

CHAPTER 11

BIOTURBATION AND BIOGENIC SEDIMENTARY
STRUCTURES IN CONTOURITESA. Wetzel, F. Werner *and* Dorrik A.V. Stow

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11.1. INTRODUCTION

Modern contourite drifts exhibit a typical overall geometry and internal stratigraphic configuration that can be distinguished from other sedimentary deposits based on seismic-reflection data analysis (Stow et al., 2002c). Because of a lack of information about large-scale drift geometry, as well as concerning the local palaeoceanographic and palaeobathymetric conditions, contourite deposits are, however, much more difficult to recognize in cores or outcrops (Stow et al., 1996b, 1998). In addition, small-scale primary sedimentary structures that might otherwise be diagnostic are generally scarce or lacking due to bioturbation, except for specific cases, for

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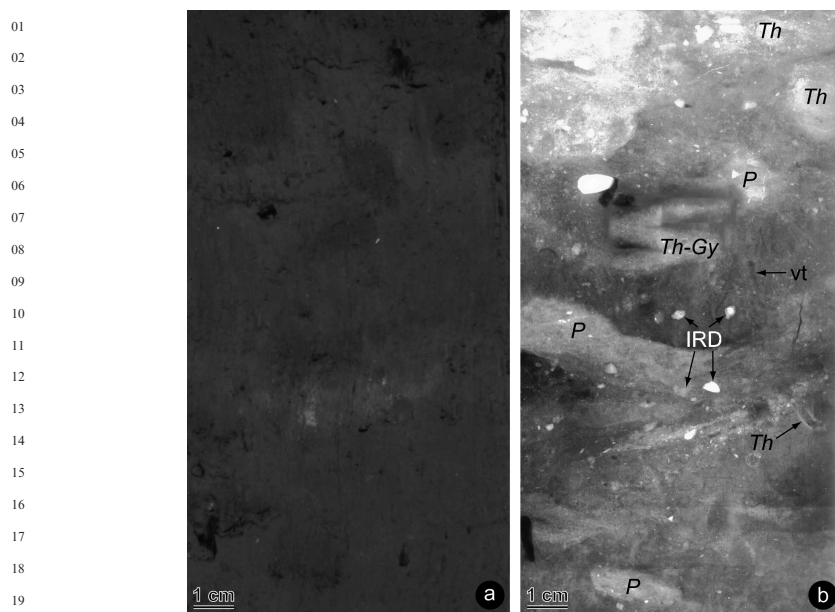


Figure 11.1 Completely bioturbated Late Pleistocene sediments interpreted as contourites. Ice-rafted debris (IRD) has been reworked by bottom currents and bioturbated subsequently. (a) Fresh core surface. Institute of Geosciences Kiel (Germany) core 16820-2, 137–152 cm, from the southern side of the Iceland–Faeroe Ridge, taken at the NW slope of a channel parallel to the ridge crest (62°35.56'N, 14°18.62'W, 1649 m water depth). (b) X-radiograph (negative; coarse material is light, fine-grained material dark) of the same interval. Note how much more detail is observed in X-radiographs compared with fresh core. *P* = *Planolites*; *Th* = *Thalassinoides*; *Th-Gy* = *Gyrolithes*-like *Thalassinoides*; vt = vertical tube.

instance, when the sedimentation rate exceeds the bioturbation rate (Figure 11.1; see also Martin-Chivelet et al., 2008).

The overall accumulation rate of contourites is low because contour currents are generally very low-concentration flows and because episodes of winnowing and erosion alternate with deposition (Gross and Williams, 1991). Slowly accumulating, well-oxygenated deep-sea sediments are normally completely bioturbated (Wetzel, 1991; Bromley, 1996). Burrowing animals displace and, eventually, destroy primary sedimentary structures. In contrast, the resulting biogenic sedimentary structures provide valuable information about environmental conditions at the sea floor, because endobenthic organisms respond sensitively to oceanographic and sedimentary changes (Schäfer, 1962; Ekdale et al., 1984; Wetzel, 1991). Numerous studies deal with strong bioturbation of contourites as evident in visual examination of fresh cores (several contributions in Stow et al., 2002f). Only a few studies, however, address bioturbation structures in more detail based on analysis through high-quality X-radiograph images. These reveal much more detail than is possible with visual core analysis alone (Fu and Werner, 1994; Baldwin and McCave, 1999; Löwemark et al., 2004b).

The purpose of this chapter is to present a compilation of information available on bioturbation, bioturbation structures and the resultant ichnofabrics in contourites.

11.2. EFFECTS OF CONTOUR CURRENTS ON BENTHIC HABITATS

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Contour currents are typically produced by movement of well-oxygenated cold water masses formed at high latitude in the Pacific and Atlantic Oceans (Stow et al., 1996b; Salon et al., 2008; Shanmugam, 2008; Zenk, 2008). The mean flow velocity of contour currents is in many cases between 10 and 30 cm s⁻¹ (McCave et al., 1980; Stow et al., 2002c). On a short-term scale (a few days to several weeks), however, the current speed can fluctuate between a state of quiescence and that of benthic storms (>70 cm s⁻¹; Richardson et al., 1981). As a consequence, contour currents may re-distribute sediment particles on the sea floor (winnowing and erosion) and/or take up suspended particles settling in the water column. Bottom currents may thus carry in suspension a considerable amount of fine material (<2–12 μm) and particulate organic matter (McCave, 1985a; Thomsen et al., 2002), which form the so-called nepheloid layer (Ewing and Thorndike, 1965).

Because suspended organic matter is often adsorbed onto suspended clay minerals (Mayer, 1994; but see also Thomsen et al., 2002), contour currents supply food to deep-marine benthic organisms (Thistle et al., 1985; Lavaleye et al., 2002). In contrast, the changing bottom-current velocity and resultant alternation of erosion, non-deposition, and deposition, exert physical stress on the benthic habitat. Finally, it is important to note that burrowing leads to a rough sediment surface, which is important for the initiation of sediment transport by contour currents through substrate erosion (Hollister and Nowell, 1991).

11.2.1. Biota

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In the absence of horizontal bottom water flow, benthic fauna is fuelled only by the vertical flux of organic matter, which decreases exponentially with water depth (Suess, 1980). Consequently, the benthic biomass decreases with increasing water depth (Rowe, 1983). Where, however, the vertical particle flux is supplemented by lateral current-carried supply, the benthos exhibits a higher biomass and population density than on adjacent tranquil sea floor (Thistle et al., 1985; Lavaleye et al., 2002).

On the continental slope off Northwest Spain, contour currents move on average at less than 10 cm s⁻¹. The nepheloid layer carries between 2 and 4 g m⁻³ of suspended material, of which 40–100 mg m⁻³ are composed of particulate organic matter (Thomsen et al., 2002). The abundance of benthic megafauna across the continental slope does not decrease with depth, as would be expected in the absence of bottom currents (Lavaleye et al., 2002). The bottom currents sustain a benthic population dominated by filter feeders rather than deposit feeders.

Northwest of Ireland, at the BENBO (*BEN*thic *BO*undary Layer) experimental sites, at water depths of 1100 m (Rockall Plateau), 1925 m (Feni Drift) and 3750 m (Porcupine Basin), local hydrodynamic conditions, controlled by contour currents of variable intensity, affect the relative contribution of the mega-, macro- and meiofauna to the benthic biomass (Gage, 1979; Hughes and Gage, 2004).

