1979

Earth-Science Reviews, 14 (1979) 251—291

Contourites: Their Recognition in Modern and Ancient Sediments

D.A.V. Stow and J.P.B. Lovell

ABSTRACT

Stow, D.A.V. and Lovell, J.P.B., 1979. Contourites: their recognition in modern and ancient sediments. Earth-Sci. Rev., 14: 251—291.

We suggest that publication of evidence that the continental rise of the western North Atlantic has been shaped by bottom currents flowing parallel to bathymetric contours (Heezen, Hollister and Ruddiman, 1966) marked the beginning of a revolution in sedimentology comparable to the turbidite revolution launched by Kuenen and Migliorini in their classical 1950 paper.

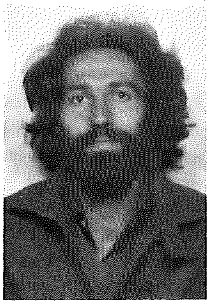
Intensification of slow, thermohaline circulation on the western margins of the ocean basins leads to high-velocity, deep, boundary currents, capable of eroding, transporting and depositing fine-grained sediment. Long-period, direct current measurements suggest a complex, periodic flow for these currents, while bottom photographs indicate their influence on the sediment surface. Sediment ridges in the North Atlantic can be closely related to the deep-water circulation pattern. Other morphological features (ripples, furrows, waves), echogram characteristics, and the presence of well-developed nepheloid layers cannot be uniquely attributed to the action of bottom currents.

Critical review of marine-based investigations reveals a lack of generally accepted criteria for the recognition of contourites on the basis of sediment character. We discuss the problems in establishing such criteria and recognize that: (a) a continuum may exist between dilute turbidity flows, bottom currents and hemipelagic settling; (b) interbedded turbidites, contourites and hemipelagites are common, especially in a rise environment; and (c) composition and other criteria may be only locally applicable. However, we can identify two main contourite groups, muddy contourites and sandy contourites, and have proposed new criteria for their recognition. Muddy contourites are generally bioturbated, have poorly defined bedding, and contain biogenic sand often concentrated into irregular layers. They may be texturally and compositionally distinct from interbedded turbidites, and have relatively high $CaCO_3$ and organic carbon contents. Sandy contourites occur as thin, bioturbated, irregular lag-deposits, or as reworked tops of sandy turbidites. In the latter case they may be clean, well sorted, parallel- or cross-laminated, but show no offshore trends or vertical structural sequence. Grain orientation shows the bottom current direction, often superimposed upon the original turbidite fabric.

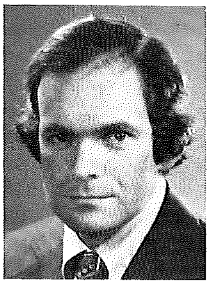
Reveiw of land-based work shows that there is growing recognition of the need for a new concept to complement turbidity-current theory, but that there have been relatively few claims of firm contourite identification. Recognition of ancient contourites has been based either on the application of previous sedimentological criteria, or on an interpretation of the broader environmental framework. It is suggested that it is lack of suitable criteria for the identification of contourites rather than a true scarcity of these rocks that has led to such a restricted literature.

Mindful of problems created by diagenesis, tectonic activity and the limited preservation potential of many diagnostic features of marine contourites, we do suggest criteria, and a procedure, for the recognition of contourites in land-based work. Sandy contourites of the reworked-turbidite variety may be the most easily recognised; the presence of bimodal palaeocurrent directions at about 90° is an important indicator of this type.

The geological significance of contourites in palaeo-oceanographical, palaeogeographical and tectonic reconstructions is emphasised, especially in relation to work on passive (Atlantic-type) continental margins. We also refer to the possible economic significance of contourites as exploration for hydrocarbons moves into deeper waters.



Dorrik A.V. Stow, B.A., M.A., PhD., F.G.S., graduated from Cambridge University, U.K. in 1974; and from Dalhousie University, Canada in 1977 where he obtained a PhD in marine geology. He is currently employed with the British National Oil Corporation, Glasgow, Scotland. He has worked on the sedimentology of recent deep marine environments and their ancient equivalents on land. His particular research interests are in the fields of fine-grained sedimentation and petroleum sedimentology. He is a keen member of the Association of Geoscientists for International Development with interests in marine science affairs and the law of the sea.



Bryan Lovell (born 1942) graduated M.A. (Oxford) in 1963, and worked in southwest England with H.G. Reading at Oxford (B.Sc. 1964) before going to Harvard (Ph.D. 1968) to study turbidites of the Eocene Tyee Formation, Oregon Coast Range with R. Siever. He has been lecturer in geology at the University of Edinburgh since 1969. Besides work on turbidites, he has published on the petrography of sands and sandstones, red beds, diagenesis, sedimentation in reservoirs, trace fossils, and tectonics and sedimentation. Recent publications include a new set of palaeogeographical maps (*The British Isles Through Geological Time: A Northward Drift*, George Allen and Unwin). He maintains an interest in the broader implications of science for society through teaching outside the science faculty, consultancy work and an active commitment to politics.

INTRODUCTION

Following the thesis of Kuhn (1970), Walker (1973, p. 3) suggested that the turbidity current theory represents the only true revolution in this century concerning clastic rocks. This revolution has as its *manifesto*, the paper 'Turbidites as a cause of graded bedding' by Kuenen and Migliorini (1950).

We believe that work on turbidites has stimulated a second revolution in our thinking about depositional processes in the deep sea. As more oceanographic and sedimentological data was gathered from the marine environment, opponents of the turbidity current theory began to suggest alternatives. Several early papers acknowledged the geological significance of deep geostrophic currents (Heezen, 1959; Heezen and Hollister, 1964; Hubert, 1964). A 'contourite' was then defined as the sediment deposited from contour-following bottom currents (Heezen et al., 1966) and the evidence for this type of sedimentation was documented (Hollister, 1967; Hollister and Heezen, 1967; Schneider et al., 1967). In just over a decade many hundreds of papers have been published identifying contourites from all parts of the world's oceans (Heezen, 1977).

There is already, then, a large volume of literature on contourites and there has been much controversy over the relative roles of discontinuous turbidity currents and continuous 'bottom currents'[1] on deep-water continental margins. Although most workers now accept that both mechanisms are operative, there are still no generally accepted criteria for distinguishing between the two types of deposit.

This paper aims to review critically the information about contourites that has been derived from both marine-based and land-based investigations. We identify two clearly distinct contourite facies: *muddy contourites* deposited from the fine suspended material in nepheloid layers associated with bottom currents; and *sandy contourites* that result from the winnowing of muds and the reworking of turbidite sands. We propose new sets of criteria for the recognition of contourites; these are significantly different from many previously suggested criteria. The geological significance of these sediments is then discussed.

DEEP-SEA CIRCULATION AND BOTTOM CURRENTS

Pioneering work by Wust (1933, 1935, 1936) established the major characteristics (salinity, temperature and oxygen values) of Atlantic water masses. Subsequent work has improved our understanding of other water masses and probable patterns of deep-sea, thermohaline circulation (Sverdrup et al., 1942; Neumann, 1968). Bottom water in the oceans is

---

[1] 'bottom current' is here used in preference to 'contour current' as it appears more in line with current literature.

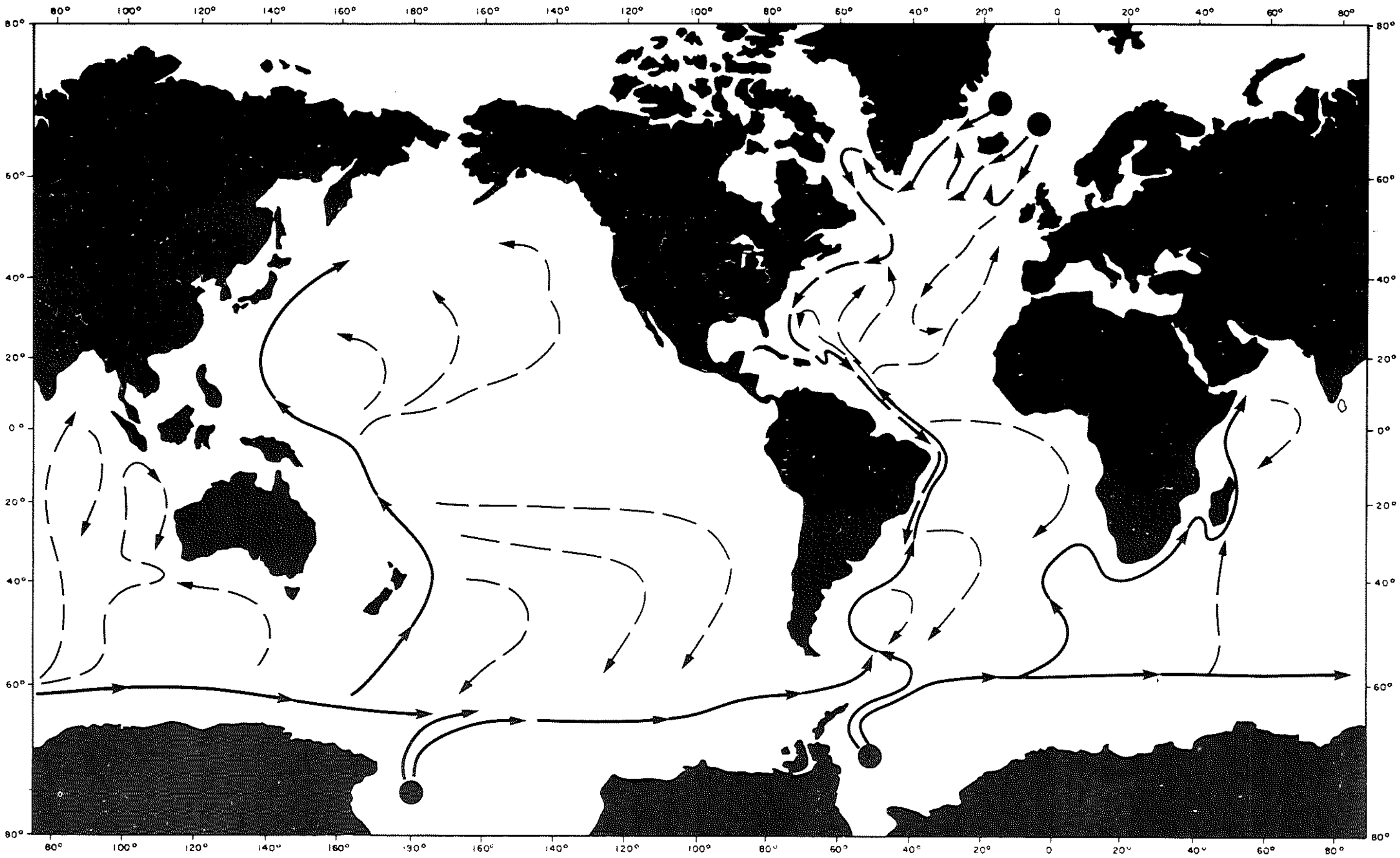


Fig. 1. Deep thermohaline circulation after Stommel (1958), Wust (1955), Defant (1961), Heezen and Hollister (1971). Western Boundary Undercurrent shown by heavy, dashed line; and weak return flows shown by thin, dashed lines. Major sources of cold, dense waters shown as black circles.

TABLE I

Details of bottom current measurements in different parts of the world's oceans, and in different bottom water masses

Study area and current system *	Type of study ** duration of direct measurements in brackets (hours)	Depth (m)	Current velocity (cm s^{-1}) average or range; highest recorded velocity in brackets	Volume of transport ($\times 10^6$ m^3 s^{-1})	Other comments D = level of no motion (m) W = current width (km)	References
North Atlantic, NSOW/WBUC						
SE of Iceland	hydrographic/direct	2100 slope rise	20—30 0—10	5.4	D, 100—1800, increases to SE	1
Greenland—Iceland—Faeroes Ridge	hydrographic/direct (30)	2000—3000	0—12	4.6	volume of transport elsewhere in N Atlantic 27.6 × 10^6 m^3 s^{-1}	2
Iceland—Faeroes Ridge	direct		20—30 (109)			3,4
Charlie—Gibbs Transform Fault	direct (48—72)		7.4 (21)			5
SE of Iceland (Rockall Trough, etc.)	direct (24—168)		4—15 (21)			6,7,8,9
Western North Atlantic, WBUC						
Western North Atlantic	hydrographic	2000—3000	2—17			10
Off Blake Plateau	hydrographic/direct	3300—3500	9—18 (20)		D 1900	11
Off Cape Cod	hydrographic/direct (17—22)	10—3200	10—21.5	50	flow to both E and W noted	12
North Atlantic (25°—60°N)	hydrographic		2—6 (9.5)		highest velocity in return flow (East N Atlantic)	13
Antillean—Caribbean Basins						14
(outer)	hydrographic	4000—8000	10			
(inner)	hydrographic	1800—3000	slow advection			
Off Cape Hatteras	hydrographic/direct		4—21	4—12	W, 20—80 two or more flows D, 500—3000 + increases offshore	15
West Bermuda Rise	direct (8—16)	5200	12—17		Gulf Stream, 10 cm s^{-1} on bottom (3600 m)	16

(continued on next page)

TABLE I (continued)

Study area and current system *	Type of study ** duration of direct measurements in brackets (hours)	Depth (m)	Current velocity ($cm\ s^{-1}$) average or range; highest recorded velocity in brackets	Volume of transport ($\times 10^6\ m^3\ s^{-1}$)	Other comments D = level of no motion (m) W = current width (km)	References
Off North Carolina	hydrographic	1500—4000	0—25		W, 20—80, three distinct flows	17
Labrador Sea	direct (12—72)	1700—2400		1		18
Blake Bahama Outer Ridge	hydrographic	4300—5200	6(26)	22	D, 500—3500 increases to E	19
Rise, near Hatteras Canyon	direct		20(33)		shallow, up-canyon currents noted	20
Rise, off New England	direct	3000—5000	10—20 (26.5)		flow to both E and W, variable velocity	21
Greater Antilles Outer Ridge	hydrographic/direct (4—16 months)	5300—5800	2—10(20)		Gulf Stream, 9—16 cm s^{-1} on bottom (5000 m)	22
Blake Bahama Outer Ridge	direct (96—44)		5(11)			23
Rise, off New England	direct (68—96)		4—8(20)			24
Western South Atlantic, AABW						
Western South Atlantic	hydrographic	>3500	2—15			25
Argentine Basin	hydrographic/direct		13.5(30)	10—90		26
Vema Channel	hydrographic/direct		20—25			27
Western South Pacific, AABW						
E Slope Tonga—Kermadoc Ridge	hydrographic	2500—4500		8—12	W, 70	28
Tonga Trench and vicinity	hydrographic/direct	<4400 >4800 (trench)	5 5—15 (19)		tidal component, 3 cm s^{-1}	29
Western South Pacific, 22°S	hydrographic		1—10	13	2 flows, W, 200 and 350	30
Samoan Passage	hydrographic/direct (72—240)		15—20 (50)			31,32
Samoan Apron	direct (1 month)		1 (10)			33

Western South Indian, AABW					
E of Madagascar 12°S	hydrographic	4500	6—7	W, 500	
35°S				W, two narrower flows	34
Other Regions					
E Pacific off California	direct (<1½ months)	3700—4300	1—3	tidal component, 2 cm s^{-1}	35,36
Central Pacific, various	direct (<1½ months)	5500	2—5 (10)		37,38,39, 40,41,
E Pacific, Ecuador Trench	direct (<1½ months)		34 (40)		42,43
Arctic Ocean, Mendeleyer Ridge	direct (<1)		4—6		44
Canada Abyssal Plain			1		
Mediterranean Sea	hydrographic		slow advection		45

* NSOW = Norwegian Sea Overflow Water; WBUC = Western Boundary Undercurrent; AABW = Antarctic Bottom Water.

