2011). Close to Gibraltar, a gravel lag and large-scale erosional structures (furrows) have been observed (Kenyon and Belderson 1973). Downflow, the deposits become silty with sand patches and sand waves, which is in agreement with the progressive decrease in MOW energy (Kenyon and Belderson 1973; Mélières 1974;

Faugères et al. 1985a; Nelson et al. 1993, 1999). The sedimentary bodies, which occur mainly in valleys between adjacent ridges through which the MOW is channelized, show a progressive downflow decrease in grain size. On the seaward side of the channels, the MOW velocity decreases sharply and fine particles are deposited to form thick successive sediment accumulations, so-called contourite drifts (Mougenot and Vanney 1982). Of these, the Faro, Albufeira, Portimao and Lagos drifts are formed by the MUW, whereas the Guadalquivir Drift is formed by the MLW (Llave et al. 2007; García et al. 2009). The drifts are composed of muddy sediments and grew in size from the Messinian to the Present after the Mediterranean–Atlantic connection was formed (Faugères et al. 1985b). Despite the presence of erosional surfaces within the drift sequences (Llave et al. 2006), deposition in the contourite drifts is mostly continuous, thus enabling good palaeoceanographic reconstructions (e.g. Voelker et al. 2006; Toucanne et al. 2007). It is for this reason that the original contourite type sequence was described from this region (Gonthier et al. 1984; core CADI2KS08, Figs. 1 and 2). In the western part of the Gulf of Cadiz, the energy of the MOW is low and sedimentation therefore dominated by downslope gravity processes responsible for creating the classical seafloor morphology characterized by canyons and gullies.

Another part of the MOW flows westwards and, after spilling over a topographic high, strongly decelerates to deposit its load in the form of extensive fields of sediment waves in the 1,000–1,200 m depth interval (Fig. 1). This flow may be partly channelled through large conduits such as the Gil Eanes Channel. The deceleration after spillover results in high sedimentation rates forming the giant contouritic levee identified by Mulder et al. (2003). These high sedimentation rates in association with active seismicity in the Gulf of Cadiz and neighbouring areas (Zitellini et al. 1999; Gutscher et al. 2002) have generated numerous slope failures on the leeward side of the levee (Mulder et al. 2009).

Material and methods

This study is based on grain-size analyses and indurated thin sections of four Kullenberg cores collected along the pathway of the MLW during two cruises aboard the RV *Suroît* (see Fig. 1 for locations): core CADI2KS08 (cf. above, Cadisar 2 cruise, September 2004), and cores CADKS14, 18 and 24 (Cadisar 1 cruise, August 2001). Mulder et al. (2003, 2006) have provided some preliminary information on the physical setting characterizing these cores.

The typical contourite sequence (Fig. 2) sampled in core CADI2KS08 (36°40.890′N, 08°06.240′W, water depth 789 m) is from the sheeted part of the Faro Drift affected by the MLW/IMB. This sequence is dated from the Younger Dryas (Gonthier et al. 2010). Core CADKS14 (36°24.998′N, 07°31.044′W, water depth 738 m) is located on the Guadalquivir Drift close to the Guadalquivir Channel affected by the MLW/PMB. The studied sequence in this core is dated from Marine Isotopic Stage 3 (Gonthier et al. 2010). It should represent classical sedimentation within a contourite drift, similar to core CADI2KS08 from the Faro Drift. It was chosen for this study because it is affected by the same water mass as cores CADKS18 and CADKS24, i.e. the MLW.

Core CADKS18 (36°18.08′N, 07°24.78′W, water depth 1,001 m) is located southeast of the Guadalquivir diapiric ridge, in a circular topographic low interpreted as a dissolution depression, and is affected by the MLW/SMB. No clear dating could be obtained on this core because of intense reworking. Core CADKS24 (36°04.944′N, 07°56.523′W, water depth 1,316 m) is located in the very distal part of the Cadiz CDS, in the south-western sector of the Cadiz Channel, and also affected by the MLW/SMB. The thin section has been deposited during the Last Glacial Maximum (Gonthier et al. 2010). Core interpretation shows the superposition of muddy contourites with silty sand intercalations.

