Faro–Albufeira drift complex, northern Gulf of Cadiz

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Abstract: The northern margin of the Gulf of Cadiz is swept by Mediterranean Outflow Water between about 500 and 1000 m water depth. This warm, saline, thermohaline, bottom current attains velocities in excess of 1 m s^{-1} through the narrow and relatively shallow Gibraltar gateway, and then descends and slows as it moves towards the north and west around the Iberian margin. It was established in its present form in the latest Miocene, following tectonic re-opening of the Gibraltar gateway, and has since helped to sculpt the slope region in conjunction with downslope processes and diapiric intrusion. The principal area of contourite deposition, up to 600 m in thickness, is the Faro–Albufeira drift complex in a mid-slope setting some 30 km south of Faro. This comprises an elongate low-mounded drift (Faro–Albufeira) and adjacent broad sheeted drifts (Faro and Bartolomeu Dias Planaltos), flanked and partly dissected by deep, erosional, bottom-current channels and buried channels. The seismic character is one of progradational-aggradational depositional units with laterally extensive sub-parallel reflectors, widespread discontinuities and a large-scale cyclicity in seismic facies. The upper 10 m of cored section comprises muddy, silty and sandy contourites of mixed terrigenous and biogenic composition, that show small-scale cyclicity in grain size and associated sedimentary features. Rates of accumulation varied from < 1 to 14.5 cm ka^{-1} (cores), and 3.5 to 29.5 cm ka^{-1} (seismics). The large and small-scale cyclicity noted can be related to fluctuation in bottom current velocity related to climate and sea-level changes, although the precise correlation between these events remains uncertain.

The Faro–Albufeira drift complex is located in a mid-slope setting on the northern margin of the Gulf of Cadiz. The influence of Mediterranean Outflow Water (MOW) on contourite drift construction along this margin was first recognized by Vanney & Mougenot (1981) and Mougenot & Vanney (1982), who distinguished a series of relatively small elongate drifts south of the Iberian peninsula, including the Faro and Albufeira Drifts. Detailed sedimentological and seismic studies of the Faro Drift were then carried out in the early 1980s (Faugères *et al.* 1984; Gonthier *et al.* 1984; Stow *et al.* 1986, amongst others). The now standard contourite facies model first emerged from this work, by comparing Faro Drift contourites with those of other North Atlantic contourites in particular (Stow 1982; Stow *et al.* 1986). These early studies also characterised growth of the Faro Drift by progradation and aggradation at the northern end of the Faro–Cadiz Planalto (e.g. Faugères *et al.* 1985*a*, *b*). This platform area, together with the neighbouring Bartolomeu Dias Planalto, we now interpret as a broad sheeted drift, and describe the whole as the *Faro–Albufeira drift complex* (Table 1, Fig. 1).

This contribution brings together a range of different datasets that have been collected over the past 20 years in the Faro–Albufeira region (Figs 2 & 3). There is a dense network of single-channel and multichannel seismic reflection profiles across the region, that can be correlated with oil company boreholes drilled on the adjacent shelf and slope. Analysis of these data is currently in progress, with some abstracts and preliminary papers recently published (e.g. Llave *et al.* 2000, in press). Extensive sediment data were gathered in 1982 by the French oceanographic vessel, *RV Noroit*, including 300 km of 3.5 kHz seismic profiles, 24 piston/gravity core sites, and five sites for seafloor photography. Most of these data have been published previously and are referred to as appropriate. Considerable research activity continues at present in the Gulf of Cadiz in general, including swath bathymetric and deep-tow sidescan sonar mapping, mainly to the south of our present study area, as well as interpretation of a suite of giant piston cores collected in 1999 by the *Marion Dufresnes* research vessel.

Table 1. *Principal characteristics of the Faro–Albufeira Drift Complex*

Location	northern margin of Gulf of Cadiz, eastern N Atlantic
Setting	mid-slope setting, 500–900 m water depth
Age	latest Miocene/Pliocene to Recent
Drift type	elongate mounded drift and sheet complex closely associated contourite/turbidite channel network
Dimensions	mounded drift 40–80 km × 15–20 km, max 600 m thick, but only low relief (< 50 m) above the adjacent sheeted drift sheeted drift 60–80 km × 40–60 km, max 400–500 m thick
Seismic facies	progradational to aggradational seismic depositional units, laterally extensive, low-high amplitude sub-parallel reflectors, widespread discontinuities – erosional to non-depositional, large-scale cyclicity in seismic facies characteristics
Sediment facies	muddy, silty and sandy contourite facies, mixed terrigenous (dominant) and biogenic composition, small-scale grain-size cyclicity evident through top 10 m cored

Geological and oceanographic setting

Geological framework

The Gulf of Cadiz, located in the eastern sector of the central North Atlantic, forms a deeply concave indentation between the African and European continents (Fig. 1). The Faro–Albufeira drift complex is located on the slope above the transition between the Gloria transform zone, which marks the African–Eurasian plate boundary in the Atlantic realm, and the western front of the Betic-Rif orogenic belt, represented by the Gibraltar Arc. Kinematic studies of the African and Eurasian plates (Dewey *et al.* 1989; Olivet 1996) show that the area was situated in a N–S convergence setting from the Late Cretaceous to the Tortonian.

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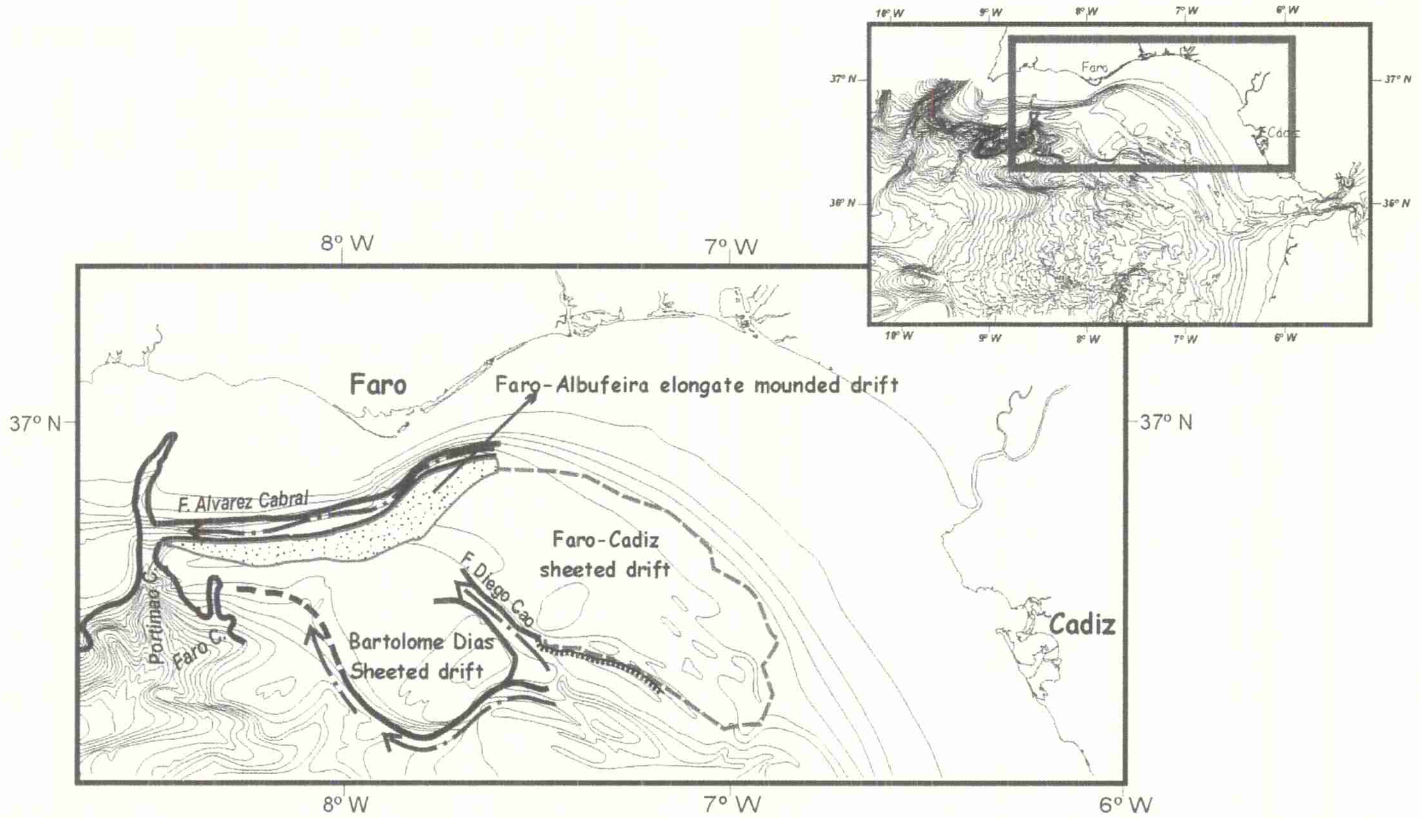

Fig. 1. Faro–Albufeira drift complex location maps. General location on the south Iberian continental margin, Gulf of Cadiz, together with regional bathymetry. Detailed inset shows location and nomenclature for parts of the drift complex (outline as dashed line). Stippled region shows single mounded elongate drift form recognised in this study, formerly named separately as the Faro and Albufeira drifts.

From Late Miocene to the present, the convergence between Africa and Eurasia has become a transpressive NW–SE regime (Argus *et al.* 1989) (Fig. 4).

Evolution of the Gulf of Cadiz is marked by three successive phases (Somoza *et al.* 1999) (Fig. 5): (1) construction of a passive margin of Mesozoic age, related to opening of the North Atlantic; (2) development of a compressional regime during the Late Eocene to Early Miocene, related to the closure of the Tethys Alpine sea; and (3) the Miocene foredeep evolution, associated with formation of the Betic–Rif orogen and opening of the Western Mediterranean basin. This stage was characterized by collision of the Betic–Rif accretionary front with the passive margins of the Iberian Peninsula and Africa, which involved the emplacement of a large tectonic olistostrome over the Gulf of Cadiz margin during the Middle Miocene. Since the Late Tortonian, oblique convergence and extensional collapse have progressively given way to more stable conditions during the Upper Pliocene and Quaternary (Maldonado & Nelson 1999; Maldonado *et al.* 1999).

Drift development is believed to have begun in the latest Miocene to early Pliocene, at first smoothing and covering a topographically irregular surface, as well as being influenced by early tectonic activity in the region. Diapirism is still active throughout the Gulf of Cadiz, with both salt and mud diapirs showing surface expression and breakthrough.

Oceanographic setting

The circulation pattern in the Gulf of Cadiz is presently characterised by an exchange of water masses through the Strait of Gibraltar, here referred to as the Gibraltar gateway (Fig. 6). This exchange involves flow into the Atlantic Ocean of Mediterranean Outflow Water (MOW) near the bottom, and an influx to the Mediterranean of Atlantic water (AI) at the surface. MOW is warm (>13°C) and saline (>36.4‰) with a relatively low oxygen content (4.1–4.6 ml l^{-1}), whereas AI is a turbulent, less saline cool-water mass (Ambar *et al.* 1976, amongst others). The Gibraltar gateway has controlled the dynamics of water mass exchange over time, modulating that exchange between the Gulf of Cadiz and Alboran Sea and amplifying the Quaternary high-frequency sea-level changes noted in the Alboran Sea basin.

The MOW itself comprises two different water masses that shallow and mix as they pass through the Gibraltar gateway (Fig. 6): Mediterranean Intermediate Water (MIW) and Mediterranean Deep Water (MDW). MIW is generated in the Western Mediterranean basin, flows through the Alboran Sea, bifurcating around the Alboran Islands, where it attains a velocity of about 5–10 cm s^{-1} around the base of the Spanish continental margin. MDW is generally more sluggish in the Mediterranean, with a velocity of about 2 cm s^{-1} around the base of the African slope, before rising towards the sill of Gibraltar gateway (Lacombe & Tchernia 1972; Millot 1987; Parrilla & Kinder 1987; Perkins *et al.* 1990). MOW is constrained as it passes through the Gibraltar gateway at a water depth of as little as 200 m, and hence reaches a peak velocity measured at approximately 300 cm s^{-1}, decreasing to 180 cm s^{-1} immediately west of the gateway.

