

## FACIES DISTRIBUTION AND TEXTURAL VARIATION IN FARO DRIFT CONTOURITES: VELOCITY FLUCTUATION AND DRIFT GROWTH

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### ABSTRACT

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Detailed study of seismic profiles, piston cores and bottom photographs from the Faro Drift on the southern margin of Portugal has led to a better understanding of drift development and its relationship to bottom current circulation. Data on the contourite facies characteristics and the surface microphysiography have been published elsewhere; here, we concentrate on sediment distribution and geometry. Longitudinal trends in facies types, mean grain size, sedimentary structures and composition can be interpreted in terms of relative intensity of currents over different parts of the Drift. These are generally more intense in the marginal channels and at the upstream or eastern end of the drift. Three different scales of vertical variation of facies can be identified. At the large scale, 300–500 m of sediment has accumulated over 4–5 Ma in a regular vertical succession due to the northward progradation of the Drift. At the medium scale, the upper 20–30 m of sediment shows alternating phases of active lateral progradation and uniform vertical accumulation that may correlate with episodes of more and less current activity related to high and low sea-level stands respectively over the past 0.3 Ma. At the small scale, the topmost 2–3 m of sediment deposited in approximately 0.03 Ma shows three zones of coarser-grained sediments separated by finer-grained contourites. This sequence can also be interpreted in terms of long-term fluctuation in bottom current activity. Although the signal is clearly complex, this kind of analysis of sedimentary drifts can lead to more accurate reconstruction of paleocirculation patterns.

### INTRODUCTION

The Faro Drift is a relatively small contourite drift located on the continental margin south of Portugal (Mougenot and Vanney, 1982). It was the subject of detailed investigation as part of the "Faegas IV" programme run by the Laboratoire de Géologie et Océanographie de Bordeaux, including some 300 km of 3.5 kHz seismic profiling, piston and gravity coring at 19 sites and bottom photography at five sites (Fig.1). Results concerning the distribution of surface sediments related to bottom microphysiography and the sedimentary characteristics of contourite facies have already been published (Faugères et al., 1984a, b; Gonthier et al., 1984). In this paper we describe in detail the

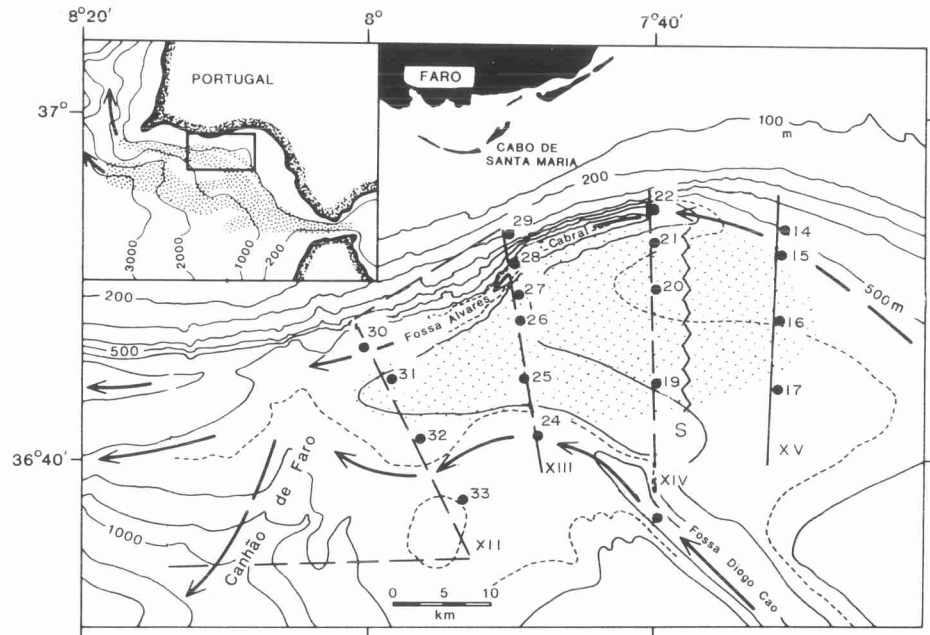


Fig.1. Location bathymetric map of study area showing the core sites (14–33), 3.5 kHz reflection profiles (XII–XV), seismic reflection profile (S), and principal bottom currents (arrows). Inset map shows outflow of Mediterranean Water through the Strait of Gibraltar.

distribution of contourite facies over the Faro Drift and interpret this in terms of Drift development through the late Quaternary related to fluctuation in the deep Mediterranean Outflow through the Strait of Gibraltar (Heezen and Johnson, 1969; Madelain, 1970; Ambar et al., 1976). We also review the various factors that influence the lithology and texture of contourites and hence interpret the small-scale variations in these properties noted in Faro Drift cores.

Most previous work on contourite drifts has been on those of very large dimensions (several hundreds of kilometres long), mainly in the North Atlantic, and with only very widely spaced sampling sites (e.g. Hollister and Heezen, 1972; Stow and Holbrook, 1984). Although these studies have allowed documentation of contourite facies (e.g. Stow and Lovell, 1979; Stow, 1982) they have not been able to show in any detail the horizontal and vertical distribution of facies. The growth mechanisms of contourite drifts have also been rarely addressed (Lonsdale and Hollister, 1979; McCave et al., 1980).

The Faro Drift, some 50 km long and 10–25 km wide, provides a good example for considering these problems of facies distribution and drift growth.

## LABORATORY METHODS

Cores were split and described centimetre by centimetre in the Sedimentology Laboratory at Bordeaux University. Selected core sections were further slabbed to 1 cm thickness with an osmotic knife and X-radiographed. X-radiograph descriptions were compared carefully with the visual core descriptions in order to more fully understand the nature and origin of the sedimentary structures.

Several hundred samples were taken for further analysis, paying particular attention to the sections which had been X-radiographed and which showed characteristic facies sequences. The sampling interval varied with the homogeneity of the core section from less than 1 cm to over 10 cm spacing. Grain-size analyses were carried out on bulk sediment samples by sedimentograph. We believed it was particularly important not to remove carbonate prior to this analysis but, rather, to examine the nature of the carbonate material in the fractions analysed, as much of it was clearly a part of the current-transported load and not an in-situ pelagic contribution.

Clay fraction analyses were carried out by X-ray diffraction; whereas the sand fraction was examined under the microscope after separation into different size fractions. The micropaleontological and oxygen-isotope studies were carried out by colleagues; reference is made to their data as appropriate.

## MORPHOLOGY AND HYDROLOGY

The Faro Drift began to develop in the late Miocene–early Pliocene and has attained a thickness of at least 300 m and probably as much as 500 m in its axial region (Giesel and Seibold, 1968; Mougenot and Vanney, 1982; Faugères et al., 1985; and Fig.2). It extends longitudinally in an ENE–WSW direction on a broad platform that breaks the Algarve continental slope (Vanney and Mougenot, 1981), and increases in depth from about 500 m in the east to 700 m in the west. Its westward extent is limited by the Faro Canyon; to the north it is bounded by a sinuous valley, the Fosse Alvarez Cabral, and to the south it merges with the slope platform which is deeply incised by the Fosse Diego Cao. This southern valley widens and becomes less pronounced towards the northwest where it debouches onto the Bartolomeu Dias platform and the western extremity of the Faro Drift.

At its eastern or “upstream” end the Drift is least developed (profile XV, Fig.1), so that the continental slope merges gradually with the platform and the northern valley has a relief of little more than 5–10 m. The middle part of the Drift (profiles XIV and XIII, Figs.1 and 3) is most pronounced with an asymmetric profile, steep to the north and gentle to the south, and a relief of 140–160 m. At its western or “downstream” end, its width and relief decrease rapidly and its profile becomes more symmetrical (Faugères et al., 1984b).

The warm, saline Mediterranean Water outflow through the Strait of Gibraltar, at the present day, divides into three main flows in the Gulf of Cadiz

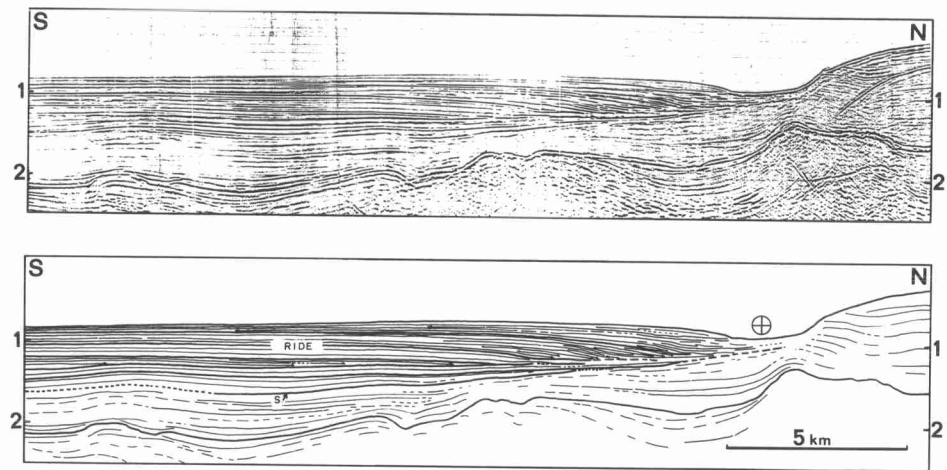


Fig.2. Seismic reflection profile and interpretation across the "upstream" end of the Faro Drift (profile S, Fig.1). Drift (= Ride) built over substrate (S): principal axis of bottom current shown in northern valley (⊗). Vertical scale in two-way travel time (seconds).

