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Sedimentary Geology 115 (1998) 53–80

**Sedimentary  
Geology**

## Bottom-current-controlled sand deposits — a review of modern shallow- to deep-water environments

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Received 15 June 1995; accepted 5 June 1997

### Abstract

Different examples of modern marine-sand accumulations generated or strongly influenced by the action of bottom currents, are here presented. They are drawn from a variety of tectonic and morphological settings and grouped into three water-depth zones: deep-water (>2000 m), mid-water (300–2000 m), and outer-shelf/upper-slope (50–300 m). Deposits in the first two of these depth zones are normal contourites, according to their original definition (Heezen and Hollister, 1971) being those sediments that have been transported and deposited by contour currents in deep-water environments. Those deposited at shallower depths, under the influence of surficial geostrophic currents combined with other hydrodynamic factors (shelf currents induced by wind, tide and waves, gyres, internal waves, etc.), are more properly referred to as outer-shelf/upper-slope bottom-current sands (or shallow-water bottom-current sands). We have elaborated a facies model for each bathymetric zone. Deep-water sandy contourites are relatively rare, thin- and very thin-bedded, highly bioturbated and mainly of bioclastic composition. They are interbedded with muddy contourites and pelagites or, in some areas, with turbidites. In the latter case, thin bottom-current-reworked, sandy tops of turbidites provide a different and distinct facies. Mid-water sandy contourites are more common, ranging up to a metre in thickness, and may form extensive sandy sheets in a variety of slope, bank and channel settings. They are mainly of mixed siliciclastic–bioclastic composition, typically bioturbated, and associated with muddy/silty contourites in coarsening-up/fining-up complete or truncated sequences. Shallow-water bottom-current sands occur in particular outer-shelf/upper-slope settings, where they may develop relatively thick (1–20 m), laterally extensive sheets covered by fields of sandwaves, megaripples and ribbons. Internal structures may be preserved along with much bioturbation. Their composition varies from mainly siliciclastic to bioclastic, and they may be interbedded with both inner-shelf facies and slope hemipelagites. The principal factors that control the deposition of sandy contourites and shallow-water bottom-current sands are the hydrodynamic regime of the basin, the availability of coarse-grained (sandy) sediments and the physiographic context of the area swept by the currents. The greater the depth, the finer and rarer the bottom-current or sandy contourite deposits. Global sea-level and climatic changes and the time involved in the depositional history play an ultimate role in the development of important sand accumulations of this sort by controlling the ocean-circulation pattern and its long-term persistence. From the present analysis, we conclude that mid-depth sandy contourites are the most commonly found in modern environments, and that shallow-water bottom-current sands constitute the most significant potential oil reservoirs to be found in the geological record. © 1998 Elsevier Science B.V. All rights reserved.

**Keywords:** bottom currents; contourites; outer shelf; slope

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## 1. Introduction

The last twenty years have been marked by a technological jump in oceanographic instrumentation and data acquisition, and a consequent advance in our understanding of global oceanic circulation. The main attributes of the thermohaline circulation pattern have been carefully documented (Peterson and Stramma, 1991; Mantyla and Reid, 1995; Rhein et al., 1995). Major geostrophic currents have been identified flowing in deep water parallel to the contours as well as across isobaths (Reid, 1989; Price and Baringer, 1994), and surficial geostrophic currents are known to impinge on the sea floor at great depths (Peggon and Weatherly, 1991; Huthnance, 1992).

Many advances have also been made in defining the sedimentary deposits, known as contourites, that are linked to the bottom activity of these currents (see for reviews: Stow and Lovell, 1979; McCave and Tucholke, 1986; Stow and Faugères, 1993). Closely following the original concept of Heezen et al. (1966) and Hollister and Heezen (1972), contourites can be defined as “sediments in relatively deep water, deposited or significantly reworked by stable geostrophic currents” (Faugères and Stow, 1993). In that paper, a water depth of greater than about 500 m was proposed, whereas in this volume, Stow et al. (1998) suggest an upper limit of 300 m and re-affirm the importance of geostrophic currents in the formation of contourites.

Most of the contourites that have been described to date from sediment drifts in the present-day oceans are fine-grained terrigenous muds and silts or biogenic-rich marls and oozes, whereas sandy contourites are relatively rare. However, there have been several reports recently of sandy contourites in ancient deposits (e.g. Mutti et al., 1980, 1992; Carmignati and Scarton, 1991; Mutti, 1992; Shanmugam et al., 1993), some of which include very thick massive sands interpreted as contourites (Enjorlas et al., 1986). There have also been reports of sandy contourites from relatively shallow-water depths in the Messina Strait off Sicily (Collella, 1990).

In this paper, we first review the occurrence and characteristics of modern sandy contourites both from intermediate or mid-water depths (300–2000 m approximately) and from deeper water (>2000 m approximately), and then review examples of modern

outer-shelf/upper-slope sands that have accumulated under the influence of mixed shelf processes (Fig. 1). Some of the chosen examples lack a detailed grain size analysis in their original publication. We present a refined facies model for both sandy contourites and outer-shelf/slope sands, and suggest that the latter are a better analogue for some of the so-called sandy contourites in ancient sequences. We also consider the controlling factors and hydrocarbon implications of these different types of bottom-current sands.

## 2. Mid-depth sandy contourites

The most common examples of sandy contourites occur at intermediate water depths (300–2000 m approximately) and are the result of a favourable balance between sediment availability, current intensity, physiography and preservation potential. The main currents are those related to intermediate-depth water masses and seldom to the deep activity of geostrophic surface currents. Their upper limit is hydrographic while the lower one is physiographic. Upslope, the shallower limit of mid-depth sandy contourites coincides with the deepest influence of regular surficial circulation, varying from basin to basin in accordance with the factors controlling that circulation (wind-induced currents, tides, surficial waves, including storm waves, etc.) and generally ranges from 300 to 500 m. Downslope, their lower edge coincides with the slope–rise transition typical on passive margins (commonly ranging from 2000 to 3000 m). The sandy contourites that occur at mid-water depths are mostly relatively thin units (up to one metre or so), and comprise both carbonate-rich and siliciclastic sediments and mixtures of both.

### 2.1. *Sandy contourites on the Hebrides slope (NE Rockall Trough; Howe, 1994; Howe et al., 1994)*

#### 2.1.1. *Morphological background*

Continental slope between 400 and 2000 m water depth; the dip of the slope ranges from 1 to 4° on the Hebrides slope and 8 to 10° on the southern foot of the Wyville–Thomson Ridge (Fig. 1).

#### 2.1.2. *Hydrology*

This area is swept by the Eastern North Atlantic Deep Water in a Deep Northern Boundary Current

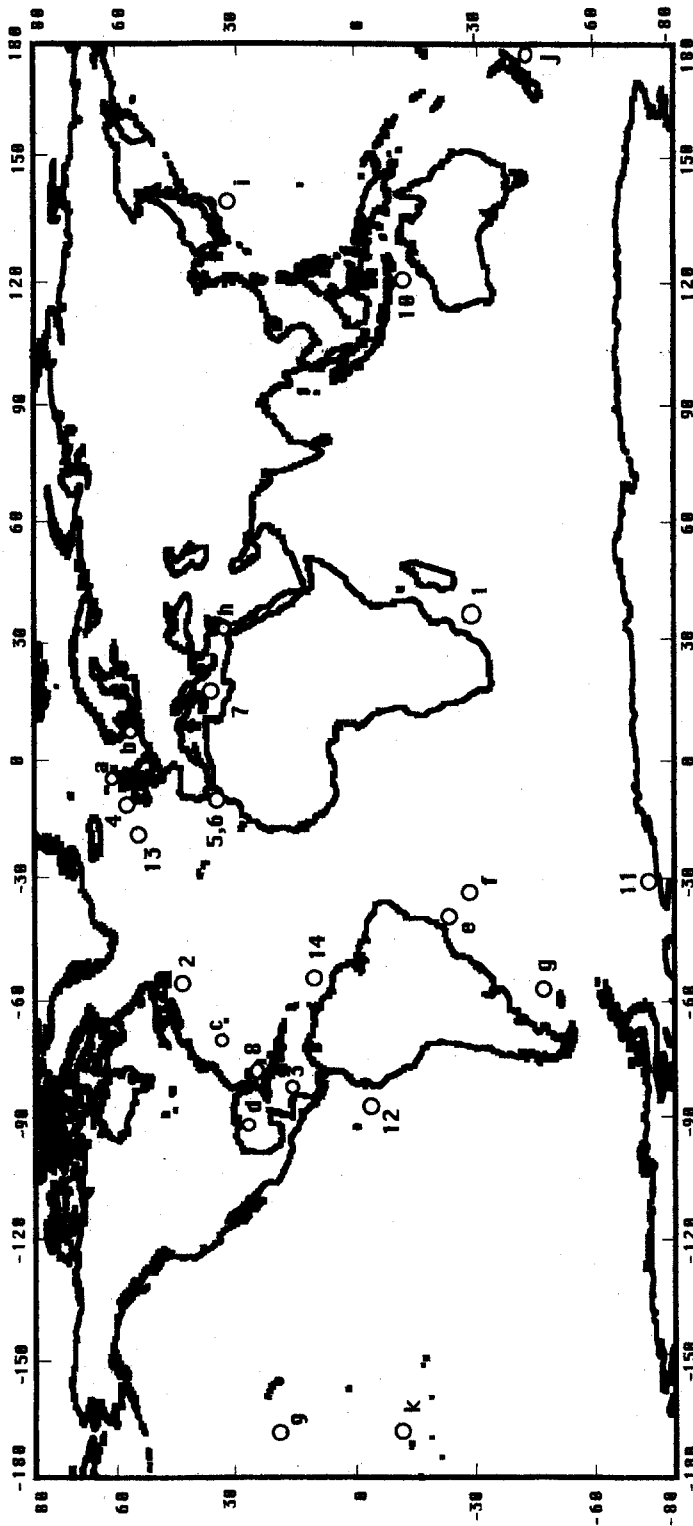


Fig. 1. Location of the contourite and bottom-current sand sites referred to in the text, numbered in the order in which they appear. 1 = Sodwana Bay, SE Africa; 2 = western Grand Banks, Newfoundland; 3 = Bawihka Channel, Nicaraguan Rise; 4 = Hebrides Slope; 5 = eastern Gulf of Cadiz; 6 = Faro Drift; 7 = Messina Strait; 8 = Florida Straits; 9 = mid-Pacific seamounts; 10 = Sumba Basin; 11 = Weddell Sea; 12 = Carnegie Ridge; 13 = Hatton Drift. Letters correspond to some other cited bottom-current-related deposits: a = Faeroe-Shetland Strait; b = Skagerrak Strait; c = USA eastern continental margin; d = Gulf of Mexico; e = Campos Basin; f = Rio Grande Rise/Vema Channel area; g = Argentine Basin; h = Israel continental shelf; i = Miyako islands, Japan; j = Chatham Rise, New Zealand; k = southwest Pacific.

(McCartney, 1992). As there is very little depth stratification, the current involves most of the water column, and flows northward up to the eastern margin of the Rockall Trough as a continuation of the cyclonic loop present in the southern Rockall Trough. The measured velocity ranges from 3 to 30 cm/s on average, but with variations according to water depth, including flow peaks of 48 cm/s at 400–600 m depth, and 15 to 25 cm/s at about 1000 m.

### 2.1.3. *Bedforms and geometry*

The sandy contourite bed constitutes a veneer at the surface of contourite accumulations of various types: a broad sheeted drift (490 m thick, 60 m relief, extending several tens of km), with a large field of sediment waves (550 km<sup>2</sup>, 200 m thick); a mounded elongate drift (300 m thick, 60 km long, 20 km wide, maximum relief of 150 m), with associated sediment waves; and small moat-related isolated drifts (30–100 m thick, 1–4 km wide). The most common bedforms are asymmetrical linguoid ripples. Ice-rafted clasts are seen winnowed from the sea-bed with scours and lee-side drifts.

### 2.1.4. *Sediments*

The surficial coarse-grained deposits form a bed 3 to 40 cm thick (Fig. 2). They are muddy sands with 30 to 80% moderately well-sorted medium to fine sands and common lithic clasts. They are predominantly structureless although locally some cores display cross-lamination. A variety of burrows are present including *Zoophycos* and *Planolites*. The basal contacts are gradational and bioturbated or sharp and erosional.

