

North Atlantic contourite sand channels

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Abstract: Two sand-rich channelized depositional systems, formed by strong contour currents, were studied west of the Faeroe Bank Channel and in the Gulf of Cadiz. Both are areas beyond the exit of constrictions where water overflows from the Norwegian Sea and the Mediterranean Sea, respectively. West of the Faeroe Bank, newly mapped channels are developed mainly under the influence of a geostrophic current and are characterized by significant lateral migration, which determines the marked cross-sectional asymmetry and the architecture of the deposits. The pathways of the Mediterranean Undercurrent in the Gulf of Cadiz are complex, with the greater proportion flowing under geostrophic conditions along a terrace but with some of the denser water becoming ageostrophic and descending downslope owing to gravity. A series of 'peel-off' channels is formed, with the largest one, Gil Eanes, being about 40 km long. Most of the channel fills consist of medium-coarse sand. Levees are mainly silts with a higher sand content in the vicinity of the channel. Both depositional systems have a variety of contourite sand channels, which in most respects are remarkably similar. In both cases there are stretches where the flow is ageostrophic, with water descending downslope for as much as 400 m before resuming geostrophic flow at deeper levels. In each case the main pathway of the densest water is the shallowest and several branches turn off to the left of this main pathway before bending to the right under the influence of Coriolis forces. In both cases there are channel fills of medium-coarse sand, probably cross-bedded, and up to 200 m thick. Sheets of sand with a thickness of a few metres to a few tens of metres are common. Similarities to turbidite channels are the aggradational nature of some channel floors and the flanking muddy or silty sediment waves. Contourite channel depositional complexes are distinguished from turbiditic ones by their coarsening-up rather than fining-up sand units, the asymmetry in channel architecture, the presence of regional unconformities, and the distribution pattern with well-marked boundaries of current-derived deposits.

Geostrophic contour currents are known to be important agents of sediment transport in the deep sea. Giant bodies of muddy sediment formed by contour currents are recognized in many parts of the slope and rise (e.g. McCave & Tucholke 1986; Faugères *et al.* 1993). Normally sand makes up a rather insignificant portion of the net sediment volume (Viana *et al.* 1998). However, there are several sedimentary systems where sand does play an important role, forming significant accumulations that can be considered as potential hydrocarbon reservoirs. Two such systems were studied during several cruises conducted by the UNESCO–IOC Training-through-Research (TTR)

Programme and by the Challenger Division of the National Oceanography Centre, Southampton, in the areas lying west of the Faeroe Bank Channel and in the Gulf of Cadiz (Fig. 1).

Methods

Datasets used for this study were collected with a wide range of echosounders, sidescan sonars, seismic systems, bottom sampling systems and cameras. In the Faeroe Bank area the survey included 10 kHz OKEAN long-range sidescan sonar, a single-channel seismic system with 1.81 air-gun source and 30 kHz OREtech deep-towed

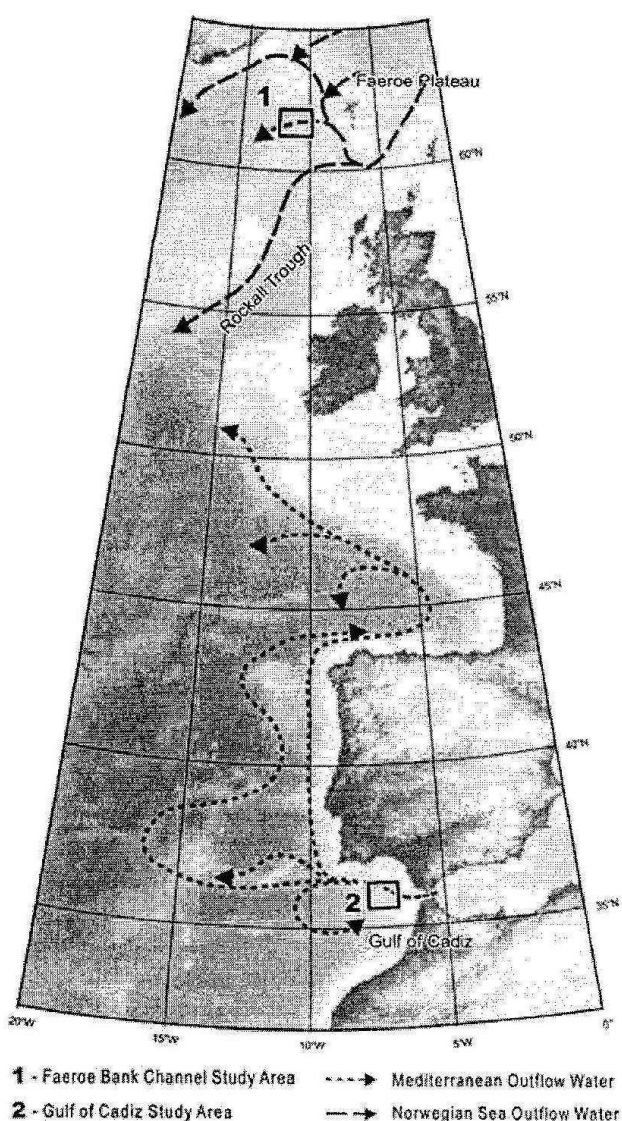


Fig. 1. General map showing study areas. Norwegian Sea Outflow pathways adapted from Hansen & Østerhus (2000), Mediterranean Outflow pathways adapted from Iorga & Lozier (1999).

sidescan sonar with built-in bottom 7 kHz profiler. Acoustic and seismic data from the Gulf of Cadiz area were collected using 11–12 kHz SEAMAP long-range sidescan sonar, operated by the US Naval Oceanographic Office and the Naval Research Laboratory, 30 kHz TOBI deep-towed sidescan sonar, operated by the NOC, Southampton, and a single-channel seismic system. Underwater television and bottom sampling with conventional box and large-diameter gravity corers and a giant piston corer were used for groundtruthing.

Acoustic data were digitally enhanced and geographically registered. Seismic processing included predictive deconvolution and band-pass filtering. Cores were visually logged with subsequent measurement of magnetic susceptibility using a Bartington MS2 system with a MS2C core logging sensor. A

grain-size analysis was undertaken on selected samples from the Faeroe Bank Channel area with a Fritsch Analysette A22 laser particle sizer.

Area west of Faeroe Bank Channel

The cold Norwegian Sea Outflow Water (NSOW) flows with considerable speed through the Faeroe Bank Channel, which is the deepest passageway for bottom water out of the Norwegian Sea into the North Atlantic (Fig. 2). To the south of the Faeroe Islands the outflow is confined between the Faeroe platform and Faeroe Bank where, as a result of its topographic restriction, its speed reaches 1 m s^{-1} (Crease 1965; Saunders 1990). To the NE of the Faeroe Bank the channel broadens rapidly and as a result the outflow speed can decelerate to about 20 cm s^{-1} on average (Crease 1965). Part of the flow carries on along the slope of the Faeroe–Iceland Ridge with its core at a depth of between about 900 and 1100 m, where its pathway is marked by a zone of sandy bedforms (Dorn & Werner 1993). To the NW of the Faeroe Bank, published bathymetric maps (Crease 1965; Fleisher *et al.* 1974; Hansen & Meincke 1979; British Oceanographic Data Centre 1997) show the presence of channels in the depth range of 1200–1400 m. Bathymetry derived from satellite-altimetry with shipborne sounding control (Smith & Sandwell 1994) also shows a pattern of anastomosing channels (Fig. 2a). Several researchers have reported the presence of dense, cold (3°) Norwegian Sea Outflow Water associated with these channels (Crease 1965; Kuijpers *et al.* 1998). The channels are believed to be formed by a fast-flowing bottom current representing an outlet of NSOW that diverts to the left from the main pathway along the Faeroe–Iceland Ridge after it leaves the Faeroe Bank Channel mouth. The current is known to have been operating in this area since the Early Miocene (Boldreel *et al.* 1998; Kuijpers *et al.* 1998) or possibly even since earlier Oligocene as suggested by Davies *et al.* (2001), which indicates that the channels have had a relatively long evolution. Additional sidescan sonar, seismic and groundtruthing data have resolved the channel pattern and their morphology, and the processes of sediment transport and deposition. They were obtained during one of the ECs ENAM-II cruises onboard R.V. *Pelagia* in 1995 and on the seventh TTR cruise onboard R.V. *Professor Logachev* in 1997.

Channel pattern and geometry

Sea-floor sonographs. Long-range OKEAN sidescan sonar and single-channel seismic surveys conducted west of the mouth of the Faeroe Bank

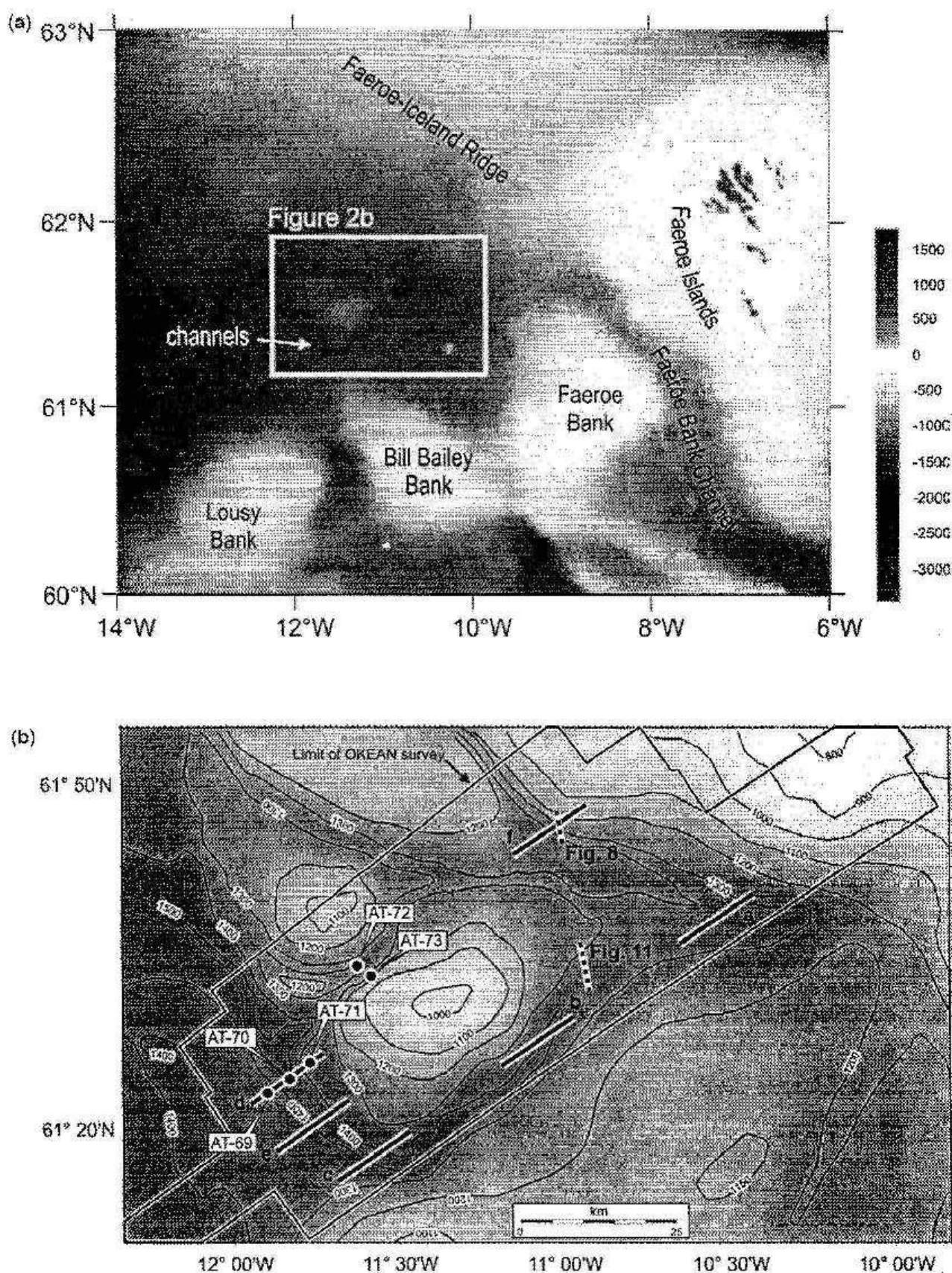


Fig. 2. (a) Satellite-derived bathymetry image showing channels west of the Faeroe Bank; (b) location map of the study area (lower-case letters correspond to seismic sections shown in Fig. 7).