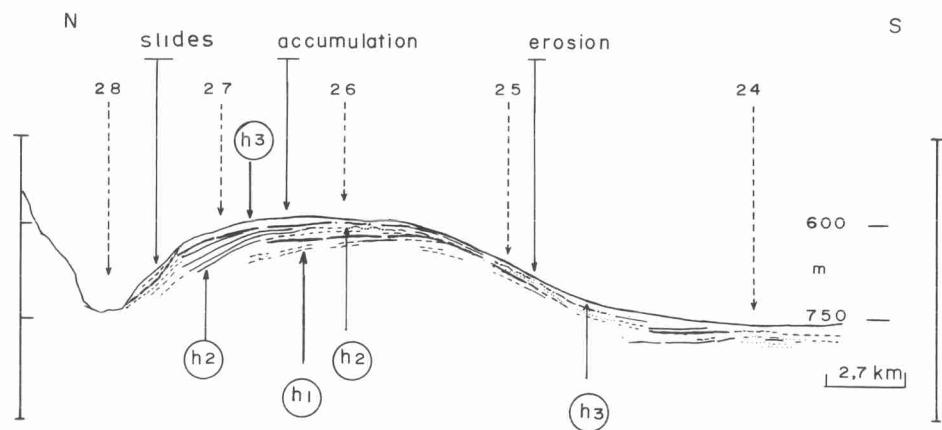
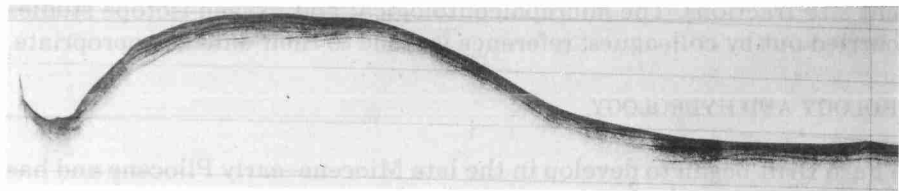


Fig.3. Example of 3.5 kHz reflection profiles (XIII) across the Faro Drift; see Fig.1 for location. Line drawing shows interpretation and seismic intervals  $h1$ ,  $h2$  and  $h3$ .

(Fig.1), between about 1000–1300, 700–900 and 500–700 m (Madelain, 1970; Zenk, 1975; Reid, 1978; Ambar and Howe, 1979; Ambar, 1983). These flows appear to be controlled largely by bottom topography and are partly interconnected in the vicinity of downslope canyons. The shallowest flow is restricted and therefore intensified by the channel north of the Drift, where velocities of 40–80 cm have been measured (Madelain, 1970; Mélières et al., 1970), whereas the intermediate level flow is channelised to the south of the Drift. The Drift morphology is probably important in separating these two flows leaving a weaker, broader flow over the Drift itself, that is in part directed along the crest (e.g. Faugères et al., 1984a) but that in part crosses the Drift obliquely.

#### SEISMIC FACIES AND GEOMETRY

Examination of the 3.5 kHz profile shows clear longitudinal trends in the thickness and characteristics of the deposits. The sediment thickness is least in the east, increases downstream and then decreases at the western extremity. In parallel, the echofacies type changes from strong but diffuse reflectors in the east towards thinner better-defined reflectors towards the west, suggesting a probable decrease in grain size of the sediment downstream. The transverse profiles also show a depositional maximum on the northern flank of the Drift, a progressive decrease in thickness towards the south and a marked thinning or erosion on the southern flank.

Three seismic intervals can be recognised in each of the profiles, representing the upper few tens of metres of sediment (Fig.3). The lower interval (h1) is characterised by thin distinct parallel reflectors that are inclined more steeply to the north than to the south. In the central part of the Drift these reflectors abut against the upper seismic interval (h3) and appear to be cut by a surface of erosion or of non-deposition. The crest of the Drift, following deposition of interval h1, lay clearly to the south of its present position.

The middle interval (h2) forms a sigmoidal lenticular body over the northern flank and crest of the Drift, and comprises more or less distinct semi-continuous reflectors (e.g. profile XII). Towards the south these reflectors appear to pinch-out between the upper and lower seismic intervals, h1 and h3, whereas to the north they disappear into the strong diffuse surface reflection of the Alvares Cabral valley. There is also some evidence of slumping within this interval down the steep northern flank (e.g. profile XIII).

The upper interval (h3) is present over the entire Drift with a much more constant thickness than either of the other intervals but, nevertheless, is slightly thicker over the northern flank and thins to the south.

The geometry of these most recent reflectors on our 3.5 kHz profiles shows that construction of the Drift involved progradation to the northwest, confirming indications on deeper seismic profiles (Mougenot and Vanney, 1982; and unpublished data). There appears to have been an alternation of periods of active lateral and vertical progradation (h2), during which the principal loci of deposition were the northern flank and crest, with periods of slower prograda-

tion and more uniform deposition (h1 and h3). During periods of active progradation there was erosion or non-deposition over the southern flank.

#### STRATIGRAPHY AND FACIES

##### *Stratigraphy*

Stratigraphic correlation of the nineteen Faro Drift cores (Fig.4) is based on studies of the pelagic foraminifera (M. Devaux, pers. commun., 1984) and

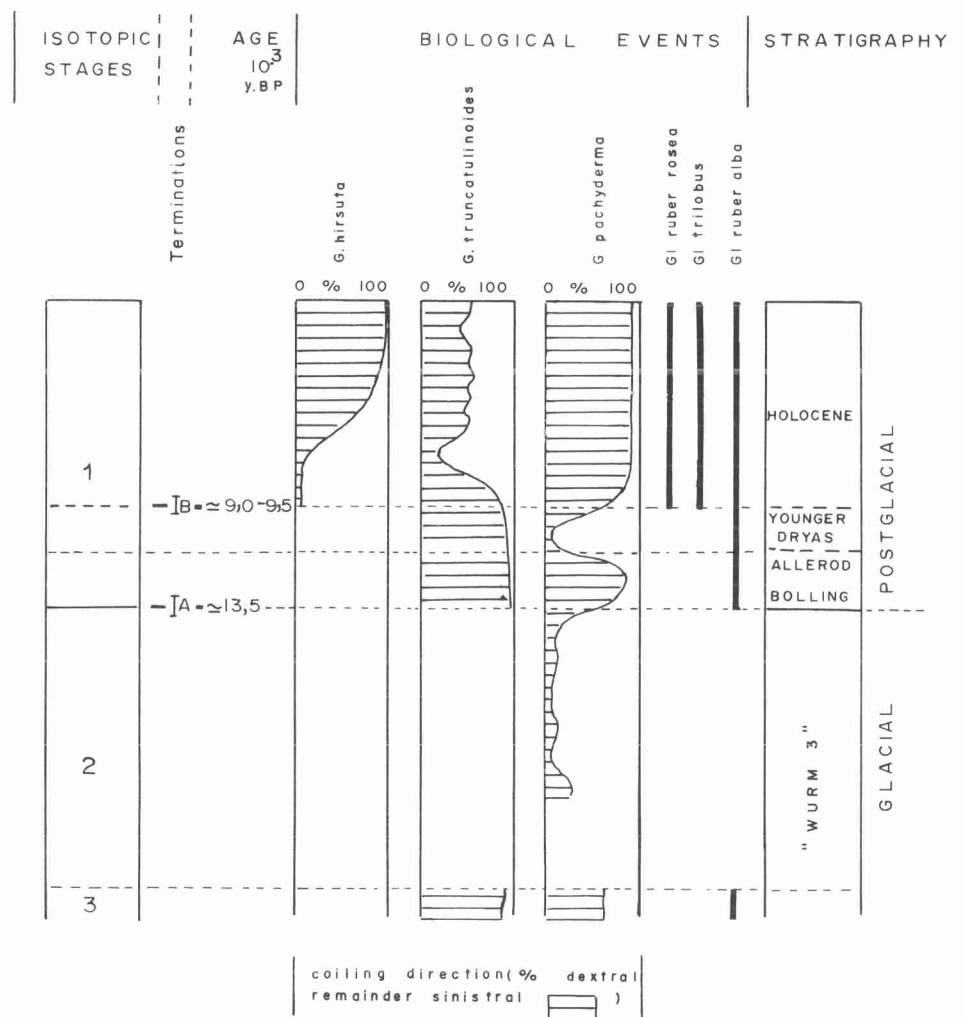


Fig.4. Stratigraphic data for region used in dating and correlation of cores. Compiled from Pujol (1980), Duprat (1983) and M. Devaux (pers. commun., 1984).

oxygen isotopes (C. Vergnaud-Grazzini, pers. commun., 1984). Probably as a result of local reworking by bottom currents, these studies have not been able to provide as precise a stratigraphy as has been possible for other deeper sites within the Gulf of Cadiz and within the eastern Mediterranean Sea (e.g., Duprat, 1983; P. Weaver, pers. commun., 1984). However, we can be relatively confident in recognising the onset of the third cold stage (W3) of the Würmian glacial stage (isotopic stage 2) in most of the cores, and in assigning an age of about 28,000 yrs B.P. to this horizon (Pujol, 1980; Duprat, 1983).

For the discussion of facies and facies distribution in this paper, therefore, we will consider mainly the deposits from these last 28,000 yrs.

### *Contourite facies*

The sediments of the Faro Drift are almost all contourites (Fig.5). Three main types have been distinguished (Gonthier et al., 1984): silty-sandy contourites and homogeneous mud contourites, equivalent to the sandy and muddy contourites respectively of Stow and Lovell (1979), Stow (1982), and a mottled silty-muddy facies intermediate between these two types. The chief distinguishing features that these facies have in common are: (1) sedimentary structures (poorly developed lamination, sharp and erosive contacts) related to the action of bottom currents; (2) pervasive bioturbation that has been continuous with deposition and that varies in its nature with the changes in grain size of the sediment; (3) a fine grain size (mean mostly  $< 63 \mu\text{m}$ ) and a distribution that indicates some current transport and deposition, but mostly

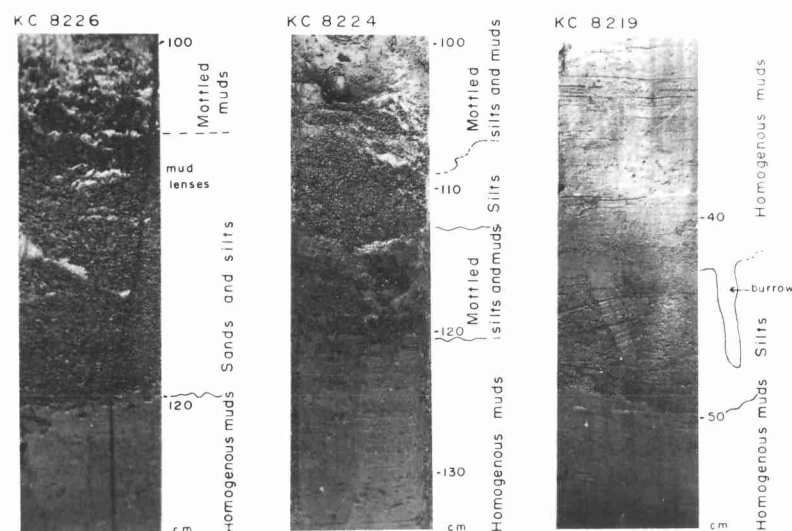


Fig.5. Photographs of characteristic contourite facies from the Faro Drift. Left: muddy contourite; centre: mottled silt-mud contourite; right: sandy contourite overlying muddy contourite.

without very good sorting; and (4) a similar suite of components throughout the drift, but with variations in the relative proportions of different components (20–50% biogenic carbonates, either pelagic or benthonic), and 50–80% terrigenous material (quartz, micas and heavy minerals with amphibole and pyroxenes predominant).