Indurated 30-μm thin sections of soft sediment were obtained according to the impregnation protocol described by Zaragosi et al. (2006). Fresh core samples were dehydrated sequentially in acetone, and hardened with an epoxy resin. Fluorescent dye was added to the resin to enable subsequent fluorescent light analysis by which indurated and non-indurated parts can be distinguished. The bonded blocks were cut to approximately 100 μm using a precision saw and thereafter hand polished to a thickness of 30 μm by means of a rotating lapidary unit. Thin-section images were acquired under a fully automated Leica DM6000 B digital microscope at multiple magnifications.

Bulk sediment subsamples were taken for grain-size measurements using a Malvern MasterSizer S (0.05 to 878.67 μm). Mud is defined as the <63 μm fraction, i.e. silt and clay (Twenhofel 1937; cf. also Flemming 2000).

Results

In the selected cores, three contourite facies are observed: muddy contourites (Fig. 3, core CADKS24), silty contourites (Figs. 4 and 5, cores CADKS14 and CADKS18) and gravelly contourites (Fig. 5, core CADKS18). Muddy and silty–sandy contourites represent the typical facies of the base/top and middle contourite sequences respectively (cf. Fig. 2, core CADI2KS08). Gravelly contourites represent a more unusual facies in higher-energy environments (Stow and Faugères 2008). An intermediate facies composed of sand is not represented in the available data. Such a facies would represent lag deposits in contourite channels (Hernández-Molina et al. 2003; Hanquiez et al. 2007). Sandy contourites also form