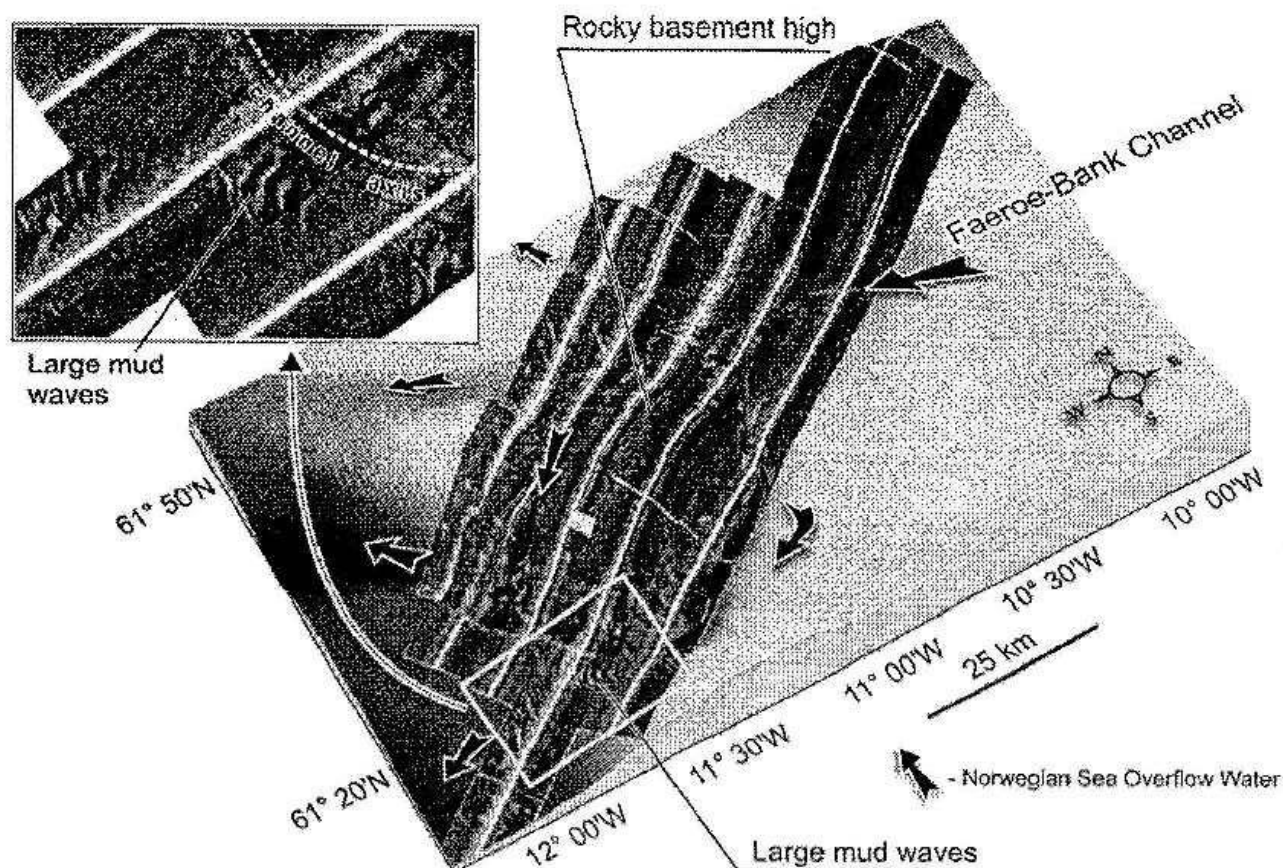


Fig. 3. Perspective view of the OKEAN mosaic draped over bathymetry. Major NSOW pathways are indicated by arrows. High backscatter is shown by darker shades.

Channel show that channels formed by the NSOW outlet have an anastomosing pattern that is controlled by a flat-topped acoustic basement high standing about 200 m above the surrounding sea floor (Fig. 2b). The outflow water enters the area from the east, where the fast-flowing bottom current sweeps the sea floor, forming an extensive area of erosion and non-deposition clearly seen on seismic records (see below). OKEAN sonographs also show a large-scale seabed lineation of a higher acoustic backscatter, indicating the presence of a strong bottom current (Fig. 3).

Most of the bottom water forming the newly mapped channels is the main flow of NSOW coming out of the Faeroe Bank Channel. However, there is evidence on the TOBI 30 kHz sonographs (Kuijpers *et al.* 1998) that there is a contribution from a proportion of the NSOW approaching from the south (Fig. 4). This is Norwegian Sea water that overflows the Wyville-Thomson Ridge and follows the bottom contours at a depth of about 1000 m. It flows clockwise around the Faeroe Bank and Bill Bailey Bank (Boldreel *et al.* 1998; Kuijpers *et al.* 1998) as shown by areas of sea-bed erosion and coarse sediment transport, observed on TOBI sonographs (Kuijpers *et al.* 1998; Fig. 4).

It is postulated here that this branch of the NSOW rejoins the main flow and that the water masses combine before flowing into the North Atlantic. The shallowest filament flows along the Faeroe-Iceland Ridge at a depth of about 1000 m (Dorn & Werner 1993). At the basement high the flow bifurcates and forms several distinct channels bending around either side of the plateau. The more prominent channel runs around the southern side of the plateau, becoming progressively deeper as it does so (Fig. 5). It makes an almost 90° change of direction around the southwestern corner of the plateau and then runs to the NW at a depth of about 1400–1500 m. Another filament flows north of the plateau, bifurcating twice before one branch eventually rejoins the clockwise flow at a depth of 1400–1500 m. This is deeper than used to be supposed for fast-flowing NSOW in this region (e.g. Hansen & Meincke 1979) but in keeping with there being several cores (e.g. Hansen & Østerhus 2000).

An OKEAN 10 kHz sonograph shows that this channel has a generally weakly backscattering floor and left-hand bank, whereas the right-hand bank has stronger backscatter. Such a backscatter pattern was also observed on a 30 kHz TOBI sonograph that partially overlaps with the OKEAN

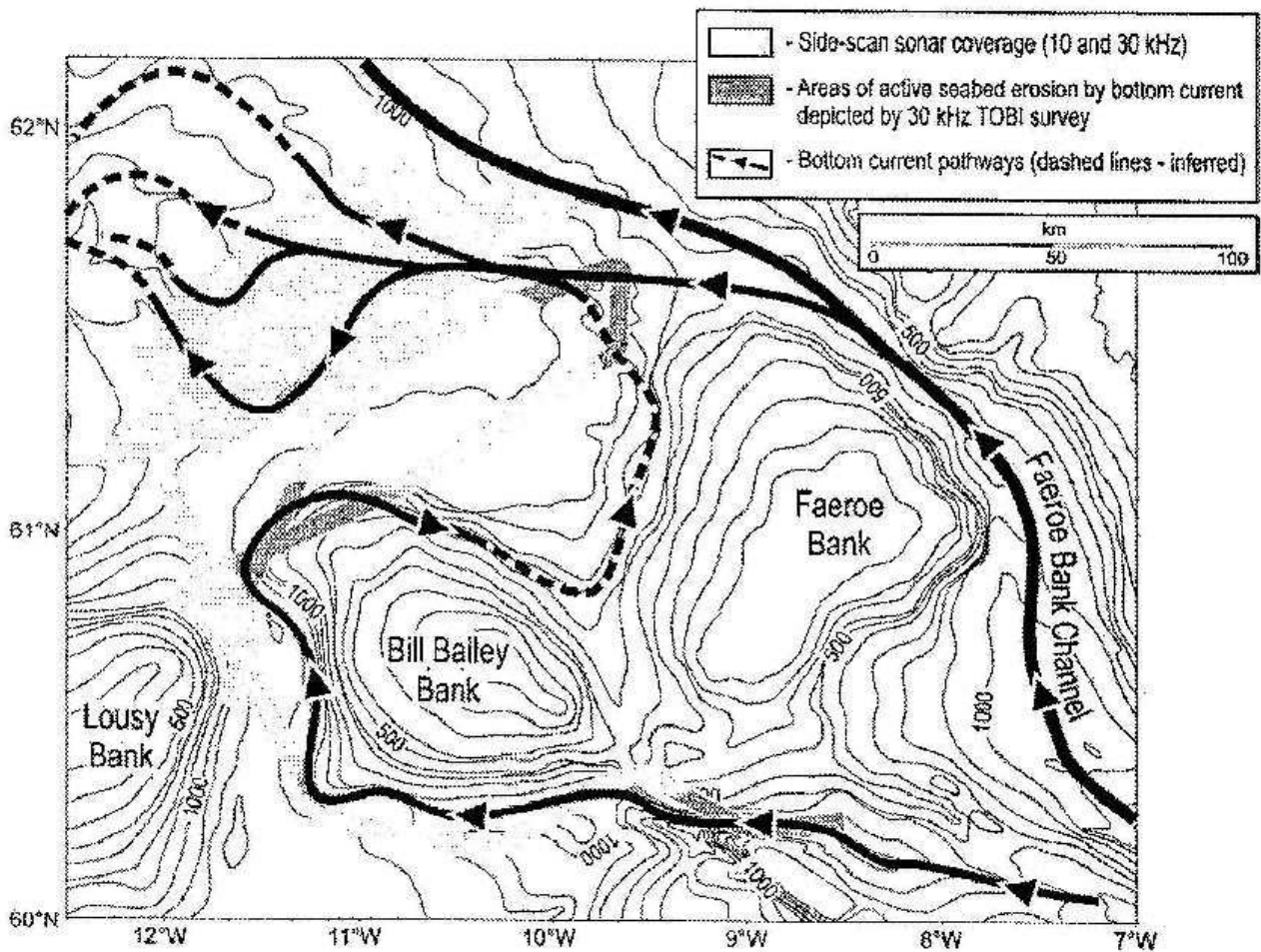


Fig. 4. Main bottom-current pathways in the Faeroe Bank area. The pathway around the Bill Bailey Bank is from Kuijpers *et al.* (1998).

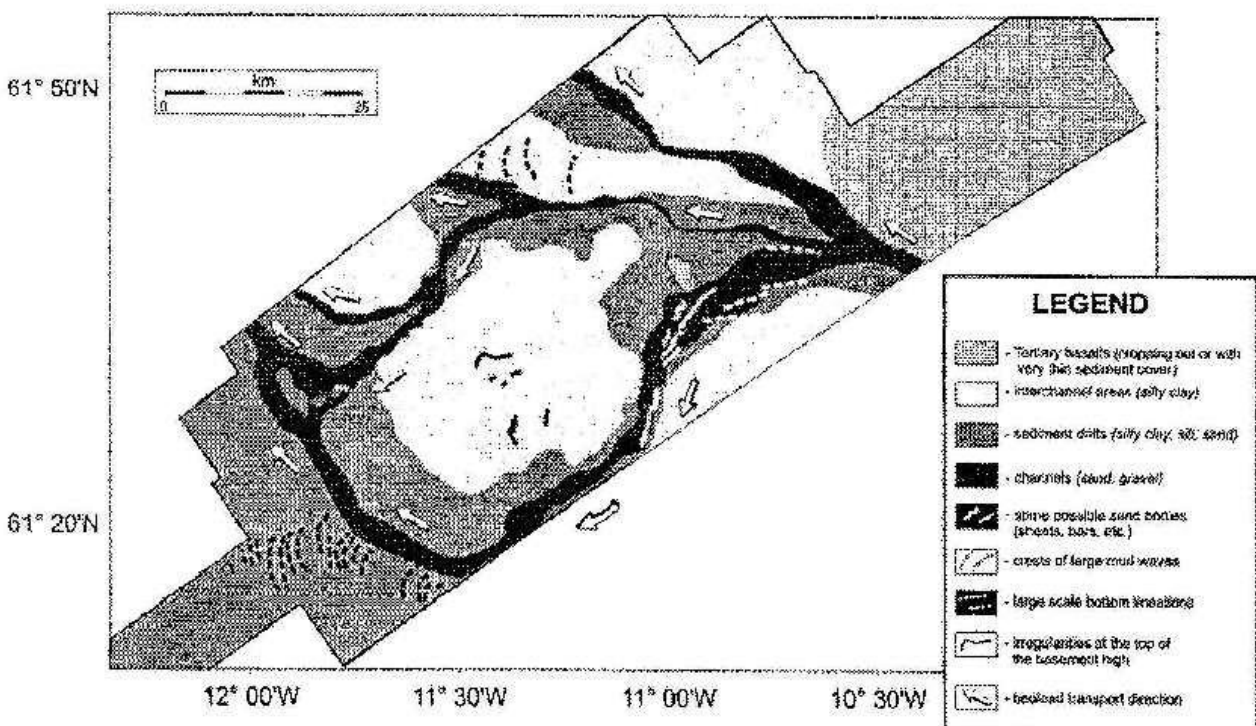


Fig. 5. Map of the main features and bedload transport pathways west of the Faeroe Bank Channel based on integrated interpretation of seismic, sidescan sonar and bottom sampling data.

sonograph and provides a more detailed picture of this fragment of the channel (Fig. 6). Apparently a transition from the channel floor and the right-hand wall is marked by the sharp boundary between low and high backscatter areas, where low backscatter corresponds to the channel floor and high to the channel wall. Next to this boundary

there is a 300 m wide zone of transverse bedforms. These are believed to be sand waves, with a wavelength of about 100 m (Kuijpers *et al.* 1998), based on their shape and on the low backscattering characteristics, as low backscattering is usually associated with sand on sonographs (c.g. Belderson *et al.* 1972). A similar backscatter pattern was observed