** Dynamic computations for hydrographic data follow La Fond (1951); Stommel (1956); Defant (1961); etc.

References:

1. Steele et al. (1962)
2. Worthington and Volkman (1965)
3. Crease (1965)
4. Joseph (1967)
5. Shor et al. (1976)
6. Hollister et al. (1976)
7. Lonsdale and Hollister (1976)
8. Hollister et al. (1976)
9. Lonsdale and Hollister (in press)
10. Wust (1936, 1950)
11. Swallow and Worthington (1961)
12. Volkmann (1962)
13. Lappo (1963)
14. Wust (1963)
15. Barrett (1965)
16. Knauss (1965)
17. Rowe and Menzies (1968)
18. Swallow and Worthington (1969)
19. Amos et al. (1971)
20. Rowe (1971)
21. Zimmerman (1971)
22. Tucholke et al. (1973)
23. Hollister et al. (1974b)
24. Johnson and Lonsdale (1976)
25. Wust (1955, 1957)
26. Ewing et al. (1971)
27. Johnson et al. (1976)
28. Reid et al. (1968)
29. Reid (1969)
30. Warren and Voorhis (1970)
31. Hollister et al. (1974a)
32. Lonsdale (1974)
33. Lonsdale (1975a)
34. Warren (1970)
35. Isaacs et al. (1966)
36. Nowroozi et al. (1968)
37. Johnson (1972a, b)
38. Lonsdale et al. (1972)
39. Lonsdale and Malfait (1974)
40. Earle (1975)
41. Normark and Spiess (1976)
42. Lonsdale (1975b)
43. Hagen and Lonsdale (1976)
44. Hunkins et al. (1969)
45. Wust (1961)

formed in polar regions by the cooling, freezing and wind-forced convection of surface waters (Gill, 1973; Killworth, 1973). This cold, dense water sinks along the slopes of the continental margin and spreads out over the bottom to all other parts of the ocean where it moves slowly upwards (Fig. 1). The Weddell Sea and Ross Sea bordering Antarctica are the most important sources for Antarctic Bottom Water. Deep and bottom water in the North Atlantic is formed in the Greenland and Norwegian seas and spills over the Greenland—Iceland—Faeroes Ridge to contribute to the North Atlantic Deep Water (Stefansson, 1968; Worthington, 1970). This seems to merge with Arctic Bottom Water formed to the south and southeast of Greenland.

Most of the deep-sea floor is repeatedly swept by very slow (<2 cm s^{-1}) thermohaline currents. These are intensified on the western margins of ocean basins as a result of the Earth's rotation (Stommel and Aarons, 1960), and in narrow passages by the acceleration of constricted flows. The characteristics of the deep western boundary currents are becoming better known, and direct current measurements of over 40 cm s^{-1} have been reported (Table I). More commonly, velocities are in the range of 10-20 cm^{-1}, although most measurements have been made over short periods of time. Current measurements over an eight-month period on the upper continental rise south of Cape Cod, Massachusetts (Luyten, 1977) have shown that, although there is a mean westward flow along the contours at 5 cm s^{-1}, the current pulsates in strength, flowing at up to 40 cm s^{-1} to both east and west.

There is little doubt that the higher velocity bottom currents are capable of transporting and depositing a range of fine-grained sediments (Einstein and Krone, 1962; Partheniades et al., 1969). Studies of the threshold of sediment movement (White, 1970; Miller et al., 1977), and of fine-grained sediment erosion (Migniot, 1968; Einsele et al., 1974; Yound and Southard, 1976), suggest that bottom currents are capable of significant bed erosion. Evidence for the influence of bottom currents on deep-sea sedimentation is discussed in the following section.

MARINE-BASED INVESTIGATIONS OF CONTOURITES

Morphological evidence

Long, isolated, ridges composed of thick piles of sediment have been recognised from seismic reflection profiles over the deep-sea floor. In the North Atlantic (Fig. 2) these sediment ridges can be closely related to the known deep-water circulation pattern (Johnson and Schneider, 1969; Jones et al., 1970). It is believed that the ridges result from the interaction of a sediment-carrying bottom current and a relatively static water mass, and form along the margins of the flow. In the case of two oppositely directed currents which are slowed and diverted on meeting, deposition would occur preferentially in the zone of interaction, where the effect of gravitational settling on particles becomes greater than that of eddy diffusion in a hori-

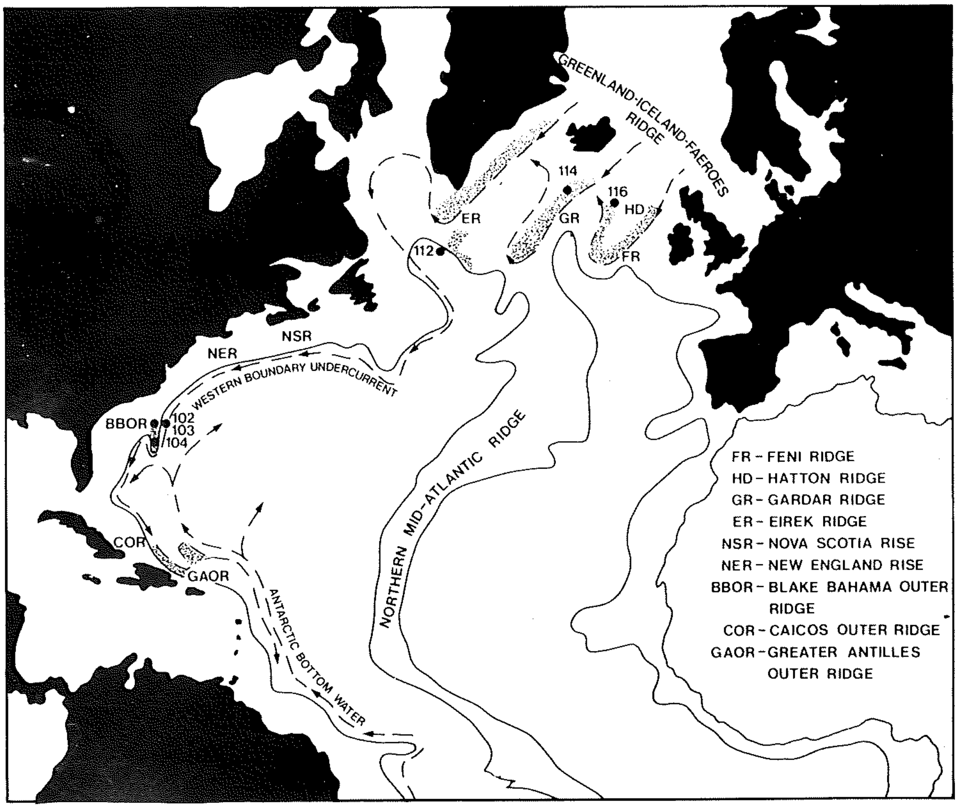


Fig. 2. Bottom currents in relation to deep-sea sediment ridges (stippled) in the North Atlantic Ocean. Deep Sea Drilling Project sites which have recovered thick contourite sequences are shown by a black circle and site number. Contour at 4000 m depth.

zontal turbulent flow. This has been demonstrated by Bryan (1970) and Markl et al. (1970), who suggested that the Blake Bahama Outer Ridge is a consequence of the interaction of the Gulf Stream and the Western Boundary Undercurrent.

Where the bottom current encounters a solid obstacle such as a seamount its velocity increases, causing sediment erosion (Johnson and Lonsdale, 1976) or, at least, reducing the sedimentation rates (Heezen and Rawson, 1977), and thereby producing a characteristic moat or marginal channel (Heezen and Johnson, 1963; Davies and Laughton, 1972; Roberts et al., 1974). Increased desorption in the lee of the seamount may also occur (Lowrie and Heezen, 1967).

Similarly, at topographical sills or deep-sea straits and passages increased bottom-current velocity will have a pronounced effect on sedimentation. Erosion or non-deposition occurs in the passage with corresponding sediment drift at the end (Hollister et al., 1974a; Heezen and Rawson, 1977). In extreme cases, such as the powerful bottom currents flowing through the Strait of Gibraltar (Kelling and Stanley, 1972), the channel floor consists of coarse sand and gravel lag-deposits and bare rock outcrops.

There are also many reports of very large sediment waves on the deep-ocean floor, on continental slopes, rises and abyssal plains (Ewing et al., 1971; Jacobi et al., 1975; Embley and Langseth, 1977; Hess et al., in prep.). These mud waves mostly have a wavelength of 1—5 km, an amplitude of 10—40 m, and internal reflectors suggesting upslope and/or upcurrent migration. They have in many cases been interpreted as depositional bedforms produced by bottom currents, and occur on sediment ridges such as the Feni Ridge (Lonsdale and Hollister, in press) and the Blake Bahama Outer Ridge (Hollister et al., 1976). They also occur on the backsides (sides away from the channel floor) of levees bounding deep-sea channels (Hamilton, 1967; Damuth, 1975; Hess and Normark, 1976) where they are most probably related to large-scale turbidity currents. Physical interpretation of these waves using a simple two-layer model (Hess et al., in prep.) suggests that they are formed by thick (several hundred metres), low-velocity (about 10 cm s^{-1}), low-sediment-concentration (about 2.5 mg l^{-1}) turbidity flows. A unique interpretation of these features is not yet possible.

With improved seismic techniques, including the development of a deeply towed instrument package (Spiess and Mudie, 1970), still smaller scale morphological features can be recognised (Lonsdale and Spiess, 1977). Current ripples and medium-scale sand waves (Lonsdale and Malfait, 1974) and mud waves (Johnson and Lonsdale, 1976) have all been found beneath high-velocity currents in the deep ocean. Erosional furrows on the Blake—Bahama Outer Ridge were studied in detail by Hollister et al. (1974b, 1976) and Flood et al. (1974). Small furrows are 1—4 m wide, 0.75—2 m deep and 20—125 m apart; large furrows are up to 150 m wide, 20 m deep and 50—200 m apart. Both small and large furrows appear to be parallel to the regional bottom currents but oblique to the larger sediment waves. They have been interpreted as the result of helical vortices developed in the boundary layer of a bottom current system interacting with the sediment.

Echogram characteristics

Many studies over the past ten years have used echograms, produced by high frequency (3.5—12 kHz) precision depth recorders, to study sedimentary processes on the deep-ocean floor. The widely spread spaced data-lines usually obtained can only be used for broad regional interpretations, but the results are nevertheless useful for characterising areas where bottom currents have had an effect on sedimentation.

Hollister (1967), Schneider et al. (1967) and Hollister and Heezen (1972) have discussed the echogram characteristics of the western North Atlantic margin. They find that distinct continuous echoes, either single or with strong sub-bottom reflectors, are common on the abyssal plains and on parts of the upper and middle continental rise. These flat-lying 'hard' reflectors they interpret as turbidites. Over much of the continental rise they find poor bottom reflectivity with hyperbolic or prolonged, 'mushy' echoes indicating a series of parallel, linear elevations. The distribution of these echo-characters parallel to the contours has been suggested as evidence for bottom-current control of deposition.

Davies and Laughton (1972) characterise the acoustic nature of turbidites as having high reflectivity with sea-bed multiples, strong stratification, and flat beds with an absence of waves of ridges. Contourites, on the other hand, are relatively transparent, lack strong internal layering, and commonly have a wavy upper surface.

Damuth (1975) and Damuth and Kumar (1975) have discussed the detailed characteristics of bottom echoes from the western equatorial Atlantic floor. They also record distinct and indistinct echoes, the latter including continuous prolonged and hyperbolic types. The hyperbolic echoes are recorded from small isolated portions of the continental rise, and do not parallel the bathymetric contours as is the case in the western North Atlantic. They are interpreted as reflections from the wavy surfaces of levees and interchannel areas produced by deposition from turbidity currents that have flowed over the banks of the channels. In general the regional distribution of the three main echo types indicates dispersal of sediment downslope via turbidity currents, and suggests that bottom currents have been unimportant in shaping the continental rise. A similar interpretation has been made in an extension of this study to the east Brazilian continental margin (Damuth and Hayes, 1977). There is, as yet, no critical echo-character which can be attributed solely to bottom-current deposition. Sediment waves are apparently common to both turbidites and contourites, and recent work by Uchupi (pers. comm., 1977) over the Laurentian Fan has shown that there the hyperbolic echoes are confined to turbidity-current channels.

The nepheloid layer

Nepheloid layers were first recognised, by means of their light-scattering properties (see Ewing and Thorndike, 1965), as concentrations of suspended matter over certain parts of the ocean floor. The zone of highest concentration in the nepheloid layer of the western North Atlantic Basin coincides approximately with the continental rise—abyssal plain boundary and with the inferred axis of the Western Boundary Undercurrent; this has led to the close association of contourite deposition with the presence of nepheloid layers (Heezen et al., 1966). The significance of the layer has been stressed by Eittreim and Ewing (1972, p. 124): 'The nepheloid layer is apparently the agent of transport [for] most of the continental rise and probably the Bermuda Rise lutite deposits, and is therefore of great importance regarding the sedimentation in this basin'.

Well-developed nepheloid layers are indeed associated with high-velocity bottom currents in many parts of the ocean basins (Eittreim et al., 1969, 1972, 1976; Jacobs and Ewing, 1969; Connary and Ewing, 1972; Biscaye and Eittreim, 1977). These currents are thought to maintain the fine (average size 12 μm) particles in suspension by turbulent eddy diffusion for a residence period of about one year (Eittreim and Ewing, 1972). Random measurements of suspended sediment concentrations in deep-sea nepheloid layers suggest values of 0.3—0.01 mg l^{-1} (McCave and Swift, 1976; Pierce, 1976; Swift, 1976), and an average thickness of about 1 km. Shelf nepheloid layers are thinner and have higher sediment concentrations of 2—3 mg l^{-1} (Drake, 1976).

The dominant immediate source of suspended fines for the nepheloid layer is from land, presumably via turbidity flows (Eittreim and Ewing, 1972). There have been recent reports of nepheloid layers in the vicinity of submarine canyons (Beer and Gorsline, 1971; Drake and Gorsline, 1973: Drake, 1974; Baker, 1976a, b; Stokke et al., 1977) which support the idea of downslope movement of fine-grained material in thick, dilute, turbidity flows (Stow, 1977a; Stow and Bowen, 1978) or thin turbid-layer flows (Moore, 1969).