These sandy contourites are Holocene in age and, in many cases, they represent early Holocene deposits (>7.5 ka) with the later Holocene section either eroded or non-deposited. Accumulation rates for the preserved Holocene section vary from about 16 cm/ka to 64 cm/ka, although these figures are an average for both sandy and muddy contourites. The sandy contourites appear to result from the winnowing of muddy glacial material due to an increase in the intensity of deep circulation and hence bottom-current velocity following the end of the last Glacial period.

2.2. *Mediterranean undercurrent sandy contourites, eastern Gulf of Cadiz continental slope* (Heezen and Johnson, 1969; Mélières et al., 1970; Kenyon and Belderson, 1973; Faugères et al., 1985; Nelson et al., 1993)

#### 2.2.1. *Morphological background*

Uneven slope (300 to 1000 m deep) with linear diapiric ridges perpendicular to the slope contour, valleys and terraces. Coarse-grained contourites are located on the upper slope and sand dune facies on the up-stream mid-slope terraces.

#### 2.2.2. *Hydrology*

The Mediterranean Outflow Water (MOW) flows westward through the Straits of Gibraltar and along the Cadiz continental slope up to 1400 m depth. The maximum current speeds vary from 250 to 180 cm/s along the upper continental slope near the Straits. They decrease rapidly away from the Straits to between 80 and 40 cm/s and are deflected northward as a result of the Coriolis effect. In this area, the flow splits into several branches showing various trends and intensities as a result of the channelling effect of a very complex morphology. Currents that are forced to flow down valleys may reach 60 to 100 cm/s in an area where the contour-parallel flow is only about 40 cm/s.

#### 2.2.3. *Bedforms and geometry*

The sandy beds may form sand ribbons (100 m wide and 3 km long) or sand dunes (3 to 10 m high, 30 to 75 m wavelength and 30 to 1500 m crest length). The ribbons occur on the upper slope and the dunes either on terraces or on valley lateral levees located on the mid-slope or the lower slope. Sand deposits are also present in drifts banked against diapiric ridges. A large range of ripple types of various sizes are common superficial bedforms associated with the dunes.

#### 2.2.4. *Sediments*

The surface sandy contourite layer is 0.2 to 1.2 m thick and has been formed during the present Holocene high sea-level stand. The underlying sediments (up to 2 m below the sea floor) are interbedded sands, coarse silts and muds. The sandy layers are commonly reverse-graded and may show cross-lam-

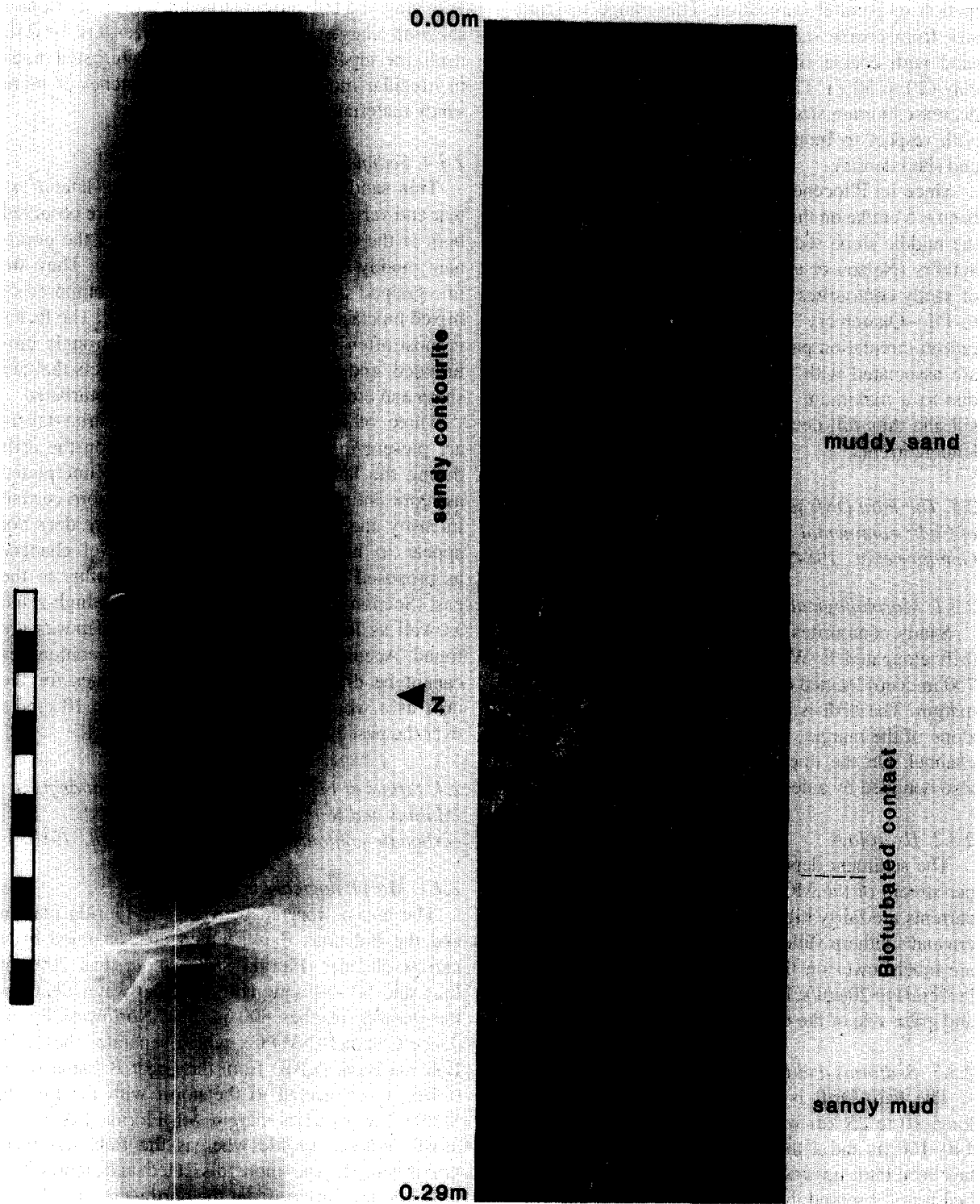


Fig. 2. X-radiograph (left) and core photograph (right) of the bioturbated sands that constitute the mid-depth sandy contourites from the Hebrides slope (from Howe, 1994). Scale bar in centimetres.

ination or parallel lamination. They range in grain size from coarse sands with gravel to fine-grained sand with coarse silt and a significant amount of clay (20 to 30%). There is a westward (along-flow) decrease in grain size and in siliciclastic components with respect to biogenic components (foraminifers and shell debris).

Since its Pliocene origin, the deposition rate has been <5 cm/ka on the upper slope and <13 cm/ka on the middle slope sediment drift. According to some authors (Nelson et al., 1993), the cyclic deposition of sandy contourites and mud drapes can be related to Plio–Quaternary sea-level changes and Mediterranean circulation patterns. High-stands of sea-level are associated with the periods of sand deposition due to a maximum water depth over the Gibraltar sill and thus full development of the Mediterranean Undercurrent.

### 2.3. *The Faro Drift sandy contourites, northern Gulf of Cadiz continental slope (Faugères et al., 1984; Gonthier et al., 1984; Stow et al., 1986)*

#### 2.3.1. *Morphological background*

Sandy contourites are deposited on and around a drift elongated E–W on a shallow plateau (500 to 700 m deep) located on the upper part of the Algarve margin. The drift is banked against the steep upper slope of the margin, but separated from it by a deep channel. On the open southern margin the drift is also bounded by a deep channel.

#### 2.3.2. *Hydrology*

The sediment deposition is controlled by the upper stream of the MOW. Measured velocities of the currents are fairly high (40 to 80 cm/s) in the northern and southern valleys which bound the drift. They are much lower on the drift itself, probably from a few cm/s to 20 cm/s, based on the observed bedforms and grain size of the deposits.

#### 2.3.3. *Bedforms and geometry*

The Faro Drift is a giant elongate drift, 50 km long, 10 to 25 km wide, with a maximum relief of 140–160 m and a thickness of 300 to 500 m, that has been built up since the end of the Miocene. The bedforms observed in the marginal valleys vary from sandy and gravely irregular lag deposits associated

with crag and tail current structures, to sandy ripples showing a large range of types and sizes. On the drift itself, the superficial sediments are bioturbated muds in irregular mounds with localised patches of more sandy material.

#### 2.3.4. *Sediments*

Thin sandy contourite layers of large lateral extent and variable thickness (5 to 35 cm) are observed both at the surface and interbedded with the dominant muddy deposits of the drift (Fig. 3). They are fine-grained sands with coarse silts and composed of mixed bioclastic and siliciclastic material. The facies is most often structureless, sometimes strongly bioturbated, and with basal and upper contacts that are sharp and erosional or gradational and bioturbated.

Three of such coarse-grained contourite layers are present in the sediments deposited on the drift during the last 18,000 years. They are interpreted as representing periods of increased bottom-current intensity and circulation. Their occurrence does not appear to be related to global sea-level changes as proposed by Nelson et al. (1993) farther to the east (Section 2.2) and, consequently both high-stand as well as low-stand sandy contourite deposits are found. Accumulation rates for the sandy contourites cannot be differentiated from overall rates for the drift as a whole, which range from 3 to 10 cm/ka over the past 30,000 years approximately.

### 2.4. *Straits of Florida: carbonate sediment drifts (Mullins and Neumann, 1979, 1980) and carbonate-contourite sands (Gardner et al., 1989)*

#### 2.4.1. *Morphological background*

The area is located between the Florida margin and the Bahamas Bank, which are separated by a narrow channel (Florida Strait) more than 200 km long and 60 km wide (Fig. 4). The water depth in the thalweg reaches 800 m. The Northwest Providence Channel (NWPC), which separates the Little Bahama Bank (LBB) from the Great Bahama Bank (GBB) is connected to the north with the Florida Strait. The western margin off Florida has a relatively smooth profile whereas the Bahamas margin is steeper and more dissected and shows two large sedimentary drifts at the northwest end of each bank.

