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## Fossil contourites: a critical review

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### Abstract

Despite three decades of study, there is still great controversy over the recognition and interpretation of fossil contourites exposed in ancient series on land. In order to best examine this problem, we briefly review the evidence from modern systems, including the many examples of Cenozoic contourites that have been recovered from DSDP/ODP drilling on major drifts in the present-day oceans. The range of contourite facies described from both deep-water (>2000 m) and mid-water (300–2000 m) drifts are mostly fine-grained, bioturbated and homogeneous, often with a distinct bedding cyclicity, and with some coarser-grained sandy contourites developed under higher-energy bottom currents. There are also a number of current-controlled sediment bodies that have formed in outer shelf/upper slope settings (50–300 m) under the influence of counter currents, underflows and major surface currents. These are not considered contourites *sensu stricto*, but may be mistaken as such in ancient examples. The most commonly described fossil contourites in the literature have been interpreted by the authors concerned as bottom-current reworked turbidites. However, a critical review suggests that these are the facies most subject to misinterpretation and many of the sediments claimed as fossil contourites are almost certainly fine-grained turbidites, whereas others were more likely formed under outer shelf/upper slope current systems. There remain very few ancient examples that are more closely comparable to modern contourites; these include the Cretaceous Talme Yafe Formation in Israel, the Ordovician Jiuxi Drift in China, and parts of the Paleogene Lefkara Formation, Cyprus and the Neogene Misaki Formation in Japan. We present a set of possible criteria for the recognition of fossil contourites and bottom-current reworked turbidites. © 1998 Elsevier Science B.V. All rights reserved.

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### 1. Introduction

The search for ancient contourites on land has been an elusive one, fraught with problems of false interpretation and poor understanding of deep-water processes. However, much progress has been made in recent years in the description of mod-

ern contourite facies through widespread coring programmes, in recognition of ancient contourites from the many boreholes now drilled into large-scale drift deposits, particularly during the Deep Sea Drilling Program (DSDP) and Ocean Drilling Program (ODP), and in documentation of bottom current processes by in-situ observation (e.g. HEBBLE programme, Hollister et al., 1985). The time is right for a critical appraisal of the current status with respect to recognising contourites in the field.

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The main objectives of this paper, therefore, are:

(a) to highlight the range of depositional processes, morphological and hydrological settings, and sediment patterns associated with contourite deposition;

(b) to summarise the large body of data on ancient contourites recovered from boreholes through known drift deposits in the present-day oceans; and

(c) to review critically the many examples of fossil contourites described from outcrop, based on our current level of understanding of facies and processes.

From this approach, the most reliable criteria for identifying fossil contourites can be evaluated and the problems of process interaction in the formation of such deposits, particularly bottom-current reworking of turbidite tops, discussed. The importance of correctly identifying and interpreting ancient contourites has been thrown sharply into focus by the contention that sandy contourites may act as hydrocarbon reservoirs (e.g. Shanmugam et al., 1993), as well as by the fact that fossil contourites hold a distinctive signature of past changes in bottom circulation linked to climatic oscillation (Robinson and McCave, 1994).

## 2. Processes and settings

Although the first descriptions of contourites were from great depths beneath a major deep-water bottom current (Heezen et al., 1966; Hollister, 1993), we now recognise several settings in which contourites may occur (Faugères and Stow, 1993; Viana et al., 1998) and from which fossil examples have been described.

### 2.1. Deep-water drifts

Deep-water drift deposits generally occur in water depths in excess of 2000 m beneath semi-permanent bottom currents. They are well represented along the foot of the continental slope, particularly beneath strong western boundary undercurrents, are associated with deep-sea passageways that act as gateways between the deeper compartmentalised portions of ocean basins, and also occur over parts of abyssal basin floors, in some cases as giant sediment wave fields.

Many examples are known from the present oceans (e.g. McCave and Tucholke, 1986; Faugères et al., 1993) including the giant elongate drifts, contourite sheets, channel-related drifts and contourite fans defined by Faugères and Stow (1993). The sediments are fine grained, mainly silt and mud grade with rare sandy horizons, and are more or less rich in biogenic material. The specific characteristics of these contourites have been amply described in the literature (e.g. Stow and Lovell, 1979; Stow, 1982; Gonthier et al., 1984). An up-to-date review of these drifts and their deposits is given in Section 3 (see Table 1). One ancient example described below that might have formed in these water depths is that of the Lefkara Formation in Cyprus (Kahler, 1994; Kahler and Stow, 1998).

### 2.2. Mid-water drifts

Mid-water drift deposits are those that occur in intermediate water depths (300–2000 m) on the continental slopes of the world's oceans as well as in mid-depth passageways and sills. Although some giant elongate drifts form at this depth, many are smaller elongate bodies or much flattened contourite sheets. They form in association with geostrophic bottom waters flowing alongslope at intermediate levels in the water column (e.g. Mediterranean Underwater and the NE Atlantic Boundary Current), and with water masses flowing downslope from their surface origin at high latitudes or following the breaching of shallow intra-ocean basin gateways.

Numerous examples of this type have been described from shallow-penetration cores (e.g. Stow et al., 1986; Akhurst, 1993; Howe et al., 1994). The sediments are very similar to those of the deep-water drifts in that they are mostly fine grained, bioturbated and homogeneous. In addition, high-latitude contourites are typically mixed with coarse-grained ice-rafted debris (Yoon and Chough, 1993), and the more upslope contourites under the influence of higher-energy bottom currents may be sand-rich (e.g. Nelson et al., 1993). Of the several ancient examples discussed below, the more reliable are those from the Talme Yafe Formation in Israel (Bein and Weiler, 1976), the Jiuxi Drift in south-central China (Duan et al., 1993), and the Misaki Formation in Japan (Stow and Faugères, 1990).

### 2.3. Outer shelf/upper slope drifts and related deposits

There are a number of current-controlled sediment bodies that have formed in relatively shallow water (50–300 m) but away from the influence of coastal or inner shelf processes. They form on the outer shelf or upper slope under the influence of high-level bottom waters (e.g. counter currents or underflows), or are more directly linked to major surface currents, such as the Gulf Stream or Kurushio Current. Very deep tidal currents, storm waves, internal waves and other clear-water currents may operate at these depths on outer shelves, upper slopes, in straits, such as the Messina Strait off Sicily, or in the head regions of submarine canyons.

The nature of such deposits is known from several well described modern systems (see review by Viana et al., 1998), including the large field of sand waves on the Sodwana Bay outer shelf under the influence of the Agulhas Current (Flemming, 1980; Ramsay, 1994), and the sand banks on the outer Grand Banks off Newfoundland formed under the combined influence of the Labrador Current, tidal currents and waves (Dalrymple et al., 1992). Carbonate drifts with sand waves and dunes have been described from shallow water, and extending to as much as 800 m water depth, from the Bawihka Channel off Nicaragua (Hine et al., 1992) and in the Straits off Florida (Mullins and Neumann, 1979). Adjacent to the sandy deposits and under quieter current conditions, finer-grained sediments are deposited with their traction current structures more affected by strong bioturbation.

We do not consider these as contourites *sensu stricto* (Faugères and Stow (1993), but several examples that have been described as fossil contourites seem to have been deposited under such conditions. These are discussed below, including those from the Upper Cretaceous of SW Switzerland (Villars, 1991), the Triassic of Chile (unpublished data), and the Plio–Pleistocene of Calabria (Collela and d'Allessandro, 1988).

### 2.4. Bottom-current reworked turbidites

The most commonly described fossil 'contourites' in the literature are interpreted as bottom-current

reworked turbidites. In our opinion, these are the facies most subject to misinterpretation. It is true, of course, that most of the world's continental slopes and basin plains are the sites of episodic turbidity current input, so that almost all regions under the influence of strong bottom currents are potential sites for reworking of turbidites.

However, it is perhaps surprising that there are so very few good descriptions of Recent turbidites that have been demonstrably reworked by bottom currents. The clean, well-sorted sands originally described as contourites from the NE American continental margin (Hollister, 1967) are now seriously questioned as such, and are perhaps better interpreted simply as fine-grained turbidites. Bioturbated and disturbed, but relatively well-sorted sands from the Nova Scotian margin (Stow and Lovell, 1979) are better candidates, as are the lenticular silts and muds of the Antarctic margin (Piper and Brisco, 1975). More recently, a series of top-truncated silt turbidites from the southern Brazil Basin have been shown to possess characteristics indicative of turbidite reworking by bottom currents (Massé et al., 1998).

Conversely, there are a wealth of ancient examples of so-called reworked-turbidite contourites that have been proposed but not confirmed. Of those discussed below, only some parts of the St. Croix (Stanley, 1988), Japanese Kasuza Group (Ito, 1996) and Sicilian examples (Faugères et al., 1992) are possible contenders.

## 3. Cenozoic contourites of deep-water drifts

The best known ancient contourites remain those that have been recovered by drilling on major deep-water drifts in the present-day oceans. A number of these giant elongate drifts first originated in the Oligocene or Early Miocene and, since that time, have accumulated several hundreds of metres of contourite sediments. DSDP and ODP boreholes therefore provide us a good and unequivocal record of contourite facies characteristics, both modern and ancient. Sites that have been drilled through such drifts are listed in Table 1 together with the principal characteristics of both the drifts and their sediments. We also list some of the sites where ancient contourite deposits have been claimed, but for which the evidence for their origin is more equivocal.