At the HEBBLE (*High Energy Benthic Boundary Layer Experiment*) site off Nova Scotia in about 4800 m water depth, also affected by bottom currents, the

01 macro- and meiofauna are on average much more abundant than expected and
 02 compare to that 2000 m shallower (Thistle et al., 1985). Due to the repeated
 03 physical disturbance induced by bottom water flow, the faunal parameters resemble
 04 those typically obtained in re-colonization experiments (Thistle et al., 1991). With
 05 respect to behavioural groups, suspension feeders are not abundant, probably as
 06 their filter apparatus can easily be plugged when suspension concentration is
 07 periodically very high (Thistle et al., 1991). Only the taxa that passively extract
 08 drifting particles from sea water by maintaining a relief on the sea floor exhibit
 09 increased abundance (Aller and Aller, 1986). Furthermore, mobile organisms that
 10 live both on and within the sediment occur at a higher proportion than at tranquil
 11 sites (Thistle et al., 1985). A high organic-matter flux and physical disturbance by
 12 bottom currents stimulate the production of bacterial biomass on the sea floor,
 13 being 6–8 times higher than at a reference site not affected by bottom currents
 14 (Yingst and Aller, 1982).

15 The following four different hydrodynamic situations can be distinguished
 16 (Aller, 1989, 1997):

- 17 1. High current velocity ($>25 \text{ cm s}^{-1}$) removes sediment, organic matter and
 18 many organisms, in particular epifauna, micro-organisms, larvae and juveniles.
 19 Bacterial biomass is low. High-velocity currents support filter feeders and, to
 20 some degree, surface feeders. After a high-energy event, the fauna recovers
 21 during a long time span dependent on the size of organisms.
- 22 2. Flow deceleration leads to rapid deposition of up to several centimetres of
 23 sediment. Bacteria and meiofauna can rapidly respond to surplus trophic levels
 24 by increasing the standing stock within days to weeks (Hughes and Gage, 2004).
 25 The benthic meio- and macrofauna are at a maximum during these periods.
- 26 3. Intermediate current velocity ($5\text{--}15 \text{ cm s}^{-1}$) results in deposition of fresh organic
 27 matter and removal of metabolites. Microbial production is enhanced. Epifaunal
 28 abundances decrease, but numbers of burrowing and tube-building organisms
 29 increase.
- 30 4. Low current velocity ($<5 \text{ cm s}^{-1}$) leads to a depositional regime. Addition of labile
 31 particulate organic matter favours a significant increase in the standing stock of the
 32 meio- and macrofauna; mean body sizes are larger, and there is greater diversity in
 33 feeding strategies and life habits than encountered in most deep-sea habitats.
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36 11.2.2. Burrowing activity in current-affected settings

37 Benthic organisms mix the sediment so effectively that even short-lived radio-
 38 isotopes exhibit a roughly constant concentration within the so-called surface
 39 mixed layer (Erlenkeuser, 1980). Expressing benthic mixing as a diffusion-like
 40 process, calculated mixing parameters and organic-matter flux appear to be posi-
 41 tively correlated (Trauth et al., 1997).

42 At the HEBBLE deep-water site, sediment mixing is as rapid as in near shore
 43 environments. The mixing rates vary considerably in space and time because
 44 repeated physical reworking occurs before equilibrium has been reached (DeMaster
 45 et al., 1991). The mixing profile is often discontinuous (Thomson et al., 2000), as
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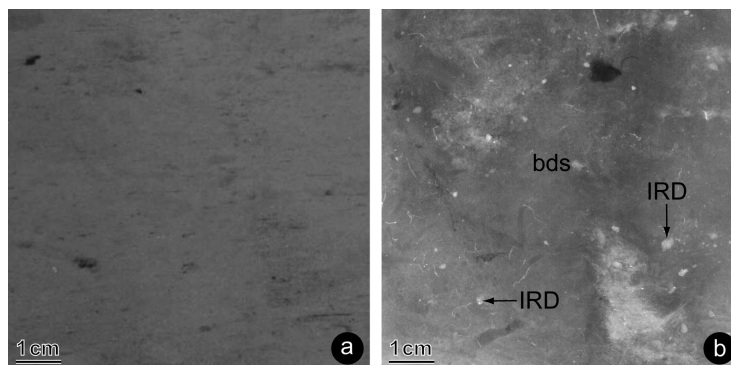
01 burrowing organisms transfer material from the surface of the sediment to distinct
 02 depth (Hughes et al., 2005). Probably due to repeated reworking and deposition,
 03 radiotracers do not outline any obvious link between faunal parameters and mixing
 04 modes (Hughes and Gage, 2004).

06 11.2.3. Bioturbation, trace fossils and ichnofabrics

08 The amount of labile organic matter within the sediment decreases with depth
 09 below the sea floor (Soetaert et al., 1998), followed, in general, by the benthic
 10 biomass (Rowe, 1983). Also the amount of oxygen provided by molecular diffu-
 11 sion from above decreases with depth in the sediment (Glud et al., 1994), forcing
 12 deep-burrowing organisms to maintain an open connection to the sea floor.
 13 Furthermore, the sediments consolidate and become stiffer downward because of
 14 the increased overburden (Einsele, 1977).

15 It follows that the ecospace within the sea floor exhibits a partitioning, and
 16 various burrowing animals occupy specific depth intervals, the so-called “storeys”
 17 (Wetzel, 1981) or “tiers” (Ausich and Bottjer, 1982). A fossil tier comprises trace
 18 fossils that cross-cut each other while being cross-cut by deeper ones (Wetzel,
 19 1981). The fossilization potential of a trace is higher the deeper it is produced
 20 within the sediment, where about 50 cm is the maximum depth at which a
 21 complete tier can be produced in abyssal sediments (Werner and Wetzel, 1982).
 22 It is therefore important to analyse deep-tier burrows to understand whether they
 23 represent responses to environmental conditions at the time of deposition of this
 24 layer or at the time of burrowing.

25 Two types of bioturbation structures are distinguished by Schäfer (1956):
 26 (1) biodeformational structures have indistinct outlines and destroy pre-existing
 27 structures (Figure 11.2); they are, as a rule, produced near the surface, for



41 **Figure 11.2** Ice-rafted debris (IRD) has been reworked by bottom currents and bioturbated
 42 subsequently. The biodeformational structures (bds) destroy pre-existing structures and have
 43 no sharp outlines, but an eddy-like appearance. (a) Fresh core. Institute of Geosciences Kiel
 44 (Germany) core 16820-2, 417–425 cm, from the southern side of the Iceland–Faeroe Ridge,
 45 taken at the NW slope of a channel parallel to the ridge crest (62°35.56'N, 14°18.62'W, 1649 m
 46 water depth). (b) X-radiograph (negative; light: coarse material; dark: fine-grained material).

01 instance, by grazing animals in soft sediments (Thayer, 1979); (2) trace fossils
 02 have distinct outlines and a defined shape allowing classification in terms of
 03 paleontological nomenclature. Some trace fossils occurring in contourites are
 04 shown in Figure 11.3.