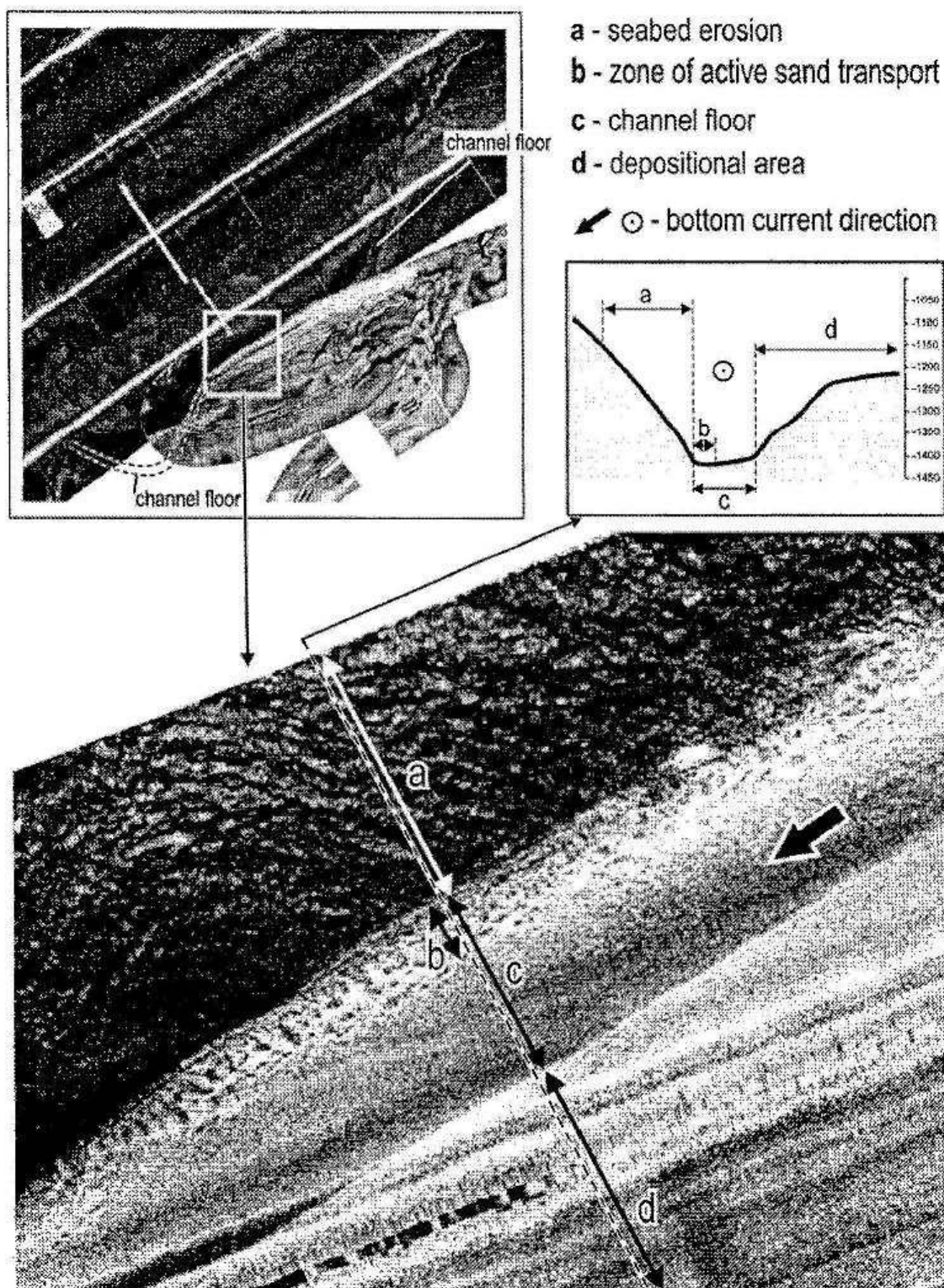


Fig. 6. Details of a contourite channel on the OKEAN and TOBI images. High backscatter is shown by darker shades.

on the OREteck 30 kHz sonograph that runs across one of the northwesterly directed channels. The slightly higher resolution sonograph also shows a characteristic sea-bed current lincation on the channel floor, similar to that reported by Kuijpers *et al.* (1998) on the TOBI sonograph to the north of the Faeroe Bank. A series of large mud waves with a wavelength of about 1.5 km appears on the OKEAN sonograph that covers the channel running south of the plateau. They are on the outside of the major channel bend. Waveforms of similar size were also noticed on the TOBI sonograph further to the SW, although they are more probably associated with the NSOW branch that flows around the Bill Bailey Bank.

Seismic and sub-bottom profiler expression. NSOW pathways in the study region are identified on the seismic records as areas of non-deposition or erosion or as well-marked channels. The former are encountered to the east where the Faeroe Bank Channel outlet enters the region and a strong bottom current prevents deposition of fine sediments.

The lower part of the seismic succession represents an acoustic basement that is topped by a pronounced high-amplitude reflector (Fig. 7). Its internal structure is mostly chaotic, although in the upper part prolonged parallel reflectors are common. The upper part of the succession comprises a pattern of lower-amplitude continuous parallel, often sinuous, reflectors. The surficial succession becomes more complex within the banks to the left of the channels, with three units being identified. The lower unit (Unit I) forms a sedimentary drape over the acoustic basement and has a set of parallel continuous reflectors. Near the channels the upper boundary of the unit is marked by an erosional unconformity and the overlying middle unit (Unit II) has a pattern of sigmoidal reflectors. The thickness of the unit is about 100 ms and it pinches out away from the channels. Toward the channel the erosive character of its base becomes more obvious and high-amplitude events associated with channel fills can be recognized. The seismic pattern suggests that the channels have migrated to the NE; that is, to the right of the flow direction. The upper boundary of the middle unit is also an erosional unconformity and most of the upper unit (Unit III) comprises a set of parallel continuous reflectors. The erosion at the base of the upper unit becomes more pronounced towards the channel, where the unit lies directly on the basement and forms most of the bank of the channel. The bank is a broad elevation about 75 m high and the thickness of the unit here reaches 450 ms. In the lower part of the unit sigmoidal reflectors are observed whereas the uppermost part reveals a characteristic pattern of parallel continuous

reflectors typical for contourite drifts (Faugères *et al.* 1999). The seismic pattern also suggests that the banks or walls to the left of the channels are formed mainly as a result of lateral accretion. The right-hand banks or walls are either erosional or have a reduced sedimentary succession suggesting either very low sedimentation rates or erosion. A high-resolution 3.5 kHz profile running across one of the channels also shows that the right-hand bank is more gentle and erosive whereas the left-hand one is steeper because of accumulation of presumed fine-grained sediment (Fig. 8). According to the thickness of individual layers resolved on the record the sedimentation rate is five times higher on the left-hand bank compared with the surrounding area.

Seismic records show that channels have flat floors and are 2–3 km wide and about 180 m deep. High-amplitude reflectors beneath some of the channels suggest the presence of a possible coarse aggradational deposit that can be up to 200 ms thick. High-resolution data also suggest the presence of the coarse sediment on the channel floor, where an acoustically transparent lens-like sediment body about 10 m thick is observed on the record. This agrees with observations from 3.5 kHz TOBI profiler records obtained from the main channel, where a sand body with a thickness <10 m was reported (Kuijpers *et al.* 1998).

Sediment cores

Five cores were collected from the banks and channel floors to groundtruth sidescan sonographs and to calibrate different morphological elements of contourite channels. Although no age determinations were performed on these cores it was possible to perform partial correlation with existing cores from the area (Kuijpers *et al.* 1998) on the basis of the presence of an ash layer and available magnetic susceptibility (MS) data.

Channel banks. Three cores from banks recovered mainly a silty-clayey sequence topped by a Holocene sand layer (Fig. 9). Grain-size analysis revealed typical contourite successions (Stow 1979) with a coarsening-upward trend. Correlation with cores collected to the south of the area (Kuijpers *et al.* 1998) showed that cores from left-hand banks contain an extended sedimentary succession as a result of higher sedimentation rates compared with cores from right-hand banks. Marine Isotope Stages (MIS) are allocated based on attribution of the ash layer to the boundary of MIS 2–3 or to the top of MIS 3 and on the comparison with the MS curve of the core ENAM-33 by Kuijpers *et al.* (1998). Clays are taken to represent extreme glacial periods; for instance, MIS 2 clayey intervals recognized in

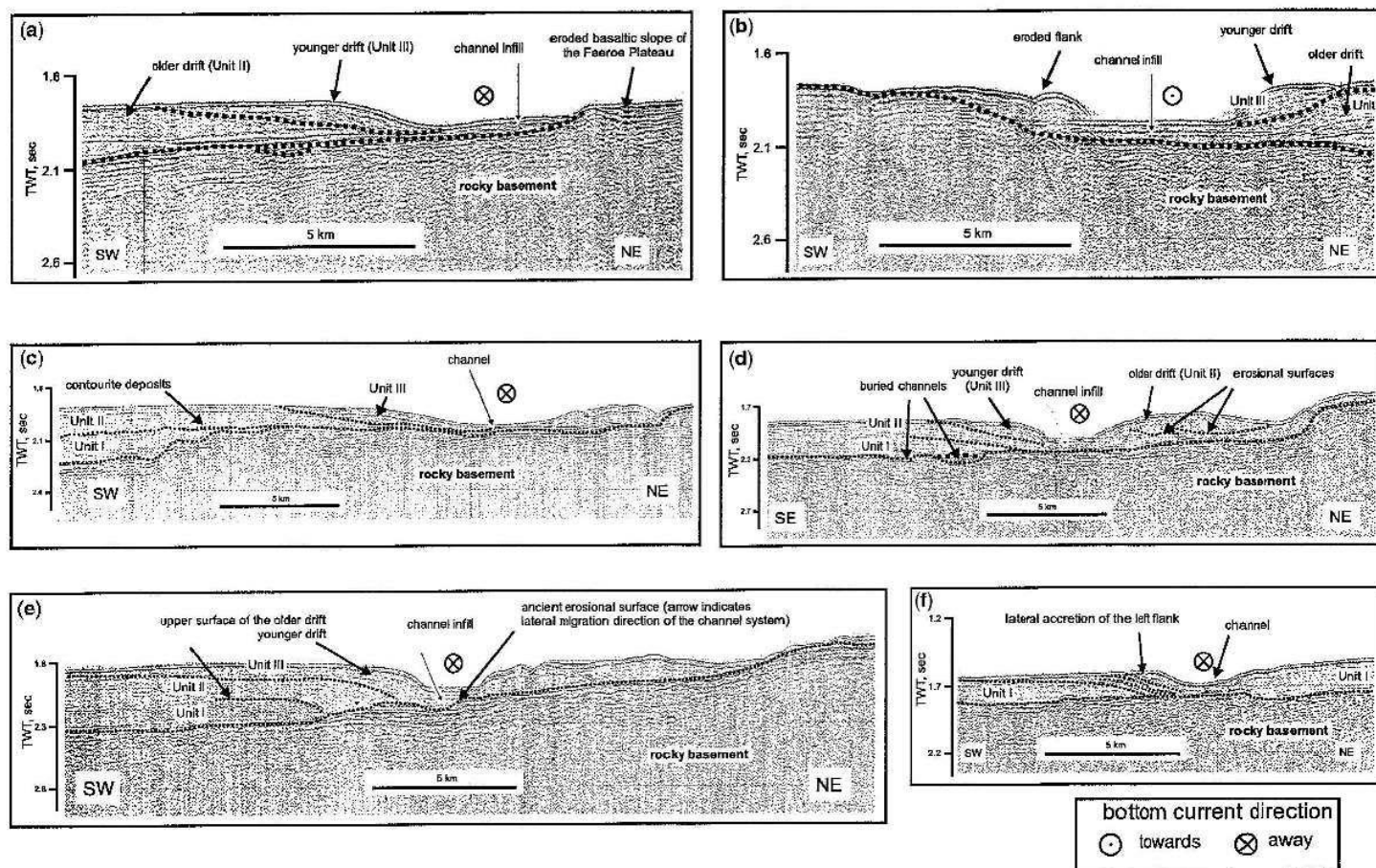


Fig. 7. Seismic profiles across channels showing asymmetry of deposition or erosion and migration of channels to the right. TWT, two-way travel time.

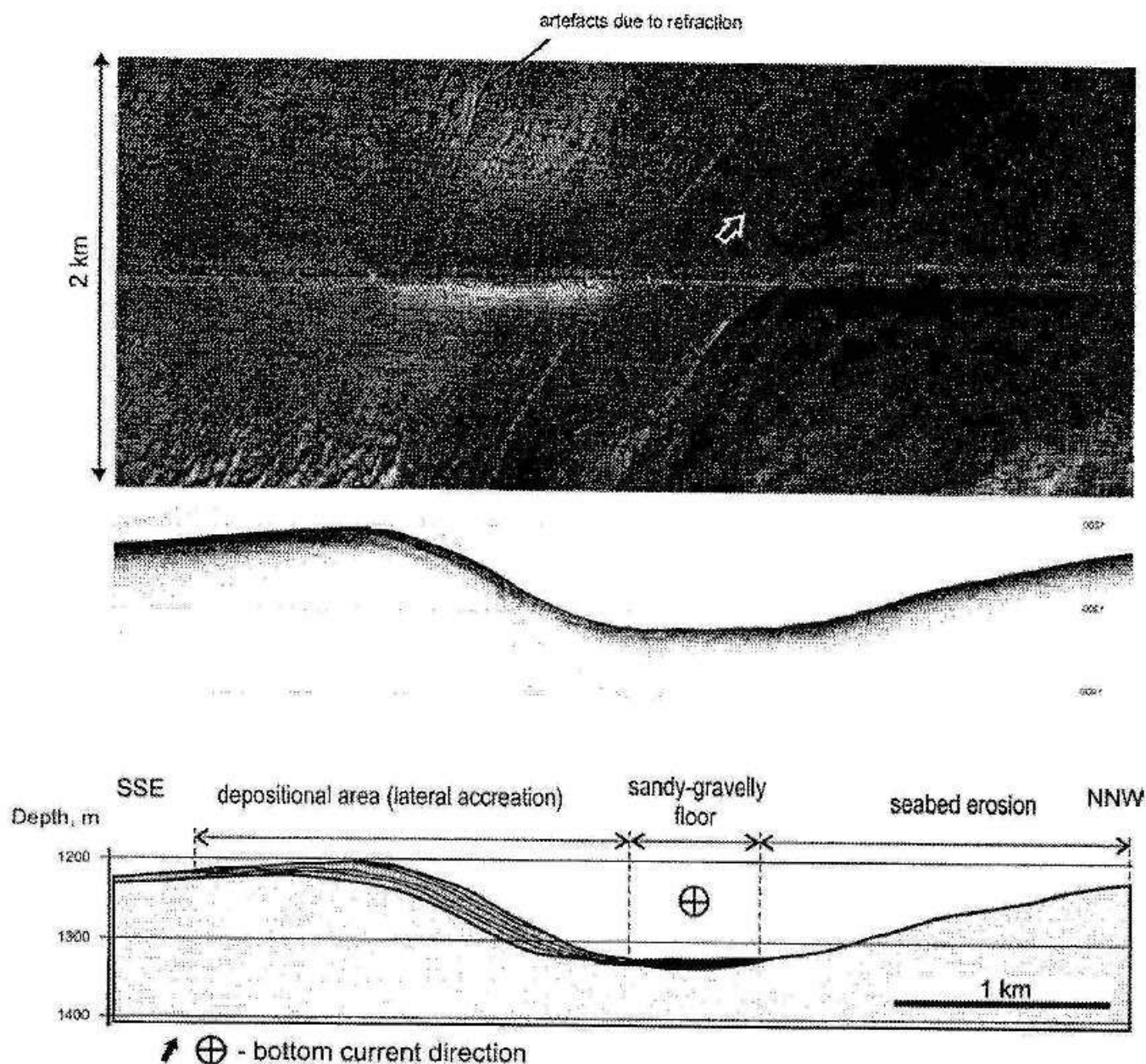


Fig. 8. High-resolution sidescan sonar and bottom profile across a contourite channel showing migration of channel to the right.

cores AT-69G and AT-73G (left-hand banks) are characterized by 2.1–2.5 times higher sedimentation rates than MIS 2 clay in the core AT-71G, taken from a right-hand bank. The sedimentary section in core AT-71G also has a higher content of sandy intervals, which indicates more active bottom dynamics. These observations are in a good agreement with seismic and 3.5 kHz data indicating active deposition of fine-grained material on the left-hand banks of channels and erosion or suppressed sedimentation on the right-hand ones.