Table 1  
Details of contourite drifts and sediment facies drilled during the DSDP and ODP programme

Location	Leg	Sites	Current	Sediment age and lithofacies (from DSDP, IPOD and ODP books)	Contourite-facies type (interpretation from the authors)
<b>ARCTIC OCEAN and NORWEGIAN SEA</b>					
W Norway	104	643–644	Norwegian current	Pliocene–Quaternary silty clayey muds with pebble- and sand-rich layer. No evidence of bottom current activity. Evidence of major change in bottom waters in the Middle Miocene with bottom current erosion in the Upper Miocene	Glacial deposits with possible muddy contourite
Iceland–Greenland	152	915–919	NADW	Early–Late Miocene hard-ground/coarse sand couplets in nannofossil chalk and silt	Possible contourite deposits
<b>NORTH ATLANTIC basins: Rockall Trough; Icelandic, Irminger, Baffin basins</b>					
Gloria Outer Ridge	12	112	NSOW	Late Miocene–Pliocene calcareous mud and marls	
Eirik Drift		113	NADW and NSOW	Plio–Quaternary clayey silty calcareous muds	
Bjorn Drift		114	NSOW	idem	Muddy contourite
Hatton Drift		115	idem	idem	
Iceland–Faeroe Ridge	38	336 N. flank	NSOW	Upper Plio–Pleistocene glacial muds and sandy muds with pebbles partly overlying Upper Oligocene calcareous ooze mud and clay	Glacial muddy contourite?
Rockall plateau, Hatton Drift	48	352 S. flank	idem	Neogene Quaternary foram–nannofossil ooze and chalks with interbedded calcareous muds	Calcareous biogenic contourite and muddy contourite
NNW flank of Reykjanes Ridge (Snorri Drift)	49	403–404–406	NSOW	Plio–Pleistocene calcareous muds with interlayered nannofossil ooze and terrigenous muds	Possible muddy contourite interbedded in pelagic and hemipelagic deposits
SW Rockall Plateau	81	407	NSOW (NADW)	Mio–Pliocene nannofossil ooze with scattered lamination of silt-sized material (mainly glauconitized ash)	Muddy contourite with some calcareous biogenic sandy contourite
		408	idem	Neogene cyclic foraminifera nannofossil ooze, and calcareous mud and marls with some foraminifera-rich sandy lamination resulting from winnowing by bottom currents	Possible contourite
Hatton Drift				Early Oligocene chalk with intact and broken manganese Condensed series nodules (Oligocene) Late early Eocene thick Mn crust	‘Chemogenic’ contourites idem
Icelandic and Rockall Basin: Feni Drift	94	610	NSOW	Neogene cyclic nannofossil ooze, calcareous marls and muds	Muddy and sandy muddy contourites
Gardar Drift		611	idem	idem	

Irminger Basin:	105	Eirik Drift	646	NSOW–NADW	Late Miocene–Pleistocene: silty clayey siliciclastic muds with some pebbly sandy layers and nanofossil-rich layers	Muddy contourite with glacial patterns	
		Gloria Drift	647	idem	Pliocene–Pleistocene cyclic nanofossil-rich silty clay with gravel-rich silty layers	idem	
<b>NORTH-WEST ATLANTIC margins and basins</b>							
North Bermuda Rise	43		387	WBUC	Lower Cretaceous limestone with possible current influence	?	
			385–386	idem	Upper Oligocene–Quaternary hemipelagic clay: deposition partly controlled by bottom currents	Muddy contourite	
Great Antilles Outer Ridge	4		28	WBUC	Neogene pelagic clay ('red clay')	Clayey contourite	
Caico Outer Ridge	11		99	WBUC	Neogene–Quaternary hemipelagic ooze	Muddy contourite	
Blake–Bahama Outer Ridge			101–102–103–104	idem	Neogene Quaternary hemipelagic silty carbonaceous clay, Cretaceous limestone with current-bedding	Muddy contourite	
Hatteras rise			106	idem	Tertiary hemipelagic clay and silty clay with sediment structures supposed to be produced by bottom currents	Muddy contourite	
Hatteras lower continental rise	44		388	WBUC	Upper/Middle Miocene–Pliocene clayey and silty clayey muds with reworked microfossils, deposited by bottom currents, Quaternary calcareous muds, ooze and terrigenous sands	Muddy contourite	
Hatteras Drift	93		603	WBUC	Pleistocene–Lower Pliocene/Upper Miocene: nanofossil clay; Upper-middle Miocene: quartz-mica-bearing clay; Middle Lower (?) Miocene: biogenic siliceous-bearing clay with silt-rich layers due to bottom current reworking	Muddy contourite	
Blake–Bahama	76				Quaternary interbedded nanofossil (silty) marl and silty (nanofossil) clay with few evidences of bottom current winnowing	Muddy contourite	
		Outer Ridge	533	WBUC	Middle to Late Pliocene stiff silty (nanofossil) clay called 'mud' contourites	Possible siliceous biogenic sandy contourite	
		Basin	534	?	Callovian radiolarian sand layers with a lenticular shape and considered as produced by bottom current winnowing		
Barbados active margin, abyssal plain	78A		543	WBUC–AABW?	Quaternary terrigenous silt and sand layers corresponding either to turbidite or to contourite (piston cores collected in the abyssal plain, south site 543)	Siliciclastic sandy silty contourite	
		Tiburón Rise	110	672	WBUC	Oligocene fine sand and silt laminae interpreted as contourite or turbidite	?

Table 1 (continued)

Location	Leg	Sites	Current	Sediment age and lithofacies (from DSDP, IPOD and ODP books)	Contourite-facies type (interpretation from the authors)
<b>NORTH-EAST ATLANTIC</b> margins and basins					
NW African margin	14	138	AABW	Neogene quartzic sandy contourite (Sarnthein, 1978)	Siliciclastic sandy contourite
	41	368–367	AABW	Pleistocene foraminifer-rich ooze, deposited by bottom current	Calcareous biogenic sandy contourite
	108	659	idem?	Eocene radiolarian ooze with Mn-rich layers, deposited by bottom current	Siliceous biogenic silty contourite
Iberic margin	47	398	AABW?	Upper Miocene–Pliocene marly nannofossil oozes and pelagic hemipelagic cyclic deposits with evidence of bottom current structures and winnowing	Muddy contourite and biogenic calcareous contourite
				Pleistocene siliciclastic silty clay with well-sorted silts and sandy silts and bottom current transported diatoms and radiolarians	Muddy and sandy-silty contourites
<b>SOUTH-WEST and EAST ATLANTIC</b> margins and basins					
North Argentine Basin	36	331	AABW	Neogene nannofossil ooze and chalk with beds of increased sandy foraminifera-rich fraction due to periodic bottom current winnowing; alternation of red and greyish shales as a result of pulses of bottom currents	Calcareous biogenic sandy contourite
				Upper Cretaceous carbonate siltstones deposited by bottom currents or distal turbidites?	?
South Cape Basin	40	361	AABW	Neogene–Quaternary terrigenous clay and silt with displaced diatoms transported by bottom currents and silt contouritic laminations	Muddy contourite
South Brazilian Basin	72	515	AABW	Mid Oligocene–Early Miocene pelagic calcareous nannofossil sediments with silty lenticular beds (contouritic) associated with cherts and red clays with Mn micronodules	Silty and possible muddy clayey contourites associated with pelagites
<b>ANTARCTICA</b> margins and basins					
East Ross Sea (South Australia)	28	268	AABW	Mid Oligocene–Miocene thin sandy silty contouritic beds associated with clayey siltstone and silty turbidites	Silty and possible muddy contourite
				Late Miocene–Pliocene claystone units with thin silt layers, relict deposits winnowing by bottom currents	?
Bellingshausen Basin (South East Pacific Ocean)	35	322	AABW	Few evidences of bottom current activity	Interbedded silty and muddy contourite (glacial muddy contourite)
				Plio–Pleistocene clay with thin sandy silty contouritic layers interbedded (turbidity current-derived sediment by contour currents)	
		323	ACPW		
		324	CPCC		



Table 1 (continued)

Location	Leg	Sites	Current	Sediment age and lithofacies (from DSDP, IPOD and ODP books)	Contourite-facies type (interpretation from the authors)
<b>PACIFIC OCEAN</b>					
Southwest Pacific Ocean: Hebrides Basin and Coral Sea Basin	30	286–287	AABW	Major hiatus (Early–Middle Oligocene) due to bottom current in turbiditic–pelagic deposits	?
Ontong–Java Plateau	30	288–289	? Oceanic current with tidal variations	Oligocene–Pleistocene foraminifera and nannofossil oozes with bottom current structures	Calcareous biogenic contourite
Ontong–Java Plateau	7	64	?	Eocene–Quaternary calcareous nannofossil ooze; some Eocene limestone and chert at the hole base	?
NE Australian margin: Marion Drift	133	815	East Australia boundary current	Pleistocene–Late Pliocene: draping foraminifera–nannofossil ooze Early Pliocene: mounded foraminifera–nannofossil ooze and chalk with color changes (episode of maximum building of the drift) Miocene: dolomitized and lithified foraminifera packstone	Pelagic deposits Calcareous biogenic contourite
Central Pacific Ocean	7	65	AABW	Neogene radiolarian sandy–silty contourites with Mn micronodules and reworked volcanic tuffs	Siliceous biogenic contourite and volcanoclastic contourite
		66	AABW	Neogene diatom and radiolarian oozes	Siliceous biogenic contourite?
		67	AABW	Neogene volcanic silty clays and sands with erosional contacts indicating strong bottom currents	Volcanoclastic muddy to sandy contourites
				Paleogene radiolarian sediment (porcelanite and chert)	?
East Pacific Ocean: NE Pacific Ocean	5	32, 35, 36, 43	AABW	Neogene siliceous mud and red clay with likely bottom current transport of particles	Muddy contourite and clayey contourite?
SE Pacific Ocean, Chili margin	141	862–863	Humboldt current	Upper Pliocene–Quaternary clay and silty sands with thin cross-laminated sandy intervals interpreted as contourites	Sandy contourite?
North Pacific Ocean: Meiji Drift	19	192	Kamchatka current	Quaternary to Middle/Lower Miocene clays and diatom oozes; displaced diatoms by bottom currents	Muddy contourite and siliceous biogenic contourites
	145	882–883–884	idem		

AABW = Antarctic Bottom Water; AAIW = Antarctic Intermediate Water; ACPW = Antarctic Circumpolar Water; ACC = Antarctic Circumpolar Current; ACZ = Antarctic Convergence Zone; CPDW = Circumpolar Deep Water; CPCC = Circumpolar Counter Current; WBUC = Western Boundary Undercurrent; NADW = North Atlantic Deep Water; NSOW = Norwegian Sea Water Overflow.

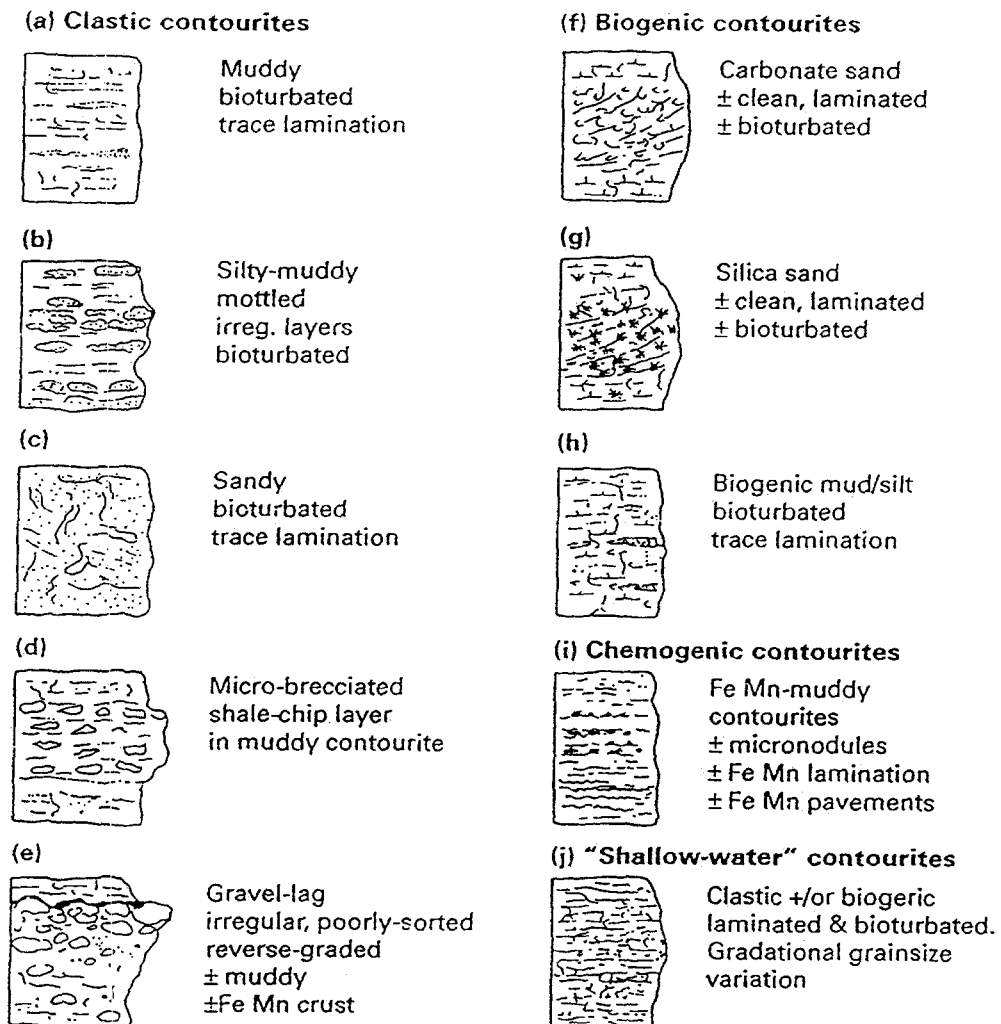


Fig. 1. Contourite facies models for clastic, biogenic, chemogenic and 'shallow-water' contourites (from Stow et al., 1996).