Bottom photographs

Strong evidence for the effects of bottom currents on the present-day sediment surface comes from the large number of orientated underwater photographs that have been taken over the last fifteen years (Hollister, 1967; Stanley, 1969; Heezen and Hollister, 1971; Taylor et al., 1975; Kolla et al., 1976). These photographs show a variety of ripple or wave forms, current lineations, scours, sediment mounds and bending organisms to the deep-sea floor, many of which suggest current directions parallel to the inferred bottom currents. Ferromanganese pavements swept clean of sediment (Kennett and Watkins, 1976) and coarse lag deposits (Kelling and Stanley, 1972) have also been photographed.

Such photographs do of course show only the topmost layers of sediment and indicate present-day oceanographical conditions. They do not necessarily prove a reliable guide to earlier depositional processes or circulation patterns. For example, it is possible that the Holocene period has been a time of intense bottom-current activity in the western North Atlantic, whereas the Pleistocene period was dominated by turbidity currents (Field and Pilkey, 1971; Stow, 1977a). The sediment surface will therefore reflect a process different from that inferred from the (deeper) laminated sediments in many piston cores.

Sediment character

It is important to identify the various turbidity-current and bottom-current mechanisms that have been proposed for deep-marine sedimentation.

(a) high-concentration turbidity currents;
(b) low-concentration, thick, turbidity flows;
(c) low-concentration, thin, turbid-layer flows (or flows along a density interface within the water column);
(d) low-concentration, turbidity current overflow (with or without deflection by Coriolis Force and/or bottom currents);
(e) low-concentration bottom currents (of various velocities and concentrations);
(f) very low concentration, hemipelagic and pelagic deposition.

Several of these processes involve similar concepts. Low-velocity turbidity currents measured by Shepard and co-workers (Shepard and Marshall, 1973a, b; Shepard et al., 1974, 1975, 1977) and the nepheloid layers in submarine canyons (see earlier discussion) suggests that an expansion of the turbidity-current theory is required (Stow, 1977a). It seems probable that a continuum exists between dilute turbidity flows, bottom currents and hemipelagic deposition from the nepheloid layer, and hence gradation between turbidites, contourites and hemipelagites. Various authors have admitted great difficulty in distinguishing between such deposits (Stanley, 1969; Hesse, 1975; Kelling and Stanley, 1976; Piper, 1978).

There are at least two clearly distinct contourite facies which can be defined. Stow (1977a, b) referred to these as 'winnowed' and 'distal', but we prefere the more general terms 'sandy' and 'muddy' contourites. Sandy contourites include reworked rubidite sands, and coarse lag-deposits resulting from the winnowing and removal of fine material by bottom currents. Muddy contourites are the fine-grained sediments deposited directly from nepheloid layers associated with bottom currents, and are volumetrically more important than sandy contourites.

Previous criteria for the recognition of contourites

The principal sediment characteristics of turbidites and contourites as developed by Hollister (1967), Hollister and Heezen (1972), Bouma (1972, 1973) and Bouma and Hollister (1973) are shown in Table II. These criteria have become firmly established in the literature and have been used repeatedly for the subsequent identification of contourites. It is therefore important to examine them in some detail.

The Heezen—Hollister—Bouma criteria are based on a comparison of thick, sandy turbidites with thin, silt 'contourites'; according to Piper and Brisco (1975, p. 729): 'they [Bouma and Hollister, 1973] have not satisfactorily demonstrated that their 'contourites' are not distal turbidites. Furthermore, some of Hollister's generalisations about turbidites, while they may be true for the area which he investigated, are not applicable to all turbidites'. Detailed work on fine-grained, thin-bedded or 'distal' turbidites has shown their similarity to previously described contourites (Griggs, 1969; Griggs and Kulm, 1970; Piper, 1973, 1976; Mutti, 1974; Rupke and Stanley, 1974; Hesse, 1975; Stow, 1977a, b; and others). In particular, the turbidite beds

TABLE II

The Heezen—Hollister—Bouma criteria for the recognition of turbidites and contourites (modified after Hollister and Heezen, 1972)

	Turbidite	Contourite	Conclusions
Size sorting	moderate to poorly sorted >1.50 (Folk)	well to very well sorted <0.75 (Folk)	contourite is better sorted
Bed thickness and frequency	usually 10—100 cm infrequent	usually <5 cm abundant	contourite has thinner bedding, and many more beds per core length
Primary sedimentary structure			
grading and bedding contacts	normal grading ubiquitous, bottom contacts sharp, upper contacts poorly defined	normal and reverse grading, bottom and top contacts sharp	contourite tends to be less regularly graded and has sharp upper contacts
cross laminations	common, accentuated by concentrations of lutite	common, accentuated by concentration of heavy minerals	contourite contrasts sharply with turbidite in that heavy mineral placers are in the form of small-scale stratification
horizontal laminations	common in upper portion only, accentuated by concentration of lutite	common throughout, accentuated by concentrations of heavy minerals or foraminifera shells	
massive bedding	common, particularly in lower portion	absent	contourite is ubiquitously laminated
grain fabric	little or no preferred grain orientation in massive graded portions	preferred grain orientation parallel to the bedding plane is ubiquitous throughout bed	contourite has better grain orientation
Principal constituents of sand and silt beds			
matrix (<2 μm)	10—20%	0—5%	contourite has less matrix
microfossils	common and well preserved, sorted by size throughout bed	rare and usually worn or broken, often size sorted in placers	contourite shows more evidence or reworking
plant and skeletal remains	common and well preserved, sorted by size throughout bed	rare and usually worn or broken	contourite shows more evidence of reworking
Classification (Pettijohn)	graywacke and subgraywacke	sub-graywacke, arkose and orthoquartzite	contourite is more "mature"

show the supposed 'contourite' characteristics of good sorting, thin bedding, and high frequency per length of core. The turbidite layers may also show horizontal- or cross-lamination throughout, both of which types of lamination may be accentuated by concentrations of heavy minerals or foraminifera (Chough and Hesse, 1977; Chough, 1978).

Piper and Brisco (1975) have described probable contourite silts from the continental rise of Wilkes Land, Antarctica (DSDP site 268). These laminae are very thin (<5 mm), lenticular or discontinuous, have sharp or gradational contacts, and a petrographic (biogenic) composition which reflects that of the interbedded muds. These features are different from those of the turbidite silts in the neighbouring rise and abyssal plain cores (DSDP sites 269 and 274). The results suggest that in these cores contourite silt laminae do not have heavy mineral placers, do not show pronounced grain orientation, that matrix content or other textural characteristics are not a basis for distinction from turbidites, and that microfossils are commoner than in turbidites.

Nelson et al. (1975a) concur with Piper and Brisco (1975) in suggesting that contourite silts display irregular bed-thickness and discontinuous lamination. However, Mutti (1977) describes lenticular, thin-bedded turbidites from the lobe fringe and channel-mouth environments of the Eocene Hecho Group in the Pyrenees, Spain. Nelson et al. (1975b) also find lenticular sands and starved ripples in certain parts of the modern submarine canyon and fan system. Stow (1977a) and Stow and Shanmugam (in prep.) show that lenticularity may be common in certain divisions of their standard structural sequence for both modern and ancient fine-grained turbidites (see also Piper, 1978).

Various authors have attempted to elaborate the textural distinctions between turbidites and contourites included in the Heezen—Hollister—Bouma criteria.

Tucholke et al. (1976) identified muddy contourites on the lower rise off the Antarctic Peninsula (DSDP site 324), partly from the characteristic symmetrical sigmoidal cumulative curves of grain-size analyses. However, similar sigmoidal grain-size distributions have been interpreted as characterising muddy turbidite and hemipelagic sediments (Piper, 1973; Rupke and Stanley, 1974). Stow (1977a) finds a gradation from a bimodal distribution in Laurentian Fan turbidite silts to a sigmoidal distribution in presumed turbidite silts of the southern Sohm Abyssal Plain. These latter grain-size distributions are identical to those of probable contourite silts of the Blake—Bahama Outer Ridge.

Other detailed textural studies have interpreted essentially the same features (sinusoidal trends of pairs of grain-size parameters) to indicate different processes (Hubert, 1964, 1967; Horn et al., 1971; Jipa, 1974; Nelson, 1976; Stow, 1976). Sandy contourites may show negative skewness (Duane, 1964), as opposed to the positive skewness of most turbidites (Horn et al., 1971).

The importance of compositional criteria in determining provenance and depositional process has been stressed by Pilkey and co-workers in various studies of cores from the continental margin off eastern North America (Field and Pilkey, 1971; Pilkey and Field, 1972; Froelich et al., 1972; Fritz and Pilkey, 1975; Klasik and Pilkey, 1975; Cleary et al., 1977). Studies of sands from two areas of the Carolina continental rise led to the suggestion that contourite sands contain less shallow-water material, have lower contents of organic matter and $CaCO_3$, and show less variability of the heavy-mineral fraction. However, the turbidite sands these authors describe from the Hatteras Fan region are thick, coarse and graded while the contourite sands from the adjacent rise are thin, fine and appear ungraded. The compositional differences observed may be due to the textural differences between channel and interchannel (overbank) turbidites. Pilkey and others do note a lack of offshore trends in the 'contourite' sands of the rise, which is consistent with along-slope transport.

Although sediment composition can be a valuable tool in determining depositional process, its usefullness may be local.

Interbedded turbidites and non-turbidites

Several authors have attempted to distinguish between closely interbedded turbidites and non-turbidites by careful sedimentological study and comparison of the different beds.

Stow (1977a, b) recognised fine-grained turbidites and contourites in cores from the deep-water margin off Nova Scotia in the western North Atlantic. The most useful criteria for distinguishing between the two were those which indicated transport perpendicular or parallel to the slope contours; marked trends in fining and sorting; regional mineralogical and compositional patterns; and grain fabric (where geographical orientation of the core was by palaeomagnetic means (Ellwood and Ledbetter, 1976, 1977).

Stow found that much of the Wisconsin sequence was deposited by large, fine-grained, turbidity flows (Stow and Bowen, 1978). However, during Wisconsin interstades and most of the Holocene the relatively high rate of hemipelagic deposition was controlled by the Western Boundary Undercurrent. The resultant hemipelagic/contourite muds (Fig. 3) are highly bioturbated (burrows and mottling), and have relatively high contents of $CaCO_3$ (15—40%) and organic carbon (0.5—1.0%). The dispersed sand fraction is composed largely of biogenic tests; these may be concentrated in irregular layers as a result of bottom-current winnowing, as suggested for biogenic lag-deposits in the western Mediterranean (Ryan, Hsü et al., 1973a, b; Rupke and Stanley, 1974). There is also evidence that montmorillonite in the clay fraction has been derived from farther north, as proposed by Zimmerman (1972) for clays on the New England continental rise.

Rupke and Stanley (1974) and Rupke (1975) described distinctive properties of turbidite and hemipelagic muds which alternate in the domi-

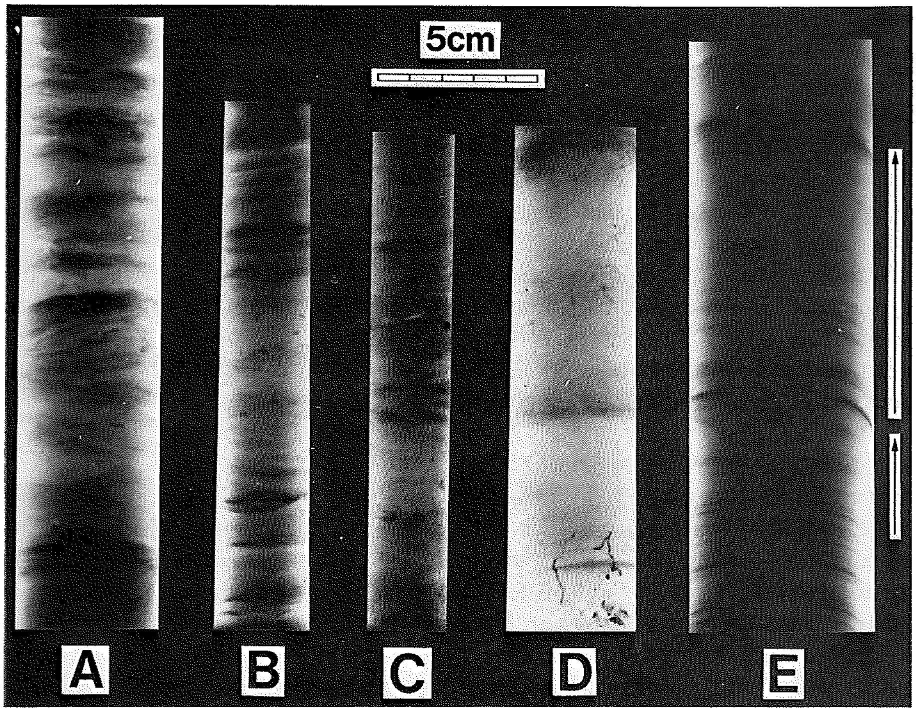


Fig. 3. X-radiograph positives of muddy contourites (A—D) and mud turbidites (E) in piston cores from the Nova Scotian Continental Rise. A—D: Irregular coarse layers (dark) in structureless mud (contourite/hemipelagite). The scattered dark mottles and burrows (in D) are diagenetic iron sulphide. D has a greater hemipelagic input. E: Silt-laminated turbidite mud for comparison. Note the fine, regular, silt laminae (darker), and the graded, laminated units (shown by arrows).

nantly muddy cores of the Algero-Balearic Basin of the western Mediterranean. The hemipelagic muds are macroscopically homogenous, and occur above the turbidite muds which overlie turbidite sands or silt laminae. They are from 0 to 50 cm in thickness, ungraded, and comparatively coarse (up to 16% sand) due to interspersed foraminifera and pteropod shells. They generally have higher $CaCO_3$ contents (26—46%) than the turbidite muds, and may show other slight compositional differences (e.g. peak-height ratios of clay minerals). Rupke and Stanley (1974) observed some evidence of bottom-current activity (winnowed concentrations of foraminifera) within the hemipelagic sediment, but not within the turbidite muds.

From work on Cretaceous flysch sequences in the eastern Alps, Hesse (1975) defined a model basin in which carbonate turbidites are deposited below the carbonate compensation depth. The non-turbidite layers (including pelagic, hemipelagic, bottom-current and nepheloid-layer deposits) are carbonate-free, usually bioturbated and contain siliceous biogenic remains. The turbidites contain transported carbonate material that has been buried rapidly before dissolution. Modern examples of such depositional areas include Bay of Biscay Abyssal Plain (Laughton, Berggren et al., 1972, DSDP sites 118 and 119), the Caroline Abyssal Plain in the west Pacific (Heezen, McGregor et al., 1973, DSDP site 199), the Peake and Freen Deeps on the Mid-Atlantic Ridge (Davies and Jones, 1971), and the Puerto Rico Trench (Conolly and Ewing, 1967).

The distinction of turbidites and non-turbidites becomes more difficult in basins with little carbonate input or in those lying above the carbonate compensation depth. In these, the non-turbidites generally have higher biogenic and carbonate contents. They are thoroughly mottled by bioturbation and homogenous in texture and mineralogy.