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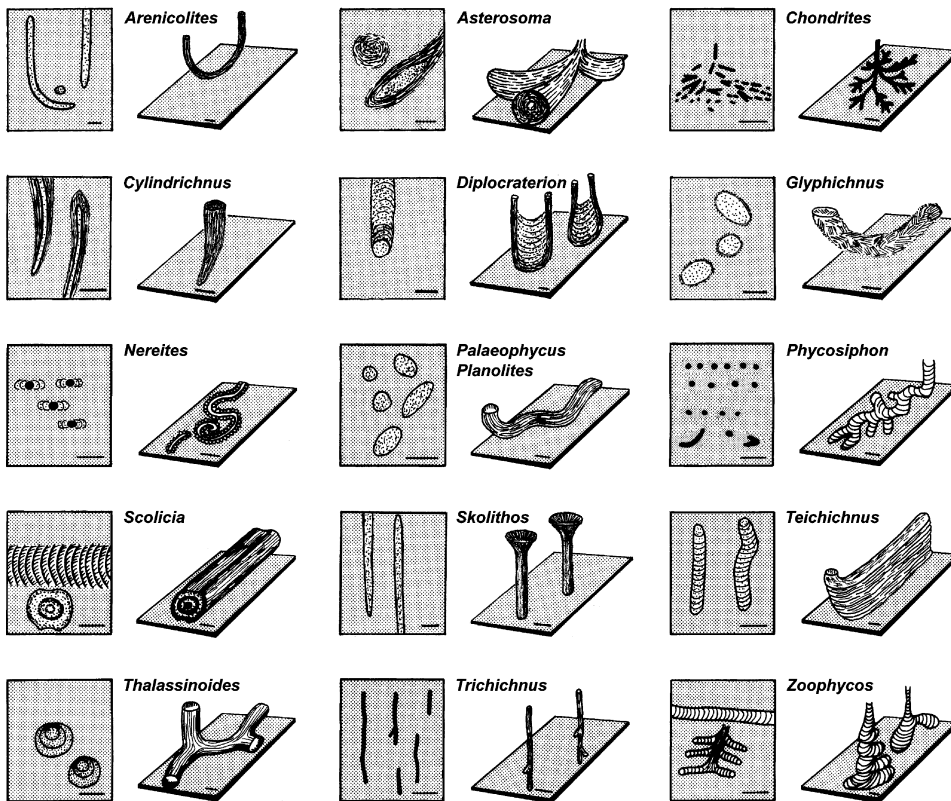
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33 **Figure 11.3** Trace fossils commonly encountered in contourites. *Arenicolites* represents a
 34 vertical U-tube without spreiten; the tube diameter varies between 1 and 2 mm, and the limbs
 35 are 20–60 mm apart. The depth of the burrow is in the range of 20–40 mm. *Asterosoma* consists
 36 of elongate (several centimetres long, a few centimetres wide) bulbous segments with a
 37 terminal or excentric, laminated fill. The segments are oriented (sub)horizontally and are
 38 arranged around a central vertical, somewhat twisted axis. *Asterosoma* occurs in impure
 39 unsorted? mixed? muds, in vertical sections very similar to *Patagonichnus* (Olivero and López-
 40 Cabrera, 2005). *Chondrites* is a three-dimensional, regularly branching tunnel system
 41 consisting of an open connection to the surface and numerous tunnels, which ramify at acute
 42 angles to form a dendritic network. The producers of *Chondrites* appear to tolerate low-
 43 oxygenation conditions (Bromley and Ekdale, 1984). *Cylindrichnus* is a subconical burrow. It
 44 consists of a slightly curved tube, 2–5 mm in diameter, which is surrounded by a thick wall
 45 composed of concentric layers that thicken towards the sediment surface. Here the burrow
 46 is 10–20 mm in diameter. *Diplocraterion* is a U-shaped, vertical burrow with protrusive
 (common) or retrusive (seldom) spreite. Openings to the sea floor are often funnel-shaped.

01 11.2.4. Hiatuses

02 When bottom currents prevent deposition for a considerable time span, and/or
 03 erode sediments, submarine hiatuses develop, represented by semi-consolidated
 04 firm- or hardgrounds or stable cohesive partially dewatered muddy substrates. In
 05 addition, iron and manganese oxides may be precipitated and cause partial indura-
 06 tion of the sediment surface (Chester, 2000; Faugères et al., 2002b). In these cases,
 07 distinct, mainly vertical to sub-vertical, sharp-walled, unlined burrows are pro-
 08 duced that exhibit scratch marks along the walls. They may subsequently be
 09 passively filled (Pemberton et al., 2001; Figure 11.4).

10 When levels representing a hiatus become buried by new sediments, a marked
 11 contrast in consistency occurs between the two layers, which can be deciphered
 12 from burrow morphology (Wetzel and Aigner, 1986). In addition, the change in
 13 lithology from under the hiatus horizon to the contouritic sediments above renders
 14 these transitions even more evident in the sedimentary record. When sandy
 15 material fills open tubes across a hiatus horizon, the ichnofabric can be ascribed
 16 to the *Glossifungites* ichnofacies. Such intervals are clearly recognizable in the fossil
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21 **Figure 11.3** (Continued) exceed 300 mm. *Glyphichnus*/*Spongiomorpha* represents an arcuate,
 22 vertical and probably U-shaped burrow with 10–15 mm long scratching marks (bioglyphs)
 23 sub-parallel to the burrow axis. Four to six grooves are arranged in fan-shaped groups
 24 (Bromley and Goldring, 1992). *Nereites* is a winding to regularly meandering trace, consisting
 25 of a median back-filled tunnel enveloped by an even to lobate zone of reworked sediment (for
 26 details, see Uchman, 1995; Wetzel, 2002). *Planolites* is a normally unbranched, smooth or
 27 ornamented, lined, essentially cylindrical, predominantly horizontal burrow of variable
 28 diameter. The fill is typically structureless and of similar lithology as the host rock. *Phycosiphon*
 29 consists of a compound system of U-shaped burrows in an antler-like arrangement, with
 30 horizontal or inclined spreiten. A single spreiten is 1–5 mm wide, the marginal tube is thinly
 31 lined and 0.5–1 mm wide (Wetzel and Bromley, 1994). *Scolicia* is a large, bilaterally
 32 symmetrical, sub-cylindrical burrow having meniscate lamellae often divided into two
 33 concave sets. In traverse cross-section, a concentric structure of bilobate lamellae surrounds an
 34 excentric axis. Today, *Scolicia* is produced by *Echinocardium*-like sea urchins that prefer to live in
 35 sandy to silty sediments (Wetzel, 1984; Fu and Werner, 2000). *Skolithos* is a straight, simple,
 36 unbranched, normally vertical tube having a uniform diameter (4–10 mm). *Teichichnus* is a
 37 vertical, blade-like elongate spreiten structure resulting from the upward or downward
 38 displacement of the causative tube. *Teichichnus* shows some preference to occur in sandy to silty
 39 muds. *Thalassinoides* consists of horizontally branched networks connected to the surface by
 40 steeply inclined or vertical shafts; swellings may occur at points of branching. An eccentric fill
 41 structure often results from active filling by the burrowing organism or collapse of the burrow
 42 walls. The tubes are 5–20 mm in diameter and smooth-walled. Shrimps or shrimp-like animals
 43 can produce *Thalassinoides*. *Trichichnus* is a thread-like and rarely branching cylindrical burrow
 44 up to several tens of centimetres in length. Other small, hair-like, often horizontally oriented
 45 burrows have been informally called “mycellia” (Blanpied and Bellaiche, 1981). *Zoophycos* is a
 46 1–20-mm-thick spreiten structure that surrounds a central shaft in distinct levels or coilings.
 The regular fill structure appears as crescentic en echelons in vertical sections. A marginal tube
 (open or stuffed) borders the spreite; the whole trace is connected to the sediment surface
 through a vertical shaft. The vertical extension of a *Zoophycos* burrow may exceed 1 m (Wetzel
 and Werner, 1981). The modern *Zoophycos* producers feed a least episodically from the surface
 (Löwemark et al., 2004a).

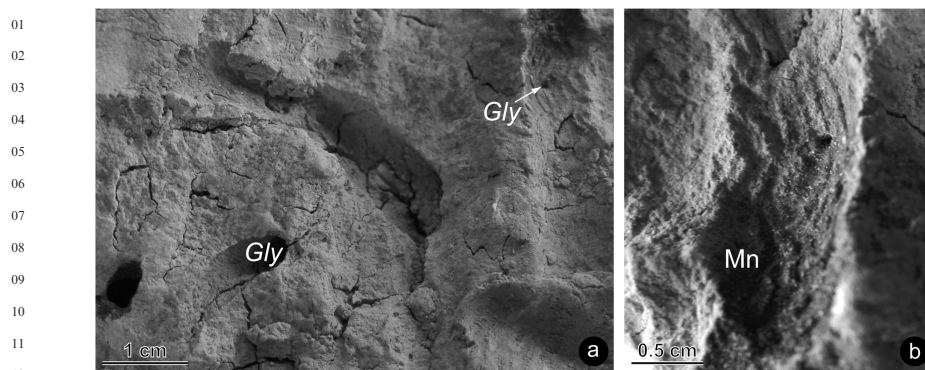


Figure 11.4 Modern hiatus horizon produced by bottom currents that traverse a seamount chain within the South China Sea (14°52.4'N, 118°35.4'E; 3940 m water depth; core SO 114-16). The sediment has been partly eroded. Staining by Fe and Mn oxides [Mn in (a)] indicates the hiatus. A stiff sediment consistency is indicated by numerous open burrows and ornamentation of burrow margins by claw sculptures, typical for *Glyphichnus* (*Gly*) burrows. (a) Overview. (b) Detail of the *Glyphichnus* margin.