MOW then descends, spreads out and is deflected northwards by the Coriolis effect, forming a strong bottom current moving at a water depth of 300–1500 m along the Iberian slope (Fig. 6). There is an overall decrease in velocity, concomitant with a northward and westward broadening and deepening of the water mass, from around 30–40 cm s^{-1} in the vicinity of Faro Drift to 10–20 cm s^{-1} at the west end of the Gulf. In places it divides into several branches due to the influence of bottom topography, and is funneled along deep submarine canyons and valleys (Madelain 1970; Caralp 1988; Ochoa & Bray 1990; Nelson *et al.* 1993, 1999; Beringer & Price 1999). The interaction of MOW has led to

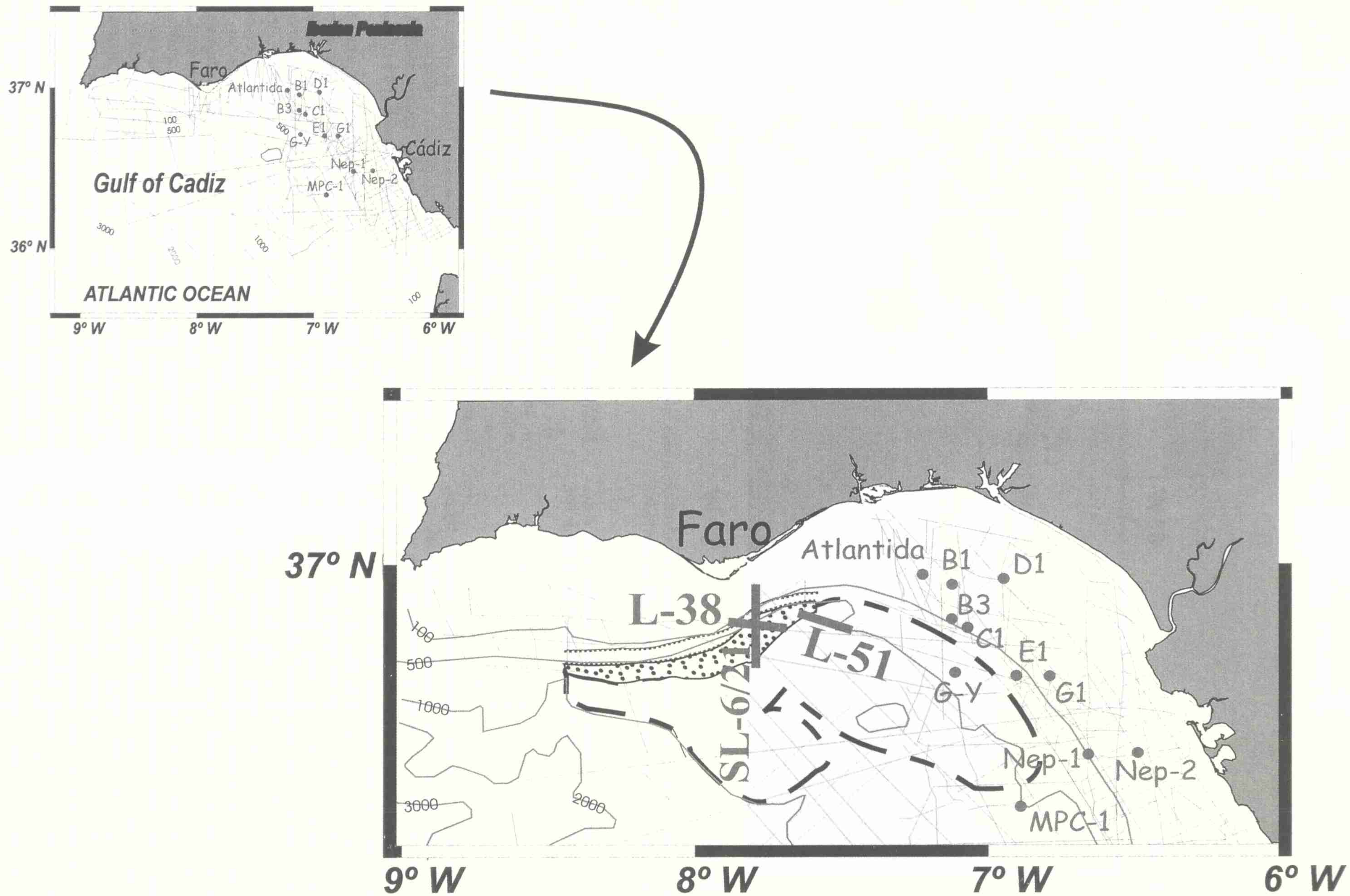

Fig. 2. Seismic and borehole database for the Gulf of Cadiz and study areas. The highlighted portions of L-38 and L-51 are illustrated in Figure 11.

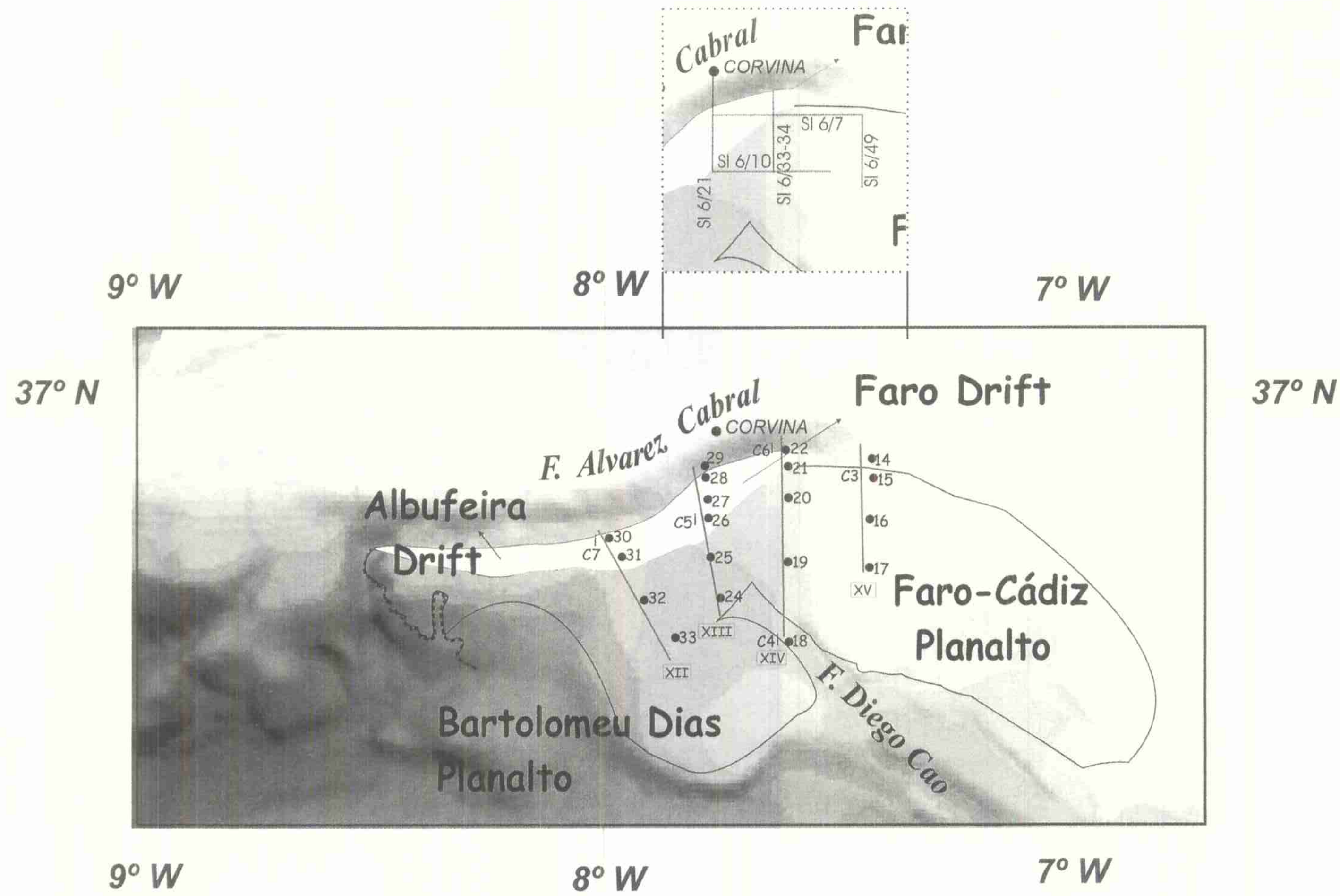

Fig. 3. Database used in Faugères *et al.* (1985*a*, *b*) and Stow *et al.* (1986). (**A**) seismic profiles and location of the Corvina borehole, used for stratigraphic calibration. (**B**) cores (28), camera stations (C4) and 3.5 kHz profiles (XIV).

construction of a series of contourite drifts (Gonthier *et al.* 1984; Nelson *et al.* 1993, 1999). Atlantic Surface Water flows towards the SE above MOW.

Palaeoceanography

Reconstruction of the evolving palaeocirculation pattern during the period of drift growth is still a matter of considerable discussion. Careful decoding of seismic and borehole data through the drifts may help resolve this problem in the future, but our current knowledge is largely theoretical. We can assume that the modern circulation pattern started to develop after the re-opening of the Gibraltar gateway at the end of the Messinian salinity crisis in the Mediterranean (Nelson *et al.* 1993). During the Lower Pliocene, an estuarine-type water-mass exchange though the Gibraltar gateway (inflow of Atlantic intermediate water and outflow of Mediterranean surface water), may have developed as a response much more humid conditions in the Mediterranean region than at present (Thunell *et al.* 1991). However, marked global cooling from around 2.4 Ma triggered a shift to more arid conditions in the Mediterranean region, resulting in an anti-estuarine water-mass exchange between the Mediterranean and the Atlantic similar to the present-day situation (Loubere 1987; Thunell *et al.* 1990, 1991). Since 2.4 Ma, the water-mass exchange is believed to have undergone significant variations in relation to climatic and sea-level changes, though the precise nature and timing of these changes remains unknown (Huang & Stanley 1972; Diester-Haas 1973; Grousset *et al.* 1988; Vergnaud-Grazzini *et al.* 1986; Caralp 1988, 1992; Nelson *et al.* 1993).

Bathymetry

The Gulf of Cadiz has a variable width shelf (15–40 km) with a shallow gradient (0.32–0.2°), and a shelf-break located at a water depth of 140–200 m (Figs 1 & 7). Beyond this, the physiography is quite complex, with some portions of the slope gradient being relatively steep (from 2–8°), but overall showing a low gradient outward bulge with a slope of around 1.5° in the upper part to 0.5° in the lower parts. This general profile is broken by broad platform areas, covered by sheeted and mounded drifts, downslope and alongslope directed channels, and local diapiric relief.

The Faro–Albufeira mounded drift extends in a generally E–W direction along the northern margin of the Gulf, and increases in crestal depth from about 500 m in the east to 700 m in the west. Actual relief above the adjacent sheeted drift platform region to the south is everywhere less than 50 m, though the depth to the northern channel varies up to 220 m. The Faro Canyon was originally believed to cut across the Faro Drift at its western extremity, thereby separating it from the Albufeira Drift. However, more detailed bathymetry now shows, at most, a slight bathymetric dip in the longitudinal profile of the combined drift system, such that the Faro Canyon appears to extend only from its southern flank. The true western extremity is marked by the well-developed Portimao Canyon. To the north, it is bounded by a slightly sinuous valley, the Alvarez Cabral channel, that deepens from zero relief at its upstream end to a maximum mid-drift relief of around 220 m. To the south and east (or upstream end) the drift merges with the Bartolomeu–Dias and Faro–Cadiz platform area that is deeply incised by the Diego Cao channel, and flanked to the south by the even deeper Guadilquivir channel.

