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Contourite drift molded by deep Mediterranean outflow

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ABSTRACT

Since its inception in early Pliocene time, the deep Mediterranean outflow has eroded and sculptured the southern Iberian margin. The 50-km-long, 300-m-thick Faro Drift, constructed by this powerful bottom current, has been the subject of detailed study. Sandy, silty, and muddy contourite facies can be clearly characterized, and a distinctive vertical arrangement or "sequence" of these facies can be related to hydrodynamic fluctuation. These results are important for the identification of ancient contourites, the reconstruction of paleocirculation patterns, and documentation of the effects of Quaternary climates on the Mediterranean outflow.

INTRODUCTION

That the deep thermohaline circulation in the oceans produces currents of sufficent intensity to sculpture the seafloor, transport fine particles over thousands of kilometres, and deposit giant sediment drifts is now well known. Long-term records have shown that these deep flows vary dramatically in direction, velocity (<5 cm/s to >100 cm/s), and periodicity (e.g., Shor et al.,

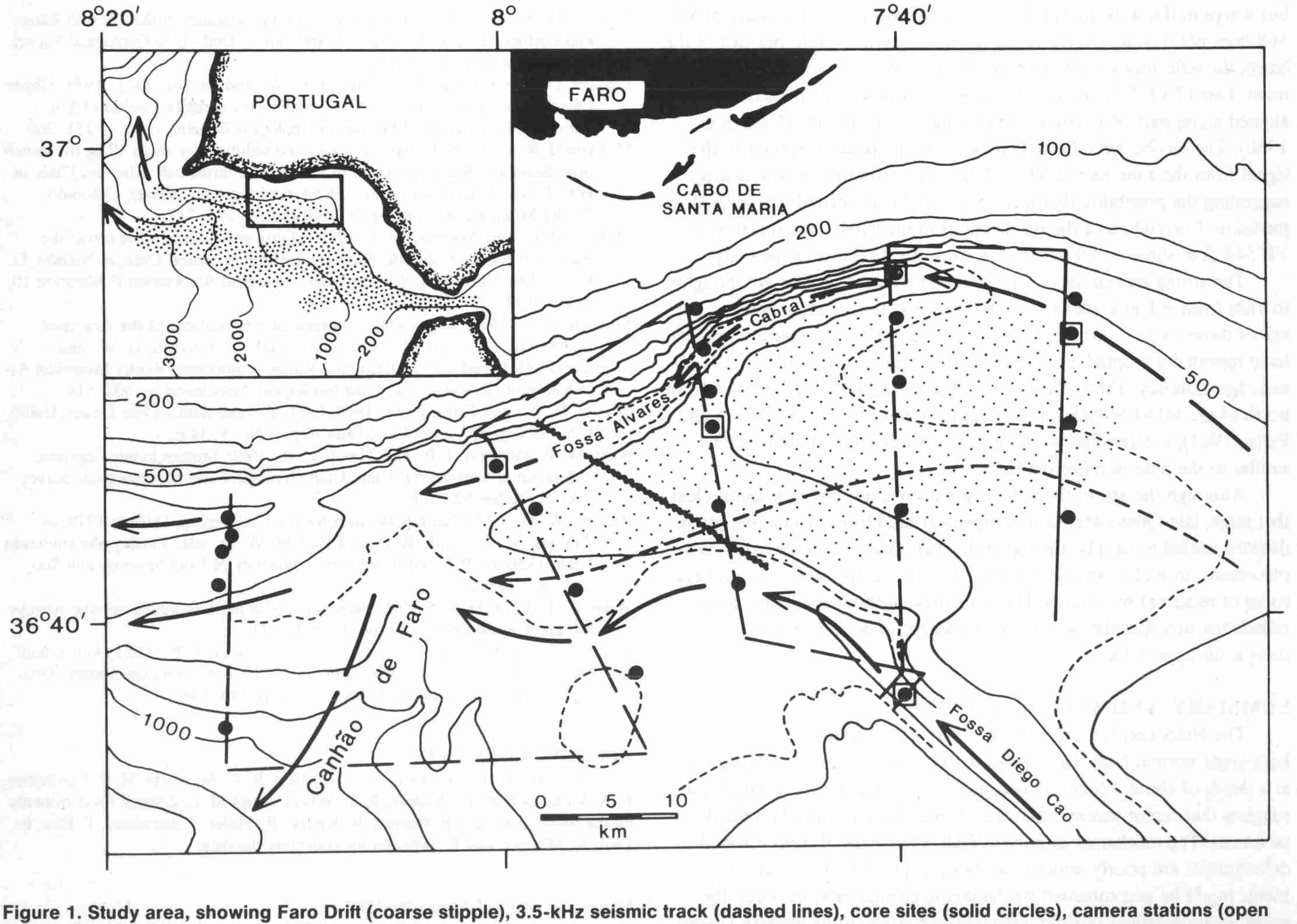

Figure 1. Study area, showing Faro Drift (coarse stipple), 3.5-kHz seismic track (dashed lines), core sites (solid circles), camera stations (open squares), known flow (heavy arrows) and inferred flow (dashed-line arrow) of Mediterranean water, and location of seismic profile shown in Figure 2 (zigzag). Contours in metres. Inset map shows passage of Mediterranean outflow water over seafloor and location of study area.

subsurface faults with substantial vertical displacements are not associated with scarps, suggesting that during the last surface-faulting event, only selected faults ruptured. Profile data were collected along a 7.9-km-long line, but because of recording problems, a 2.7-km-long central segment was lost. Thus, only a 2.2-km-long western part (Figs. 3A, 3B) and a 2.9-km-long eastern part (Figs. 3C, 3D) of the line are available.

A two- to three-cycle reflection with numerous vertical displacements (labeled B in Figs. 3B, 3D) between 0.2 and 0.4 s is obvious on these profiles. The data gap precludes direct correlation of these reflections across the entire scarp system, but the similarity in signal strength, waveform, and travel time on both segments supports the correlation. Because of the high reflectivity of B, virtually no coherent energy was returned from deeper horizons.