### *Turbidite facies*

In core KC8229 from the continental slope, and KC8230 from the bottom of the northern Alvarez Cabral valley, turbidites comprise 20% and 40% respectively of the sediments. On the Drift itself a single thin turbidite is observed in each of cores KC8231 and KC8232 from near the Faro Canyon, representing no more than 2% of the sediments. This turbidite was probably the result of a single event which in fact took place prior to the period being discussed in this paper.

In the northern valley, the turbidites occur as relatively thin beds (5–15 cm thick) that are clearly graded, well-laminated and with erosive bases and sharp tops (Fig.5). Bioturbation is generally absent. The mean size at the base may exceed 100  $\mu\text{m}$  and the distribution is typically parabolic (fine tail, positively skewed). The composition is quite distinct from that of the contourite facies, comprising 30–40% biogenic carbonate (mainly shallow water benthonic forms) and 60–70% terrigenous material, including significant glauconite and a more varied suite of heavy minerals (with more resistant species such as tourmaline, andalusite and staurolite).

### FACIES DISTRIBUTION

#### *Traverse XV*

Four cores were recovered from a transect across the most upstream (eastern) end of the Drift where its morphology is least well developed (Figs.1 and 6).

*Core KC8214* was taken in a water depth of 448 m at the foot of the upper part of the continental slope. The sandy, silty and mottled contourite facies comprise some 40% of the section in several distinct intervals or beds from a few centimetres to a few tens of centimetres thick. The contacts between these beds and the homogeneous muds are most commonly sharp or erosive. An irregular horizontal lamination is common in both the muddy and mottled facies. The coarser-grained facies are mostly structureless, with a mean grain size up to 65  $\mu\text{m}$ , an average of 5–10% clays and up to 50% carbonate material. The overall sedimentation rate through the past 28,000 yrs has been at least 10 cm  $10^3 \text{ yr}^{-1}$  at this site.

*Core KC8215* was located in the axis of the slight depression that marks the beginning of the northern channel, at a depth of 498 m. At the top there is 15 cm of a mottled silty facies of late Holocene age overlying sediments of an

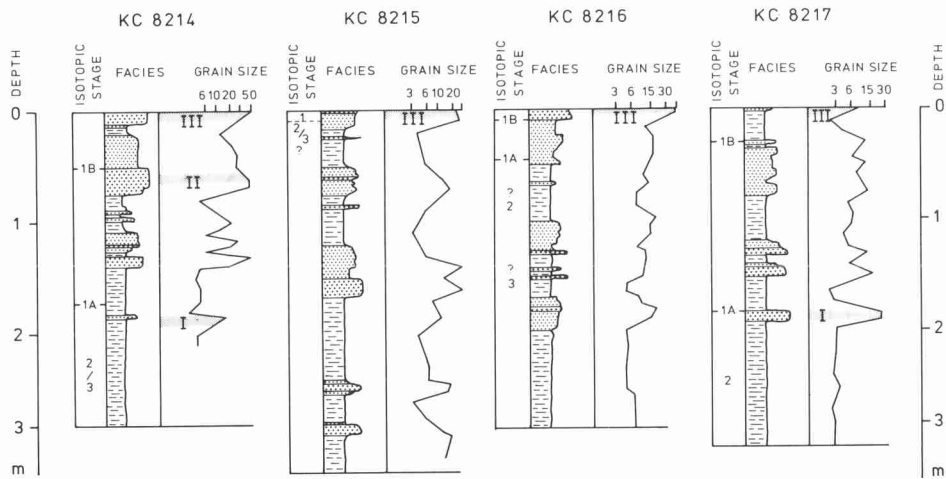


Fig.6. Lithological, grain-size and stratigraphic data for cores 14–17 (KC8214–KC8217) on traverse XV. See Fig.1 for location.

earlier Würmian age (isotopic stage 3, i.e. prior to 28,000 yrs). These sediments are of similar contourite facies to those of KC8214. The significance of this core, therefore, is the hiatus in sedimentation through much of the early Holocene and late Würmian (isotopic stages 1 and 2). The overall sedimentation rate for the past 28,000 yrs was less than  $1 \text{ cm } 10^3 \text{ yr}^{-1}$ .

*Core KC8216*, located on the crest of the incipient Drift at a depth of 510 m, comprises 12 cm of silty-sandy facies (maximum mean grain size of  $45 \mu\text{m}$ ) overlying an alternation of the mottled and homogeneous mud facies. The mottled facies makes up 25% of the section and the muddy facies is relatively silty (mean  $6\text{--}15 \mu\text{m}$ ). Contacts between these facies are often sharp or slightly erosive, and irregular horizontal lamination is common. Sedimentation rates were up to about  $5 \text{ cm } 10^3 \text{ yr}^{-1}$ .

*Core KC8217* was taken in a water depth of 555 m on the plateau to the south of the Drift. The sediments comprise mottled (30%) and homogeneous mud (70%) contourites, all relatively fine-grained with a mean grain size of  $3\text{--}6 \mu\text{m}$  for the muds and  $15\text{--}30 \mu\text{m}$  for the coarsest horizons. Contacts are mostly gradational and lamination rare. Although dating is uncertain for this core, it appears that the sedimentation rate was at least  $11 \text{ cm } 10^3 \text{ yr}^{-1}$  for the last 14,000 yrs (the base of isotopic stage 2 was not penetrated).

#### Traverse XIV

Five cores were recovered from this transect across a morphologically well-developed part of the Drift (Figs.1 and 7).

*Core KC8222* from the northern valley (water depth 635 m) comprises a 10 cm thick cover of late Holocene silty muds over relatively compact and signifi-

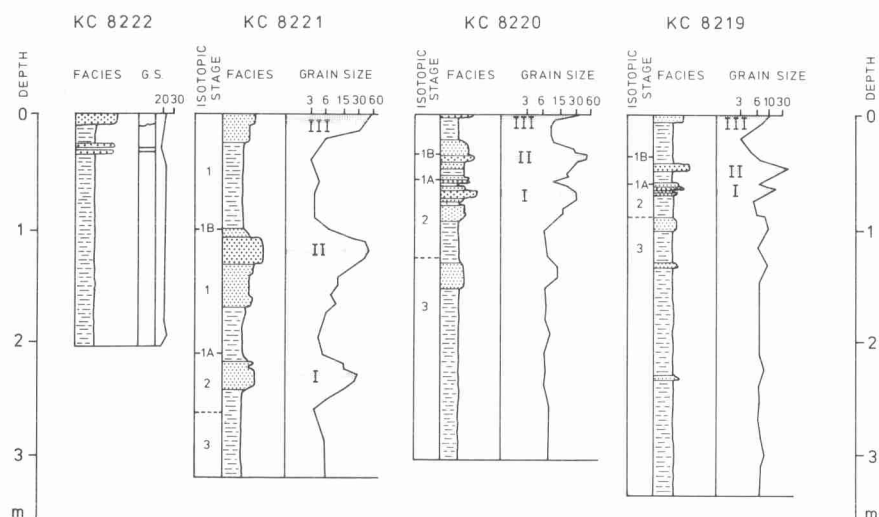


Fig.7. Lithological, grain-size and stratigraphic data for cores 19–22 (KC8219–KC8222) on traverse XIV. See Fig.1 for location.

cantly older muds and clays. The onset of the hiatus in sedimentation is not well dated.

*Core KC8221* from the northern flank of the Drift (water depth 580 m) comprises 10% silty, 30% mottled and 60% homogeneous mud facies, without any true sandy contourites and a mean grain size for the coarsest intervals of  $55 \mu\text{m}$ . Three coarser horizons are present, each between 20 and 60 cm thick, separated by thicker muddy intervals. Sharp and erosive contacts are associated with these coarser layers. The average sedimentation rate was about  $10 \text{ cm } 10^3 \text{ yr}^{-1}$ .

*Core KC8220* from the crest of the Drift (water depth 520 m) has a very similar association of facies to that of KC8221, with 15% silty, 35% mottled and 50% homogeneous mud contourites, although both the mottled and mud facies are siltier and the number of sharp or erosive contacts is greater. The average sedimentation rate was about half as much, at  $5 \text{ cm } 10^3 \text{ yr}^{-1}$ .

*Core KC8219* from the foot of the southern flank of the Drift (water depth 580 m) is much finer grained than any of the other cores on this radial with 25% mottled facies (mainly clay-rich) and 75% homogeneous muds. Some evidence of current deposition is present with sharp and erosive contacts and irregular horizontal lamination. Sedimentation rates were still lower, at  $3 \text{ cm } 10^3 \text{ yr}^{-1}$ .

*Core KC8218* was taken in the bottom of the southern Diego Cão valley (water depth 850 m). All that was recovered was a thin superficial cover of late Holocene biogenic sand over 30 cm of fine well-compacted mud of early Quaternary or late Pliocene age, marking, therefore, a significant hiatus through most of the Quaternary period.

### Traverse XIII

This transect is also across a well-developed part of the Drift and a similar suite of five cores were recovered (Figs.1 and 8).

Core KC8228 from the northern valley (water depth 750 m) only recovered a few centimetres of coarse-grained glauconite sand and, we assume, the corer then impacted either a very compacted older sediment or still coarser sand and gravel and was thus prevented from penetrating further.

Core KC8227 from the northern flank of the Drift (water depth 619 m) contained relatively fine-grained contourite facies, 25% mottled facies and 75% homogeneous muds both being clay-rich. The coarsest silty horizons attain a maximum of only  $30\ \mu\text{m}$  mean grain size and occur in three thin (few centimetre thick) layers separated by thick finer muddy zones. Contacts between facies are rarely sharp or erosional, although there is some evidence of lamination. Average sedimentation rates were  $12\ \text{cm}\ 10^3\ \text{yr}^{-1}$ .