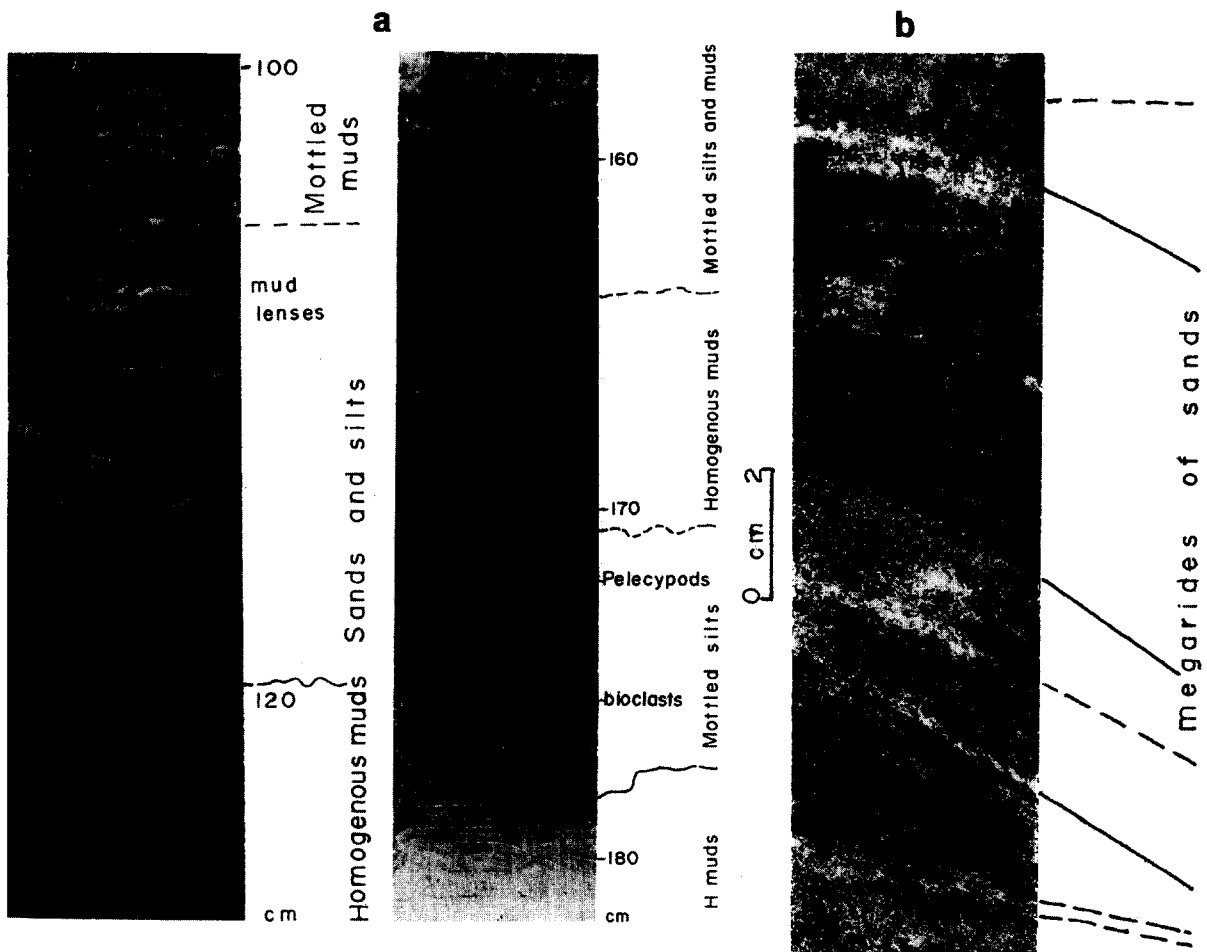


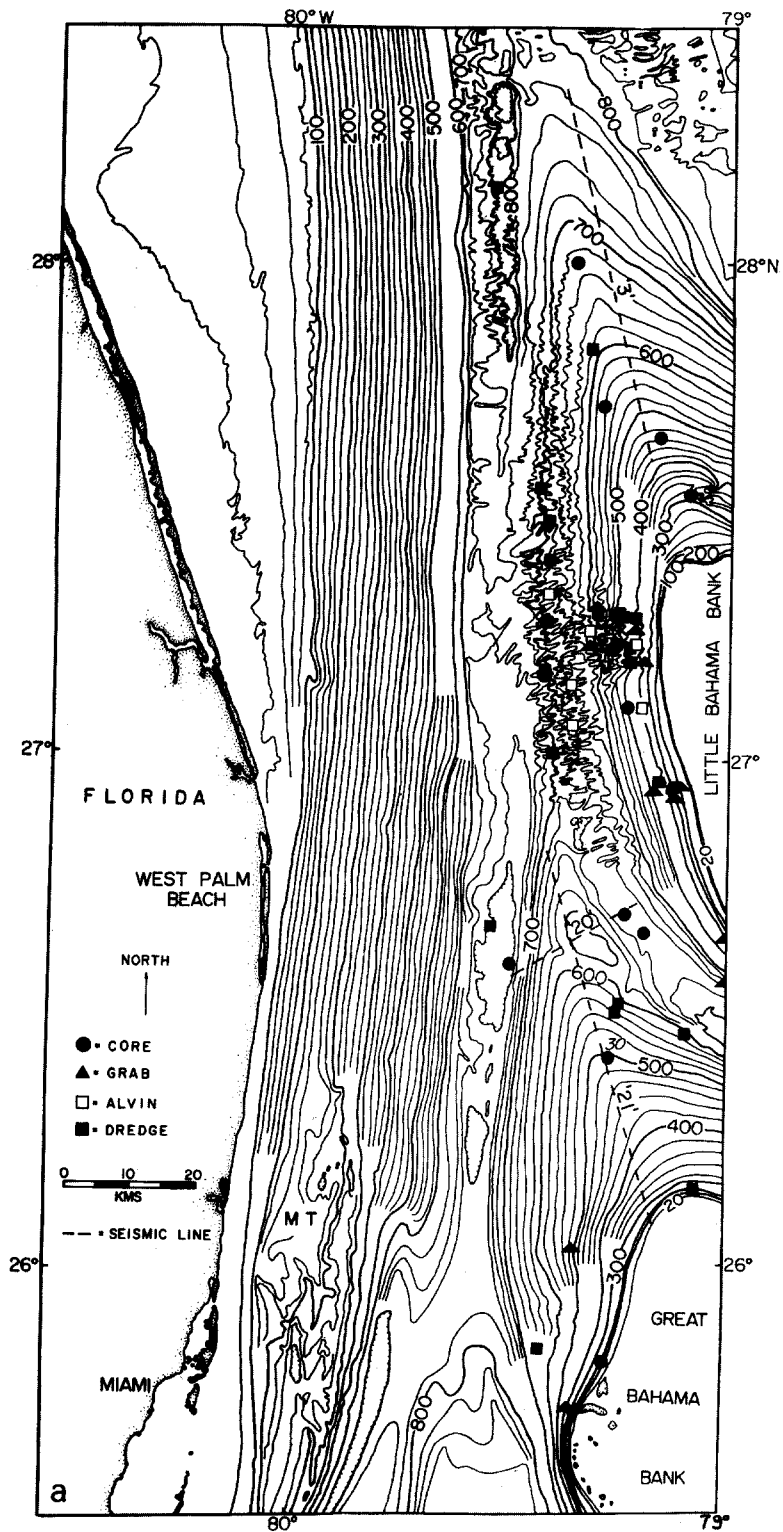
Fig. 3. Mid-depth sandy contourites facies from (a) Faro Drift (from Gonthier et al., 1984), and (b) east Gulf of Cadiz (Faugères et al., 1985).

#### 2.4.2. Hydrology

Oceanic circulation in the area is dominated by the northward flow of the Florida Current and Antilles Current, both merging at the northern end of LBB to develop the Gulf Stream. Superficial currents may reach speeds of 200 cm/s. Along the Florida margin a southerly near-bottom undercurrent flows with velocities ranging from 2 to 50 cm/s. At the eastern margin of the Straits a near-bottom northward current may reach velocities up to 60 cm/s. Along the NWPC both superficial and bottom-currents flow in opposite directions on either side of the channel, with superficial currents reaching velocities up to 200 cm/s.

#### 2.4.3. Bedforms and geometry

The drifts are up to 3000 km<sup>2</sup> in area, 600 m thick, with a maximum length of 100 km for the LBB Drift and 85 km for the GBB Drift, and up to 60 km wide. They are hemiconical in shape, mounded in the transverse section and wedged in the longitudinal section. Both dip 2° in a downcurrent (north-northwestward) direction. Seismically the mounds present an oblique progradational pattern with minor parallel and chaotic internal reflections, and downlapping at the base. Sandwaves (1 to 6 m high, wavelengths 30 to 60 m) are confined to the western side of the strait, in an area 2 km wide and 70 km long, and patches (10 to 50 m wide, hundreds of metres long) of sand ripples and megaripples merging locally into sand ribbons, are



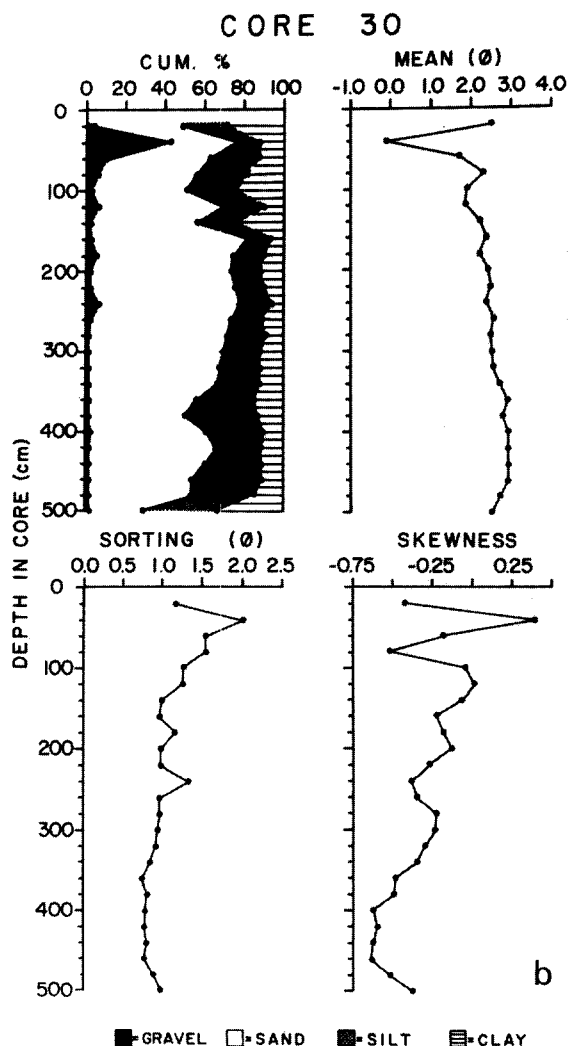


Fig. 4 (continued). (b) Grain-size distribution and statistical parameters from core 30 located over the conic submarine projection of the Great Bahama Bank.

observed on the eastern side. These deposits are associated with coral mounds and zones of non-deposition.

#### 2.4.4. Sediments

The drifts are composed of a mixture of shallow-water bank- and pelagic-derived carbonate sediments, and massive intraclasts. The granulometry is

dominantly sand-sized, with some granules (Fig. 2). They develop massive beds with downslope pinchouts, cross-stratification and erosional discontinuity surfaces. Some early diagenetic features like heavily bored, submarine cemented hardgrounds and geopetals are also observed. Laterally there is a facies transition to pelagic sediments and to gravity-flow deposits, whereas vertically they grade to shallow-water carbonates. The size of these sandy accumulations coupled with their excellent porosity (30–40%) and permeability (1000 millidarcies) characteristics, make them attractive analogues for hydrocarbon reservoirs.

In the western and eastern channels, bedforms are composed of coarse to fine sandy biogenic contourites, made up of foraminiferal and pteropod shells. The thickness of these accumulations was not determined.

#### 2.5. Foraminiferal sandy contourites on mid-Pacific seamounts (Lonsdale et al., 1972; Cacchione et al., 1988).

##### 2.5.1. Morphological background

Top of 'Horizon Guyot' (1500 m deep), a volcanic seamount in the east tropical Pacific.

##### 2.5.2. Hydrology

Current due to internal waves and reinforced by the effect of the relief on the wave motion ('barotropic tidal currents'). Maximum speeds are up to 30 cm/s.

##### 2.5.3. Bedforms and geometry

Field of sandy dunes (1 m high and 20 to 30 m wavelength) and ripples (10 to 30 cm wavelength).

##### 2.5.4. Sediments

Sands are medium to fine, well-sorted and mainly composed of foraminifers. The surficial sandy layer is up to 2 m thick and similar beds have been observed deeper below the surface. They are sandy lag-contourites that result from the winnowing of pelagic sediments by internal-wave-induced currents.

Fig. 4. Mid-depth sandy contourites of the Florida Straits. (a) General bathymetry, and core 30 (b) and seismic profile 21 (c) locations. Note the bottom-current-induced conic morphology developed at the north-northwestern end of both the Great and Little Bahama Bank.