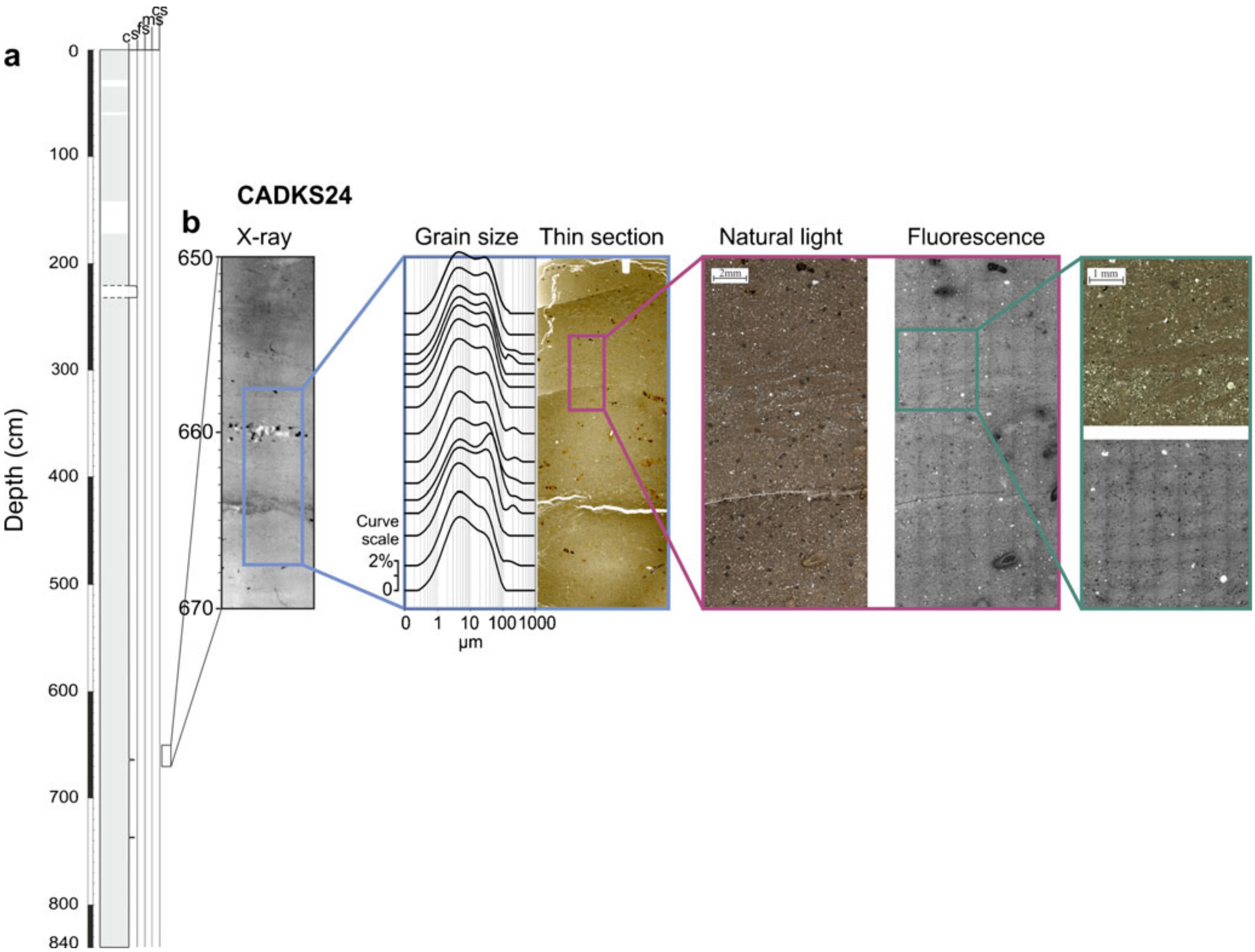

Fig. 3 Core CADKS24, distal sector of Cadiz contourite depositional system. **a** Core log (*c* clay, *s* silt, *fs* fine sand, *ms* medium sand, *cs* coarse sand; see Fig. 1 for core location). **b** Muddy contourite: X-ray, grain size, and indurated thin sections under natural light and fluorescence

cm-thick beds in cores recovered from essentially fine-grained contourite drifts (Gonthier et al. 1984) and correspond to periods of increased MOW velocity (colder climate periods) or represent coarse-grained deposits within contourite channels mostly in the so-called ridge and channel sector of the CDS (Hernández-Molina et al. 2003; Hanquiez et al. 2007, 2010). These would be interpreted in a similar way as the gravelly contourite facies illustrated in this paper.

Most of the deposits in contourite drifts are composed of muddy sediment (Fig. 3; Gonthier et al. 1984). This is also the most common facies found in the classical contourite sequence (Fig. 2). The muddy contourites are composed of clay and fine silt with subordinate contributions of coarse silt and sand. Grain-size analyses (Fig. 3) show distributions with a high peak located in the clay–fine silt range extending from 3 to 30 µm.

The silty contourites (Fig. 4) show a vertical superposition of clayey fine silts alternating with coarse silt–fine sand, the former corresponding to the so-called mottled facies. Thin sections clearly show that the transitions between the two facies are sharp rather than continuous (c1 and c2 in Fig. 4). Grain-size measurements along the thin sections confirm the sharp transition between the mottled mud and the coarse silt–fine sand facies. Below the sharp c1 contact, the quartz particles have a modal diameter of about 10 µm (fine silt), whereas above the sharp c1 contact the grain-size distribution curves are bimodal with a second peak around 40 µm (medium to coarse silt), thus revealing the arrival of a coarser quartz silt population at this study site. This change in sediment composition corresponds to the transition from the fine-grained mud facies to the muds containing silt lenses within the mottled facies. The silt deposits are laminated, the laminations being enhanced by several millimetre-long elongated clasts of mollusc shells (ms in Fig. 4). Above the sharp c2 contact, the grain-size distribution becomes trimodal, signifying the arrival of a third particle group having modal diameters ranging from 100 to 110 µm. This population also consists of quartz grains and includes a few indurated sand-sized mud clasts.

