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Seismic features diagnostic of contourite drifts

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Seismic features diagnostic of contourite drifts

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Abstract

The sedimentary construction of oceanic margins is most often carried out by the combined action of gravitational processes and processes related to bottom (contour) currents. One of the major difficulties encountered in the interpretation of seismic profiles crossing such margins is the differentiation of these two types of deposit, especially where they display very complicated imbricated geometries. The aim of this paper, therefore, is to derive criteria for the recognition of contourite vs. turbidite deposits, based on the analysis of many seismic profiles from both published and unpublished sources. The following features are the most diagnostic for the recognition of contourite drifts. At the scale of the basin, four different drift types can be distinguished according to the morphostructural context, their general morphology and the hydrodynamic conditions. These are: contourite-sheeted drifts (including abyssal sheets and slope-plastered sheets), elongate-mounded drifts (detached and separated types), channel-related drifts (including lateral and axial patch drifts and downstream contourite fans), and confined drifts trapped in small, tectonically active basins. At the scale of the drift, three features provide the best diagnostic criteria for recognising contourite deposits on seismic profiles: major discontinuities that can be traced across the whole drift and represent time lines corresponding to hydrological events, lenticular, convex-upward depositional units with a variable geometry, and a specific style of progradation–aggradation of these units that is influenced by interaction of the bottom current with Coriolis force and with the morphology. At the scale of depositional units, the seismofacies show a wide variety of reflector characteristics, many of which are very similar to those observed in turbidite series. Distinction between sediment wave seismofacies deposited by turbidity currents and bottom currents still remains ambiguous. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: contourite drift; turbidite; seismic pattern; Cenozoic; reservoir

1. Introduction

Many studies have demonstrated the combined action of downslope gravity-driven processes and

alongslope processes linked to bottom currents in the sedimentary construction of oceanic margins (Heezen et al., 1966; Hollister and Heezen, 1972). This is particularly true in the North and West Atlantic (Egloff and Johnson, 1975, 1978; Mountain and Tucholke, 1983, 1985; Tucholke and Laine, 1983; Tucholke and Mountain, 1986; Myers and Piper, 1988; McMaster et al., 1989; Hesse, 1992; Locker

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and Laine, 1992; Einiken and Hinz, 1993; Howe et al., 1994; Stöker, 1998, among many others), the South Atlantic (Massé et al., 1998; Viana and Faugères, 1998), the Southwest Indian (Dingle et al., 1987; Ben-Avraham et al., 1994), and Antarctic (Kuvaas and Leitchenkov, 1992; Rebesco et al., 1996, 1997) passive margins, but has also been noted along active margins such as the Sumba Basin off the Indonesian archipelago (Reed et al., 1987) and the east New Zealand margin (Carter and McCave, 1994).

The deposits controlled by deep-water bottom currents (contour currents) resulting from thermohaline circulation in the oceans form accumulations known as contourite drifts. These drifts are particularly well-shown in the Atlantic Ocean (Fig. 1). They have dimensions directly comparable to those of deep-sea fans constructed by turbidity current and related processes. They range from small patch drifts (< 100 km² in area), equivalent in size to isolated

turbidite lobes or debris flow masses on slopes, to giant elongate drifts (> 100,000 km² in area) which match many of the world's large muddy elongate fans (Stow et al., 1996). Along some margins and in certain ocean basins, for example parts of the NW Atlantic margin and the South Brazilian and Argentinian basins (Flood and Shor, 1988) in the SW Atlantic, the contourite deposits are more extensive than those of turbidites.

Wind-driven currents also can play an important role in drift formation even at abyssal depth (Hollister and McCave, 1984). It is more particularly in the case of the Antarctic Circumpolar Current (ACC) along the continental margin west of the Antarctic Peninsula (Rebesco et al., 1996) or off southern New Zealand as revealed by the recent ODP Leg 181.

One of the major difficulties encountered at present in the interpretation of seismic profiles across continental margins is the differentiation between turbidite and contourite deposits and their associated

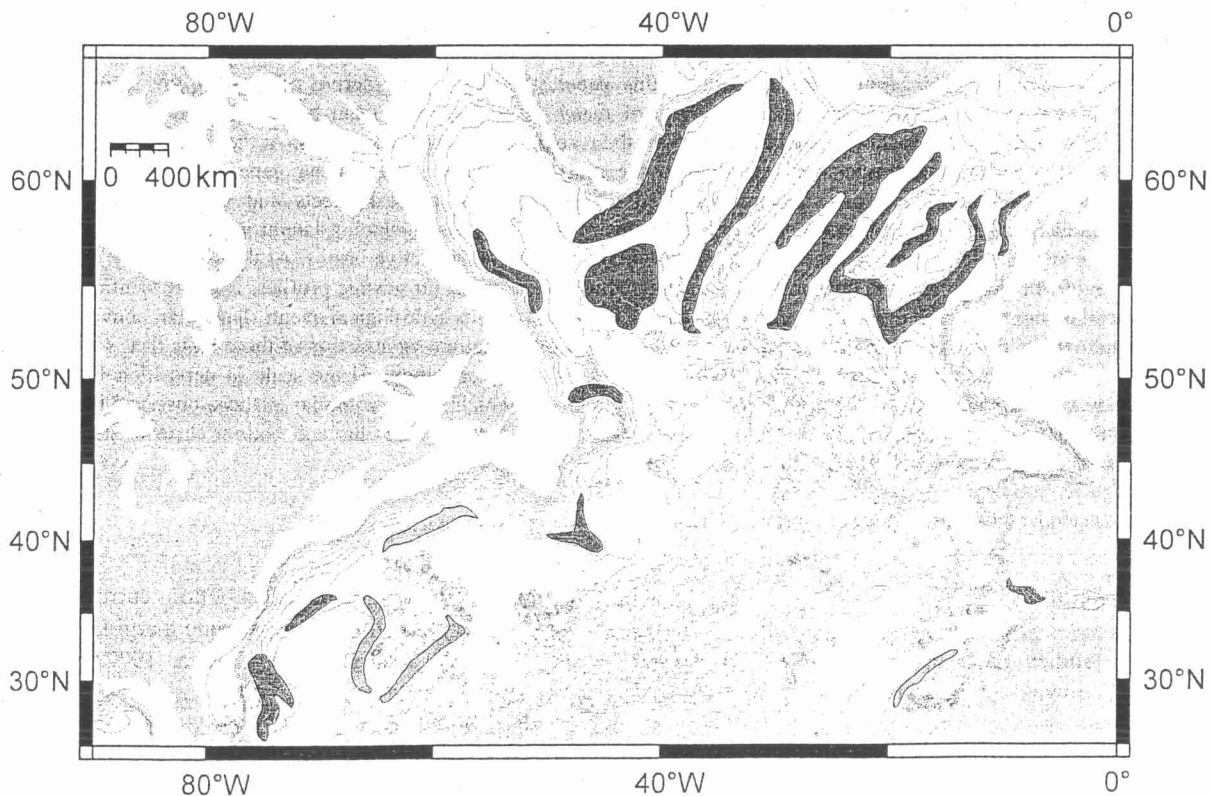


Fig. 1. Contourite sediment distribution in the North Atlantic.

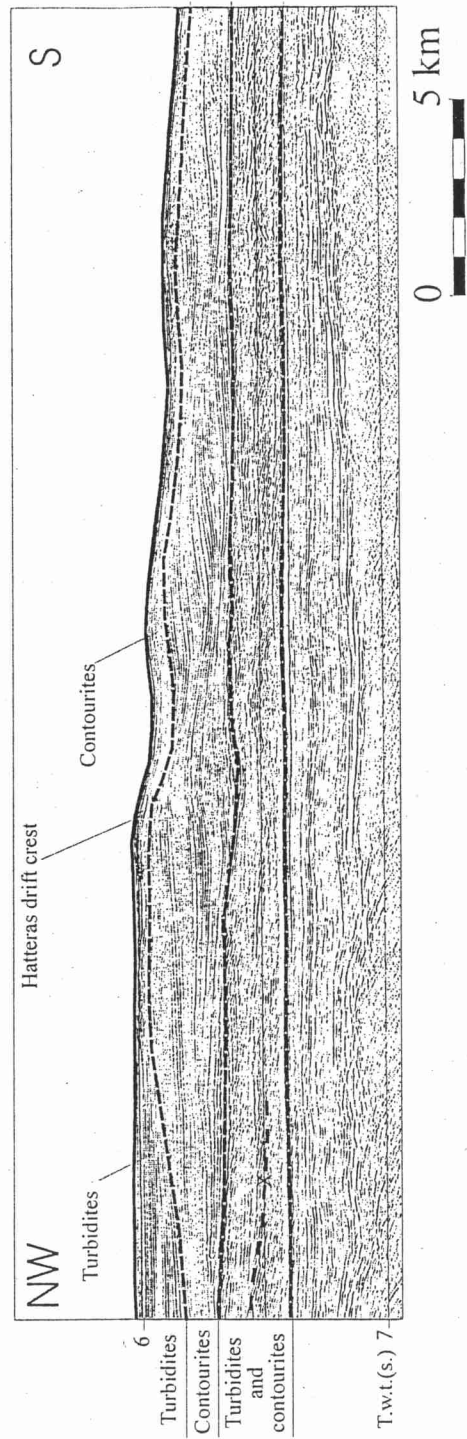


Fig. 2. Imbrication of turbiditic and contourite deposits in the northern Hatteras Outer Ridge, eastern US margin, off Cape Hatteras (after Locker and Laine, 1992, multichannel seismic line).

facies. This difficulty is even greater in regions where the two types of deposit are closely interbedded. For example, the eastern margin of the USA off Cape Hatteras is both dissected by canyons and channels carrying material downslope and swept in the deeper parts by the Western Boundary Undercurrent (WBUC; Tucholke and Mountain, 1986; McMaster et al., 1989). The sediment prism is a complex arrangement of intercalated turbidite and contourite units (Fig. 2) whose nature and geometry are difficult to interpret from seismic evidence alone. Even with the addition of cored and logged borehole data (e.g., DSDP Site 603, van Hinte et al., 1983) the problem is not always easy to resolve.

Seismic stratigraphic models tend to represent major turbidite accumulations as distinctive of low-stand systems tracts (Haq, 1991; Vail et al., 1991) although there are important exceptions to this rule, especially in carbonate systems or where tectonic control is relatively more important than sea level. There is less agreement about the occurrence of contourite drifts with respect to sea level stand, for they seem to develop: (a) during periods with medium-intensity bottom currents, whatever the sea level and (b) during periods of low to moderate turbidite contribution, otherwise the latter would mask the effects of bottom currents. This would imply that they commonly form as part of the high-stand system tract and during falling sea level (Faugères et al., 1993a).

The seismic characteristics of turbidite and related deposits have been the subject of many diverse studies and are well-known from all the major deep-sea environments (Mitchum, 1984; Bouma et al., 1985; Weimar and Link, 1991; Pickering et al., 1995, among others). Those of contourite deposits are only more recently gaining recognition (e.g., Mougénot and Vanney, 1982; Faugères et al., 1985a, 1998; Kennard et al., 1990; Einken and Hinz, 1993; Marani et al., 1993; Mézerais et al., 1993; Carter and McCave, 1994; Howe et al., 1994; Stoker, 1998; Viana et al., 1998, among others), and are most commonly dispersed through the literature as single profiles, for example, in initial reports volumes of DSDP, IPOD and ODP drilling program. These studies have shown that seismic characteristics of both types of deposits are often more or less identical, and that those similarities have led to an underestimation

of the role of contourite deposits in the building of margins or the filling of basins. Furthermore, sediment bodies presenting similar geometries and seismic facies can be made up of either contourite muds or turbidite sands. Potential deep-sea reservoir sands may turn out to be muddy drift deposits.

It is clearly very important for sedimentologists and petroleum geologists to be able to accurately determine the diagnostic seismic characteristics for both types of deposit. This is essential if we are to properly refine the seismic stratigraphic models for deep-water systems and to confidently distinguish reservoir sands from muddy drifts.

This paper, therefore, is an attempt to review a large number of seismic sections across contourite drifts, using both published and unpublished data, and hence to propose some guidelines for differentiation of contourite drifts from turbidite accumulations. It rapidly became apparent during this study that for a proper diagnosis it is essential to consider a range of features including: (1) overall drift morphology and larger scale geometry, (2) detailed stacking patterns of component depositional units (e.g., progradational–aggradational geometry, channel–levee migration), and (3) specific seismic facies (Fig. 4). Thus, it is necessary to carry out any investigation at different scales.

However, different scales of study generally require different seismic sources, which are not always available for any one area under consideration. It is clearly important to assess the advantages and limitations of the seismic system used and to recognise what type and scale of information can be gleaned from its record. We first briefly discuss this issue.

2. Seismic methods

Very different scales of resolution are possible using different seismic sources. These include the following.

(1) *High resolution, low or non-penetration* seismic systems are used to investigate modern environments. Very high frequency sound used in echo profilers and side-scan sonar sources (7.5–24 kHz and up to 500 kHz for long-range side-scan sonar), gives almost no penetration of the sea floor but is extremely useful for identifying surficial morphology

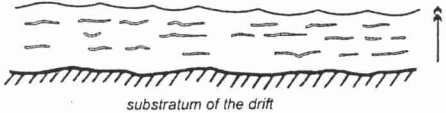
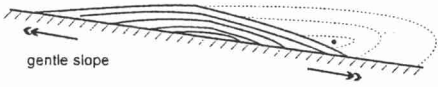
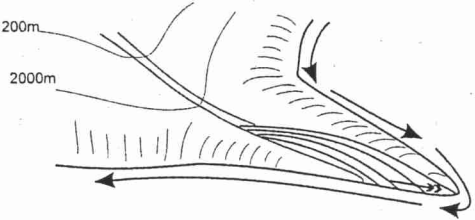
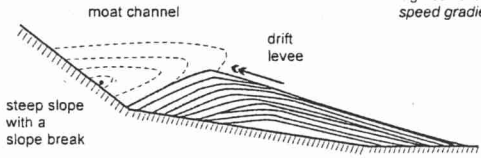
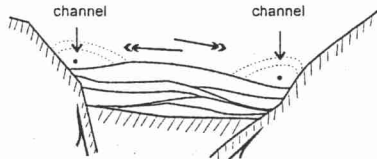
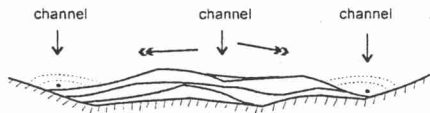
		ABYSSAL SHEET DRIFT: mostly aggradation	
		transparent to wavy reflections	
		Ex: Gloria drift, Argentine Basin drifts	substratum of the drift
migration and aggradation any type of reflections, except horizontal/parallel reflections	GIANT ELONGATED DRIFTS	Plastered drift	<i>low current speed gradient</i>
		- alongslope migration (downstream of the current flow) - down and upslope migration	
		Ex: Gardar drift	gentle slope
		Detached drift	
		Separated drift	<i>high current speed gradient</i>
		- alongslope migration (downstream of the current flow) - upslope migration	
	Ex: Faro drift	steep slope with a slope break	
MOUNDED DRIFTS:	CONFINED DRIFTS	- predominant downcurrent migration - limited lateral migration	
	Ex: Sumba drift	in between high tectonic or volcanic reliefs	
	CHANNEL-RELATED DRIFTS	- predominant downcurrent migration - random lateral migration	
	Ex: Vema contouritic fan	downstream of a deep channel issue	

Fig. 3. Summary of the different types of contourite drifts (after McCave and Tucholke, 1986; Faugères et al., 1993a,b) showing the drift general geometry and trend of migration–aggradation (double black arrow).

that can be very diagnostic of contourite and turbidite systems. These are not considered further here.

(2) *High resolution, low penetrating* systems that penetrate the upper few meters to tens of meters of sediment have been widely used for many years. The most popular is the 3.5-kHz profiler which can be used to infer surface morphology, nature of the sediment and detailed geometry of the sub-recent environment. These 3.5-kHz records are not considered here, except for improving detailed seismic interpretation, but the characteristics of both turbidite and contourite systems have been well-illustrated in an abundance of literature (e.g., Damuth, 1975, 1980; Jacobi, 1982; Kolla et al., 1980; Mézerais et al., 1993; McCave and Carter, 1997, among many others).