Channel floor. Two cores taken from channel thalwegs recovered mainly sandy deposits (Fig. 10). Core AT-70G collected from the main channel contained a coarsening-upward, 50 cm long succession of fine-medium well-sorted terrigenous

sand with an interbedded layer of foraminiferal sand. Clay content varies from 15 to 40%. Core AT-72G was taken from a distributary channel to the north of the plateau and the succession is also composed of interbedded layers of terrigenous and foraminiferal sands. Some sandy intervals are coarsening upwards. Both cores have coarse sand-gravel top layers, which are thought to have formed as a result of increased activity of NSOW in the Holocene (Stage 1).

Geometry of sand bodies

Seismic, sidescan sonar and coring data indicate that most of the sand is transported along the channels. High-amplitude reflectors observed on the seismic records beneath channels suggest that

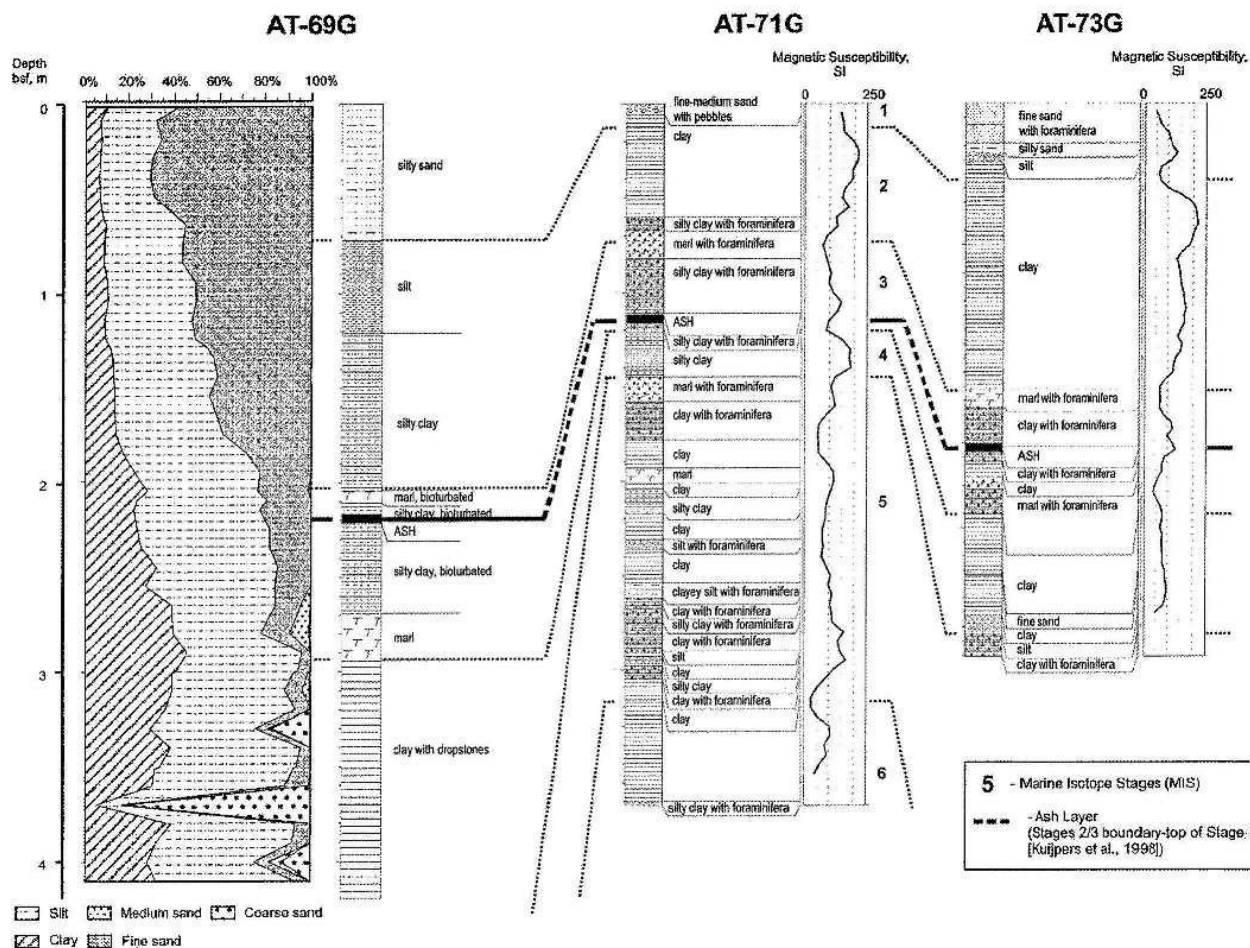


Fig. 9. Logs of cores from contourite channel walls, bsf, below sea floor.

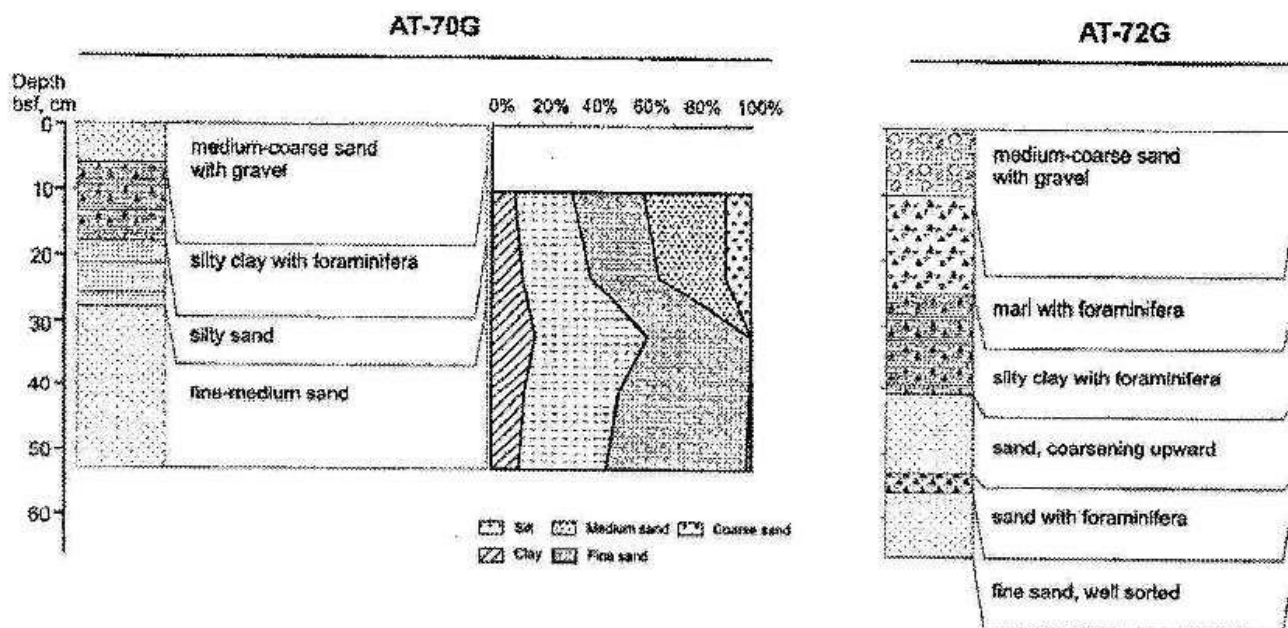


Fig. 10. Logs of cores from contourite channel thalwegs.

sand forms a significant part of channel infills. High-resolution sidescan sonar data obtained across the southern channel show fields of sand about 2 km wide covered in places with trains of sand waves with 50 m wavelength (Fig. 11). These sand fields in turn are fragments of linear low backscattering features about 10–20 km long, also seen on the 10 kHz OKEAN sonograph. Deep-towed 3.5 kHz profiles across one of the sand fields reveal the presence of an acoustically transparent lens-like sedimentary body, about 7 m thick, which is interpreted as a homogeneous sandy deposit (Fig. 11). Similar lens-like sand bodies were observed in the eastern Porcupine Seabight (Akhmetzhanov 2003), in another area of strong bottom current where a large number of such bodies were stacked to form a sheet of sand up to 10 m thick. The presence of similar sheets can also be expected in the study area as shown by seismic records. Unit II, with its sigmoidal high-amplitude reflectors, is interpreted as a sequence of such buried sand sheets formed during channel migration.

Cores collected from the flanks of nearby banks also contain sand-rich intervals, some of which are about 2 m thick (Kuijpers *et al.* 1998) and mainly consist of winnowed Foraminifera shells (50–75% CaCO_3). Sand-rich intervals seem to be more common on the right-hand side of these channels.

Gulf of Cadiz

One of the largest known expanses of sand laid down in the deep sea by a contour current is in the Gulf of Cadiz, where the Mediterranean Undercurrent decreases in speed as it comes out of the Strait of

Gibraltar (Fig. 12a). The bedform distribution and the geometry of the sandy deposits are best known in their proximal setting (Heezen & Johnson 1969; Kenyon & Belderson 1973; Nelson *et al.* 1993; Mulder *et al.* 2003) where there is a sequence of bedform zones of gravel and sand similar to those mapped on current-swept continental shelves. They are spread across a terrace on the continental slope at depths between about 700 and 900 m. Several filaments of the Undercurrent plunge downslope along channels (Fig. 12b), as shown by Madelain (1970) and Kenyon & Belderson (1973). An extensive dataset has been obtained over the three most proximal channels with a 12 kHz SEAMAP long-range sidescan sonar, a deep towed, 30 kHz TOBI sidescan sonar, single-channel seismic and underwater video systems (Kenyon *et al.* 2000, 2001; Habgood *et al.* 2003). The widest of the channels (Channel 2 of Kenyon & Belderson 1973) is controlled by NE–SW-trending diapiric ridges but the two most proximal channels, a newly discovered channel and Channel 1 of Kenyon & Belderson (1973), named the Gil Eanes Channel by Kenyon *et al.* 2000), are not controlled by underlying topography, at least at present. Their location is thought to be associated with the unconstrained bottom current peeling off downslope through gaps in a longitudinal sandy contourite ridge (Kenyon & Belderson 1973), which acts as a barrier to restrict the main flow of the MOW to the broad current-swept terrace.

Channel pattern and geometry

Sea-floor sonographs and 3.5 kHz profiler records. At least five downslope running channels are identified from the available bathymetric data

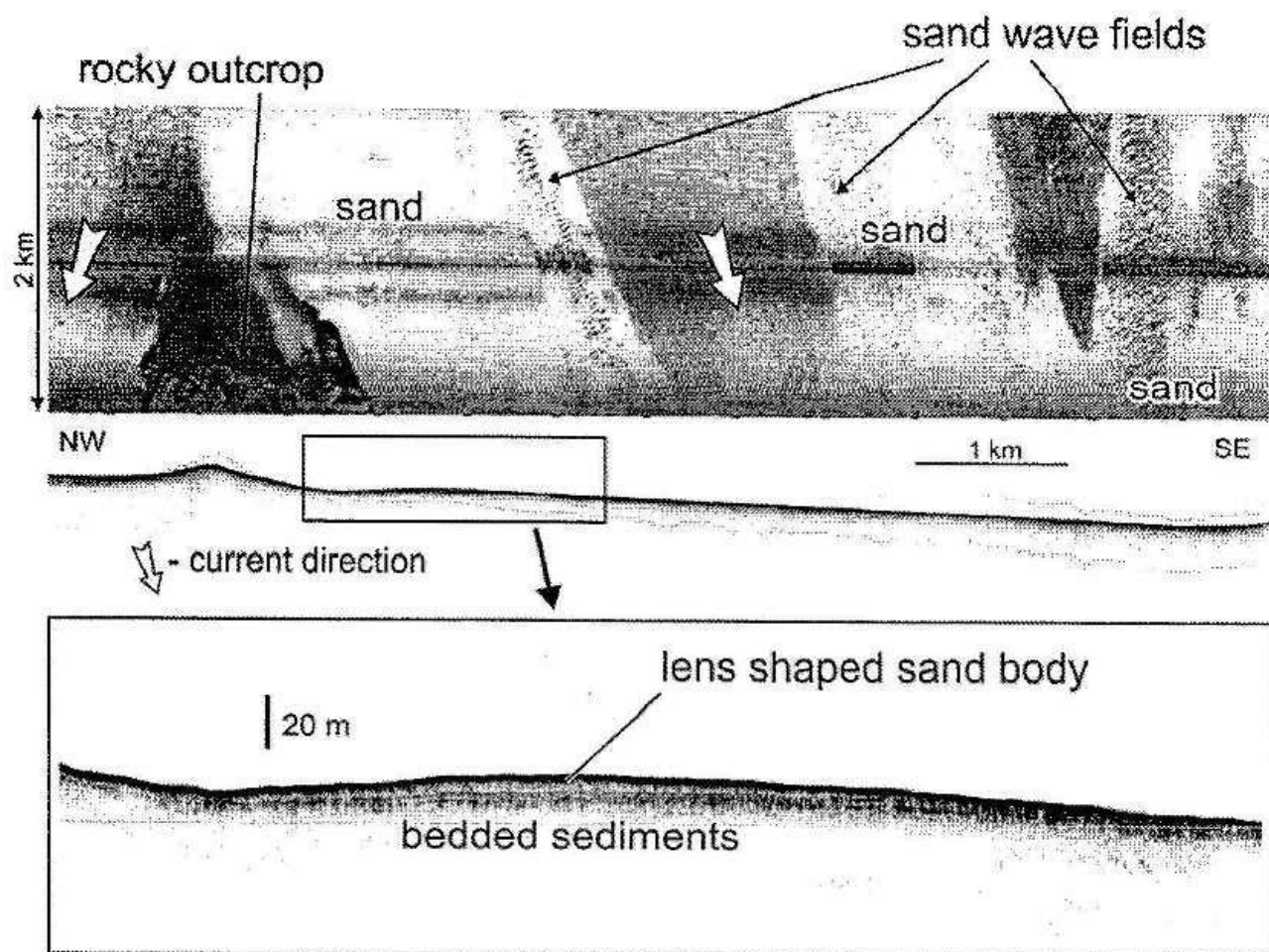


Fig. 11. High-resolution sidescan sonar and sub-bottom profiler records showing sand sheets (lower backscattering shown by lighter shades) on a contourite channel floor.