Contourites of deep-sea sediment ridges

The accumulation of contourite muds in deep-ocean ridges controlled by abyssal circulation patterns has been discussed in an earlier section (see also Davies and Laughton, 1972). The sedimentary growth of such ridges may be clearly interpreted from seismic reflection records as due to processes other than downslope turbidity currents. If, as seems most reasonable, these ridges were constructed largely by bottom currents, then an examination of their sediments will help to define the sedimentary characteristics of contourites.

The Blake—Bahama Outer Ridge provides the classic example of a bottom-current depositional area (Heezen et al., 1966), an interpretation supported by the presence of Upper Carboniferous palynomorphs from eastern Canada in the sediments (Needham et al., 1969). Heezen et al., (1966, p. 508) conclude that: 'Massive transport of continental rise sediment parallel to the contours for at least 1500 km is demonstrated by the construction of the Blake—Bahama Outer Ridge'. Deep-sea Drilling Project Sites 102, 103 and 104 on the Outer Ridge (Hollister, Ewing et al., 1972) revealed a thick rapidly accumulated 'hemipelagic', silty, carbonaceous clay of late Tertiary and Quaternary age. Piston cores from the region between the Hatteras Canyon and the southernmost tip of the Outer Ridge (Klasik and Pilkey, 1975) show broad, along-slope variation of $CaCO_3$ content, mineralogy and accumulation rate. Coarse layers are uncommon, thin and ungraded, and some cores show mottling throughout.

Laughton, Berggren et al., (1972) describe contourites from the Gardar Ridge (DSDP site 114), southern Labrador Sea ridges (DSDP site 112), and the eastern side of the Hatton—Rockall Basin (DSDP site 116). The Gardar Ridge sediments are mostly structureless, clayey silts (soft mudstones), with a very few faint laminae. They show some evidence of mottling by bioturbation and have $CaCO_3$ contents of up to 20%. They are compositionally uniform, comprising clays, micas, volcanic glass, biogenic tests and foraminiferal sand. Pyritised worm tubes and foraminiferal moulds are common. In the southern Labrador Sea sedimentation has been slower so that the generally structureless muds (most laminae destroyed by burrowing) are thoroughly mottled, have higher $CaCO_3$ contents (mostly 10—25% and up to 40%), and are rich in biogenic material. Pyrite is again common.

Tucholke and Ewing (1974) present considerable evidence for the formation of the Greater Antilles Outer Ridge by a southward extension of the Western Boundary Undercurrent. The character of the sediments are described by Tucholke (1973, 1974) from piston cores and by Bader et al., (1970, DSDP site 28). They are homogenous, terrigenous, silty clays with cyclic variations in $CaCO_3$ content (0—36%), and enriched organic carbon content (up to 2%), and a northerly derived mineral assemblage (especially chlorite and illite). Biogenic material is found throughout, and is occasionally concentrated in scattered layers.

Work recently completed on the differentiation of turbidites and contourites from the Eirek Ridge and North West Atlantic Mid-Ocean Channel (Chough and Hesse, 1977; Chough, 1978) describes muddy contourites that are very similar to those of other deep-ocean sediment ridges and to those identified by Stow (1977a). They are for the most part highly bioturbated and contain a large amount of pelagic and hemipelagic material. The turbidite—contourite problem is currently being investigated in the Iceland Basin (A.N. Shor, pers. comm., 1977).

Accumulation rates

Several estimates of accumulation rates of presumed contourites are given in Table III. These mostly range down from about 10 cm per 1000 years, except for the very high rates suggested by Bouma and Hollister (1973) that are believed by us to include deposition of fine-grained turbidites. Accumulation rates for turbidites may be of a similar order of magnitude or much greater (Piper, 1978). Instantaneous depositional rates are considerably less for contourites than for most turbidites.

TABLE III

Accumulation rates of contourites

Davies and Laughton (1972)	North Atlantic sediment ridges	0.6—12
Hollister et al. (1972)	Blake Outer Ridge	2—20
Bouma and Hollister (1973)	general	10—100
Klasik and Pilkey (1975)	Blake Bahama Outer Ridge	2—13
Stow (1977a)	Scotian Slope and Rise	
Piper (1978)	general	8—12

Summary

Criteria for the recognition of contourites in marine-based investigations

From the foregoing discussion it will be evident that there are still many contradictions within the present criteria used in distinguishing between turbidites and contourites. However, it is possible to recognise the following problems:

(a) Different, but closely related mechanisms exist for the deposition of fine-grained sediment. A continuum may exist between dilute turbidity flows, bottom currents and hemipelagic settling.

(b) At least two very different contourite facies exist: muddy contourites deposited slowly from nepheloid layers associated with bottom currents; and sandy contourites that result from the winnowing of muds and the reworking of turbidite sands. Criteria are needed to distinguish each type from the equivalent turbidite facies.

(c) Interbedded turbidites, contourites and hemipelagites exist, especially in a rise environment. Regional observations of echogram character and other surficial features must be used with caution. Evidence of bottom currents from photographs of the sediment surface, direct current measurements and the presence of nepheloid layers does not necessarily apply to more than the topmost layers of sediment.

(d) General criteria for distinguishing between the various deposits are difficult to establish. Each case or locality needs to be considered separately as there may be considerable variation in the applicability of certain criteria from one region to another.

With due attention to the limitations outlined above and recognising the need for further investigation of deep-sea contourites, we propose the following as the most important criteria for the recognition of contourites in the marine environment:

(a) General environment
— isolated, deep-sea, sediment-constructed ridges
— continental rises (especially on the western margins of ocean basins), with interbedded turbidites and hemipelagites
— constricted, deep-sea passages

(b) General evidence
— direct current measurements
— morphological evidence (moats, ripples, waves, sediment drift, some of which may be related to turbidity currents)
— accoustically transparent sediment, with low reflectivity and lacking internal layering (evidence of echocharacters paralleling contours and presence of wavy or hyperbolic surface must be treated with caution)
— the presence of a distinct nepheloid layer
— photographic evidence (ripples, lineations, scour, lag-deposits, bending organisms)

(c) Sediment character
Muddy contourites (see Table IV and Fig. 3)
Sandy contourites (see Table V and Fig. 4)

TABLE IV

Muddy contourites: sedimentary characteristics

	Conclusions from marine-based studies	Comment on potential for preservation, and use in land-based studies
Occurrence	thick sequences of hemipelagic/contourite sediment (sediment ridges) in association with turbidites — overlying graded muds or sands on the continental rise	good, but identification depends on features listed under other headings
Structure	dominantly homogenous, bedding not well defined bioturbational mottling generally common burrows (? mycelia and pyrite mottles) present in many places coarse lag concentrations (especially biogenic) reflect composition of coarse fraction in mud primary silt/mud lamination — rare, but where present may be similar to very fine-grained turbidites though lacking structural sequence	good, unless extreme tectonic deformation, but note problem of distinction from very fine-grained turbidites
Texture	dominantly silty mud frequently high sand content (0—15%) of biogenic tests medium to poorly sorted, ungraded no offshore textural trends may show marked textural difference from interbedded turbidite if transport distances are different	not good, likely to be very substantially altered by diagenesis and tectonic deformation
Fabric	mud fabric; smaller, more randomly arranged particle clusters than the large, oriented groupings of mud turbidites (preliminary findings Stow, 1977a) primary silt laminae or coarse lag deposits show grain orientation parallel to the current (along-slope) interbedded, reworked turbidite layers may show widely bimodal grain orientations	not good, because of diagenesis and tectonic deformation coarser layers may preserve useful features (see discussion in Scott, 1967)
Composition	generally combination of biogenic and terrigenous material (may be distinct from interbedded turbidites) terrigenous material dominantly reflects nearby land/shelf source with some along-slope mixing and small amount of far travelled material (no down-slope trends)	fair, diagenesis, especially of biogenic material, likely to create problems; each region needs to be considered on its merits (see text).

TABLE IV (continued on next page)

	Conclusions from marine-based studies	Comment on pòtential for preservation, and use in land-based studies
	biogenic material usually rich — coccoliths, forams, diatoms, radiolaria, etc. (but varies with productivity of surface waters, and depth in relation to CCD)	
	$CaCO_3$ content often relatively high (10—40%) except where low productivity or below CCD	
	organic carbon content often high (0.5—2%) except as above	
	pyrite (and other iron sulphides) may be common?	
	general absence of shallow-water material; may have broken shallow benthonic forams	

LAND-BASED INVESTIGATIONS OF CONTOURITES

The need for a new concept to complement turbidity-current theory

In 1964 Kuenen wrote (p. 9): 'Although no serious attempts have been made to explain deep-sea sands as the product of normal marine currents, there have been some passing suggestions to this effect . . .'. Three years later (1967, p. 203) Kuenen had to write in a different tone: 'Recently several attempts have been made to explain deep-sea sands or flysch-type sandstone beds by normal currents, instead of by turbidity currents'.

In the intervening years Hsü (1964, p. 379) had offered evidence that '. . . cross-laminated sediments in several instances were transported by turbidity currents to deep-sea bottom and deposited originally as graded beds but subsequently were reworked and redeposited by the rippling action of deep marine bottom currents'.

Ballance (1964, p. 466) had written of a facies within Lower Miocene turbidites near Auckland: 'The interturbidite rippled sand is lithologically identical with, but finer-grained than, turbidite sand; it is interpreted as turbidite sand redistributed by bottom currents'. Scott (1966, p. 72), describing Cretaceous flysch in southern Chile, had put forward the hypothesis of 'downslope lateral supply by gravity-controlled mechanisms . . . into a regime of marine bottom currents sufficiently powerful to distribute detritus and produce sedimentary structures'. Klein (1966, p. 308), discussing flysch in the Ouachita fold belt, had suggested: 'An oceanographic model consisting of sand emplacement by gravity-induced processes and later resedimentation by axially oriented ocean currents . . .'. In a later (1967) review of palaeo-

TABLE V

Sandy contourites: sedimentary characteristics

	Conclusions from marine-based studies	Comment on potential for presentation, and use in land-based studies
Occurrence	thin lag deposits in muddy contourite sequences reworked tops of sandy turbidites in interbedded sequences coarse lag in deep-sea channels and straits	good, but identification depends on features listed under other headings
Structure	frequently disturbed and bioturbated; irregular coarse layers with little primary structure where undisturbed — horizontal and cross lamination similar to those in turbidites but with no regular structural sequence, and an orientation parallel to the bottom current direction may show reverse grading near the top, and a sharp upper contact	good, especially evidence of current directions, which may well be crucial (Anketell and Lovell, 1976); in the case of the current directions land-based investigations of contourites may prove more fruitful than marine-based studies.
Texture	silt to sand-sized, more rarely gravel may be relatively free of mud and well sorted tendency to low or negative skewness values no offshore trends	not good, likely to be very substantially altered by diagenesis and tectonic deformation
Fabric	indication of grain orientation parallel to the bottom current (along-slope) may show secondary mode of turbidite fabric (? at right angles) may show more polymodal or random fabric (disturbed)	not good, because of diagenesis and tectonic deformation? Scott (1967, p. 274) argues that grain orientations in substantially deformed beds do in at least one case "primarily reflect sedimentation"
Composition	dependent on region and immediate supply of sandy material concentration of grains of higher specific gravity (frequently biogenic lag in muddy contourites) compositional grading in turbidites obscured by reworking some evidence of along-slope reworking	fair, diagenesis may create problems, especially with biogenic material; each region needs to be considered on its merits (see text)

current analysis in relation to modern marine sediment dispersal patterns, Klein (1967) emphasised the role of bottom currents.

The idea of 'longitudinal' and 'lateral' supply involved in these discussions was certainly not new [for example, Kuenen (1957) wrote on 'Longitudinal

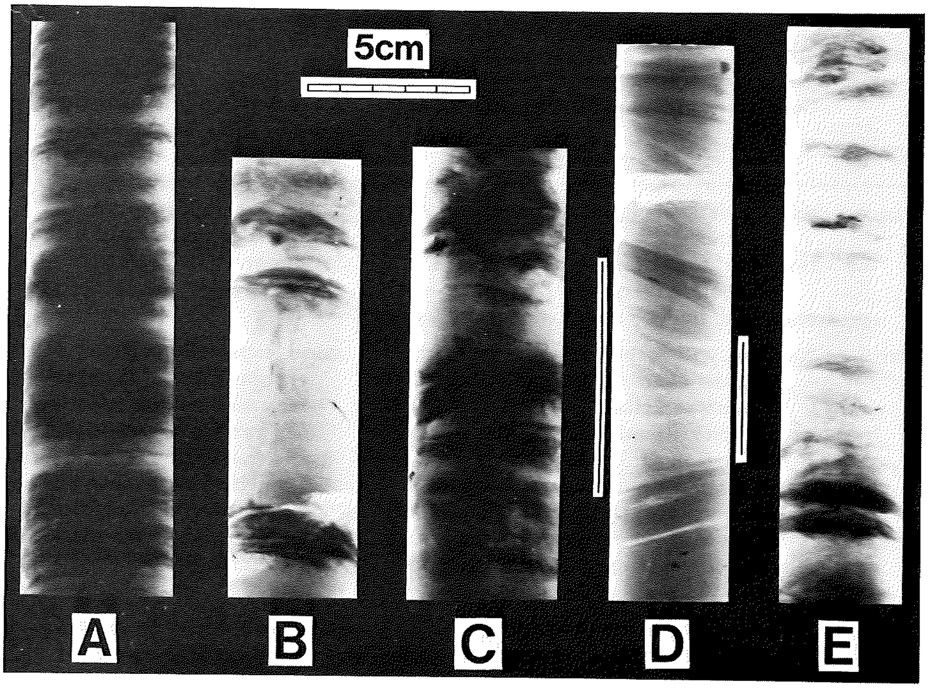


Fig. 4. X-radiograph positives of sandy contourites in piston cores from the Nova Scotian Continental Rise. A and C: Irregular, coarse, sandy layers (dark) in bioturbated mud. B: 'Reworked-turbidite' contourite (near top) — internally laminated and with sharp top. Dark iron sulphide mottles in coarse layer near bottom. D: Zone indicated by white lines is a bottom current reworked, foraminiferal sand. E: Muddy contourite with irregular 'winnowed' concentrations of foraminifera and sand.

filling of oblong sedimentary basins'], nor was the idea of reworking of turbidite material by bottom currents a novelty [see, for example, the discussion of work in the Southern Uplands of Scotland by Craig and Walton (1962), Kelling (1958, 1964) and others in Dzulynski and Walton (1965, pp. 252—254)]. It was the more fundamental challenge to the turbidite concept of those, like Hubert (1964), who ascribed a dominant role to bottom currents in the production of deep-sea sands, that provoked Kuenen's famous (1967, p. 241) concluding paragraph: 'The application of any broad concept in geology cannot fail to produce many puzzles, and turbidity flow is no exception. But hasty substitution of turbidity currents by normal currents is like jumping from purgatory, where there is still hope, into hell, where there is none'.