Several different contourite facies can be recognised on the basis of variations in grain size and composition. Schematic facies models are shown in Figs. 1 and 2 and some of the main facies illustrated in Fig. 3. The main facies types are listed below:

- Muddy (siliciclastic) contourites
- Silty (siliciclastic) contourites
- Sandy (siliciclastic) contourites
- Gravel-rich (siliciclastic) contourites
- Muddy–silty–sandy volcanoclastic contourites
- Calcareous biogenic contourites
- Siliceous biogenic contourites
- Manganiferous muddy contourites

The main features of siliciclastic and volcanoclastic contourites are very similar, and have been documented previously (Stow, 1982; Stow and Holbrook, 1984). *Muddy contourites* are homogeneous, poorly bedded and highly bioturbated, with rare primary lamination, typically partly bioturbated, and irregular winnowed concentrations of coarser material. They have a silty-clay grain size, poor sorting and a mixed terrigenous (or volcanoclastic)–biogenic composition. The components are in part local, including a pelagic contribution, and in part far-travelled. *Silty contourites* (also referred to as *mottled silty contourites*) commonly show a mottled to indistinctly

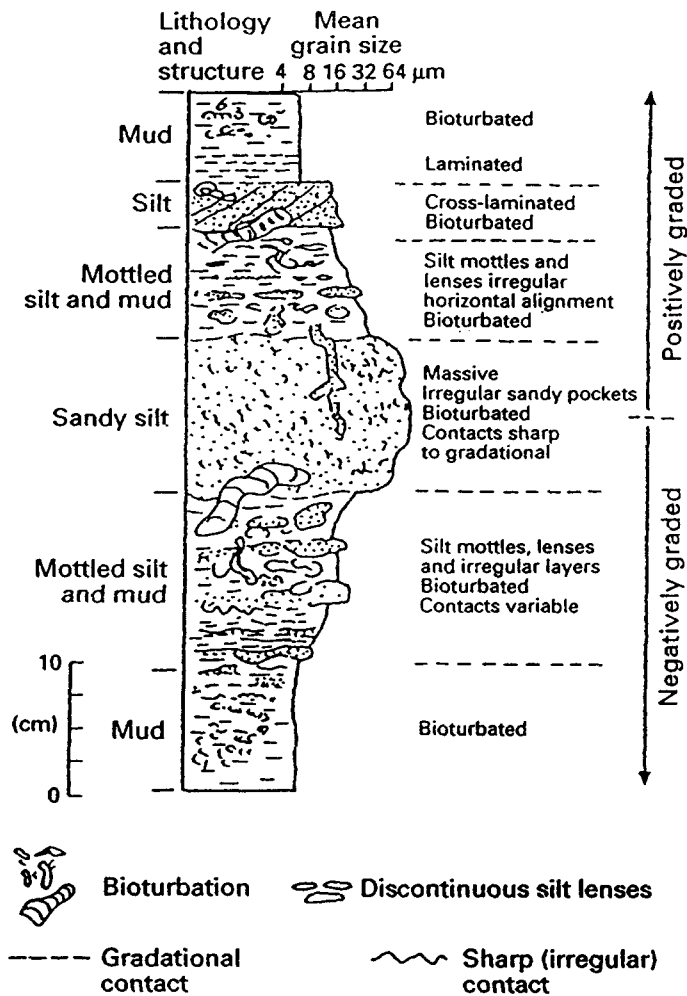


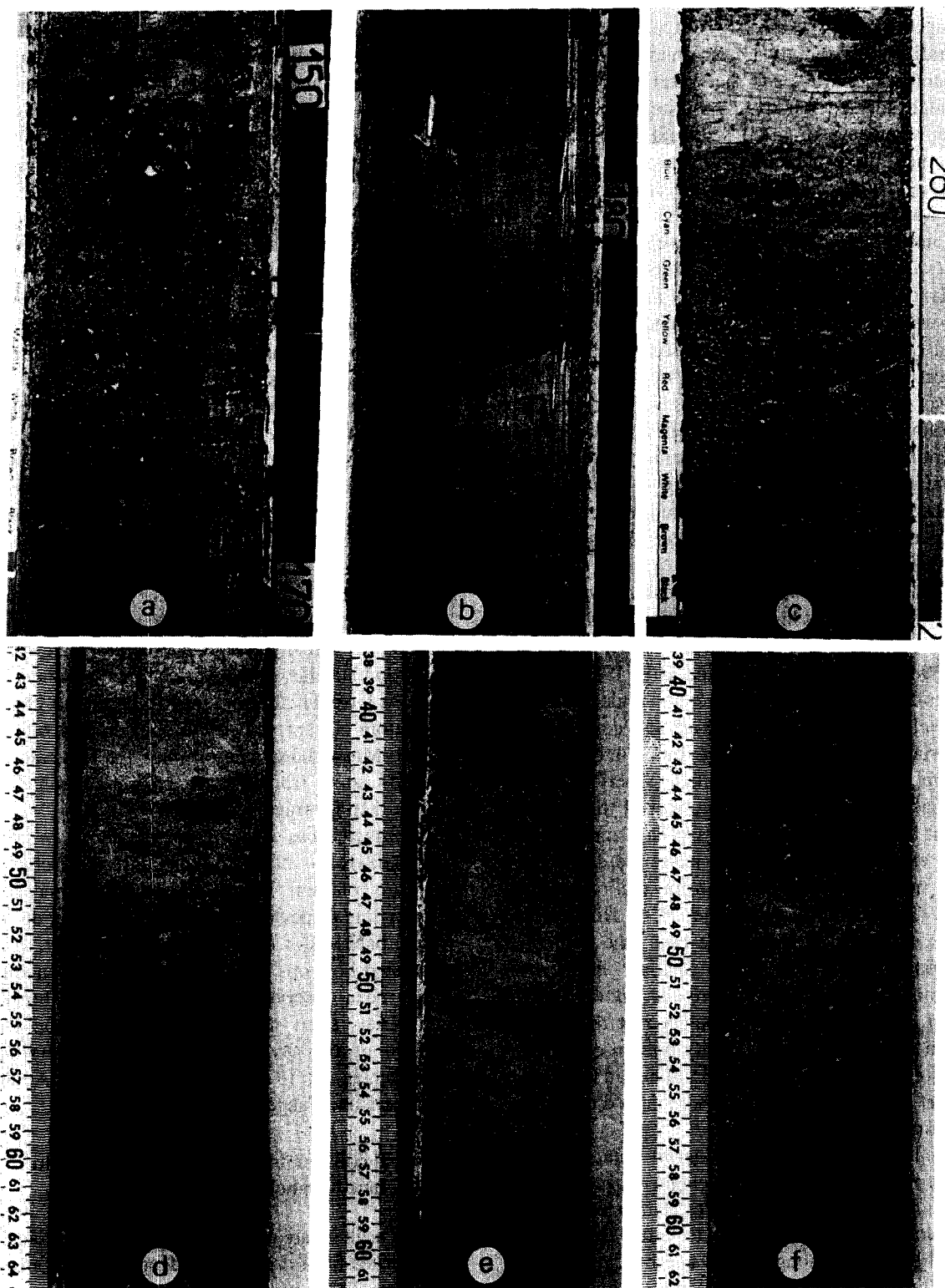
Fig. 2. Composite contourite facies model showing grain-size variation through a mud-silt-sand contourite sequence (modified from Stow et al., 1986).

laminated interbedding with both muddy and sandy contourite facies, and a high degree of bioturbation. They have a poorly sorted clayey-sandy silt size and a mixed composition. *Sandy contourites* occur as thin irregular layers within the finer-grained facies and are generally thoroughly bioturbated. In some cases, primary horizontal and cross-lamination is preserved, together with irregular erosional contacts and coarser concentrations or lags. The mean grain size is normally no greater than silty fine sand, and

sorting is mostly poor, but more rarely clean and well sorted sands occur. Both positive and negative grading may be present. A mixed terrigenous-biogenic composition is typical, with evidence for abrasion of biogenic debris and iron-oxide staining.

Muddy, silty and sandy contourites, of siliciclastic, volcanoclastic or mixed composition, commonly occur in composite sequences or partial sequences a few decimetres in thickness. The ideal or complete sequence, first recognised on the Faro Drift

Fig. 3. Photographs of contourite facies from cores drilled through existing drift systems. (a-c) Faro Drift; (d) Blake-Bahama Outer Ridge; (e) Gloria Drift; (f) Snorri Drift. Core widths 10 cm.



(Faugères et al., 1984; Stow et al., 1986), shows overall negative grading from muddy through silty to sandy contourites and then positive grading back through silty to muddy contourite facies (Fig. 2). Such sequences of grain size and facies variation have now been recognized in several of the ancient drilled drift deposits (Kidd and Hill, 1987; Dowling and McCave, 1993; Robinson and McCave, 1994), and may be more or less well developed. The sandy facies is generally less well developed in deep-water drifts, compared with present-day mid-slope to shallow-water drifts, and direct evidence of current influence is often meagre. Mean sedimentation rates typically vary from 5 to 15 cm/ka over a time period of several millions of years, but this mean rate undoubtedly masks shorter episodes of slow to fast, continuous to episodic sedimentation, as well as erosional events linked to high-energy benthic storms. Primary lamination is best preserved where sedimentation rates are relatively high and food supply for burrowing benthos is limited.