(Fig. 12a) and are best seen on the 11 kHz SeaMap sonograph mosaic (Fig. 13). The largest channel, Channel 2 of Kenyon & Belderson (1973), is controlled by NE–SW-trending diapiric ridges, which act as a partial barrier across the MOW pathway. The floor of this channel is characterized by relatively high backscatter resulting from scoured rock outcrop and basal conglomerate, across which sand is transported as longitudinal and transverse bedforms.

There are also non-topographically controlled channels (the ‘free-standing’ channels of Habgood *et al.* (2003)), of which the largest is the Gil Eanes Channel. All of the channels run downslope and trend perpendicular to the main pathway of the MOW (Fig. 13). These channels and their setting have been described by Habgood *et al.* (2003) and so will not be described in detail here. The head of the Gil Eanes Channel is *c.* 6 km wide, and is at a depth of 900 m, and the channel extends downslope for 40 km, terminating at 1250 m water depth. The flanks of the channel are covered with a dense pattern of sediment waves. The morphology and lithology of these flanking

waves changes with depth as the influence of the main flow of the MOW lessens. There seems to be a continuum of sediment waves related to this change in current speed, divided here into sand waves, muddy sand waves and mud waves. Their appearance in plan and profile has been shown by Habgood *et al.* (2003).

Sand waves. The sand waves are confined to a part of the terrace, and to the floors and levees of the downslope channel (Fig. 12). With the higher resolution of the TOBI sidescan system several sandy bedforms are differentiated. Most of the sand waves on the terrace are small asymmetrical sand waves (wavelength about 40 m) on the back of large asymmetrical sand waves (wavelength about 300 m). The 3.5 kHz profiles show small, overlapping hyperbolae, with vertices that are tangential to the sea floor. Shorter straight-crested transverse waves with wavelengths of 200–260 m are also common.

Muddy sand waves. This type of wave is mostly found on the flanks of the Gil Eanes Channel. In

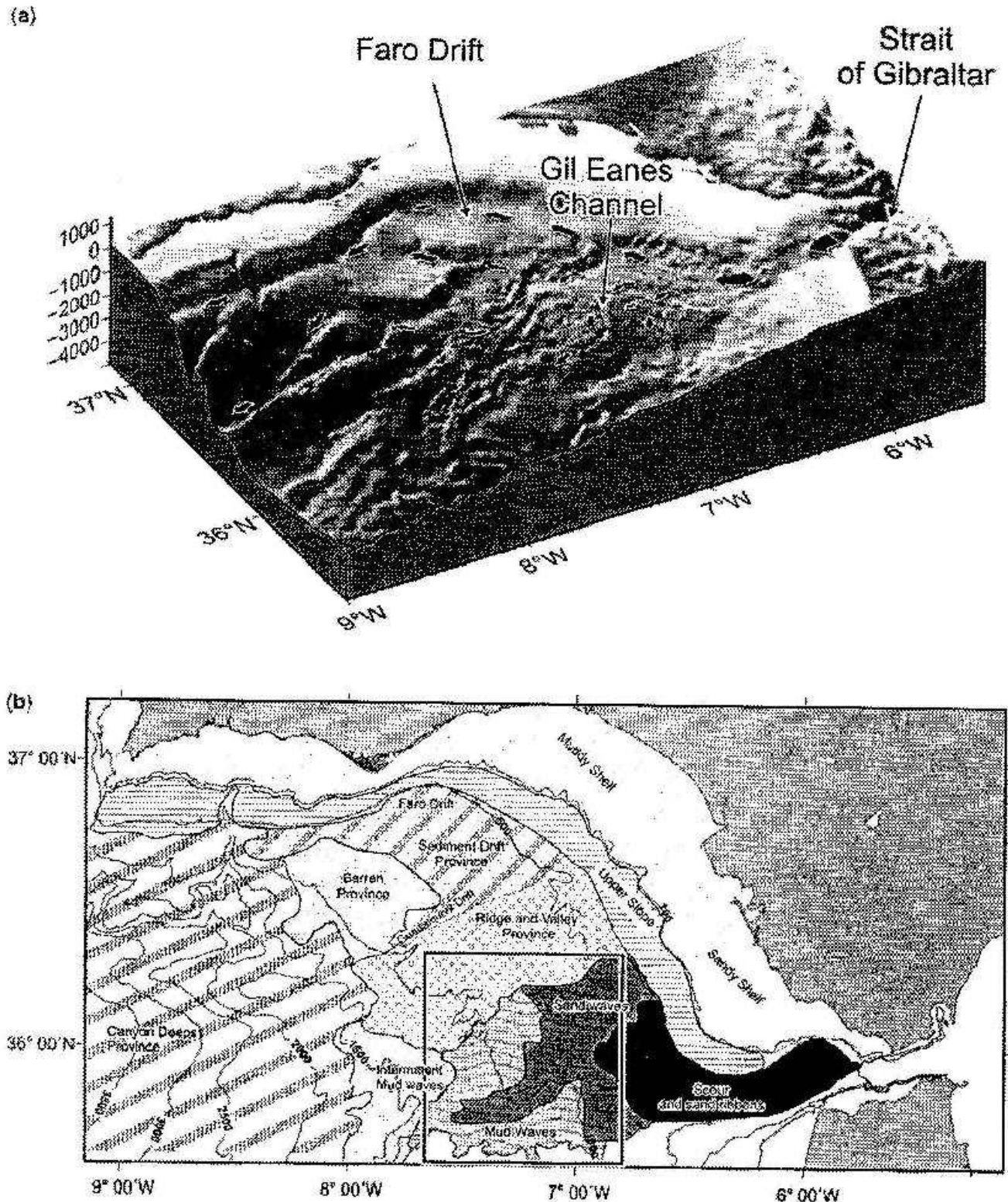


Fig. 12. (a) Perspective view of the Gulf of Cadiz sea-floor topography. Arrows show major Mediterranean Outflow Water pathways. (b) Physical provinces of the Gulf of Cadiz (modified from Heezen & Johnson 1969; Kenyon & Belderson 1973; Nelson *et al.* 1993, 1999; Baraza *et al.* 1999; Maldonado *et al.* 1999; Habgood *et al.* 2003).

plan view these waves are mainly sinuous to crescentic with short crestlines of c. 600 m. Wavelengths range from 300 m to over 600 m but with an average of 350 m. The echo response from 3.5 kHz profiles is of steep-sided, overlapping hyperbolae, thus the waves are interpreted as having relatively steep sides and narrow troughs. This hyperbolic

response is similar to the profile type IIB-2 from the western equatorial Atlantic (Damuth 1975) and has been associated with both turbidity-current processes and bottom-current processes.

Mud waves. These waves occur in deeper water beyond the fields of muddy sand waves on the

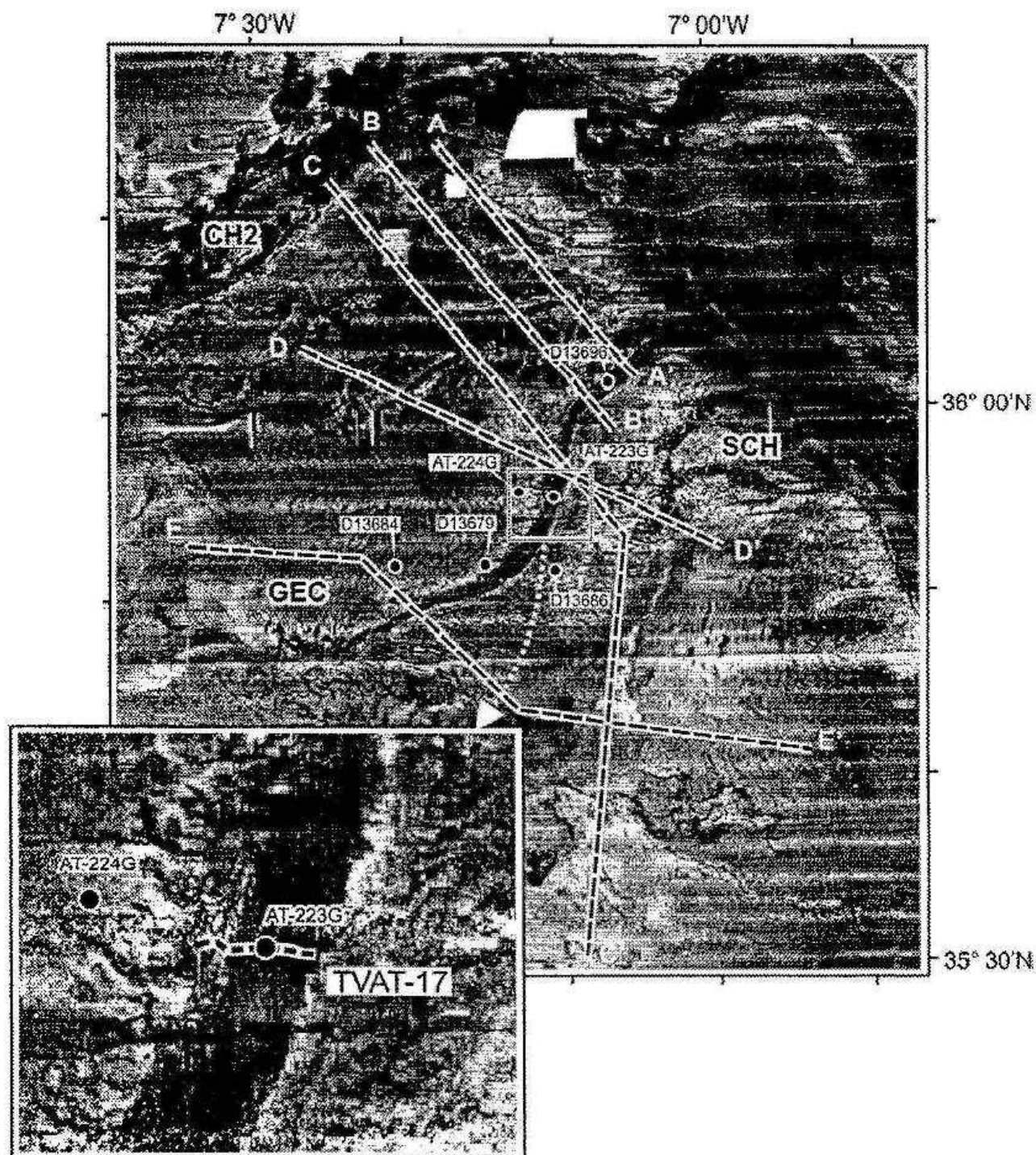


Fig. 13. A portion of SeaMap sea-floor imagery showing the Gil Eanes Channel (GEC) and smaller (SCH) peel-off channels. Seismic lines, sampling stations and TV run discussed in the text are also shown. CH2 is Channel 2 of Kenyon & Belderson (1973), which is topographically steered by diapiric ridges. High backscatter is shown by darker shades.

flanks of the channels. The currents that form them are weaker than those that form the sandier waves. The wave orientation on both flanks is at c. 40° to the channel, making a V shape that points down-channel. The mud waves are generally straight crested, with wavelengths between 600 and 1000 m and amplitudes of 25–35 m. On our

seismic profiles they have broad, low-amplitude, non-overlapping hyperbolae, often with parallel sub-bottom reflectors equivalent to the type II-B4 of Damuth (1975).

Seismic expression. A set of seismic lines was obtained across the Gil Eanes Channel and adjacent

areas of the contourite drift (Fig. 13). Four major seismic units are recognized (Fig. 14). The lowermost unit, Unit I, has a chaotic seismic signature and its upper surface shows a number of diapir-like features protruding into the overlying sedimentary sequence. This unit is attributed to the Olistostrome Unit and Middle Miocene deposits described by Maldonado *et al.* (1999). Unit II is about 0.8 s thick and forms a sedimentary drape over the Olistostrome Unit. It has parallel continuous reflectors and is correlated with the Lower Miocene–Pliocene strata of Maldonado *et al.* (1999). The upper unit, Unit III, is found where the peel-off channels occur and is an Upper Pliocene–Quaternary sequence according to Maldonado *et al.* (1999). The unit tends to fill the sub-basins formed by undulations of the surface of the middle unit and has a lens like-geometry, thinning out at its flanks, which is a characteristic of contourite deposits. The thickness of the unit increases downslope from about 200 to 600 ms. At its base there is an erosional unconformity, otherwise it onlaps or downlaps on the underlying strata. The internal structure of Unit III is complex and three seismic facies have been recognized.