Core KC8226 from the crest of the Drift (water depth 585 m) shows a similar but still finer-grained facies association than KC8227. There is only 15% of the mottled silty facies, with a maximum grain size mean of  $15\text{--}30\ \mu\text{m}$ , and 85% of a very clay-rich homogeneous mud facies. Sedimentation rates were nearly  $9\ \text{cm}\ 10^3\ \text{yr}^{-1}$ .

Core KC8225 from the southern flank of the Drift (water depth 645 m) comprises 40 cm of fine-grained homogeneous mud contourites of Holocene age (post 10,000 yrs B.P.), overlying an older more silty mottled facies of isotopic stage 3 (i.e. pre 28,000 yrs B.P.). The hiatus in sedimentation at this site

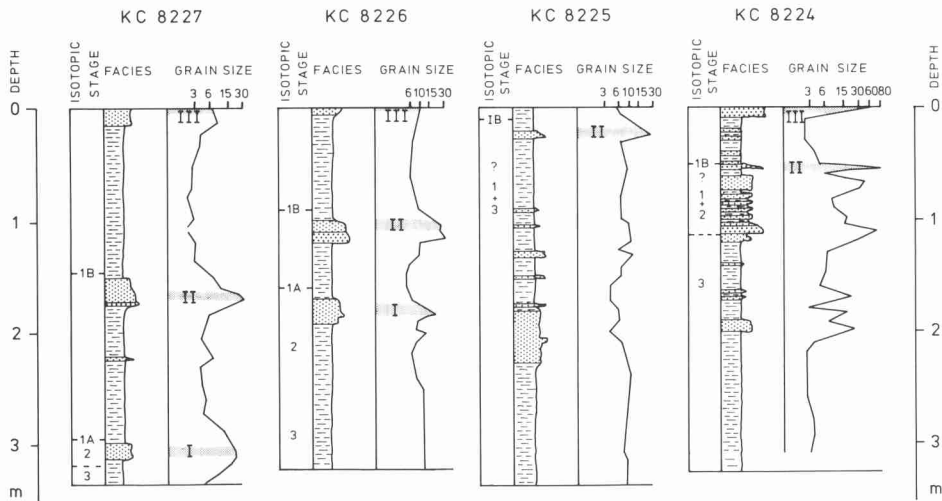


Fig.8. Lithological, grain-size and stratigraphic data for cores 24–27 (KC8224–KC8227) on traverse XIII. See Fig.1 for location.

therefore lasted about 18,000 yrs, giving a low apparent sedimentation rate of  $1.5 \text{ cm } 10^3 \text{ yr}^{-1}$ .

Core *KC8224* is located in the southern valley (water depth 765 m) where it opens out towards the west. The Holocene sediments comprise 35% sandy and silty contourites with a mean grain size up to  $63 \mu\text{m}$ , and 65% clay-rich homogeneous muds. These overlie contourites of an earlier period (isotopic stage 3) with the hiatus in sedimentation being exactly as for *KC8225*. The facies types vary frequently, commonly with sharp or erosive contacts between layers. Average sedimentation rates were  $2.5 \text{ cm } 10^3 \text{ yr}^{-1}$ .

### Traverse XII

Traverse XII is the shortest of the four transects, across its most downstream or western end. The Drift in this region is still well developed morphologically although with a reduced amplitude. Four cores were recovered (Figs.1 and 9).

Core *KC8230* was taken from the northern valley (water depth 735 m) and comprises 6% sandy and silty contourites at the surface, 50% very fine-grained homogeneous mud contourites, and 45% turbidites in beds from a few centimetres to a metre in thickness. There is a sharp contact between the muddy and sandy contourite facies, and the latter have a mean grain size up to  $140 \mu\text{m}$ . Both have been dated as late Holocene, but dating of the turbidites and the rest of the core is uncertain so that the sedimentation rate cannot be calculated.

Core *KC8231* from the crest of the Drift (water depth 675 m) comprises mostly homogeneous mud contourites (88% of the section), that are slightly siltier than those of *KC8230*, and only 12% of a clay-rich mottled facies. Contacts may

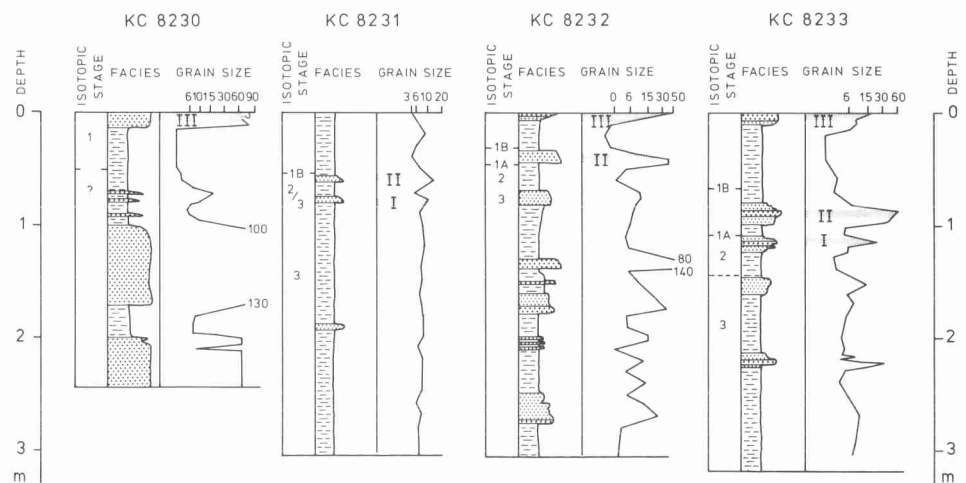


Fig.9. Lithological, grain size and stratigraphic data for cores 30–33 (KC8230–KC8233) on traverse XII. See Fig.1 for location.

be erosive and sharp as well as gradational, and lamination is mostly irregular or absent. The minimum sedimentation rate was of the order of  $3 \text{ cm } 10^3 \text{ yr}^{-1}$ , although minor hiatuses may be present in the section.

*Core KC8232* from the southern flank of the Drift (water depth 725 m) where the slope gradient is very gentle, comprises mainly fine-grained homogeneous muds (80% of the section), but with 20% silty contourites of up to  $35\text{--}40 \mu\text{m}$  mean grain size. Contacts between facies are in some cases erosive or sharp. The average sedimentation rate was low, about  $2.5 \text{ cm } 10^3 \text{ yr}^{-1}$ .

*Core KC8233* is located on the broad plateau (Bartolomeu-Dias, water depth 745 m) south of the Drift. It comprises 10% sandy and silty contourites with a mean grain size up to  $65\text{--}70 \mu\text{m}$ , 10% of the mottled silty facies and 80% very fine-grained homogeneous muds. The contacts between facies can be sharp or erosive. The average sedimentation rate was  $5.2 \text{ cm } 10^3 \text{ yr}^{-1}$ .

#### *Vertical succession of facies*

The vertical succession of facies in the different cores appears to some extent irregular at first sight, and "bed" thickness varies widely from less than 5 cm to over 1 m. However, it is possible to distinguish both negative and positive sequences of facies types on a scale of about 10–150 cm. These involve, respectively, gradation from homogeneous muds through mottled silts and muds to silts and sands, and the reverse facies sequence. These facies changes are associated with changes in grain size, sedimentary structures, bioturbation types and composition that are more fully documented in our paper on contourite facies (Gonthier et al., 1984).

Although dating is not precise for all the cores studied and despite the facies and sequence variability in some cores, we can identify three main zones within the top 2–3 m of sediment that show an increase in the coarser-grained facies, more evidence of current induced structures (erosive and sharp contacts, irregular lamination) and better grain-size sorting with less clays and slightly more carbonate material (Figs.6–9). These three zones are correlatable over many of the cores and can be approximately dated as 14,000–15,000, 9000–10,000 and 0–2000 yrs B.P., on biostratigraphic and isotopic evidence. In the following sections we refer to these zones as Peaks I, II and III, respectively.

In most cores there is a fourth less well-developed zone (or peak) of increased grain size at around 28,000 yrs B.P. In the valley cores and those on the southwest flank of the Drift there are a number of more or less marked grain-size fluctuations prior to 28,000 yrs B.P., whereas in most of the Drift cores the sedimentation in this period consisted of only the very fine-grained homogeneous mud facies. In some cores this is over 3.5 m in thickness, extending to the base of the recovered section.

## CHARACTERISTICS OF GRAIN-SIZE PEAKS

*Sequence and sedimentary structures*

Peaks I and II are of the "type sequence" described by Gonthier et al. (1984) showing a coupled negative-positive (reverse-normal) graded succession. The thickness of a complete sequence varies between cores from a few centimetres to a few decimetres. Peak III shows only the lower or negatively-graded part of the sequence, having a maximum grain size at the surface of the cores and varying in thickness from a few centimetres to about 30 cm.

In certain cores that show particularly low sedimentation rates (Table 1), peaks I and II are either less well defined and relatively thin, or correspond to a significant sedimentary hiatus, as determined from biostratigraphical analysis. These hiatuses are particularly evident in those sites immediately underlying the axes of the most intense bottom currents, i.e. those of the northern and southern valleys.

The maximum development of the peaks corresponds to a silty or sandy contourite facies, commonly showing sharp or erosive contacts with adjacent facies and irregular lamination or lenticular lag-type concentrations of coarser material. These primary dynamic sedimentary structures are often more or less masked by bioturbation. The mottled facies adjacent to the peak maxima showing varying evidence of current deposition, such as irregular, commonly undulating lamination, subparallel lenses and sharp contacts, and of bioturbation. The interbedded, finer-grained, homogeneous mud contourites show more gradational contacts, some well-developed horizontal slightly irregular lamination, and significant bioturbation.

*Composition of peak maxima (Table 2)*

At the scale of the Drift, all three peaks have a *relatively* homogeneous composition. Biogenic carbonate makes up between 25 and 45% of the sediment. The coarsest fraction ( $> 150 \mu\text{m}$ ) is dominantly biogenic, including much reworked planktonic and benthonic foraminiferans and various shell debris. The sand fraction ( $63\text{--}150 \mu\text{m}$ ) is richer in terrigenous material, including quartz, mica, rare heavy minerals, pyrite, iron coated grains and very rare glauconite. The biogenic component is similar to the coarser fraction but with less shell debris. Of the fine fraction ( $< 63 \mu\text{m}$ ), clay minerals make up some 5–15% comprising illite (45–55%), chlorite (15–25%), kaolinite (15–20%), and montmorillonite (10–20%).