The west segment of the profile crosses two scarps (Fig. 3A). The westernmost scarp (VP 177) has a surface offset of 2.7 m (Bucknam and Anderson, 1979b). A trench about 75 m south of the MINI-SOSIE line shows that the scarp is from a single surface-faulting event with 3.7 m of stratigraphic throw (Crone, 1983). The MINI-SOSIE data show a very steep east-dipping fault beneath the scarp, with reflectors B vertically displaced about 46 m. This displacement is comparable to 12 to 17 faulting events of the size that produced the present surface scarp. The other scarp, at the extreme east end (VP 239) of this segment, is where poor record quality makes the interpretation of any subsurface faults suspect. Several other faults without any surface expression displace the reflectors on the western segment; the most obvious feature is a 250-m-wide horst between VP 141 and VP 157, with 40–45 m of displacement on both marginal faults.

The eastern segment of the line (Fig. 3C) contains numerous faults, but scarps in this area are small, about 1 m high or less. The scarp at VP 568 does not directly overlie an identified subsurface fault, but east of the scarp, the reflectors are offset about 80 m, with the same sense of movement. East of VP 575, the profile crosses a narrow ridge of basalt that is aligned along part of a system of high-angle normal faults (Nash et al., 1980). The incoherent reflected energy over the basalt is similar to the signal from the zone east of VP 544, the site of another notable scarp, suggesting the possibility that this scarp may be associated with a shallow intrusion. Correlation of the B reflections immediately east and west of VP 544 does show an 80-m offset in the same direction as the scarp.

The strong reflections on the Drum Mountains profiles are thought to arise from volcanic rocks at the base of a section of alluvium, but the age of those rocks is difficult to estimate because nearby volcanic centers have repeatedly erupted, beginning 42 m.y. ago to as recently as 0.31 m.y. ago (Lindsey, 1982; Nash et al., 1980). Drill hole E (Fig. 1), 9.5 km north of the MINI-SOSIE line, encountered lava at 214 m (Mower and Feltis, 1964), a depth that would generate a reflection at about 0.23 s, similar to the time of reflectors B.