Facies 1. The facies has a chaotic character and yet is acoustically transparent and is mainly found in the uppermost part of the sequence in the areas where sand waves and muddy sand waves are seen on the sonographs. The facies is found within channel levees, and is interpreted as a mainly sandy sequence formed by aggradation of sand waves and muddy sand waves outside the peel-off channels.

Facies 2. The facies has prolonged or short parallel reflectors onlapping or downlapping on the underlying Unit II. The facies is more common in the lower part of Unit III and is interpreted as a primarily silty sequence with some sand beds.

Facies 3. The facies is characterized by short, high-amplitude coherent reflectors and is found mainly underneath channels. It is interpreted as coarse-grained channel fills.

The Gil Eanes Channel, the largest of the channels associated with Unit III, has a U-shaped profile and is about 120 m deep. At the upper part of the slope where Unit III is only about 100 ms thick the channel is incised into Unit II. The channel has an asymmetric profile with a higher right-hand 'levee', which shows an erosional character with truncated beds of Unit II cropping out at the sea floor. The left levee crest is about 75 m lower and has an aggradational nature. From the vertical distribution of Facies 3 it is inferred that the position of the channels through time was

relatively stable. In the deeper part of the slope to the west of the Gil Eanes Channel, where small channels are rare, the sequence is dominated by Facies 2.

Sediment cores

Channel flanks. Four cores were taken from different locations along the Gil Eanes Channel flanks (Fig. 13) and their composition is shown in Figure 15.

Core D13684, from the outer part of the western flank of the Channel, has an almost 8 m long sequence of fine-grained sediments with the upper 1.6 m being homogeneous silty mud underlain by 6.4 m of bioturbated mud that contains a 55 cm thick fine silty sand interval. The sand coarsens up in its lower part and fines up in its upper part. Core AT-224G, which was taken upslope and closer to the channel, has 2.5 m of homogeneous, well-sorted clayey silt with foraminifer casts and shell fragments. Core D13679, from the top of the western flank of the Gil Eanes Channel, consists of 373 cm of muddy sands and silts. From visual examination there is a major cycle composed of three main units with gradational contacts between each. However, a closer examination of the continuous wet bulk density profiles identifies a series of smaller cycles. A bioturbated muddy fine sand unit, 116 cm thick, has three coarsening-up–fining-up sequences, each between 30 and 40 cm thick. This is overlain by a similar coarsening-up–fining-up muddy sand fining up into a muddier silt, 60 cm thick. A 14 cm thick muddy unit grades up into muddy sand of similar composition to the base unit; the sand appear to coarsen up throughout and is 142 cm thick.

Core D13686, from the eastern levee of the Gil Eanes Channel (Fig. 15), consists of a 292 cm long cyclical series of coarsening-up muddy fine sands, with sharp erosive tops directly overlain by bioturbated mottled muds. Several phases of bioturbation can be determined within the muds and *Chondrites* is often identifiable. Lenses of muddy silt are common within the sand and silty lenses within the muddy bases. Muddy intervals make up between 4 and 8 cm of a cycle with the muddy sands between 20 and 25 cm of a cycle.

The study of core logs confirmed observations from seismic and sub-bottom profiler records suggesting that there is a more sandy character for the eastern flank of the channel.

Channel floor. Deposits from the channel floor were tested by two cores and an underwater TV line. Core D13696 was collected from the mouth of the Gil Eanes Channel at a water depth of 854 m and recovered 363 cm of biogenic sand (Fig. 15). The core can be subdivided into four

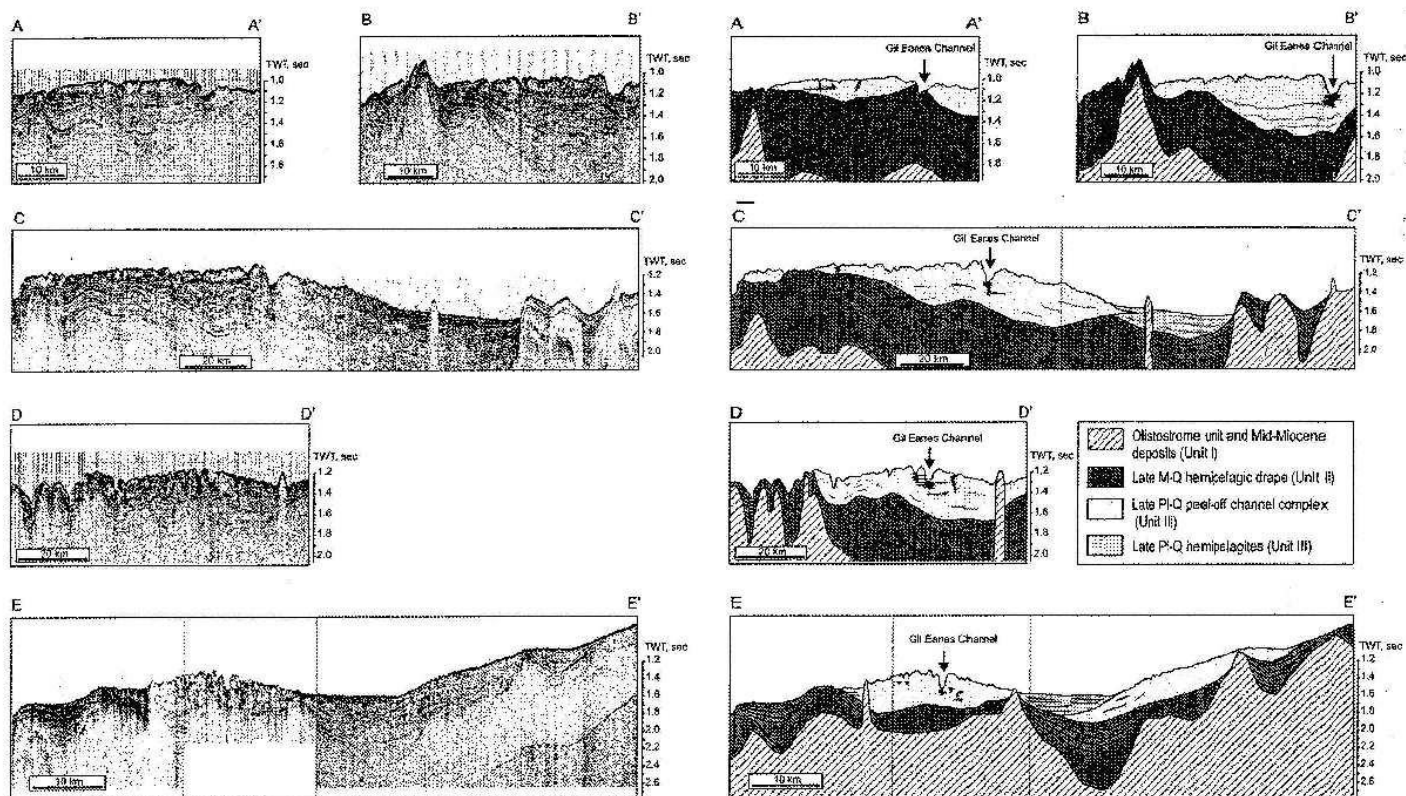


Fig. 14. Interpretation of seismic profiles across the Gil Eanes Channel showing downslope evolution of the channel complex. Profiles are located on Figure 13.

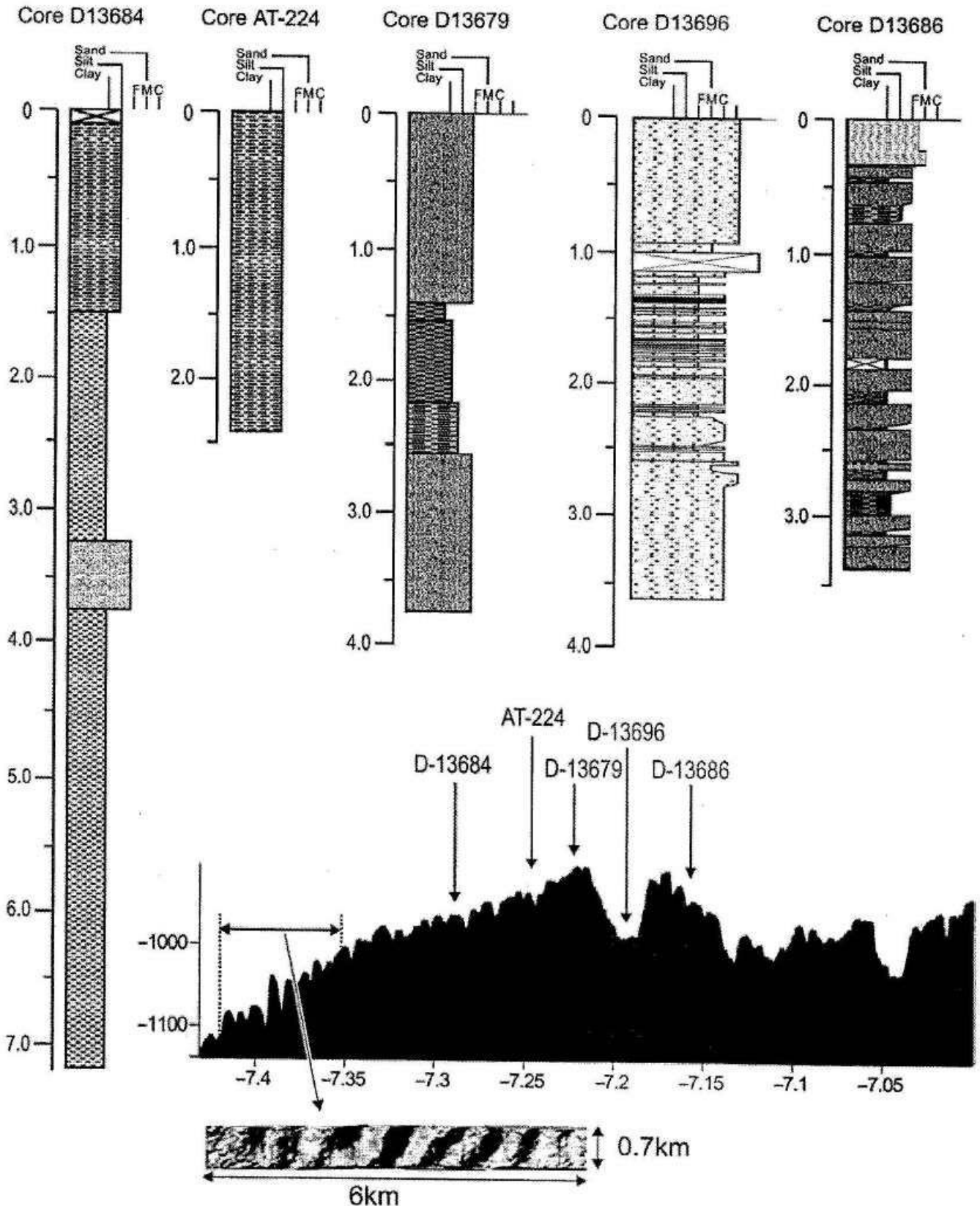


Fig. 15. Core transect and profile across the Gil Eanes Channel and its flanking levee-like features. Available multibeam data and cores show that there are mud waves on the deeper part of the 'levees'.

intervals: a poorly sorted, coarse to very coarse, massive biogenic sand (363–279 cm); a unit with thick coarse sands interbedded with thin fine biogenic sand (279–269 cm); an interbedded sequence of fine–coarse biogenic sands with sharp tops and

bottoms (259–114 cm); and a poorly sorted, very coarse biogenic sand, similar to the base unit but having more shelly fragments. Core AT-223G, taken 12 km down the channel, recovered only a small amount of well-sorted medium–coarse sand.