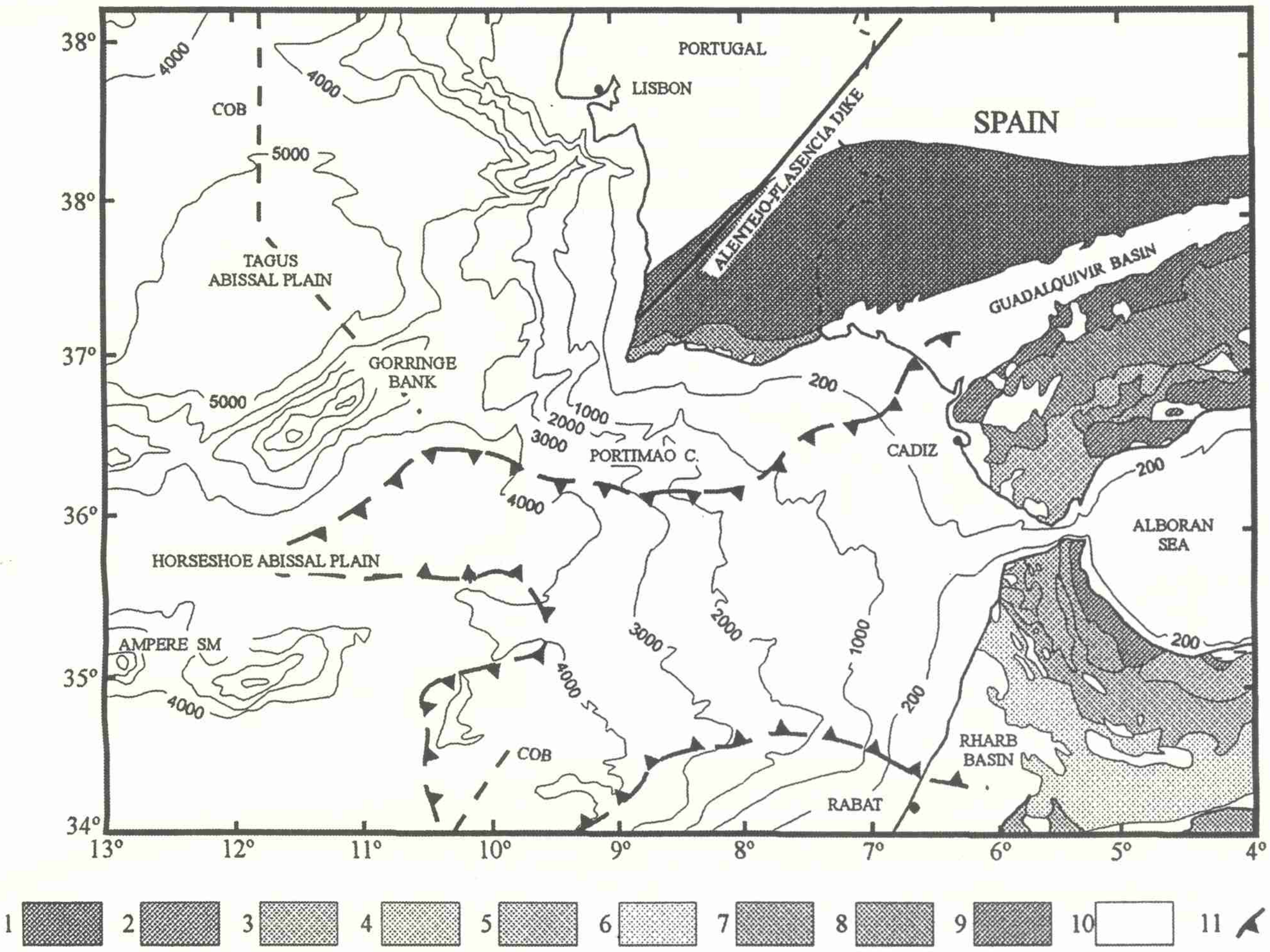

Fig. 4. Geological setting and simplified bathymetry of the Gulf of Cadiz and surrounding region. 1, Hercynian Massif; 2, Betic-Rif Internal Zones; 3, Complex dorsal; 4, Fysch units; 5, Meso- and Intra-Rifian units; 6, Pre-Rifian units; 7, Betic External Zone; 8, Mesozoic palemargins of Iberia and Africa; 9, Guadalquivir olistostrome; 10, Neogene sedimentary basins; 11, Olistostrome front. COB, continent-ocean boundary; bathymetry in metres. (After Maldonado *et al.* 1999).

Stratigraphic context

We can ascertain the principal stratigraphic events within the Gulf of Cadiz by careful correlation of seismic profiles with a number of oil company boreholes now drilled into shelf sediments north of our study area (Faugères *et al.* 1985*a*; Maldonado *et al.* 1999; Llave *et al.* 2000) (Figs 8–10). One example of this correlation is shown in Figure 10, in which seismic profile SL 6-21 has been correlated with the Corvina borehole (from Faugères *et al.* 1985*a*).

The top of the more highly tilted basement rocks (Jurassic–Cretaceous) occurs close to the Cretaceous–Tertiary boundary and is marked by a generally weak reflector (our *reflector K*), only notable because it marks a clear angular unconformity. Overlying Palaeogene sediments have also been affected by tectonic movements and are marked at their top by a second unconformity, which shows less discordance but a stronger and more distinct reflector (our *reflector O*). This is the top of the acoustic basement noted by Faugères *et al.* (1985*a*) and corresponds to an important late Oligocene unconformity, pre-Aquitanian and post-Stampian in age. A third important basin-wide discontinuity marks the onset of drift development in the region (our *reflector M*) and can be correlated with further tectonic adjustments in the Gulf which resulted in re-opening of the Gibraltar gateway. This is dated to within the latest Miocene Messinian stage.

The Faro–Albufeira drift complex, therefore, began to grow in the south during the late Messinian, with major drift accumulation and progradation to the north and west during the Plio–Quaternary. Sequence stratigraphic analysis through the drift complex allows recognition of six third order sequences above *reflector M*, and further subdivision of each of the two Quaternary sequences into at least four fourth order sequences. These are described below under *Seismic Characteristics* and shown in Figure 8.

Dating and correlation of the 19 cores recovered so far from the Faro–Albufeira drift complex is documented by Stow *et al.* (1986) amongst others, based on studies of pelagic foraminifers and oxygen isotopes (Fig. 9). The dating is not everywhere as precise as might be expected, probably as a result of extensive bottom current reworking, but the onset of the third cold phase (W3) of the Wurmian glacial stage (isotopic stage 2) is clearly present in most cores. This can be dated to 28 000 Ka. Several of the cores show significant hiatuses, and in one core from the northern valley there is a thin Holocene veneer over harder, more compacted sediment that could not be dated.

Seismic characteristics

The present seismic database for the area (Fig. 2) includes medium resolution (Sparker 3, 4 and 7.5 kJ, and Airgun), high resolution (Geopulse 300 and Uniboom), and very high resolution (3.5 kHz) seismic profiles. The maximum depth of penetration to *reflector O* beneath the drift complex is 1.5 s TWT (equivalent to about 1.1–1.4 km of section), whereas maximum thickness of the drift itself is about 0.8 s TWT to *reflector M* (equivalent to around 600–650 m).

The pre-drift unit (Unit I of Faugères *et al.* 1985*a*; Fig. 10) is

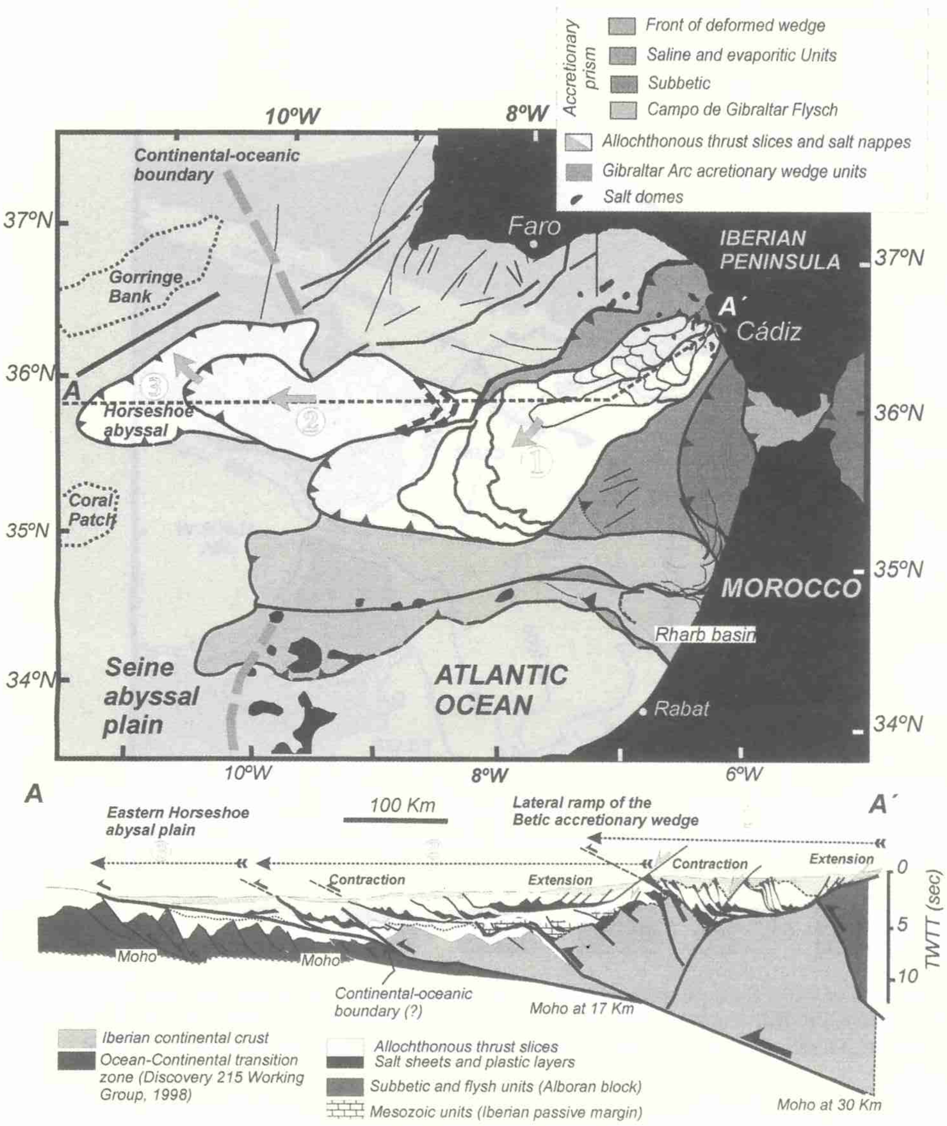

Fig. 5. Tectonic setting of the Gulf of Cadiz (after Somoza *et al.* 1999), showing accretionary prism units, inferred allochthonous olistostrome mass, salt nappes and diapirs.

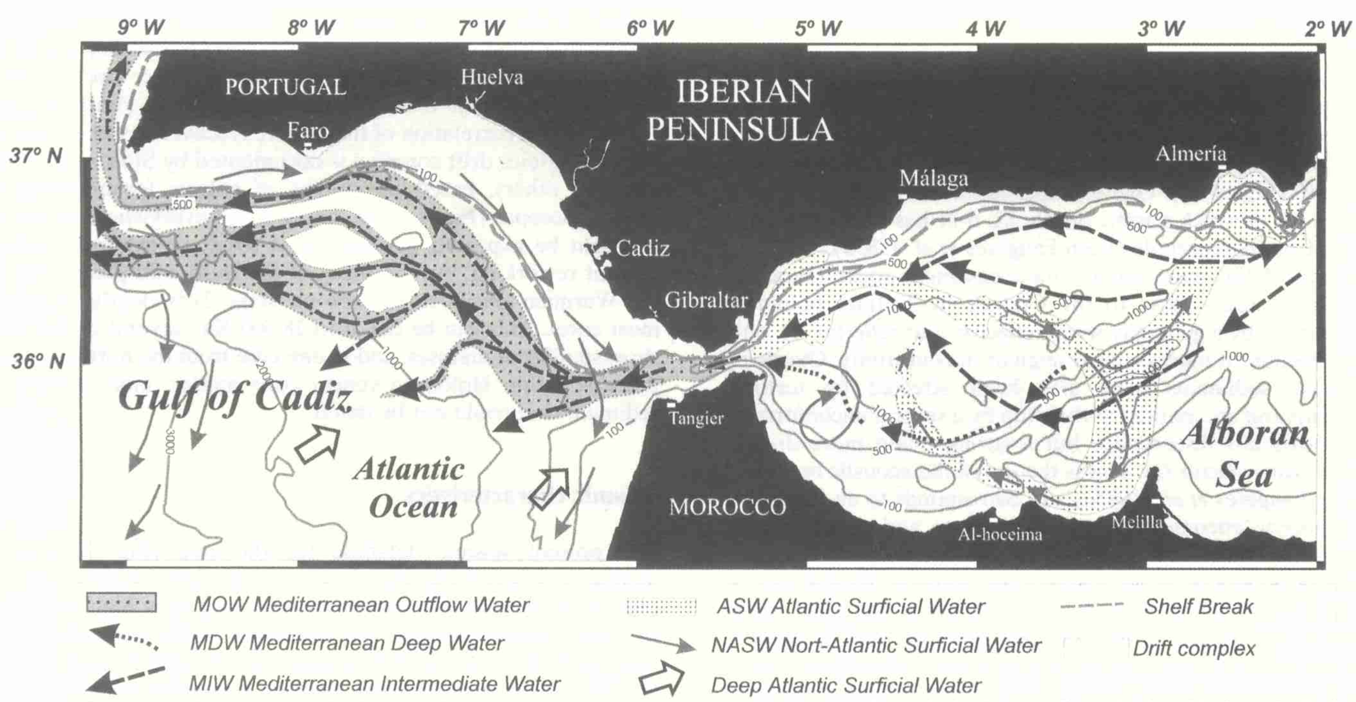

Fig. 6. Oceanographic setting showing deep-water and surface-water circulation in the Alboran Sea, through the Gibraltar gateway and in the Gulf of Cadiz.