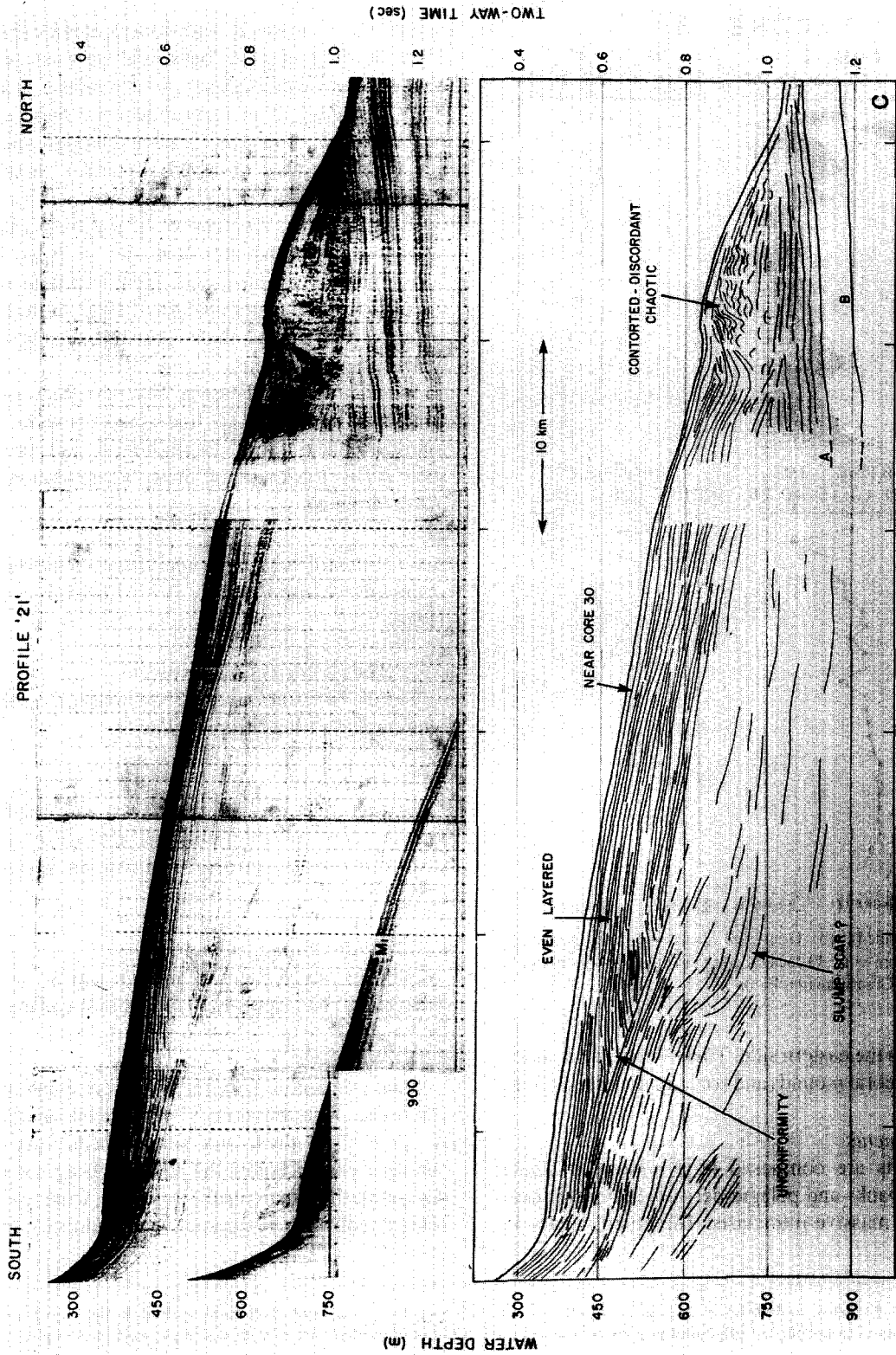


Fig. 4 (continued). (c) Single-channel, air-gun seismic profile 21 and line drawing interpretation along the crest of the conic feature, near core 30 (figures from Mullins et al., 1980).

## 2.6. Sumba Basin and Ridge in an intra-oceanic forearc trench system (Eastern Sunda Arc, Indonesia) (Reed et al., 1986, 1987)

### 2.6.1. Morphological background

The Sumba sill (1150 m deep) connects the Sumba Basin (1500 m deep) in the west to the Banda Sea in the east. The E–W-elongated Sumba Basin is constrained between the Sumba Ridge and the Sawu–Timor overthrust ridge, and bounded to the east by the sill. It opens and deepens toward the west.

### 2.6.2. Hydrology

The sill is one of the compulsory pathways followed by currents derived from the southern Intermediate Pacific water and the deep Pacific water and flowing from the west Pacific Ocean into the east Indian Ocean (the Indonesian Through Flow). The currents spill over the sill and sweep the Sumba Basin floor.

### 2.6.3. Bedforms and geometry

On the sill and on the slope downstream of the sill, sediment waves and furrows are present. Over the sill crest at the Sumba Ridge, an irregular and hummocky relief is developed. On the inner part of the Sumba Basin floor, an elongate drift (Central Mound) has been constructed by the passage of SW-flowing bottom currents.

### 2.6.4. Sediment

Winnowed foraminiferal sandy contourites (Fig. 5) are found on the crest of the Sumba Ridge, at both sides (NE and SW) of the sill gap, and in the boundary channels of the Central Mound. These sediments are unconsolidated, highly reworked, matrix-poor, consisting of late Quaternary whole and fragmented foraminiferal tests, presenting an average carbonate content of 83%.

## 2.7. Comment

Further examples of mid-depth sandy contourites have been reported from the Faroe–Shetland Channel, a NE-trending deep-water (1000–1700 m) trough on the northwestern British continental margin, where muddy silts and sands with sharp or erosive bottom surfaces constitute sandy contourite

accumulations (Taizhong et al., 1994; Stoker et al., 1998), and the southeastern Brazilian margin, an open passive margin where accumulations of centimetres to metres of fine to coarse bottom-current-reworked or -transported sands are found in water depths down to 750 m (Caddah et al., 1998; Viana et al., 1994, 1995, 1998). The sandwaves observed in the Messina Strait, Sicily, from 500 m to 1400 m water depth (Montenat et al., 1987; Collela and d'Allessandro, 1988; Collela, 1990), have a deep tidal origin and are not therefore considered contourites *sensu stricto*.

## 3. Deep-water sandy contourites

Rare examples of deep-water modern sandy contourites are recorded in the literature, although the interpretation of some of these accumulations as contourites is still controversial and requires further studies. The deposits discussed are developed on continental rises, lower continental slope aprons and in basin plains at water depths in excess of about 2000 to 3000 m. The main currents involved are essentially deep thermohaline currents. The sandy deposits are thin (millimetres to centimetres), fine-grained, and generally interbedded in muddy sequences of carbonate or siliciclastic composition.

### 3.1. Abyssal dunes of foraminiferal sand on the Carnegie Ridge, equatorial E. Pacific) (Lonsdale et al., 1972; Lonsdale and Malfait, 1974)

#### 3.1.1. Morphological background

Northern flank of the W–E-extending Carnegie Ridge, between the Galapagos Islands and the Equator, at a water depth of 2650 m, on the flat floor of a deep S–N valley (Sand Dune Valley, 400 m deep and 8 km wide), cutting into the ridge.

#### 3.1.2. Hydrology

Bottom currents with velocities in excess of 30 cm/s episodically spill over the ridge from the Peru Basin in the south to the Panama Basin in the north.

#### 3.1.3. Bedforms and geometry

Dune fields comprising asymmetric transverse dunes (mean wavelength 20 m, mean height 0.6 m) and barchans (length 6 to 80 m) are arranged in long,

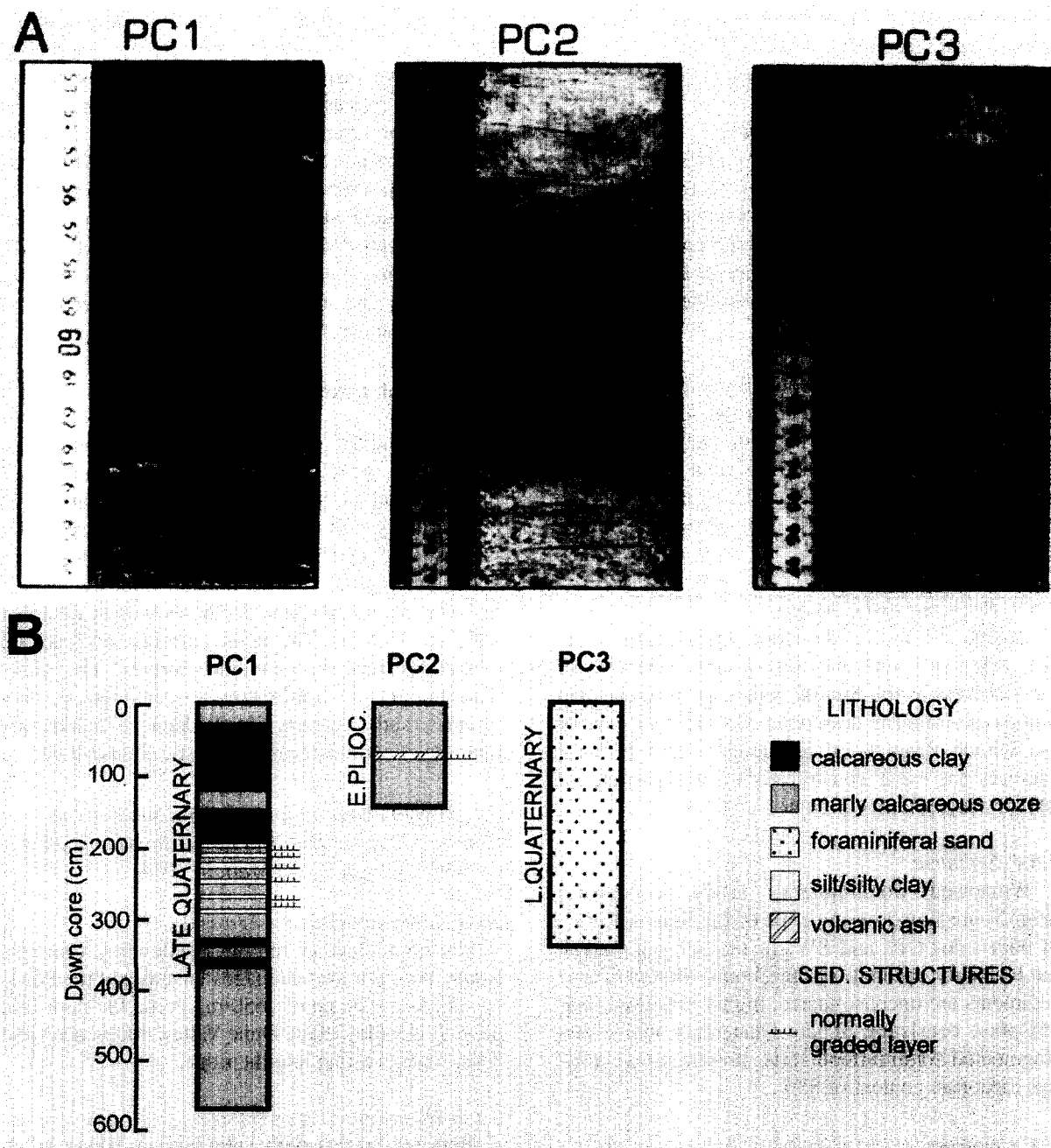


Fig. 5. Piston cores from Sumba Ridge. (A) Photographs of portions the cores. (B) Schematic stratigraphic sections. PC3 is a mid-depth contourite composed of winnowed, broken foram sands (figure from Reed et al., 1987).

narrow belts or are more or less isolated indicating that the supply of sands is limited. They prograde downstream on the valley floor which is paved by a continuous crust of black manganese oxide.

3.1.4. Sediments

Moderately sorted biogenic sands, composed of broken fragments and tests of Quaternary foraminifera, are interpreted as lag deposits formed

from the coarsest pelagic material. These bioclastic sandy contourites are well-preserved, being far above the CCD. Elsewhere, as observed in numerous very deep valleys swept by strong bottom currents (AABW in the Vema Channel, Mézerais et al., 1993; abyssal circulation in the Pacific Ocean, Lonsdale, 1976, Samoan Passage, Lonsdale, 1981) no contouritic sands are preserved due to carbonate dissolution and the lack of terrigenous sand as a consequence of the large distance from land.

*3.2. Hatton Drift, Icelandic Basin, northeast Atlantic (McCave et al., 1980; Stow and Holbrook, 1984; Robinson and McCave, 1994)*

### *3.2.1. Morphological background*

Sands occur along the foot of the Hatton Drift which is plastered against the northwest slope of the Rockall Plateau at a water depth of 2600 to 3200 m.

### *3.2.2. Hydrology*

There is a strong NE-flowing boundary current, formed by the deeper part of the NADW mixed with Lower Deep Water (LDW), formed when Antarctic Bottom Water enters the northeast Atlantic through the Vema Fracture Zone (McCartney, 1992); the maximum recorded speed reaches 23 cm/s.