The finer-grained interbedded facies throughout the Drift show very much the same general composition, but with notable variations in the relative proportions of the different components.

There are, on a more detailed scale of analysis, certain significant variations in the relative proportions of components between the different peaks and different sites (Table 2). The carbonate content is least for peak I (about 25%)

TABLE 1

Rates of sedimentation in  $\text{cm } 10^3 \text{ yr}^{-1}$  for the last 28,000 yrs in Faro Drift cores. The presence of significant hiatuses is also noted

Cores	Sedimentation rates ( $\text{cm}/10^3 \text{ yr}^{-1}$ )	Presence of hiatuses
KC8214	12	
KC8215	< 1	+
KC8216	4	
KC8217	$\geq 13$	
KC8218	< 1	+
KC8219	3.5	
KC8220	6	
KC8221	12	
KC8222	< 1	+
KC8224	4	+
KC8225	$\leq 1.5$	+
KC8226	11	
KC8227	14.5	
KC8230	?	+
KC8231	3.5	+
KC8232	3	
KC8233	6	



values on the crest of the Drift than on the flank, and the highest values in the channels and on the southwestern part of the Drift where a high-velocity flow emerges from the southern valley.

However, the relative grain sizes of the different peaks show some variations between sites. In certain cores, the medians of all three peaks are approximately equal (e.g. KC8220); in others the differences are more marked, with the coarsest being either peak I (e.g. cores KC8221, 8227), or peak II (e.g. cores KC8226, 8227, 8231), or both (e.g. core KC8224). In comparison with the interbedded contourite muds, the coarser median grain sizes tend to occur where the muds are relatively silty, and vice versa, although this is not always the case (e.g. cores KC8215, 8224, 8227).

#### DISCUSSION: FACTORS INFLUENCING THE LITHOLOGY AND TEXTURE OF CONTOURITES

##### *Previous work*

Both lithological and, more particularly, textural variations in contourite facies have been used to infer bottom current direction (Stow, 1979a, b) and velocity. In a series of papers on sedimentation related to bottom current flow through the Vema Channel in the SW Atlantic, the mean size of the non-carbonate silt fraction has been shown to be an important indicator of both present-day current intensity (Ledbetter and Ellwood, 1980; Blaeser and Ledbetter, 1982; Bullfinch et al., 1982) and paleovelocity fluctuation (Ledbetter and Johnson, 1976; Ellwood and Ledbetter, 1977, 1979; Ledbetter, 1979).

McCave and Swift (1976) developed a model to explain varying rates of deposition in the deep sea related to probabilities of erosion, bottom roughness and biogenic resuspension. More recently, McCave (1984) has extended this discussion on the erosion, transport and deposition of fine-grained marine sediments, and presents a considerably refined and more realistic diagram relating shear velocity to grain size, with fields of transport and deposition, than that proposed by Hjølstrom (1939). Gonthier et al. (1984) have used McCave's diagram (his fig.26) to calibrate the grain-size variation of Faro Drift contourites in terms of current velocities.

However, sediment texture is clearly a function of many factors besides bottom current velocity (e.g. Auffret and Pastouret, 1979) including primary biological productivity, syn- and post-depositional mineralogical changes, variation in terrigenous input, and the intervention of other depositional processes, such as turbidity currents. Ledbetter (1979) and Gonthier et al. (1981) attempted to remove the "noise" due to primary carbonate productivity of sediments before analysis. Auffret (Auffret and Pastouret, 1979; Auffret et al., 1981) used a more refined method for relating textural properties to bottom current variation in the Bay of Biscay. He calculated a correlation coefficient between values of the average median of bulk and decalcified samples: good correlation and a high value of the coefficient were taken to indicate

significant hydrodynamic control. Other authors have relied more on additional lithological characteristics as corroborating evidence of current fluctuation. Such studies include those of Samoan Passage contourites in the SW Pacific (Lonsdale, 1981), the South Arabian margin (Faugères and Gonthier, 1983), Agulhas Passage drift deposits in the SW Indian Ocean (Westall, 1984) and lacustrine "contourites" from Lake Superior (Halfman and Johnson, 1984).

Auffret and Pastouret (1979) reached the same conclusion as we have from our study of the Faro Drift, that it is only by the synthesis of all available data, including sedimentation rates, sedimentary structures, sediment composition and texture, that one can decipher the significance of variation in any one parameter such as grain size.

In the following discussion, therefore, we first examine the role of the different factors that may theoretically influence the grain size of contourites: i.e. current velocity, sediment supply, primary productivity, dissolution and diagenesis. We then attempt to interpret the observed variations in lithology and texture of the Faro Drift sediments (as detailed above) in terms of the dominance of one or the interaction of several of these factors.

#### *Current velocity*

Whereas a large number of short-term measurements of bottom currents have been made from different parts of the world's oceans (see table in Stow and Lovell, 1979), still relatively few continuous records exist of over six-months duration (e.g. Luyten, 1977; McCave et al., 1980; Shor et al., 1980; Camden-Smith et al., 1981; Westall, 1984). However, these longer-term records have shown us that the semi-permanent bottom currents in fact show marked variations in velocity, sometimes with a periodicity that appears to be tidal or seasonal. Velocity changes of over  $50 \text{ cm s}^{-1}$  can occur and complete temporary current reversals have been observed, while the mean flow remains unidirectional. Large-scale eddies (hundreds of metres to a few kilometres in diameter) and some degree of current meandering appear to be the norm.

In such a system, fine-grained sediment will be continually on the move, and may undergo numerous episodes of transport, deposition, resuspension and redeposition before finally being incorporated into the accumulating contourite sediment. The grain size, composition, sedimentary structures and other attributes will therefore reflect an average current velocity, perhaps an average maximum velocity. It is for the most part the longer-term fluctuation in this mean velocity over periods of say  $10^3$ – $10^4$  yrs, that may then be recognised in the sediment record as general trends in textural and other parameters (see discussion above). Whether or not a particular grain size can be readily interpreted as the result of a particular mean velocity, as has been attempted by Gonthier et al. (1984) is not yet certain.

An important point to consider is that any apparent change in velocity at a single site or within a single core may reflect *either*, a general change in mean

velocity of the current system, *or*, a lateral displacement of the main current axis. To resolve this ambiguity, deposits of the same age from different sites must be studied.

#### *Sediment supply*

For a given current velocity the grain size of the deposit will be equally dependent on the grain size of the material available. This material may be introduced into the bottom current either upstream from or in the immediate vicinity of a contourite deposit and be supplied via: (a) surface plumes of hemipelagic material, including glacial meltwater plumes; (b) mid-water turbid-layer flows; (c) up and down-canyon currents; (d) turbidity currents; (e) interaction with a different bottom (contour) current; (f) resuspension of bottom sediment by biogenic or current activity; or (g) pelagic settling of biogenic particles.

*If there is only fine-grained material* supplied to the current system then only fine-grained sediments will be deposited. If the current velocity increases this may be reflected by sediment hiatuses, reduced sedimentation rates, and clear current-produced structures. By contrast, *if coarse-grained material* is introduced into a weak current it will be rapidly deposited and show little evidence of current-produced structures. Clearly, an analysis of sedimentary structures and related features in addition to grain size is necessary to help resolve the ambiguity of textural changes being related to either current velocity or sediment supply. Similarly, an analysis of horizontal trends in grain size parameters, as well as compositional character etc. . . ., should help distinguish between a local lateral sediment supply (e.g. via turbidity currents) and material that has been transported in the bottom current for a greater alongslope distance.

A major reduction in terrigenous sediment supply to a bottom current system will result in a fine grain size of the terrigenous fraction, a relative increase in the proportion of biogenic material in the sediment, and a grain size change towards the mean size of the biogenic tests. In this situation an increase in grain size may therefore occur under conditions of only very weak bottom currents and without change in primary productivity; stronger currents would cause increased winnowing, biogenic lag deposits and possible hiatuses in the dominantly biogenic contourite.

#### *Primary productivity*

Primary biological production in the surface waters varies due to climatic conditions and nutrient supply, either from upwelling or from terrigenous runoff. A marked increase in primary productivity in the surface waters overlying a bottom current system may be translated to the bottom sediments as an increase in biogenic material and, commonly, as an increase in grain size, if the mean size of the biogenic tests is coarser than the underlying

deposits (e.g. sand-sized foraminiferans or siliceous tests). This dual change in texture and composition without change in sedimentary structures should allow recognition of the effects of primary productivity in contourite deposits.

#### *Dissolution and diagenesis*

Changes in the level of the carbonate compensation depth and the possible corrosive action of cold, CO<sub>2</sub>-charged bottom currents can profoundly influence the composition and texture of the biogenic (particularly carbonate) content of contourites, irrespective of current velocity and sediment supply. Carbonate material can be dissolved or corroded both in the water column and within the top few centimetres of sediment.

Authigenesis and diagenesis can also affect the nature of contourites. The growth of authigenic minerals at the sediment surface (e.g. clays, glauconite, phosphorite, ferromanganese nodules or micronodules), and subsequent diagenetic mineral changes (e.g. growth of iron-sulphides, formation of dolomite, alteration of volcanogenic material), are well known from the top few metres of marine sediments, including contourites.

As with all sediments, the effects of recrystallisation and cementation on deeper burial will serve to obscure any original textural, compositional or structural attributions and therefore make interpretation that much more difficult.

#### *Interaction of variables*

The most common case in any contourite deposit will be that two or more of the factors outlined above are acting simultaneously to modify the sediment. In the following section, we attempt to resolve the relative influence of these various factors on the contourite sediments of the Faro Drift.

#### INTERPRETATION OF FARO DRIFT SEDIMENTS

Detailed analysis of variations in the lithology and texture of contourites from the Faro Drift leads us to infer that the principal, but not the only, control has been the variation in intensity of bottom currents rather than changes in sediment supply, primary productivity or dissolution and diagenesis. The main arguments are the following:

(1) The vertical succession of different facies recognised in all the cores studied and the common occurrence of coupled negative–positive graded sequences, in which the current-induced sedimentary structures are more pronounced in the coarser-grained facies, suggest a relationship between more intense current activity and the times of maximum development of the peaks, particularly peaks I and II.