*Gravel-rich contourites* are locally developed in deep-water drifts at high latitudes as a result of input from ice-rafted debris (e.g. Baffin Bay, Hiscott et al., 1989; Feni Drift, Kidd and Hill, 1987; among others). However, in deep water and under relatively low-velocity currents, the gravel and coarse sandy material remains as a passive input into the contourite sequence directly related to periods of ice rafting and not subsequently reworked to any great extent by bottom currents. Gravel lags indicative of more extensive winnowing of ice-rafted debris have been noted in piston cores from shallower slope drifts (Hebridean Slope, Leslie, 1993; Howe et al., 1994), although even in these cases the degree of reworking is not very great. Shallow straits, narrow moats and passageways are also known to have gravel pavements locally developed at the present day in response to high-velocity bottom current activity (e.g. Gonthier et al., 1984), although these have not yet been recognised in ancient drilled contourite successions.

*Calcareous and siliceous biogenic contourites* occur in regions of dominant pelagic biogenic input, including open ocean sites (e.g. Hatton Drift, Stow and Holbrook, 1984, Feni and Gardar drifts, Kidd and Hill, 1987; among others) and beneath areas of upwelling (e.g. Equatorial Atlantic, Sarnthein and

Faugères, 1993). In most cases bedding is indistinct, but may be enhanced by cyclic variations in composition, and primary sedimentary structures are poorly developed or absent, in part due to thorough bioturbation. In some cases, the primary lamination appears to have been well preserved (Sarnthein and Faugères, 1993). The mean grain size is most commonly silty clay or clayey silt, poorly sorted and with a distinct sand size fraction representing the coarser biogenic particles that have not been too fragmented during transport. The composition is typically pelagic to hemipelagic, including nanofossils and foraminifera as dominant elements in the calcareous contourites and radiolaria or diatoms dominant in the siliceous facies. Many of the biogenic particles are fragmented and stained with either iron oxides or manganese dioxide. There is a variable admixture of terrigenous or volcanoclastic material.

Biogenic contourites typically occur in sequences of a decimetric scale that show variation in the biogenic/terrigenous ratio, which is generally linked to a grain size variation (Fig. 2). This cyclic facies pattern is closely analogous to the Milankovitch cyclicity recognised in many pelagic and hemipelagic successions and is believed to be driven by the same mechanism of orbital forcing superimposed on changes in bottom current velocity (Robinson and McCave, 1994). Mean sedimentation rates for biogenic contourites range from 1.5 to 7.5 cm/ka, which are higher than for true pelagites.

*Manganiferous contourites* are those in which manganiferous- or ferro-manganiferous-rich horizons are common. This metal enrichment may occur as very fine dispersed particles, as a coating on individual particles of the background sediment, as fine encrusted horizons or laminae, or as micronodules. It has been observed in both muddy and biogenic contourites from several drifts (e.g. Hatton Drift, Roberts et al., 1984; Blake Outer Ridge, Hollister, Hollister et al., 1972; and the Equatorial Atlantic, Sarnthein and Faugères, 1993).

#### **4. Fossil contourites exposed on land and in subsurface boreholes**

Just as there are many reliable sightings of ancient contourites from drilled drift deposits, there are still more *unreliable* sightings made in outcrops exposed

on land. In their review of deep-marine environments, Pickering et al. (1989) state: "Only one of 30 ancient successions for which a claim of contour-current influence has been made is sufficiently convincing to form the basis of a case study". That example was the Talme Yafe Formation (Bein and Weiler, 1976). Indeed, many of the early claims have been reviewed previously and found wanting (Stow and Lovell, 1979; Lovell and Stow, 1981). These are only briefly dealt with in the following section. However, we do focus on some of the more recent claims, some of which appear convincing and others not. Most of the examples are based on outcrop studies, whilst some report exclusively on subsurface material.

#### 4.1. Early claims

In some of the early 1960's work on turbidite successions, a number of authors noted a divergence in apparent current directions of as much as 90 degrees when comparing measurements on sole marks with those of ripple marks (Craig and Walton, 1962; Kelling, 1964; Dzulynski and Walton, 1965). In some cases, there was also a difference between slope directions inferred from slump folds and current directions from turbidite tops (Dzulynski and Walton, 1965). The explanation given from a variety of localities around the world was essentially the same — that of downslope supply via turbidity currents and lateral or axial reworking by alongslope bottom currents (Hsu, 1964; Ballance, 1964; Scott, 1966; Klein, 1966).

However, it is now clear that there are a number of possible explanations for such divergence in current directions including within-channel meandering and reflection of the more dilute parts of a single flow, the influence of local and whole basin topography, the derivation of turbidites from different margins and their movement along either axial or lateral transport pathways, and so on (Lovell and Stow, 1981). In fact, although the reasons are not yet fully clear, it appears normal for there to be a marked divergence of this sort in many turbidite systems.

#### 4.2. Next claims

Following publication of detailed criteria for recognition of contourites (Hollister and Heezen,

1972; Bouma and Hollister, 1973), there were a spate of papers that identified ancient contourites using these criteria, in some cases combined with regional arguments and evidence of current directions. These *so-called* contourites were all in well known turbidite successions, including the Cambro-Ordovician Meguma Group in Nova Scotia (Schenk, 1970), the Cretaceous Niesenflysch in Switzerland (Bouma, 1972), the Silurian Grogal Sandstones in Wales (Anketell and Lovell, 1976), and the Albian Lgota beds of the Polish Carpathian Flysch (Unrug, 1977, 1980). Despite severe criticism of these criteria and even a retraction of his earlier contourite interpretation of the Niesenflysch by Bouma (1973), there were publications on many more examples of this kind through the 1980's. Even in a recently published paper, Jones et al. (1993) argue strongly for a contourite interpretation of clean, thin-bedded, rippled sands in an Ordovician turbidite succession in eastern Australia.

All these examples suffer the problem of being very similar to fine-grained turbidites. All the features once considered characteristic of this type of contourite, have been recognised repeatedly in fine-grained turbidites throughout the world in both modern and ancient examples (e.g. Stow and Shanmugam, 1980; Cremer and Stow, 1986; Piper and Stow, 1991), in many cases where the action of bottom currents is known to be absent. Furthermore, this type of ripple-laminated, sand-silt facies has not been recognised in *any* of the well-established contourite drift systems from the present oceans, apart from in the original description of Hollister (1967) of the eastern North American slope-rise sediments, for which a downslope turbidity current explanation can be found. Most recently, Massé et al. (1998) have described a similar facies from the modern Brazil Basin, in which they tentatively identify a progressive series of features indicative of bottom-current reworking of fine-grained turbidites. This problem is discussed below.

#### 4.3. Reworked thin-bedded fine-grained turbidites

As mentioned earlier, present-day bottom current systems in many areas flow over extensive turbidite bodies and, provided they are sufficiently strong, will inevitably cause some reworking (e.g. see pho-

tographic evidence in Hollister and Heezen, 1972). There are very few examples where the effects of this reworking has been clearly demonstrated for modern sediments (but see Massé et al., 1998), but a much more extensive literature of ancient examples. Five of these are detailed below, together with one sub-surface example from the Gulf of Mexico, in which bottom-current reworking is invoked.

#### 4.3.1. Upper Cretaceous, Sainte Croix, US Virgin Islands (Stanley, 1987, 1988)

Stanley begins his 1988 report on the St. Croix system with these words: "It is the premise of this investigation that sandy marine layers, which are intermediate, or transitional, variants between classic turbidites and strata reworked by well-defined bottom currents, are probably much more common and widespread than is generally recognised." He proceeds to describe a thick succession of classical turbidites and associated slump, slide and debrite beds that were most probably deposited in a base-of-slope or similar setting. Many of the thin-bedded sandstones that display regular to lenticular bedding, sharp tops and bases, and internal lamination,

cross-lamination (some picked out by heavy mineral concentrations) and fading ripples, are interpreted as contourites. A range of beds intermediate between classical (Bouma A–E) turbidites and these inferred contourites, are described as progressively winnowed and reworked turbidites, as illustrated by an elegant model reproduced here in Fig. 4.

#### 4.3.2. Cretaceous Niesenflysch, Switzerland and Eocene Annot Sandstone, France (Stanley, 1993)

In developing his turbidite-to-contourite model, Stanley (1993) returns once more to the Lower Niesenflysch and also to the classic area of the Annot Sandstone near Peira Cava, where Bouma carried out his seminal work in 1962, and interprets some of the thinner bedded units in each case as bottom-current reworked turbidites.

#### 4.3.3. Oligo–Miocene Numidian Flysch, Sicily (Wezel, 1969, 1970; Faugères et al., 1992)

Wezel (1969) first drew attention to some rather atypical thin-bedded siltstones and mudstones in an otherwise coarse-grained turbidite succession of the Numidian Flysch in Italy. He likened these to Hol-

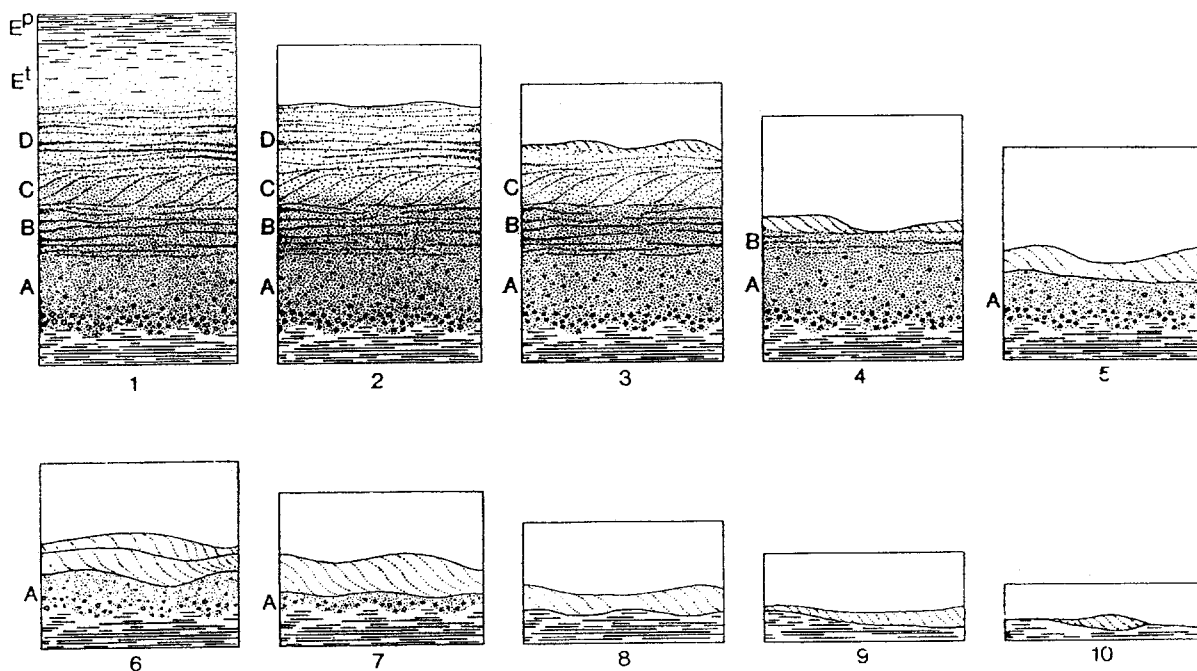


Fig. 4. Scheme of Stanley (1988) showing continuum of sediment types that may result from the reworking of a classical turbidite. Progressive erosion and reworking are depicted from (1) to (10) (from Stanley, 1988).

lister's (1967) contourites from the western North Atlantic. In a more recent study of parts of the Numidian Flysch, Faugères et al. (1992) describe thin beds and laminae of sandstone, siltstone and mudstone with internal micro-lamination and cross-lamination, lenticular laminae and bipolar current directions, that are highly bioturbated. These occur in association with other fine-grained slope deposits, rather than in a channel levee setting. They infer reworking of fine-grained turbidites, either by other turbidity currents or the tails of those that originally deposited the beds, or, more likely, by a true bottom current system.