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record and represent possible candidates to generate high seismic reflectivity because of the density and acoustic velocity contrast they represent.

11.3. EXAMPLES OF BIOTURBATION IN CONTOURITES

11.3.1. Gulf of Cadiz

The Mediterranean Outflow Water (MOW) flows into the Atlantic Ocean through the Strait of Gibraltar as bottom current and then moves to the northwest along the southern margin of the Iberian Peninsula (Tomczak and Godfrey, 1994; Hernández Molina et al., 2008a). The outflow is warm ($>13^{\circ}\text{C}$), saline ($>36.4\text{‰}$), and relatively low in oxygen ($4.1\text{--}4.6\text{ ml O}_2\text{l}^{-1}$) (Zenk, 1975). Flow velocities decrease from about 300 cm s^{-1} in the Strait of Gibraltar to 180 cm s^{-1} just west of the Strait, to $30\text{--}40\text{ cm s}^{-1}$ in vicinity of Faro Drift, and finally to $10\text{--}20\text{ cm s}^{-1}$ south of Cape St Vincent (Baringer and Price, 1999). The sea floor swept by this current is in places free of sediment. Where the MOW decelerates, a series of sediment drifts have developed (Stow et al., 2002b; Hernández-Molina et al., 2008a; Mulder et al., 2008). The MOW density and intensity are thought to have varied through time since the Messinian (5.5 Ma) in response to climatic changes (Baas et al., 1998; Stow et al., 2002b; Löwemark et al., 2004b). Turbidites constitute 20–40% of the deposits outside the Faro drift complex, but only 2% within the drift (Stow et al., 2002b).

At a proximal location within the upper MOW vein, a sand-rich (40%) interval covering Marine Isotopic Stage (MIS) Termination I is ascribed to increased winnowing, and is intercalated between greyish silty muds (Löwemark et al., 2004b). The sedimentation rate averages $<20\text{ cm ka}^{-1}$. This interval is completely bioturbated, with dominant *Planolites* and *Thalassinoides* burrows (Figure 11.5a).

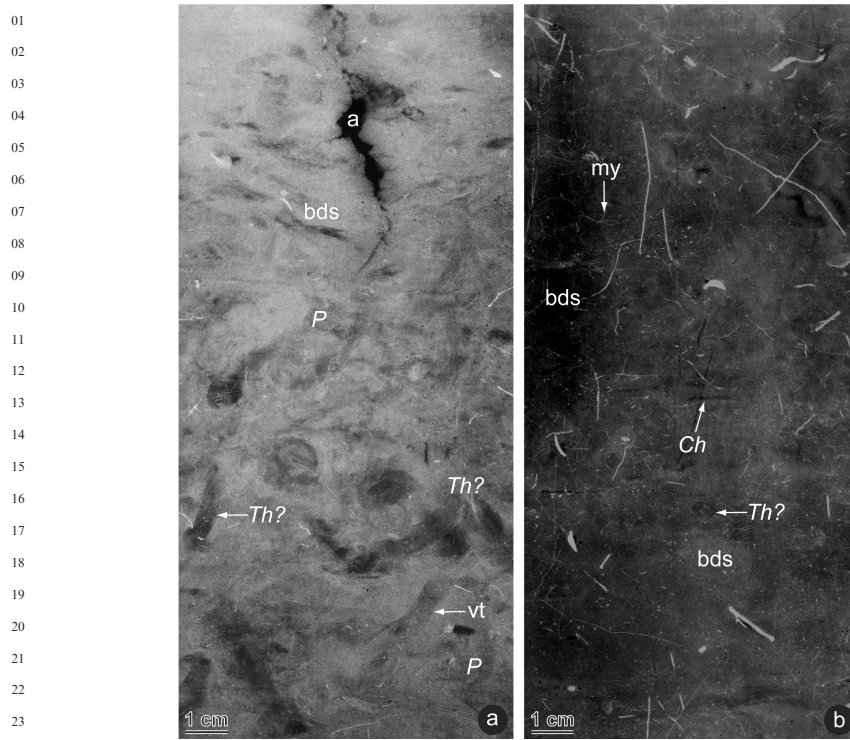


Figure 11.5 Sediments affected by bottom currents of the Mediterranean Outflow Water, Gulf of Cadiz (Institute of Geosciences Kiel, Germany, core M39008; 36°22.8'N, 7°04.3'W; 577 m water depth); X-radiographs (negative; coarse material – light, fine material – dark). For sedimentological and ichnological details, see Löwemark et al. (2004b). (a) Sand-rich facies (sand content 35–45%, sedimentation rate 17 cm ka⁻¹; 0.3% C_{org}) representing the Bølling–Allerød time span (404–420 cm). (b) Mud-rich facies (sand content <1%, rapidly deposited at ~250 cm ka⁻¹, organic-rich ~0.8% C_{org}); Holocene in age (254–270 cm). bds = biodeformational structures; Ch = *Chondrites*; my = “mycellia”; P = *Planolites*; py = pyrite, in many instances probably pyritized *Trichichnus*; vt = vertical tube; Th = *Thalassinoides*.

The muds, which contain about 1% sand and 0.8% C_{org}, have accumulated rapidly due to sluggish bottom currents (~250 cm ka⁻¹) and are completely bioturbated by a low-diversity ichnofauna mainly consisting of *Chondrites*, *Trichichnus*, “mycellia” and pyritized microburrows (Figure 11.5b).

Further downflow, the Faro Drift Complex formed at an average rate of up to 15 cm ka⁻¹ in the late Pleistocene. Hiatuses due to winnowing occur in 40% of the cores and are most likely directly correlatable with peak sand concentrations in adjacent areas (Stow et al., 2002a). Clay and silt particles (<63 μm) dominate, and intense bioturbation has been continuous with deposition (Gonthier et al., 1984). The following three interbedded lithologies have been distinguished.

- 01 1. *Sand- and silt-dominated intervals* have mostly irregular, sometimes gradational or
02 sharp contacts. Current bedforms on the modern sea floor suggest that the sandy
03 layers were originally laminated and have been mixed later by bioturbation.
04 Many small-diameter bioturbational tubes occur.
- 05 2. *Mottled silts and muds* have sharp to gradational, often mottled contacts. Some
06 remnants of indistinct wavy lamination may occur. *Chondrites*, *Planolites*,
07 *Teichichnus* and ?*Thalassinoides*, in addition to unidentified small burrows, have
08 been encountered.
- 09 3. *Homogeneous muds* have sharp to erosional, but commonly gradational contacts.
10 Faint lamination occurs rarely; otherwise, the muds are thoroughly bioturbated.
11 The low-diversity ichnofauna is dominated by *Chondrites*, *Trichichnus* and
12 “mycellia”. Large burrows have not been observed. Pyritization is common.

14 11.3.2. Nova Scotia rise

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16 The continental rise off Nova Scotia is affected by southward flowing North
17 Atlantic Deep Water (McCave and Hollister, 1985). At the HEBBLE site, radio-
18 tracers document a long-term average sedimentation rate of about 5 cm ka^{-1}
19 (DeMaster et al., 1985). However, intermittent benthic storms generate faster
20 flowing currents ($<70 \text{ cm s}^{-1}$) capable of eroding and re-suspending the sediment
21 about once a year (Gross and Williams, 1991). When the current velocity decreases
22 again, up to several centimetres of sediment can be deposited within a few days or
23 weeks (McCave, 1985b). Burrowers mix the sediment so effectively that only 6% of
24 the surface mixed layer carries a primary fabric (Flood et al., 1985).