(3) *Moderate resolution, moderate penetration* systems are those that use a single-channel sparker source with a frequency ranging from about 0.1 to 3 kHz. These have a corresponding range of penetration from about 100 m to 1 km and a resolution of between 1 and 10 m. They are most commonly used on marine research vessels throughout the world and some of our examples come from these systems.

(4) *Low resolution, high penetration* systems include large airguns, sleeve guns and water guns, with a low frequency sound source, typically 10–100 Hz, and penetration of several kilometers but correspondingly lower resolution. These are generally coupled to multichannel recording systems and are commonly used for industrial purposes, including 3D

seismic surveys. Some of our records are of this type.

Following collection, seismic records can be variously treated or migrated. This is particularly necessary for deeper penetration records in order to clean up noise and remove seafloor multiples from the parts of the section under scrutiny. The resulting records are therefore clearer and more readily interpreted. Modern techniques in acquisition and treatment of multichannel seismic data provide an improvement in vertical reflector definition (Bourgeois et al., 1988; Guimaraes et al., 1991; Lericolais et al., 1994).

3. Seismic patterns at the scale of the drift

3.1. Drift morphology / geometry

Several different drift morphologies have been recognised (Stow and Holbrook, 1984; McCave and Tucholke, 1986; Faugères et al., 1993b) on the basis of numerous examples documented in the present-day ocean basins (Fig. 3). Their overall geometry is controlled principally by four interrelated factors: (1) the morphological context or bathymetric framework, (2) the current velocity and variability, (3) the amount and type of sediment available, and (4) the length of time over which the bottom current processes have operated. Drift geometry can also be

Table 1
Drift morphology and classification

Drift type	Subdivisions	Size	Examples
Contourite-sheeted drift	(a) abyssal sheet	10^5 – 10^6 km ²	(a) Argentine Basin; Gloria drift
	(b) slope plastered sheet	10^3 – 10^4 km ²	(b) Gulf of Cadiz; Campos margin
	(c) slope patch sheet	< 10^3 km ²	
Elongate-mounded drift	(a) detached drift	10^3 – 10^5 km ²	(a) Eirik drift; Blake drift
	(b) separated drift	10^3 – 10^4 km ²	(b) Feni drift; Faro drift
Channel-related drift	(a) patch drift/channel- (moat-) related drift	10 – 10^3 km ²	(a) NE Rockall Trough
	(b) contourite fan	10^3 – 10^5 km ²	(b) Vema Channel exit
Confined drift		10^3 – 10^5 km ²	Sumba drift E Chatham Rise
Modified drift–turbidite systems	(a) extended turbidite/contourite levees	10^3 – 10^4 km ²	(a) Columbia levee (Brazil-Basin); Hikurangi fan drift (New Zealand)
	(b) sculptured turbidite bodies	10^3 – 10^4 km ²	(b) SE Weddell Sea
	(c) intercalated turbidite–contourite bodies	can be very extensive	(c) Hatteras Rise

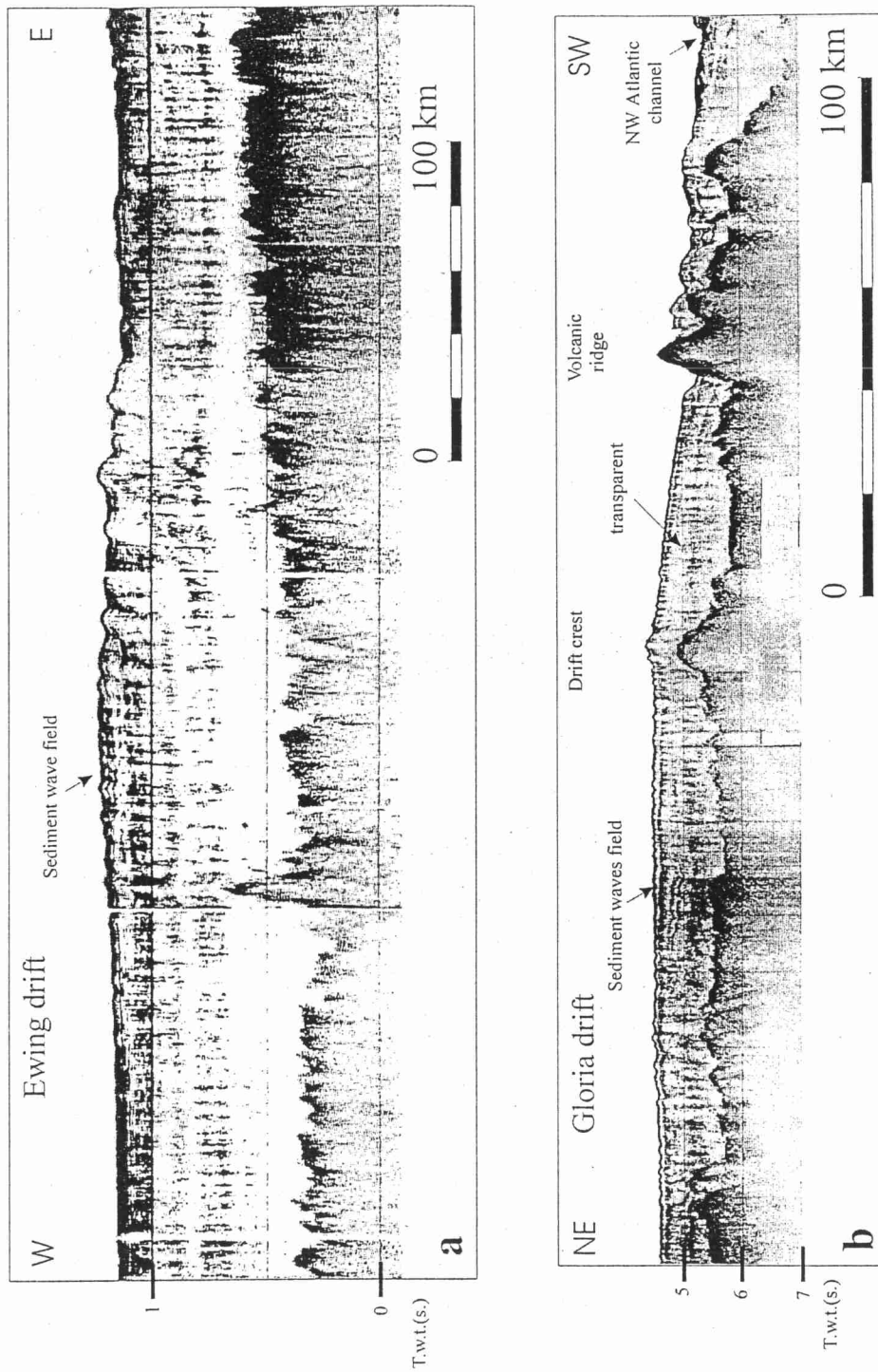


Fig. 4. Abyssal contourite sheet drifts linked to bottom currents trapped on a basin sea-floor: note the transparent seismofacies and fields of sediment waves: (a) sparker seismic line over the Irminger Basin (Gloria drift, after Eglöf and Johnson, 1975), (b) single-channel airgun seismic line over the North Argentine Basin (Ewing drift, Flood and Shor, 1988; after Barker et al., 1977).

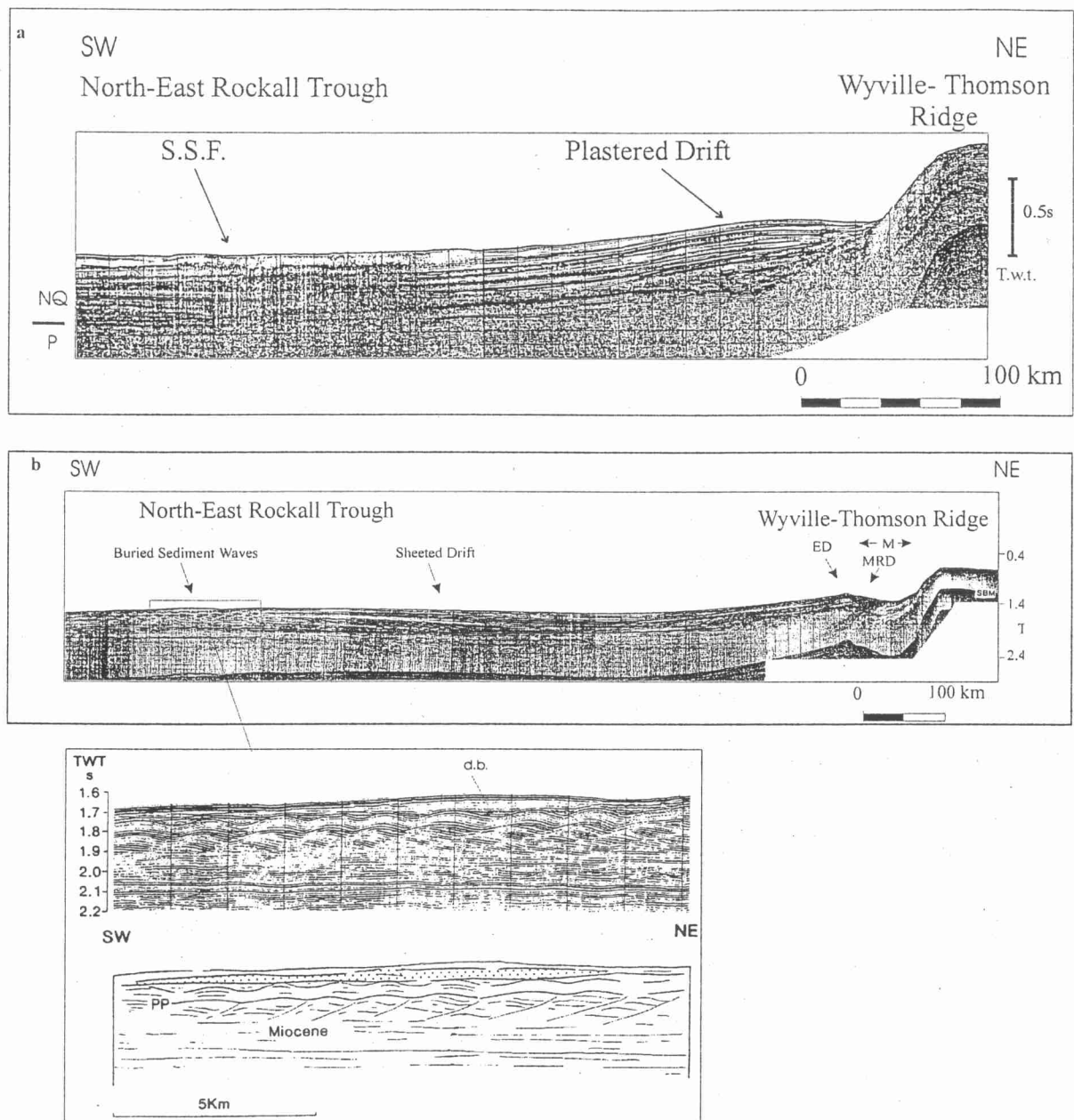


Fig. 5. Slope contourite-sheeted and -plastered drifts. (a) Hebrides slope, adjacent to the Wyville Thomson Ridge (single-channel airgun, Howe et al., 1994; Stoker, 1998; Stoker et al., 1998): seismic line showing a sheeted/plastered drift geometry, merging laterally and buried westward by a deep-sea fan (SSF: Sula Segeir fan, P: Paleogene, N–Q: Neogene–Quaternary). (b) Hebrides slope, adjacent to the Wyville Thomson Ridge (single-channel airgun, Howe et al., 1994; Stoker, 1995, 1998; Stoker et al., 1998): seismic line showing a buried sediment wave field overlain by debris flow (d.b.) package (transparent reflection; PP: base of Plio-Pleistocene) and a sheeted drift merging into a plastered/separated drift (ED: elongated low-mounded relief) associated with moat-related drift (MRD). (c) Hebrides slope, adjacent to the Wyville Thomson Ridge (single-channel airgun, Howe et al., 1994; Stoker et al., 1998): seismic line showing the lateral relationships between a sheeted drift (SD), a ED and a MRD. (d) Northeastern Chatham rise (eastern New Zealand margin): typical geometry of a plastered drift (airgun profile, after Wood and Davy, 1994).

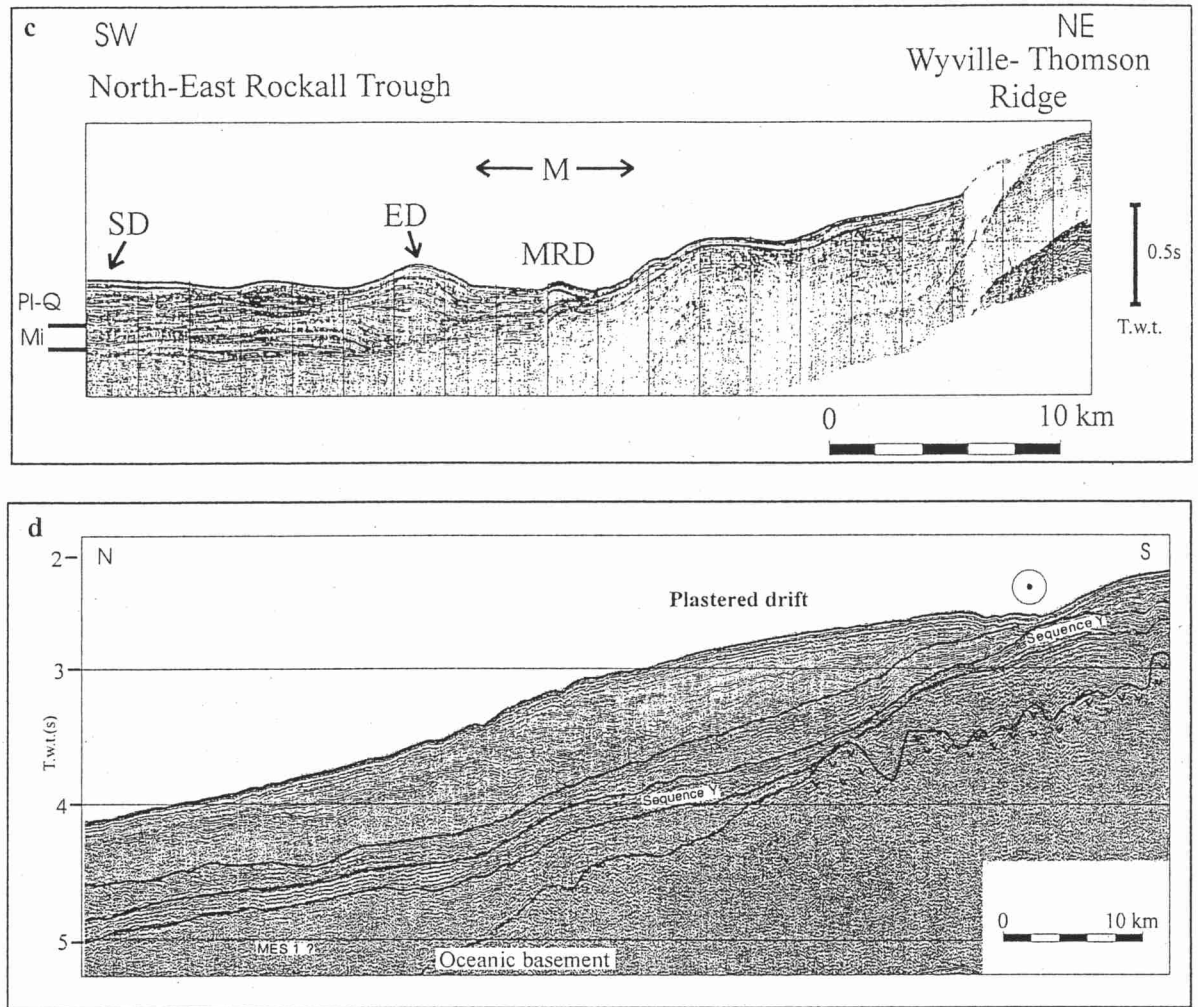


Fig. 5 (continued).

modified by interaction with downslope processes and their deposits.