#### 4.3.4. *Plio–Pleistocene Kasuza Group, southern Japan (Ito, 1996)*

In a very detailed outcrop study on the Boso Peninsula in southern Japan, Ito (1996) interpreted some of the thin- and medium-bedded outer fan and basin plain deposits of the Kasuza Group as bottom-current reworked deposits or sandy contourites. Ito (1996) further suggested that they were most likely reworked by an ancestral Kurushio Current, a strong surface current system known to act on the present-day seafloor at depths of at least 1.5–2 km. The chief characteristics of these sandy contourites, according to Ito, include ripple-cross and parallel lamination, minor inverse grading and wave ripple lamination, mud drapes, lenticular bedding and internal erosion surfaces. Paleocurrent directions are variable but mainly alongslope in contrast to those from the interbedded turbidites that are distinctly downslope.

#### 4.3.5. *Plio–Pleistocene Ewing Bank Block 826 Oilfield, Gulf of Mexico (Shanmugam et al., 1993)*

Thin-bedded sandstones and siltstones interbedded with mudstones recovered in oilfield cores from the northern Gulf of Mexico have recently been interpreted as turbidites reworked by an ancestral version of the present-day Loop Current, a strong wind-driven surface current that impinges on the bottom at depths in excess of 3 km. Shanmugam et al. (1993), by stating that “primary physical structures are better indicators of reworked sands than bioturbation and paleocurrent directions . . . ” have returned to the earlier and simple contention that bottom current deposits can be recognised solely

on the basis of sedimentary structures. Their criteria for recognising bottom-current reworked sands include: an abundance of thin-bedded or laminated sand, silt and mud layers, sharp contacts to sand–silt layers, internal erosional surfaces, lamination, cross-lamination, lenticular bedding, flaser bedding, mud offshoots and inverse grading.

Clearly, there is still a serious problem with the understanding and interpretation of certain structures in deep-water fine-grained sediments. In our opinion, the great majority of features presented in the studies detailed above are characteristic of fine-grained turbidites and do not require bottom-current reworking for their formation.

The St. Croix study finds that the thin-bedded sands and silts do not conform to the Bouma (1962) model for turbidites, which is hardly surprising if they are, in fact, fine-grained turbidites for which significantly different models exist that are now well established (e.g. Stow and Shanmugam, 1980). Stanley's model for progressive reworking could equally well indicate progressively more ‘distal’ portions of fine-grained turbidites. The same applies to the Niesenflysch, Kasuza and Annot examples. There are some unusual characteristics in the Sicilian examples, including bioturbation and grain-size character, but not enough evidence to be certain of a reworked interpretation at this stage. The criteria advanced by Shanmugam et al. (1993) for reworking are nearly all typical of turbidites, as proposed by Shanmugam himself in an earlier paper (Stow and Shanmugam, 1980).

There appear to be several common misconceptions about turbidity current deposition that need to be cleared up before addressing the problem of evidence for reworking:

(a) turbidity currents will often produce non-graded beds, as well as inverse grading in places (Kneller, 1995); they are also capable of autoerosion;

(b) the lamination and cross-lamination in classic turbidites is a result of tractional processes during deposition (Walker, 1965) — there is nothing incompatible about traction and deposition from turbidity currents;

(c) sharp tops to the silt or sand portions of turbidites are the norm for relatively slow deposition — only rapid dumping will result in poorly sorted, continuously graded sand–mud beds;

(d) fading ripples or starved ripples are indicative of relatively rapid fall-out from fine-grained turbidity currents as the small amount of silt is deposited and grades up into the inter-laminated and overlying mud; the same applies to the mud offshoots described by Shanmugam et al. (1993).

These and other features of fine-grained turbidites are illustrated in Fig. 5, using examples from bore-holes through present-day deep-sea fan systems that do not have any connection with known bottom currents. Many more of exactly the same structures are reported from ancient turbidite successions the world over (e.g. Pickering et al., 1989, p. 55, fig. 3.8; Piper and Stow, 1991, figs. 1–3) (Fig. 5) Not all of these could plead bottom-current reworking. However, the problem remains — we know such reworking exists but we do not know for certain what form it will take, nor what structures will be formed. We return to this problem in Section 5.

#### 4.4. Reworked medium- and thick-bedded turbidites

There have emerged recently a spate of interpretations of much thicker-bedded sandstone bodies as of contourite or bottom-current reworked origin. These include very thick deep-water massive sandstones, associated with turbidite or hemipelagite facies, that are structureless and therefore difficult to interpret. Some of these have been interpreted as contourites on the basis subsurface cores in oilfields where they form important hydrocarbon reservoirs. They are described briefly below, together with an example of well-laminated sands that outcrop in the Delaware Basin.

##### 4.4.1. Permian Bushy Canyon Member, Delaware Basin, USA (Mutti et al., 1992)

In a re-interpretation of the Bushy Canyon sandstones, presented simply as photographic plates in his 1992 book, Mutti describes medium to thick, structureless sandstones interbedded with thin to

very thin beds of rippled sandstones. Locally there is large-scale cross-stratification. The grain size is fine to very fine sand, nearly mud-free, and in parts, there is irregular, lenticular interbedding of the thin sands with darker (mud-rich?) siltstones. Whereas previous authors have invoked a turbidity current origin (Jacka et al., 1968; Harms, 1974), Mutti points out how similar the facies is to that of subtidal sandstones and, therefore, calls them contourites.

##### 4.4.2. Paleogene sandstones, North Sea, UK Continental Shelf (Heritier et al., 1979; Enjolras et al., 1986)

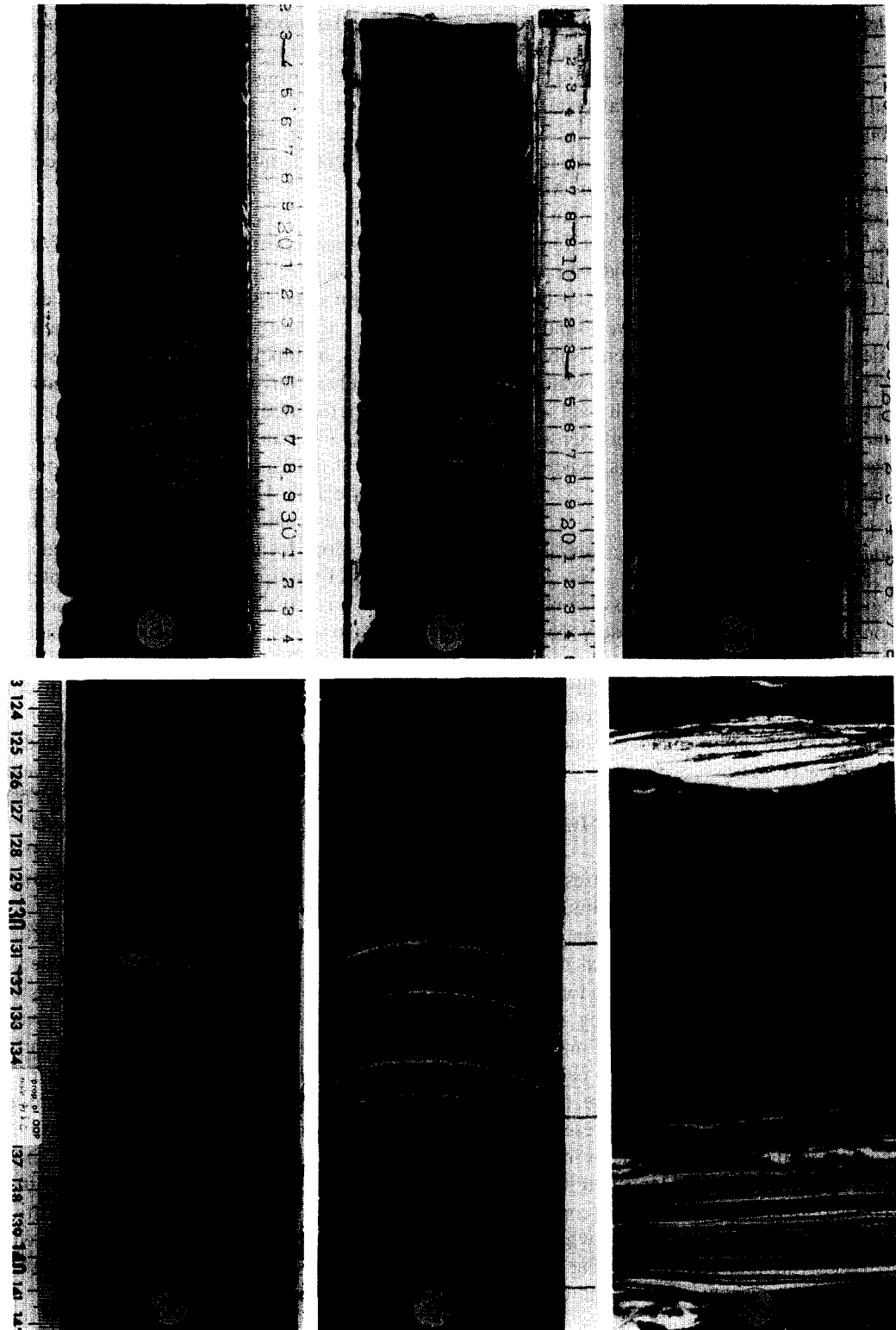
Well known as deep-water oil and gas reservoirs, some of the North Sea fields have very thick sections of more or less structureless sandstones. Some authors, on the basis of the general lack of structures, as well as on seismic expression, have interpreted these bodies as representing turbidites strongly winnowed, reshaped and redeposited by bottom currents.

##### 4.4.3. Paleogene sandstones, Campos Basin, Brazil (Mutti et al., 1980)

In a similar vein to the North Sea re-interpretations noted above, there is controversy surrounding the re-interpretation of some of the Campos Basin reservoir facies. Thick, structureless sandstones, fine-grained rippled sandstones and highly bioturbated silty sandstones and mudstones have all been described as contourites. These all occur in association with more classic turbidite facies in a known slope setting.