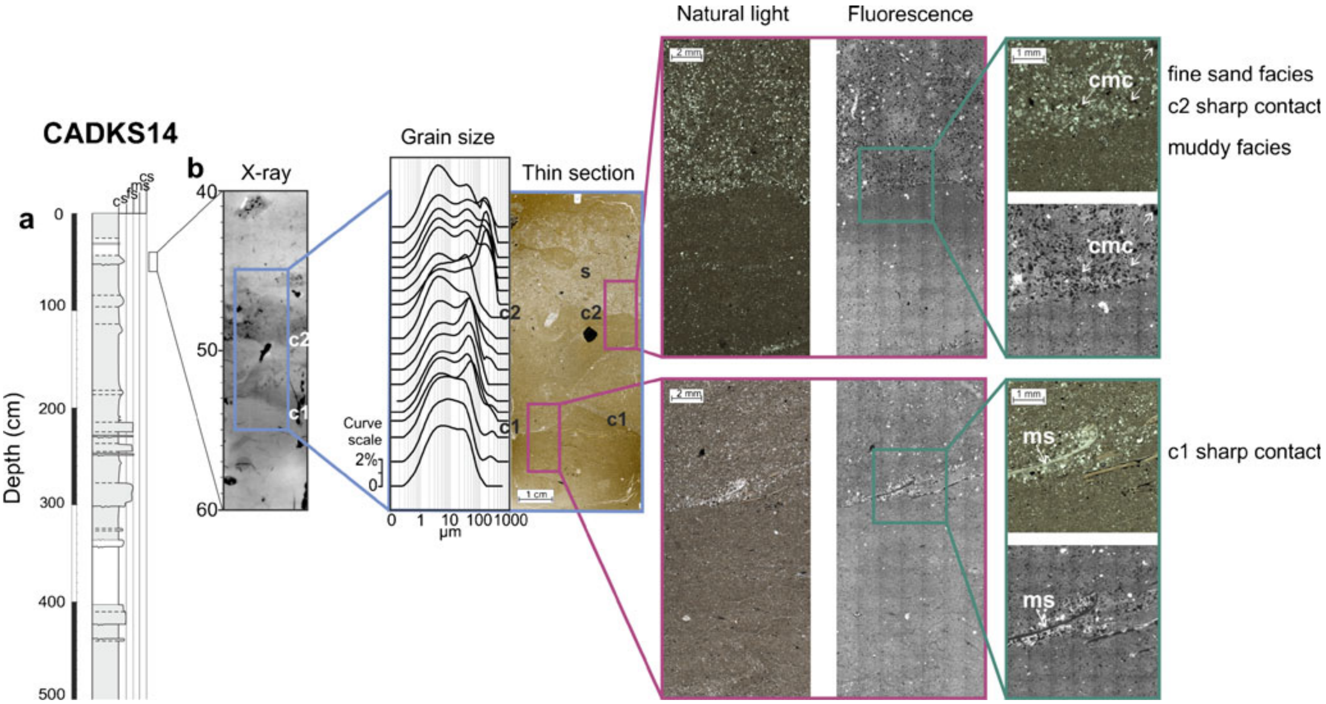

Fig. 4 Core CADKS14, Guadalquivir Drift. **a** Core log (see Fig. 1 for core location and Fig. 3 for legend). **b** Silty contourite: X-ray, grain size, and indurated thin sections under natural light and fluorescence; *c1*, *c2* sharp contacts, *s* sand, *ms* mollusc shell, *cmc* consolidated mud clasts