We retain here the classification of drift morphologies developed in Faugères et al. (1993b) and summarised by Stow et al. (1996), but have added two categories: *confined drifts* that occur in relatively small, tectonically active basins, and *modified drifts* for those that display considerable interaction with downslope systems. The complete classification is given in Table 1.

It is important to note, however, that these distinctive morphologies are simply *type members* within a continuous spectrum. An evolution from abyssal

sheet to plastered (slope) sheet to mounded elongate drift, for example, will be illustrated in a later section.

3.2. Contourite-sheeted drifts

The overall geometry of contourite sheets (Figs. 3 and 4) differs only very subtly from turbidite sheet fill of basin plains or their cover of lower slope and interchannel regions. They form a layer of more or less constant thickness (up to a few hundreds of meters) that covers a large area, but which have a very slight decrease in thickness towards its margins,

i.e., having a very broad low-mounded geometry. The internal seismofacies is typically one of low amplitude, discontinuous reflectors or, in some parts, is more or less transparent. They may comprise or be covered by large fields of sediment waves, as shown by several examples: i.e., South Brazilian, (Damuth, 1975; Damuth and Hayes, 1977; Mézerais, 1991) and Mozambique Basins (Kolla et al., 1980), where they can be also capped in the central region by giant elongate-bifurcated drifts as in the case of the Irminger (Egloff and Johnson, 1975), and Argentinian Basins (Flood and Shor, 1988).

These accumulations can be observed in different hydrological and morphological contexts, which allow us to define abyssal sheets and slope sheets (or plastered drifts). The former carpet the floors of abyssal plains and other deep-water basins which are limited on their periphery by pronounced relief. This relief partially traps the bottom currents and determines very complex gyrotory circulations (e.g., Glo-

ria drift: Egloff and Johnson, 1975, 1978; Argentine Basin: Flood and Shor, 1988; Agulhas and Mozambique Basins: Kolla et al., 1980; Ben-Avraham et al., 1994). Such drift accumulations have been observed either still active on the sea-floor surface (see figs. 5 and 6 in Stoker, 1998) or buried by gravity deposits (Fig. 5a–b), as in North Rockall Trough (Richards et al., 1987; Howe et al., 1994; Stoker, 1995)

Slope sheets occur (a) near the foot of slopes where outwelling or downwelling bottom currents exist (Gulf of Cadiz: Kenyon and Belderson, 1973; Malod, 1982; Faugères et al., 1985b; Nelson et al., 1993), and (b) plastered against the slope at any level, particularly where gentle relief and smooth topography favour a broad non-focussed bottom current (Fig. 5; e.g., Hebrides margin: Howe et al., 1994; Stoker, 1995, 1998; Stoker et al., 1998; Chatham Rise: Wood and Davy, 1994; Gardar drift, see fig. 3 in Kidd and Hill, 1986). They are generally of more limited extent than abyssal sheets. Their

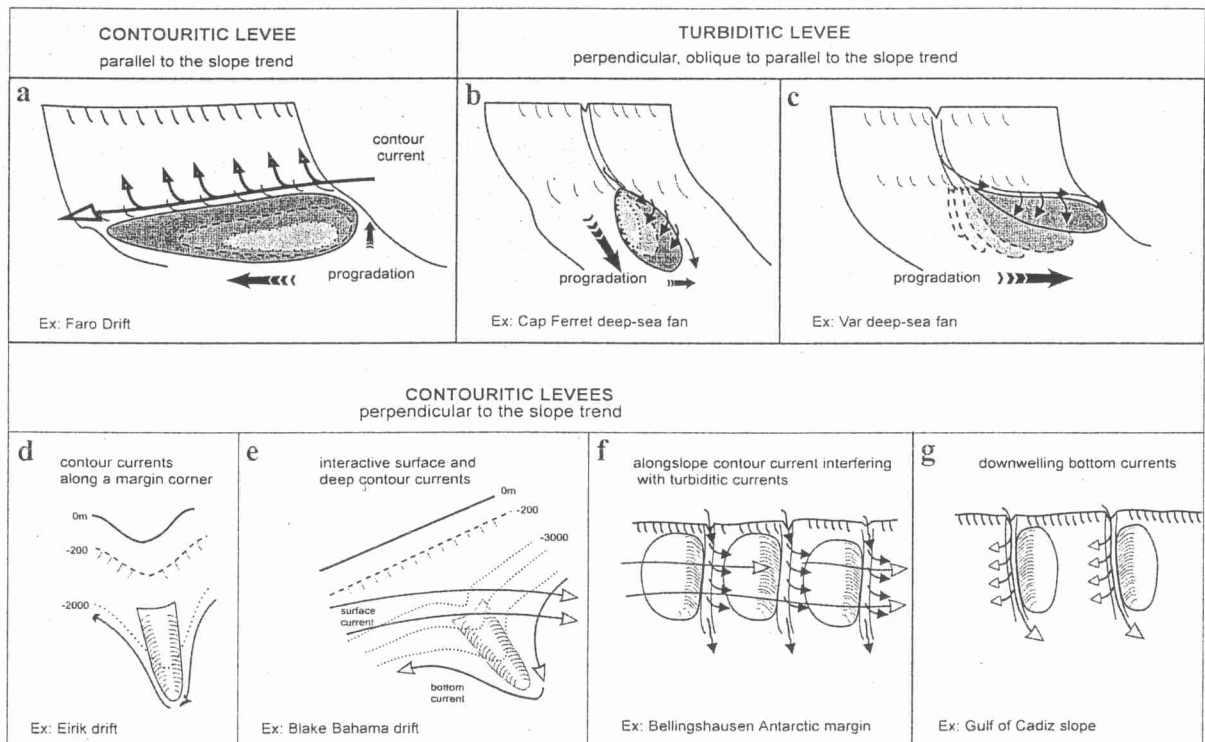


Fig. 6. Summary of the relationship between the trend of contourite and turbiditic levees and the trend of the margin along which the drifts are developed. (a) Usual trend for contourite drift, (b) usual trend for turbiditic levee, (c) possible trend variations during the growth of turbiditic levees, (d) to (g) various scenarios for contourite levees perpendicular to the slope trend.

very broad low-mounded geometry is similar to that of terminal lobes on many deep-sea fans, from which distinction may be possible on the basis of their

morphological context or specific seismic facies. Fan lobes typically have continuous, parallel, slightly convex, high-amplitude reflectors intersected by

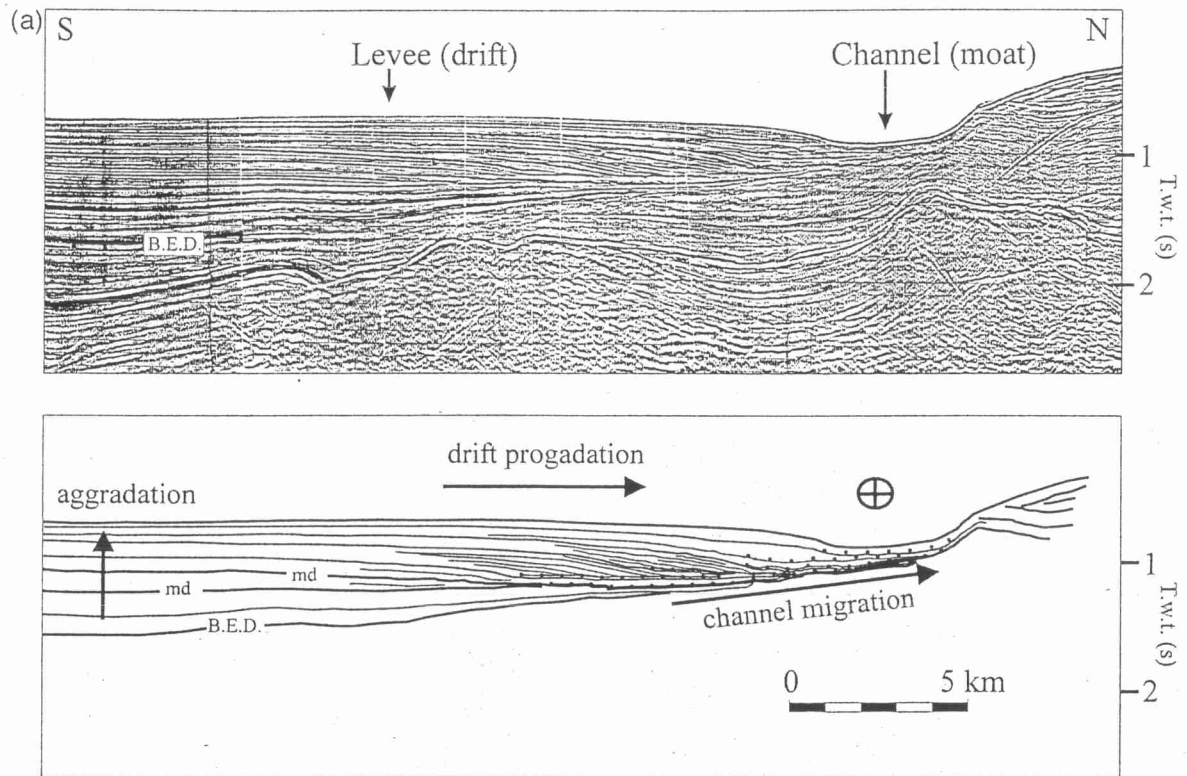


Fig. 8. Elongate-mounded drifts: examples of sections over separated drifts. (a) The Faro drift, on the upper slope of the north margin of the Gulf of Cadiz (after Cremer et al., 1985; Mougénot, 1988; multichannel seismic line). Note the upslope progradation trend of the drift and the various seismofacies underlining the drift depositional patterns: continuous semi-parallel (aggradation) to less continuous, oblique to sigmoidal (progradation) reflections and local slightly erosive truncation underlining the channel axis migration (B.E.D.: basal erosive discontinuity of the drift; md: major discontinuity). (b) The Guadalquivir horst drift on the lower slope of the north margin of the Gulf of Cadiz (after Mougénot, 1988; multichannel seismic line). Note the upslope migration of the drift and the lenticular geometry of the deposit units (1, 2, 3: major Neogene unconformities; 2: drift basal erosive unconformity; 1: intradrift major discontinuity). (c) The Feni drift, on the northeast margin of the Rockall trough (after Stoker, 1998). (c1) The drift is bounded by two major discontinuities, reflector C at the base (early to Late Eocene), reflector A at the top (Middle Miocene), and is draped by a Middle Miocene–Holocene veneer of sediments. Downslope the drift, note the occurrence of an erosive area followed by a second upslope prograding drift accumulation. (c2) Detail of the upper termination of the Feni drift (sparker profile) showing the gradual increasing dip of the upslope prograding reflectors. We can notice that the Feni drift is no longer active in this region being draped by probable hemipelagic sediments. (d) The Davie drift (Mozambique channel, Indian Ocean, single-channel watergun; after Virlogeux, 1987; Raillard, 1990; and unpublished data on the courtesy of D. Mougénot). (d1) Seismic section over the Davie complex drift system. It has been built by a northward flowing bottom current and is formed by a plastered/separated active drift (moat–levee), elongated against the Davie Volcanic Ridge (DVR) and prograding westward. The upper part of the drift system is mainly built by sediment waves and has undergone local erosion. Downslope, we can notice the presence of a buried drift showing the same westward progradation. (d2) The Davie plastered/separated drift and sediment waves (detail of (d1)). Notice that the process responsible for the wavy geometry remain speculative; an hydrodynamic or a structural control could be advocated as well as both interacting processes. (d3) The Davie buried drift (detail of (d1)). Notice the occurrence of a SW prograding buried channel–levee system overlain by slightly undulated semi-parallel reflectors (standing to slightly migrating sediment waves interpreted as due to contour current activity).

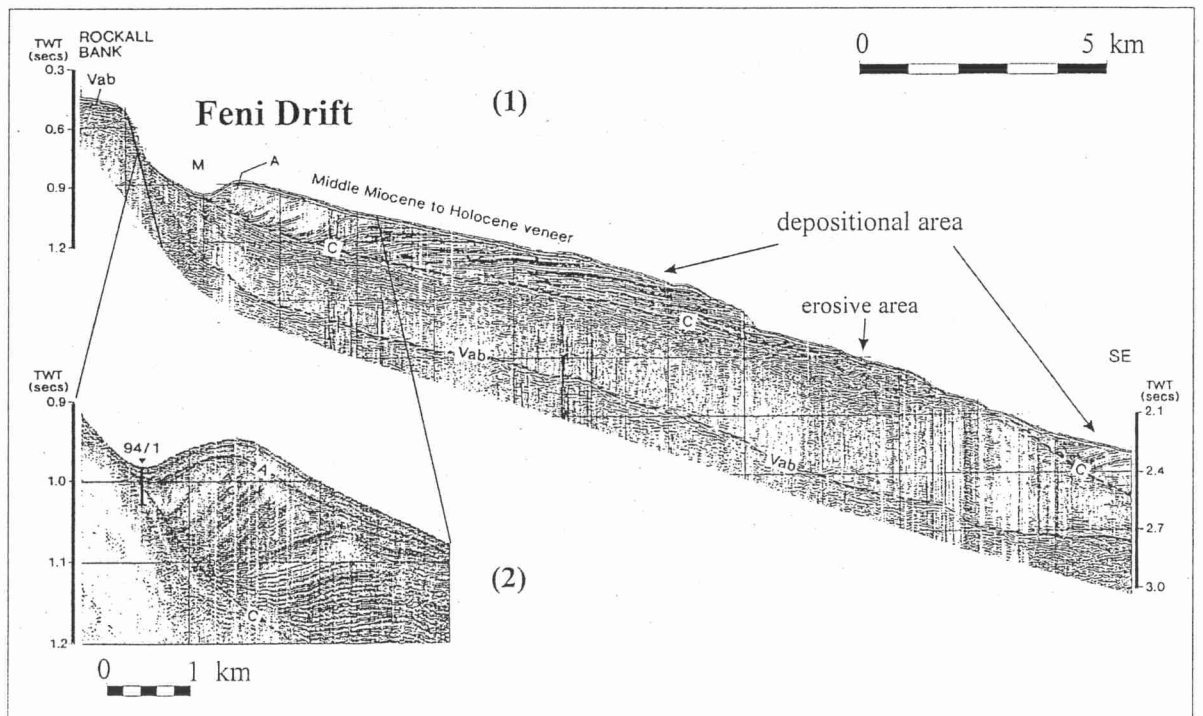
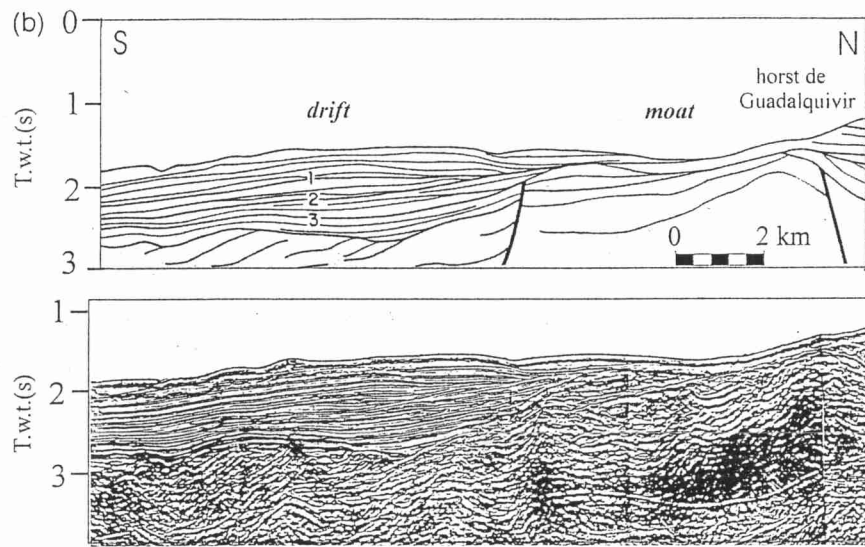


Fig. 8 (continued).