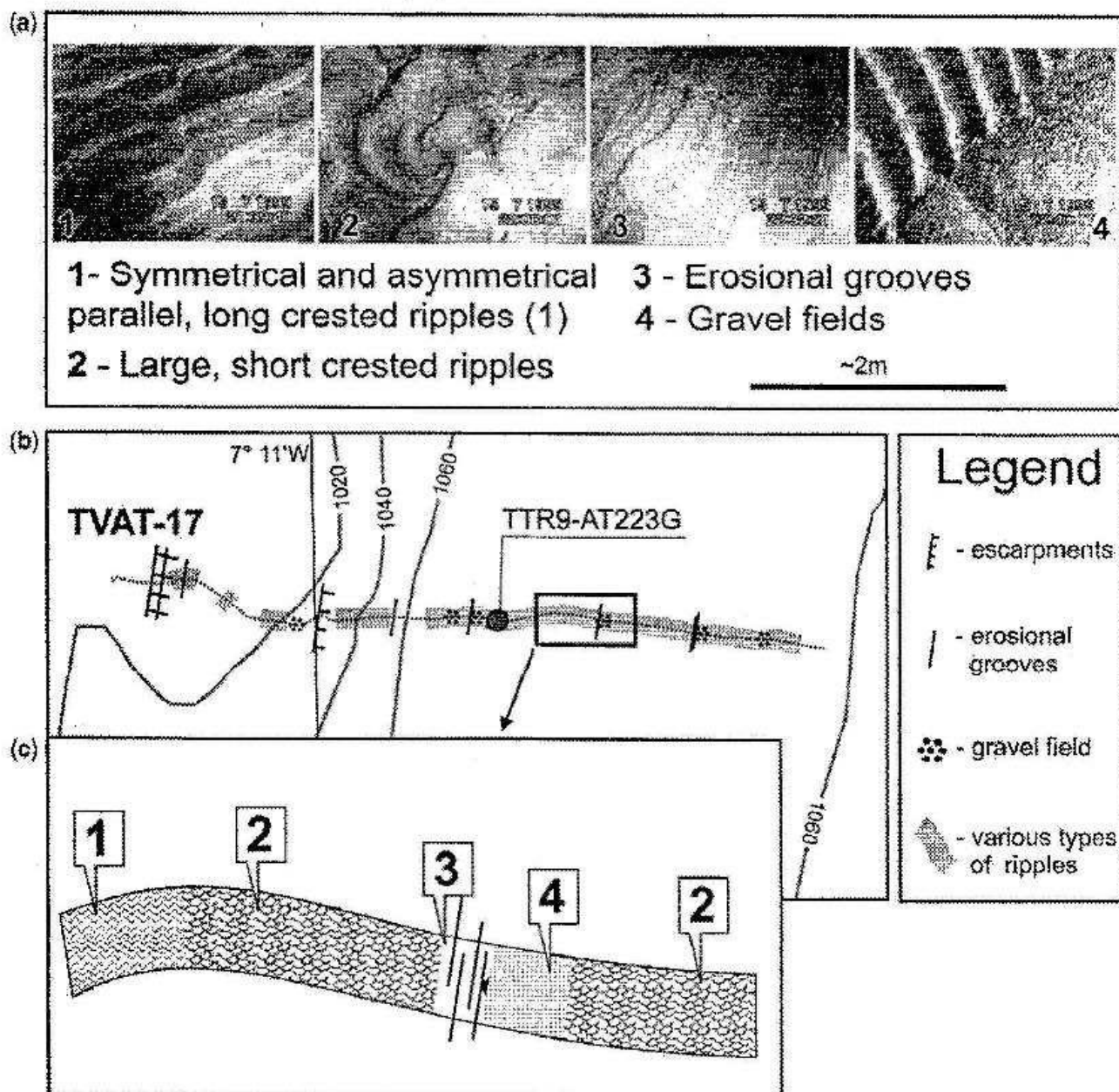


Fig. 16. (a) Video stills showing main types of small bedforms observed across the Gil Eanes Channel thalweg; (b) interpretation of an underwater video transect (TVAT-17); (c) sequence of bedforms reflecting variations of current velocity across a secondary flow filament.

The character of the sea bed in the vicinity of the core was observed during a deep-towed camera run across the channel, the location of which is shown in Figure 13, that was briefly discussed by Habgood *et al.* (2003). The channel wall has a smoothed silty-clay surface that is intensively bioturbated. Escarpments (Fig. 16), a few metres high, are believed to be formed by sediment failures where the channel wall is undercut by current erosion near the base. The erosion has caused striations. Near the base of the wall ripples become larger and have more irregular shapes. Below 1060 m the profile crosses the relatively flat channel floor on which there are ubiquitous fields of ripples of various shapes and abundant gravels (Fig. 16). The most common are large

linguoid ripples, which have a denser distribution towards the centre of the channel. Other frequently encountered bedforms include fields of gravel with parallel ripples, sand streaks and erosional grooves.

Bedforms on the channel floor form the following sequence, which is repeated across the channel floor (Fig. 16): parallel symmetrical ripples, parallel asymmetric ripples, large linguoid ripples and gravel fields with longitudinal sand ribbons and erosional grooves. This sequence is very similar to the one observed in shallow environments, where it was related to changes of bed shear stress (Allen 1968). In the Gil Eanes Channel it is thought to reflect the current velocity distribution across longitudinal flow filaments. The parallel symmetrical ripples correspond to lower velocities in the outer part of

the filaments and the erosional grooves to higher velocities in the inner part of the filaments. Using ripple morphology as a proxy for bottom-current velocity (e.g. Lonsdale & Spiess 1977) the peak current velocities within flow filaments are estimated at $17\text{--}22\text{ cm s}^{-1}$ for parallel ripples, $30\text{--}50\text{ cm s}^{-1}$ for large linguoid ripples and above 50 cm s^{-1} for gravel fields and erosional grooves.

Discussion

Styles of contourite channels

In the studied areas there are both geostrophic, contour-following channels, which seem to descend gently in the direction of flow, and ageostrophic channels that run down relatively steep slopes. Well-marked channels are developed where the bottom current is constricted between a topographic high, such as the basement plateau in the Faeroe Bank area, and an actively growing sediment drift. Such a constriction will cause flow acceleration, which may in turn be followed by stronger erosion on the right-hand side of the channel. Channels in the Faeroe Bank area resemble the moats known from many contourite drift systems worldwide (Faugères *et al.* 1993).

The Mediterranean Undercurrent forms a complex channel pattern in the Gulf of Cadiz, which also comprises both geostrophic and ageostrophic modes. Here too, a significant portion of the flow has geostrophic behaviour, following contours, and often is cited as an upper core and a lower core (Ambar & Howe 1979; Baringer & Price 1997). Eventually, muddy sediment drifts such as the upper Faro Drift (Gonthier *et al.* 1984; Stow *et al.* 1986) are built in the area where the current speed has fallen. SW–NE-trending diapiric ridges topographically steer several filaments of the Undercurrent to the left of its main course but they reassert themselves on the alongslope course once the ridges are passed (Kenyon & Belderson 1973). As a result, the channel distribution has an anastomosing pattern, separated by lozenge-shaped drift bodies, similar to the pattern formed by the channels found west of the Faeroe Bank. A portion of the Undercurrent, known as the lower core, descends downslope without topographic steering and forms peel-off channels including the Gil Eanes Channel and several smaller channels, and thus shows ageostrophic behaviour, being driven downslope primarily by a density contrast. It is not clear from the present dataset whether sediment failure is involved in the initiation of these contourite channels. There are several small-scale, slightly sinuous channels with associated sand lobes found beyond the contourite channels (Habgood *et al.* 2003), which indicate that sandy accumulations at

the ends of these channels fail and are redeposited downslope by gravity flows. At depths of about 1200–1300 m the SeaMap image shows that channels terminate abruptly. According to oceanographic observations at these depths the MOW reaches its density equilibrium level and by mixing with colder North Atlantic Central Water (Baringer & Price 1997) becomes intermediate in character and lifts off the sea floor (Thorpe 1976). This explains the build-up of sand that has then repeatedly failed and produced the gravity-driven channel and lobe systems.

Factors controlling channel development and sand distribution

Both studied channel systems are formed by persistent bottom currents, which were operating over a long period. Recent drilling in the Faeroe–Shetland Channel showed that the onset of deep-water exchange between Arctic and North Atlantic Oceans was established in the early Oligocene (Davies *et al.* 2001). As the Faeroe Bank Channel is a part of this gateway, the thermohaline bottom current has operated in the area for the last 35 Ma. Contourite channels are primarily formed by filaments of fast-flowing current but their geometry can be affected by a growth of sediment drift predominantly on the outer side (left-hand side in the northern hemisphere) of the current pathway. This process seems to be compensated by erosion on the opposite flank, where the current is piled up against the slope by the Coriolis force. As a result, channels migrate laterally. They can be steered by large-scale, resistant sea-bed features, such as the basaltic plateau in the Faeroe Bank Channel area and the diapiric ridges in the Gulf of Cadiz, which can split the flow into several filaments and thus produce the anastomosing pattern. Channels may be narrower in the vicinity of such obstacles, as a result of the resistance of the materials.

A geostrophic bottom current restricted within a channel is often strong enough to be able to transport and deposit sand. The source for this sand is to be sought in the vast amounts of terrigenous material introduced into the area during Late Pliocene–Pleistocene glacial cycles and reworked by the strong bottom current. Sandy sediment is mainly concentrated along the channels and represents a lag deposit, whereas fines are washed out by the fast bottom current and are deposited on the flanks, forming levee-like features. As a channel migrates it forms a continuous sheet of sand overlain by a muddy levee sequence.

The Mediterranean Undercurrent has been operating in the Gulf of Cadiz for almost 5 Ma, since the Early Pleistocene, and has formed several large, fine-grained drifts such as the Faro Drift in the north (e.g. Stow *et al.* 1986). Most of the

Gil Eanes sequence has a seismic signature typical for a Quaternary section (Rodero *et al.* 1999). The formation of this and other peel-off channels can be closely related to the southeastward progradation of shelf prodeltaic deposits during late Quaternary time. Such an abundant supply into the area affected by strong bottom currents resulted in further reworking and formation of significant accumulations of coarse sediments in the upper part of the slope. The latter in turn are redeposited further downslope, primarily by a descending portion of the Undercurrent, although gravity flows may be important at all stages of channel development as there is the potential for rapid accumulation of sand on what are, in some places, steep gradients. Study of the Gil Eanes Channel revealed that its infill is a sand-rich sequence. Seismic records show the presence of an aggradational channel-levee complex with little lateral migration of the channel in time. Levees are composed of silts with increased sand content in the upper part of the sequence where currents are stronger.

Comparison with other channel systems

Channels in the deep sea are formed by two main processes: gravity flows and bottom currents. Turbidity currents are the most common type of gravity flows and are responsible for the formation of the majority of the channels. Bottom currents, and geostrophic contour currents in particular, are also widespread in the deep sea and often form large accumulations called drifts, consisting primarily of fine-grained sediments. Channels are not a typical element of bottom-current systems but may be common in the ocean gateway areas such as the Vema Channel (Johnson 1984) and the areas described here. Previous studies revealed that both contourite and turbidite systems have similar features and can be confused with each other. For instance, similar depositional lobes were reported from the Vema contourite channel and from the Cap Ferret turbidite system (Faugères *et al.* 1998).

Distinguishing between sandy turbidites and sandy bottom-current deposits on seismic data or in the rock record is important because of the economic potential of sands as hydrocarbon reservoirs. The examples studied here show that significant sand accumulations can be formed in contour-current systems and that these present-day examples can be considered as analogues for hydrocarbon reservoirs.

Channel-levee complexes are known to be an important element of turbidite systems but they are also found in areas swept by both the NSOW and the MOW. Channels in the area west of the Faeroe Bank have a remarkable asymmetry, with

one flank being erosional and the other aggradational, and their architecture can be compared with fluvial systems on land. Seismic records from the area, showing prolonged discontinuities and buried palaeo-channels, have a clear resemblance to seismic records across the Vema Channel, suggesting a similar origin for both channel systems. The presence of sandy infill in the Faeroe Bank Channel indicates that peak current speed is about $30\text{--}50\text{ cm s}^{-1}$ (e.g. Johnson *et al.* 1982), which is higher than the current speed reported from the Vema Channel (about 20 cm s^{-1}) (Johnson 1984). Mud waves in the Faeroe Bank Channel region are found only on the outside of channel bands, as they are for turbidite channel systems such as the Monterey (Normark *et al.* 1980; McHugh & Ryan 2000), Toyama (Nakajima *et al.* 1998), Var (Migeon *et al.* 2001) and other systems. This suggests that flow stripping, which is believed to cause sediment wave formation on the flanks of channelized turbidite systems (Piper & Normark 1983), happens mostly at the bends and otherwise most of the flow is concentrated within the channels.

The Gil Eanes Channel forms an aggradational sequence with a stacking pattern of palaeo-channels that is very similar to that for turbidite channel sequences. A variety of sediment waves covers the levees and outer part of the channel (Fig. 15), indicating that overflowing of the descending MOW plume is a frequent, if not near-continuous, process. Fields of sediment waves are not usually as extensive on the levees of turbidite channels, where they mainly occur at bends. However, waves do occur beyond the mouths of turbidite channels, where the turbidity currents become unconfined (e.g. Wynn *et al.* 2000).

The sediments deposited by the Gil Eanes and other peel-off channels have a limited distribution as the traction process that moves them terminates relatively abruptly where the current lifts off the sea bed. Such abrupt terminations of flow and the resultant sand accumulations are not typical for turbidity currents, which usually travel a long way beyond the channel mouth, forming varied and extensive sheet-like deposits as on the Mississippi Fan, Gulf of Mexico (Garrison *et al.* 1982), Indus Fan, Indian Ocean (Kolla & Coumes 1987), Var sedimentary system, Mediterranean Sea (Mulder *et al.* 1998), Pochnoi Fan, Bering Sea (Kenyon & Millington 1995), and in many other turbidite systems.

Conclusions

The study of two channelized depositional systems controlled by contour currents or bottom currents revealed that they can form significant sand

accumulations in the deep sea. Channel–levee complexes can be formed by both geostrophic and ageostrophic bottom currents. The channels formed by the NSOW, west of the Faeroe Bank Channel, are developed under the influence of both geostrophic currents and ageostrophic currents and are characterized by significant lateral migration, usually to the right, which determines the channel architecture with its cross-sectional asymmetry. Prolonged unconformities marking the onset of the bottom-current dominated environment and also resulting from channel migration are typical of this system. Sand bodies are mostly associated with channel infills, whereas outside the channels, sequences are typically fine grained.

The bottom-current system in the Gulf of Cadiz formed by the Mediterranean Undercurrent has a complex pattern with a large portion of the water mass flowing under geostrophic conditions, but some of the densest water becomes ageostrophic and descends downslope as a result of gravity. As a result, a series of channels is formed with the largest one, Gil Eanes, being about 40 km long. Medium–coarse sand and fine gravels are predicted to form most of the channel infills, and sand is also abundant in the upstream areas, where fields of sand waves form on the broad slope terrace developed by the Undercurrent. Flanking the channels are features resembling levees. These consist mainly of silty sequences that have a significantly higher sand content in the shallower water.