Although the age of the reflecting datum is unknown, it seems clear that large, late Quaternary fault scarps near the Drum Mountains can be directly related to steeply dipping faults that offset competent rock. Displacements in rock many times larger than the scarps suggest several episodes of recurrent movement. Unfortunately, without resolvable deep reflections, any speculation relating the scarps to deeper regional structures is unsupportable.

SUMMARY AND CONCLUSIONS

The Holocene(?) scarp at Clear Lake is the surface expression of a high-angle normal fault that merges with the Sevier Desert detachment at a depth of about 3.5 km. Holocene(?) movement on the normal fault suggests that recent tectonic movements may have occurred on the detachment. The mechanics of normal fault movement of subhorizontal detachments are poorly understood, but it is possible that future movements might be accompanied by damaging ground motion. Thus, the seismogenic potential of similar detachment faults in the western United States may need to be reconsidered. The most prominent late Quaternary scarps near the Drum Mountains overlie steep faults in competent rocks that have had recurrent movement. Many subsurface faults with substantial displacements are not associated with scarps. High-resolution reflection profiles provide valuable shallow structural data that complement other types of structural information.

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1980). The High Energy Benthic Boundary Layer Experiment (HEBBLE) study has shown a complex interaction of bottom current, turbidity current, and pelagic deposition processes in a small area on the Nova Scotian rise (Richardson et al., 1981; Shor et al., 1984). It is vital for the reconstruction of paleo-oceans and deep paleocirculation patterns that we learn to decode the record that current fluctuation and interaction has left in the sediments. Many earlier studies of these sediments (contourites) concentrated on the eastern continental margin of North America, where the close interbedding of contourites and fine-grained turbidites led to serious differences over the recognition of contourites (Stanley et al., 1971; Hollister and Heezen, 1972; Pilkey and Field, 1972; Stow, 1979).

Studies of the major sediment drifts of the North Atlantic (e.g., Laughton et al., 1972; Tucholke, 1975; Shor and Poore, 1978; Montadert et al., 1979; McCave et al., 1980) have allowed a more accurate documentation of the contourite facies (Stow and Lovell, 1979; Faugères et al., 1979; Stow, 1982). However, most of these studies were of isolated cores or Deep Sea Drilling Project (DSDP) sites on giant drifts, so we still have very few data on the horizontal and vertical variability of such sediments. We also lack data on small-scale facies changes that result from short-period bottom-current fluctuation.

To help fill in some of these important gaps in our knowledge, a detailed study, combining 3.5-kHz seismic profiling, bottom photography, and closely spaced piston and gravity coring, was carried out on a relatively small contourite drift (the Faro Drift) in the Gulf of Cadiz, west of Gibraltar, using the French oceanographic vessel RV *Noroit.*

CURRENTS AND DRIFT MORPHOLOGY

The present-day oceanography of the Gulf of Cadiz is well known. A deep outflow of warm, saline Mediterranean water through the Straits of Gibraltar spreads north and west along the southern margins of Spain and Portugal in three interconnected flows between 400 and 1,400 m depth (Fig. 1; Heezen and Johnson, 1969; Ambar and Howe, 1979a, 1979b). Current velocities decrease from 180 cm/s just west of Gibraltar (up to 300 cm/s in the Strait of Gibraltar) to 10–20 cm/s off Cape St. Vincent, and they are locally affected by bottom topography.

The narrow Iberian shelf is separated by a moderately steep slope from an area of narrow erosional valleys and low constructional mounds or drifts that parallel the margin and are interrupted by downslope canyons (Mougenot and Vanney, 1980, 1982). The Faro Drift is the most easterly of the drifts; it lies between the Fossa Alvares Cabral and Fossa Diego Cao valleys, through which two relatively high-velocity flows of Mediterranean water are known to pass. The Faro Drift is 40–50 km long, 10–20 km wide, and up to 300 m thick, with a maximum present-day channel-to-crest relief of 160 m. It appears to have been constructed over a late Miocene or early Pliocene erosional surface, presumably following the onset of Mediterranean outflow into the Atlantic, and to have prograded steadily northward (Mougenot and Vanney, 1982).