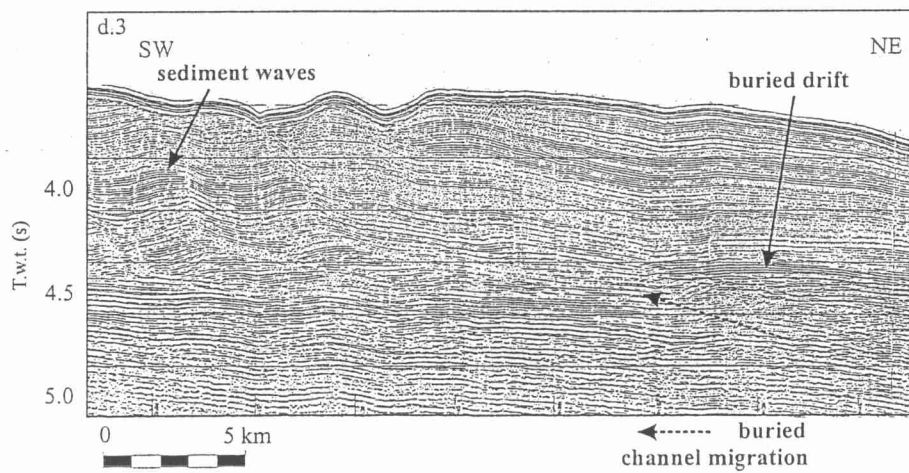
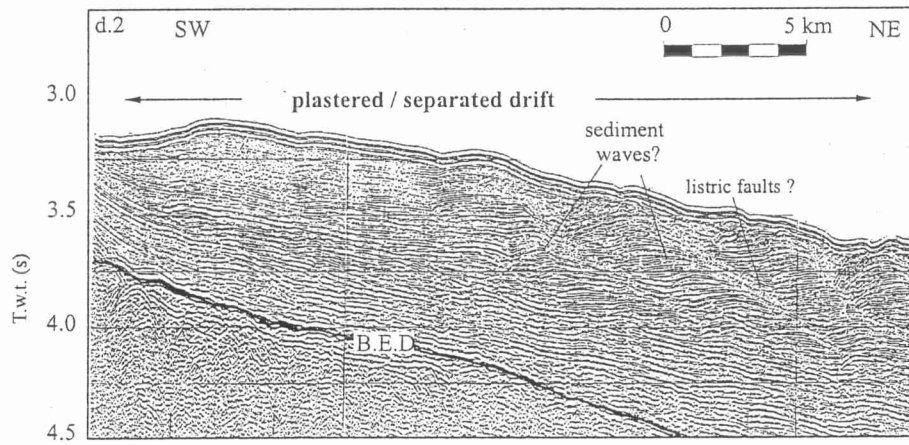
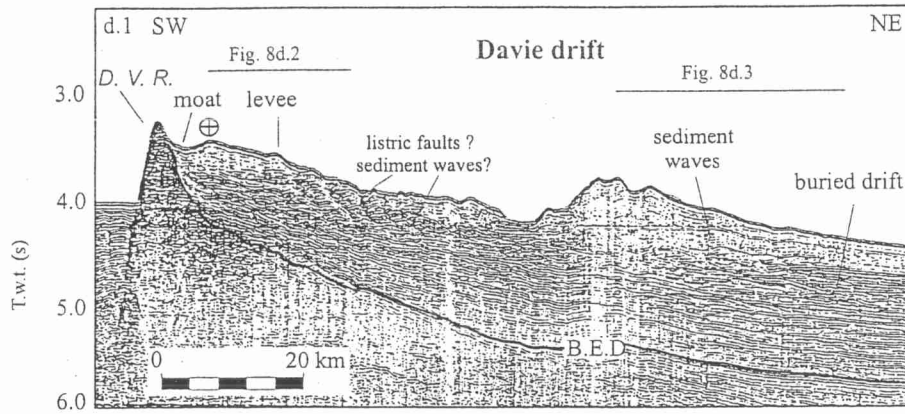


Fig. 8 (continued).

small channels and gutters and a rather smooth surface. The presence of sediment waves on both contourite drifts and turbidite systems will be discussed in Section 5.4.

3.3. Elongate-mounded drifts

This type of contourite accumulation is distinctly mounded and elongate in shape (Fig. 3). The dimensions are very variable from a few tens of kilometers to over 1000 km long, length-to-width ratios from 2:1 to 10:1, and thicknesses up to several hundred meters. They may occur anywhere from the outer shelf/upper slope, such as those east of New Zealand (Fulthorpe and Carter, 1991) to the abyssal plains (Faugères et al., 1993b). Those that occur within channels or in very confined basins are considered separately (see Table 1).

Both the elongation trend and direction of progradation can vary with respect to the contours of the margin of the continent or basin, and are dependent upon an interaction between the morphology (i.e., slope gradient and regularity), the current system and intensity, and the Coriolis force. Elongation is generally parallel or subparallel to the margin (Fig. 6a), with both detached and separated types recognised (McCave and Tucholke, 1986; Table 1), but progradation can lead to parts of the drift being elongated almost perpendicular to the margin (Fig. 6d, e).

The development of drifts perpendicular to a margin can result from: (a) progradation in response to a change in the margin's trend (Eirik drift, Fig. 6d and Fig. 7a) and (b) the interaction between surface and bottom currents (Fig. 6e and Fig. 7b, Cape Hatteras and Blake–Bahama drifts, McCave and Tucholke, 1986). Normal downslope turbiditic channels and canyons that cut across a margin strongly influenced by alongslope bottom currents will develop elongate asymmetric levees of part turbidite and part contourite construction (Fig. 6f, Antarctic margins; Weber et al., 1994; Rebesco et al., 1996). The erosion of downslope channels wholly by downwelling bottom currents has been proposed for the Chatham Rise off eastern New Zealand (Barnes, 1992, 1994) and the Gulf of Cadiz (Fig. 6g, Faugères et al., 1985b; Nelson et al., 1993) in which case the 'levees' are elongate contourite drifts. However, this now seems less viable than a mixed turbidite–contourite system.

Confusion between elongate-mounded drifts and turbidite levees can, therefore, occur on several counts: (a) drifts can be elongated downslope as in the cases outlined previously, (b) turbidite channel–levee systems are usually elongated downslope (Fig. 6b) but can, in part, be elongated alongslope (Fig. 6c) where migration has been influenced by the Coriolis force or tectonic control, (c) both have a similar elongate-mounded geometry, and (d) true hybrid levee drifts exist.

Distinction from turbidite levees cannot necessarily be made, therefore, on the basis of mounded geometry or elongation trend except where the mounds are clearly isolated from downslope supply, as is the case of separated drifts. Clearly, though, an alongslope orientation is typical of many contourite drifts and is an important pointer towards interpretation. One obvious pattern of a turbidity current origin is the frequent paired nature of the levees with a levee formed on either side of the channel and, in high latitudes, preferential development of one levee in accord with the Coriolis force (see Section 4.2).

In addition, mounded contourite drifts commonly lie on a more or less flat, major erosion surface, which is the same age over its full extent. This hiatus corresponds to an important hydrological event which accompanied the initiation of active bottom-water circulation in the area. It is then overlain by contourite drift deposits that accumulate due to the slowing down of this circulation and that prograde in different directions as outlined above. Good examples of a basal erosion surface overlain by mounded drifts include the Hatteras, Blake, Feni, Faro, Guadalquivir and Marion drifts in the Atlantic Ocean (Figs. 2 and 7–10).

Once contourite accumulation has ceased, following a major change in bottom circulation, for example, the mounded drift is progressively covered either by onlapping turbidites and/or by draping pelagite/hemipelagite deposits (Figs. 2 and 9).

In the first case, the change in sedimentation regime is commonly abrupt. Turbidites begin by filling in lows such as the back drift basin, marginal moats and the troughs of sediment waves, and eventually bury the drift system entirely. This scenario is illustrated at the foot of the eastern US continental margin where Plio-Quaternary turbidites are being ponded against the continent-side of the Hatteras

Drift and in the troughs of the abyssal rise hills (Fig. 2 and see figs. 5 and 7, site 603 in van Hinte et al.,

1983). Complete burial is seen in the same region with the Chesapeake Drift and wave field covered by

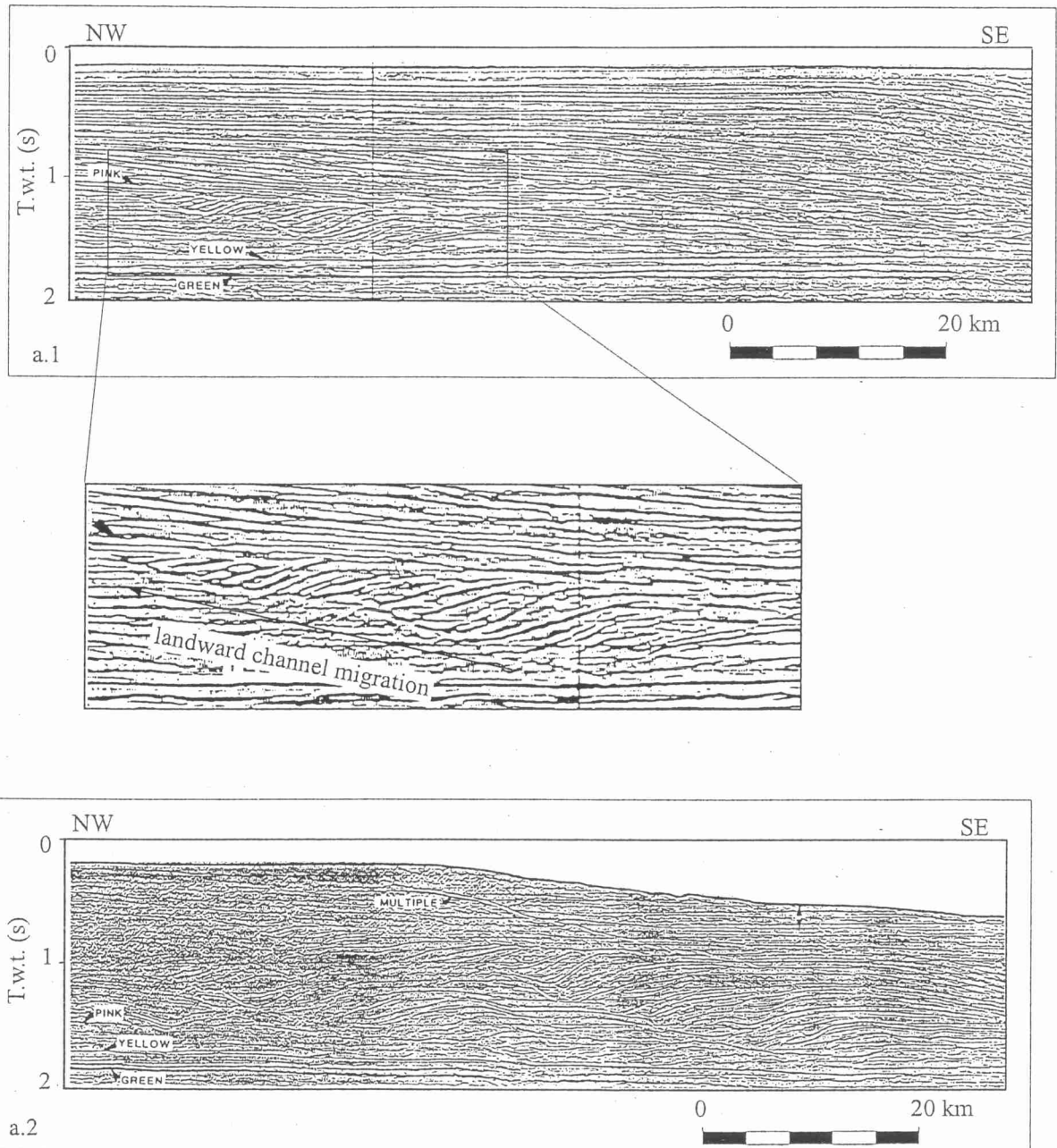


Fig. 9. Buried contourite drifts. (a) Shallow water drift on the SE New Zealand margin (multichannel airgun sections, after Fulthorpe and Carter, 1991). (a1) Notice on the inset the striking leftward migration of a contourite channel-levee system built by northward flowing bottom currents. (a2) Complex imbrication of several contourite channel-levee systems built by bottom currents running as separated, parallel flows. (b) The Sackville spur separated drift on the northeastern New foundland margin (north Flemish Cap; seismic profile after Kennard et al., 1990; Mitchum, 1984) is buried by draped deposits that preserve the channel-levee morphology.