That there were problems connected with the role of 'bottom' or 'normal' currents in reworking turbidity current deposits is clearly recognised by Walker in a major review published in 1970 (p. 223): 'The combination of the oceanographic data, and the anomalous orientations of ripples and slump folds in ancient sandstone—shale couplets, has led to the present era of disenchantment with turbidity currents among some writers . . .'. By 1973 (p. 29) Walker, in another review, goes further and writes: '. . . it is now clear that in studies of ancient turbidites, sole-mark current indicators must be clearly separated from cross-lamination current indicators. It may even be possible to reconstruct ancient palaeoslope and contour-current directions, although no such claims have yet been made.' [see below for discussion of such a later (1976) claim by Anketell and Lovell].

By 1977 some of the difficulties of distinguishing turbidites, 'reworked' turbidites, and contourites had become more apparent. For example, Walker again (1977, p. 928): '. . . it is worth emphasising a point that the proponents of contourites (Bouma and Hollister, 1973) and overbank turbidites (Nelson et al., 1977) tend to ignore — namely that there should be a consistent paleocurrent divergence between downchannel or downslope turbidity current flow, and overbank (or contour current) flow'. As the preceding review of marine-based studies indicates, this can be taken a stage further; it is of course necessary to distinguish between overbank *turbidite* facies on submarine fans [for reviews see papers by Normark (1974), Nelson and Nilsen (1974), Mutti (1974), Whitaker (1974), and Picha (1974)] and *contourites.*

The turbidity current theory has proved resilient, as Kuenen hoped, but from an early stage in its investigation it has been clear to some workers that it is necessary to invoke other deep-sea currents to explain some of the features of ancient turbidites and their associated facies.

Ancient contourites

In 1975 Hesse (p. 389) wrote, in the paper on Cretaceous flysch in the east Alps discussed above: 'Identification of the deposits of ocean bottom currents is not attempted in this paper, because available data appear insufficient at present . . .'. It is perhaps understandable caution such as this, rather than a real lack of ancient contourites that has led to such a scarcity of formal identifications of contourites in the geological record since the publication of the key paper by Heezen, Hollister and Ruddiman in 1966. An early, if not the first, claim to have recognised ancient contourites is Wezel's (1969) paper on the Oligocene—early Miocene Numidian flysch of Sicily. Wezel (English Abstract, p. 8) states: 'Facies 2 comprises brown argillite with interbedded numerous thin clean quartzsiltite beds with sharp bases and upper surfaces'. He recognises a 'lateral downcurrent transition' to a Facies 3 of '. . . brown-grey pelites with interbedded lithic quartz wacke (10% of matrix) layers that exhibit 'typical' turbidite structures . . .' He continues: 'This pattern is difficult to explain with [a] Bouma (1962, p. 98) model of base cut out sequences with the increase of the distance from the source. A good agreement there is instead with the deep ocean currents ('contour currents') hypothesis of Heezen and his students.' Facies 2 is interpreted as a continental rise deposit, Facies 3 as the turbidites of the abyssal plains. 'The paleocurrents and the facies variations over the Numidian Flysch basin strongly suggest a lateral derivation of the material from the southern margin by mass movements and turbidity currents, while ocean bottom currents carried the material of Facies 2 in a longitudinal direction.' The details of the regional setting are described by Wezel elsewhere (1970, 1974).

Schenk (1970) suggests that bottom currents may have been important in the deposition of the Lower Palaeozoic Meguma Group of Nova Scotia. Developing earlier work by Harris and Schenk (1968), he argues (p. 142) 'The Meguma flysch appears to have been deposited from gravity-controlled, traction-type processes that moved sediment north-northwestward downslope from a broad source area to the south-southeast . . .. Distribution of sedimentary properties of the flysch was modified by a consistent, extremely long-term current pattern . . . this persistent current moved across, not downslope over the area.' As Schenk puts it in his abstract (p. 153): 'Currents appear to 'contour' scalar properties.' Schenk's arguments are based on analysis of regional patterns of sedimentation in the Meguma Group, rather than on the resemblance of any particular facies to modern contourites.

In contrast Bouma (1972a, b, 1973) follows Hollister and Heezen (1972) in seeking to identify ancient contourites by a detailed comparison of the structure of individual beds. On the strength of such comparisons, Bouma recognises contourites in the Niesenflysch of Switzerland. In an important (December 1972) comment in 'Errata and Additions' to his (1972a) paper on 'Recent and ancient turbidites and contourites' Bouma writes: 'My interpretation of contourites in part of the lower Niesenflysch is brought forward rather strong[ly] without sufficient field evidence. A total basin analysis is required to allow proper paleogeographic interpretations that may lead to bottom current deductions. The whole concept of debrites—turbidites—contourites should be regarded in the broader environmental framework of deep-sea sand deposition'.

This is of course true, but difficult to achieve in ancient sediments, as Bein and Weiler (1976) recognise in their study of the Cretaceous Talme Yafe Formation. This is (p. 511): '. . . a huge prism-shaped accumulation (more than 3000 m thick, about 20 km wide, and at least 150 km long) of calcareous detritus at the northwest continental margin of the Arabian Craton (Israel)'. The formation was studied in both onshore and offshore boreholes, in limited onshore exposures, and with seismic work. Bein and Weiler identify eight main characteristics of the Talme Yafe Formation (p. 529), none of which directly follows any of the Hollister and Heezen (1972) criteria for the identification of contourites used by Bouma (1972a, b, 1973). As with Schenk's (1970) work with the Meguma Group, the arguments are based mainly on regional setting and large-scale distribution of, in this case, neritic carbonates and pelagic marls.

In their study of rocks exposed at the base of the classical turbidite Aberystwyth Grits Formation (Llandoverian, Central Wales) Anketell and Lovell (1976) identified possible contourites following the Heezen—

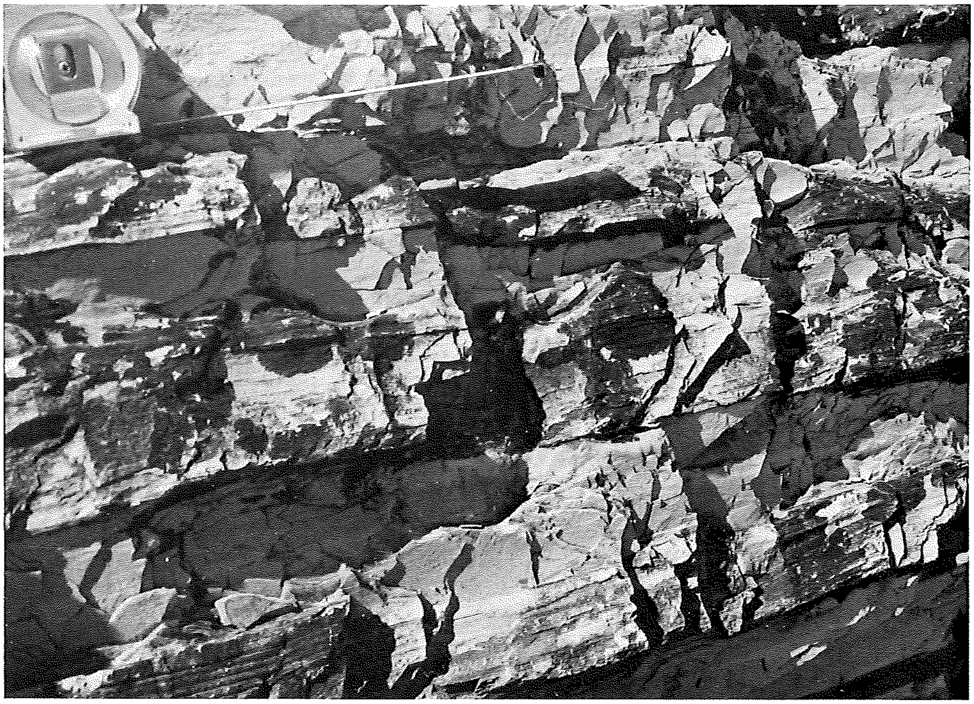


Fig. 5. Silurian contourites, Grogal Formation, Central Wales, after Anketell and Lovell (1976, plate Ib). Tape 20 cm long.

Hollister—Bouma criteria, and then attempted to check this identification against 'the broader environmental framework' of Bouma (see above). The supposed contourites of the Grogal Sandstones Formation (Fig. 5) lie conformably below the Aberystwyth Grits Formation. Detailed work on cross-laminations, sole marks and many other features of the Aberystwyth Grits (Wood and Smith, 1959; Lovell, 1970) leaves little doubt that they are the deposits of turbidity currents flowing downslope from roughly southwest to northeast (present-day direction). Measurements of the cross-laminations in the Grogal Sandstones Formation (Anketell, 1963; Anketell and Lovell, 1976) show that currents flowed at right angles to this, alongslope, as well as downslope. Where Grogal Sandstones (contourite) and Aberystwyth Grits (turbidite) facies are interbedded at the base of the Aberystwyth Grits Formation, both 'along-slope' and 'down-slope' sole marks and cross-laminations are found.

An alternative explanation of the Grogal Sandstones facies as overbank deposits from turbidity-current flow down channels running from southwest to northeast is considered less likely: the rocks are distinctly more like the Heezen—Hollister—Bouma contourites and our 'sandy contourites'

(Table V) than overbank turbidites, and the current directions so far recorded fall into two distinct groups: southwest—northeast and southeast—northwest, with little of the scatter that might be expected with overbank turbidites.

The problem of scatter of current directions in possible contourites is consiered by Laird (1972) in his account of the sedimentology of the late Precambrian (?) Greenland Group of South Island, New Zealand. Here there is evidence from current ripples in a turbidite succession of periodic reversal of flow of along-slope currents, which Laird suggests (p. 386) may be 'caused by tidal current activity' (see also Andrews, Packham et al., 1975; Klein, 1975, 1977, for discussion of the extent of tidal influence on oceanic sediments).

We have little doubt that given reliable criteria many more rocks could be identified as contourites, including many that have been described in the course of the immense amount of writing on the turbidite problem. To take just one example, even in the middle of his vigorous (1967) defence of turbidites against the proponents of the dominance of 'normal' currents (see above), Kuenen has this to say (p. 231): 'There is one situation, however, in which the action of normal currents is less improbable, namely, where the interbeds are silty and reveal signs of current action. The best example has been described by Kelling (1958, 1964) from Scotland. Not only is there plenty of evidence of currents in the interbeds, but Kelling also found ripples modified by a second, later set with an entirely different orientation.'

Criteria for the recognition of contourites in land-based investigations

Following a classical uniformitarian approach, we consider here the potential for preservation of the features suggested above as criteria for the recognition of contourites in marine-based investigations. Our conclusions are summarised in Tables IV and V, and require little further explanation. The role of diagenesis is still to a large extent an open question, as is the effect of tectonic deformation on primary sedimentary fabrics, but we suggest that there are criteria with reasonable potential for preservation that may be recognised by careful field and laboratory studies in land-based investigations.

It is clear from Tables IV and V that the question of scale is crucial. Many of the larger-scale topographical and oceanographical features from which the possible presence of contourites may be inferred in marine-based studies do not have any direct potential for preservation in the geological record. Yet many of the smaller-scale features listed in Tables IV and V only become truly diagnostic of contourites when considered in a regional context.

We have suggested that the term contourite covers a range of facies. Contourites recognised so far in the land-based investigations are in the main closely associated with turbidites, and their identification in some cases relies in particular on the identification of down-slope current directions in the associated turbidites. For example, Anketell and Lovell (1976, p. 107) discuss a possible origin for a contourite facies associated with Silurian turbidites (see above). '. . . the *coarser beds* . . . result from reworking parallel to contours of the continental rise of sediment brought in downslope from the southwest by turbidity currents. The *mudstone beds* which alternate with the coarser beds presumably represent more continuous sedimentation on the continental rise by contour currents or dilute turbidity currents . . .'. This hypothesis suggests that if there was no supply of coarser material from down-slope turbidity currents, there would be no cross-laminated sandstone/siltstone beds, and, of course, no crucial evidence indicating down-slope direction. Identification of the mudstone beds alone as contourites clearly becomes very much more difficult in such circumstances.

In ancient rocks the identification of contourites is at this stage probably made most easily where they are associated with turbidites. This does involve problems such as the distinction of fine-grained overbank turbidites, and fine-grained distal (*s. str.*, Lovell, 1969, p. 951) turbidites from the contourites. We suggest that this be done in three stages, on a progressively increasing scale:

(1) *Small scale*: On the scale of the exposure (and if necessary with laboratory studies too), do the coarser beds have the range of features suggested in our Table V? In particular, do the current directions show bimodality at ca. 90° and limited scatter (cf. Anketell and Lovell, 1976, fig. 1)?

(2) *Medium scale*: If so, does the regional pattern of palaeocurrents and facies distribution support the notion of both down-slope and along-slope movement of the coarser sediment?

(3) *Large scale*: If so, is the suggestion that these are contourites compatible with what is known with reasonable certainty concerning large-scale patterns of continental distribution and oceanic circulation (e.g. Schenk, 1970, p. 148)? (Of course, sufficient certainty in stages 1 and 2 may well lead to revision of existing hypotheses involved in stage 3).

This procedure may in turn lead to the more confident recognition of sandy contourites that are not directly associated with turbidites in the field area (our 'winnowed' type, see above), and to the identification of muddy contourites also. Here the procedure suggested above for the 'reworked turbidite' contourites may be to some extent reversed; it may be regional work that suggests the possible existence of muddy contourites, which can then be studied on a small scale both in the field, and, more importantly in the case of this finer-grained sediment, in the laboratory.

The turbidite literature is already full of possible candidates for the description 'contourites' (see above and Keith and Friedman, 1977; Unrug, 1977). How freely is the term to be applied? For example, one of us (Lovell, 1975, p. 269) forbore to apply the term 'contourite' to a turbidite facies reworked by along-slope currents, because of uncertainty concerning the palaeogeography: were these currents flowing in a freshwater lake, a small sea, or an ocean (Burne, 1973)? Must we restrict the use of the term to 'oceanic' contourites? For the moment it seems wise to do so, for the term is already very broad, and will require a good deal of refinement and qualification as work proceeds.

THE GEOLOGICAL SIGNIFICANCE OF CONTOURITES

Even if one restricts the term 'contourites' to those sediments formed in environments analogous to the type area in the western North Atlantic Ocean, and even if one were to accept the claim of Stanley et al. (1971) that in at least part of that type area (specifically the lower continental rise east of middle Atlantic states) predominant sediment dispersal is perpendicular to isobaths, one may still claim that any contourites that are preserved in a future orogenic belt formed in that area will be highly useful in palaeo-oceanographical, palaeogeographical and tectonic work.

If, as we suggest here, the term 'contourite' also covers sediments formed by contour-following bottom currents in areas of more complex submarine topography, the potential geological significance is even greater. But here difficulties of recognition increase. There is, for example, a contrast between patterns of contourite deposition in different parts of the North Atlantic. It is relatively simple in much of the west and undoubtedly complex in at least parts of the east. In the Rockall Bank—Feni Ridge area, changes in deep oceanic circulation patterns with changing sea-floor topography make even *present-day* reconstructions of patterns of sedimentation difficult (Jones et al., 1970; Roberts, 1975).