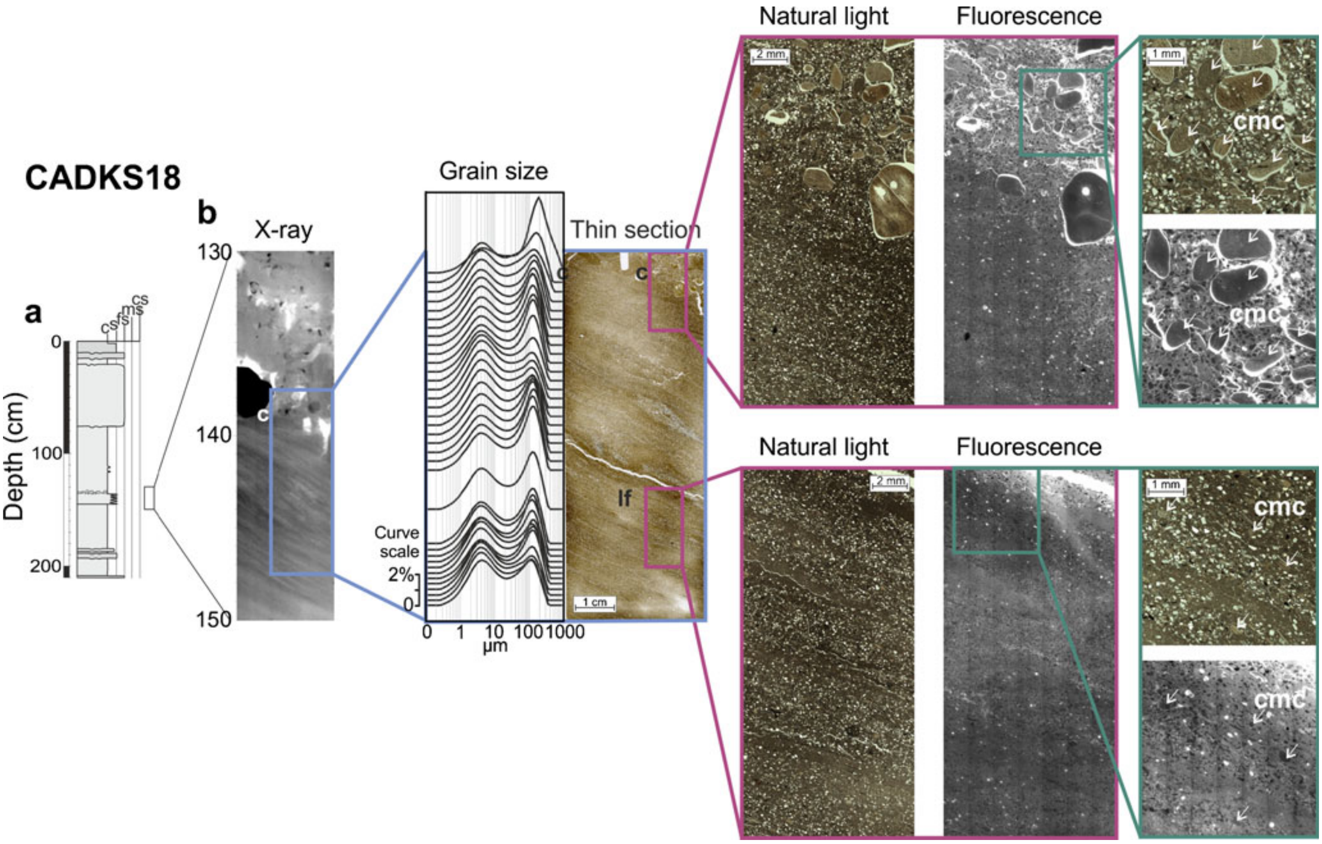

Fig. 5 Core CADKS18, topographic low near Guadalquivir Ridge. **a** Core log (see Fig. 1 for core location and Fig. 3 for legend). **b** Laminated and gravely contourite (lower right panel extracted from Faugères and Mulder 2011): X-ray, grain size, and indurated thin sections under natural light and fluorescence; *c* contact, *lf* laminated facies, *cmc* consolidated mud clasts

Figure 5 shows a thin section with a similar superposition of several alternating laminae composed of mud and very fine sand. In these silt-dominated contourites, the grain-size distribution is bimodal, the second particle group having a well-defined modal diameter >110 μm (very fine–fine sand). It is composed of quartz and a few sand-sized indurated mud clasts.

In addition to the change in grain-size composition, the fluorescence analysis revealed a change in the nature of the grains below and above the sharp contacts (Figs. 3, 4 and 5). In the muddy facies below, the dark grains in the fluorescence image consist entirely of quartz. In the silty facies above, by contrast, the dark grains are formed by quartz and sand/silt-sized indurated mud clasts, suggesting that consolidated mud has been eroded along the path of the MOW and subsequently redeposited in the contourites. This is an indication that the facies change corresponds to an increase in flow velocity/competency accompanied by a new input of one or more grain-size populations derived from either an autochthonous source represented by bottom sediment erosion (indurated sand/silt-sized mud clasts) or an allochthonous (external or remote) source supplying sand-sized quartz particles (e.g. by slope failure and turbidite activity, increased river discharge). For example, Rosa et al. (2011) have shown that, during periods of sea-level lowstands, the Guadiana River discharges its bed load directly onto the SW Iberia Shelf. During sea-level highstands, by contrast, the bed load drops out at the river mouth, whereas the suspended load is carried out to sea.

Figure 5 also shows a thin section with a sharp contact between a silty contourite (coarse silt and fine sand) and a gravelly contourite. In the very coarse part above the sharp contact, mm-size grains float in a sandy matrix without showing any preferred grain orientation. Three grain-size populations are observed. The grain-size distributions of the two finest ones have been measured by means of a Malvern microgranulometer and are visible as discrete peaks on the grain-size curves. The coarsest grain-size population is made of aggregated and slightly lithified (darker on the fluorescence image) mud clasts which are visible only in the thin section. This population is still associated with fine grains but in much lower concentrations compared to the mud facies.

Discussion

Thin section analysis shows that most of the contacts between the classical contourite facies (mottled, fine sand, coarse sand) are sharp. This suggests that the facies transitions do not reflect a steady increase in current competency but rather the response to sudden events, consistent with suggestions by Stow and Faugères (2008). The contacts may indicate periods of sediment bypassing with eventual erosion of the bed itself.