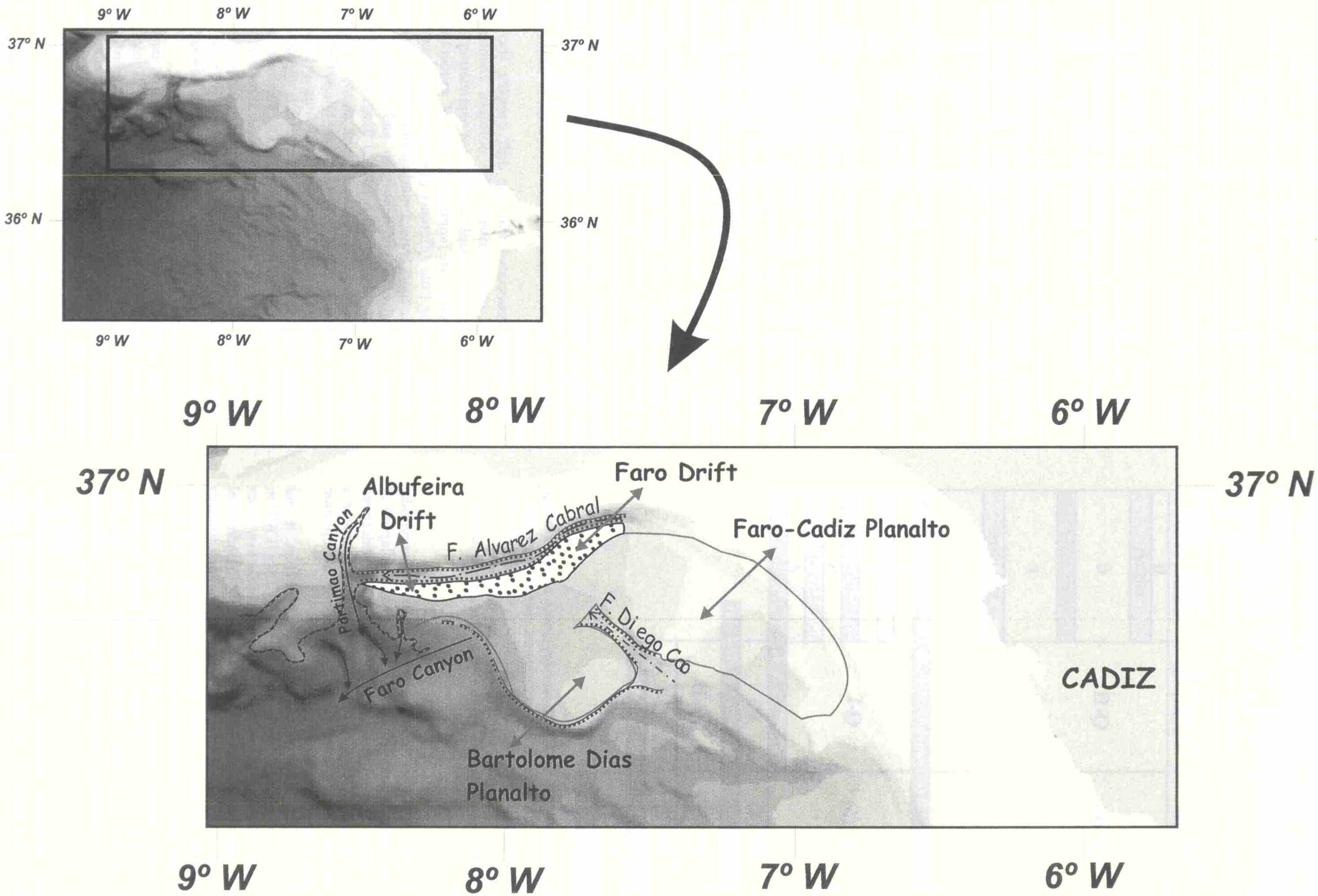

Fig. 7. Regional bathymetry for the Gulf of Cadiz and study area.

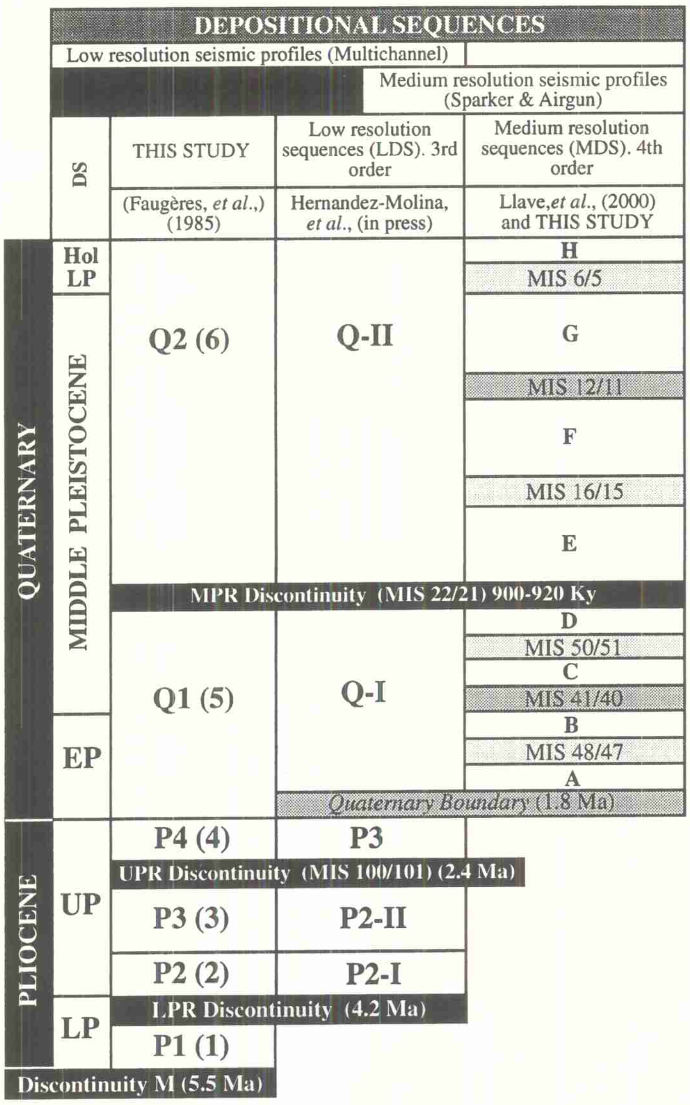

Fig. 8. Drift stratigraphy for the Plio–Quaternary section based on seismic analysis of low and medium resolution multichannel, sparker and airgun profiles. Nomenclature for this study (P1–4, Q1–2) compared with that of Faugères *et al.* (1999) and Llave *et al.* (2000). Principal and minor discontinuity surfaces shown together with approximate age and isotopic stage (MIS).

between 0.3 and 0.6 s thick, and shows generally low-amplitude, irregular and discontinuous reflectors. There is some onlap fill of small depressions and an overall smoothing of the underlying irregular topography. *Reflector O* at the top of this unit marks a regular, distinct, discontinuity surface; it is a high-amplitude reflector with a notable basinward dip.

The drift complex (Unit II of Faugères *et al.* 1985*a*; (Figs. 10 and 11) is generally around 0.5 s to a maximum of 0.8 s TWT in thickness (400–650 m). It shows more continuous reflectors, from low to high amplitude, aggradational to sigmoid progradational geometry, with onlap to downlap reflector terminations towards the north. As the drift has migrated against and along the northern slope there has been a progressive increase in relief of the Fosse Alvarez Cabral channel, coupled with its upslope migration and some erosion of the continental slope. In more detail, six distinct third order seismic sequences can be identified within the drift complex: P1–4 of inferred Pliocene age, and Q1–2 of Quaternary age. From base to top, these are described briefly below.

P1 Sequence: moderate amplitude, continuous reflectors, oblique progradation then pinching-out and becoming less distinct to the north.

P2 Sequence: moderate amplitude, continuous reflectors; more or less constant thickness, transgressive over *P1* with apparent erosion by the northern channel; slight undulations reflect last phase of tectonic instability in the area.

P3 Sequence: moderate amplitude, continuous reflectors, showing oblique progradation to the north, but overall regressive with respect to *P2*; first sign of low relief drift-channel geometry.

P4 Sequence: moderate to high amplitude reflectors sandwich a zone of low amplitude; thickness relatively constant, but progradation more marked with accentuation of the mounded drift relief, a steeper northern slope and distinct channel form.

Q1 Sequence: alternation of zones of moderate-high and low amplitude reflectors, showing marked progradation and thickening from south to north; downlap reflector terminations into the northern channel, which shows evidence of non-deposition and erosion alternating with periods of accumulation.

Q2 Sequence: very similar to *Q1* showing strong sigmoid progradational geometry coupled with aggradation, and an internal cyclicity of zones of high to low amplitude reflectors.

The cyclic alternation of low to high reflectivity couplets, noted in *P4*, *Q1*and *Q2*, can be considered as fourth order sequences (A to H in Figs 8 & 11). *Q1* and *Q2* are separated by a particularly high amplitude reflector, that is locally erosive, and that can be correlated with the Mid-Pleistocene Revolution at 900–920 ka (see later discussion). This is referred to as *reflector MPR*.

Diapirism has been active in the Gulf of Cadiz since at least the Miocene, and is still active today as witnessed by locally elevated seafloor and exposure of both mud and salt diapirs. These occur as small isolated more or less circular features, more irregular large diapiric zones and in linear trends. In all cases they have had a marked effect on bottom current flow and hence on sediment distribution observed in seismic records. The crestal regions above diapiric intrusions are subject to generally reduced sedimentation and erosion, locally with thicker drift accumulation and erosive moats. Where breakthrough and exposure of the soft diapiric material has occurred, then a crestal depression or linear channel may be sculpted.

The channels associated with the drift complex also show a range of seismic characteristics. The northern channel shows strong lateral migration coupled with basal aggradation. Channel sub-bottom reflectors are continuous and of moderately high amplitude, showing little difference in seismic facies from those of the adjacent drift, apart from a marked thinning of depositional sequences indicative of non-deposition and erosion. There is strong incision into the northern (slope) flank, as well as much evidence of slumping. The southern flank shows a prograding deposition and less slumping. The southern (Diego Cao) channel is more markedly erosive, though diminishing in relief as it debauches onto the Batolomeu Dias platform. It appears to have developed along a linear trend of diapirs. The Portimao canyon in the west is a typically incised, downslope directed, turbidity current channel system. The Faro canyon may have been similar in origin, but has subsequently been buried by drift infill. Smaller filled channels of unclear origin are observed in seismic records towards the western end of the Faro drift (Fig. 11).