The main problem remains one of preservation. Careful field work, including the clear recognition of contourites, in an orogenic belt in, say, 500 m.y. time, should lead to a reasonable idea of the nature of the western flank of a former Atlantic Ocean. But the changes in sea-floor topography that appear to have controlled sedimentation in the Rockall Bank—Feni Ridge area in the east will not of course be preserved directly in the geological record, and any contourites preserved will be less easy to recognise as such. The relative scarcity of clues to the down-slope sedimentation direction compared with the western North Atlantic will make matters worse.

Another problem may be the persistence of oceanographical conditions favouring strong bottom-current development. The present time is clearly favourable, as supported by direct current-measurements and photographic evidence. Glacial periods may have experienced much weaker deep-oceanic circulation because of widespread ice-cover of high-latitude ocean basins (Field and Pilkey, 1971; Hughes et al., 1977). In pre-Triassic time there may even have been a qualitative difference in the style of continental margins (Ziegler, 1977) and hence ocean circulation.

There are good geological and economic reasons for recognising the potential significance of contourites despite these difficulties. Dott, in his review of 'The geosynclinal concept' writes (Dott and Shaver, 1974, p. 10): '. . . (There is a) need to distinguish among ancient turbidites formed on passive continental rises, arc-rear basins, arc fronts and trenches and abyssal plains . . .'. In these problems, and in associated problems of 'polarity', especially on passive continental margins, contourites have obvious applications.

An extended quotation from Damuth and Kumar (1975, p. 2172) indicates the economic significance of contourite recognition as hydrocarbon exploration moves into deeper water on continental margins: 'The process which formed any particular continental rise may have an important bearing on the potential of that rise as a hydrocarbon province. Continental-rise sequences shaped by turbidity-current processes (such as the western Equatorial Atlantic) would seem to contain both excellent source and reservoir rock; whereas good reservoir rock apparently would be absent from continental rise sequences shaped by contour currents (such as the western North Atlantic)'. They explain (p. 2180) that though the sediments on the western North Atlantic continental rise '. . . may be good source rocks because of high organic content, the absence of thick, coarse sand beds suggests that no suitable reservoirs would be available'. Though we agree in the main, we suggest that some sandy contourites associated with turbidites might have hydrocarbon potential.

In October 1977 there was a meeting at the Royal Society to discuss 'The evolution of passive continental margins in the light of recent deep drilling results' (a report will be published by the Royal Society). It became clear in several contributions that one of the more important distinctions that has to be made in examining some DSDP/IPOD cores is that between turbidites and contourites. Yet this is a distinction that may in some cases be made more easily in ancient sediments exposed on land, where it is possible to gather relatively easily in the field the vital evidence of directions of current flow.

We have attempted in this review to bring together work at sea and on land bearing on the contourite problem, in the belief that a better understanding of contourites is crucial to progress in both spheres of research.

We repeat our suggestion that a major part of sedimentology is experiencing its second revolution in thirty years. We suggest that the work of Heezen, Hollister and their associates will come to assume an even greater historical significance in future than it does now.

ACKNOWLEDGEMENTS

We thank Drs. N.B. Price and A.H.F. Robertson for criticism of the manuscript, and other colleagues for useful discussions. D.S. acknowledges tenure of a Canadian Commonwealth Scholarship, during which time part of this study was carried out, and of a Royal Society John Murray Travelling Studentship.

REFERENCES

Amos, A.F., Gordon, A.L. and Schneider, E.D., 1971. Water masses and circulation patterns in the region of the Blake-Bahama Outer Ridge. Deep-Sea Res., 18: 145—165.

Andrews, J.E., Packham, G., et al., 1975. Initial Reports DSDP 30. U.S. Government Printing Office, Washington, D.C., pp. 423—442.

Anketell, J.M., 1963. The Geology of the Llangrannog District, Southwest Cardiganshire. Thesis, Queen's University, Belfast.

Anketell, J.M. and Lovell, J.P.B., 1976. Upper Llandoverian Grogal sandstones and Aberystwyth Grits in the New Quay area, Central Wales: a possible upwards transition from contourites to turbidites. Geol. J., 11: 107—108.

Bader, R.G. et al., 1970. Site 28. In: R.G. Bader et al., Initial Reports DSDP, 4. U.S. Government Printing Office, Washington, D.C., pp. 125—143.

Baker, E.T., 1976a. Temporal and spatial variability of the bottom nepheloid layer over a deep-sea fan. Mar. Geol., 21: 67—79.

Baker, E.T., 1976b. Distribution, composition and transport of suspended particulate matter in the vicinity of Willapa submarine canyon, Washington. Bull. Geol. Soc. Am., 87: 625—632.

Ballance, P.F., 1964. Streaked out mud ripples below Miocene turbidites, Puriri Formation, New Zealand, J. Sediment. Petrol., 34: 91—101.

Barrett, J.R., 1965. Subsurface currents off Cape Hatteras. Deep-Sea Res., 12: 173—184.

Beer, R.M. and Gorsline, D.S., 1971. Distribution, composition and transport of suspended sediment in Redondo Submarine Canyon and vicinity (California). Mar. Geol., 10: 153—175.

Bein, A. and Weiler, Y., 1976. The Cretaceous Talme Yafe Formation, a contour current shaped sedimentary prism of Cretaceous debris at the continental margin of the Arabian Craton. Sedimentology, 23: 511—532.

Biscaye, P.E. and Eittreim, S.L., 1977. Suspended particulate loads and transports in the nepheloid layer of the abyssal Atlantic Ocean. Mar. Geol., 23: 155—172.

Bouma, A.H., 1962. Sedimentology of Some Flysch Deposits. Elsevier, Amsterdam, 168 pp.

Bouma, A.H., 1972a. Recent and ancient turbidites and contourites. Trans. Gulf. Coast Assoc. Geol. Soc., 22: 205—221.

Bouma, A.H., 1972b. Fossil contourites in Lower Niesenflysch, Switzerland. J. Sediment. Petrol., 42: 917—921.

Bouma, A.H., 1973. Contourites in Niessenflysch, Switzerland. Ecolog. Geol. Helv., 66/2: 315—323.

Bouma, A.H. and Hollister, C.D., 1973. Deep ocean basin sedimentation. In: G.V. Middleton and A.H. Bouma (Editors), Turbidites and Deep Water Sedimentation. Soc. Econ. Paleontol. Min., Tulsa, Okla., pp. 79—118.

Bryan, G.M., 1970. Hydrographic model of the Blake Outer Ridge. J. Geophys. Res., 75: 4530.

Burne, R.V., 1973. Palaeogeography of southwest England and Hercynian continental collision. Nature, Phys. Sci., 214: 129—131.

Chough, S.K., 1978. Morphology, Sedimentary Facies and Processes of the North West Atlantic Mid-Ocean Channel Between 61° and 52°N, Labrador Sea. Thesis, McGill University, Montreal, Que., 167 pp.

Chough, S.K. and Hesse, R., 1977. Channel fill and spill-over facies of Northwest Atlantic Mid-Ocean Channel of Labrador Sea. AAPG-SEPM, Progr. Abstr., p. 35.

Cleary, W.J., Pilkey, O.H. and Ayers, M.W., 1977. Morphology and sediments of three ocean basin entry points, Hatteras Abyssal Plain. J. Sediment. Petrol., 47: 1157—1170.

Connary, S.D. and Ewing, M., 1972. The nepheloid layer and bottom circulation in the Guinea and Angola Basins. In: A.L. Gordon (Editor), Studies in Physical Oceanography, 2. Gordon and Breach, New York, N.Y., pp. 169—183.

Conolly, J.R. and Ewing, M., 1967. Sedimentation in the Puerto Rico Trench. J. Sediment. Petrol., 37: 44—59.

Craig, G. and Walton, K., 1962. Sedimentary structures and palaeocurrent directions from the Palaeozoic rocks of Kircudbrightshire. Trans. Edinb. Geol. Soc., 19: 100—119.

Crease, J., 1965. The flow of Norwegian Sea water through the Faeroe Bank Channel. Deep-Sea Res., 12: 143—150.

Damuth, J.E., 1975. Echo-character of the western equatorial Atlantic floor and its relationship to the dispersal and distribution of terrigenous sediments. Mar. Geol., 18: 17—45.

Damuth, J.E. and Hayes, D.E., 1977. Echo character of the east Brazilian continental margin and its relationship to sedimentary processes. Mar. Geol., 24: 73—95.

Damuth, J.E. and Kumar, N., 1975. Late Quaternary depositional processes on the continental rise of the western equatorial Atlantic: comparison with the western North Atlantic and implications for reservoir rock distribution. Bull. Am. Assoc. Pet. Geol., 59: 2172—2181.

Davies, T.A. and Jones, E.J.W., 1971. Sedimentation in the area of Peake and Freen Deeps (Mid Atlantic Ridge). Deep-Sea Res., 18: 619—630.

Davies, T.A. and Laughton, A.S., 1972. Sedimentary Processes in the North Atlantic. In: A.S. Laughton, W. Berggren et al., Initial Reports DSDP, 12. U.S. Government Printing Office, Washington, D.C., pp. 905—934.

Defant, A., 1961. Physical Oceanography, 1. Pergamon Press, London, 729 pp.

Dott, R.H. and Shaver, R.H. (Editors), 1974. Modern and Ancient Geosynclinal Sedimentation, Soc. Econ. Pet. Miner., Spec. Publ., 19: 380 pp.

Drake, D.E., 1974. Distribution and transport of suspended solids in submarine canyons. In: R. Gibbs (Editor), Suspended Solids in Sea Water. Plenum Press, New York, N.Y., pp. 133—153.

Drake, D.E., 1976. Suspended sediment transport and deposition on continental shelves. In: D.J. Stanley and D.J.P. Swift (Editors), Marine Sediment Transport and Environmental Management, John Wiley, New York, N.Y., pp. 127—158.

Drake, D.E. and Gorsline, D.S., 1973. Distribution and transport of suspended particulate matter in Hueneme, Redondo, Newport and La Jolla submarine canyons, California. Bull. Geol. Soc. Am., 84: 3949—3968.

Duane, D.B., 1964. Significance of skewness in recent sediments. J. Sediment. Petrol., 34: 864—874.

Dzulynski, S. and Walton, E.K., 1965. Sedimentary Features of Flysch and Graywackes. Elsevier, Amsterdam, 274 pp.

Earle, M.D., 1975. Current measurement in the eastern central North Pacific Ocean. Deep-Sea Res., 22: 875—881.

Einsele, G., Overbeck, R., Schwarz, H.U. and Unsold, G., 1974. Mass physical properties, sliding and erodibility of experimentally deposited and differently consolidated clayey muds. Sedimentology, 21: 339—372.

Einstein, H.A. and Krone, R.B., 1962. Experiments to determine modes of cohesive sediment transport in salt water. J. Geophys. Res., 67: 1451—1461.

Eittreim, S. and Ewing, M., 1972. Suspended particulate matter in the deep waters of the North American Basin. In: A.L. Gordon (Editor), Studies in Physical Oceanography, 2. Gordon and Breach, New York, N.Y., pp. 123—167.

Eittreim, S., Ewing, M. and Thorndike, E.M., 1969. Suspended matter along the continental margin of the North American Basin. Deep-Sea Res., 16: 613—624.

Eittreim, S., Thorndike, E.M. and Sullivan, L., 1976. Turbidity distribution in the Atlantic Ocean. Deep-Sea Res., 23: 1115—1128.

Eittreim, S., Gordon, A.L., Ewing, M., Thorndike, E.M. and Bruchhausen, P., 1972. The nepheloid layer and observed bottom currents in the Indian-Pacific, Antarctic Sea. In: A.L. Gordon (Editor), Studies in Physical Oceanography, 2. Gordon and Breach, New York, N.Y., pp. 19—35.

Ellwood, B.B. and Ledbetter, M.T., 1976. Detection of bottom current velocity changes using particle alignment and size in deep-sea sediment in the Vema Channel. EOS, 57 (12, 072): 938.

Ellwood, B.B. and Ledbetter, M.T., 1977. Antarctic bottom water fluctuations in the Vema Channel: Effects of velocity changes on particle alignment and size. Earth Planet. Sci. Lett., 35: 189—198.

Embley, R.W. and Langseth, M.G., 1977. Sedimentation processes on the continental rise of northeastern South America. Mar. Geol., 25: 279—297.

Ewing, M. and Thorndike, E.M., 1965. Suspended matters in deep-ocean water. Science, 147: 1291—1294.

Ewing, M., Eittreim, S.L., Ewing, J.L. and Le Pichon, X., 1971. Sediment transport and distribution in the Argentine Basin: part 3. Nepheloid layer and processes of sedimentation. In: L.H. Ahrens, F. Press, S.K. Runcorn and H.C. Urey (Editors), Physics and Chemistry of the Earth. Pergamon Press, London, pp. 55—77.

Field, M.F. and Pilkey, O.H., 1971. Deposition of deep sea sands: Comparison of two areas of the Carolina Continental Rise. J. Sediment. Petrol., 41: 526—536.

Flood, R.D., Hollister, C.D., Johnson, D.A., Southard, D.A. and Lonsdale, P.F., 1974. Hyperbolic echoes and erosional furrows on the Blake—Bahama Outer Ridge, EOS, Trans. Am. Geophys. Union, 55: 285.

Fritz, S.J. and Pilkey, O.H., 1975. Distinguishing bottom and turbidity current coarse layers on the continental rise. J. Sediment. Petrol., 45: 57—62.

Froelich, P., Golden, B. and Pilkey, O.H., 1972. Organic carbon in sediments of the North Carolina continental rise. J. Sediment. Petrol., 41: 526—536.

Gill, A.E., 1973. Circulation and bottom water production in the Weddel Sea. Deep-Sea Res., 20: 111—140.

Griggs, G., 1969. Cascadia Channel: the Anatomy of a Deep-Sea Channel. Thesis, Oregon State University, Corvallis, Ore., 183 pp.

Griggs, G.B. and Kulm, L.D., 1970. Sedimentation in Cascadia Channel. J. Geol., 78: 611—619.

Hagen, R. and Lonsdale, P.F., 1976. Inflow of bottom water to the Panama Basin. EOS, Trans. Am. Geophys. Union, 57: 260 (abstract).

Hamilton, E.L., 1967. Marine geology of abyssal plains in the Gulf of Alaska. J. Geophys. Res., 72: 4189—4213.

Harris, I. McK. and Schenk, P.E., 1968. A study of sedimentary structures in the Goldenville Formation, eastern Nova Scotia. Marit. Sed., 4: 1—3.

Heezen, B.C., 1959. Dynamic processes of abyssal sedimentation: erosion, transportation and redeposition on the deep sea floor. Geophys. J. R. Astron. Soc., 2: 142—163.

Heezen, B.C. (Editor), 1977. Influence of abyssal circulation on sedimentary accumulations in space and time. Mar. Geol., 23 (special issue).

Heezen, B.C. and Hollister, C.D., 1964. Deep-sea current evidence from abyssal sediments. Mar. Geol., 1: 141—174.

Heezen, B.C. and Hollister, C.D., 1971. The Face of the Deep. Oxford University Press, New York, N.Y., 650 pp.

Heezen, B.C. and Johnson, G.L., 1963. A moated knoll in the Canary passage. Dtsch. Hydrol. Z., 16: 269.