SEDIMENT FACIES AND SURFACE FEATURES

There is a distinct difference between the sediment and bottom features of the drift and of the adjacent valleys. The surface sediments over the drift are fine silty muds or muddy silts; photographs of the drift-top site show a field of current ripples (flow to northwest), now attenuated and partly covered by a silty mud and extensively burrowed. The echo-facies character is one of a relatively strong surface reflector and parallel, more or less continuous subsurface reflectors, with zones of thicker or thinner accumulation and of minor erosion across the drift.

The valley floors on either side of the drift comprise a much coarser sandy or granular, very poorly sorted, heterogeneous material. The echo profiles show that the steep northern margins of the valleys have been extensively eroded and are commonly slumped, whereas the valley floors allow little penetration. The surface features and sediment thickness vary along the length of each valley and from one valley to the other, and they may be directly related to the intensity of the currents. Thus, in the northern valley the sediment fill is coarser and has a thinner surface layer where the valley is narrowest. In the southern valley, where current velocities of up to 80 cm/s have been measured, there is only a thin covering of coarse sand over indurated sediments of Neogene age. The bottom photographs show transverse megaripples with amplitudes of about 50 cm partly covered by smaller ripples of a few centimetres amplitude. Locally, the smaller linguoid ripples pass laterally into longitudinal bedforms (Fig. 2).

The distribution of echo facies over the region shows the presence not only of the two

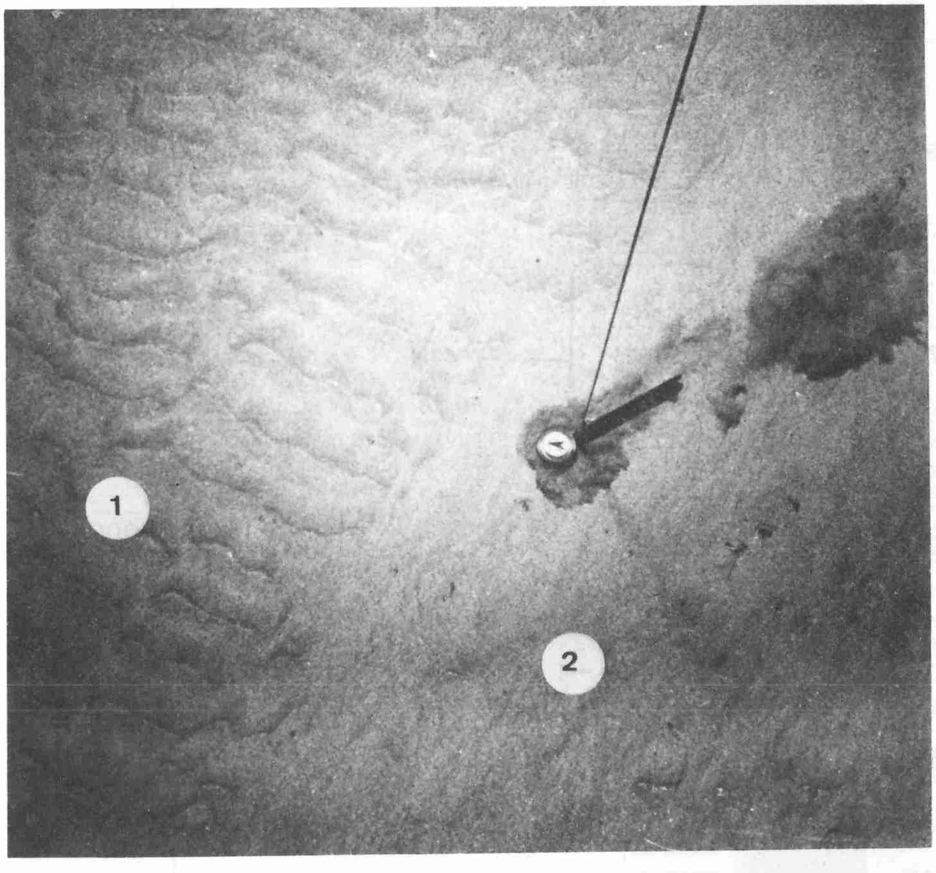

Figure 2. Bottom photograph from Fossa Diego Cao (Fig. 1) showing adjacent fields of transverse ripples (1) and longitudinal lineation (2). Surface irregularities (pebbles?) to right of compass show crescentic scour marks. Inferred current direction is northeast to southwest. Compass diameter is 30 cm.

flows that have eroded and sculptured the northern and southern valleys, but also of an intermediate flow along the length of the drift. This is inferred from a zone of dense, less penetrable echo facies associated with sediment thinning and erosion.