### *3.2.3. Bedforms and geometry*

NE-migrating, asymmetric ripples (2–3 cm high, 20–25 cm wavelength) and low sand waves (less than 1 m high) appear to form a continuous field along the entire length of the drift (about 300 km long and tens of km wide).

### *3.2.4. Sediments*

The foraminiferal sandy contourites on the surface and at depth are fine-grained and mainly composed of foraminifera associated with minor quartz and feldspars. The sedimentation rates are relatively high, when compared with purely pelagic sites, and variable both spatially, between troughs and crests of sediment waves, and temporally, between Late Pleistocene glacial and interglacial stages. This variability of sedimentation rates is coincident with coarse to fine grain size changes and is believed to result from flux strength oscillations. Some authors suggest a

23 ka orbital precession control in the cyclic pattern of sedimentation presented in the area (Robinson and McCave, 1994). The development of even a relatively thin foraminiferal sandy contourite requires accumulation over a long period of time, together with winnowing and removal of a substantial amount of finer-grained material (I.N. McCave, pers. commun., 1995). Hence the long time persistence of favourable factors is demanded in order to obtain significant deposits.

*3.3. Demerara Rise, central W. Atlantic Ocean (Damuth and Kumar, 1975; Moyes et al., 1975; Embley and Langseth, 1977; Cremer et al., 1982; Poutiers and Faugères, 1983)*

### *3.3.1. Morphological background*

The inferred contourite deposits are limited to the part of the rise immediately north of the Demerara Plateau. They are deposited on a broad levee (3800 to 4500 m deep), located on the southern side of a major turbidity current channel linked to the Orinoco deep-sea fan system.

### *3.3.2. Hydrology*

The NADW sweeps this region with a SE-trending bottom-current flow across the channel and then over the levee.

### *3.3.3. Bedforms and geometry*

The levee is inferred as a contourite drift covered by a field of sediment waves.

### *3.3.4. Sediments*

Several thin layers (0.5 to 10 cm) of non-graded and well-sorted sands with sharp bottom and top contacts occur interbedded with finer-grained muddy deposits. Horizontal and cross-lamination is common in the thin sands, which are composed of quartz-rich coarse silt to very fine-grained sand.

The drift is supplied by the continental terrigenous material transported down the channel which is then pirated by the along-slope deep currents. The deposits formed by the transport and reworking of these materials are more expressive in glacial intervals, when the continental supply is more intense.

### 3.4. Nova Scotian Rise, western N. Atlantic Ocean (Hollister and Heezen, 1972; Stow and Lovell, 1979; Nowell, 1991)

#### 3.4.1. Morphological background

The Nova Scotian Rise is a typical broad passive continental margin offshore eastern North America that has been the site of thick sediment accumulation since the Jurassic. In parts it is made up of irregular mass-flow deposits and lensoid channel lobes derived from the upper parts of the margin that are more highly dissected by slope gullies and slide scars. In other parts it has a smoother topography, partly as a result of bottom-current moulding.

#### 3.4.2. Hydrology

The NE-flowing Gulf Stream dominates the upper part of the water column over the Scotian Rise, whereas the seafloor in excess of about 4000 m is swept by the powerful SW-directed Western Boundary Undercurrent (WBUC). Long-term bottom-current measurements reveal a highly variable system with mean SW flow of around 5–10 cm/s, involving periods of higher velocity as well as reverse flow eddies. Particularly high-velocity episodes (20–40 cm/s) lasting for periods of several days are known as benthic storms.

#### 3.4.3. Bedforms and geometry

Much of the Scotian Rise that is relatively smooth may be the result of normal hemipelagic drape and bottom-current moulding into a sheeted drift form. This sedimentary geometry intercalates with bodies of downslope origin (lobes, slide masses, etc.). The marked asymmetry of turbidity channel levees, particularly those on the Laurentian Fan to the east of the area, is believed to be due in part to the southwest deflection of dilute turbidity currents by the WBUC. Small-scale bedforms such as sediment ripples have not been observed on the present-day seafloor, although intensive bioturbation revealed by irregular mounds may have destroyed any primary bedforms.

#### 3.4.4. Sediments

The Pleistocene–Holocene sedimentary record is dominated by silt-laminated mud turbidites, prevalent during glacial episodes, and hemipelagic/con-

tourite muds deposited during interglacial periods. The turbidites are entirely siliciclastic and mostly fine-grained, but include some thin-bedded fine-grained sands, whereas the contourites are mixed bioclastic–siliciclastic. The only sandy contourites identified with certainty are very rare winnowed foraminiferal sands (3–10 cm thick, laminated and cross-laminated), and rare examples of originally turbiditic thin sand beds (2–5 cm, bioturbated) that show evidence of reworking and short along-slope transport by bottom currents.

#### 3.5. Comment

Although deep-water bottom currents are known to have strong erosion and transport potential, and are very important agents in shaping deep-sea morphology, they mainly affect fine-grained sediments, both siliciclastic and biogenic. The major drifts identified throughout the deep-sea realm are dominantly made of siliciclastic muds and fine biogenic material (Stow et al., 1986, 1998), and most sandy sediments found in continental rise sequences, even where these partly comprise sheeted drifts, are more likely to be turbidites than contourites. The major HEBBLE study on the Nova Scotian Rise (Nowell, 1991) failed to find any sands reworked by the WBUC downstream of sandy turbidites on the Laurentian Fan. Similarly, turbidites to the north and east of the Bounty Fan are crossed by the Deep Western Boundary Current that fails to accumulate downstream a significant amount of sand (Ian McCave, pers. commun., 1995).

The rare contourite sands that do occur at these depths tend to be thin, irregular and highly bioturbated. They are either bioclastic, commonly winnowed concentrations of foraminiferal or radiolarian sand, or mixed bioclastics–siliciclastics. Bottom-current reworked tops of sandy turbidites almost certainly occur wherever turbidites are deposited beneath a major bottom-current system, but their unequivocal identification is relatively rare as yet (see review by Stow et al., 1998). In some cases, mainly silt-sized sediments make up the bulk of contourite-like accumulations in deep water as, for instance, the case of the southeast Weddell Sea (Pudsey et al., 1988; Kuvass and Kristoffersen, 1991; Weber et al., 1994).

#### 4. Outer-shelf/slope sands

Bottom-current, outer-shelf sand deposits are reported from many different continental margins. They result from the action of relatively strong surficial geostrophic currents, typically combined with storm wave-induced near-bottom orbital motion, tidal-currents, and the rotatory effect of current eddies sweeping the seafloor (the *seafloor polishing effect* of Viana et al., 1998). The resultant deposits, in some cases, show an unexpected combination of features, such as bottom-current-induced bedforms associated with storm- and tide-related structures, and may provide a good analogue for some ancient sandy deposits of enigmatic origin (e.g. those described by Mutti et al., 1980; Enjorlas et al., 1986; Villars, 1991; Kindler et al., 1994, etc.).

Outer-shelf sands are the sedimentary expression of various physical exchange processes at the shelf edge, comprising mainly bed-load transport, but also minor suspension-load transport. The combination of processes and the relatively shallow water depths involved in their accumulation precludes using the term *contourites* for such deposits. However, they develop important sandy deposits, often drift-like ones away from continental margins, with clear evidence of bottom currents and related processes. Such high-energy environments generally result in well-sorted sands that may be up to several metres thick. In the ancient record, they represent a much more significant reservoir potential than the mid-depth or deep-water sandy contourites discussed above. However, preservation in the rock record requires a delicate equilibrium between processes, sediment availability and adequate space for their accumulation.

4.1. *Sodwana Bay outer-shelf giant sand dunes, SE African margin (Flemming, 1978, 1980, 1981; Ramsay, 1994a,b)*

##### 4.1.1. *Morphological background*

The most spectacular example of bottom-current-reworked shelf-sands is that described from the Sodwana Bay continental shelf, on the southeast coast of Africa, under the influence of the western boundary Agulhas Current (AC). The continental shelf in this area is extremely narrow (3 km wide), the shelf break lies at depths of between 45 m and 70 m and is cut by

twelve submarine canyons. The coast is linear, clastic, with well-vegetated sand dunes up to 180 m high.

##### 4.1.2. *Hydrology*

The western boundary southward-flowing Agulhas Current is the most important oceanographic feature in the area. Its core is located just offshore the shelf edge, and it sweeps the continental shelf with extreme velocities up to 3 m/s, with average velocities exceeding 0.5 m/s in the south and less than 0.25 m/s in the north. The presence of an eddy north of the area, diverting the general trend of the AC may be responsible for such a marked decrease in velocity. High-energy large-amplitude southeasterly waves and a low mesotidal range (2 m) also characterise the Sodwana Bay area.

##### 4.1.3. *Bedforms and geometry*

The large subaqueous sand dune fields occupy an area greater than 65 km<sup>2</sup> with a maximum thickness of approximately 20 m. Individual waves are up to 17 m in height, 4 km long and 1.2 km wide at water depths greater than 50 m. They are transported southward by the AC at a migration rate of 125 m/year. Inshore meandering of the AC activates the sediment transport of the inner dunes while the outer dunes are continuously being transported by the normal AC flux. Bedload parting is observed as a consequence of the rotatory motion of the bottom currents provoked by the eddies generated at the passage of the AC over the canyon heads. Subordinate hummocky structures and oscillation ripples are observed at depths of 60 m indicating that storm wave energy is sometimes superimposed on the current action, as observed by Butman et al. (1979) and Dalrymple et al. (1992) in the western North Atlantic.

##### 4.1.4. *Sediments*

The giant dunes comprise fine-grained, moderately- to well-sorted, quartzose sands, with minor fragmented bioclastic material (foraminifers, molluscs, bryozoans, etc). Inner-shelf sands are better sorted than the sediments from greater depths (>50 m), probably due to wave action.

Ramsay (1994a) reports dune migration towards the numerous canyon heads that dissect the Sodwana Bay shelf (Fig. 6). The sediments then cascade down the canyon valley as gravity flows. The erosive ac-

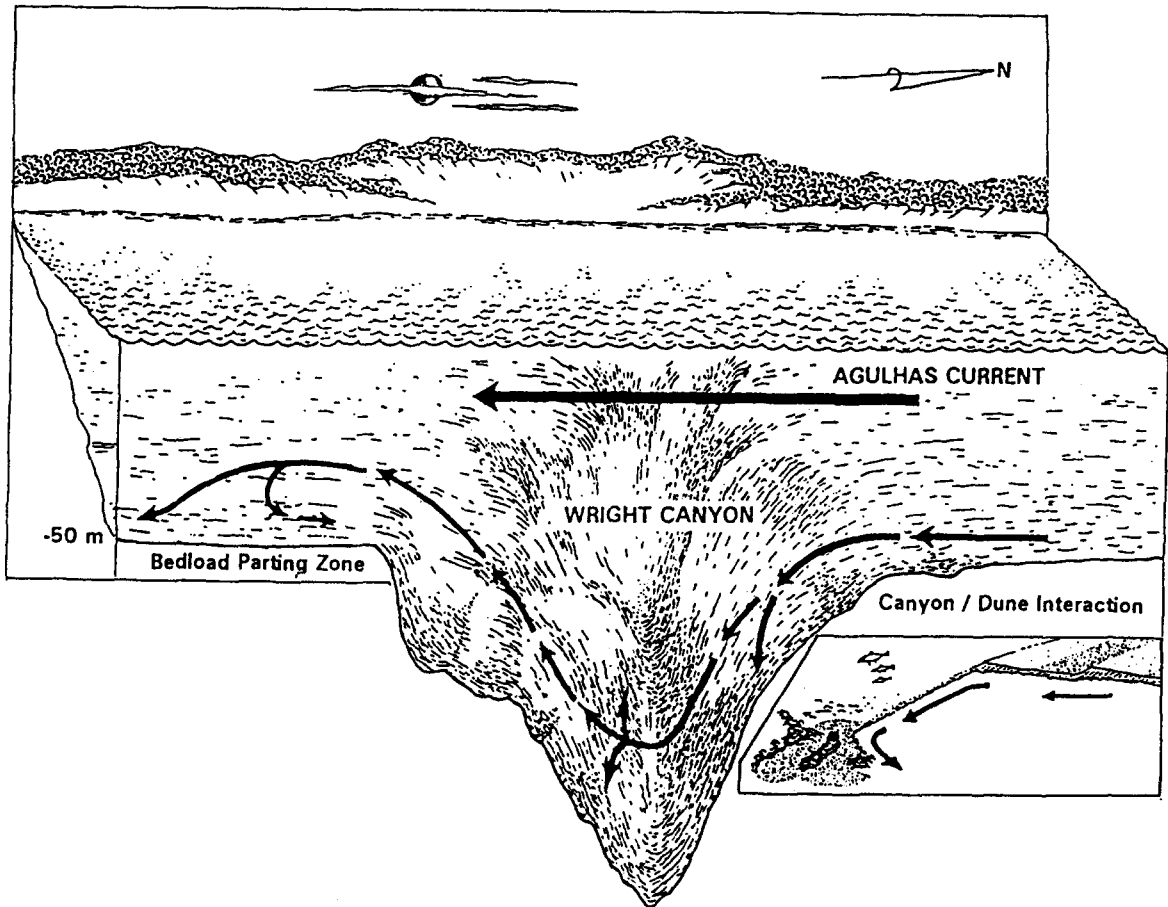


Fig. 6. Example of shallow-water bottom-current sands. Schematic block diagram from Sodwana Bay, southeast Africa, showing the relationship between the Agulhas Current (AC) and the development of bedforms associated with the undisturbed parts (subaqueous dunes) and physiographically disturbed parts of AC bottom flow (eddy generation and the occurrence of bedload parting zones). The shelf incising canyon head is constantly supplied by migrating sands (figure from Ramsay, 1994b).

tion of such flows increases the canyon dimensions and result in a net loss of shelf sediments to the canyon heads where they are trapped or transported down-canyon by gravity processes. Continuation of this mechanism over a medium to long time period will result in the erosional stripping of shelf sediments far more rapidly than they can be replaced by supply from the continent.