In most cases the clayey fine silt population (5–8 μm) remains present in all the facies (Fig. 3). Consequently, the increase of the mean grain size in contourite facies is not necessarily the result of winnowing of the finest fraction but possibly a consequence of the supply of additional coarser silt particles which change the proportional composition in favour of the coarser fraction. The presence of laminations enhanced by shell fragments and the concentration of quartz grains suggest a discrete grain (sortable silt) input as bed load at the base of the contour current (cf. McCave 2008; Masson et al. 2010). This confirms that bed load transport is a major characteristic of contour current deposition (Shanmugan 2012).

In other cases (Fig. 4b), the grain-size evolution in the superposed facies forming the contourite sequence suggests either a progressive removal of the clayey fine silt population, and a corresponding proportional enhancement of the coarser silt population without the input of new material, or simply a replenishment of the coarser silt population with additional material resulting in its proportional growth relative to the finer population. But once again, the sharp transition between facies suggests that this replacement is not a continuous process.

This interpretation—mud and sand are both transported and deposited by contour currents during periods of increased current velocity combined with increased sand particle supply—is consistent with the hypothesis of Masson et al. (2010). This is also consistent with the clean sand concentrations observed in all channels of the Gulf of Cadiz (Hanquiez et al. 2007), and explains the better sorting of sandy contourites when compared to sandy turbidites as suggested by Shanmugan (2012).

Classical interpretations using Huljström- or Shields-type diagrams suggest that a progressive increase in flow velocity is necessary to erode and transport particles corresponding to non-cohesive clay and fine silt, coarse silt, fine sand, cohesive mud and coarse sand, in that order. This is consistent with the classical interpretation of the increase in the mean grain size in contourite sequences. However, the fact that the increase in mean grain size can result from both the removal of the finer fraction and/or a new supply of coarser grains suggests that contourite sequences cannot only be interpreted as simply reflecting an increase in flow competency. A slight increase in flow velocity can certainly be responsible for the progressive removal of the finest grains if these are non-cohesive. In addition, a more substantial increase in current velocity may involve the mobilisation and downstream transport of “new” particles which may consist (1) of autochthonous indurated mud clasts eroded from upstream contourite channel flanks, and/or (2) of allochthonous sand- and silt-sized quartz grains derived from more remote (external) sources.

In areas where the current velocity is low, eroded mud clasts would be mixed with the pre-existing particles. The laminated facies (lf in Fig. 5, core CADKS18) suggests that the coarse particle stock is mobilized or supplied rhythmically within the period of contourite deposition. This rhythm is probably masked by the bioturbation in most of the contourite sequences, as represented in particular by the mottled facies where primary structures are rarely preserved. In the case of core CADKS18, however, primary sedimentary structures are preserved because of a lack of bioturbation and erosion, consistent with the core being located in a topographic depression. Although this situation is quite rare, it nevertheless contributes towards a better understanding of how contourite sequences can be generated.

Conclusions

The classical model of a contourite sequence described from the deeper parts of the Gulf of Cadiz, and which has been interpreted as the response to a successive increase and decrease in contour current velocity and competency, is here shown to be potentially more complex than that. This paper also shows that the vertical grain-size evolution and the intensity of bioturbation are good diagnostic criteria for the recognition of contourites. Detailed analyses of grain-size distributions and the identification of grain-size populations have thus revealed a number of additional potential sedimentary processes involved in contourite deposition.

1. An increase in flow velocity can result in the progressive removal of the finest particles, while rhythmic velocity pulses produce alternations of silt- and clay-dominated mud laminae.
2. Rare preserved laminae confirm the importance of bed load transport in contourite deposition.
3. The finer/coarser grain alternations and all primary sedimentary structures can be destroyed by bioturbation, making process–response interpretations difficult but indicate that the deposition of the whole sequence has taken a considerable length of time.
4. Increases in current velocity result in periods of sediment bypassing which are recorded by sharp contacts at the top of the underlying mud facies; these sharp contacts are enhanced by a new supply of coarse particles which are derived either from the erosion of local upstream deposits or from an input of sediment from external sources (e.g. downslope processes).
5. With increasing MOW velocity and, hence, competency, the same facies succession can be derived by either the selective removal of the finer fraction or a supply of new sediment which may be eroded from an upstream autochthonous source—e.g. the side walls of contourite channels (indurated muddy clasts)—and/or an external allochthonous source supplying a new stock of coarser-grained quartz derived from remote sources such as high river loads during cold periods. Either process enhances the proportional contribution of one population relative to the other.
6. The concept of sortable silt can be used in interpreting grain-size distributions in contourites but should be associated with a determination of the nature of the grains and/or clasts constituting the deposits.

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