Three main contourite facies can be distinguished in the Holocene and later Pleistocene sediments recovered: silt and sand (5% of the sediments cored), mottled silt and mud (20%), and homogeneous mud (68%), corresponding to the sandy and muddy contourites described in the literature (Stow and Lovell, 1979) and to a gradation of types between these two facies that we have grouped together as the mottled silt and mud. There is, in addition, a small percentage of turbidites (4%) in or near the Faro Canyon to the west and of indurated and slumped mud (3%) in the valley floors. The silt and sand occur in distinct beds from a few centimetres to 20 cm thick, surrounded by mottled silt and mud that form less distinct horizons averaging 10–20 cm thick (range 2–70 cm). The apparently homogeneous mud made up most of the rest of the cores, forming intervals from a few centimetres to a few metres thick.

The two principal sedimentary structures that indicate the action of bottom currents are sharp or erosional contacts and lamination. Contacts between the different facies may be more or less planar and sharp, distinctly erosional, or completely gradational, and all three types are equally common at the base or at the top of separate beds. The sharp and erosional contacts are most probably due to the abrasive action of a sediment-charged current that smooths and/or scours the surface before depositing its load. Lamination, as seen on X-radiographs of thin (~1 cm) slabs of sediment (Fig. 3), is mostly irregular and undulating. It is very rare in the silts and sands, whereas the mottled silt-mud facies and the apparently homogeneous mud commonly show either an alternation of silty and muddy layers continuous across the width of the core or the horizontal alignment of thin, discontinuous lenses. More rarely, there is a finely spaced regular and continuous lamination.

Bioturbation is characteristic of all three facies. It is best observed on X-radiographs (Fig. 3) or in thin sections of resin-impregnated sediment. Mottling occurs throughout at a micrometre, millimetre, or centimetre scale, together with other more or less distinct and isolated pockets and streaks. Certain specific trace fossils can be identified on the basis of their more regular form or internal structure (Werner and Wetzel, 1982), including *Chondrites, Planolites, Scolocia,* and *Teichichnus.* This bioturbation was clearly a continuous process that has modified or destroyed much of the original structure, has partially or completely altered the nature of the contacts, and is probably responsible in large part for the chaotic melange of sediments within the mottled facies. There appears to be a preference of large forms for the silt-sand and mottled facies, to which the *Scolicia*-type burrows are restricted. Smaller scale bioturbation and very thin, long sulfide filaments are more common in the finer grained facies.

The sediments are all relatively fine grained, silt and clay grade, and mostly poorly sorted. The mean grain size of the silt-sand facies mainly varies between 30 and 50 μm, and is the best sorted of the facies. The homogeneous muds vary below about 8 μm mean size and the mottled facies between 8 and 30 μm. The forms of the cumulative frequency grain-size curves (Rivière, 1977) are parabolic-hyperbolic for the silts and sands, hyperbolic for the mottled facies, and closer to logarithmic for the homogeneous muds. Progressive increase or decrease in grain size (i.e., both positive and negative grading) is common in all facies on a small scale (centimetre) as well as over 10–50 cm of section.

The composition of all three facies is similar: 20%–40% biogenic carbonate, mainly benthonic and planktonic foraminifera, shelly debris and ostracods; and 60%–80% terrigenous quartz,