#### 4.2. Campos Basin outer-shelf/upper-slope sands, SE Brazilian margin (Viana et al., 1994, 1995, 1998)

##### 4.2.1. Morphological background

The Campos continental shelf is more than 100 km wide, with an abrupt shelfbreak at depths rang-

ing between 80 m in the north to 130 m in the south. Steep off-shelf gradients are locally up to 15°, whereas most of the continental slope has a gentler gradient (average 2.5°). It averages 40 km in width and is dissected by several large submarine canyons. Locally the shelf is broader, developing an outward bulge beyond which the upper slope (250–350 m deep) is covered by a system of low, narrow erosional ridges and valleys, 50 m high, 0.5 to 1.0 km wide, and up to 10 km long in a N–S direction. Below this zone is a broad erosional terrace at around the 450 m isobath. To the south, the shelf edge is cut by several gullies. The base of the shelf edge escarpment acts as a gradient inversion providing a favourable site for sand accumulation. Over the

shelf, small topographic irregularities up to 10 m high, induced by the presence of fossil beach-rocks and carbonate banks, act as sediment traps.

#### 4.2.2. *Hydrology*

Superficial circulation over the Campos shelf edge/upper-slope is controlled by the western boundary Brazil Current (BC), whose flow is channelled and intensified in the area of the outward bulge of the shelf (up to 1 m/s, 5 m from the seafloor, 200 m water depth), and over the erosional terrace. Flow perturbation to the south causes anticyclonic mesoscale eddies that penetrate onto the shelf. These geostrophic current excursions together with storm waves and tidal currents develop combined outer-shelf bottom currents with off-shelf peak velocities (ESE) greater than 50 cm/s. Upper-slope currents of the same magnitude, both along-slope (southerly currents, related to the South Atlantic Central Water, SACW, the Brazil Current countercurrent) and cross-slope (downslope extension of storm fronts, tide and eddy energies) were identified during measurements made over a 12-month period (2 m from the bottom, 400 m water depth).

#### 4.2.3. *Bedforms and geometry*

On the outer-shelf, low-amplitude (1.0 m high) sand dunes and megaripples occupy an area of more than 100 km<sup>2</sup>. They trend east-northeast, with an apparent off-shelf direction of migration. The upper slope, north of the São Tomé canyon, is marked by a succession of current-related structures (scours, comet-marks). To the south of the canyon, low-amplitude sand waves, trending downslope, are observed in a narrow terrace at the base of the shelf edge. Cone-like, gravity-derived deposits are found attached to the gully mouths, and sheet-like muddy sand deposits are spread all over the upper slope.

#### 4.2.4. *Sediments*

Outer-shelf current-reworked deposits are medium- to coarse-grained siliciclastic sands, rounded to sub-rounded, locally fine to very fine, greenish, with minor bioclastic components (red and green algal fragments, bryozoa, foraminifera), some feldspar, glauconite, micas and heavy minerals. They may develop accumulations at the present day up to 20 m thick, and more than 5 m thick in the subsurface,

the sands in each case forming the top of a shallow-ing-upward trend. Upper-slope sands have the same compositional characteristics as the shelf sands. To the south, they are finer (very fine to fine, locally medium-grained), highly bioturbated, with well preserved shallow-water components (e.g. miliolids) and interbedded hemipelagic muddy deposits in the deeper portion of the upper slope. They develop more than 10 m thick accumulations at the base of the shelf edge escarpment, that thin gradually downslope. Gravity- and current-reworked deposits are interbedded as a result of alternation of cross-slope offshore spilling and along-slope BC and SACW reworking. To the north, the vigorous flux of the funnelled BC is responsible for the reworking of coarse to pebbly sediments (siliciclastic and bioclastic) that infill erosional valleys in the upper-slope terrace.

This example from the Campos margin illustrates the ability of surficial geostrophic currents, their on-shelf penetration and combination with other shelf currents, to develop sand deposits over the continental shelf and to export sediment to the upper slope. Channellization of these currents induces higher velocities, large erosional features and greater competence in transporting coarse to pebbly sediments. To the south a calmer but still strong along-slope geostrophic circulation reworks and accumulates fine sand exported from the shelf.

### 4.3. *Grand Banks outer-shelf, offshore Newfoundland, NW Atlantic Ocean (Dalrymple et al., 1992)*

#### 4.3.1. *Morphological background*

The Grand Banks of Newfoundland are located in the northwest Atlantic Ocean. They consist of a series of shallow and very flat banks separated from each other and from the mainland by deeper channels or enclosed basins. They occupy an area of 160,000 km<sup>2</sup> in a region where the shelf break occurs at a depth of about 120 m. The outer banks are located more than 200 km from land in water depths between 60 and 80 m. The channels are 10 to 75 km wide, over 70 km long and reach depths of 200 m (i.e. up to 100 m deeper than the adjacent banks).

#### 4.3.2. *Hydrology*

The regional circulation is dominated by the Labrador Current, a permanent, southerly flowing,

cold ocean current. Mean flow speeds in the middle of the water column (about 50 m) vary between 5 and 15 cm/s. The region is also characterized by a microtidal regime (up to 1.80 m), with maximum tidal speeds reaching 8 cm/s, generally oriented N–S. The large number of storms, especially during the winter months are responsible for a strong wave regime, with waves higher than 6 m occurring 5% of the time. The largest and longest-period waves produced by storms generated in the north induce a south-southwesterly current that may intensify the Labrador Current flow and attain speeds up to 75 cm/s. The highest speeds occur over the banks where a clockwise rotation of the currents accompanies the storm-front passage. Wave-orbital motion is also co-linear with the general trend of the bedforms.

#### 4.3.3. *Bedforms and geometry*

Sand waves, gravel waves and megaripples are present over the whole area whereas sand ribbons occur in water depths of less than 100 m. Sandwaves may be up to 3 m in height, with wavelengths between 30 m and 200 m, and they occur singly or in small fields. Megaripples are generally >1.0 m in height, with wavelengths ranging from 6.5 m to 20 m, and are present over large areas including the lee and stoss sides of sandwaves. The trend of the bedform crests indicates a south-southwest transport. Sand ribbons typically have heights of <2.0 m. The average thickness of these modern sand deposits rarely exceeds 15 m in the channels and a few metres over the banks. The units become thicker to the south-southwest, in accordance with the trend of the Labrador Current.

#### 4.3.4. *Sediments*

The sands are mainly siliciclastic and with a grain size that varies with depth and intensity of hydrodynamic forces. Medium to coarse sand and gravel are found in some parts. Gravel occurs in the shallower zones over the banks, exposed to the more intense current flow, whereas medium sand, thoroughly bioturbated, occurs in water depths down to 300 m. The strong storm waves and tidal currents appear to amplify the effects of the Labrador Current without noticeably affecting the resultant deposits (Fig. 7).

#### 4.4. *Bawihka Channel, Nicaraguan Rise, Caribbean Sea (Hine et al., 1992, 1994)*

##### 4.4.1. *Morphological background*

The Bawihka Channel is an open seaway 125 km long, 8 km wide and 220 m deep. It lies between two carbonate platforms, the Miskito and Bawihka banks, on the Nicaraguan Rise, a major NE–SW-trending structural feature on the northwestern part of the Caribbean Plate. The carbonate banks have their flat tops lying at water depths of between 20 and 40 m as a consequence of the particular sponge–algal biotic association that constitutes the bank margins.

##### 4.4.2. *Hydrology*

The area is dominated by the northward flow of the Caribbean Current, a part of the North Atlantic western boundary current. This current may develop turbulent flows with superficial velocities reaching up to 250 cm/s. As a consequence of the lack of the protective coral-barrier rims, such as those typical in the Bahamas, the carbonate banks are traversed by long-period oceanic swells, large storm waves and the Caribbean Current flow.

##### 4.4.3. *Bedforms and geometry*

The floor of the seaway is characterized by an absence of bedforms. The coarse nature of the deposits and a rapid cementation stimulated by the strong currents appear to have prevented the development of sandwaves. A sediment drift deposit is developed at the northern end of the seaway.

##### 4.4.4. *Sediments*

The sediments that feed the drift are probably derived from both off-bank overspill and deeper-water reworking in the Bawihka Channel, although the drift itself has not been sampled. Bank top sediments (water depths between 20 and 50 m) are predominantly coarse-sand-sized *Halimeda* plates, with bryozoans, red algae, molluscs and worm tubes as minor constituents. Deeper-water sediments (water depths >50 m) are more variable with an increase in pelagic forms (pteropods and planktonic foraminifera). The northern channel is dominated by coarse sand to muddy turbidites and current-winnowed sediments, with the finest in the mid-channel axis and the coarsest at the base of slope (165 m).

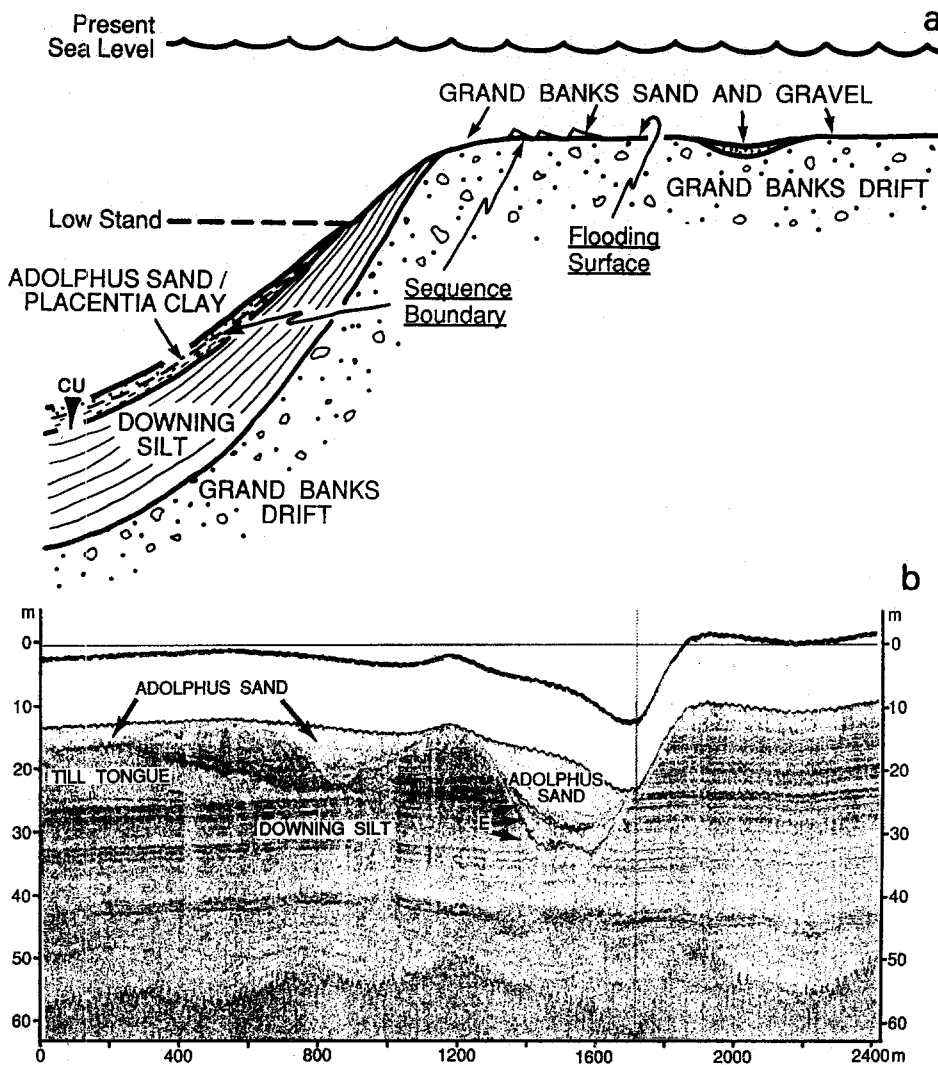


Fig. 7. Shallow-water bottom-current sands of western Grand Banks. (a) Diagrammatic section, from Dalrymple et al. (1992), showing the distribution of (1) outer-shelf bottom-current sands, that develop megaripple fields or occupy intra shelf depressions, and (b) upper-slope bottom-current sands. (2) High resolution seismic profile illustrating the confinement of slope sands to erosional depressions. Zero on the vertical scale does not correspond to the sea surface (from Dalrymple et al., 1992).