(2) Sedimentary hiatuses and/or low rates of sedimentation (Table 1) are best developed in the zones of known high current intensity (i.e. the northern and

southern valleys). They are also synchronous with the coarse-grained peaks in zones of lesser current intensity (i.e. drift crest). This suggests temporal variation in bottom current intensity.

(3) The relative compositional homogeneity of all facies at the scale of the Drifts, implied a constancy of sediment sources and supply. The absence of exotic mineral assemblages, similar to those recovered from the Faro Canyon and the adjacent shelf, suggests little or no direct influence of turbidity currents over the Drift. The slight variations observed between different sites and peaks and the concomitant increase noted in both biogenic and terrigenous material, imply bottom current activity that has varied in time and place over the Drift, rather than general changes in the upstream sediment supply.

(4) The mixture of both terrigenous and biogenic in the coarser fractions and the significant presence of reworked shelly debris and benthonic foraminifera, suggest the influence of bottom currents, rather than a purely pelagic source of biogenic material from increased primary productivity.

The fact that both the terrigenous and biogenic (planktonic and benthonic) contents of the sand fraction in the coarser intervals have increased relative to their content in the sand fraction of finer-grained contourites, also mitigates against the influence of primary productivity.

(5) The interbedding of coarse-grained with very fine-grained contourites must be explained by the currents capable of transporting the coarser elements either slowing sufficiently to deposit the finer sediments, or being deflected away from the site of deposition.

(6) The longitudinal trends that are observed in sediment texture suggest that deposition was from alongslope bottom currents that decrease in intensity from east to west. The relatively higher grain size values to the south of the Drift argue against the influence of turbidity currents coming from the adjacent margin; and both the variability between sites and horizontal trends mitigate against variation in any other *local* supply of material being the prime control on grain size variation. Changes in supply to the current system further *upstream* cannot be ruled out entirely, although spatial variation in current intensity must be invoked to explain the variable distribution of coarser elements and temporal variation is required to allow deposition of the extremely fine-grained sediments inbetween coarser intervals.

(7) There are significant variations in the relative median grain-sizes of the different peaks at different sites over the ridge, favouring current control rather than upstream variation of sediment supply.

However, we also recognise certain arguments that favour at least some contribution to these lithological–textural changes by the factors other than current variation.

(1) The higher carbonate content and dominance of planktonic foraminifera in the sand fraction of peak II sediments suggest some influence related either to increased primary productivity, or to decreased terrigenous supply.

(2) The relatively high content of quartz in the sand fraction of peak I sediments and the approximate coincidence of the interval with an important

phase of deglaciation (14,000–15,000 yrs B.P.), suggest that increased terrigenous supply may also have been important.

It seems most probable that late Quaternary and Holocene climatic changes, affecting both atmospheric and oceanic circulation patterns, are ultimately responsible for the inferred fluctuation in bottom current activity associated with the Mediterranean Outflow. Our peaks I and II correspond with the termination I marking the end of the last glacial isotopic stage 2 (Broecker and Van Donk, 1970), a complex "event" subdivided into terminations Ia and Ib by Duplessy et al. (1981), and with the onset of warmer climatic conditions in the Holocene. All three zones are broad and complex in many of the cores, so that much of the interval from about 15,000 yrs B.P. to the present day is relatively coarser-grained than the underlying sediment deposited during the last glacial stage.

We would suggest, therefore, that renewed current activity in the area was associated with climatic amelioration and sea-level rise, and that it has remained more intense for much of the Holocene warm period. The precise oceanographic or climatic factors forcing the three main periods of current intensification and the many smaller-scale oscillations, we do not fully understand.

There have been significant studies in the general area of the Gulf of Cadiz and Northwest African margin in relating late Neogene climatic fluctuations (e.g. Diester-Haass and Chamley, 1982), to changes in oceanic circulation patterns (e.g. Sarnthein et al., 1982) and to variations in late Quaternary fluxes of sediment (e.g. Thiede et al., 1982). The picture that emerges is an extremely complex one with considerable local variability. For this reason and because of the inherent uncertainties in precise dating of events in ours, as well as in other studies, we hesitate to attempt correlation of our grain size peaks with the climatic/oceanographic changes documented elsewhere. We note, however, the possible significance of the pulses of temperature increase over the past 15,000 yrs (Sarnthein et al., 1982) and the hypsithermal temperature maximum between 8700 and 5000 yrs B.P. (Sarnthein, 1978).

On the other hand, there appears to be no relationship between our grain size peaks and the so-called pteropod spikes described in previous studies at around 17,000, 13,000, 11,000–9000 and 8000–5000 yrs B.P. (Kudrass, 1973; Berger, 1978; Sarnthein et al., 1982). These are believed to relate to a lowering of the aragonite compensation depth during periods of reduced upwelling. However, there is little evidence of much pteropod contribution to the biogenic fraction of Faro Drift cores. Neither do we see any evidence that supports or refutes the contention that there was a current reversal in the Strait of Gibraltar at about 10,000 yrs B.P. (Vergnaud-Grazzini and Bartolini, 1970; Diester-Haass, 1973).

## DRIFT GROWTH

*Longitudinal facies trends*

The comparison of facies and characteristics traverse by traverse shows the existence of clear longitudinal trends parallel to the Drift (Fig.10) that can be interpreted in terms of different hydrodynamic influences over different parts of the system.

The northern valley is predominantly an environment of transport and erosion. From east to west the surface sediments become coarser grained and the sedimentary structures observed in bottom photographs indicate strong

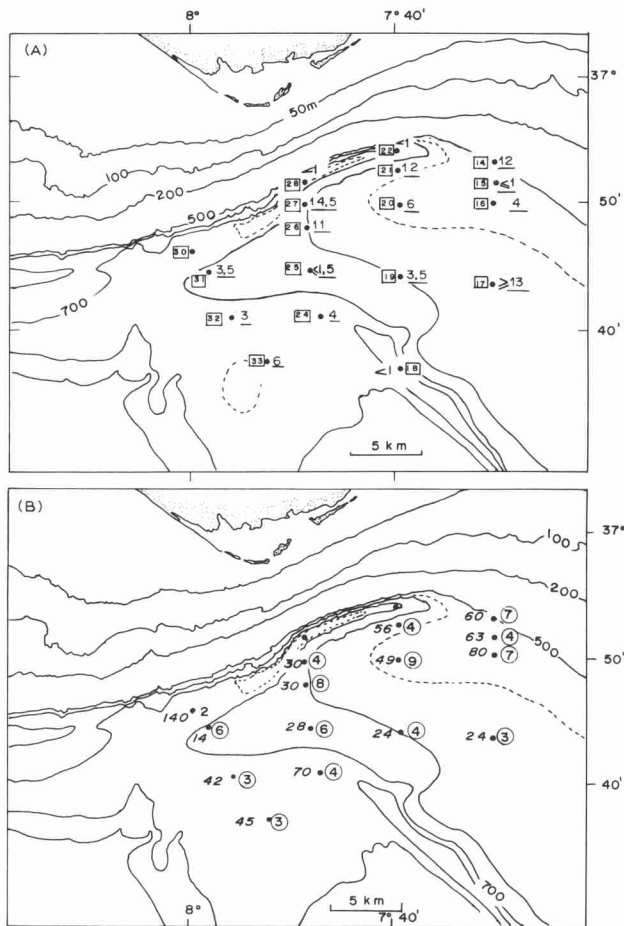


Fig.10. Regional distribution of (upper) average sedimentation rates in different core sites (core numbers in squares), and (lower) median grain size in  $\mu\text{m}$  from coarsest facies at each core site (plain figures) and finest facies (numbers in circles).

currents accelerating towards the west (Faugères et al., 1984b). The hiatus observed beneath the thin late Holocene cover also appears to be more important in the western than eastern cores supporting a westward intensification of currents. Sedimentation rates were low in the axis of the valley, but greater in the east, on the slope to the north, and in the west where turbidites are interbedded with the contourite facies.

The northern flank of the Drift is, by contrast, primarily an environment of deposition. The sediments are dominantly fine-grained and sedimentation rates relatively high, with a slight trend towards higher rates and finer sediments in the west. Clearly, bottom currents have remained relatively weak over the northern flank, perhaps showing a slight decrease in intensity westwards.

The crest of the Drift is, similarly, an area of important deposition, maximum in the central portion, although showing generally lower rates of sedimentation and slightly coarser sediments than those of the northern flank. The grain-size trend decreases towards the west indicating a decreasing current intensity in this direction, but nevertheless a greater intensity than for the northern flank. These reduced current effects are also observed on bottom photographs from our crestal station (KC8226) (Faugères et al., 1984b).

The southern flank of the Drift shows a rather different hydrodynamic influence in the east than in the west. The very fine-grained sediments and relatively high (but variable) rates of sedimentation in the eastern sector reflect the influence of only weak currents, similar to those of the northern flank. However, towards the west where the southern valley opens out onto the Bartolomeu-Dias plateau, the presence of coarser sediments, low sedimentation rates, and the same hiatus as observed in the northern valley cores bear witness to the influence of much stronger currents issuing from the southern valley.

These strong currents in the Diego Cao valley are clearly evident from our two cores and one photographic station, as well as from the direct current measurements reported by Madelain (1970).