3.5 kHz seismic profiles have been studied from parts of the Faro Drift (Faugères *et al.* 1985*a*, *b*; Fig. 3). These show a maximum penetration up to about 40 m and three distinct echo-facies: (a) a strong, thick bottom reflector and no clear sub-bottom reflectors; (b) a moderately strong bottom reflector over less distinct irregular sub-bottom reflectors; and (c) a weaker bottom reflector with multiple, sub-parallel sub-bottom reflectors. Broadly, these are distributed according to inferred bottom current intensity – type (a) in the channels, type (b) on the flanks

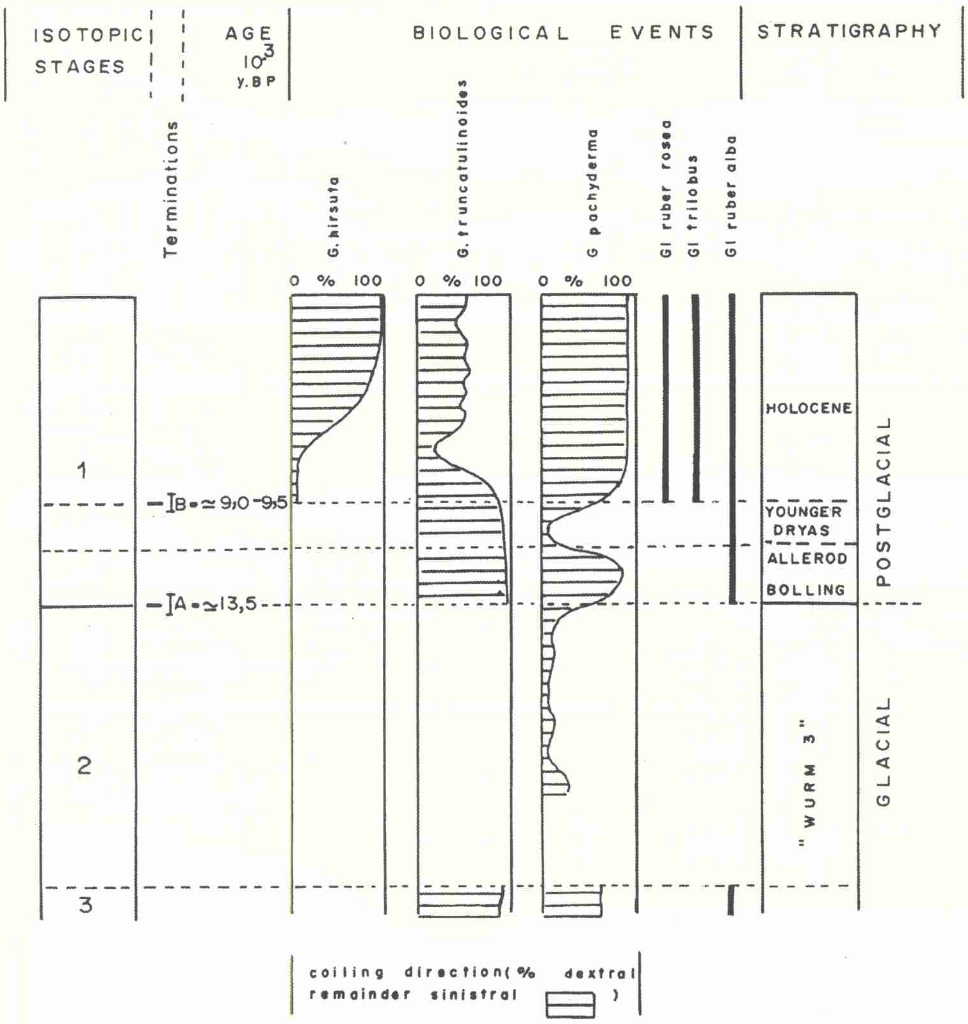

Fig. 9. Drift stratigraphy for the late Quaternary cored section based on biostratigraphic and oxygen isotope studies. (After Stow *et al.* 1986).

and type (c) over the main part of the drift complex. Where sub-bottom reflectors are apparent, these reveal the distribution of the most recent (late Quaternary–Holocene) sedimentation over this part of the drift complex, as well as its overall morphology.

Profile XV at the proximal end of the drift shows minimal development of the Alvarez Cabral channel at the foot of the continental slope and a low crestal portion of the drift that slopes gently down to the more extensive Faro platform. Diapiric highs occur in the central portion and at the southern edge of the platform, adjacent to a deeply incised Diego Cao channel, and in each case show marked reduction in sediment thickness over the diapir itself.

Profiles XIV and XIII, lying respectively 15 and 30 km to the west, reveal a well developed northern channel, a broad low-mounded drift relief and progressive decrease in depth and erosion of the southern Diego Cao channel. By *Profile XII*, the southern channel has completely disappeared and drift relief is relatively low. All three profiles show that the main site of deposition has been over the crest and northern flank of the drift, progradation has occurred towards the north, and minor erosion or non-deposition has taken place over the southern flank.

Sediment characteristics

Sea-floor photographs

A series of bottom photographs serve to show the principal variation in seafloor characteristics across the drift and in the adjacent valleys (Fig. 12). The northern valley shows a hard heterogeneous substrate with distinct current lineation of gravel material at its downstream (western) end. At its upstream end, the substrate is more muddy and bioturbated, with scattered shell fragments and other coarse debris, as well as local colonies of crinoids and crabs. Drift top sites are generally muddy and bioturbated, either with no evidence for current activity or showing weak current lineation and mud-draped ghosts of ripples. The southern valley shows much evidence of recent current activity, with a variety of asymmetric ripple and megaripple forms on a bigenic sandy substrate. In every case the orientation of the bedforms indicates bottom current flow consistent with that due to the MOW.

It is important to note that in none of the cores taken at sites showing photographic evidence of current activity were any traces of current structures preserved. Continuous and active bioturbation had served to completely destroy such primary sedimentary structures.

Sediment facies

The sediments of the Faro–Albufeira drift complex are nearly all interpreted as contourites. The principal facies include: very fine-grained muddy contourites, mottled silty-muddy contourites, and silt to fine-sand contourites (Fig. 13). These are arranged in somewhat irregular coarsening-up to fining-up cyclic sequences, mostly from 0.25 to 1.5 m in thickness. The chief distinguishing features of these contourites are:

- Rarely preserved primary sedimentary strutures, including poorly developed lamination and sharp, erosive contacts;

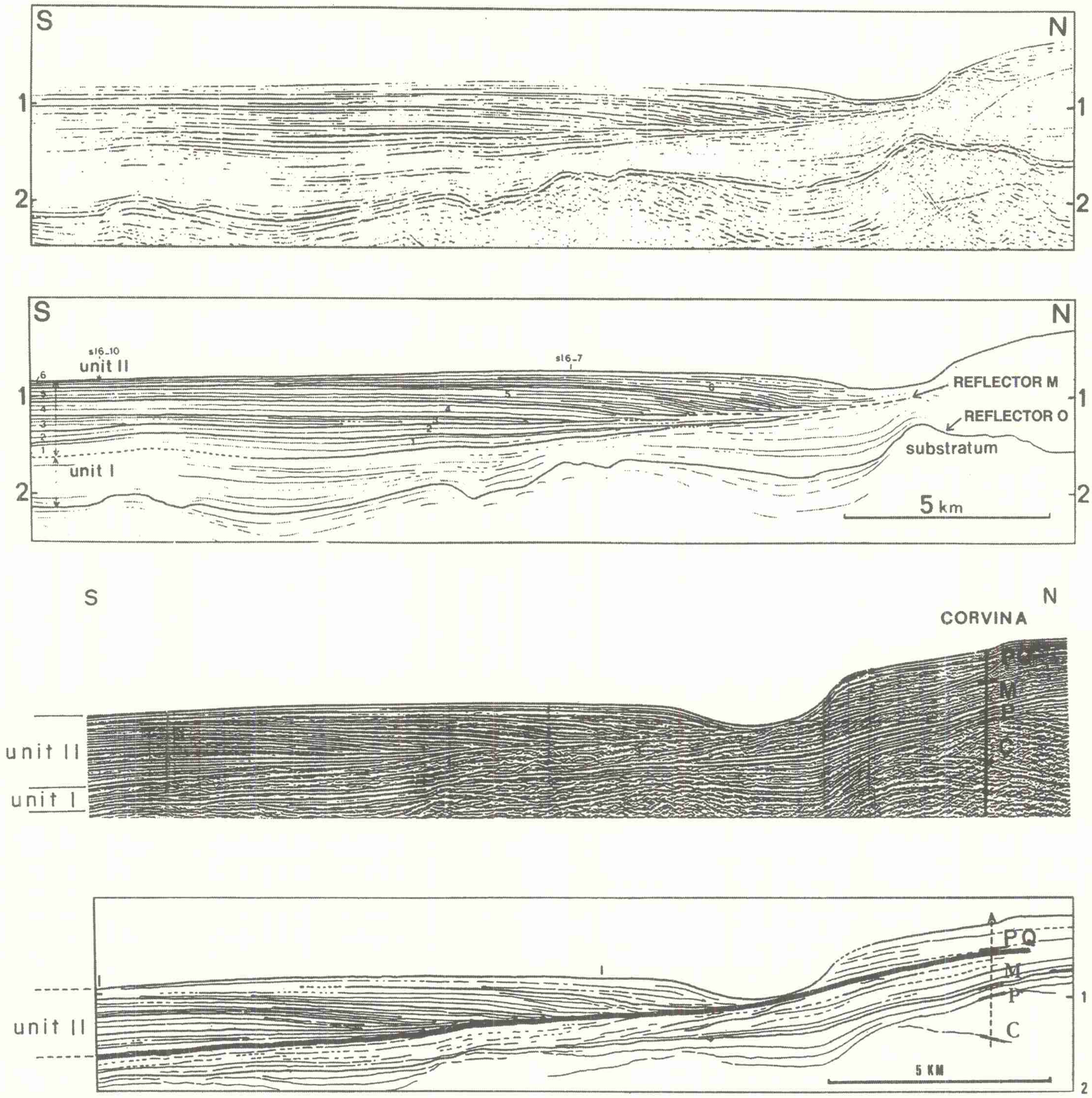

Fig. 10. Seismic reflection (multichannel) profiles (N-S orientation) from proximal and medial portions of the Faro–Albufeira drift (from Faugères *et al.* 1985*a*, Stow *et al.* 1986). (**A**) part of Line 6–34 with interpretation; (**B**) part of line 6–21, with interpretation and borehole correlation. See Figure 3 for profile location.

- Intense and pervasive bioturbation that has been continuous with deposition, and that shows ichnofacies variation associated with grain size changes in facies;
- Generally fine grain size (mean mostly < 63 μm) and poor to moderate sorting, with sandy silts showing slightly better sorting and grain-size distributions indicative of current influence;
- Mixed biogenic-terrigenous composition in variable proportions, with 20–50% biogenic carbonates (planktonic and benthonic foraminifers, bivalves, ostracods) and 50–80% compositionally immature siliciclastic material; fragmentation of biogenics and iron-coating of grains are common.

Turbidites were recovered from slope core 29 and from the mouth of the northern valley, where they constitute 20% and 40% respectively of the succession. On the drift itself, a single thin turbidite is present in each of cores 31 and 32, representing only 2% of the section. All turbidites are very distinctive in terms of coarser grain size at their base, normal grading, primary structures, and a different more terrigenous composition.