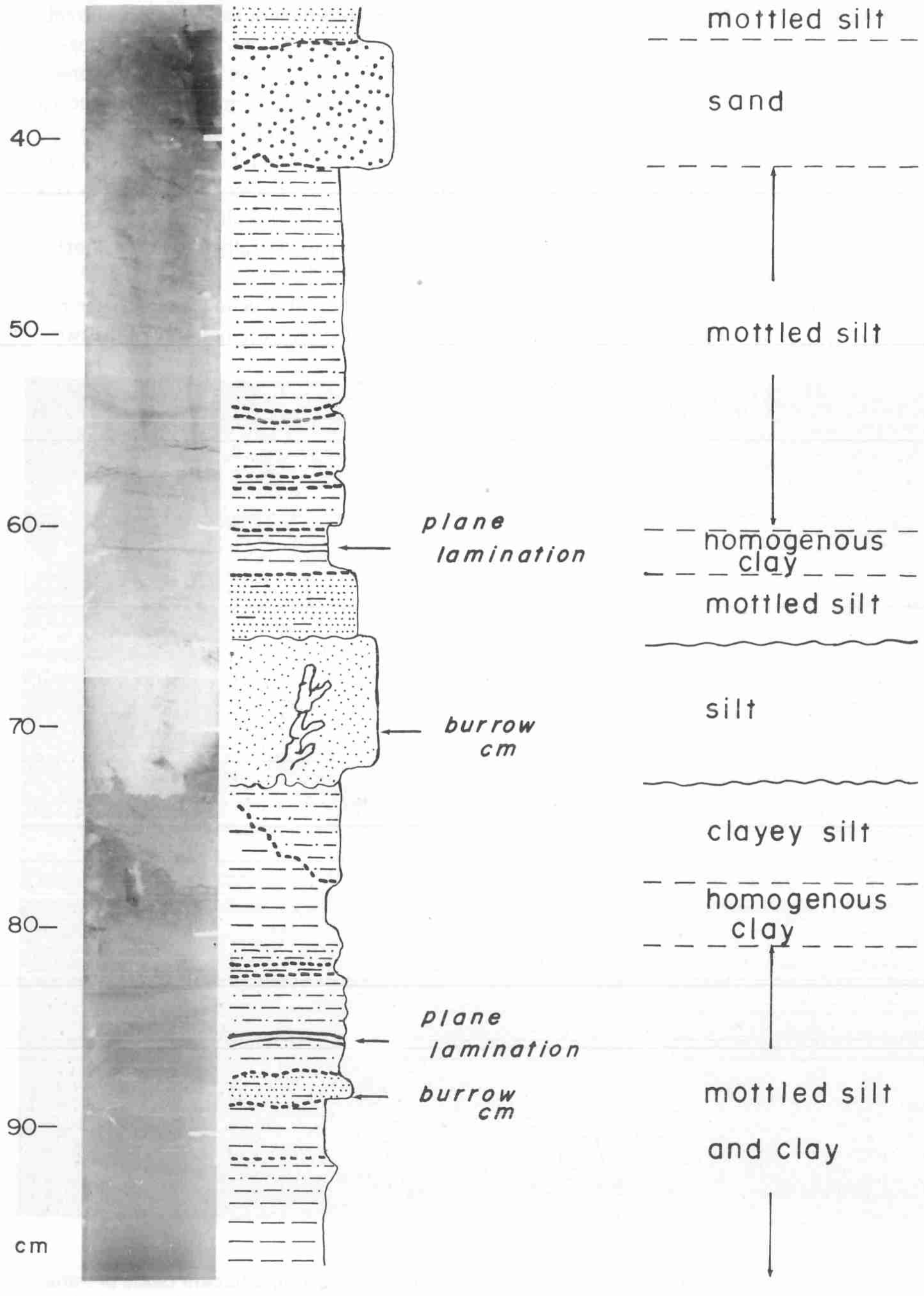

Figure 3. X-radiograph print of 1-cm-thick sediment slab, with sketch showing sediment facies and structures.

clay, mica, iron-stained minerals, rare glauconite and amber, and variable amounts of diagenetic pyrite. The chief variation between facies is the greater proportion of terrigenous material and of larger biogenic debris in the coarser facies, the greater proportion of benthonic to planktonic foraminifera in the mud, and the relative size of the planktonic compared with the other biogenic elements, which is greatest in the mud and least in the sand. Many of the biogenic elements are fragmented, and some of the grains are iron-stained.