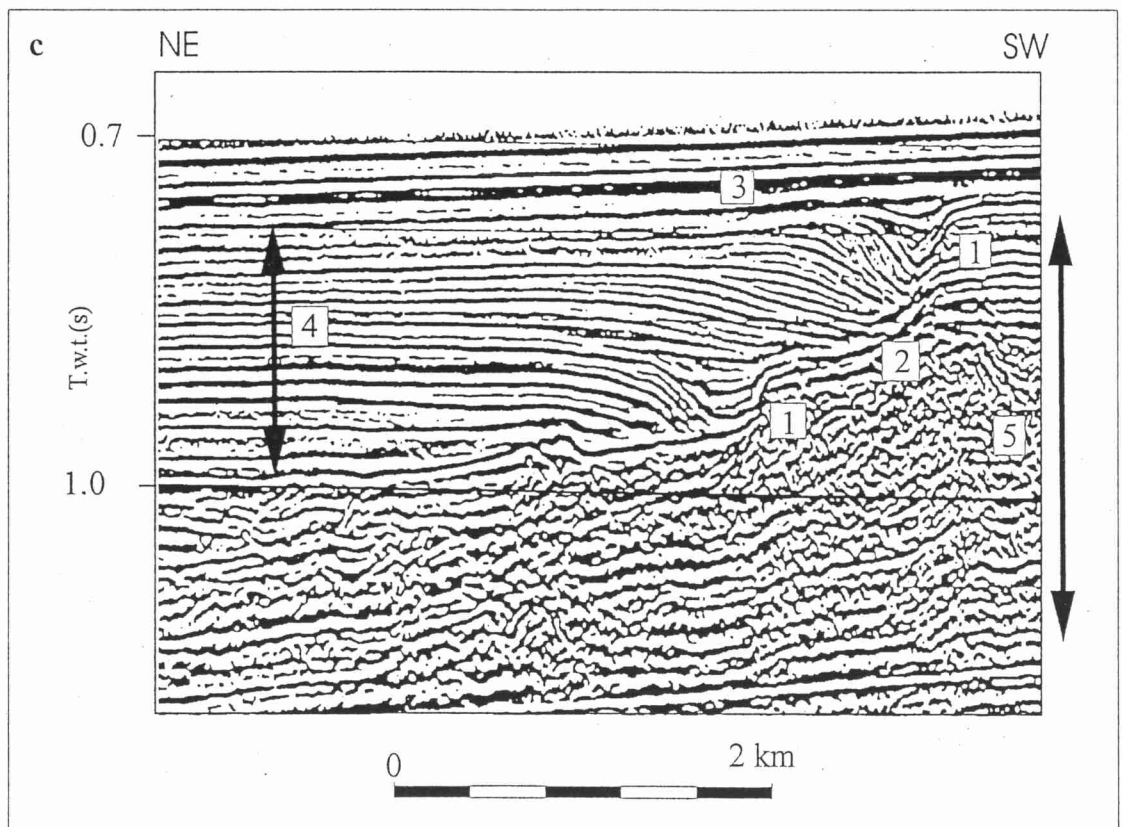
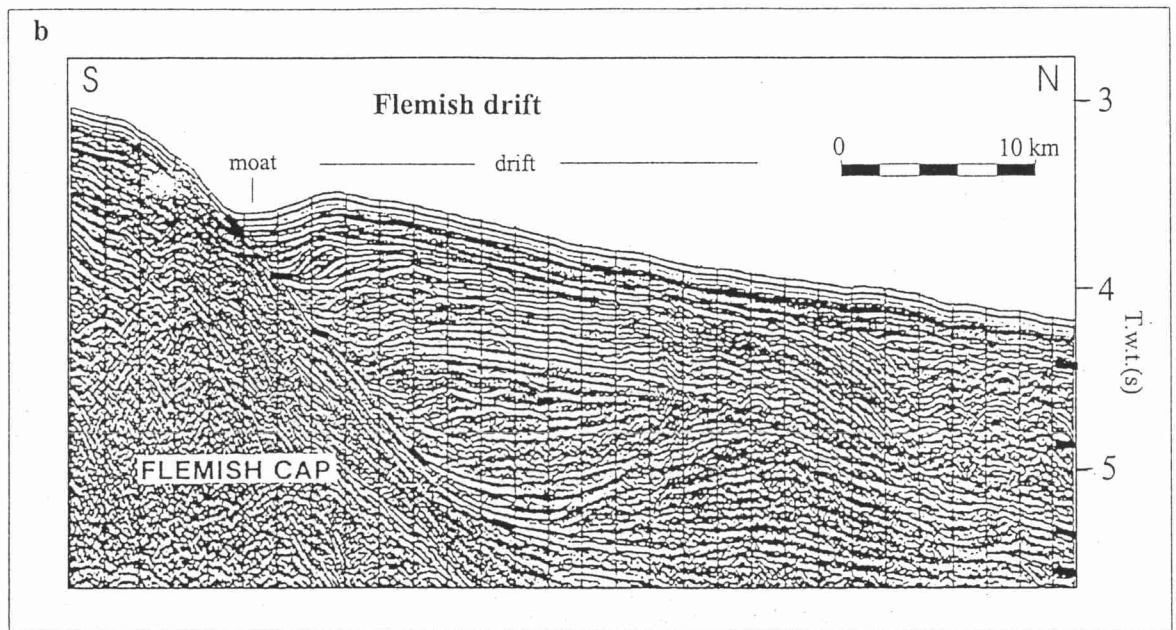
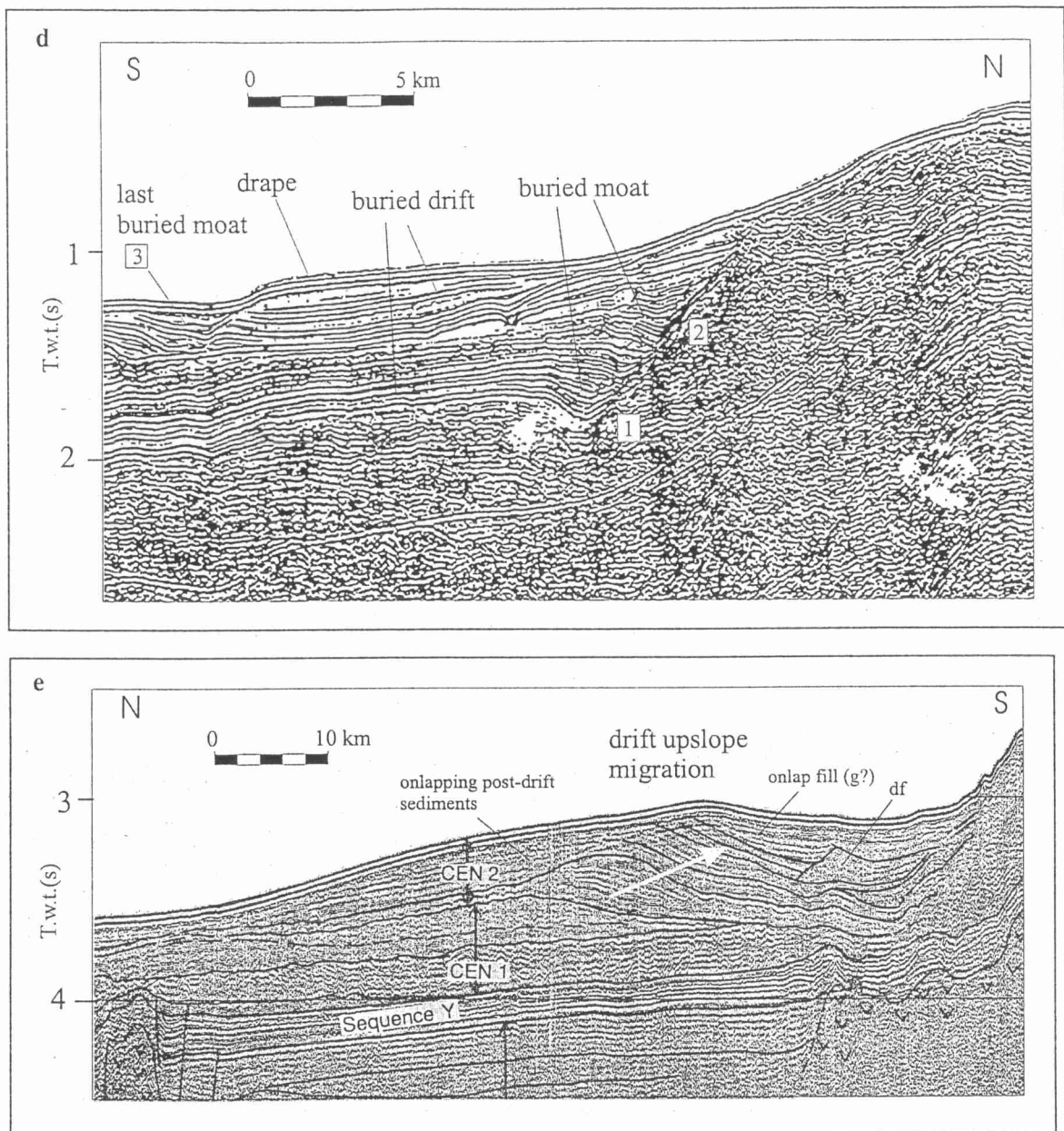


Fig. 9 (continued).



the Norfolk–Washington fan (see figs. 8–29 in Mountain and Tucholke, 1985; Locker and Laine, 1992).

In the second case, there is a progressive change from contourites to pelagic/hemipelagic deposits linked to a slow decrease in the strength of bottom water circulation (Fig. 9b–e). The pelagic/hemipe-

lagic cover drapes the pre-existing bedforms and conserves the original drift morphology (e.g., Fig. 9b, Flemish Cap, Mitchum, 1984; Kennard et al., 1990). This can give the impression of continual contourite deposition, which is perhaps the case for many examples of standing waves such as on Feni Drift (Kidd and Hill, 1987) where bottom currents

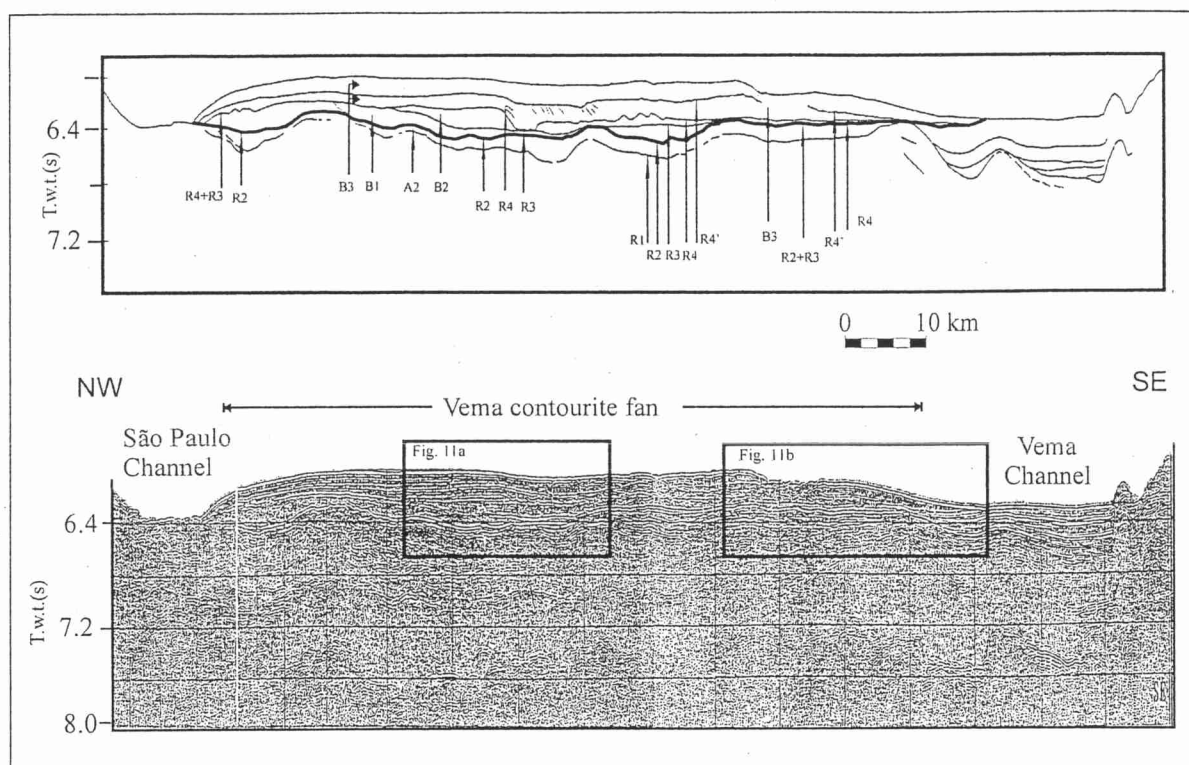


Fig. 10. A mound, channel-related drift: the Vema contourite fan (South Brazilian Basin), at the downstream exit of the Vema Channel (after Mézerais, 1991; Mézerais et al., 1993; Faugères et al., 1998). Watergun cross-section and interpreted profile show the major widespread discontinuities (R1 to R4') and the drift lenticular depositional units (B1 to B3); R2: drift basal erosive surface.

are now extremely slow, or on the western margin of the Gulf of Mexico where apparent sediment waves occur in the absence of any known bottom currents (Berhens, 1994).

Numerous examples of buried elongate-mounded drifts come from various domains of the continental oceanic margins, for instance the shelf break (Fig.

9a), upper slope (Fig. 9c), rise (Fig. 9e), and large deep channels (Fig. 8d and Fig. 9d).

3.4. Channel-related drifts

This type of contourite deposit is related to deep channels or passageways (Fig. 3) through which the

Fig. 9 (c) Marion separated drift on the northeastern Australian margin, (multichannel watergun seismic line, after Davies et al., 1991): The buried Marion drift accumulation (black arrow 4) was built along a carbonate platform (arrow 5) by contour currents flowing northwestward. Different periods of bottom current activity are suggested by channel–levee geometry: (1) and (3) are narrow and deep channels associated with strong currents; (2) corresponds to a large and shallow channel related to slow currents. Surficial drape could be associated to a strong deceleration of the bottom currents as soon as the platform relief has been overflowed. (d) Florida drift in the Florida strait (multichannel airgun seismic line; after Denny et al., 1994). The Florida drift shows successive buried moat–levee systems, all prograding northward (upslope). It has been built during the Neogene time by a westward flowing bottom current. It is now draped by modern sediments deposited under a low energy bottom current regime. Notice the shift of the buried moat–drift systems (from 2 to 3), following a change in the slope morphology (1, 2 and 3: moat–channel axis). (e) Northeastern Chatham drift on the eastern New Zealand margin (airgun seismic line, after Wood and Davy, 1994). Upslope migrating drift buried by onlapping sediments possibly associated to bottom currents of reduced activity and/or gravity currents, and moat infill due to probably gravity processes (CEN1 and CEN2: Late Oligocene, -Miocene to recent deposit sequences; g?: gravity currents?; d.f.: debris-flow).

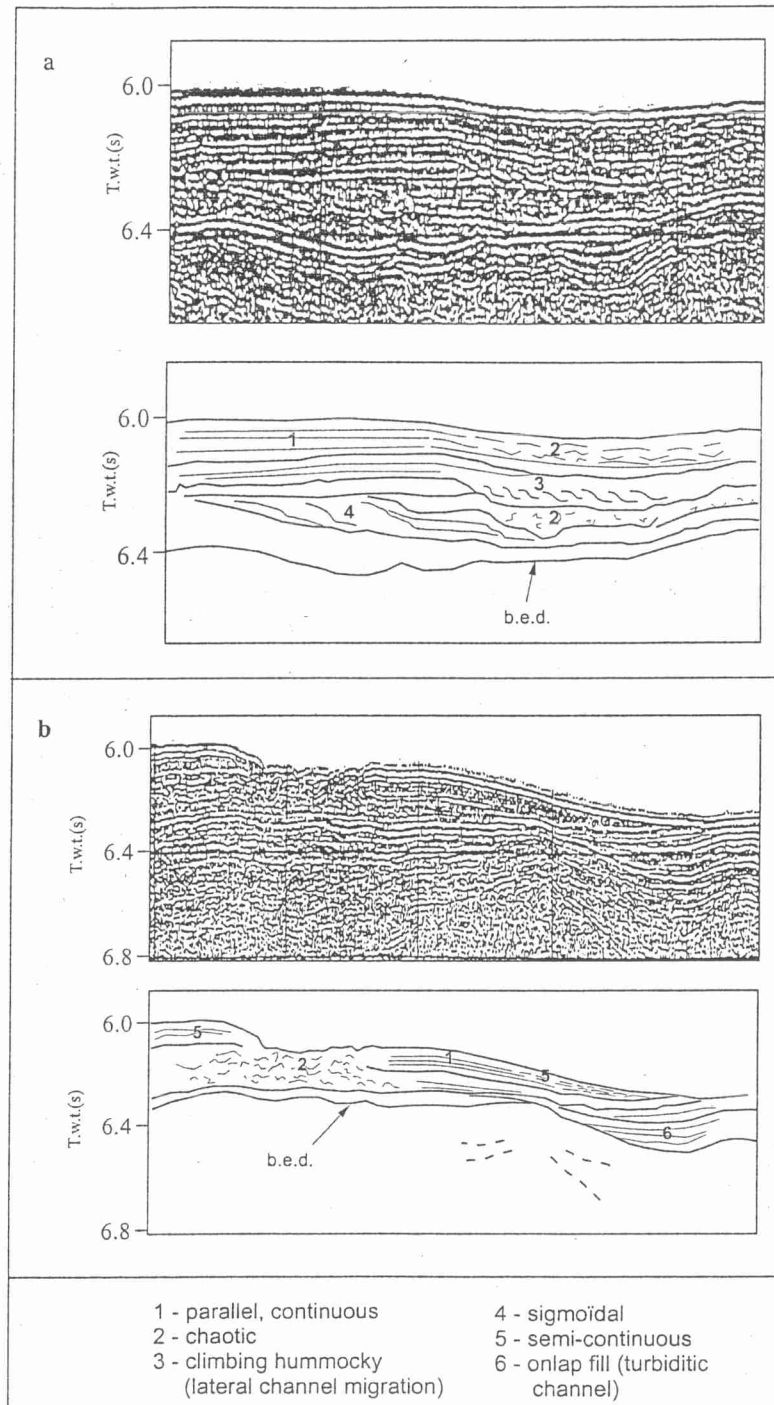


Fig. 11. The Vema contourite fan (South Brazilian Basin), two expanded seismic sections located in Fig. 10. Notice the large variety of seismicofacies and the erosional patterns of the major discontinuities (b.e.d.: basal erosive discontinuity).

bottom circulation is constrained so that flow velocities are markedly increased (e.g., Vema Channel, Kane Gap, Samoan Passage, Almirante Passage, Sand Dune Valley, etc.; Lonsdale, 1981; Lonsdale and Malfait, 1974; Hollister et al., 1974; Johnson, 1984;

Johnson et al., 1983; Meinert, 1986). In addition to significant erosion and scouring of the passage floor, irregular discontinuous sediment bodies are deposited on the floor and flanks of the channel, as axial and lateral patch drifts or channel- (moat-)