The distribution of these principal facies, together with grain size variation, is shown in Figure 14 for all four drift transects currently available. The vertical succession of facies in each of the cores is characterized by a repetition of cyclic contourite

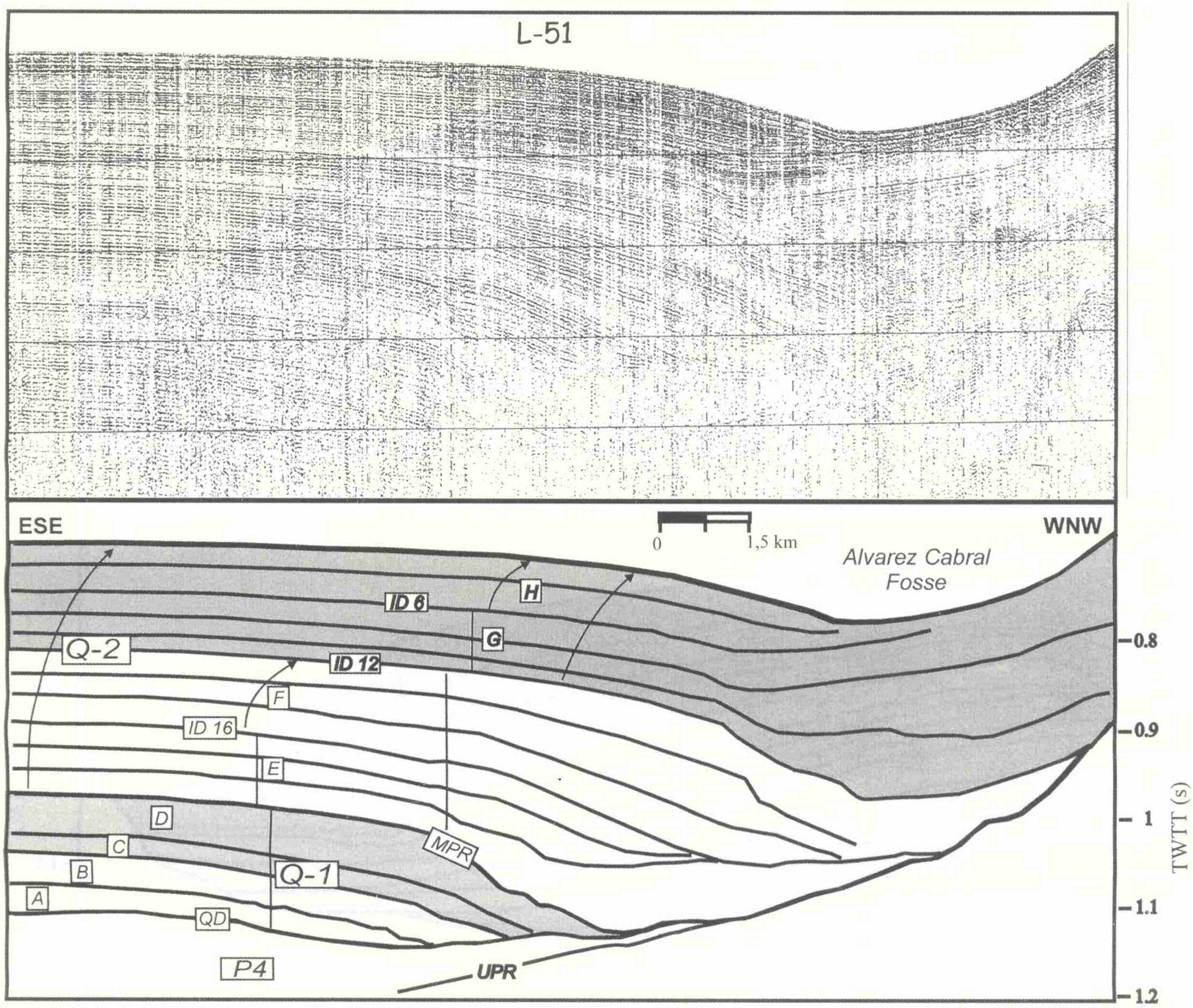

Fig. 11. Seismic reflection (sparker) profiles (approximate E-W orientation) from proximal and medial portions of the Faro–Albufeira drift (from Llave *et al.* 2000). (**A**) Part of Line L-51 with interpretation; (**B**) Part of Line L-38 with interpretation. See Figure 2 for profile location.

sequences, which appear somewhat irregularly distributed due to variation in thickness and completeness of the sequences. However, three cycles in the upper 3 m of section are apparent in many of the cores, and the sandy silt peaks of these cycles are referred to as *Peaks I, II and III*. The topmost *Peak III* occurs at the present sediment surface, so that particular 'cycle' comprises only the lower coarsening-up sequence. These peaks are correlateable over many of the cores and can be dated approximately, by biostratigraphic and isotopic means, as 14 000–15 000, 9 000–10 000 and 0–2 000 a^{-1} BP. In most cores, there is a further less well developed grain size peak at around 28 000 a^{-1} BP, whereas in the valley cores to the south there are several earlier undated peaks that appear to correspond only with muddy contourites on axis of the drift.

Sedimentation rates and hiatuses

The presence of hiatuses is noted in about 40% of the cores recovered from the drift complex, including both drift margin/channel sites as well as drift top sites. Where it has been possible to date these cores, the average sedimentation rates for the past 28 000 years are extremely low, i.e. generally < 1.5 cm ka^{-1} and everywhere < 4 cm ka^{-1}. For the other sites, there is a wide range of rates from about 3 to 15 cm ka^{-1} (Table 2).

Based on seismic records and the seismic depositional units identified (Fig. 8), we can infer accumulation rates for the past 5.5 Ma for both the mounded drift and sheeted drift sections (Table 3). Without applying any correction for increased sediment compaction with depth, mean accumulation rates for the mounded drift are seen to have increased markedly through time, from 35 m Ma^{-1} in the late Pliocene to an average of 103.5 during the early Quaternary, and to 295 m Ma^{-1} in the latest Quaternary. This might be expected from the rapid progradation that has occurred, with none or very little accumulation evident prior to 2.4 Ma.

Approximately the reverse seems to be true for the sheeted platform drift. Here the rates during the whole of the Pliocene ranged from 82.5 to 188.6 m Ma^{-1} (an average of nearly 120 m Ma^{-1}), decreasing to 82.5 and 55 m Ma^{-1} through the early and late Quaternary respectively.

The most significant discontinuities marked by widespread

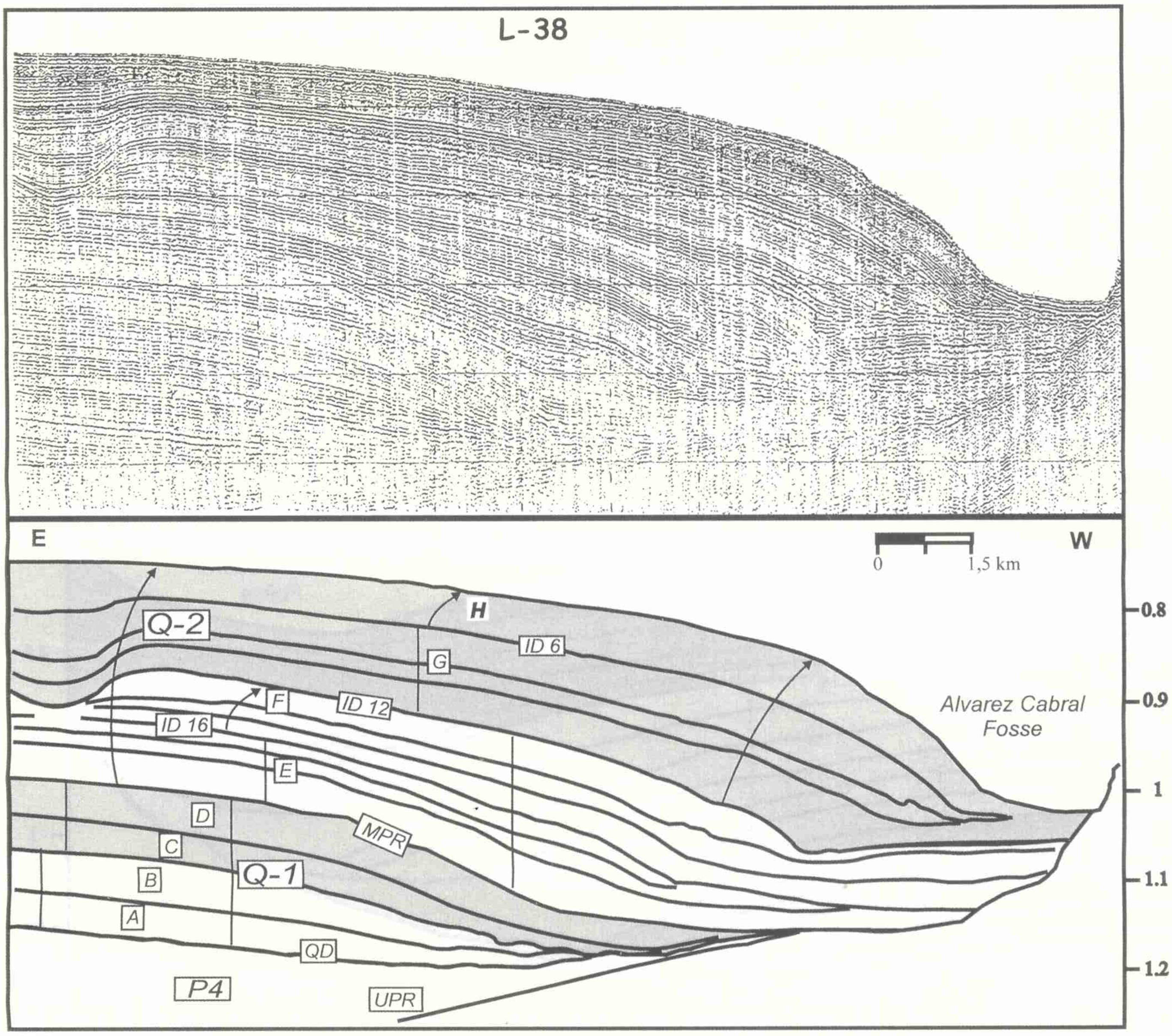

Fig. 11(B).

Table 2. *Sedimentation rates for the last 28 000 a in cores from the Faro–Albufeira drift complex. The presence of hiatuses is also noted. For core locations see Figure 3*

Cores	Sedimentation rates m Ma^{-1} (cm ka^{-1})	Hiatus present
KC8214	120 (12)	
KC8215	< 10 (< 1)	yes
KC8216	40 (4)	
KC8217	>130 (> 13)	
KC8218	< 10 (< 1)	yes
KC8219	35 (3.5)	
KC8220	60 (6)	
KC8221	120 (12)	
KC8222	< 10 (< 1)	yes
KC8224	40 (4)	yes
KC8225	< 15 (< 1.5)	yes
KC8226	110 (11)	
KC8227	145 (14.5)	
KC8230	?	yes
KC8231	35 (3.5)	yes
KC8232	30 (3)	
KC8233	60 (6)	

Table 3. *Accumulation rates for the last 5.5 Ma based on seismic records from the Faro–Albufeira mounded drift and sheeted drift systems. A seismic velocity of 1500 m s^{-1} has been taken to convert seismic Two-Way-Travel-Time (TWT) to thickness, and no adjustment has been made for compaction*

Mounded drift Seismic units	Age at base Ma	Thickness s (TWT)/m	Accumulation rate m Ma^{-1} (cm ka^{-1})
Q2 H-G	0.42	0.165/124	295 (29.5)
F-E	0.90	0.176/132	275 (27.5)
Q1 D-C	1.30	0.066/49.5	124 (12.4)
B-A	1.70	0.044/33	83 (8.3)
P4	2.40	0.033/25	35 (3.5)
P1–3	5.50	Thin to absent	Zero to very low
Sheeted drift Seismic units			
Q2 H-E	0.90	0.066/49.5	55 (5.5)
Q1 D-A	1.70	0.088/66	82.5 (8.25)
P4	2.40	0.176/132	188.6 (18.86)
P3	3.00	0.110/82.5	137.5 (13.75)
P2	4.20	0.088/66	82.5 (8.25)
P1	5.50	0.220/165	127 (12.7)