HORIZONTAL AND VERTICAL FACIES DISTRIBUTION

From the four core transects studied (Fig. 1), our first results show both a lateral (north-south) and longitudinal (east-west) systematic variation of facies that is particularly well marked by changes in the thickness and abundance of the silt-sand beds. These show a decrease from the northern to southern flanks of the drift and from east to west in a downstream direction. There are slight perturbations in these trends, both at the extreme west of the drift, in the zone of convergence of the Mediterranean flows and the down-canyon flow, and along the valleys and their flanks. The distribution of the mottled facies is less systematic, partly because it comprises a broad mixture of coarser and finer sediments, whereas the homogeneous muds are most abundant on the crest of the drift in the zone of maximum accumulation.

This facies distribution reflects the prevailing hydrodynamic conditions at the bottom. The sand occurs where the flows are most rapid in or close to the valley floors, and it becomes less common in the intermediate zone, where the flow is more feeble and where the homogeneous mud predominates. The effects of the flow in the deeply eroded southern valley are not felt over much of the drift except at the extreme western or downstream end.

The vertical arrangement of facies is characterized by frequent changes of facies type without any *regular* order or periodicity. However, two general types of vertical succession or "sequence" can be recognized (Fig. 4): (1) a negative or reversely graded sequence from a fine homogeneous mud through mottled silt and mud of increasing grain size to a sandy silt or silty sand; and (2) a positive or normally graded sequence with the inverse arrangement of facies. The scale of these sequences (5–100 cm) and their vertical separation can both vary. They may also be incomplete, with not all the facies represented, and with sharp, erosive, or gradational contacts between the separate units.

Figure 4 is a schematic representation of the superposition of these two sequences as they are actually observed in several of the cores studied, together with the measured variation in grain size. Such a vertical succession of facies type, grain size, and nature of contacts can be interpreted hydrodynamically as having been deposited from a bottom current of steadily increasing and then decreasing velocity. Variation in sediment supply will also have some effect, although we believe that this was not important on the Faro Drift during the Holocene and late Pleistocene (Gonthier et al., 1984).

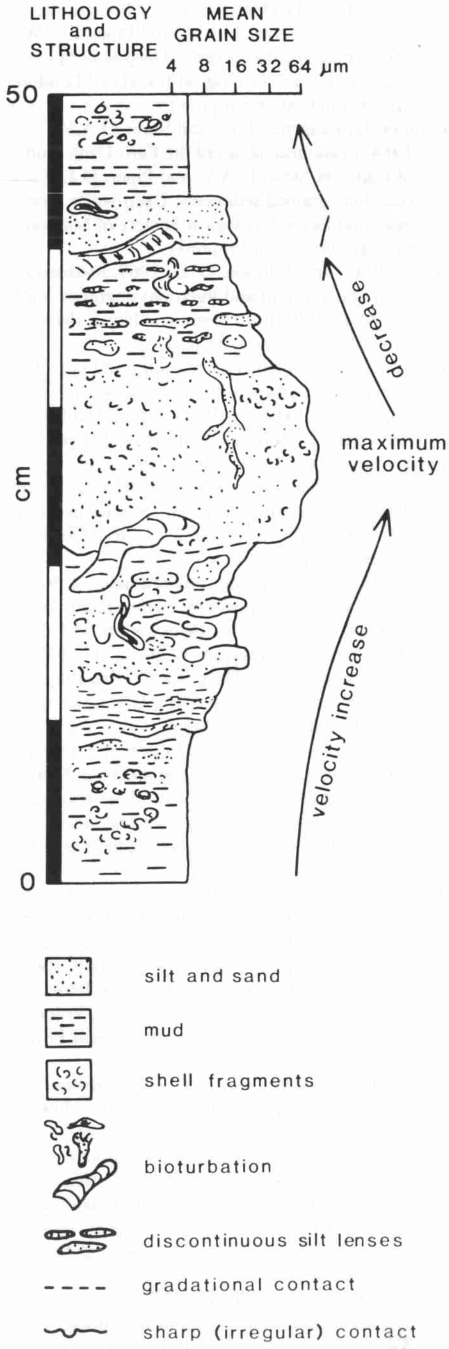

Figure 4. Schematic vertical succession of contourite facies from Faro Drift, showing typical superposition of coarsening-upward (negatively graded) and fining-upward (positively graded) "sequences" over 50 cm of section. Variation in mean grain size can be interpreted in terms of increase and then decrease in bottom current.