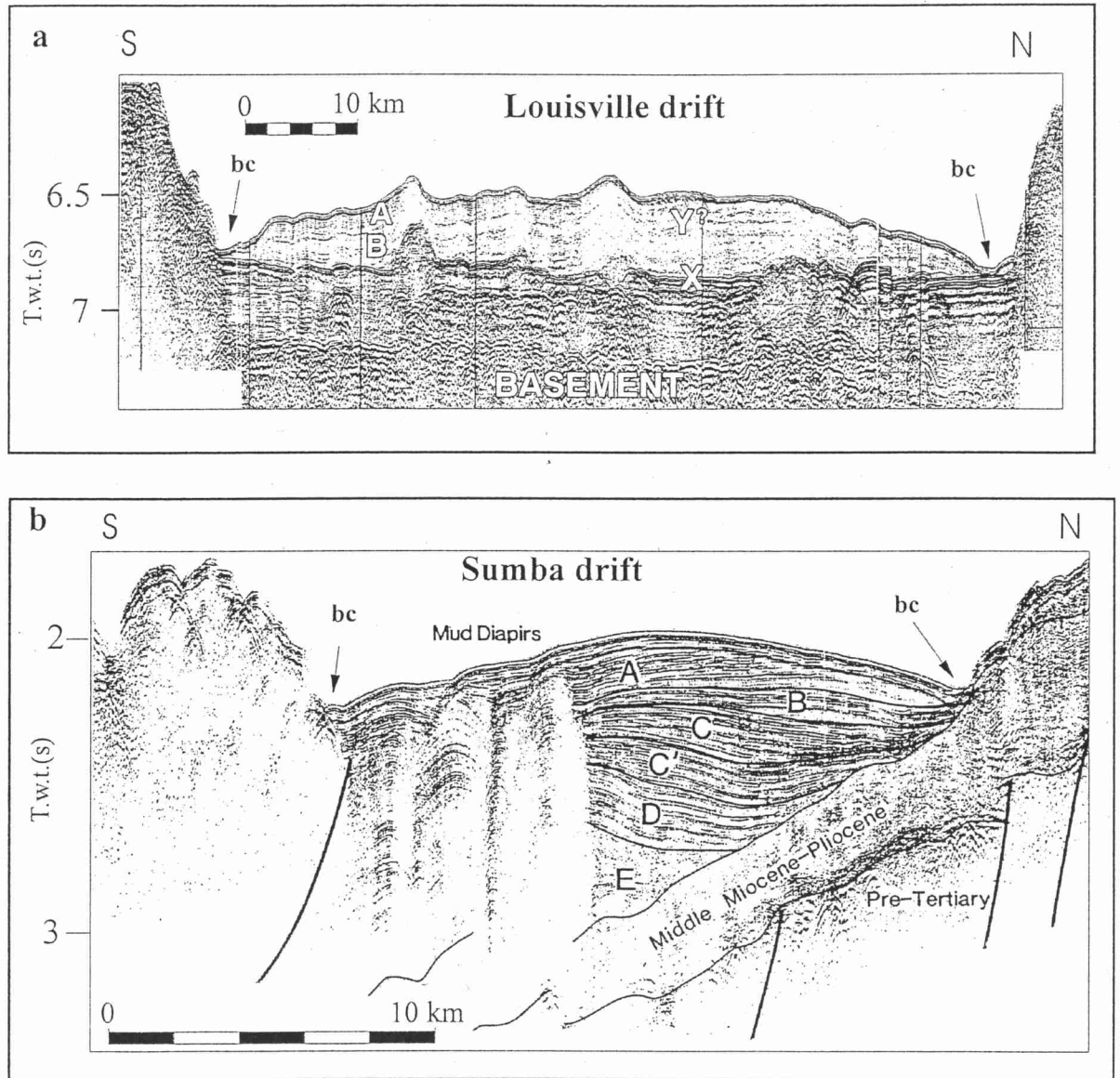


Fig. 12. Mounded confined drifts. (a) The Louisville drift, eastern New Zealand margin (airgun seismic line, after Carter and McCave, 1994). This drift is confined by the sides of a moat along which the bottom currents are constrained (bc: boundary channels on both side of the drift). (b) The Sumba drift on the southern Indonesian margin (eastern Sunda arc, watergun section, after Reed et al., 1987). Notice the presence of b.c. on both sides of the accumulation and the lenticular geometry of the deposit units (A, B, C, ...) associated with active mud diapirs.

related drifts (Howe et al., 1994; McCave and Carter, 1997), and at the downcurrent exit of the channel, as a contourite fan (Mézerai, 1991; Mézerai et al., 1993).

Patch drifts (Fig. 5b and c) are typically small (a few tens of km² in area, 10–150 m thick) and either irregular in shape or elongate in the direction of flow. They can be reflector-free or with a chaotic seismic facies very similar to debris flow lobes and masses. Contourite fans are much larger cone-shaped deposits, up to 100 km or more in width and radius and 300 m in thickness (e.g., Vema contourite fan, Mézerai et al., 1993; Faugères et al., 1998). As such they are very similar to some small and medium-sized turbidite fans, and may even contain distinct channel-overbank units within the overall complex. Their relative thinness, coupled with laterally extensive erosional discontinuities, can help distinguish them from purely turbidite systems (Figs. 10 and 11).

3.5. Confined drifts

Relatively few examples are currently known of drifts confined within relatively small basins or troughs. These typically occur in morphotectonically peculiar areas, such as the Louisville drift (Fig. 12a) in a very deep part of the eastern New Zealand margin that undergoes an isostatic subsidence (Carter and McCave, 1994), the Sumba drift (Fig. 12b) in the Sumba forearc basin of the Indonesian arc system (Reed et al., 1987), the Meiji drift in the Aleutian trench (Scholl et al., 1977) and an unnamed drift in the Falkland trough (Cunningham and Barker, 1996; Howe et al., 1997). Apart from their topographic confinement, the gross seismic character appears similar to mounded elongate drifts having distinct moats along both margins.

Modified drift–turbidite systems are discussed subsequently.

3.6. Erosional discontinuities

The architecture of deposits within a drift is complex, stressing variations of the processes and accumulation rates linked to changes in current activity. In many cases, the history of contourite drift construction is marked by an alternation of periods of sedimentation and erosion or non-deposition, the lat-

ter corresponding to a greater instability of and/or to a drastic change in current regime. The result is the superposition of depositional units whose general geometry is lenticular (Figs. 7a, 8, 11 and 12b) and whose limits correspond to major discontinuities, more or less strongly erosive (Faugères et al., 1998). These discontinuities can be traced at the scale of the accumulation as a whole and are marked by a continuous reflector of strong amplitude, commonly underlined by a change in seismofacies linked to modifications of current strength. Such extensive and synchronous discontinuities are typical of many of the individual drifts and of all the drift types cited above (Figs. 2 and 7–10).

In other cases, major changes in current regime are less important during drift construction. Although widespread erosion does not occur, extensive discontinuities are still formed as a result of grain-size or compositional change (e.g., SiO₂/CaCO₃ ratios as in Eirik drift, Arthur et al., 1989). They can be due to minor changes in the current regime, the grain-size of the delivered sediments, and more drastic variations in the water chemistry or some combination of these factors. Such changes also affect the style of progradation and the distribution of seismic facies within the drift. These effects are discussed below.

Erosional or non-depositional discontinuities that are both synchronous and of great lateral extent are not common in turbidite fan systems. Erosion is generally restricted to channels and to proximal slide/slump regions. Where they extend over greater distances then they are diachronous due, for example, to progressive channel migration. Reduced sedimentation leading to fan-wide condensed sections is typical of high-stand systems tracts, but these are not accompanied by erosion (Cremer, 1983; Cremer et al., 1985; Mézerai, 1991; Faugères et al., 1998).

4. Seismic patterns at the scale of depositional units

4.1. Unit geometry, progradation and aggradation

Depositional units in contourite drifts that can be recognised on seismic profiles are generally lenticular in shape, with more or less smooth to irregular bounding surfaces (Figs. 7a, 8, 11 and 12b). They

delineate an upwardly convex geometry that is non-parallel to the accumulation surface created by the preceding erosional event. The extent and detailed geometry of the units are very variable, depending on the intensity of the erosion and degree of reworking that has taken place. In some cases, it is the most recent unit that shows most clearly the nature of progradation (oblique downlapping reflections) and/or aggradation as it has not yet undergone an episode of significant erosion as for the Vema contourite fan (Fig. 10).

The upward and oblique stacking of units reveals the general migration of the sediment body, the direction of which is different for different drift types (Fig. 3).

(a) For the *abyssal sheet drifts* (Figs. 3 and 4), there is no significant migration because the deposits tend to carpet the whole area swept by the currents. Migration will only occur when the current is shifted laterally due to oceanographic changes. Consequently, the depositional units can form with a fairly regular thickness (Stoker, 1998) and aggradational stacking pattern.

(b) For *slope-plastered sheets* (Figs. 3 and 5), there is generally little apparent migration in which gently downlapping reflections show only slight downcurrent progradation, with either a basinward or landward oblique component. The smaller size *slope patch sheets* show similar or no apparent migration.

(c) For *giant elongated mounded drifts* (Figs. 3, 5b and c, 7 and 8), progradation is generally more evident than for sheeted drifts, and the migration direction is dependent on the location of the axial flow pathway. There is typically a downflow oblique basinward progradation in the case of detached drifts and oblique landward (upslope) progradation in the case of separated drifts. Sigmoid progradation reflector patterns (Figs. 8a and c, 9a and c) result from a combination of progradation and aggradation.

(d) For *channel-related drifts* (Figs. 3, 10 and 11), contourite fans are composed of an aggradation of flat irregular lensoid depositional units of limited extent, which are the sedimentary relics following each major erosional event. There is little clear or consistent migration evident, although the topmost unit will normally show downflow progradation (Mézeris et al., 1993). Patch drifts in channels show no regular progradational geometry.

(e) For *confined drifts* (Figs. 3 and 12), the sediment body is composed by either a single unit or an aggradation of several lenticular units bounded by erosional discontinuities and with internal reflectors that do not conform to deeper discontinuities. Each unit seems to fill in the whole trough with only some erosion along the lateral boundary channels. We suspect a downstream progradation of the drift.

4.2. Contourite vs. turbidite channel–levee systems

Contourite fans and separated drifts both show channels or moats with an elongate mound or drift developed primarily along one flank. Superficially, these have a geometry and seismic expression comparable to turbidite channel–levee systems from submarine fan, slope apron and basin plain settings. In addition, the seismofacies of both systems can present close similarities, for example chaotic to strong impenetrable reflectors in the channel or moat, and parallel to wavy reflectors on the levee or mound.

However, it is possible to distinguish between contourite and turbidite systems by considering their progradation direction in relation to the overall trend of the margin on which they have been deposited, together with the flow direction. As a general rule, deep-sea sediment bodies of any type tend to migrate according to four principal factors: the flow direction, the Coriolis effect, the morphological context, and any interaction with other currents.

Firstly, whatever the type of current, the turbiditic levee or contourite drift tends to migrate downstream. Typically, this will be downslope for turbidity currents and alongslope for bottom currents (Fig. 6a and b).

Secondly, according to which type of current is involved in the sediment transport process, lateral migration of the levee or drift differs as a consequence of the Coriolis effect. In the northern hemisphere (Fig. 6b), if the flow is directed downslope as for turbiditic systems, the turbidity currents are deflected to the right. Where they reach the continental rise or where channel relief has diminished sufficiently, they preferentially overflow the right flank of the channel and build up a prominent levee on this side. With continued preferential deposition on the right, the channel and levee both tend to migrate towards the left so that the channel–levee system

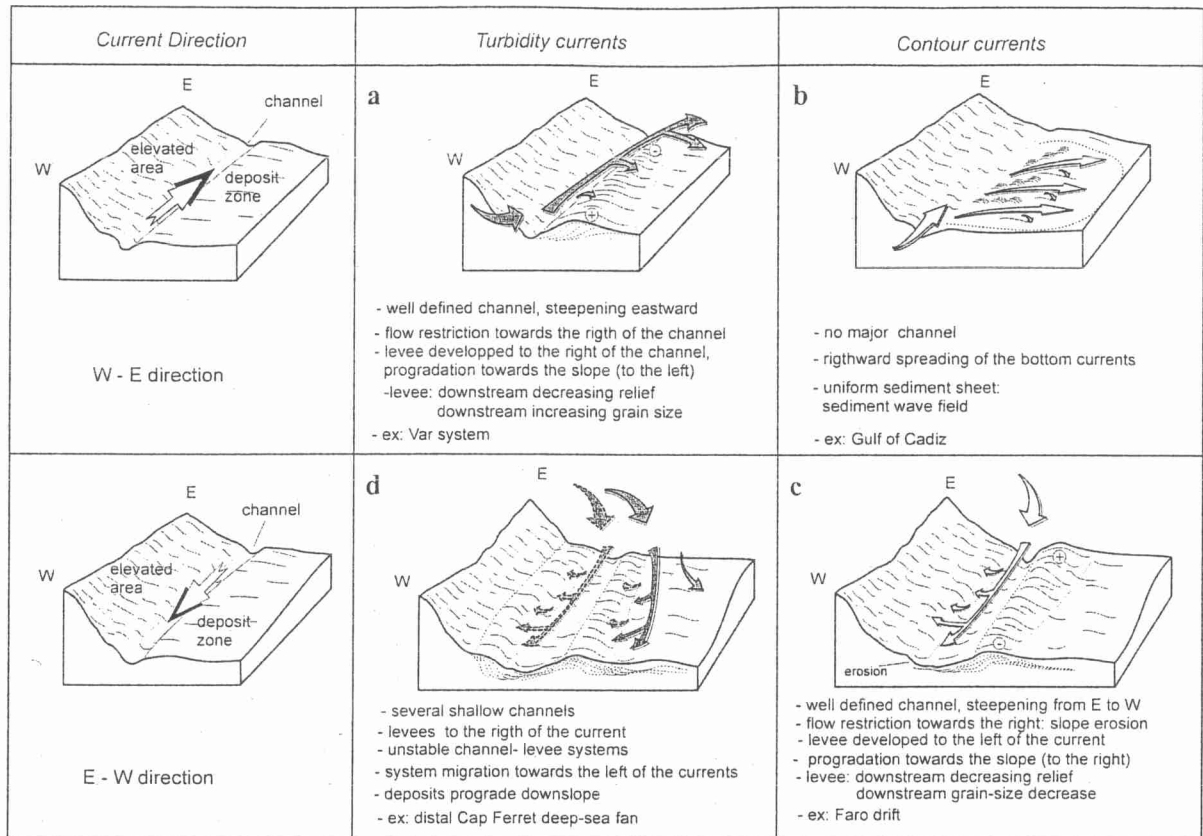


Fig. 13. Different scenarios illustrating the possible relationships between the slope trend, the current trend and the sediment levee pattern when either turbidity or contour current are involved in sediment deposition (in the N hemisphere).

becomes orientated more and more oblique to the slope (Fig. 6c and Fig. 13a). Where the flow is directed alongslope, as with bottom currents (Fig. 6a and Fig. 13c), the Coriolis effect again deflects the flow to the right, effectively constraining the flow against the slope. Being so constrained the flow intensifies, erosion occurs and a channel develops. Lower velocities to the left of the flow favour deposition and drift construction, with the drift tending to migrate upslope as well as prograde alongslope. Such patterns are well-illustrated by the relationships between the drift geometry and current trend on Figs. 8 and 9.

Thirdly, both types of flow are significantly affected by bottom morphology. A change in margin trend or in steepness of the slope may cause the initiation or cessation of deposition and drift construction by a bottom current (Fig. 9c, d), or a

change, for example, from a mounded drift with distinct progradation to a plastered slope drift with less defined progradation but clear aggradation (Fig. 5a–c). Turbidity current interaction with, for example, a base-of-slope seamount will cause flow deflection, possible erosion near the seamount and downstream deposition.