The development of the Faro Drift during the late Quaternary period was clearly related to this current system which we have schematised in Fig.11, and which explains the observed facies distribution. The currents in the valleys allow little net deposition and both winnow and erode the sediment. The obstacle presented by the crest of the Drift to the relatively thin (50–100 m; Ambar, 1983) oblique flow would create increased activity at the bottom and hence deposition of a slightly coarser-grained facies than that observed for other parts of the Drift. Interference between flows of different velocities and between counter-flowing eddies and the main current might explain the greater deposition on the northern flank in particular and hence the general northwestward migration of the Drift. The influence of the more intense flow through the southern valley is reflected by the hiatuses and coarser-grained facies at the southwest end of the Drift. Presumably the general dispersion of bottom water will have been similar since the onset of the

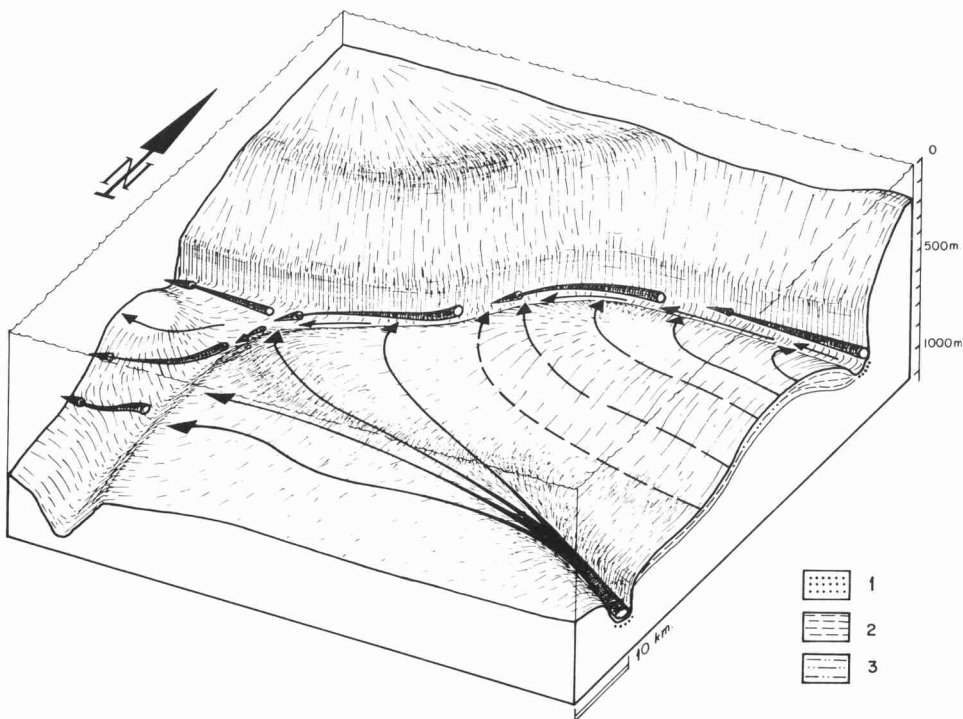


Fig.11. Schematic reconstruction of bottom current circulation across the Faro Drift. Principal sediment types shown on transverse section: 1=sandy or silty contourites, relatively low sedimentation rates and/or erosion; 2=homogeneous mud contourites, relatively high rates of sedimentation; 3=silty-muddy contourites, average rates of sedimentation.

Mediterranean Outflow in the late Miocene to early Miocene. However, the exact distribution of currents will have been modified by the developing morphology.

#### *Initiation and morphology*

There are several factors that probably led to the initial development of a drift in this area: (a) the geometry of the continental margin which interrupted the northwestward flow of Mediterranean Water; (b) the addition of significant sediment to the bottom waters via erosion in the Strait of Gibraltar and via important rivers draining the southern Iberian land mass; (c) the decrease in bottom current velocity from the extreme values ( $> 2 \text{ m s}^{-1}$ ) in the Strait such that deposition could occur; and (d) the influence of structural controls on bottom morphology and hence current flow, for example the probable development of the southern valley along a structural lineament. Termination of the Drift at its western end is not wholly due to the interruption by the Faro Canyon as the decrease in Drift size begins further to the east. It is probably

related also to a diminution in sediment load as a result of deposition, and to the erosive effects of the currents flowing out of both the southern and northern valleys.

Whereas progradation of the Drift is predominantly to the north or northwest elongation is in an east–west direction. This margin-parallel evolution presumably is mainly a result of the northern valley current system preventing deposition and possible northward prolongation.

### *Three scales of growth*

The detailed core analysis, 3.5 kHz seismic records and deep seismic profiles have allowed us to recognise three different scales of facies variation and sediment geometry that give us some indication about the processes of Drift growth and their relationship to the Mediterranean Outflow.

At the *small scale*, there are three main coarser-grained zones or peaks within the top 2–3 m of sediment dated at around 15,000, 9500 and from about 2000 yrs B.P. to the present time. These peaks are interpreted as being primarily related to periods of more intense bottom current activity as discussed in the previous section.

At the *medium scale*, we can see more clearly on the 3.5 kHz records the alternation of periods of active progradation possibly related to more intense currents, with periods of slower more uniform deposition associated with lesser current activity. The topmost 20–30 m of sediment shows a lower uniform depositional unit (h3), a middle sigmoidal progradation unit (h2), and an upper second uniform unit (h1). On the basis of facies characteristics and distribution in the cores, we would suggest that the topmost 1–3 m may represent a return to an active progradational phase (h0). Extrapolation of late Quaternary sedimentation rates would give a very approximate age for these top four units of about 300,000 yrs, and hence a rough correlation of more intense current activity and progradational phases with higher sealevel (interglacials and interstadials), while reduced current activity and uniform accretion correlates with lower sealevel (glacials).

Although this inference is clearly tenuous it is supported by various evidence that suggests a similar correlation between sealevel and bottom current intensity in the North Atlantic (e.g. Hughes et al., 1977; Kellogg, 1977; Schnitker, 1979, 1980; Volat et al., 1980); and by micropaleontological evidence for reduced bottom-water outflow from the Mediterranean during glacial periods (J.P. Peypouquet, pers. commun., 1984). In terms of the sediment record we would expect, therefore, the coarser-grained contourite facies and associated hiatuses to alternate with finer-grained contourites with a periodicity that bears some relationship to high and low stands of sea level. The vertical spacing of such cycles would then be of the order of a few metres.

At the *large scale*, there has been 300–500 m of accumulation in a time period of 4–5 m.y., accompanied by a north to northwestward progradation of some 10 km. Drift growth has varied between periods of active progradation and

more even vertical accumulation. The shape of the drift has apparently remained elongate in a west–east direction throughout its growth (Faugères et al., 1985). Progradation has been in the general sense of the cross-drift currents or eddies with a streamlining of the Drift shape by currents in the valley axis.

If the horizontal distribution of facies described in this paper has remained more or less similar throughout growth, then lateral progradation would have produced an overall vertical succession at the scale of the drift comprising: (a) coarse-grained contourites of the “channel” facies with significant hiatuses, as a thin basal unit; (b) very fine-grained contourites of the “drift-flank” facies as a thick succeeding unit; (c) slightly coarser-grained contourites of the “drift-crest” facies, with minor hiatuses; and (d) a second thick fine-grained interval of the southern “drift-flank” facies as the topmost unit. However, when the drift was considerably smaller in its initial stages of growth, the northern channel may not have been so clearly defined and hence the basal unit (a) of the Drift may not everywhere be especially coarse-grained.

#### CONCLUSIONS

The Faro Drift on the southern margin of Portugal in the Gulf of Cadiz is a clear example of an oceanic contourite drift constructed by deep-water bottom currents. Detailed seismic and sediment studies make it a good model for understanding drift growth in relation to climatic and oceanographic influences. In particular, careful analysis of sediment facies, sequences, structures, composition and textures in the top 3 m of section, has enabled us to resolve the principal factors controlling lithological variations in Faro Drift contourites. The main control has been bottom current velocity fluctuation with secondary controls including sediment supply and primary productivity. There is no evidence for dissolution or diagenesis having significantly affected the sediments. More accurate monitoring of the early development of the Faro Drift and its record of the variations in Mediterranean Outflow will have to await the results of deeper drilling in the area.

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#### REFERENCES

- Ambar, I., 1983. A shallow core of Mediterranean water off west Portugal. *Deep-Sea Res.*, 30: 677–680.
- Ambar, I. and Howe, M.R., 1979. Observations of the Mediterranean outflow — II. The deep circulation in the vicinity of the Gulf of Cadiz. *Deep-Sea Res.*, 26A: 555–568.

- Ambar, I., Howe, M.R. and Abdullah, M.I., 1976. A physical and chemical description of the Mediterranean outflow in the Gulf of Cadiz. *Dtsch. Hydrogr. Z.*, 29: 58–68.
- Auffret, G.A. and Pastouret, L., 1979. Upper Cretaceous to Quaternary sedimentary processes in the Bay of Biscay from textural mineralogical and coarse fraction studies. In: L. Montadert, D.G. Roberts et al., Initial Reports of the Deep Sea Drilling Project, Vol. 48. U.S. Govt. Printing Office, Washington, D.C., pp.791–829.
- Auffret, G.A., Sichler, B. and Colerno, B., 1981. Deep-sea sediments texture and magnetic fabric, indicators of bottom currents regime. *Ocean. Acta*, 4: 475–488.
- Berger, W.H., 1978. Deep-sea carbonate: pteropod distribution and the aragonite compensation depth. *Deep-Sea Res.*, 25: 447–452.
- Blaeser, C.R. and Ledbetter, M.T., 1982. Deep-sea bottom currents differentiated from texture of underlying sediment. *J. Sediment. Petrol.*, 52: 755–768.
- Broecker, W.S. and Van Donk, J., 1970. Insolation changes, ice volumes and  $O^{18}$  record in deep sea cores. *Rev. Geophys. Space Phys.*, 8: 169–198.
- Bullfinch, D.L., Ledbetter, M.T., Ellwood, B.B. and Balsam, W.L., 1982. The high velocity core of the Western Boundary Undercurrent at the base of the US continental rise. *Science*, 215: 970–973.
- Camden-Smith, F., Perrins, L.-A., Dingle, R.V. and Brundrit, G.B., 1981. A preliminary report on long-term bottom current measurements and sediment transport/erosion in the Agulhas Passage, southwest Indian Ocean. *Mar. Geol.*, 39: M81–M88.
- Carter, L. and Schafer, C.T., 1983. Interaction of the Western Boundary Undercurrent with the continental margin off Newfoundland. *Sedimentology*, 30: 751–768.
- Diester-Haass, L., 1973. No current reversal at 10,000 B.P. in the Strait of Gibraltar. *Mar. Geol.*, 15: M1–M9.
- Diester-Haass, L. and Chamley, H., 1982. Oligocene and past-Oligocene history of sedimentation and climate off NW Africa (DSDP Site 319). In: U. Von Rad et al. (Editors), *Geology of the NW African Continental Margin*. Springer, Berlin, pp.529–544.
- Duplessy, J.C., Delibrias, G., Turon, J.L., Pujol, C. and Duprat, J., 1981. Deglacial warming of the northeastern Atlantic Ocean: correlation with the paleoclimatic evolution of the European continent. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 35: 121–144.
- Duprat, J., 1983. Les foraminifères planctoniques de Quaternaire terminal d'un domaine péricontinental (Golfe de Gascogne, Côtes ouest-ibériques. Mer d'Alboran): écologie-biostratigraphie. *Bull. Inst. Géol. Bassin Aquitaine*, 33: 71–150.
- Ellwood, B.B. and Ledbetter, M.T., 1977. Antarctic bottom water fluctuations in the Vema Channel: Effects of velocity changes on particle alignment and size. *Earth Planet. Sci. Lett.*, 35: 189–198.
- Ellwood, B.B. and Ledbetter, M.T., 1979. Paleocurrent indicators in deep-sea sediments. *Science*, 203: 1335–1337.
- Faugères, J.-C. and Gonthier, E., 1983. Evolution de la sédimentation profonde au Quaternaire récent sur une marge continentale stable, jeune: la marge sub-arabique (Sukra). *Bull. Soc. Géol. Fr.*, 25(4): 451–460.
- Faugères, J.-C., Gonthier, E. and Stow, D.A.V., 1984a. Contourite drift molded by deep Mediterranean outflow. *Geology*, 12: 296–300.
- Faugères, J.-C. et al., 1984b. Physiography and contourite characteristics on the surface of a drift built by Mediterranean bottom currents (Faro Drift, Cadiz Gulf). *Bull. Soc. Geol. Fr.*, 8,I(1): 35–47.
- Faugères, J.-C., Monteiro, H. and Cremer, M., 1985. Essai de reconstitution des processus d'édification de la ride sédimentaire du Faro (Plio-Quaternaire, marge sud-portugal). *Ciencias de Terra, Lisbon* (in press).
- Giesel, W. and Seibold, E., 1968. Sedimentechogramm von Ibero-Marokkanischen Kontinentalrand. *Meteor. Forschungsergeb.*, 1: 53–75.
- Gonthier, E., Faugères, J.-C. and Weber, O., 1981. Signification des méthodes granulométriques pour la reconstitution des processus hydrodynamiques à partir de sédiments profonds terrigènes carbonatés. *Bull. Inst. Géol. Bassin Aquitaine*, 30: 31–49.
- Gonthier, E., Faugères, J.-C. and Stow, D.A.V., 1984. Contourite facies of the Faro Drift, Gulf of