25 Aspects of bioturbation at the HEBBLE site have been studied by Baldwin and
26 McCave (1999) using X-radiographs. They recognized four tiers from top to bottom.

27 In *Tier 1* ($<6 \text{ cm}$ thick), the degree of bioturbation depends on the time since
28 deposition, but normally exceeds 50%. Typically, biodeformational structures
29 occur in addition to “mycellia”.

30 In *Tier 2* (2–4 cm thick), the degree of bioturbation reaches 60%, but some
31 lamination is still present. Barrel-shaped burrows like *Bergaueria* or *Conostichus*,
32 funnels like *Monocraterion*, tubes like *Skolithos* and spirals like *Helicodromites* can occur.

33 In *Tier 3* (4–15 cm thick), the degree of bioturbation is 70–100%. *Palaeophycus*/
34 *Planolites* occur throughout, as well as *Scolicia* in the upper part and *Chondrites* in the
35 lower part.

36 *Tier 4* ($>20 \text{ cm}$) is completely bioturbated, in particular by *Thalassinoides*.

37 The recurrent funnels and barrel-shaped burrows may record a nutritional strategy
38 of passive collection of food particles (Aller and Aller, 1986). The common vertical
39 shafts and the openings at the surface support the observation that many benthic

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40 organisms inhabiting the deposits are also active on the sea floor (Thistle et al., 1995).

41 Because the number of shafts below *Tier 2* is low, most of these organisms are thought
42 to burrow in *Tiers 2* and *3* only. *Scolicia* occurs in reworked (turbiditic) silts and

43 sands in an intermediate tier position. The burrow producers are very active and,
44 hence, *Scolicia* dominates in the fossil record in silt- and sand-rich deposits. In muds,

45 *Palaeophycus*/*Planolites* dominate; *Phycosiphon* and *Chondrites* may occur in addition.

46 In deep tiers, *Thalassinoides* may occur abundantly and *Zoophycos* more rarely.

01 Further to the south on the Northwest Atlantic Margin, off New Jersey, a late
 02 Pleistocene succession interpreted to include contourites was studied ichnologically by
 03 Savrda et al. (2001). During times of warm climate and high sea level, sediments at the
 04 sea floor have been reworked by bottom currents to form contourites. Their grain-size
 05 composition varies between muddy sands and sandy muds; brownish grey banding
 06 indicates temporarily enhanced oxidation (Mangini et al., 2001). The sediments are
 07 completely bioturbated and exhibit abundant trace fossils, in particular *Thalassinoides*,
 08 occurring in two variants. When associated with firm- or hardgrounds, these burrows
 09 are filled with coarse material and, hence, can be ascribed to the *Glossifungites* ichnofacies
 10 (see above), typical of non-deposition horizons. Other *Thalassinoides* have been
 11 produced in soft substrates. The occurrence of *Thalassinoides* matches the observations
 12 made at the HEBBLE site that crustaceans temporarily exploit the sediment surface, but
 13 are dwelling within the deposits (see above).

14 11.3.3. Iceland–Faeroe Ridge

16 The Iceland–Faeroe Ridge separates the Norwegian Sea in the north from the North
 17 Atlantic in the south. Cold Norwegian Deep Water flows into the North Atlantic
 18 partly over the crest, but mainly through the Faeroe Bank Channel that continues
 19 into the Faeroe–Shetland Channel (Borenäs and Lundberg, 2004). During the late
 20 Pleistocene and Holocene, bottom currents reworked the mainly muddy terrigenous
 21 sediments, with abundant coarse-grained ice-rafted debris, forming intensely biotur-
 22 bated glacial glaciogenic contourites (Stoker et al., 1998a; Akhurst et al., 2002; Van Weering
 23 et al., 2008). The currents were relatively slow, leading to the accumulation of fine-
 24 grained, poorly sorted, organic-rich muds, with a monospecific *Chondrites* assemblage
 25 and some (pyritized) micro-burrows (Fu and Werner, 1994; see Figure 11.6).

26 On the southern slope of the Iceland–Faeroe Ridge, the Norwegian Sea overflow is
 27 deflected by the Coriolis force northwestwards into a deep-sea channel system oriented
 28 parallel to the ridge (Meincke, 1983). Within the channel system, there is an asymmetric
 29 distribution of contouritic sediments (Dorn and Werner, 1993). In response to frequent
 30 fluctuations of the current velocity, the sedimentary regime varied between erosion,
 31 non-deposition, and deposition of sand and mud. On the northeastern side of the
 32 channel system, a thin, mostly coarse sediment cover documents repeated reworking
 33 and deposition under high-velocity conditions. An alternation of trace fossil assemblages
 34 in the channel system comprises *Planolites*, *Teichichnus/Thalassinoides*, *Trichichnus* and
 35 *Zoophycos* (Fu and Werner, 1994; Figures 11.6a and b).

36 On the southwestern side of the channel system, currents favour deposition of well
 37 sorted deposits (Fu and Werner, 1994). Within sand-rich intervals, *Scolicia* prevails
 38 (Figure 11.6c); *Chondrites*, *Palaeophycus*, *Phycosiphon*, *Planolites* and *Thalassinoides* are
 39 present in lower abundance. As the mud content increases, *Scolicia* becomes sparser and
 40 finally disappears, whereas *Chondrites*, *Phycosiphon*, *Planolites*, *Thalassinoides* or *Teichi-*
 41 *chus*, *Trichichnus* and *Zoophycos* are present (Figure 11.6d; Fu and Werner, 1994).

43 11.3.4. Faeroe–Shetland Channel

44 Within the Faeroe–Shetland Channel, the uppermost part of the drift succession is
 45 dominated by muds and sands that accumulated at an average rate of 3–7 cm ka⁻¹,
 46