#### 4.5. Comment

Other examples of bottom-current-reworked sand accumulation in outer-shelf/upper-slope environments include those from the USA Atlantic margin (Hunt et al., 1977; Butman et al., 1979; Bunn and McGregor, 1980; Stanley et al., 1981), the Skagerrak (Liebezeit et al., 1993; Hass, 1993; Kuijpers et al., 1993), the continental shelf off Israel (Golik, 1993), the Japan Sea (rhodoliths and foraminiferal

sands, Tsuji, 1993) and the east China Sea (Chen et al., 1992). In these areas, coarse-grained sediment accumulation and the development of sand waves and other bottom-current-induced bedforms appear to have been the direct result of the passage of geostrophic currents, combined with action of storm waves, tides and internal waves.

These bottom-current sands grade coastwards into typical mid- and inner-shelf facies, where the action of shelf/littoral processes (tides, waves, along-shore

currents) is dominant resulting in the development of tempestites, hummocky and swaley cross-stratification, shore-face deposits and the whole set of inner-shelf facies. Downslope, they grade into upper-slope hemipelagites, mud turbidites or sand spillover facies. All of these facies may occur intercalated as a consequence of slight tectonic and sea-level variations. A delicate combination of controlling factors is required for the preservation of such shallow-water bottom-current sands in the geological record — these are discussed in the following section.

A number of ancient deposits, some of which have been termed contourites in the literature, are probably best interpreted as shallow-water outer-shelf/upper-slope sands. These include the Lower Cretaceous Greensand, from the North Celtic Sea Basin, offshore Ireland (Winn, 1994), parts of the Kenilworth Member, Book Cliffs, Utah (Pattison, 1995), some of the Lower Tertiary sands in the North Sea (Enjorlas et al., 1986), Eocene sands of the Campos Basin (Mutti et al., 1980), the Eocene of the Ultrahelvetic pre-Alps in France (Kindler et al., 1994), amongst others.

## 5. Discussion

### 5.1. Definition of sandy contourites

Sand accumulates under the influence of bottom currents everywhere from the inner shelf to the deepest parts of the ocean. Most authors concur with a definition of contourites as those sediments that have been deposited or significantly reworked by stable geostrophic bottom currents in relatively deep water. This is the concept originally proposed by Hollister and Heezen (1972) and is currently widely accepted (see Stow et al., 1996). The precise water depth is less easily defined: Faugères and Stow (1993) suggested greater than about 500 m, and have recently refined that upwards to greater than about 300 m (Stow et al., 1998). We now accept this latter figure.

It is clear, therefore, that only the mid-depth and deep-water sands described above can be considered as contourites *sensu stricto*, whereas the shallower-water sands, whose origin has involved a combination of processes, should be referred to as *shallow-water bottom-current sands* or *outer-shelf/upper-slope bottom-current sands* in order to avoid

confusion. It is also important to distinguish a further class or sub-class of bottom-current sand deposits that we refer to as bottom-current-reworked turbidites, where the reworking has only partly affected the turbidite, for example by removal of the topmost fines. Complete reworking, of course, yields a true contourite following the accepted definition (Fig. 8).

### 5.2. Sandy contourites facies models and controls

The most widely used facies model for sandy contourites is that developed by Stow (1982; Stow et al., 1986, 1996). However, this is a generalised model applicable to widely varying deposits, and could therefore be refined to take into account some of the variations that are now well established. The bathymetric subdivision of sandy contourite deposits here proposed would permit development of more tightly constrained facies models for the typical characteristics of such deposits (Table 1), thus yielding the basis for further predictive research of modern and ancient analogues. We therefore present below, facies models for our three depth-defined bottom-current sands, together with a model for bottom-current-reworked turbidite sands taken from Stow et al. (1998). We also discuss the principal factors that control sand accumulation and preservation in each case.

#### 5.2.1. Outer-shelf/upper-slope bottom-current sands

These comprise deposits developed in water depths between 50 and 300 m and are not considered as true contourites. They are related to the on-shelf penetration of surficial geostrophic currents and to the overspilling of shelf sediments to the continental slope. Among the several depositional environments analysed in the literature, only Walker (1984, p. 165) differentiates “shelves dominated by intruding ocean currents” from classical storm-dominated and tide-dominated shelves, referring to the example of southeast Africa presented by Flemming (1978, 1980), although he does not propose a specific facies model for this kind of deposit. The compilation of shelfbreak studies presented by Stanley and Moore (1983) deals extensively with processes and the sedimentary response, but also lacks a facies model for this particular setting. Recent development

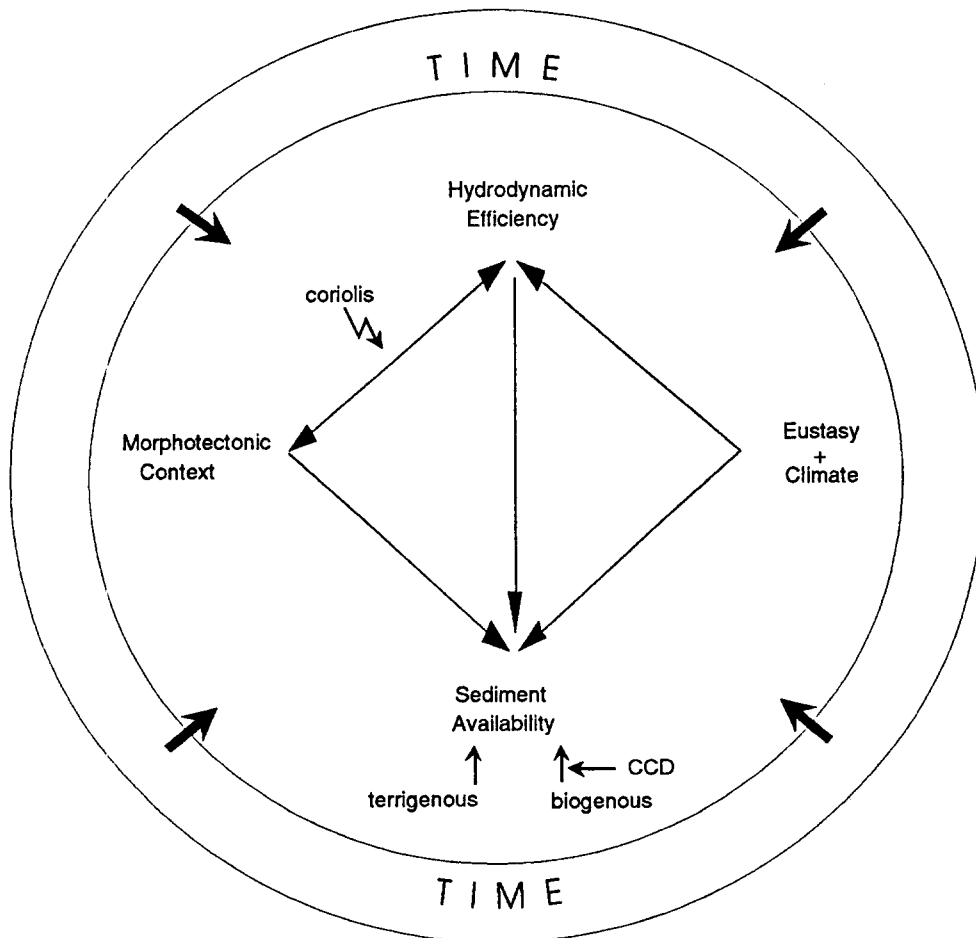


Fig. 8. Diagram of the relationship between the factors that drive the deposition of sandy contourite deposits.

of new sequence stratigraphic models, including the forced regression parasequence (Posamentier et al., 1992), together with oil exploration and discovery in reservoir sands that are neither deep water nor typically shelf deposits, has served to focus attention on the outer-shelf/upper-slope environment.

**5.2.1.1 Facies characteristics.** Based on data from the four case studies presented above (Section 4) and from six other published examples, we can be confident in profiling the following principal sedimentary characteristics.

**Drift geometry:** sheet-like patches on the outer shelf and sheet- to wedge-like spillover pockets on the upper slope; tens of km<sup>2</sup> in extent elongated in direction of the main geostrophic flow; typically

1–20 m thick, but may become thicker if favourable conditions persist.

**Beds:** numerous sets evident within sand body, with flat, inclined or irregular boundaries; abrupt upper and lower contacts typical.

**Structures:** dunes, megaripples and sand-ribbon bedforms common in association with smaller-scale bedforms (ripples, etc); internal structures show parallel and cross-stratification, including large-scale sets indicative of a high-energy current regime; bioturbation can be moderate to intense, but insufficient to destroy primary structures.

**Textures:** medium- to coarse-grained sands most common, with moderate sorting and maturity; long time periods may produce better sorted and highly mature sands.

*Composition:* typically mixed siliciclastic–biogenic sands; may be more or less siliciclastic depending on sediment supply.

*Accumulation rates:* not well constrained and apparently very variable, 20–200 cm/ka.

*Associated facies:* lateral and vertical transition to mid- and inner-shelf facies, or to typical hemipelagites, fine-grained turbidites and other mass-flow deposits of the upper slope; likely transitions also into fine-sand and silt-sized, bottom-current deposits formed under less vigorous hydrodynamic conditions, although these facies are not well documented; no standard vertical facies sequence identified.

*5.2.1.2 Controlling factors.* A delicate combination of controlling factors is required for the formation and preservation of such bottom-current sands. These are itemised below.

(1) The principal *hydrodynamic* requirement is for a strong surficial geostrophic current flowing along the upper slope, but with marked perturbations onto the outer shelf. This kind of inshore displacement is well known for major geostrophic currents, including the Gulf Stream (Huthnace, 1992), the Kuroshio Current (Chen et al., 1992), the Brazil Current (Garfield, 1990) and the Agulhas Current (Flemming, 1978, 1981), among others. Short-term perturbations that enhance winnowing and reworking at the seafloor include storm- and tide-induced bottom currents, and the downward propagation of shelf eddies from the main flow (e.g. Viana et al., 1995, 1998). This combined hydrodynamic system acting on the seafloor must be sufficient to allow sediment influx and intense winnowing, but to prevent excessive erosion and off-shelf sand loss.