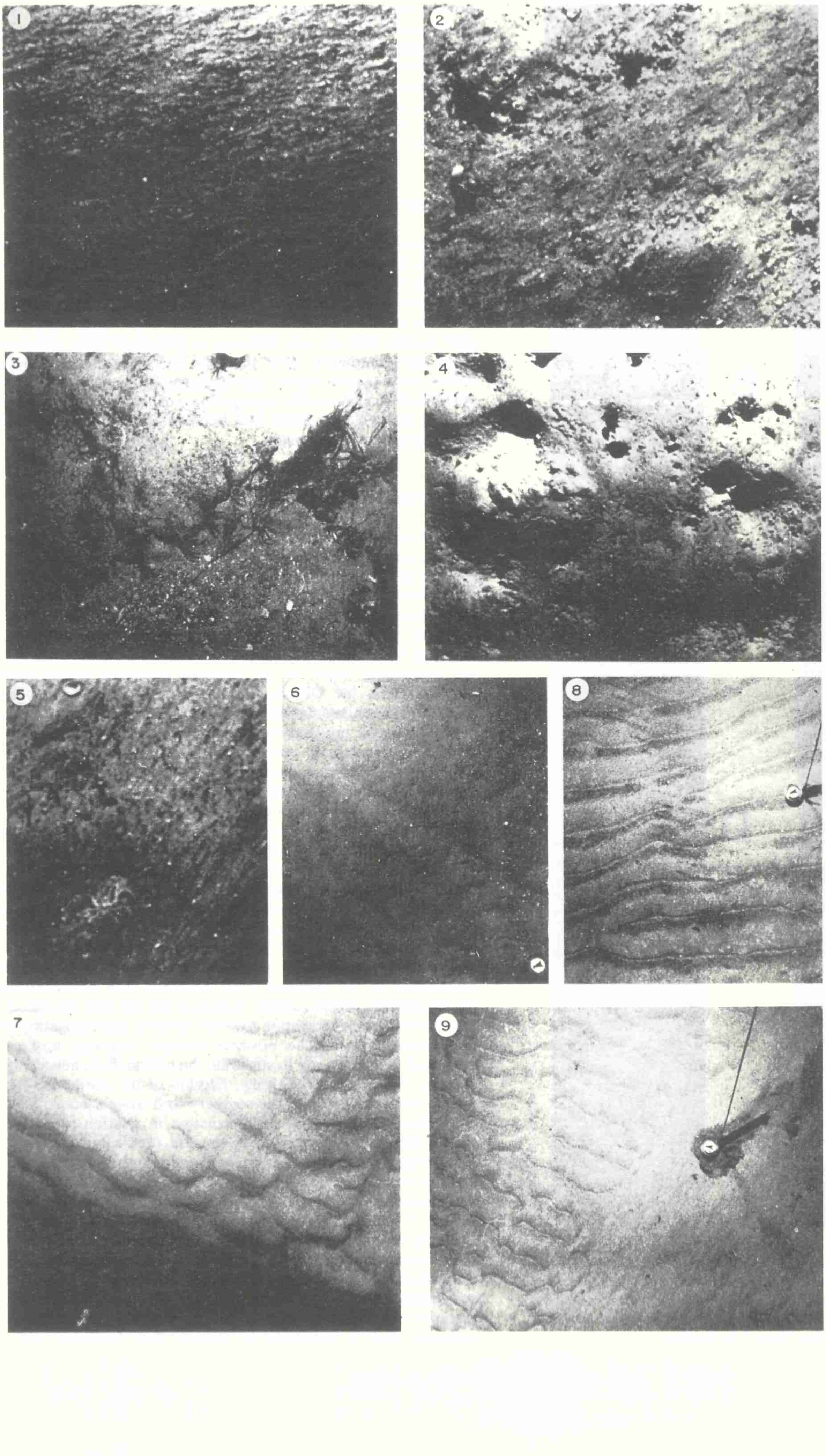

Fig. 12. Bottom photographs from Camera Stations C3-C7 (see Fig. 3 for location). All photos after Faugères *et al.* (1985*b*). 1, Northern valley (C7). Heterogeneous seafloor with current lineation shown by alignment of gravel material. Width of view approx. 50 cm. 2, Northern valley (C6). Heterogeneous seafloor with current-aligned shell fragments and other coarse debris over mud. Bioturbational mounds also show current elongation. Width of view approx. 50 cm. 3, Northern valley (C6). Heterogeneous and irregular seafloor with patchy distribution of shell fragments and other coarse debris over mud. Small colony of crinoids and crabs. Width of view approx. 50 cm. 4, Drift top (C5). Muddy seafloor with bioturbational mounds, probably formed from excavating crabs; no evidence of current activity. Width of view approx. 30 cm. 5, Drift top (C3). Muddy seafloor with scattered shell fragments, small bioturbational mounds and weak current lineation, flow direction ENE–WSW. Width of view approx. 40 cm. 6, Drift top (C5). Thin veneer of bioturbated mud with rare scattered shell fragments overlying ghosts of former (?sand) ripples. Flow direction SSE–NNW. Width of view approx. 90 cm. 7, Southern valley (C4). Sandy seafloor showing part of megaripple bedform overrun by a system of smaller-scale linguoid to sinuous-crested ripples. Width of view approx. 100 cm. 8, Southern valley (C4). Sandy seafloor with system of straight to curved-crested asymmetric ripples, flow E–W. Width of view approx. 110 cm. 9, Southern valley (C4). Sandy seafloor with current lineation apparently overrunning a system of linguoid ripples. Both systems show flow direction from SE–NW. Width of view approx. 150 cm.

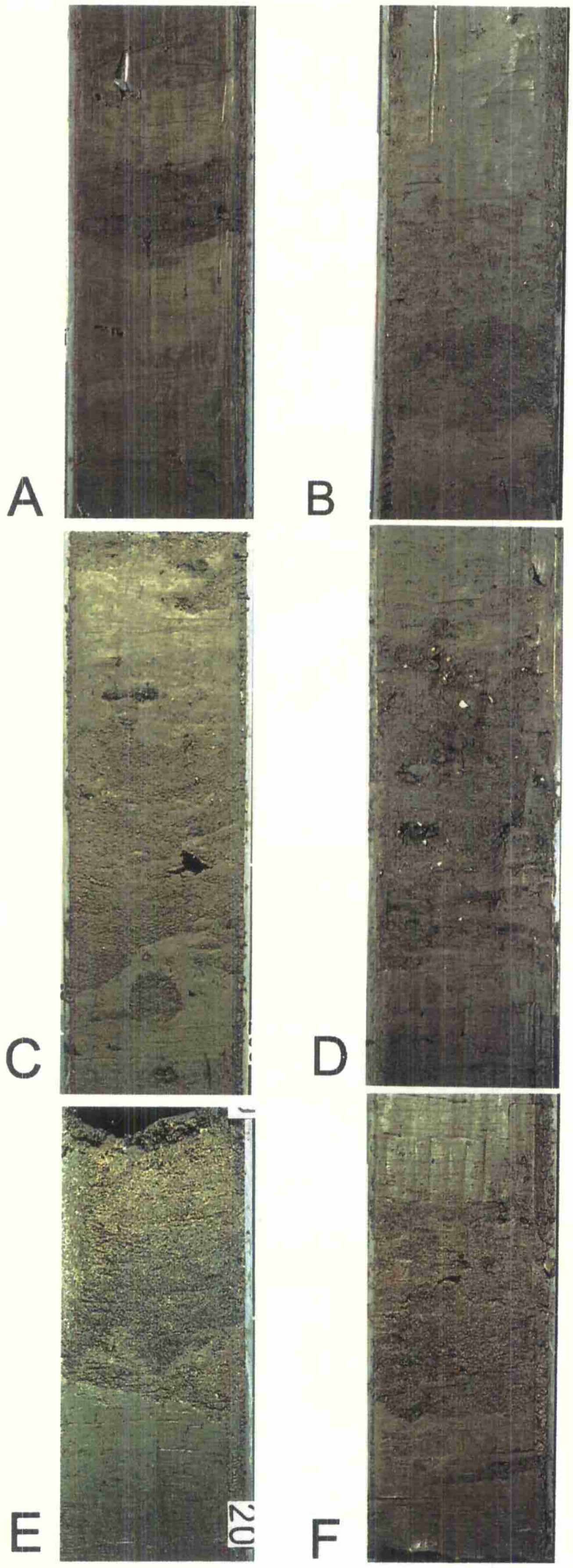

Fig. 13. Photographs of contourite facies from Faro–Albufeira drift cores. These illustrate a range of facies from muddy contourites (**A**), through various silt-mottled intervals (**B**, **C**, **D**, **F**) within a silty muddy contourite facies, to sandy contourite (**E**). Core width 10 cm; core number as shown to right of centimetre scale. See Figure 3 for location.

erosion and non-deposition are inferred at approximately 0.9 Ma, 2.4 Ma and 4.2 Ma. Less important discontinuities are most likely represented by less widespread hiatuses inferred between the other third and fourth order depositional sequences (Fig. 8). Condensed sequences are everywhere apparent overlying diapiric intrusive zones, with much expanded deposition in the intervening regions. Erosion is associated with both diapiric crests and channels.

Discussion

The Faro–Albufeira drift complex is a clear example of an elongate low mounded drift coupled with a dissected sheeted drift, that can be closely linked to a strong bottom current system developed from the MOW. Careful analysis of diverse datasets from the area has permitted, we believe, a robust interpretation of drift growth since the late Miocene, as well as of facies development and distribution over the past 28 000 years. We briefly review these aspects below, and highlight further questions that would best be answered by a programme of shallow drilling in the Gulf of Cadiz closely allied with detailed sidescan mapping and oceanographic measurements.

Drift origin and development

Several factors have led to drift development in the Gulf of Cadiz: (1) the onset of MOW following re-opening of the Gibraltar gateway at the end of the Miocene; (2) the existing morphology in the northern Gulf, with a broad platform abutting a relatively steep slope, serving both to focus bottom currents and trap their sediment load; (3) the Coriolis Force that is responsible for diverting MOW northwards and confining the water mass against the continental slope; (4) an abundant sediment supply from erosion within the Gibraltar gateway, continental runoff and downslope resedimentation from the Iberian peninsula, and primary biogenic productivity yielding mainly microfossil remains; (5) a slow decrease in bottom current velocity away from the Gibraltar gateway as a result of flow spreading and deepening, that has allowed for the deposition of sediment load.

The initial period of drift growth (seismic sequences *P1–3*) was as a broad sheeted drift that spread out across the Faro slope platform and prograded towards the north and northwest as it aggraded in thickness. As the drift relief built up (seismic sequence *P4*) so a broad depression or channel form was created against the slope in the north. This served to refocus the bottom flow leading to erosion or non-deposition in the channel axis and on the slope margin, and differential sedimentation over the evolving drift. Continued progradation coupled with marked aggradation of the mounded Faro–Albufeira drift characterized the Quaternary period (seismic sequences Q1–2). This was associated with minor progradation towards the west and elongation of the mounded form. The northern channel migrated upslope, continued to deepen and to constrain the bottom flow, hence augmenting current velocity locally. Erosion of the northern slope margin and deposition on the southern drift margin occurred. A more detailed analysis of drift evolution in relation to bottom current flow is presented by Faugères *et al.* (1985*a*).

Whereas we can visualize in this way the progressive development of the northern channel (Alvarez Cabral) in response to drift progradation, it is uncertain to what extent and at what periods it may also have been excavated by turbidity currents. Certainly turbidites are present in its more recent fill. We are less clear about the nature and origin of the southern channel (Diego Cao) which deeply dissects the sheeted drifts and then shallows and debauches onto the Bartolomeu Dias platform. Certainly this presently channels a very active stream of MOW and associated sediment load, as evidenced by channel floor bedforms and a