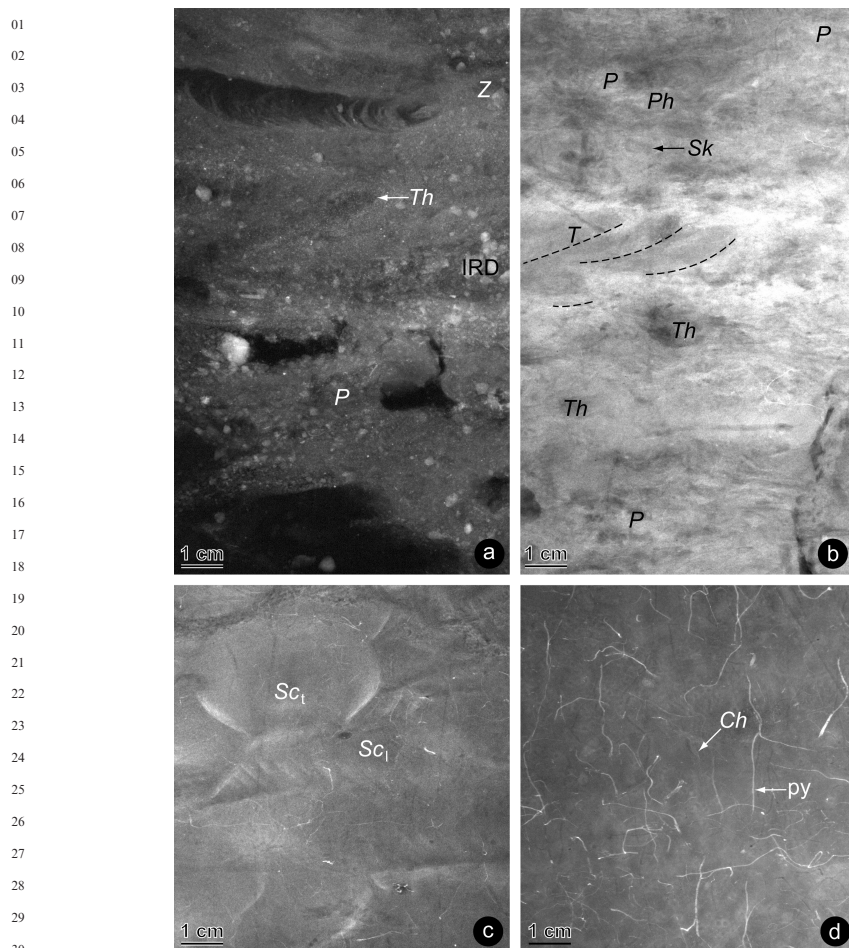
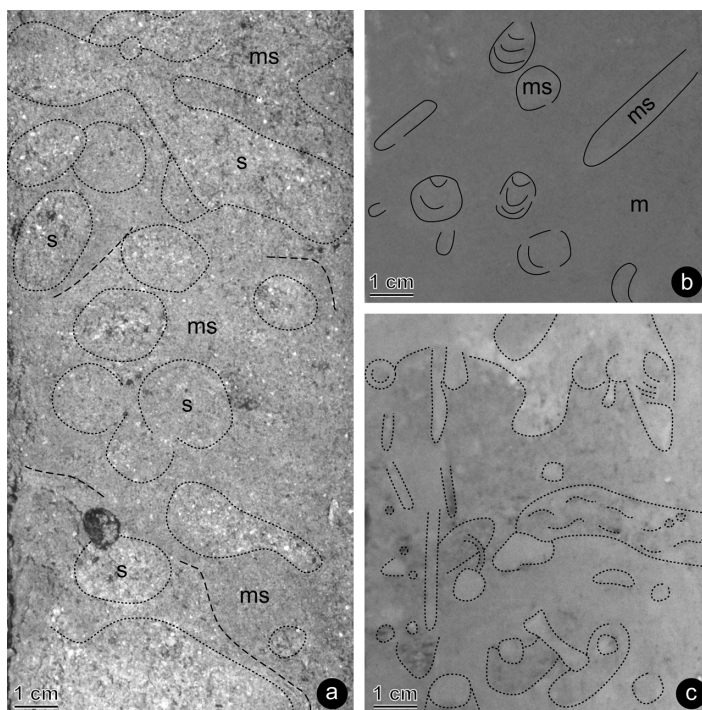


Figure 11.6 Bottom-current-affected sediments from the southern flank of the Iceland–Faeroe Ridge, Late Pleistocene (X-radiographs, negative; dense and/or coarse material – light; fine-grained, water-rich sediment – dark). (a) Bioturbated glacigenic sediments interpreted as contourite. Current-reworked ice-rafted debris (IRD) has subsequently been mixed by bioturbation; sand content >40% (Fu and Werner, 2000), NE flank of the crest-parallel channel. Institute of Geosciences Kiel, Germany, core 16397-2 (460–473 cm), 1145 m water depth (61°52.35'N, 11°10.72'W). *P* = *Planolites*; *Th* = *Thalassinoides*; *Z* = *Zoophycos*. (b) Muddy sand facies, NE flank of the crest-parallel channel. Institute of Geosciences Kiel, Germany, core 16397-2 (132–145 cm). *P* = *Planolites*; *Ph* = *Phycosiphon*; *Sk* = *Skolithos*; *Th* = *Thalassinoides*; *Sk* = *Skolithos*. (c) Silty facies from the SW side of the crest-parallel channel system; in the silty deposits. *Scolicia* dominates, *Sc_t* = *Scolicia* in traverse section, *Sc_l* = *Scolicia* in longitudinal section (for details, see Fu and Werner, 2000). Institute of Geosciences Kiel, Germany, core 16396-1 (135–144 cm), 1145 m water depth (61°52.33'N, 11°14.54'W). (d) Rapidly accumulated, organic-rich muds. Institute of Geosciences Kiel, Germany, core 16384-2 (342–351 cm), 1255 m water depth (61°57.55'N, 11°53.15'W). Faint *Chondrites*-like burrows cross-cut by iron sulphide (*py*).

01 with a peak rate of 10 cm ka^{-1} . Muddy sands, sandy muds and muds, representing
 02 8%, 60% and 26% of the cored intervals, respectively, are interpreted as contourites
 03 (Akhurst et al., 2002).

- 04 1. *Muddy sands* are dark grey to brownish (oxidized), and colour-banded with
 05 individual layers of 0.1–0.7 m thick. They appear structureless and thoroughly
 06 bioturbated; small-scale homogenizing bioturbation is accentuated by some large,
 07 distinct burrows (Figure 11.7a). Relicts of primary lamination are very rare. The basal
 08 contacts are gradational or relatively unbioturbated, the upper ones are gradational.
- 09 2. *Sandy muds* are olive grey and occur as beds up to 3 m thick. They appear mostly
 10 structureless and intensely bioturbated. Small-scale (<5 mm), homogenizing
 11 burrows are cross-cut by some large, unidentified trace fossils. Bedding contacts
 12 are gradational, or locally sharp at the base of coarser horizons (Figure 11.7b).



37 **Figure 11.7** Glacial sediments interpreted as contourites from the Iceland–Shetland
 38 Channel. Fresh-core photographs (for details, see Akhurst et al., 2002). (a) Sand-rich facies,
 39 current-reworked sediments have been mixed by bioturbation to muddy sand (ms);
 40 subsequently, sand-enriched burrows (s) were produced. British Geological Survey core
 41 61-04/39 ($61^{\circ}03.5'N$, $3^{\circ}25.1'W$; 1125 m water depth) 274–290 cm (Late Pleistocene). (b) Sandy
 42 mud facies; sands have been mixed into muds, after a early phase of homogenization
 43 producing uniform sandy mud (m), distinct burrows containing some more sand (ms) have
 44 been formed, which may be ascribed to *Teichichnus* or *Thalassinoides*. (c) Muddy facies, light mud
 45 resting on grey mud, the contact has been heavily bioturbated, vertical tubes and halo burrows
 46 (*Palaeophycus*, *Planolites*, *Thalassinoides*) are common; British Geological Survey core 60-05/50
 ($60^{\circ}49.7'N$, $4^{\circ}12.5'W$; 1100 m water depth), 247–254 cm (Late Pleistocene).

01 3. *Muds* are dark olive to olive grey, and form beds up to 2.3 m thick. These
 02 deposits appear structureless and thoroughly homogenized by bioturbation;
 03 distinct burrows may occur, for instance *Zoophycos*. Rarely cross-lamination is
 04 preserved. Bed contacts are gradational (Figure 11.7c).

07 11.4. DISCUSSION AND CONCLUSIONS

08
 09
 10 On a small scale (cores and outcrops), the recognition of contourites is
 11 problematic because diagnostic criteria such as primary sedimentary structures and
 12 grain-size variations have mostly been obliterated by intense bioturbation. In
 13 response to the fluctuating current velocity, periods of erosion, non-deposition,
 14 winnowing and deposition may alternate through time at a specific site. The effects
 15 of strong and weak currents on bioturbation are addressed separately.

17 11.4.1. Strong currents: non-deposition horizons and sand-dominated 18 contourites

19
 20 Strong bottom currents may lead to

- 21 • erosional surfaces covered with a pebble lag deposit (Figure 11.8a);
- 22 • sharp erosional surfaces covered by sand (Figure 11.8b);
- 23 • deep erosion or long-term non-deposition, yielding indurated discontinuity
 24 surfaces marked by a stiff- to hardground ichnofauna; where overlain by sand,
 25 a typical *Glossifungites* ichnofacies is present; where covered by mud a sharp-
 26 walled piped zone (Figure 11.8c);
- 27 • coarse sediment, mostly bioturbated throughout, but in some cases with primary
 28 structures preserved (Figure 11.8d).

29
 30 These features are especially well recognizable where the coarser-grained unit
 31 has been covered by fine-grained contourites. Normal grading needs to be analysed
 32 to distinguish between a turbiditic and a contouritic origin (Table 11.1).