Heezen, B.C. and Rawson, M., 1977. Visual observations of contemporary current erosion and tectonic deformation of the Cocos Ridge Crest. Mar. Geol., 23: 73—196.

Heezen, B.C., Hollister, C.D. and Ruddiman, W.F., 1966. Shaping of the continental rise by deep geostrophic contour currents. Science, 152: 502—508.

Heezen, B.C. and MacGregor, I. et al., 1973. Initial Reports of the Deep Sea Drilling Project, XX. U.S. Government Printing Office, Washington, D.C., 958 pp.

Hess, G.R. and Normark, W.R., 1976. Holocene sedimentation history of the major fan valleys of Monterey Fan. Mar. Geol., 22: 233—251.

Hesse, R., 1975. Turbidites and non-turbiditic mudstone of Cretaceous flysch sections of the Eastern Alps and other basins. Sedimentology, 22: 387—416.

Hollister, C.D., 1967. Sediment Distribution and Deep Circulation in the Western North Atlantic. Thesis, Columbia University, New York, N.Y., 467 pp.

Hollister, C.D. and Heezen, B.C., 1967. Contour current evidence from abyssal sediments. Trans. Am. Geophys. Union, 48: 142.

Hollister, C.D. and Heezen, B.C., 1972. Geologic effects of ocean bottom currents: western North Atlantic. In: A.L. Gordon (Editor), Studies in Physical Oceanography, 2. Gordon and Breach, New York, N.Y., pp. 37—66.

Hollister, C.D., Ewing, J.I., et al., 1972. Initial Reports of the Deep-Sea Drilling Project, XI. U.S. Government Printing Office, Washington, D.C.

Hollister, C.D., Johnson, D.A. and Lonsdale, P.F., 1974a. Current-controlled abyssal sedimentation: Samoan passage, equatorial west Pacific. J. Geol., 82: 275—300.

Hollister, C.D., Flood, R.D., Johnson, D.A., Lonsdale, P. and Southard, J.B., 1974b. Abyssal furrows and hyperbolic echo traces on the Bahama Outer Ridge. Geology, 2: 395—400.

Hollister, C.D., Gardner, W.D., Lonsdale, P.F. and Spencer, D.W., 1976. New evidence for northward-flowing bottom water along the Hatton sediment drift, eastern North Atlantic. EOS, Trans. Am. Geophys. Union, 57: 261 (abstract).

Horn, D.R., Ewing, M., Horn, B.M. and Delach, M.N., 1971. Turbidites of the Hatteras and Sohm Abyssal Plains, Western North Atlantic. Mar. Geol., 11: 287—323.

Hsü, K.J., 1964. Cross laminations in graded bed sequences. J. Sediment. Petrol., 34: 379—388.

Hubert, J.F., 1964. Textural evidence for the deposition of many western North Atlantic deep sea sands by ocean-bottom currents rather than turbidity currents. J. Geol., 72: 757—785.

Hubert, J.F., 1967. Sedimentology of prealpine flysch sequences, Switzerland. J. Sediment. Petrol., 37, 885—907.

Hughes, T., Denton, C.H. and Grosswald, H.G., 1977. Was there a Late-Würm Arctic Ice Sheet? Nature, 266: 596—602.

Hunkins, K., Thorndike, E.M. and Mathieu, G., 1969. Nepheloid layers and bottom currents in the Arctic Ocean. J. Geophys. Res., 74: 6995—7008.

Isaacs, J.D., Reid, J.L., Schick, G.B. and Schwartzlose, R.A., 1966. Near-bottom currents measured in 4 km depth off the Baja California coast. J. Geophys. Res., 71: 4297—4303.

Jacobi, R.D., Rabinowitz, P.D. and Embley, R.W., 1975. Sediment waves of the Moroccan Continental Rise. Mar. Geol., 19: M61—M67.

Jacobs, M.B. and Ewing, M., 1969. Mineral source and transport in waters of the Gulf of Mexico and Caribbean Sea. Science, 163: 805—809.

Jipa, D.C., 1974. Graded bedding in recent Black Sea Turbidites: a textural approach. In: E.T. Degens and D.A. Ross (Editors), The Black Sea — Geology, Chemistry, and Biology. Am. Assoc. Pet. Geol. Mem., 20: 633 pp.

Johnson, D.A., 1972a. Eastward flowing bottom currents along the Clipperton Fracture Zone. Deep-Sea Res., 19: 253—257.

Johnson, D.A., 1972b. Ocean floor erosion in the equatoral Pacific. Geol. Soc. Am. Bull., 83: 3121—3144.

Johnson, D.A. and Lonsdale, P.F., 1976. Erosion and sedimentation around Mytilus Seamount, New England Continental rise. Deep-Sea Res., 23: 429—440.

Johnson, D.A., McDowell, S.E., Sullivan, L.G. and Biscaye, P.E., 1976. Abyssal hydrography, nephelometry, currents and benthic boundary layer structure in the Vema Channel. J. Geophys. Res., 81: 5771—5786.

Johnson, G.L. and Schneider, E.D., 1969. Depositional ridges in the North Atlantic. Earth Planet. Sci. Lett., 6: 416—422.

Jones, E.J.W., Ewing, M., Ewing, J.I. and Eittreim, S.L., 1970. Influences of Norwegian Sea overflow water on sedimentation in the northern Atlantic and Labrador Sea. J. Gephys. Res., 75: 1655—1680.

Joseph, J., 1967. Current measurements during the International Iceland Faeroe Ridge Expedition, May 30 to June 18, 1960. Rapp. Proc. Verb. Reunions Cons. Perm. Int. Explor. Mer, 157: 157—172.

Keith, B.D. and Friedman, G.M., 1977. A slope—fan—basin plain model, Taconic sequence, New York and Vermont. J. Sediment. Petrol., 47: 1220—1241.

Kelling, G., 1958. Ripple-mark in the Rhinns of Galloway. Trans. Edinb. Geol. Soc., 17: 117—132.

Kelling, G., 1964. The turbidite concept in Britain. In: A.H. Bouma and A. Brouwer (Editors), Turbidites. Elsevier, Amsterdam, pp. 75—92.

Kelling, G. and Stanley, D.J., 1972. Sedimentary evidence of bottom current activity, Strait of Gibraltar region. Mar. Geol., 13: M51—M60.

Kelling, G. and Stanley, D.J., 1976. Sedimentation in canyon, slope and base-of-slope environments. In: D.J. Stanley and D.J.P. Swift (Editors), Marine Sediment Transport and Environmental Management. John Wiley, New York, N.Y., pp. 379—435.

Kennett, J.P. and Watkins, N.D., 1976. Regional deep-sea dynamic processes recorded by late Cenozoic sediments of the southeast Indian Ocean. Bull. Geol. Soc. Am., 87: 321—329.

Killworth, P.D., 1973. A two dimensional model for formation of Antarctic Bottom water. Deep-Sea Res., 20: 941—971.

Klasik, J.A. and Pilkey, O.H., 1975. Processes of sedimentation on the Atlantic continental rise off the southeast United States. Mar. Geol., 19: 69—89.

Klein, G. de V., 1966. Dispersal and petrology of sandstones of Stanley Jackfork boundary, Ouachita fold belt, Arkansas and Oklahoma. Bull. Am. Assoc. Pet. Geol., 50: 308—326.

Klein, G. de V., 1967. Paleocurrent analysis in relation to modern marine sediment dispersal patterns. Bull. Am. Assoc. Pet. Geol., 51: 366—382.

Klein, G. de V., 1975. Resedimented pelagic carbonate and volcaniclastic sediments and sedimentary structures in Leg 30 DSDP cores from the western equatorial Pacific. Geology, 3: 39—42.

Klein, G. de V., 1977. Tidal Circulation model for deposition of clastic sediment in epeiric and mioclinal shelf seas. Sediment. Geol., 18: 1—12.

Knauss, J., 1965. A technique for measuring deep ocean currents close to the bottom with an unattached current meter and some preliminary results. J. Mar. Res., 23: 237—245.

Kolla, V., Moore, D.G. and Curray, J.R., 1976. Recent bottom current activity in the deep western Bay of Bengal. Mar. Geol., 21: 255—270.

Kuenen, Ph.H., 1957. Longitudinal filling of oblong sedimentary basins. Verh. K. Ned. Geol. Mijnb. Gen., 18: 189—195.

Kuenen, Ph.H., 1964. Deep-sea sands and ancient turbidites. In: A.H. Bouma and A. Brouwer (Editors), Turbidites. Elsevier, Amsterdam, pp. 3—33.

Kuenen, Ph.H., 1967. Emplacement of flysch-type sand beds. Sedimentology, 9: 203—243.

Kuenen, P.H. and Migliorini, C.I., 1950. Turbidity currents as a cause of graded bedding. J. Geol., 58: 91—127.

Kuhn, T.S., 1970. The Structures of Scientific Revolutions. University of Chicago Press, Chicago, Ill., 210 pp.

La Fond, E.C., 1951. Processing Oceanographic Data. U.S. Navy Hydrogr. Off. Publ. No. 614.

Laird, M.G., 1972. Sedimentology of the Greenland Group in the Paparoa Range, West Coast South Island. N.Z. J. Geol. Geophys., 15: 372—393.

Lappo, S.S., 1963. Deep currents in the North Atlantic Ocean. Okeanologiya, 3: 803—813 (English translation in Deep-Sea Res., 11: 435—439.)

Laughton, A.S., Berggren, W.A., et al., 1972. Initial Reports of the Deep Sea Drilling Project, 12. U.S. Government Printing Office, Washington, D.C.

Lonsdale, P.F., 1974. Abyssal Geomorphology of a Depositional Environment at the Exit of the Samoan Passage. Thesis, University of California, San Diego, Calif., 106 pp.

Lonsdale, P.F., 1975a. Sediment and tectonic modification of the Samoan archipelagic apron. Bull. Am. Assoc. Pet. Geol., 59: 780—798.

Lonsdale, P.F., 1975b. Detailed abyssal sedimentation studies in the Panama Basin. Cruise Report "Cocotot" Legs 2b and 3. Scripps Inst. Oceanogr., Ref. 75-4.

Lonsdale, P.F. and Hollister, C.D., 1976. Cut-off of an abyssal meander on the Icelandic insular rise. EOS, Trans. Am. Geophys. Union, 57: 269.

Lonsdale, P. and Hollister, C.D., in press. A near-bottom traverse of Rockall Trough: hydrographic and geologic inferences. J. Geophys. Res.

Lonsdale, P.F. and Malfait, B.T., 1974. Abyssal dunes of foraminiferal sand on the Carnegie Ridge. Bull. Geol. Soc. Am., 83: 289—316.

Lonsdale, P. and Spiess, F.N., 1977. Abyssal bedforms explored with a deeply towed instrument package. Mar. Geol., 23: 57—75.

Lonsdale, P.F., Normark, W.R. and Newman, W.A., 1972. Erosion and sedimentation on Horizon Guyot. Bull. Geol. Soc. Am., 83: 289—316.

Lovell, J.P.B., 1969. Tyee formation: a study of proximality in turbidites. J. Sediment. Petrol. 39: 935—953.

Lovell, J.P.B., 1970. The palaeogeographical significance of lateral variations in the ratio of sandstone to shale and other features of the Aberystwyth Grits. Geol. Mag., 107: 147.

Lovell, J.P.B., 1975. Correlation and sedimentology of Tom's Cove Shale, Bude Formation. Proc. Ussher Soc., 3: 264—270.

Lowrie, A. and Heezen, B.C., 1967. Knoll and sediment drift near Hudson Canyon. Science, 157: 1552—1553.

Luyten, J.R., 1977. Scales of motion in the deep Gulf Stream and across the Continental Rise. J. Mar. Res., 35: 49—74.

Markl, R.G., Bryan, G.M. and Ewing, J.I., 1970. Structure of the Blake Bahama Outer Ridge. J. Geophys. Res., 75: 4539—4555.

McCave, I.N. and Swift, S.A., 1976. A physical model for the rate of deposition of fine-grained sediments in the deep sea. Bull. Geol. Soc. Am., 87: 541—546.

Migniot, C., 1968. Etude de propriétés physiques de différents sédiments très fins et de leur comportement sous des actions hydrodynamiques. La Houille Blanche, 7: 591—620.

Miller, M.C., McCave, I.N. and Komar, P.D., 1977. Threshold of sediment motion under unidirectional currents. Sedimentology, 24: 507—528.

Moore, D.G., 1969. Reflection profiling studies of the California continental borderland: structure and Quaternary turbidite basins. Geol. Soc. Am. Spec. Pap., 107: 142 pp.

Mutti, E., 1974. Examples of ancient deep-sea fan deposits from circum-Mediterranean geosynclines. In: R.H. Dott and R.H. Shaver (Editors), Modern and Ancient Geosynclinal Sedimentation. Soc. Econ. Paleontol. Min. Spec. Publ., 19: 91—105.

Mutti, E., 1977. Distinctive thin-bedded turbidite facies and related depositional environments in the Eocene Hecho Group (South-central Pyrenees, Spain). Sedimentology, 24: 107—131.

Needham, H.D., Habib, D. and Heezen, B.C., 1969. Upper Carboniferous palynomorphs as a tracer of red sediment dispersal patterns in the North West Atlantic. J. Geol., 77: 113—120.

Nelson, C.H., 1976. Late Pleistocene and Holocene depositional trends processes and history of Astoria deep sea fan, North East Pacific. Mar. Geol., 20: 129—173.

Nelson, C.H. and Nilsen, T.H., 1974. Depositional trends of modern and ancient deep-sea fans. In: R.H. Dott and R.H. Shaver (Editors), Modern and Ancient Geosynclinal Sedimentation. Soc. Econ. Paleontol. Min. Spec. Publ., 19: 69—91.

Nelson, C.H., Mutti, E. and Ricci Lucchi, F., 1975a. Comparison of proximal and distal thin-bedded turbidites with current-winnowed deep-sea sands. IXme Congr. Int. Sedimentologie, Nice, 1975.

Nelson, C.H., Normark, W.R., Bouma, A.H. and Carlson, P.R., 1975b. Thin-bedded turbidites in modern submarine canyons and fans. Am. Assoc. Pet. Geol. Bull., 69: 702—703.

Nelson, H., Mutti, E. and Ricci Lucchi, F., 1977. Upper Cretaceous resedimented conglomerates at Wheeler Gorge, California: description and field guide: A discussion. J. Sediment. Petrol., 47: 926—928.

Neumann, G., 1968. Ocean Currents. Elsevier, Amsterdam, 352 pp.

Normark, W.R., 1974. Submarine canyons and fan valleys: factors affecting growth patterns of deep-sea fans. In: R.H. Dott and R.H. Shaver (Editors), Modern and Ancient Geosynclinal Sedimentation. Soc. Econ. Paleontol. Min. Spec. Publ., 19: 56—68.

Normark, W.R. and Spiess, F.N., 1976. Erosion on the Line Islands archipelagic apron: effect of small scale topographic relief. Bull. Geol. Soc. Am., 87: 286—296.

Nowroozi, A.A., Ewing, M., Nafe, J.E. and Fleigel, M., 1968. Deep ocean current and its correlation with the ocean tide off the coast of Northern California. J. Geophys. Res., 73: 1921.