- Cadiz. In: D.A.V. Stow and D.J.W. Piper (Editors), *Fine-Grained Sediments: Deep-Water Processes and Facies*. Geol. Soc. Spec. Publ., 15: 275–292.
- Halfman, J.D. and Johnson, T.C., 1984. The sediment texture of contourites in Lake Superior. In: D.A.V. Stow and D.J.W. Piper (Editors), *Fine-Grained Sediments: Deep-Water Processes and Facies*. Geol. Soc. Spec. Publ., 15: 293–307.
- Heezen, B.C. and Johnson, G.L., 1969. Mediterranean undercurrent and microphysiography west of Gibraltar. *Bull. Inst. Oceanogr. Monaco.*, 67, No. 1382, 95 pp.
- Hjulstrom, F., 1939. Transportation of detritus by moving water. In: P.D. Trask (Editor), *Recent Marine Sediments: A Symposium*. Soc. Econ. Palaeontol. Mineral., Spec. Publ., 4: 5–31.
- Hollister, C.D. and Heezen, B.C., 1972. Geologic effects of ocean bottom currents: western North Atlantic. In: A.L. Gordon (Editor), *Studies in Physical Oceanography*, Vol. 2, Gordon and Breach, New York, N.Y., pp.37–66.
- Hughes, T., Denton, C.H. and Grosswald, M.G., 1977. Was there a Late-Würm Arctic Ice Sheet? *Nature*, 266: 596–602.
- Kellogg, T.B., 1977. Paleoclimatology and paleoceanography of the Norwegian and Greenland Seas: the last 450,000 years. *Mar. Micropaleontol.*, 2: 235–249.
- Kudrass, H.-R., 1973. Sedimentation am Kontinentalhang vor Portugal und Marokko im Spätpleistozän und Holozän. "Meteor" *Forschungsergeb.*, Reihe C, 13: 1–63.
- Ledbetter, M.T., 1979. Fluctuations of Antarctic Bottom Water velocity in the Vema Channel during the last 160,000 years. *Mar. Geol.*, 33: 71–89.
- Ledbetter, M.T. and Ellwood, B.B., 1980. Spatial and temporal changes in bottom-water velocity and direction from analysis of particle size and alignment in deep-sea sediment. *Mar. Geol.*, 38: 245–261.
- Ledbetter, M.T. and Johnson, D.A., 1976. Increased transport of Antarctic Bottom Water in the Vema Channel during the last ice age. *Science*, 194: 837–839.
- Lonsdale, P.F., 1981. Drifts and ponds of reworked pelagic sediment in part of the southwest Pacific. *Mar. Geol.*, 43: 153–193.
- Lonsdale, P. and Hollister, C.D., 1979. A near-bottom traverse of Rockall Trough: Hydrographic and geologic inferences. *Oceanol. Acta*, 2: 91–106.
- Luyten, J.R., 1977. Scales of motion in the deep Gulf Stream and across the Continental Rise. *J. Mar. Res.*, 35: 49–74.
- Madelain, F., 1970. Influence de la topographie du fond sur l'écoulement méditerranéen entre le détroit de Gibraltar et le Cap Saint-Vincent. *Cah. Océanogr.*, 22, Ann. No. 1: 43–61.
- McCave, I.N., 1984. Erosion, transport and deposition of fine-grained marine sediments. In: D.A.V. Stow and D.J. Piper (Editors), *Fine-Grained Sediments: Deep-Water Processes and Facies*. Geol. Soc. Spec. Publ., 15: 35–70.
- McCave, I.N. and Swift, S.A., 1976. A physical model for the rate of deposition of fine-grained sediments in deep sea. *Geol. Soc. Am. Bull.*, 87: 541–546.
- McCave, I.N., Lonsdale, P.F., Hollister, C.D. and Gardner, W.D., 1980. Sediment transport over the Hatton and Gardar contourite drifts. *J. Sediment. Petrol.*, 50: 1049–1062.
- Mélières, F., Nesteroff, W.D. and Lancelot, Y., 1970. Etude photographique des fonds du Golfe de Cadiz. *Cah. Océanogr.*, 22, Ann. No. 1: 63–72.
- Mougenot, D. and Vanney, J.R., 1982. Les rides de contourites Plio-Quaternaires de la pente continentale sud-Portugaise. *Bull. Inst. Géol. Bassin Aquitaine*, 31: 131–139.
- Pflaumann, U., 1980. Variations of the surface-water temperatures at the eastern north atlantic continental margin. *Palaeoecol. Afr.*, 12: 191–212.
- Pujol, C., 1980. Les foraminifères planctoniques de l'Atlantique Nord au Quaternaire. *Ecologie, stratigraphie, environnement*. Mem. Inst. Géol. Bassin Aquitaine, 10, 254 pp.
- Reid, J.L., 1978. On the mid-depth circulation and salinity field in the North Atlantic Ocean. *J. Geophys. Res.*, 83: 5063–5067.
- Rivière, A., 1977. *Méthodes Granulométriques: Techniques et Interprétation*. Masson, Paris, 170 pp.
- Sarnthein, M., 1978. Sand deserts during glacial maximum and climatic optimum. *Nature*, 271: 43–46.

- Sarnthein, M. et al., 1982. Atmospheric and oceanic circulation patterns off NW Africa during the past 25 million years. In: U. Von Rad et al. (Editors), *Geology of the NW African Continental Margin*. Springer, Berlin, pp.545-602.
- Schnitker, D., 1979. The deep waters of the western North Atlantic during the past 24,000 years, and the re-initiation of the western Boundary Undercurrent. *Mar. Micropaleontol.*, 4: 265-280.
- Schnitker, D., 1980. Global paleoceanography and its deep water linkage to the Antarctic glaciation. *Earth Sci. Rev.*, 16: 1-20.
- Shor, A., Lonsdale, P., Hollister, C.D. and Spencer, D., 1980. Charlie-Gibbs fracture zone: bottom-water transport and its geologic effects. *Deep-Sea Res.*, 27A: 325-345.
- Stow, D.A.V., 1979a. Distinguishing between fine-grained turbidites and contourites on the Nova Scotia deep water margin. *Sedimentology*, 26: 371-387.
- Stow, D.A.V., 1979b. Method for silt and sand fabric analysis in deep-sea cores. *J. Sediment. Petrol.*, 39: 627-630.
- Stow, D.A.V., 1982. Bottom currents and contourites in the North Atlantic. *Bull. Inst. Geol. Bassin Aquitaine*, 31: 151-166.
- Stow, D.A.V. and Holbrook, J.A., 1984. North Atlantic contourites: an overview. In: D.A.V. Stow and D.J.W. Piper (Editors), *Fine-Grained Sediments: Deep-water Processes and Facies*. Geol. Soc. Spec. Publ., 15: 245-256.
- Stow, D.A.V. and Lovell, J.P.B., 1979. Contourites: their recognition in modern and ancient sediments. *Earth-Sci. Rev.*, 14: 251-291.
- Thiede, J., Suess, E. and Muller, P.J., 1982. Late Quaternary fluxes of major sediment components to the sea-floor at the NW African continental slope. In: U. Von Rad et al. (Editors), *Geology of the NW African Continental Margin*. Springer, Berlin, pp.605-631.
- Trask, P., 1930. Mechanical analysis of sediments by centrifuge. *Econ. Geol.*, 25: 581-599.
- Vanney, J.R. and Mougnot, D., 1981. La plateforme continentale du Portugal et les provinces adjacentes: analyse géomorphologique. *Mem. Serv. Geol. Portugal*, 28: 81 pp.
- Vergnaud-Grazzini, C. and Bartolini, C., 1970. Evolution paléoclimatique des sédiments würmiens et post-würmiens en mer d'Alboran. *Rev. Géogr. Phys. Géol. Dyn. Set.* 2, 12(4): 325-334.
- Volat, J.-L., Pastouret, L. and Vergnaud-Grazzini, C., 1980. Dissolution and carbonate fluctuations in Pleistocene deep-sea cores: a review. *Mar. Geol.*, 34: 1-28.
- Westall, F., 1984. Current-controlled sedimentation in the Agulhas Passage, SW Indian Ocean. PhD Thesis, University of Cape Town, Cape Town, 276 pp.
- Zenk, W., 1975. On the Mediterranean Outflow west of Gibraltar. "Meteor" *Forschungsergeb.*, Reihe A, 16: 23-34.