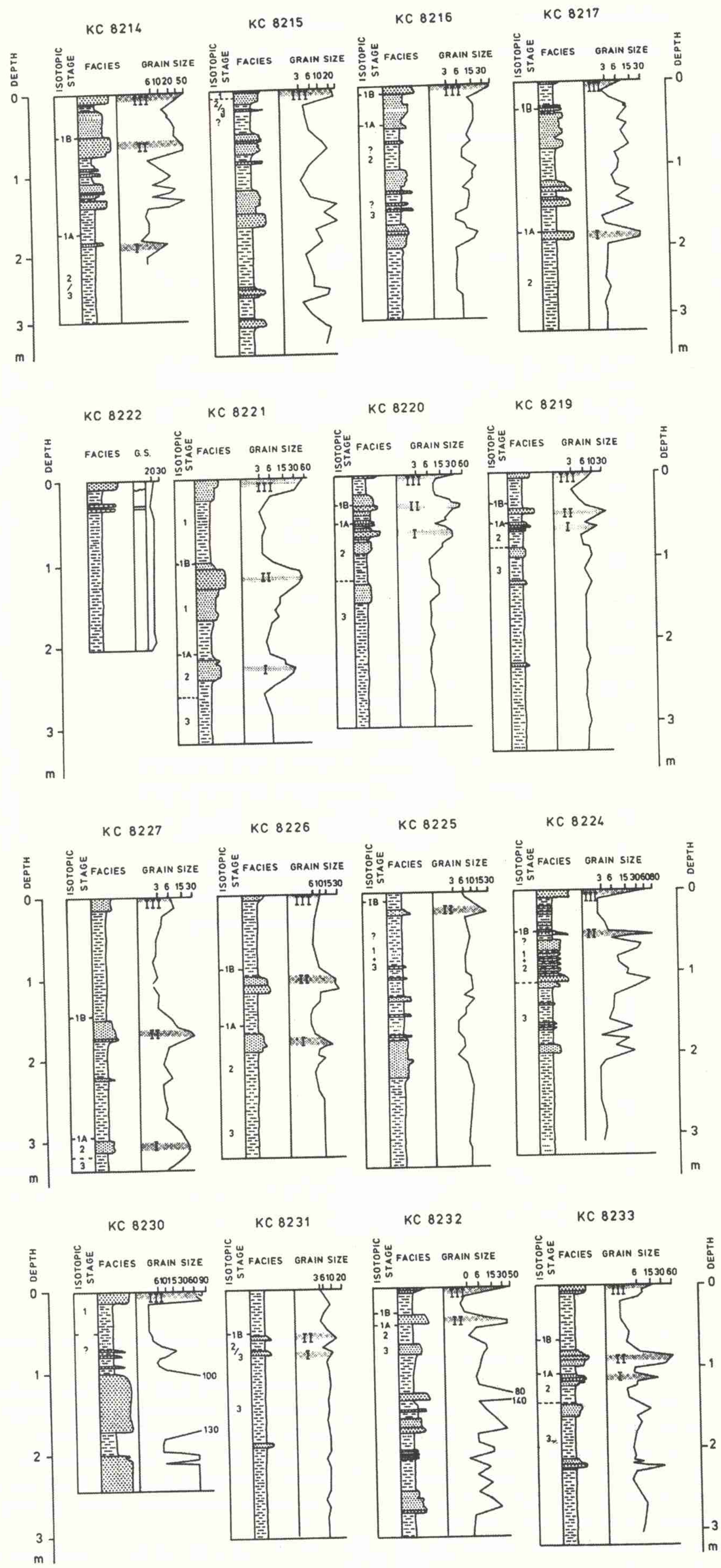

Fig. 14. Facies distribution across four drift transects (after Stow *et al.* 1986). Summary data on lithology, grain size and isotope stratigraphy shown for top 3.5 m only of each core. In most cases the remaining cored section is dominantly of muddy contourite facies.

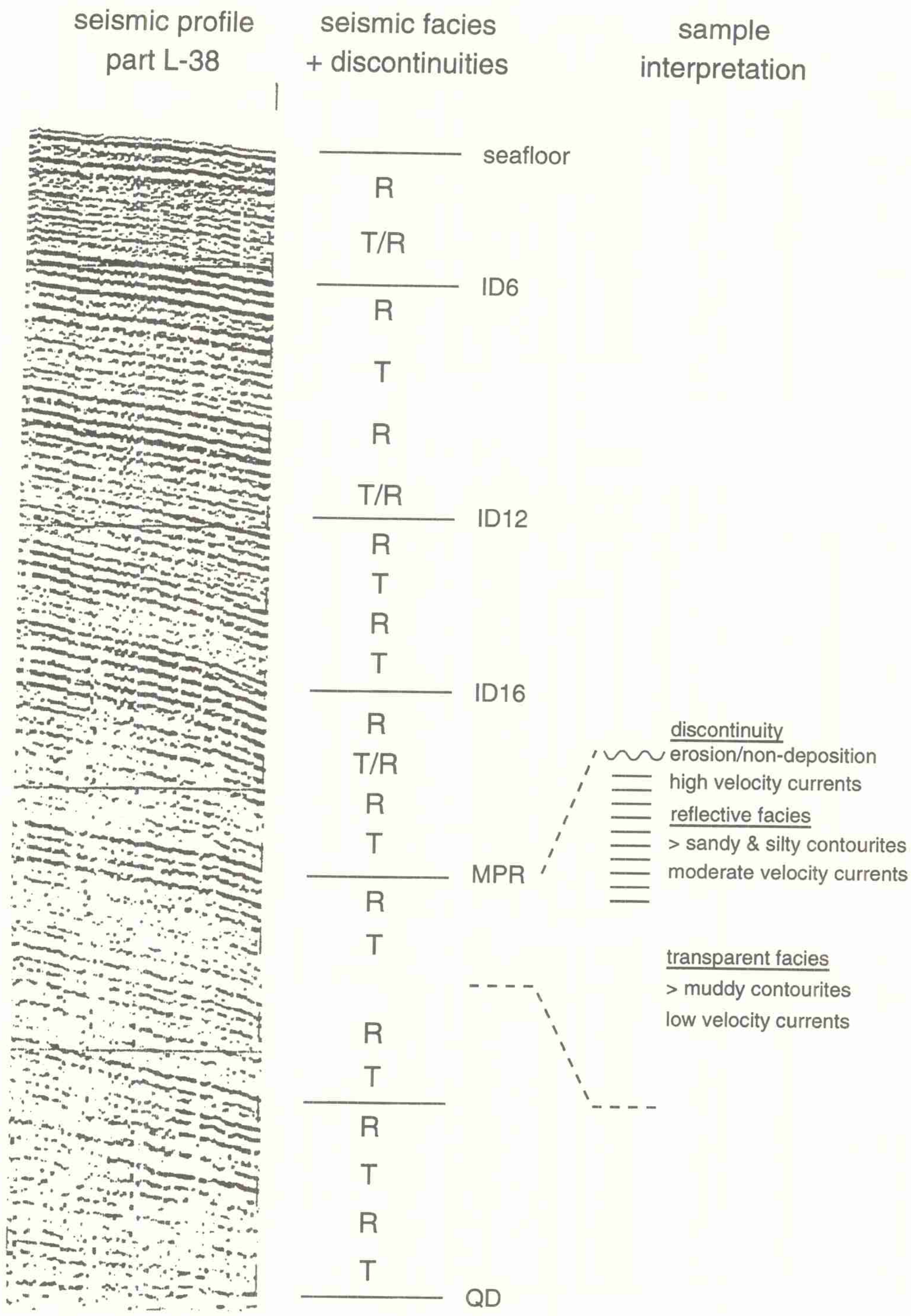

Fig. 15. Towards a model for interpreting seismic facies cyclicity in contourite successions.

condensed seismic sequence. It appears likely that it was excavated into the soft core of a linear diapiric trend by bottom current activity.

The Portimao Canyon and associated tributary complex that marks the western extremity of the drift complex is a typical and apparently active downslope turbidity current channel system, although oceanographic data show that it also serves to channelize a portion of the MOW and direct this downslope. The Faro Canyon was originally of turbidity current origin, but has now been cut off from its slope source and partially infilled by the westward prograding Faro drift. Origin of the two smaller, completely infilled channels that cut across the nose of the drift is still unclear.

Seismic facies cyclicity and sea-level change

The moderately high resolution sparker profiles through the latest Pliocene and Quaternary drift section show a very distinct alternation of a more transparent facies (T) with higher amplitude continuous reflector seismic facies (R). These are especially well defined through the mounded portion of the drift complex, where they can be recognized within the fourth order seismic sequences A–H.

In the absence of direct borehole evidence, we provisionally interpret seismic facies R as due to higher silt/sand content contourites, occurring in a series of discrete beds or zones within a more muddy contourite facies, and also with more hiatuses and

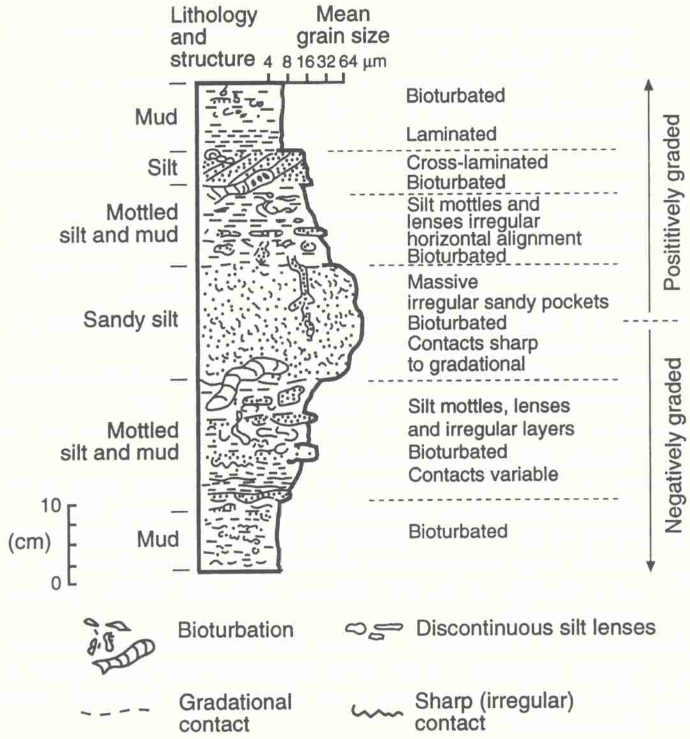

Fig 16. Standard sediment facies model for contourites, originally derived following work on Faro drift cores.

condensed sedimentation sections. This all reflects increased bottom current intensity. The more widespread discontinuities noted (e.g. UPR, MPR) are interpreted as the result of still higher bottom current velocities causing regional deposition and erosion. Seismic facies T, by contrast, is due to low silt/sand content within a more continuous and homogeneous muddy contourite section, reflecting decreased bottom current intensity.

There are about 11 such TR cycles through the Quaternary section. This slight uncertainty in number derives from the fact that the bubble pulse makes it difficult to resolve of the uppermost seismic unit H, whereas decreasing resolution at depth makes the TR cycles in units A–D less distinct. However, we interpret the observed seismic cyclicity as the result of a high amplitude climatic/eustatic cyclicity that has directly affected bottom current intensity over the drift complex. The 11 cycles would therefore correspond, at least approximately, to the principal, climatically-induced, isotopic stages identified through the Quaternary (e.g. Berger *et al.* 1994, Shackleton *et al.* 1990). We illustrate this relationship in Figure 15.

Precise dating of our TR cycles by correlation with shelf boreholes is not sufficiently accurate to allow their positive correlation with particular highstand or lowstand system tracts. Our best estimates show a temporal cyclicity of close to 100 000 years for the late Quaternary–Holocene (Q2), that might suggest eccentricity cycles, and closer to 200 000 years for the early Quaternary (Q1). There is also presently conflicting opinion on the effect that sea-level change would have on bottom current flow through the Gibraltar gateway, and insufficient evidence at this stage to resolve the issue.

Contourite facies cyclicity and bottom-current velocity

The cyclic variation in lithology and texture of contourites from the drift cores have been interpreted as largely due to variation in bottom current intensity, rather than changes in sediment supply, primary productivity, dissolution or diagenesis (Gonthier *et al.* 1984; Stow *et al.* 1986). The main arguments supporting this conclusion are:

- Current induced sedimentary structures are more evident in sandy rather than muddy contourites;
- Sediment hiatuses and/or low rates of sedimentation in adjacent valleys are coincident with the sandy peaks;
- There is a concomitant increase in both biogenic and terrigenous sand fractions in the sandy peaks, and of both benthonic and planktonic foraminifers in the biogenic fraction;
- There is a significant presence of reworked and fragmented benthonic foraminifers and shelly debris, as well as pelagic material;
- There is a relative compositional homogeneity at all sites over the drift, with exotic mineral assemblages only present in the clearly recognizable turbidites;
- The longitudinal down-drift trends in grain size as well as regional differences, such as the coarser grain sizes in the southern channel, cannot be readily explained by localized turbidity current input.

We do, however, recognize certain features that favour at least some influence of increased primary productivity contributing to the sand fraction of peak II, and increased terrigenous supply contributing to peak I.

This type of facies and textural cyclicity is now recognised as a characteristic feature of contourite successions worldwide (Fig. 16). The temporal scale for the Faro drift cycles is rather irregular, based on the relatively short lengths of cored section, and typically ranges between 5 000 and 15 000 years. We do not see any clear correlation of these with known climatic/oceanographic changes documented elsewhere, although Stow *et al.* (1986) do note the possible significance of pulses of temperature increase over the past 15 000 years (Sarnthein *et al.* 1982), including the hypsithermal temperature maximum beginning at 8700 years BP. Longer borehole sections through different parts of the Faro–Albufeira drift complex would undoubtedly refine the picture to date and help resolve some outstanding questions.

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