Partheniades, E., Cross, R.H. and Ayora, A., 1969. Further results on the deposition of cohesive sediments. Proc. 11th Conf. Coastal Engineering, London, 1968, pp. 723—742;

Picha, F., 1974. Ancient submarine canyons of the Carpathian miogeosyncline. In: R.H. Dott and R.H. Shaver (Editors), Modern and Ancient Geosynclinal Sedimentation. Soc. Econ. Paleontol. Min. Spec. Publ., 19: 126—127.

Pierce, J.W., 1976. Suspended sediment transport at the Shelf break and over the outer margin. In: D.J. Stanley and D.J.P. Swift (Editors), Marine Sediment Transport and Environmental Management. John Wiley, New York, N.Y., pp. 437—458.

Pilkey, O.H. and Field, M.E., 1972. Lower continental rise east of the Middle Atlantic states: predominant dispersal perpendicular to isobaths: discussion. Bull. Geol. Soc. Am., 83: 3537—3538.

Piper, D.J.W., 1973. The sedimentology of Silt Turbidites from the Gulf of Alaska. In: L.D. Kulm, R. von Huene et al., Initial Reports DSDP, 18. U.S. Government Printing Office, Washington, D.C., pp. 847—867.

Piper, D.J.W., 1976. Facies models of fine-grained turbidites. Geol. Soc. Can. Progr. Abstr., 1: 72.

Piper, D.J.W., 1978. Turbidite muds and silts on deep-sea fans and abyssal plains. In: D.J. Stanley and G. Kelling (Editors), Submarine Canyon and Fan Sedimentation. Dowden, Hutchinson and Ross, Stroudsburg, Pa., pp. 163—176.

Piper, D.J.W. and Brisco, C.D., 1975. Deep water continental margin sedimentation. Deep Sea Drilling Project Leg 28. Antarctica. In: D.E. Hayes, L.A. Frakes, et al., Initial Reports DSDP, 28. U.S. Government Printing Office, Washington, D.C., pp. 727—755.

Reid, J.L., 1969. Preliminary results of measurements of deep currents in the Pacific Ocean. Nature, 221: 848.

Reid, J., Stommel, H., Stroup, E.D. and Warren, B.A., 1968. Detection of a deep boundary current in the western South Pacific. Nature, 217: 937.

Roberts, D.G., 1975. Marine geology of the Rockall Plateau and Trough. Philos. Trans. R. Soc., 278A (1285): 447—509.

Roberts, D.G., Hogg, N.G., Bishop, D.G. and Flewellan, C.G., 1974. Sediment distribution around moated seamounts in the Rockall Trough. Deep-Sea Res., 21: 175—184.

Rowe, G.T., 1971. Observations on bottom currents and epibenthic populations in Hatteras Submarine Canyon. Deep-Sea Res., 18: 569—581.

Rowe, G.T. and Menzies, R.J., 1968. Deep bottom currents off the coast of North Carolina. Deep-Sea Res., 15: 711—720.

Rupke, N.A., 1975. Deposition of fine-grained sediments in the abyssal environment of the Algero-Balearic Basin, Western Mediterranean Sea. Sedimentology, 22: 95—109.

Rupke, N.A. and Stanley, D.J., 1974. Distinctive properties of turbiditic and hemipelagic mud layers in the Algero-Balearic Basin, Western Mediterranean Sea. Smithson. Contrib. Earth Sci., 13: 40 pp.

Ryan, W.B.F., Hsü, K.J. et al., 1973a. Initial Reports of the Deep Sea Drilling Project, 13. U.S. Government Printing Office, Washington, D.C. Part I: Site Reports.

Ryan, W.B.F., Hsü, K.J. et al., 1973b. Initial Reports of the Deep Sea Drilling Project, 13. U.S. Government Printing Office, Washington, D.C., 1447 pp.

Schenk, P.E., 1970. Regional variation of the flysch-like Meguma Group (Lower Paleozoic) of Nova Scotia compared to Recent sedimentation off the Scotian Shelf. Geol. Assoc. Can. Spec. Pap., 7: 127—153.

Schneider, E.D., Fox, P.J., Hollister, C.D., Needham, H.D. and Heezen, B.C., 1967. Further evidence of contour currents in the western North Atlantic. Earth Planet. Sci. Lett. 2: 351—359.

Scott, K.M., 1966. Sedimentology and dispersal pattern of a Cretaceous flysch sequence, Patagonian Andes, Southern Chile. Bull. Am. Assoc. Pet. Geol., 50: 72—107.

Scott, K.M., 1967. Intra-bed palaeocurrent variations in a Silurian flysch sequence, Kircudbrightshire, Southern Uplands of Scotland. Scott. J. Geol., 3: 268—281.

Shepard, F.P. and Marshall, N.F., 1973a. Currents along floors of submarine canyons. Bull. Am. Assoc. Pet. Geol., 57: 244—264.

Shepard, F.P. and Marshall, N.F., 1973b. Storm generated current in La Jolla submarine canyon, California. Mar. Geol., 15: M19—M24.

Shepard, F.P., Marshall, N.F. and McLoughlin, P.A., 1974. Currents in submarine canyons. Deep-Sea Res., 21: 691—706.

Shepard, F.P., Marshall, N.F. and McLoughlin, P.A., 1975. Pulsating turbidity currents with relationship to high swell and high tides. Nature, 258: 704—706.

Shepard, F.P., McLoughlin, P.A., Marshall, N.F. and Sullivan, G.G., 1977. Current-meter recordings of low-speed turbidity currents. Geology, 5: 297—301.

Shor, A.N., Lonsdale, P.F., Hollister, C.D. and Spencer, D.W., 1976. Structure and sediment drift morphology in the Charlie Gibbs Transform Fault. EOS, Trans. Am. Geophys. Union, 57: 269 (abstract).

Spiess, F.N. and Mudie, J.D., 1970. Small scale topographic and magnetic features. In: A.E. Maxwell (Editor), The Sea, IV. John Wiley, New York, N.Y., pp. 205—250.

Stanley, D.J., 1969. Sedimentation in slope and base of slope environments, In: D.J. Stanley (Editor), The New Concepts of Continental Margin Sedimentation. A.G.I. Short-Course Lecture Notes.

Stanley, D.J., Sheng, H. and Pedraza, C.P., 1971. Lower continental rise east of Middle Atlantic States: predominant dispersal perpendicular to the isobaths. Bull. Geol. Soc. Am., 82: 1831—1840.

Steele, J.H., Barrett, J.R. and Worthington, L.V., 1962. Deep currents south of Iceland. Deep-Sea Res., 9: 465—474.

Stefansson, U., 1968. Dissolved nutrients, oxygen and water masses in the northern Irminger Sea. Deep-Sea Res., 15: 541—575.

Stokke, P.R., Carson, B. and Baker, E.T., 1977. Comparison of the bottom nepheloid layer and late Holocene deposition on Nitinat Fan: Implications for lutite dispersal and deposition. Bull. Geol. Soc. Am., 88: 1586—1592.

Stommel, H., 1956. On the determination of the depth of no meridional motion. Deep-Sea Res., 3: 273—278.

Stommel, H., 1958. The abyssal circulation. Deep-Sea Res., 5: 80—82.

Stommel, H. and Aarons, A.B., 1960. On the abyssal circulation of the world ocean II. Deep-Sea Res., 6: 217—233.

Stow, D.A.V., 1976. Deep water sands and silts on the Nova Scotian continental margin. Marit. Sed., 12: 81—90.

Stow, D.A.V., 1977a. Late Quaternary Stratigraphy and Sedimentation on the Nova Scotian Outer Continental Margin. Thesis, Dalhousie University, Halifax, N.S., 361 pp.

Stow, D.A.V., 1977b. The turbidite—contourite controversy: distinguishing between fine-grained turbidites and contourites on the Nova Scotian Outer Continental Margin. Soc. Econ. Paleontol. Min. — Am. Assoc. Pet. Geol. Mem., Annu. Gen. Meet., Washington, D.C., June 1977.

Stow, D.A.V. and Bowen, A.J., 1978. Origin of lamination in deep sea, fine-grained sediments. Nature, 274: 324—328.

Sverdrup, H.U., Johnson, M.W. and Fleming, R.H., 1942. The Oceans: Their Physics, Chemistry and General Biology. Prentice Hall, New York, N.Y., 1087 pp.

Swallow, J.C. and Worthington, L.V., 1961. An observation of a deep counter-current in the Western North Atlantic. Deep-Sea Res., 8: 1—19.

Swallow, J.C. and Worthington, L.V., 1969. Deep currents in the Labrador Sea, Deep-Sea Res., 16: 77—84.

Swift, D.J.P., 1976. Continental Shelf Sedimentation. In: D.J. Stanley and D.J.P. Swift (Editors), Marine Sediment Transport and Environmental Management. John Wiley, New York, N.Y., pp. 311—350.

Taylor, D.T., Stanley, D.J., Simkin, T. and Jahn, W., 1975. Gillis seamount: detailed bathymetry and modification by bottom currents. Mar. Geol., 19: 139—157.

Tucholke, D.E., 1973. The History of Sedimentation and Abyssal Circulation on the Greater Antilles Outer Ridge. Thesis, Cambridge — Woods Hole, MIT — WHOI.

Tucholke, B.E., 1974. Sediment distribution and deposition by the Western Boundary Undercurrent: The Greater Antilles Outer Ridge. J. Geol., 83: 177—207.

Tucholke, B.E. and Ewing, J.I., 1974. Bathymetry and sediment geometry of the Greater Antilles Outer Ridge and Vicinity. Bull. Geol. Soc. Am., 85: 1789—1802.

Tucholke, B.E., Wright, W.R. and Hollister, C.D., 1973. Abyssal circulation over the Greater Antilles Outer Ridge. Deep-Sea Res., 20: 973—995.

Tucholke, B.E., Hollister, C.D., Weaver, F.M. and Vennum, W.R., 1976. Continental Rise and abyssal plain sedimentation in the southeast Pacific basin — leg 35, Deep Sea Drilling Project. In: C.D. Hollister, C.D. Craddock, et al., Initial Reports DSDP, 35. U.S. Government Printing Office, Washington, D.C., pp. 359—400.

Unrug, R., 1977. Ancient deep-sea traction current deposits in the Lgota Beds (Albian) of the Carpathian flysch. Ann. Soc. Geol. Pol., 47: 355—370.

Volkmann, C., 1962. Deep current observations in the Western North Atlantic. Deep-Sea Res., 9: 493—500.

Walker, R.G., 1970. Review of the geometry and facies organization of turbidites and turbidite bearing basins. In: J. Lajoie (Editor), Flysch Sedimentology in North America. Geol. Assoc. Can. Spec. Pap., 7: 219—251.

Walker, R.G., 1973. Mopping up the turbidite mess. In: R.N. Ginsburg (Editor), Evolving Concepts in Sedimentology, Johns Hopkins University Press, Baltimore, Md., pp. 1—37.

Walker, R.G., 1977. Upper Cretaceous resedimented conglomerate at Wheeler Gorge, California: description and field guide: reply. J. Sediment. Petrol., 47: 928—930.

Warren, B.A., 1970. Evidence for a deep western boundary current in the South Indian Ocean. Nature, Phys. Sci., 229: 18—19.

Warren, B.A. and Voorhis, A.D., 1970. Velocity measurements in the deep western boundary current of the South Pacific. Nature, 228—849.

Wezel, F.C., 1969. Prossimalita, distalita e analisi dei bacini dei flysch: un punto di vista attualistico. Mem. Soc. Nat. Napoli: Suppl. Boll., 78: 1—12.

Wezel, F.C., 1970. Numidian flysch: an Oligocene — early Miocene continental rise deposit off the African Platform. Nature, 228: 275—276.

Wezel, F.C., 1974. Flysch successions and the tectonic evolution of Sicily during the Oligocene and early Miocene. In: C. Squyres (Editor), Geology of Italy. Petrol. Explor. Soc. Libya, Tripoli, pp. 1—23.

Whitaker, J.H.McD., 1974. Ancient submarine canyons and fan valleys. In: R.H. Dott and R.H. Shaver (Editors), Modern and Ancient Geosynclinal Sedimentation. Soc. Econ. Paleontol. Min. Spec. Publ., 19: 106—125.

White S.J., 1970. Plane bed thresholds of fine-grained sediments. Nature, 228: 152—153.

Wood, A. and Smith, A.J., 1959. The sedimentation and sedimentary history of the Aberystwyth Grits. Geol. Soc. Lond. Q. J., 94: 163—190.

Worthington, L.V., 1970. The Norwegian Sea as a Mediterranean Basin. Deep-Sea Res., 17: 77—84.

Worthington, L.V. and Volkman, G.H., 1965. The volume transport of the Norwegian Sea overflow water in the North Atlantic. Deep-Sea Res., 12: 667—676.

Wust, G., 1933. Das Bodenwasser und der Gliederung der atlantischen Tiefsee. Wiss. Ergeb. Dtsch. Atlant. Exped. Meteor 1925—1927, 6(1): 1—107.

Wust, G., 1935. Schichtung und Zirkulation des atlantischen Oceans. Wiss. Ergeb. Dtsch. Atlant. Exped. Meteor 1925—1927, 6(1) (2): 108—288.

Wust, G., 1936. Schichtung und Zirkulation des atlantischen Oceans: Schnitte und Karten von Temperatur, Salzgehalt und Diclite. Wiss. Ergeb. Dtsch. Atlant. Exped. Meteor 1925—1927, 6: Atlas, Teil A, B (Stratosphäre).

Wust, G., 1950. Blockdiagramme der atlantischen Zirkulation auf Grund der 'Meteor' Ergebnisse. Kieler Meeresforsch., 7: 24—34.

Wust, G., 1955. Stromgeschwindingkeiten im tiefen und Bodenwasser des atlantischen Oceans auf Grund dynamischer Berechnung der Meteorprofile des Deutschen Atlantischen Expedition. Deep-Sea Res. (Suppl.), 3: 373—397.

Wust, G., 1957. Stromgeschwindigkeiten and Strommengen in den Tiefen des atlantischen Ozeans. 'Meteor' Werk, 6(2): 261—420.

Wust, G., 1961. On the vertical circulation in the Mediterranean Sea. J. Geophys. Res., 66: 3261—3271.

Wust, G., 1963. On the stratification and circulation in the cold water sphere of the Antillean—Caribbean basins. Deep-Sea Res., 10: 165—167.

Young, R.A. and Southard, J.B., 1976. Erosion of fine-grained marine sediments sea-floor and laboratory experiments. Address to NOAA Atlantic Oceanographic and Meteorological Lab., Miami, Fla.

Ziegler, W.L., 1977. Summing-up on seismically active margins. In: M.G. Audley-Charles, Conference Report, Structural Style of Continental Margins: a Discussion. J. Geol. Soc., 134: 84—86.

Zimmerman, H.B., 1971. Bottom currents on the New England Continental Rise. J. Geophys. Res., 76: 5865—5876.

Zimmerman, H.B., 1972. Sediments of the New England Continental Rise. Bull. Geol. Soc. Am., 83: 3709—3724.

(Received June 1, 1978; revised version accepted November 14, 1978)