There is very much less evidence in favour of the contourite interpretations listed above compared with the more difficult problem of reworked fine-grained turbidites. There are no modern contourite analogues for either the massive or the well laminated sandstones (see review of sandy contourites by Viana et al., 1998). Well documented modern sandy contourites are generally thin-bedded and well bioturbated so that any original structures are, at least,

Fig. 5. Photographs of typical fine-grained turbidites from present-day deep-water systems without bottom current influence. Note that many of the structures are similar to those claimed by some authors as characteristic of bottom-current reworking. (a) Distal Bengal Fan terminal lobe, NE Indian Ocean, ODP Leg 116. (b) Distal Bengal Fan terminal lobe, NE Indian Ocean, ODP Leg 116. (c) Central Mississippi Fan channel levee, Gulf of Mexico, DSDP Leg 96. (d–f) SE Angola Basin Plain, SE Atlantic, DSDP Leg 75. Core widths approx 10 cm.



partially destroyed. In order for a bottom current to completely rework several metres or even tens of metres of sand, strong and persistent currents would be required such as those found in tidal systems and on some outer continental shelf/upper slope settings (Viana et al., 1998). Perhaps this is the re-interpretation required for the Bushy Canyon Member. Slope or deeper water bottom currents do not fit into this category. Extensive reworking by tractional currents would undoubtedly result in abundant tractional structures (lamination and large-scale cross-lamination), not in a structureless (massive) sand, such as those described from the Paleogene subsurface examples. Several recent studies of deep-water massive sands have concluded that they fit well into the resedimented family deposited by high-density turbidity currents and sandy debris flows (Kneller and Branney, 1995; Stow et al., 1996).

#### 4.5. Carbonate contourites and muddy contourites

There are a number of reports of fossil contourites exposed on land that are more closely comparable with what we know of calcareous biogenic and muddy siliciclastic contourites from drilling on existent drift systems, than the somewhat controversial or enigmatic examples outlined above. Four of these are detailed below (Fig. 6).

##### 4.5.1. Cretaceous Talme Yafe Formahon, Israel (Bein and Weiler, 1976)

The Talme Yafe Formation comprises a huge prism of calcareous detritus that accumulated on the northwest margin of the Arabian craton. The preserved portion of this former continental margin is over 3 km thick, 20 km wide and 150 km long, much of which is known from extensive drilling and some from well exposed coastal outcrops. The main facies described are calcilaminite, calcilutite, calcarenite, calcirudite and marl, all of which were originally transported to the margin by downslope resedimentation of epicontinental platform carbonates in the east. The coarse-grained facies were deposited by turbidity currents and debris flows, mainly confined to channels and small base-of-slope fans, whereas the fine-grained facies are interpreted as having been dispersed alongslope by bottom currents and deposited as muddy (calcareous) contourites. Some of the ir-

regular, flaser-bedded calcarenites are interpreted as sandy contourites, and the marls as pelagites. The shape and setting of the sediment prism conforms to that of a drift or drift deposits on a continental slope-rise; the presence of southerly-directed bottom currents is inferred from the paleoceanographic setting.

##### 4.5.2. Ordovician Jiuxi Drift, northern Hunan, China (Duan et al., 1993)

Within a succession of deep-water carbonate sediments, including a range of resedimented facies, pelagites, hemipelagites, and macrofossils and trace fossils characteristic of deep marine environments, there is a distinctive mound-like form some 350–450 m thick, elongated parallel to the paleocontinental margin of the Yangtze Terrane. This mounded body, called the Jiuxi Drift, is composed of sediments interpreted as contourites on the basis of their mid to base-of-slope location, alongslope current indicators, features of traction flow coupled with intense bioturbation and distinctive contourite sequences (typically 30–80 cm thick). The main contourite facies are bioturbated calcilutites and burrow-mottled calcisiltites, both of which show some irregular, discontinuous lamination, together with a lesser proportion of irregularly laminated and highly bioturbated calcarenites. These occur in repeated coarsening-upward to fining-upward microsequences. Possible calcirudite contourite lag deposits are also identified.

##### 4.5.3. Paleogene Lefkara Formation, Cyprus (Kahler, 1994; Kahler and Stow, 1998)

The Lefkara Formation is a thick succession of chalks, marls and cherts, very well exposed throughout southern and central Cyprus, that was originally deposited over newly formed oceanic crust in part of the Neotethys Ocean, which is now patchily preserved in countries surrounding the eastern Mediterranean. Very detailed study of the macrofacies and microfacies of these sediments led Kahler (1994) to interpret some of the chalk facies, showing indistinct lamination, mottling and bioturbation together with a distinctive mixed composition, as of contourite origin. These are interbedded with dominant pelagite–hemipelagite facies and less common siliceous-micrite and chert turbidites.

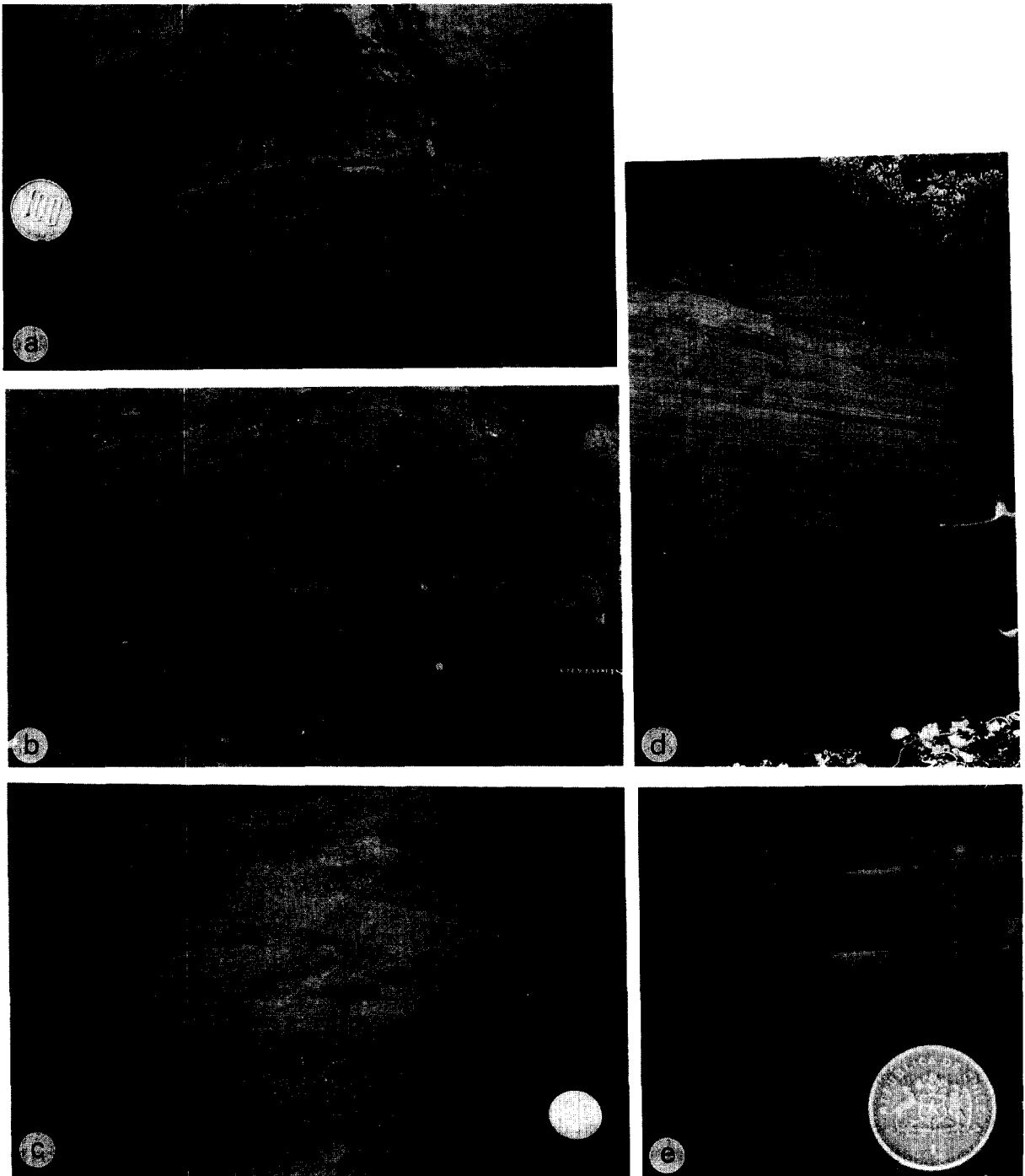


Fig. 6. Selected photographs of fossil contourites exposed on land (see text for discussion). (a–c) Misaki Formation, Miura Basin, S Central Japan, Neogene bioclastic/volcaniclastic contourites. (d–e) Los Molles Formation, central western Chile, Triassic muddy and silty.

#### 4.5.4. Neogene Misaki Formation, southern Honshu, Japan (Stow and Faugères, 1990; Stow et al., 1996)

The Middle to Late Miocene Misaki Formation of the Miura and Boso peninsulas south of Tokyo Bay, were deposited in the Pacific-facing forearc region of the proto Izu-Bonin arc. The two main facies present are pale-coloured hemipelagites, composed mainly of calcareous microfossils and pumiceous volcanoclastic clays, interbedded with thin to thick dark-coloured scoriaceous beds of turbiditic and pyroclastic fall origin. Careful field and laboratory study of the hemipelagite facies reveals the influence of bottom currents at certain horizons. Typical characteristics of these muddy contourites include irregular concentrations of coarser-grained volcanoclastic/biogenic material, sharp and erosive contacts irregularly distributed, rare micro-cross-lamination, and bioturbation continuous with deposition. Decimetric-scale variations of grain size and sedimentary structures are believed to be in part controlled by episodic volcanoclastic input and in part by fluctuation in bottom current strength.

These four examples are certainly the closest known exponents of the mainly fine-grained contourite facies recognised in modern and ancient drift deposits that have been drilled in the present-day oceans (see Table 1). For the most part, we would concur with the authors' interpretations. However, where the facies are well laminated and less highly bioturbated, or coarser-grained such as the calcirudites of the Jiuxi area and coarse-grained lenticular calcarenites of Talme Yafe, then the interpretation must remain more speculative due to the lack of modern analogues. The Marion Drift on the NE Australian continental margin does contain some coarser-grained biogenic packstones that may provide a partial analogue for such contourites (McKenzie et al., 1993).

#### 4.6. Outer shelf/upper slope drift deposits

Several ancient outcrop examples have been described recently of facies showing contourite characteristics but that were deposited in relatively shallow water depths (i.e. 50–300 m), mostly in inferred outer shelf to upper slope paleogeographic settings. The currents responsible for their deposition clearly acted on the seafloor, but were probably not bottom

currents *sensu stricto* (Stow and Faugères, 1993). Whether or not these should be classified as a type of contourite will be considered in the discussion. Two examples are presented below, together with one organic-rich laminite example, which, in our opinion, is more likely of turbidite origin, and one sandy 'contourite' deposited under a deep tidal current system.