From the cores studied, we note that there has been continuous instability and rapid or gradual fluctuation of currents related to the Mediterranean outflow during the later Quaternary. As a first approximation, from the size of grains deposited and by comparison with other areas (Auffret et al., 1981; McCave, 1984), we suggest that currents over the drift have varied from a few centimetres per second to little over 10 cm/s, whereas the bedforms, grain size, and measured currents in the flanking channels indicate currents of up to 80 cm/s.

DISCUSSION

The regional setting of the Faro Drift as an isolated body on the continental slope northwest of the Strait of Gibraltar, its elongate morphology parallel to the margin, and the well-documented bottom flow of Mediterranean water along scoured depressions on either side of the drift provide strong evidence that the Faro Drift was constructed by bottom currents. Bottom photographs show clearly the action of strong currents along the drift margins and weaker depositional currents on the drift crest. The horizontal distribution of sediment facies at the surface, as determined from core top samples and echo characteristics, conforms with this bottom-flow regime particularly in terms of grain size and the relative proportion of sandy to muddy beds.

We are confident, therefore, that the closely spaced cores recovered from the Faro Drift are true contourites. Following detailed sedimentological study, we have recognized three contourite facies: a sandy-silty facies equivalent to previously described sandy contourites, a homogeneous mud facies equivalent to muddy contourites (Stow and Lovell, 1979; Stow, 1982), and a mottled silty-muddy facies that is gradational between the two. Collectively, but not singly, the following characteristics common to all three facies should help with identification of both recent and ancient contourites, and allow their distinction from either turbidites or hemipelagites: (1) Structures indicative of current action (lamination, sharp or erosive contacts) are present, and the types of contact within and between facies are variable. In turbidites the contacts are more regular, with sharp bases and gradational tops, and in hemipelagites there are no current-induced structures. (2) Intense or very intense bioturbation has been continuous with deposition, but with changes in trace-fossil assemblages that reflect changes in grain size or rate of sedimentation. In turbidites, bioturbation is episodic and concentrated toward the tops of beds, and in hemipelagites the burrow assemblages tend to be more constant. (3) Grain size and grain-size distribution indicate current transport (except perhaps for the finest sediment) and, commonly, a wide range of grain sizes within a single facies.

In turbidites the different grain sizes are more regularly sorted through graded units, and in hemipelagites the grain size distribution shows no evidence of current transport. (4) Sediment composition at the scale of the drift is similar, overall, for all the facies (commonly mixed biogenic and terrigenous debris), but with differences in the relative proportions of the components. Turbidites commonly introduce exotic components into a uniform background sediment, whereas hemipelagites may also show some variation in the proportions of the biogenic and terrigenous components. (5) Irregular vertical succession of facies shows partial or complete "sequences" of positive and negative grading at variable scales. This is quite different from the very regular, mainly positive grading in turbidites and from the total absence of grading in hemipelagites.

This assemblage of characteristics allows the distinction of contourites from the other main facies types in the deep-sea. In particular, the vertical succession of facies without a true rhythmic sequence and the nature of the bioturbation are markedly different from those of classical turbidites (Bouma, 1962) or of fine-grained turbidites (Piper, 1978; Stow and Piper, 1984). Similarly, for the finer grained contourites, the textural characteristics, evidence for current-induced structures, and the associated vertical "sequence" of facies should permit distinction from hemipelagites (Hill, 1981; Faugères et al., 1984) or pelagites (Jenkyns, 1978).

Finally, and perhaps most important, following correct identification of a contourite facies in a particular regional context, it may be possible to relate that facies to the intensity of the prevailing bottom current. The vertical variation of facies and grain size can be related to both bottom-current fluctuation and variation in sediment supply. On the Faro Drift it appears that both rapid and gradual fluctuations in the currents associated with the Mediterranean outflow have been relatively numerous during the late Quaternary. That this fluctuation appears to have been much more frequent than the major climatic changes is clearly significant and is now being investigated further.

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