33 Most contouritic sands are poorly sorted or impure and appear to be structureless
 34 or mottled (Figures 11.5–11.7). This results from intense bioturbation driven by the
 35 organic-matter supply from bottom currents. As the bottom-current velocity fluctu-
 36 ates, especially during low-velocity stages, benthic animals may utilize preferentially
 37 organic-rich fine particles and mix them with sands. Detailed ichnological analyses are
 38 still too few to define the association and tiering position of any trace fossils present.
 39 Theoretically, the upper parts of the sand layers may contain biodeformational
 40 structures resulting from ploughers and passively ventilated tube systems. These
 41 burrows become overprinted by the deeper penetrating ones like *Skolithos*, *Scolicia*
 42 and *Planolites* in addition to burrows having a U-shaped causative tube such as
 43 *Arenicolites*, *Diplocraterion* or *Teichichnus*. Furthermore, burrows produced by deep-
 44 dwelling crustaceans such as *Thalassinoides* and *Gyrolithes* can be expected (Fu and
 45 Werner, 1994). Interestingly, *Ophiomorpha* has not been described yet from contour-
 46 ites, probably because previous bioturbation mixed so much mud into the sand that

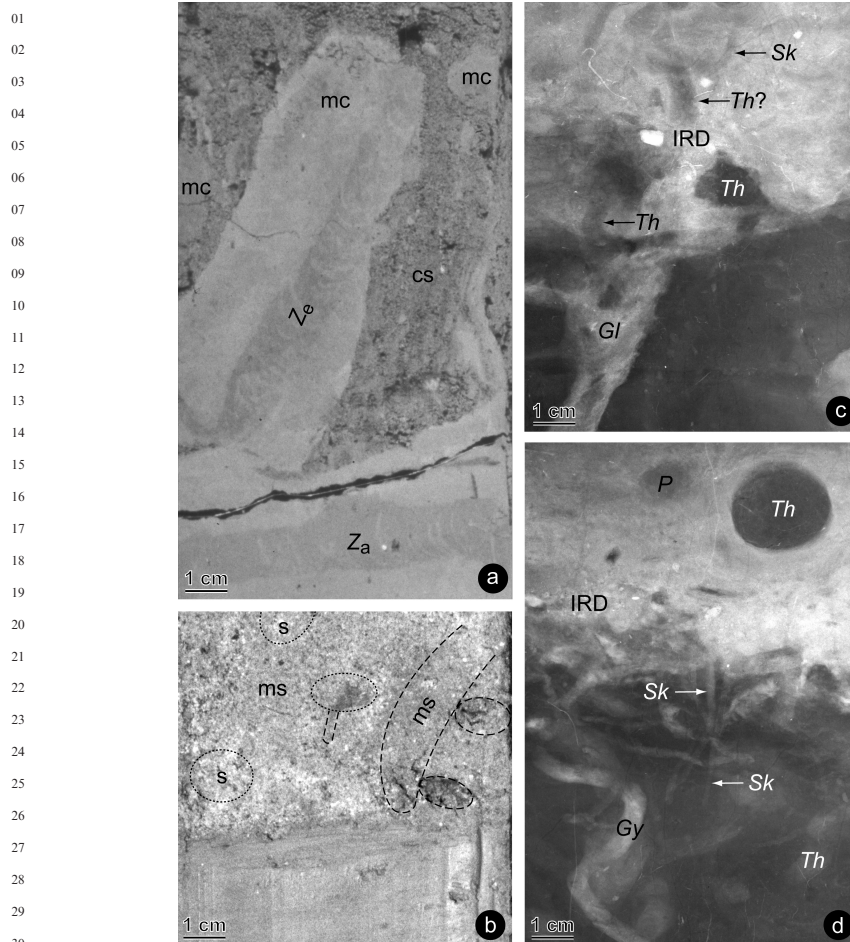


Figure 11.8 Discontinuity surfaces in bottom-current-affected settings. (a) Hiatus horizon covered with mud pebbles representing the base of the Late Pleistocene within the Iceland–Shetland Channel in 1100 m water depth. British Geological Survey core 60-05/50 (60°49.7'N, 4°12.5'W), 346–358 cm (for details, see Akhurst et al., 2002). Mud pebbles (mc), one with *Zoophycos* (Z_a), are embedded in coarse sand (cs) that in turn rests on mud with autochthonous *Zoophycos* (Z_a). The minimum amount of erosion is 40 cm, based on the burrowing depth of the *Zoophycos* producer (Wetzel and Aigner, 1986). (b) Holocene sand sharply overlying mud within the Iceland–Shetland Channel in 1125 m water depth. British Geological Survey core 61-04/39 (61°03.5'N, 3°25.1'W), 9–17 cm (for details, see Akhurst et al., 2002). (c) Sand (light) resting on mud (dark); sand has been infilled into open burrows (Gl) typical for *Glossifungites* surfaces; the sand has been intensely bioturbated. X-radiograph (negative). Institute of Geosciences Kiel, Germany, core 16384-2 (61°57.55'N, 11°53.15'W), 310–320 cm (Late Pleistocene), southern flank of the Iceland–Faeroe Ridge at 1255 m water depth. *Th* = *Thalassinoides*; *Sk* = *Skolithos*. (d) Bioturbated contact of an initially sharp contact between glacial sands (with IRD clasts) and underlying muds interpreted as contourites. *Gy* = *Gyrolithes*-like burrow; *P* = *Planolites*; *Th* = *Thalassinoides*; *Sk* = *Skolithos*. X-radiographs (negative; dense and/or coarse material – light; fine-grained, water-rich sediment – dark). Southern flank of the Iceland–Faeroe Ridge at 1255 m water depth. Institute of Geosciences Kiel, Germany, core 16384-2 (61°57.55'N, 11°53.15'W), 290–302 cm (Late Pleistocene).

01 **Table 11.1** Bioturbation in sandy turbidites and sandy contourites

	Turbidite	Contourite
04 Sediment	Instantaneous, very rapid	Intermittent deposition/ reworking; consecutive
05 accumulation		Vertical flux supplemented by lateral input
06 Organic matter supply (long-term)	Mainly vertical flux	Mainly non-refractory
07 Organic matter imported by currents	Mainly refractory	
09 Fauna	Partially killed by turbidite deposition	Partially removed by currents, but many deep burrowing survivors
11 Faunal abundance	Average, dependent on water depth	(Very) high due to additional food supply
13 Faunal structure	Survivors (deep burrowers), colonizers	Permanently, adapted burrowers, larval import by currents
15 Specialists	Pre- and post-depositional burrowers	Deep-dwelling surface utilizers
17 Bioturbation	Post-depositional	Continuous, syn- and post-depositional
19 Bioturbation rate	Normally low, dependent on local conditions	Very high
21 Degree of bioturbation	Complete reworking rare	Complete reworking normal
22 Basal layer	Often not completely bioturbated, exploited by deep burrowers	Normally completely bioturbated, vertical tubes frequent

25 *Thalassinoides* is produced instead of *Ophiomorpha* (see Kern and Warme, 1974).
26 Where the mud content increases, *Teichichnus*, *Planolites*, *Asterosoma* (or *Patagonichnus*,
27 see Olivero and López-Cabrera, 2005) and *Chondrites* may also occur.

29 Coarse-grained contourites (either sandy and/or with gravel horizons) can
30 sometimes be mis-interpreted in small-scale core or outcrop studies as being of
31 turbidite origin. Although we cannot yet provide a definitive ichnofacies association
32 and tiering structure for sandy contourites, certain marked differences between the
33 two facies are apparent (Table 11.1). Bioturbation is generally stronger and the rate
34 of bioturbation is very high in sandy contourites compared with that of turbidites,
35 leading to complete or near-complete reworking of the sediment. Biodeformational
36 structures are common, and the trace fossil assemblage quite varied (see above).