#### 4.6.1. Cretaceous Calcaires Rouges and Couches de Wang Formations, French/Swiss Alps (Villars, 1991)

Two formations of Upper Cretaceous age outcropping in the French and Swiss Alps have been interpreted as of outer shelf to upper slope contourite origin. The *Calcaires Rouges* is a thin unit (<7 m) of nodular carbonates, highly bioturbated and with a significant terrigenous component, that represents a condensed depositional sequence elongated parallel to the shelf edge. It is believed to have been formed under the influence of a localised outer shelf current. The *Couches de Wang* is a thicker unit (200–300 m), also oriented alongslope and lying above a marked erosional hiatus. It represents a diachronous unit prograding about 40–50 km in a slight upslope direction over a period of some 500–800 ka. The facies include mottled marls and calcilutites/calcisiltites, with both a high degree of bioturbation mottling and discontinuous parallel lamination. More rarely, they also show ripples, megaripples and sand waves. The finer- and coarser-grained facies alternate in beds a few tens of centimetres in thickness.

#### 4.6.2. Triassic Los Molles Formation, west central Chile (Suarez et al., unpublished data)

Well exposed along the coast just south of Los Molles in central Chile, is a 500 m thick succession of sediments that accumulated in progressively deeper water from a shoreline fan-delta setting to slope pelagites–hemipelagites and base-of-slope turbidites, debrites and slump deposits. Stratigraphically in-between the coastal tidal and fan-delta deposits and the deeper water slope sediments, there is a 20–30 m thick unit of siltstones and mudstones that show diffuse, discontinuous lamination with a moderate degree of bioturbation throughout. They occur in decimetric sequences of grain size and facies variation, passing from bioturbated muds, through mottled silts and muds, to laminated/bioturbated silts

and thin mud partings, and then back through the same gradational sequence to muds. This unit is interpreted as of contourite origin formed under outer shelf to upper slope bottom currents.

#### 4.6.3. *Cretaceous Bandol Formation, SE France (Machhour et al., 1994)*

The Bandol Formation is a 150 m thick unit outcropping in the Toulon area of SE France, directly overlying Albian black shales, which are associated with breccias and slump horizons, and underlying hemipelagite marls of the Lower Cenomanian. The dominant facies is a finely laminated series showing an alternation of light-coloured biogenic-rich calcisiltites and dark-coloured clay-rich laminae with up to 0.9% organic carbon of terrestrial origin. This facies is interbedded with coarse-grained calciturbidites, slump deposits and bioturbated horizons. The authors invoke repeated small turbidity current deposits, each reworked by bottom currents in normal oxygenated bottom waters, for the silt laminae, and slow hemipelagic accumulation in anaerobic conditions for the dark laminae.

#### 4.6.4. *Plio–Pleistocene Calabrian Sandstones, southern Italy (Collela and d'Allessandro, 1988)*

Plio–Pleistocene sands exposed along the eastern margin of the Messina Strait between peninsular Italy and Sicily are interpreted as recently uplifted examples of marine sediments that formed in the ancestral Messina Strait. Their likely origin is confirmed by submersible investigation of the present-day seafloor in the Straits (Collela, 1990). The exposed formation is some 100 m thick with an extremely complex internal geometry, that results from the accumulation of internally cross-stratified dunes and megadunes separated by reactivation surfaces. The sands are dominantly bioclastic in composition and, locally, gravel-rich.

The first two examples documented above show characteristics very similar to fine-grained contourites deposited in deeper water, but clearly originated in a shallow-water setting based on their geological context. By contrast, the Bandol Formation laminites show all the characteristics of fine-grained turbidites and are, indeed, associated with coarser-grained turbidites and other resedimented facies. The fine-grained calciturbidites in this case,

deposited from low-concentration flows or from the tails of high-concentration flows, show a clear depositional sorting of the clean silty component from the clay/organic-rich component. Deposition may have occurred in somewhat low-oxygen conditions to favour preservation of the organic carbon, although terrestrial organic matter is relatively resistant to degradation if buried rapidly in turbidites (Arthur et al., 1984). The Calabrian sandstones have a clear deep tidal origin and are not contourites *sensu stricto*.

## 5. Discussion

### 5.1. *Facies models*

In the 30 years or so since their first recognition in a present-day oceanic setting, contourites have remained, for the most part, steadfastly in the marine realm. Here, there have been many and important advances. The descriptions of ancient contourites from existent drifts, including those of Eocene, Oligocene, Miocene and Pliocene age, as well as modern contourites from many different settings, have greatly extended the range of different contourite facies known — siliciclastic, biogenic, volcanoclastic and manganiferous — and refined knowledge of their characteristics. Several different facies models can be derived from this work (Figs. 1 and 2). At the same time, it is clear that most contourites are relatively fine-grained sediments with very subtle features, that either have poor preservation potential or are difficult to recognise in ancient outcrop examples. A review of modern sandy contourites and their features is also presented in this volume (Viana et al., 1998).

### 5.2. *Drift types*

The study of present-day bottom currents and the style and distribution of drift deposits has allowed us to recognise several different scenarios in which contourites accumulate:

(a) deep-water drifts (>2000 m water depth) include giant elongate drifts, sheet drifts, channel-related drifts, contourite fans and fan drifts (Faugères and Stow, 1993; Carter and McCave, 1994);

(b) mid-water drifts (300–2000 m water depth)

can include the same drift types listed above, although sheet drifts and smaller elongate drifts are more common in slope settings (Howe et al., 1994; Viana et al., 1998);

(c) outer shelf/upper slope drifts (50–300 m) include only those sediment accumulations formed under the shallower parts of the world's main currents (surface or bottom) that form part of the general thermohaline circulation system (see discussion below, and Viana et al., 1998);

(d) turbidity current/bottom current interaction (any depth) includes the reworking of turbidites by bottom currents, the deflection or entrainment of dilute parts of turbidity currents by bottom currents, and the construction of fan drifts (see discussion below, and Massé et al., 1998).

### 5.3. Application to the ancient record

The application of contourite facies models and drift models derived from modern systems to land-based studies has been generally poor. In the foregoing review of fossil contourites reported in the literature, there are very few, in our opinion, that fit the rigorous criteria developed in earlier studies (Stow and Lovell, 1979; Lovell and Stow, 1981). Those that appear most reliable are reported by Bein and Weiler (1976), Stow and Faugères (1990), Duan et al. (1993) and Kahler (1994). Despite these promising finds, there remains some frustration at the lack of advances made and this has led to two developments. Firstly, land-based recognition appears to have taken a step backwards to rediscover the arguments of the 1970's between turbidite and contourite characteristics. Secondly, there has been a step sideways to try and annex shallow-water traction deposits into the contourite fold. These several issues are discussed further below.

### 5.4. Reworked turbidites

Although it is clear that turbidity currents and bottom currents must interact in the deep sea, the nature

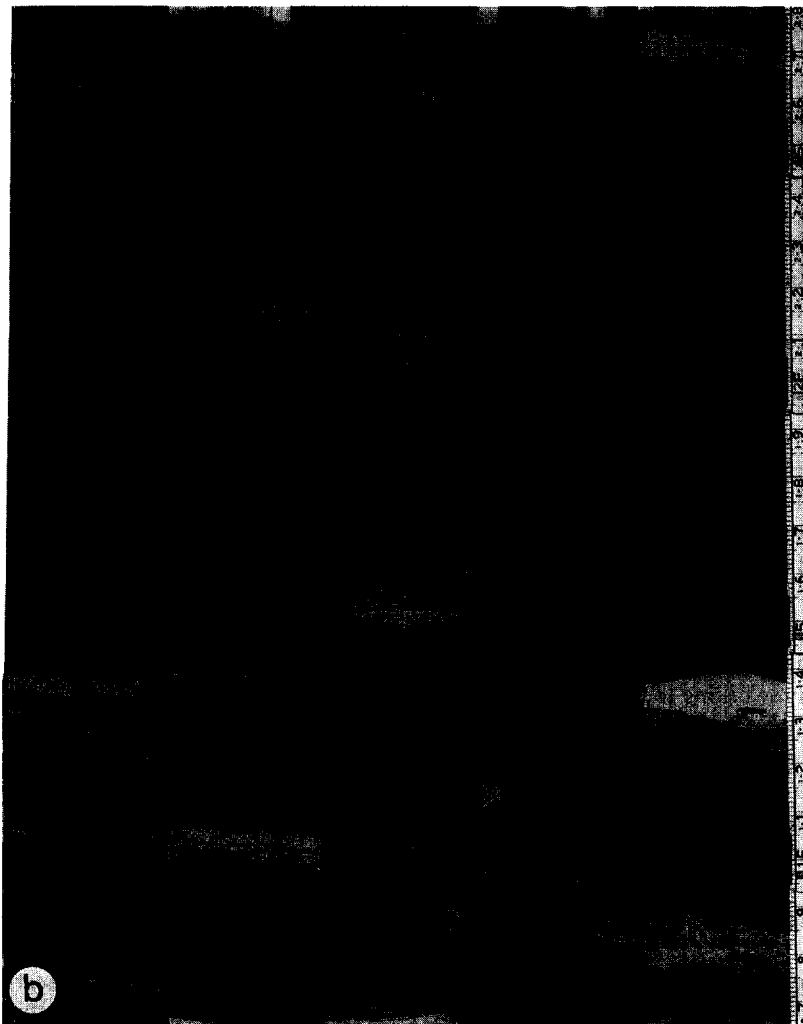
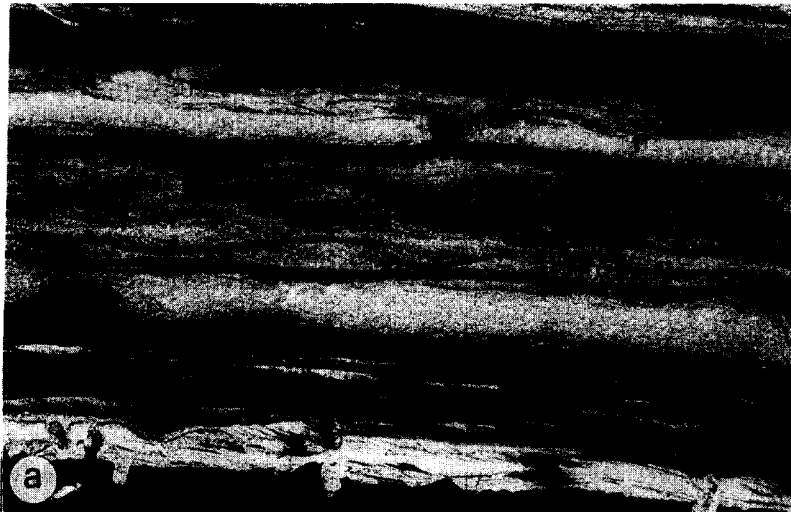
of this interaction and the results in terms of sediment removal or reworking is not well known from modern work. A recent advance in this direction is presented in the present volume (Massé et al., 1998). The attempt to address the problem solely from work on ancient turbidite sequences (e.g. Stanley, 1988; Mutti et al., 1992; Shanmugam et al., 1993) has led to several serious errors in interpretation, although it has no doubt highlighted an important subject and pointed out *some* significant criteria. The chief issues are as follows.