(2) The *morphological setting* exerts a further important control on sand accumulation. Firstly, the depth of the outer shelf is critical to the hydrodynamic efficiency of combined flows at the seafloor — too deep and the effects will be weak, too shallow and the geostrophic flow will remain off-shelf. Secondly, an irregular shelfbreak morphology, with outward projections and adjacent recesses, produces a favourable site for on-shelf meandering of the geostrophic flow. Thirdly, an outer-shelf and, particularly, upper-slope morphology that provides areas such as depressions, gullies or a stepped to-

pography to allow for sand entrapment, rather than the downslope removal of spillover sands, is essential.

(3) An adequate *supply* of sand is crucial to the build-up of sandy deposits. The chief sources of sand are: relict sediments from sea-level low-stands or transgressive episodes; storm supply from the mid- and inner shelf; planktonic biogenic material in areas of high primary productivity; and the persistent winnowing of mixed-grade sediment (e.g. glaciomarine) in the outer-shelf area. Winnowing of in-situ relict or mixed-grade sediment will serve to reduce the original sediment thickness and, in the latter case in particular, is unlikely to result in very thick deposits. Continued supply from an external source that outpaces removal by erosion is the only way to build up thick sandy deposits. This may occur most easily in a local entrapment zone on the upper slope where the supply is by spillover from the outer-shelf system.

(4) Climate and sea-level oscillation as well as local tectonic effects can all influence the other three controlling factors in various ways (Stow et al., 1985; Posamentier and Vail, 1988). Consequent variation in current intensity and position, in water depth and morphotectonic framework, and in sediment supply will then affect the accumulation and preservation of outer-shelf sands. In particular, a steady or relatively low rate of sea-level rise favours accumulation, and a long-term sea-level rise after deposition avoids erosion.

(5) The complex interplay between these different factors will act as turn-on/turn-off triggers for bottom-current sand deposition in the outer-shelf/upper-slope environment.

#### *5.2.2. Mid-depth sandy contourites*

These deposits, formed under major geostrophic flows in water depths in excess of 300 m and up to about 2000 m, are the main type of true sandy contourite known from modern systems. The six case studies presented in this paper, together with several other examples referred to, provide a good indication of the characteristics of and the controls that operate on these deposits. The facies model for sandy contourites proposed by Stow (1982; Stow et al., 1986) and recently refined (Stow et al., 1998) is presented in an elaborated form below.

### 5.2.2.1 Facies characteristics.

*Drift geometry:* mid-depth sandy contourites occur both at the surface and within sheeted-drifts, mounded elongate drifts, and channel-related irregular patch drifts and contourite fans (Faugères et al., 1993), over an area of 10's to 100's of km<sup>2</sup> elongated parallel to current flow; individual sands rarely exceed 1 m in thickness.

*Beds:* thin to medium beds (<1 m thick), rarely thicker, with sharp or gradational top and bottom surfaces.

*Structures:* various types and sizes of small- and medium-scale ripples, scour crescents, crag and tail features and current lineation, are all bedforms observed at the surface of present-day sandy contourites; resulting parallel and cross-lamination is rarely preserved as an internal structure, however, due to a high degree of bioturbation and burrowing throughout; internal erosional surfaces and irregular lenses of coarser grain size may be evident; there is no regular structural sequence as for turbidites; reverse grading present near the top in some cases, with sharp/erosive contacts common, otherwise gradational bed boundaries present.

*Texture:* fine to medium sands are typical, also sandy silt and rare coarse or pebbly sands; may be relatively free of mud and moderately well sorted in some cases with low or negative skewness values, but also more muddy where gradational into the finer-grained contourite facies; grain-size trends alongslope.

*Fabric:* indication of grain orientation parallel to the bottom current (along-slope) or more randomised by bioturbation; other features (e.g. structures) also indicate along-slope flow where preserved.

*Composition:* mixed biogenic–siliciclastic composition typical; terrigenous fraction dependent on local source; biogenic material from pelagic, benthic and resedimented sources, typically fragmented and iron-stained; organic carbon content very low.

*Accumulation rates:* estimated rates from the drifts studied are from 3 to 64 cm/ka for mixed muddy and sandy contourites deposited during the Pleistocene and Holocene; separate rates for the sands could not be resolved.

*Associated facies:* most typically associated with muddy and silty contourites, and arranged in decimetric cycles of grain-size and/or compositional

variation (i.e. the standard contourite sequence — Stow et al., 1986); partial sequences are also common (e.g. Howe et al., 1994); more rarely associated with hemipelagites or turbidites.

### 5.2.2.2 Controlling factors.

(1) Mid-depth sandy contourites require the presence of either relatively strong, semi-permanent geostrophic currents flowing at intermediate depths within the water column, or very strong surficial geostrophic currents that are able to influence the seafloor at these depths. Short-term perturbations in flow strength, during benthic storms for example, as well as longer-term variations caused by climate or sea-level change, can significantly affect the nature of the contourite deposit.

(2) Morphology exerts a primary control on sandy contourite deposition in that it directly affects bottom-current intensity. Intensification of weaker flows is caused by flow constriction through gateways or channels and over sills between basins, by the Coriolis effect along higher-latitude continental margins, and by the local steepening or curvature of a continental slope along which flow is directed.

(3) The supply of sand to mid-depth drifts is from a variety of sources both internal and external, including bottom-current erosion upstream of the drift, the pirating of direct turbidity current input, pelagic biogenic fallout, and in-situ winnowing. Long-term persistence of any of these modes of sand supply appears limited, so that individual beds are generally thin and rarely exceed 1 m in thickness.

(4) Climate, sea-level and tectonic factors can each influence drift accumulation and, as for the shallower-water bottom-current sands, act as the turn-on/turn-off mechanism for sand deposition.

### 5.2.3. Deep-water sandy contourites

Bottom-current drift deposits in water depths greater than about 2000 m are dominantly fine-grained muds and silts (siliciclastic or biogenic) with only rare thin sandy contourite intervals. The facies model presented below is modified slightly from the generalised model of Stow (1982; Stow et al., 1986), emphasising the finer grain size and typical biogenic composition, and drawing on the characteristics observed in the four case studies presented (Section 3) as well as in many other deep-water drifts

worldwide. Bottom-current-reworked turbidites are considered separately.

#### 5.2.3.1 *Facies characteristics.*

*Drift geometry:* deep-water sandy contourites can form a minor component of any of the major drift types (mounded elongate, sheeted, and channel-related), covering large areas equivalent to the drift size in thin units generally <10 cm thick.

*Beds:* very thin to thin beds (<10 cm), rarely thicker, with sharp or gradational top and bottom surfaces.

*Structures:* bedforms at the surface range from mounded by bioturbation, through smooth or lineated, to finely rippled; resulting parallel and cross-lamination is rarely preserved as an internal structure; bioturbation typically intense; no regular sequence of structures, rare reverse grading and either sharp or gradational bed boundaries.

*Texture:* very fine and fine grained, moderate to poor sorting; biogenic sands may be nominally medium to coarse grained (where tests are hydrodynamically light) and better sorted.

*Fabric:* typically randomised by bioturbation, rarely with current parallel orientation.

*Composition:* many are biogenic sands, either calcareous or siliceous, of mixed pelagic, benthic and resedimented origin; iron-staining or ferro-manganese coatings common; very low organic carbon content; less fragmentation than for mid-depth contourite sands; some sands of mixed composition also occur.

*Associated facies:* most typically associated with muddy and silty contourites, arranged in decimetric and thicker contourite cycles, partial cycles and irregular 'cycles'; also associated with pelagic, hemipelagic and fine-grained turbidite deposits.

#### 5.2.3.2 *Controlling factors.*

(1) Semi-permanent deep-sea geostrophic currents are generally less strong than for mid-depth sandy contourites and any seafloor expression of surficial currents is only very weak. The occurrence of sandy intervals may be related to general intensification of bottom-current flow with relatively long-term periodicity. Short-term perturbations by benthic storm activity during these intensified flow periods may then serve to winnow and sort the sands.

(2) Morphology exerts a control in the same ways as discussed above for mid-depth contourites — flow constriction through deep passageways and against locally steep slopes will tend to enhance flow velocity and the likelihood of sandy deposits.

(3) An adequate and continued supply of biogenic material is probably the most important supply factor involved, coupled with a point sufficiently above the CCD for calcareous sands to accumulate.

(4) Climate and sea-level variation will affect overall bottom-current intensity and hence the cycling of coarser and finer-grained contourites. Tectonic effects are generally of little importance.

#### 5.2.4. *Bottom-current-reworked turbidites*

In any normal turbidite setting where strong, semi-permanent geostrophic bottom currents have been active, the turbidites will be subject to reworking, and the resulting facies a hybrid between true turbidites and contourites. The nature and extent of reworking will depend, of course, on the nature of the original turbidite (thick, thin, sandy, muddy, etc) and the strength of the bottom current, amongst other factors. Very slight reworking will be almost impossible to detect, whereas extensive reworking over a sufficiently long time period before the next turbidite is deposited will produce a true contourite. The whole problem of normal thin-bedded silt and sand turbidites being misidentified as contourites, an issue that has plagued contourite studies since their inception in the mid 1960s, is discussed at length in another paper in this volume (Stow et al., 1998) and will not be repeated here. We simply reproduce the facies characteristics from that paper in order to contrast these with the bottom-current and contourite sands outlined above.

##### 5.2.4.1 *Facies characteristics.*

*Occurrence:* any normal turbidite setting where bottom currents have been active.

*Beds:* turbidite beds may be of any thickness and the reworked interval at the top from <1 cm to about 10 or 15 cm; deeper-penetration reworking of any one turbidite is considered unlikely.

*Structures:* lower divisions of turbidite may be preserved, with the upper divisions either removed completely or modified by reworking; bioturbation common through the reworked top; reverse grading

and irregular lag concentrations common; bi-directional cross-lamination in some cases; sharp erosive contacts within and at the top of the bed also common.

*Texture:* removal or non-deposition of fines; significant textural differences of the top-reworked unit as compared with the underlying turbidite (e.g. cleaner, better sorted, reverse graded, lag concentration).

*Fabric:* reworked turbidite layers may show widely bimodal grain orientations or a more random fabric due to bioturbation.

*Composition:* entirely reflects that of the turbidite, with part or all of the fine fraction removed; long exposure to winnowing may lead to chemogenic precipitation; organic carbon content very low.

*Associated facies:* other turbidites and normal contourites; presents a typical turbidite sequence (i.e. top-absent or top-reworked) and does not fit into a standard contourite facies cycle.

### 5.3. Ancient sandy contourites and hydrocarbon implications

The progress made in recent years with the description of modern contourite facies through widespread coring programmes and the documentation of bottom-current processes by in-situ observation, have highlighted the range of depositional processes, morphological and hydrological settings, and sediment patterns associated with contourite deposition. The transposition of such studies for the recognition and interpretation of ancient contourite sandstones is not a new effort (Stow and Lovell, 1979; Lovell and Stow, 1981) and the recognition of ancient contourites from the many boreholes now drilled into large-scale drift deposits has greatly helped in decreasing the problems of false interpretation and poor understanding of deep-water processes (see Stow et al., 1998 for a critical review of fossil contourites).

In their review, Stow et al. (1998) suggest that the major part of structureless (or 'massive') sandstones are turbidite in their origin with only rarely a minor contribution from bottom-current reworking. From that paper, and also from this present review and proposed facies model for shallow-water bottom-current deposits, many ancient sands of un-

certain deep-water affinity are believed to be outer-shelf/upper-slope bottom-current sands. Some others may be bottom-current-reworked turbidites.

From the perspective of hydrocarbon exploration, it is these two facies that are of most significance. In particular, the shallow-water bottom-current sands may constitute excellent hydrocarbon reservoirs, with high porosity, permeability and transmissibility coefficients. Misinterpretation of their depositional environment can lead to fruitless exploratory effort since geometry and facies variations are incorrectly premised, thus misguiding seismic and drilling surveys. Of secondary importance as hydrocarbon reservoirs are bottom-current-reworked turbidite sands and, in some cases, mid-depth sandy contourites. Deep-water sandy contourites are of no significance as potential reservoirs.

### Acknowledgements

Technical support for the elaboration of this study came from C.N.R.S. U.R.A. 197 – Centre National de Recherche Scientifique, PETROBRAS – Petróleo Brasileiro S.A., and TOTAL. Thanks are due to Ian N. McCave, Eliane Gonthier, Renato Kowsmann, Mario Carminatti and Patrice Imbert for constructive discussions.

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