Both of the studied depositional systems have a variety of contourite sand channels but in most respects they are remarkably similar. The main pathway of the densest water is the shallowest and several branches turn off to the left of this main pathway, and descend to a lower level before bending to the right, parallel to the main pathway, under the influence of Coriolis forces. In both cases there are proximal deposits of sand deposited as the flow becomes unconfined and the current speed slackens. In the Gulf of Cadiz these consist of extensive sheets of cross-bedded sand of the order of several tens of kilometres across and up to several tens of metres thick. The speed may pick up again as the current flows down a gentle gradient and further coarse deposits, both sand and gravel, accumulate within channels, reaching several hundreds of metres thick. At the ends of some channels in the Gulf of Cadiz there are concentrations of sand formed as the current lifts off the sea floor. Similar accumulations occur where a canyon intersects the pathway of the contour current. These deposits can fail and form sandy lobes on the floor of the nearest basin or, in the case of a canyon, on the canyon floor (Habgood *et al.* 2003).

Similarities between bottom-current–contourite sand channels and turbidite sand channels are the

aggradational nature of some channel floors and the flanking waves of finer-grained sediment. Contourite channels are distinguished from turbidite channels by their more marked asymmetry in channel profile and sand distribution, the presence of regional unconformities and their shape in plan view.

Two factors that are found in both the studied areas and may be of particular importance for the formation of contourite channels with reservoir potential are the high sand supply (including ‘pure’ sands or large volumes of sand-enriched sediments), and the long history of strong bottom-current existence.

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References

- AKHMETZHANOV, A. M. 2003. Sandy sediments of deep-water bottom current depositional systems. *Vestnik Moskovskogo Universiteta, Geology Series*, **5**, 39–47 [in Russian].
- ALLEN, J. R. L. 1968. *Current Ripples; Their Relation to Patterns of Water and Sediment Motion*. North-Holland, Amsterdam.
- AMBAR, I. & HOWE, M. R. 1979. Observations of the Mediterranean outflow—I. Mixing in the Mediterranean outflow. *Deep-Sea Research*, **26A**, 535–554.
- BARAZA, J., ERCILLA, G. & NELSON, C. H. 1999. Potential geologic hazards on the eastern Gulf of Cadiz slope (SW Spain). *Marine Geology*, **155**, 191–215.
- BARINGER, M. O. & PRICE, J. F. 1997. Mixing and spreading of the Mediterranean outflow. *Journal of Physical Oceanography*, **27**, 1654–1677.
- BELDERSON, R. H., KENYON, N. H., STRIDE, A. H. & STUBBS, A. R. 1972. *Sonographs of the Seafloor: a Picture Atlas*. Elsevier, Amsterdam.
- BOLDREEL, L. O., ANDERSEN, M. S. & KUIPERS, A. 1998. Neogene seismic facies and deep-water gateways in the Faeroe Bank area, NE Atlantic. *Marine and Petroleum Geology*, **15**, 129–140.
- BRITISH OCEANOGRAPHIC DATA CENTRE 1997. *GEBCO Digital Atlas*. British Oceanographic Data Centre on behalf of IOC and IHO.
- CREASE, J. 1965. The flow of Norwegian Sea water through the Faeroe Bank Channel. *Deep-Sea Research*, **12**, 143–150.
- DAMUTH, J. 1975. Echo character of the Western Equatorial Atlantic floor and its relationship to the dispersal and distribution of terrigenous sediments. *Marine Geology*, **18**, 17–45.

- DAVIES, R., CARTWRIGHT, J., PIKE, J. & LINE, C. 2001. Early Oligocene initiation of North Atlantic deep water formation. *Nature*, **410**, 917–920.
- DORN, W. U. & WERNER, F. 1993. The contour-current flow along the southern Iceland–Faeroe Ridge as documented by its bedforms and asymmetrical channel fillings. *Sedimentary Geology*, **82**, 47–59.
- FAUGÈRES, J. C., MEZERAIS, M. L. & STOW, D. A. V. 1993. Contourite drift types and their distribution in the North and South Atlantic Ocean basins. *Sedimentary Geology*, **82**, 189–203.
- FAUGÈRES, J. C., IMBERT, P., MEZERAIS, M. L. & CREMER, M. 1998. Seismic patterns of a muddy contourite fan (Vema Channel, South Brazilian Basin) and a sandy distal turbidite deep-sea fan (Cap Ferret system, Bay of Biscay); a comparison. *Sedimentary Geology*, **115**, 81–110.
- FAUGÈRES, J. C., STOW, D. A. V., IMBERT, P. & VIANA, A. 1999. Seismic features diagnostic of contourite drifts. *Marine Geology*, **162**, 1–38.
- FLEISCHER, U., HOLZKAMM, F., VOLLBRECHT, K. & VOPPEL, D. 1974. Die Struktur des Island-Faeroer-Rückens aus geophysikalischen Messungen. *Deutsche Hydrographische Zeitschrift*, **27**, 97–113.
- GARRISON, L. E., KENYON, N. H. & BOUMA, A. H. 1982. Channel systems and lobe construction in the Mississippi Fan. *Geo-Marine Letters*, **2**, 31–39.
- GONTHIER, E. G., FAUGÈRES, J. C. & STOW, D. A. V. 1984. Contourite facies of the Faro Drift, Gulf of Cadiz. In: STOW, D. A. V. & PIPER, D. J. W. (eds) *Fine-Grained Sediments; Deep-Water Processes and Facies*. Geological Society, London, Special Publications, **15**, 275–292.
- HABGOOD, E. L., KENYON, N. H., AKHMETZHANOV, A. M., WEAVER, P. P. E., MASSON, D. G., GARDNER, J. & MULDER, T. 2003. Deep water sediment wave fields, contourite channels and associated depositional sand lobes in the Gulf of Cadiz, NE Atlantic. *Sedimentology*, **50**, 483–510.
- HANSEN, B. & MEINCKE, J. 1979. Eddies and meanders in the Iceland–Faeroe Ridge area. *Deep-Sea Research*, **26**, 1067–1082.
- HANSEN, B. & ØSTERHUS, S. 2000. North Atlantic–Nordic Seas exchanges. *Progress in Oceanography*, **45**, 109–208.
- HEEZEN, B. C. & JOHNSON, G. L. 1969. Mediterranean undercurrent and microphysiography west of Gibraltar. *Bulletin de l'Institut Océanographique, Monaco*, **67**, 1–28.
- IORGA, M. C. & LOZIER, M. S. 1999. Signatures of the Mediterranean outflow from a North Atlantic climatology, 1. Salinity and density fields. *Journal of Geophysical Research*, **104**(C11), 25985–26009.
- JOHNSON, D. A. 1984. The Vema Channel; physiography, structure, and sediment–current interactions. *Marine Geology*, **58**, 1–34.
- JOHNSON, M. A., KENYON, N. H. & BELDERSON, R. H. 1982. Sand transport. In: STRIDE, A. H. (ed.) *Off-shore Tidal Sands: Processes and Deposits*. Chapman and Hall, London, 58–94.
- KENYON, N. H. & BELDERSON, R. H. 1973. Bedforms of the Mediterranean undercurrent observed with side-scan sonar. *Sedimentary Geology*, **9**, 77–99.
- KENYON, N. H. & MILLINGTON, J. 1995. Contrasting deep-sea depositional systems in the Bering Sea. In: PICKERING, K. T., HISCOTT, R. N., KENYON, N. H., RICCI LUCCHI, F. & SMITH, R. D. A. (eds) *Atlas of Deep Water Environments: Architectural Style in Turbidite Systems*. Chapman & Hall, London, 196–202.
- KENYON, N. H., IVANOV, M. K., AKHMETZHANOV, A. M. & AKHMANOV, G. G. (eds) 2000. *Multidisciplinary Study of Geological Processes on the North East Atlantic and Western Mediterranean Margins. Preliminary results of geological and geophysical investigations during the TTR-9 cruise of R/V Professor Logachev, June–July, 1999*. IOC Technical Series, **56**.
- KENYON, N. H., IVANOV, M. K., AKHMETZHANOV, A. M. & AKHMANOV, G. G. (eds) 2001. *Interdisciplinary Approaches to Geoscience on the North East Atlantic Margin and Mid-Atlantic Ridge. Preliminary results of investigations during the TTR-10 cruise of R/V Professor Logachev, July–August, 2000*. IOC Technical Series, **60**.
- KOLLA, V. & COUMES, F. 1987. Morphology, internal structure, seismic stratigraphy and sedimentation of Indus Fan. *AAPG Bulletin*, **71**, 650–677.
- KUIJPERS, A. H., ANDERSEN, M. S., KENYON, N. H., KUNZENDORF, H. & VAN WEERING, T. C. E. 1998. Quaternary sedimentation and Norwegian Sea Overflow pathways around Bill Bailey Bank, northeastern Atlantic. *Marine Geology*, **152**, 101–127.
- LONSDALE, P. & SPIESS, F. N. 1977. Abyssal bedforms explored with a deeply towed instrument package. *Marine Geology*, **23**, 57–75.
- MADELAIN, F. 1970. Influence de la topographie du fond sur l'écoulement Méditerranéen entre le Détroit de Gibraltar et le Cap Saint-Vincent. *Cahiers Océanographique*, **22**, 63–72.
- MALDONADO, A., SOMOZA, L. & PALLARES, L. 1999. The Betic orogen and the Iberian–African boundary in the Gulf of Cadiz; geological evolution (central North Atlantic). *Marine Geology*, **155**, 9–43.
- MCCAVE, I. N. & TUCHOLKE, B. E. 1986. Deep current-controlled sedimentation in the western North Atlantic. In: VOGT, P. R. & TUCHOLKE, B. E. (eds) *The Western North Atlantic Region*. Geological Society of America, Boulder, CO, 451–468.
- MCHUGH, C. M. G. & RYAN, W. B. F. 2000. Sedimentary features associated with channel overbank flow: example from the Monterey Fan. *Marine Geology*, **163**, 199–215.
- MIGEON, S., SAVOYE, B., ZANELLA, E., MULDER, T., FAUGÈRES, J. C. & WEBER, O. 2001. Detailed seismic-reflection and sedimentary study of turbidite sediment waves on the Var Sedimentary Ridge (SE France): significance for sediment transport and deposition and for the mechanisms of sediment-wave construction. *Marine and Petroleum Geology*, **18**, 179–208.
- MULDER, T., SAVOYE, B., PIPER, D. J. W. & SYVITSKI, J. P. M. 1998. The Var submarine sedimentary system: understanding Holocene sediment delivery

- processes and their importance to the geological record. In: STOKER, M. S., EVANS, D. & CRAMP, A. (eds) *Geological Processes on Continental Margins: Sedimentation, Mass-wasting and Stability*. Geological Society, London, Special Publications, **129**, 145–166.
- MULDER, T., VOISSET, M., LECROART, P., *ET AL.* 2003. The Gulf of Cadiz: an unstable giant contouritic levee. *Geo-Marine Letters*, **23**, 7–18.
- NAKAJIMA, T., SATOH, M. & OKAMURA, Y. 1998. Channel–levee complexes, terminal deep-sea fan and sediment wave fields associated with the Toyama Deep-Sea Channel system in the Japan Sea. *Marine Geology*, **147**, 25–41.
- NELSON, C. H., BARAZA, J. & MALDONADO, A. 1993. Mediterranean undercurrent sandy contourites, Gulf of Cadiz, Spain. *Sedimentary Geology*, **82**, 103–131.
- NELSON, C. H., BARAZA, J., MALDONADO, A., RODERO, J., ESCUTIA, C. & BARBER, J. H. JR. 1999. Influence of the Atlantic inflow and Mediterranean outflow currents on late Quaternary sedimentary facies of the Gulf of Cadiz continental margin. *Marine Geology*, **155**, 99–129.
- NORMARK, W. R., HESS, G. R., STOW, D. A. V. & BOWEN, A. J. 1980. Sediment waves on the Monterey Fan levee: a preliminary physical interpretation. *Marine Geology*, **37**, 1–18.
- PIPER, D. J. W. & NORMARK, W. R. 1983. Turbidite depositional patterns and flow characteristics, Navy submarine fan, California Borderland. *Sedimentology*, **30**, 681–694.
- RODERO, J., PALLARES, I. & MALDONADO, A. 1999. Late Quaternary seismic facies of the Gulf of Cadiz Spanish margin; depositional processes influenced by sea-level change and tectonic controls. *Marine Geology*, **155**, 131–156.
- SAUNDERS, P. M. 1990. Cold outflow from the Faroe Bank Channel. *Journal of Physical Oceanography*, **20**, 29–43.
- SMITH, W. H. F. & SANDWELL, D. T. 1994. Bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry. *Journal of Geophysical Research*, **99**, 21803–21824.
- STOW, D. A. V. 1979. Distinguishing between fine-grained turbidites and contourites on the Nova Scotian deep water margin. *Sedimentology*, **26**, 371–384.
- STOW, D. A. V., FAUGÈRES, J. C. & GONTHIER, E. 1986. Facies distribution and textural variation in Faro Drift contourites: velocity fluctuation and drift growth. *Marine Geology*, **72**, 71–100.
- THORPE, S. A. 1976. Variability of the Mediterranean undercurrent in the Gulf of Cadiz. *Deep-Sea Research*, **23**, 711–727.
- VIANA, A. R., FAUGÈRES, J. C. & STOW, D. A. V. 1998. Bottom-current-controlled sand deposits; a review of modern shallow- to deep-water environments. *Sedimentary Geology*, **115**, 53–80.
- WYNN, R. B., WEAVER, P. P. E., ERCILLA, G., STOW, D. A. V. & MASSON, D. G. 2000. Sedimentary processes in the Selvage sediment-wave field, NE Atlantic: new insights into the formation of sediment waves by turbidity currents. *Sedimentology*, **47**, 1181–1197.