(a) Nearly all the characteristics advanced recently by the authors cited above as indicative of bottom-current reworking, are typical of fine-grained turbidites, modern and ancient, the world over. These are illustrated in Figs. 5 and 7, and in many papers in the turbidite literature. However, there are two characteristics listed by Shanmugam et al. (1993) that are less typical of turbidites and may help support a bottom-current influence — these are reverse graded laminae or beds, and bidirectional cross-lamination. The model of Stanley (1988, 1993) for progressive reworking of a turbidite is readily mirrored by proximal to distal variation in fine-grained turbidites (e.g. Stow et al., 1984; Piper and Stow, 1991) and so must be treated with caution. However, there are some important pointers for possible reworking: in particular, an abundance of top-absent fine-grained turbidites in a 'known' distal setting or an abundance of clean micro-cross-laminated silts with an absence of turbidite mud. In both cases the finer-grained portions of the turbidity current load may have been removed by interaction with a bottom current.

(b) Much of the fine-grained (mud) component of turbidite successions was originally transported by turbidity currents; indeed it was essential to maintain an active turbulent suspension for the transport of any coarser material. Mud and silt–mud turbidites are generally considered to be still more common than their coarser-grained equivalents. Fine-grained turbidites have a very different set and sequence of structures to those of sand–mud (Bouma) turbidites, as discussed by Stow and Shanmugam (1980), Piper

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Fig. 7. Photographs of typical turbidites from ancient series. Note that all these features are widespread in turbidites of all ages and are generally considered to result from normal processes of deposition from turbidity currents. (a) Southern California, Paleogene fine-grained turbidites. (b) Brae oilfield, North Sea, Late Jurassic fine-grained turbidites. Core width 10 cm.



and Stow (1991) among others. The absence of these structures and sequence, not the absence of classical turbidites, the absence of the mud itself or the complete bioturbation of the muddy fraction, are all features that can alert the field geologist to the possibility of reworking. It is clearly important that the complete lithological context, including turbidity current input and background sedimentation, is taken into account in order to make valid interpretations of bottom-current reworking.

(c) Turbidity currents are capable of depositing non-graded or reverse-graded beds and of auto-eroding previously deposited beds or parts of beds. Traction structures are the norm during part of the depositional sequence of turbidites, and fading ripples are particularly indicative of rapid deposition from suspension combined with traction at the base of a mud–silt turbidity flow. Sharp tops to silt or sand parts of turbidites are more common than not in ancient turbidite successions. The presence of these features, therefore, cannot be taken as indicative of reworking. However, sharp or erosive contacts within turbidite sequences, coupled with distinctly different characteristics above and below the contact, such as bioturbation or anomalous grain-size, can indicate reworking in some instances.

(d) Bottom currents over the great majority of turbidite depositional settings in the deep sea are relatively weak although velocities attained during benthic storms are typically of the order of 50 cm/s. Even such flows are not likely to achieve significant reworking, especially the removal of cohesive mud from over sand–silt beds. They are, however, more likely to deflect and entrain the dilute portions of turbidity currents that issue into their path, resulting in the relative depletion of fines from a turbidite succession and the downflow construction of a fan drift. In order for significant reworking to occur, specific conditions of current intensification are required such as in moats, channels, passageways or, in certain cases, at higher levels on a steep slope.

A set of possible criteria for the recognition of reworked turbidites is given in Table 2.

### 5.5. *Outer shelf/upper slope ‘contourites’*

Whereas it is clear that large sediment accumulations occur in relatively shallow water on the

outer parts on continental shelves and upper parts of the slope and that these superficially resemble deeper-water drifts, it does not necessarily follow that the deposits of these shallow-water drifts should be called contourites. We prefer to retain the original concept of Hollister and Heezen (1972) and, therefore, the definition given by Faugères and Stow (1993): *Contourite* is a sediment found in relatively deep water (greater than about 300 m) that has been deposited or significantly reworked by stable geostrophic currents. This can include the sediments affected by bottom currents acting at intermediate depths as well as those affected by major surface currents impinging on the deep seafloor. It does not include sediments primarily affected by surface waves (including storm waves), wind-generated surface currents, tidal currents, clear-water canyon currents or currents related to upwelling systems. *Outer shelf deposits*, *deep tidal deposits* and even *bottom current deposits* (*sensu lato*) are all terms that can be used for sediments of this type. Where the paleo-water depth is not well constrained and the type of current system unknown, then it is unwise to refer to ancient sediments as contourites.

The shallow-water drift deposits described above from ancient sequences should not, therefore, be considered as examples of fossil contourites (see also discussion of modern sandy contourites and related sediments by Viana et al., 1998).

### 5.6. *Criteria for the recognition of fossil contourites*

It is abundantly clear that the recognition of contourites in the field is not an easy task, and yet there are several important reasons why advances must be made in this direction, not least being the impetus from the hydrocarbon industry and from climate modellers. It is also clear that field identification should not be attempted on single or even relatively few criteria — the contourite signature is generally too subtle and there is considerable danger of confusion with other deep-water facies. It is far better, of course, to make no interpretation than a false one. We suggest the following three-stage approach, as modified and expanded from earlier work (Stow and Lovell, 1979; Lovell and Stow, 1981).

(a) *Small-scale (field, borehole or lab)*. Do the sediments in question have the range of features

Table 2

Main characteristics of principal contourite facies and bottom-current reworked turbidities that may aid interpretation of fossil contourites and reworked facies

	Muddy contourites (terrigenous or biogenic)	Sandy contourites (terrigenous or biogenic)	Reworked turbidites (any composition)
Occurrence	Thick uniform sequences of fine-grained sediment in deep-water settings interbedded with turbidites and other resedimented facies on inferred continental margins	Thin to medium beds in muddy contourite sequences, rarely thick/v.thick units; reworked tops of sandy turbidites in interbedded sequences; coarse lag in deep-sea channels and straits	In any normal turbidite setting where strong, permanent bottom currents have been active
Structure	Dominantly homogeneous, bedding not sharply defined, but cyclicity common; bioturbational mottling generally common to dominant; distinct burrows (typical deep-water assemblage) present in many places; coarse lag concentrations (especially biogenic) reflect composition of coarse fraction in mud; primary silt/mud lamination-rare, but no regular sequence as in turbidites; sharp and erosive contacts common in parts	Generally bioturbated and burrowed throughout with little primary structure remaining; parallel and cross-lamination more rarely preserved (often with bioturbation); no regular structural sequence as in turbidites; may show reverse grading near top, with sharp/erosive contacts common	Lower divisions of turbidite may be preserved, with the upper divisions either removed completely or modified by reworking; bioturbation/burrowing common through reworked top reverse grading and irregular lag concentrations; bi-directional cross-lamination, may be clean micro-cross-laminated silts with bioturbation; sharp erosive contacts may occur within turbidite sequence
Texture	Dominantly silty mud; frequently high sand content (0–15%) of biogenic tests in clastic contourites; medium to poorly sorted, ungraded, no offshore textural trends; may show marked textural difference from interbedded turbidite if transport distances are different	Silt to sand-sized, more rarely gravel; may be relatively free of mud and well sorted in some cases; tendency to low or negative skewness values; no offshore trends	Removed/non-deposition of fines; significant textural differences from underlying turbidite (e.g. cleaner, better sorted, reverse grading + lag, negative skewness)
Fabric	Mud fabric — typically more parallel alignment of clays than for turbidites, but not well preserved in fossil contourites; primary silt laminae or coarse lag deposits show grain orientation parallel to the current (alongslope)	Indication of grain orientation parallel to the bottom current (alongslope) or more randomised by bioturbation; other features (e.g. structures) also indicate alongslope flow, where preserved	Interbedded, reworked turbidite layers may show widely bimodal grain orientations or a more random polymodal fabric
Composition	Mixed contourites have combination of biogenic and terrigenous material (may be distinct from interbedded turbidites); terrigenous material dominantly reflects nearby land/shelf source with some alongslope mixing and small amount of far-travelled material (no downslope trends)	Mixed biogenic/terrigenous composition typical; terrigenous composition dependent on local source; biogenic material from pelagic, benthic and resedimented sources, typically fragmented and iron-stained; organic-carbon content very low	Composition entirely reflects that of turbidite, with part of fine fraction removed; long exposure and winnowing may lead to chemogenic precipitation (probably rare); organic-carbon content very low
Sequence	Typically arranged in decimetric cycles of grain-size and/or compositional variation with sandy contourites; see model (Fig. 2) — partial sequences also common	Typically arranged in decimetric cycles of grain-size and/or compositional variation with muddy contourites; see model (Fig. 2) — partial sequences also common	Presents a typical turbidite sequence (i.e. top-absent or top reworked); does not occur within standard cyclic contourite sequence

shown in Table 2? Where there is a possibility of mixed turbidite/contourite sequences, can a distinction be made between the two facies on the basis of character and/or paleocurrent evidence? Is there sufficient evidence to discount the possibility of origin by the variety of fine-grained turbidity current processes known to occur? Particular care must be taken for inferred reworked turbidites. Where there is a possibility of mixed hemipelagite–pelagite/contourite sequences, is there sufficient evidence for the influence of bottom currents during sedimentation? Can any cyclicity present be related to variation in bottom current velocity rather than to variations in terrigenous input or biogenic productivity?

(b) *Medium-scale (formation or region)*. Do regional trends in facies occurrence, paleocurrent directions, textures, mineralogical or geochemical tracers exist that would support a bottom-current origin? Is there any other evidence of bottom-current activity such as unconformities, condensed sequences, drift geometry, etc.? Are the associated facies and paleontological data compatible with a contourite interpretation? Is it possible to reconstruct the shape and three-dimensional geometry of the whole sedimentary body? And, if so, are the elongation and propagation trends parallel or perpendicular to the inferred margin?

(c) *Large-scale (system or continent)*. Do the conclusions from (a) and (b) above fit with what is known from other independent lines of evidence concerning major paleoceanographic features and continental reconstructions? What kind of bottom current systems might have existed in the study area at the time of deposition, taking into account constraints imposed by known paleoclimatic conditions and inferred basin location and geometry?

There are doubtless many examples of fossil contourites exposed on land awaiting discovery. The sectors that would appear to offer the best chance of finding and recognising evidence for major contourite accumulations are, in the first instance, to be found in the Neogene when climatic instability and polar ice caps led to enhanced bottom-water circulation. Deep-water sediments formerly deposited on the margins of Neogene ocean basins and most recently accreted and exposed in accretionary prism complexes of tectonically active margins, such as

in New Zealand, Japan and California, offer excellent candidates for contourite preservation provided that the series have not been too deformed or metamorphosed. Paleogene and older sequences from similar settings, as well as from large tracts of emergent passive margin systems, may also yield fossil contourites, if the paleoceanographic setting is first carefully scrutinised. Smaller syntectonic basins of any age, that have been subject to significant surface and bottom water interchange with the major ocean reservoir, should offer an alternative target for the recognition of fossil contourites.

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