Fourthly, where deposition is controlled by an interaction of currents then the pattern of migration is likely to be affected. Interaction of the northward flowing Gulf Stream surficial current with southerly flowing deep WBUC off eastern North America, for example, has led to the detached Blake–Bahama Outer Ridge Complex (McCave and Tucholke, 1986). Farther north along this margin, the WBUC combines with the Coriolis effect to increase turbidity current deflection and accentuate the asymmetry of turbiditic levees on the Laurentian Fan. In the NE

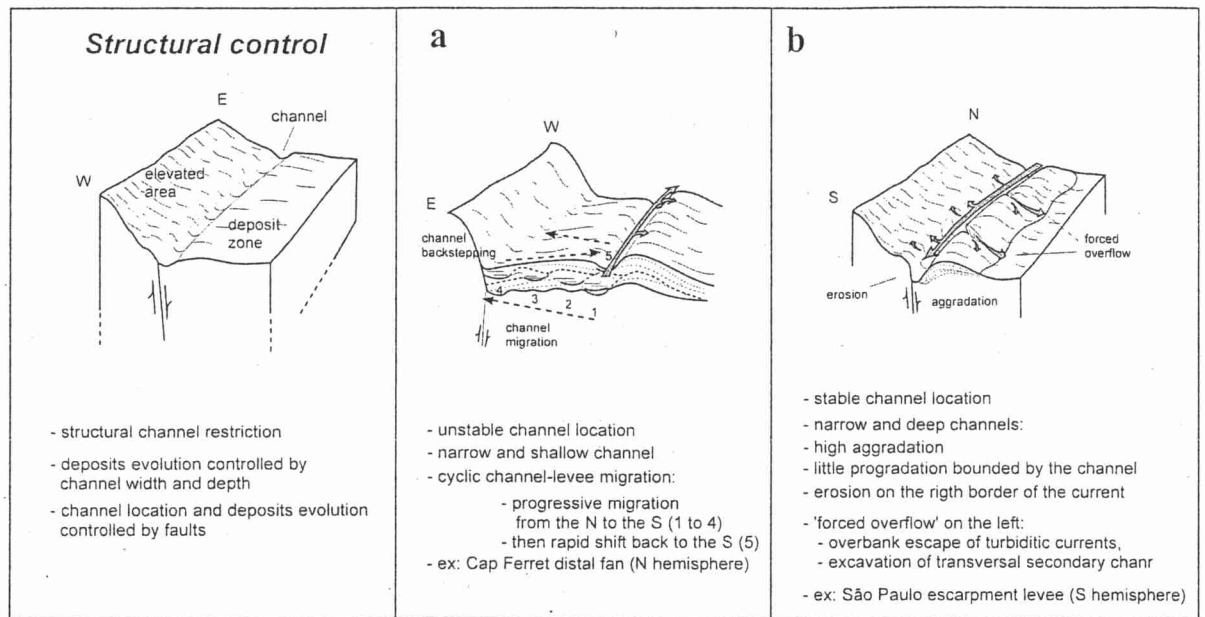


Fig. 14. Two observed scenarios of the relationships between the slope trend, turbidity current trend and the turbiditic levee patterns, when there is a strong tectonic control on the turbiditic channel. Note that the resulting sediment accumulation is elongated parallel to the fault escarpment (after Mézerais, 1991; Faugères et al., 1998; Viana et al., in preparation).

Rockall Trough, both flow interaction and topographic influence have led to a particularly complex pattern of drift construction and migration (Stoker et al., 1998).

Different scenarios are suggested for current pathway and associated deposit patterns according to the current type, the trend of the current vs. the trend of the margin, and the Coriolis effect (Fig. 13). A strong tectonic control on the turbidity current pathway may result in a deposit geometry similar to that of drifts (Fig. 14).

5. Patterns at the scale of seismic facies

5.1. Seismic facies of contourite drifts

Several different seismic facies (using single-channel sparker and multichannel airgun sources) have been described from contourite drifts and their associated channels or moats (Figs. 4 and 5b, Figs. 8, 10 and 11). (a) *Transparent layers* of variable thickness occur intercalated with zones of seismic reflectors, particularly in sheet drifts and patch drifts. (b)

Smooth, parallel reflectors of moderate to low amplitude are typically interbedded with transparent zones in sheet drifts and common throughout mounded drifts and contourite fans. Both continuous and discontinuous reflector patterns occur. (c) *Short, discontinuous to chaotic reflectors* of moderate to low amplitude can form parts of most drifts, particularly patch drifts, drift margins and moats. (d) *Sigmoid progradational reflectors* occur in mounded drifts where strong downstream and/or oblique migration has occurred. They are common in separated drifts. (e) *Both gently wavy reflectors* (irregular wavelengths > 10 km) and distinct *sediment waves* (regular wavelengths 1–10 km) are common over parts of all drifts, but generally absent from associated moats. (f) *Horizontal and low-inclination reflectors truncated* at the seafloor or by an internal erosional surface are also characteristic of all drift types.

5.2. Contourite echofacies

Large areas of seafloor have been mapped with high-resolution seismic profilers (i.e., 3.5 kHz

echosounders) and a number of distinct echofacies identified (e.g., Damuth, 1975, 1980; Jacobi, 1982). Those most commonly recognised from contourite drifts include: (a) distinct, parallel, continuous echoes with multiple sub-bottom reflectors, (b) medium prolonged echoes with discontinuous sub-bottom reflectors, (c) medium and small-scale hyperbolic echoes, more or less irregular, and (d) regular migrating waves and irregular wavy echoes with parallel to subparallel subbottom reflectors.

5.3. Distinction from turbidites

All the seismic facies and echofacies described above from contourite drifts have also been recognised from turbidite systems, so that distinguishing between the two at this scale of observation is not simple. However, certain seismic facies appear to be more typical of, or even restricted to, turbidite systems. These include the well-stratified, horizontal, parallel, high-amplitude reflectors peculiar to ponded

Table 2
Sediment waves and ridges in the deep-sea

<i>Turbidite waves</i>	
Dimensions	wavelength 0.5–10 km, amplitude 10–100 m
Orientation	perpendicular to flow pathway/channel overflow pathway
Migration	marked upstream migration, sometimes slight downstream
Variation	often downstream decrease in amplitude and wavelength down levee flank. Size increase, and deposit geometry variations downward along the levee flank similar to those observed up a stratigraphic section, due to changes in the levee morphology and associated turbidite processes and deposit grain-size
Geometry	parallel, low sinuosity wave crests; rare bifurcation
Location	particularly common on turbidite levees
Extent	relatively localised zones, 200–1000 km ² typically
Hydrodynamic interpretation	formed (as giant antidunes?) beneath competent, low- to high-concentration turbidity currents (muddy to sandy-pebbly sediments)
<i>Contourite waves</i>	
Dimensions	wavelength 0.5–10 km, Amplitude 10–100 m
Orientation	perpendicular to depositing current, but may be oblique or parallel to principal bottom current direction
Migration	slight upstream, standing waves and slight downstream migration all occur
Variation	no regular downstream changes in dimensions and deposit geometry, but irregular geometry variations up stratigraphic section
Geometry	subparallel, sinuous wave crests; common bifurcation where waves are less regular
Location	particularly common over extensive sheet drifts and large elongate drifts
Extent	can cover very large areas, up to 10,000 km ² , but also smaller, more localised zones
Hydrodynamic interpretation	form as giant antidunes beneath competent bottom currents (Froude number > 1), but differential deposition and wave migration can occur at low flow velocities due to the influence of large-scale internal lee waves (Froude number < 1); and sometimes form as lateral levee elongated parallel to the current trend
<i>Slope sediment ridges</i>	
Dimensions	wavelength 0.5–10 km, amplitude 10–100 m
Orientation	perpendicular to maximum slope gradient
Migration	apparent upslope migration, but due to plastic strain deformation
Variation	amplitude and wavelength decreases with decrease in slope gradient
Geometry	subparallel, sinuous or curved crests, laterally discontinuous/common multiple bifurcation
Location	continental slopes, most common where gradient is > 2°
Extent	can occur over small localised to relatively large areas of slopes, 100–1500 km ²
Hydrodynamic interpretation	form as a result of constant strain-induced creep leading to slope shortening and plastic deformation
<i>Mixed wave / ridge types</i>	
Interaction between two and three of these wave/ridge forming processes is common on many continental slopes	

turbidites in basin plains, as well as other high-amplitude reflectors and strong, prolonged bottom reflectors from turbidite channels filled with coarse-grained material.

Patterns indicative of progressive channel–levee migration through a seismic section, channel switching, and channel systems flanked by two clear levees are all typical of turbidite systems. Deep erosion more normally accompanies turbidity current channelling whereas mounded, sigmoid reflector patterns with less erosion typify contourite channel–drift systems.

Extremely chaotic topography associated with chaotic reflector patterns and erosive scars, together with markedly lenticular, transparent seismic/echofacies are generally indicative of slides, slumps and debris flow activity on relatively steep slopes.

5.4. Sediment waves and ridges

Sediment waves and ridges are defined as large-scale, regular bedforms (wavelength 1–10 km, amplitude 10–100 m) that form in fine-grained sediments (mainly muds and silts) and occur over large areas of the deep-sea floor.

Sediment waves are a distinctive seismic facies and echofacies from a range of deep-sea environments. Three types can be defined according to the predominant process involved. They clearly form as a result of both bottom current processes (Fig. 5b and Fig. 8d3) and turbidity current, but neither the hydrodynamic processes responsible for their deposition nor any reliable means of distinguishing between the two types have yet been established (see Lonsdale and Hollister, 1979; Normark et al., 1980; Allen, 1982; McCave and Tucholke, 1986; Kidd and Hill, 1987; Flood, 1988, 1994; Blumsack and Weatherly, 1989; Savoye et al., 1993; Manley and Caress, 1994; Brew, 1995, among many other examples). Sediment ridges on continental slopes that result from constant strain and downslope creep, present an almost identical seismic facies (O'Leary and Laine, 1996) that serves to further complicate the picture (Ballard, 1966; Bouma and Treadwell, 1975; Hill et al., 1983; Gardner et al., 1999). The distinction between these three types is still far more complex (Fig. 8d2) as interaction between two or three of the

wave/ridge forming processes is likely to be common on many continental slopes, and the original process of formation may be different from that which caused subsequent propagation and aggradation of the wave field (Howe, 1996).

However, recent results from the NW African margin (Wynn, 1999), the Gulf of Cadiz (Faugères and Gonthier, 1997), the Demerara Rise (Gonthier et al., 1999) and the Var system (off the French Riviera, B. Savoye, IFREMER, Brest, France; Migeon et al., in preparation) will shed more light on sediment wave and ridge patterns, their process of building, and suggest ways by which each of the three types noted above can be distinguished. They are based on wave distribution and 3D geometry, sediment lithology, and distribution at the scale of single wave and wave fields (Migeon et al., in preparation). The principal attributes of the three types that are known presently are summarised in Table 2.

6. Intercalated turbidite and contourite deposits

The interaction of downslope and alongslope processes and deposits at all scales is the normal condition on the margins of present ocean basins, particularly the western margins of oceans or ocean margin basins and the entire margin surrounding the Antarctic continent. This type of interaction has been the subject of much recent research (e.g., Stow et al., 1998), and has been clearly demonstrated at the scale of interbedded turbidite and contourite facies and the reworking of turbidite tops by bottom currents (Stanley, 1993; Stow et al., 1998). Over a longer time scale, and therefore more visible on seismic profiles, there has been an alternation of periods during which either downslope or alongslope processes have dominated as a result of variations in climate, sea level and bottom circulation coupled with basin morphology and margin topography. This has been particularly true since the Late Eocene onset of the current period of intense thermohaline circulation, and with the marked alternation of depositional style reflecting glacial–interglacial episodes during the past 2 Ma.

Several examples can be used to illustrate the nature and complexity of this interaction as recorded on seismic profiles.

(a) The eastern margin of the USA off Cape Hatteras (Tucholke and Mountain, 1986; McMaster et al., 1989; Locker and Laine, 1992, among others) is dissected by numerous turbidity current canyons and channels that supply the continental rise with sediment. The deeper rise is swept by the alongslope Western Boundary Undercurrent. Both processes are active simultaneously but with variable intensities. The result is a succession of periods during which each process dominates alternately and which are separated by major discontinuities linked to global hydrological events. On seismic profiles (Fig. 2), the result is a quite complex imbrication of deposits that has been referred to as a *companion drift fan* (Locker and Laine, 1992).

(b) The Chatham–Kermadec region of the active continental margin off eastern New Zealand, is swept by the SW Pacific Deep Western Boundary Current. This current has been shown to scour and erode the Bounty Fan south of the Chatham Rise as well as to directly incorporate fine-grained material from turbidity currents that have travelled down the Hikurangi Channel north of the Chatham Rise (Carter and Mitchell, 1987; Carter and Carter, 1988; Carter et al., 1990; Lewis, 1994; Wood and Davy, 1994; McCave and Carter, 1997). This material, together with pelagic and volcanoclastic input, is swept north from the downstream end of the turbidity current channel to form a deep-sea fan with the morphological characteristics of a contourite drift (Fig. 15a). The au-

thors introduce the term *fan drift* for this style of deposit.

(c) Multichannel seismic reflection profiles from the continental rise west of the Antarctic Peninsula reveal the presence of eight large sediment mounds, elongated perpendicular to the margin and separated by turbidity current channels (Fig. 15b, Rebesco et al., 1996, 1997). The asymmetry of these mounds conforms to their construction by entrainment of the suspended load of down-channel turbidity currents within the ambient southwesterly directed bottom currents (composed by the ACC and a branch of the Antarctic Bottom Water (AABW)) and their deposition downcurrent. Coriolis deflection of turbidity current material would result in the opposing asymmetry. Preliminary core data from these *giant sediment drifts* appears compatible with this interpretation (C. Pudsey, 1997, personal communication).

(d) The Rockall continental margin off NW Britain saw the onset bottom current influence on sedimentation in the early Late Eocene, and the development of a drift complex closely intercalated with deposits generated by downslope processes. Unravelling this sedimentary system using seismic reflection data calibrated with boreholes and short cores reveals a complicated pattern of intercalation in both time and space (Howe et al., 1994; Stoker, 1995; Stoker et al., 1998). The alongslope distribution of slope sediments — originally slides, debrites, turbidites and hemipelagites — by the northward-directed slope