38 11.4.2. Weak currents – mud-dominated contourites

40 Fine-grained particles and organic matter are deposited by weak bottom currents.
41 Thin sand layers may form when currents temporarily accelerate. Within such
42 organic-rich muds, oxygen consumption by benthic animals and bacteria may
43 lead to anoxic pore waters at shallow sediment depths. The small size of individuals
44 and the low biodiversity (including monospecific populations) characterize the
45 ichnofauna (Fu and Werner, 1994; Figures 11.5b, 11.6a). *Chondrites* trace fossils
46 often dominate this environment at the sea floor, and are used as an indicator of low

01 oxygenation within the sediments (Ekdale et al., 1984). Such fine-grained con-
 02 tourites are, however, very difficult to recognize in outcrops without knowing the
 03 environmental context from independent evidence.

04 In many cases, colour banding occurs. Brownish sediments pass downwards to
 05 greenish muds. First sediments are rapidly deposited by slow currents and they are
 06 often greenish. Subsequently, when currents accelerate and prevent sedimentation
 07 organic matter is oxidized from the surface downward ($<2 \text{ cm ka}^{-1}$; Jung et al., 1997;
 08 Figure 11.9). Faster currents may also lead to thin silty/sandy horizons and/or to a
 09 surface of a minor hiatus. A distinct ichnocoenosis should occur in such environ-
 10 ments, theoretically dominated by U-shaped and vertical burrows (*Arenicolites*,
 11 *Teichichnus*, *Skolithos*) accompanied by those related to surface utilization, including
 12 *Thalassinoides* and *Zoophycos*. In addition, *Planolites*, *Phycosiphon* and *Chondrites* may
 13 occur. *Nereites* may form along the redox boundary (Wetzel, 2002).

14 Alternation between reworking and deposition leads to relatively low average
 15 sedimentation rates in muddy contourites, which therefore become prone to
 16 complete bioturbation (Wetzel, 1991). When bottom currents supply additional
 17 food, the fauna becomes more abundant, and burrowing rates become higher than
 18 at reference sites without significant bottom-current influence. However, at present
 19 there is no unequivocal ichnological criterion that documents the endobenthic
 20 response to fluctuating food levels (Wetzel, 1991; Wetzel and Uchman, 1998a, b),
 21 because the organic matter content within the sediment is controlled mainly by
 22 the sedimentation rate (Müller and Suess, 1979; Mangini et al., 2001). The effects of
 23 short-term fluctuations in sedimentation on the final ichnofabrics are not yet known.

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42 **Figure 11.9** Muds deposited by a bottom current (fresh core); slowly accumulated brownish
 43 mud (bm) rests on rapidly deposited greenish mud (gm). Brownish mud has been transferred
 44 by burrowing into the greenish interval. The change in sedimentation rate probably results
 45 from changing bottom-current activity. Institute of Geosciences Kiel, Germany, core 16820-2
 46 (336–348 cm), southern side of the Iceland–Faeroe Ridge, taken at the NW slope of a channel
 parallel to the ridge crest (62°35.56'N, 14°18.62'W, 1649 m water depth).

Table 11.2 Bioturbation in hemipelagites, muddy turbidites and muddy contourites

	Hemipelagite	Muddy turbidite	Muddy contourite
Sediment accumulation	More or less continuous, slow	Instantaneous, very rapid	Intermittent deposition and reworking
Organic matter supply (long-term)	Mainly vertical flux, dependent on water depth	Suspension-carried material and vertical flux	Vertical flux supplemented by lateral input
Organic matter imported by currents	None	Mainly refractory	Refractory and non-refractory
Fauna	Continuously living	Partially killed by deposition of thick turbidite	Partially removed by currents, deep-burrowing survivors
Faunal abundance	Average, dependent on organic matter flux	Varying (partially killed, re-colonization)	(Very) high, due to additional food supply
Faunal structure	Several tiers	Surviving deep burrowers, sequential colonizers	Permanent living, adapted burrowers; fauna import by currents
Specialists	Each tier with special adaptation	Pre- and post-depositional burrowers	Burrowing surface utilizers; low-oxygen pore water
Bioturbation	Continuous	Post-depositional	Continuous, syn- and post-depositional
Bioturbation rate	Dependent on organic matter flux (average)	Normally low, dependent on local conditions	Very high
Degree of bioturbation	Complete reworking normal	Complete reworking rare	Complete reworking normal
Basal layer		Often not completely bioturbated, exploited by deep burrowers	Complete bioturbation common

Fine-grained contourites (muddy and silty facies) are, in some cases, mis-interpreted as silt/mud turbidites, although they are actually much more similar to hemipelagites in their general appearance. As for their coarse-grained counterparts, our knowledge is currently insufficient to produce a definitive ichnofacies association and tiering structure for muddy contourites, but certain characteristics are nevertheless distinctive (Table 11.2). Bioturbation is strong and continuously leading to complete reworking of the sediment, with a generally varied trace-fossil assemblage (see above). The rate of bioturbation is typically high, but does vary with

01 fluctuations in sedimentation rate and supply of organic matter. Periodically higher
 02 bottom-current velocities may lead to a silty or sandy horizon and/or to a non-
 03 deposition horizon, together with associated vertical and U-shaped burrows.

04
 05 **11.5. PERSPECTIVE**

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 08 Fluctuations of bottom-current intensity affect the burrowing fauna consider-
 09 ably (Figure 11.10). Bioturbation in such settings is fuelled by organic matter that is

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 12 **Effects of bottom currents on burrowing fauna**
 13 Hypothetical steady-state conditions

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Energy	High	Intermediate	Low
Current velocity			
Sedimentary regime	Erosional	By-pass winnowing	Depositional
Substrate	Hiatus horizon	Sandy	Muddy
Laterally advected POM	Suspended		Deposited
Microbial activity			
Current effects	Removal of POM, juveniles	Import of juveniles, larvae, POM	
Nutritional strategy	Filter feeding Interface feeding (deposit feeding)	Filter feeding Interface feeding Deposit feeding	Temporary Interface feeding Deposit feeding

33 **Fluctuating bottom current velocity**

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- erosional and depositional phases alternate
 - on-average low sedimentation rates, but short-term high
 - high benthic food level
 - various nutritional strategies
 - high bioturbation rates
- ↳ common: bioturbation rate > sedimentation rate
- impure lithologies prevail
 - deep-penetrating burrows dominate the ichnofabric
 - documenting short-term favourable conditions
- ↳ seldom and/or local: sedimentation rate >> bioturbation rate
- multiple reworking by high-speed currents that deposit coarse, fraction-transported material
 - primary sedimentary structures dominate

45 **Figure 11.10** Theoretical compilation of how contour currents affect the burrowing fauna.
 46 POM = particulate organic matter.

01 re-suspended and/or laterally advected, in addition to that directly provided by the
02 hemipelagic rain. This high-trophic mode of bioturbation results in an enhanced
03 rate of burrow production, distinct depth of bioturbation and a specialized beha-
04 viour. In particular, observations on the modern sea floor suggest that passively
05 ventilated burrows or traces are produced at high abundances by animals that collect
06 or trap food particles on the surface while living within the sediment. The
07 geometry and taxonomy of such burrows and their position within the bioturbated
08 zone is not really known as yet, although it is clear that *Thalassinoides* commonly
09 belongs to the contourite ichnofacies. Although a clear set of ichnological criteria
10 recording the contourite mode of bioturbation is not yet available, we can identify
11 certain bioturbational characteristics for both sandy and muddy contourite facies that
12 will help with their distinction from related turbidite and hemipelagites facies in
13 deep-water environments (Tables 11.1 and 11.2). Without doubt, further investiga-
14 tion of bioturbation in contourites is needed, especially using high-resolution
15 X-radiographs.



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Query No	Contents
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AU2	Reference "Thistle et al., 1995" has been cited in the text but not provided in the list. Please check.
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