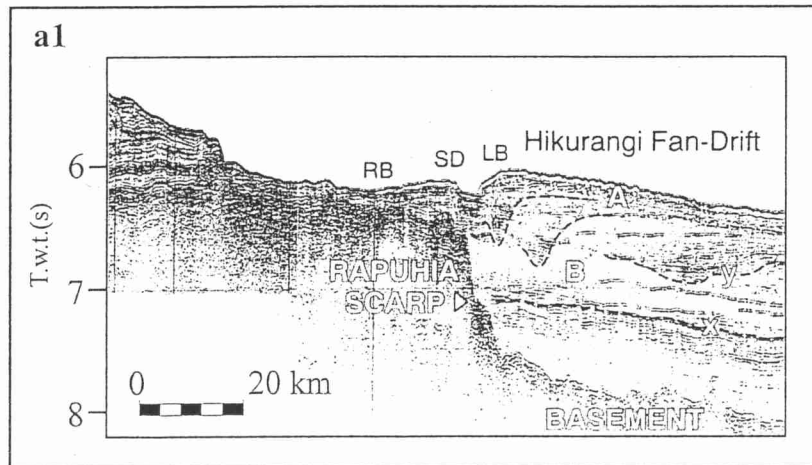
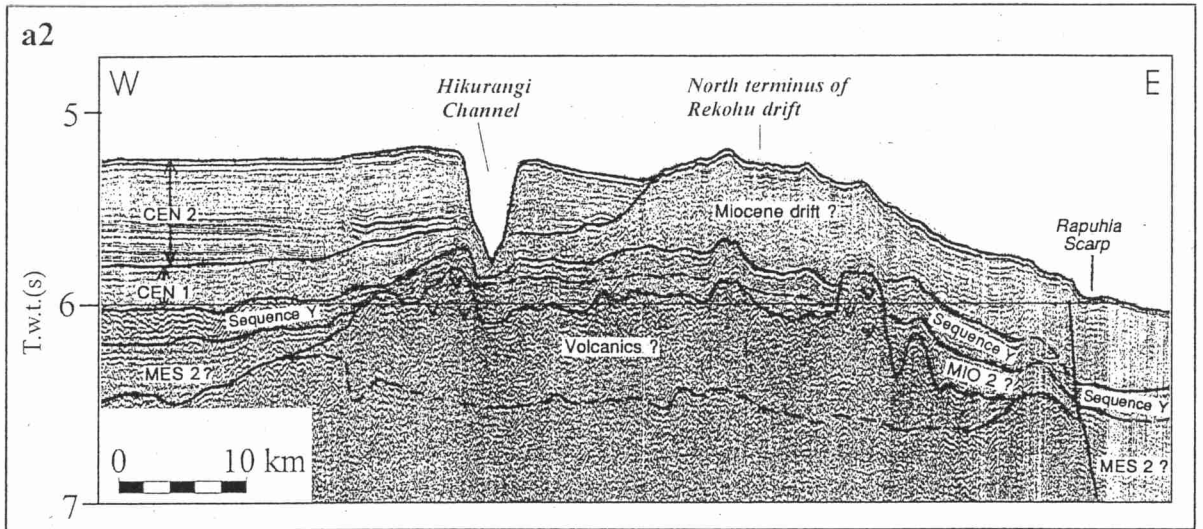
Fig. 15. Seismic lines over margins showing interfingering of turbiditic and contourite deposits. (a) Over the northeastern New Zealand margin. (a1) The Hikurangi fan drift (airgun profile, after Carter and McCave, 1994; Wood and Davy, 1994) is a large sediment levee developed on the left bank (L.B.; right bank: R.B.) of a southern distributary (S.D.) of the Hikurangi turbiditic channel. It is interpreted as resulting of interacting turbidity and contour current processes. The upslope progradation of the channel–levee system is responsible for the burying of the Rapuhia Scarp, and is consistent with both southward flowing turbidity currents and northward flowing Antarctic Bottom Water (AABW) contour currents (X: Mid- to Late Oligocene reflector, Y: Late Miocene reflector; A and B: depositional units). (a2) Seismic section over Hikurangi turbiditic channel–levee system (CEN2 unit) merging into the downslope termination of the Rekohu drift interpreted as built by the SW Pacific deep western boundary current (CEN1 and CEN2: Neogene sequences, after Wood and Davy, 1994). (b) Over the western continental margin of the Antarctica Peninsula (airgun seismic line; after Rebesco et al., 1996, 1997). The mounded drift is elongated downslope between two feeding turbiditic channels (cf. Fig. 6f). The drift deposits slightly thicken downstream of the N–S bottom currents (ACC: Antarctic Circumpolar Current) and the mound crest seems to present an upcurrent progradation. Note that the southern flank of the mound relief is drastically eroded probably by gravity mass-flow processes (M–M.h.: Middle Miocene hiatus; 1: drift maintenance stage; 2: drift growth stage; 3: pre-drift stage). (c) Seismic section over the southeastern Brazilian margin (multichannel airgun section, Viana et al., in preparation). Note the southward alongslope progradation of bottom current controlled deposits, predominantly responsible for the canyon infill. The canyon bottom is filled in by interfingering gravity current (g.) and contour current (c.) deposits. The main stages of the margin evolution are underlined by major reflectors (1 to 4; reflector 3 is Middle–Late Miocene in age). The depth of the canyon valley increases progressively since its initiation due to the stacking of the slope deposits (t.c.: turbidity current; b.c.: bottom current).

current has been clearly demonstrated for the Barra fan (Armishaw et al., 1998) which led these authors to introduce the term *composite slope-front fan* for this system.

(e) The last example of interactive gravity and contour current processes is from the SE Brazilian margin (Souza Cruz, 1995; Viana, 1998; Viana and Faugères, 1998; Viana et al., in preparation). In this region, the upper part of the Neogene continental slope is considered to be predominantly controlled by contour currents (mainly the SW flowing Brazil-

ian Current), with gravity currents mostly confined along gullies and canyons. The bottom currents would be responsible for the laterally continuous deposits which develop prograding clinoforms within some canyon valleys. These contourite infilling deposits are interfingered with gravity deposits as shown on Fig. 15c.

Numerous different scenarios for interacting downslope and alongslope processes have been abundantly described in the literature especially in the eastern North American margin (Locker and



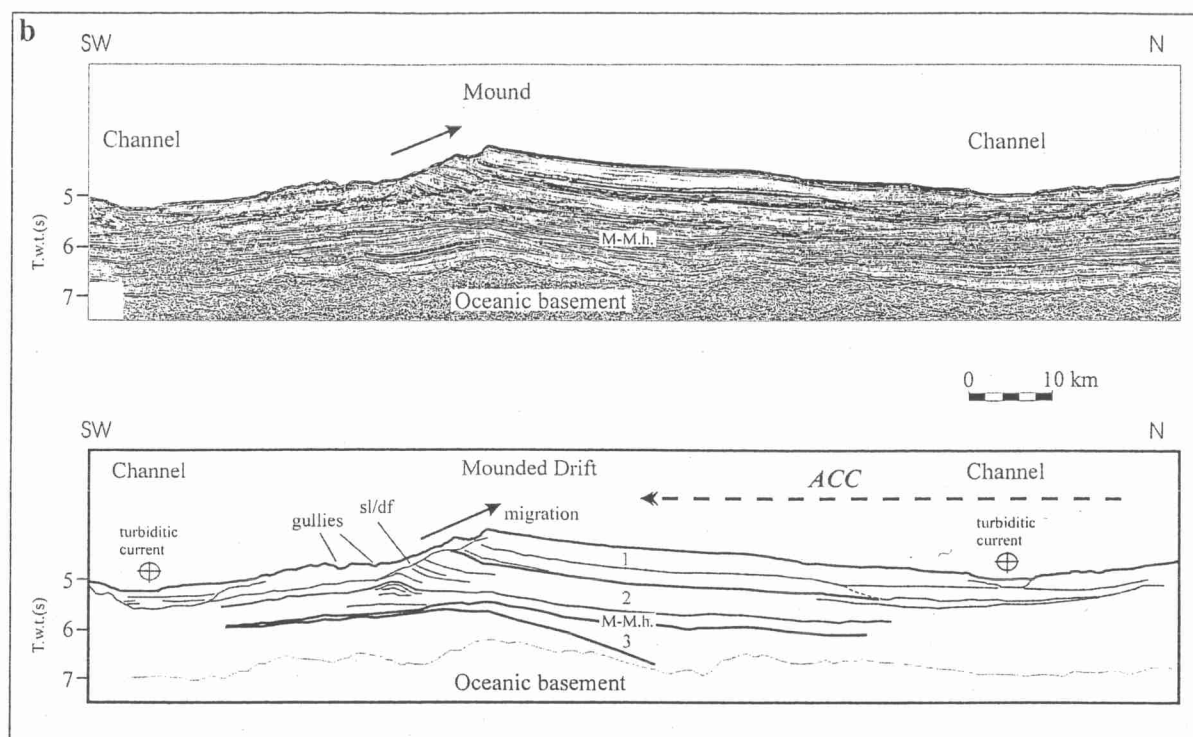


Fig. 15 (continued).

Laine, 1992; Shanmugan et al., 1993, among many others), South Atlantic Ocean (Massé et al., 1998), Antarctic Ocean (Kuvaas and Leitchenkov, 1992; Larter and Cunningham, 1993; Weber et al., 1994; Pudsey and Howe, 1998) and New Zealand margin (Carter and McCave, 1994, among others). Some of them are summarised in Fig. 16.

7. Contourite deposits and sea level variations: sequential stratigraphic models

The deposition and distribution of contourites from thermohaline bottom circulation and sometimes wind-driven circulation is controlled by three principal factors: (1) the climate, which affects the atmospheric circulation and the conditions of formation of bottom water and hence determines the intensity of bottom currents, (2) the nature and volume of sediment available for transport by bottom currents, and (3) the morphostructural context at the scale of the basin. There are no unequivocal data that permit us

to make a direct link between sea level and rates of drift accumulation or destruction, and certainly not at a time scale approaching that of the glacial–interglacial sea level fluctuations (Faugères and Stow, 1993). At best we can examine the role of the different factors itemised above and review the apparent effects of climate/sea level on drift development.

Significant accumulation on contourite drifts is favoured, on the one hand, by a moderate intensity of bottom current and, on the other hand, by relatively low rates of sediment supply via turbidity currents or other mass flows. In fact, each episode of increased bottom current circulation linked to a global hydrological event typically corresponds to a widespread surface of erosion or non-deposition in drift systems. Such events can have either a climatic origin, linked to variation in the extent of polar ice caps and sea ice, or a tectonic cause, for example the opening and closing of sills and gateways that control bottom water exchange between ocean basins. Discontinuities related to such events are well-known

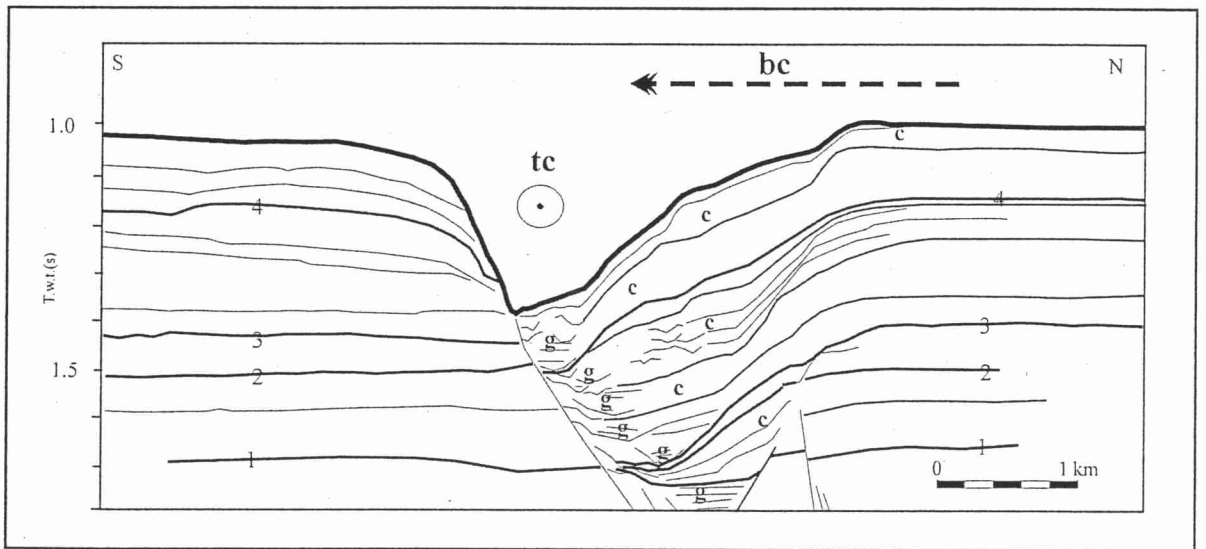
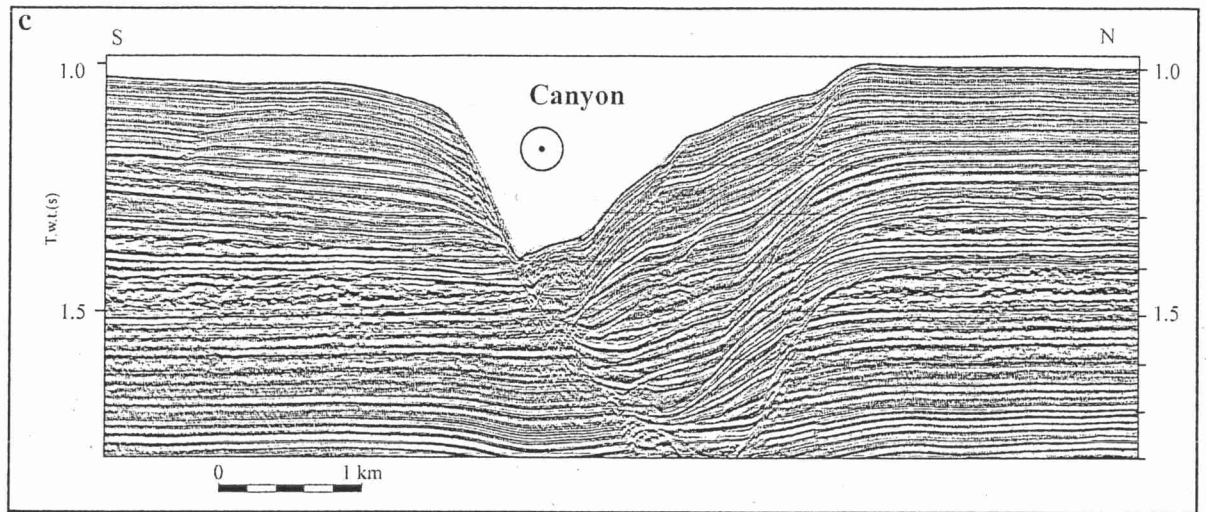


Fig. 15 (continued).

throughout the world ocean at certain periods, for example the Eocene–Oligocene boundary, the end of the Mid-Miocene and the end of the Late Miocene (Tucholke and Mountain, 1986; Haq, 1991, among many others).

Whatever the relative intensity of bottom circulation, the influx of large volumes of continental sediment into the deep-sea, related to a major sea level low stand, generally results in the masking of con-

tourite sedimentation and hence dominance of downslope deposits during that period. Such a situation is particularly clear on the continental margin off the eastern USA (Tucholke and Mountain, 1986; McMaster et al., 1989).

The global climatic fluctuations and sea level changes of the Plio-Quaternary also determine changes in production of deep-water at high latitudes and in the thermohaline circulation in general. How-

such as 20,000- to 40,000-year cycles, there is no clear link between drift development and climate or sea level.

Contrary to certain publications (Vail et al., 1977, 1991; Posamentier et al., 1988; Haq, 1991), contourite drift development does not fit neatly into high-stand, low-stand or an intermediate position in sequence stratigraphic models.

8. Conclusions

It has become increasingly clear over the past decade of deep-water research that both downslope and alongslope processes play critical and interactive roles in the construction and shaping of continental margins, as well as parts of oceanic basins. However, just as it is important to be able to distinguish in core or outcrop individual facies resulting from different processes, it is essential to recognise the seismic features that characterise turbidite vs. contourite deposits. Extensive review of existing seismic data from contourite systems allows us to approach this problem at three scales; that of the whole drift, that of discrete depositional (seismic) units, and that of individual seismic facies.

The principal features by which contourites can be distinguished on seismic profiles include the following.

8.1. Drift geometry

Drifts occur in four distinct geometries: sheets (including abyssal sheets, plastered sheets and patch sheets), elongate mounds (including detached and separated drifts), channel-related drifts (including patch drifts and contourite fans), and confined drifts. Although these geometries may, in some cases, be distinctive on seismic records they are not unique to contourite systems. There is also complete gradation between the type members.

8.2. Discontinuities

Contourite drifts are characterised by widespread discontinuities that can be traced across the whole accumulation and are marked by a continuous high-

amplitude reflector. These typically result from an erosive episode reflecting increased bottom current intensity, but may also be caused by marked grain-size or compositional change related to gentle variations in current regime, sediment supply or drastic changes in water chemistry.

8.3. Depositional (seismic) units

Depositional (seismic) units within contourite drifts are generally lenticular in shape, with an upwardly convex geometry that is non-parallel to the surface created by the preceding erosional event.

8.4. Progradation–aggradation

The stacking of depositional units reveals the general migration of the sediment body, the direction of which is different for different drift types. Down-current progradation or oblique progradation is typical, with a downlapping (top-lapping) or sigmoid progradational reflector pattern.

8.5. Migration

Lateral migration of contourite vs. turbidite channel–levee systems can, in some instances, be used to distinguish the two types provided that the morphological context, current direction and hemisphere is known.

8.6. Seismic facies

A wide variety of seismic facies (sparker and airgun profiles) and echofacies (3.5-kHz profiles) is typical of contourite drifts. Mostly, these are low to moderate amplitude reflectors, either relatively continuous or discontinuous and chaotic. Wavy reflectors and regular migrating sediment waves are common in some cases. All of these types can be found equally in turbidite systems. However, well-stratified, horizontal, parallel, high-amplitude reflectors appear to be peculiar to ponded turbidites in basin settings, and other shorter, high-amplitude reflectors typical of turbidite channels. A preliminary set of characteristics is proposed for sediment waves from the different systems.

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