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North Atlantic contourites: an overview

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SUMMARY: We present a brief overview of known bottom circulation and Tertiary to Recent sediment drifts in the North Atlantic Ocean, and outline the distinctive features of contourite sediments recovered from these drifts. There is a gradation of structural and textural characteristics between the finer-grained clayey and muddy contourites and the coarser-grained silty and fine-sandy contourites. There is also a gradation between the three compositional types identified: biogenic, mixed biogenic/terrigenous, and volcanogenic. Other features such as microfabric, or facies sequences are less well documented but potentially diagnostic.

Bottom circulation

Our knowledge of deep-water circulation in the North Atlantic is perhaps better than for any other large ocean basin (e.g. Berggren & Hollister 1974, 1977; Shor & Poore 1978; Schnitker 1980). At the present day, several different water masses are involved in this circulation. The deepest, coldest water mass is the Antarctic Bottom Water (AABW), formed in the Weddell and Ross Seas bordering Antarctica and flowing north into both the western and eastern North Atlantic basins. Dense, cold water is similarly formed in the Greenland and Norwegian Seas and flows south through the Denmark Strait, the Faeroes Bank Channel and across several sills on the Iceland-Faeroes Ridge. This Norwegian Sea Overflow Water (NSOW) mixes partially with Labrador Sea Water (LSW) formed south of Greenland and with AABW to form the North Atlantic Deep Water (NADW). Warmer saline Mediterranean Sea Water (MSW) flows out of the Straits of Gibraltar and spreads out at intermediate levels to both north and south. The possibility that MSW contributes to a relatively strong Eastern Boundary Undercurrent (EBUC) in the NE Atlantic as far north as the Rockall Trough has been noted by several authors (Swallow *et al.* 1977; Ellett *et al.* 1979).

Bottom currents associated with the movement of these water masses have now been measured in many parts of the ocean (see Table 1 in Stow & Lovell 1979) mainly with short-duration current meters, and the complex circulation shown in Fig. 1 has been demonstrated. Velocities across the Greenland-Iceland-Faeroes Ridge are up to 30 cm/s. In the Hatton Rockall and Rockall Basins velocities average 5–15 cm/s, being consistently higher (20–30 cm/s) in the core of the current and lower (0–10 cm/s) at the margins and over depositional ridges. Low velocity eddies spill over the ridge crests and flow perpendicular to the contours. A cyclonic loop of NADW in the Rockall Basin results in a narrow (10–20 km) current of up to 20 cm/s flowing northwards along the eastern margin of the Basin. Measurements over 9 months show that the NSOW flows predominantly westwards through the Charlie-Gibbs Fracture Zone with mean seasonal velocities of 0–8 cm/s and maximum of 20 cm/s. Similar velocities have been recorded from an anticyclonic loop of NSOW and LSW in the Labrador Sea.

Numerous measurements in the western North Atlantic have shown persistent westerly and southwesterly currents of 5–20 cm/s associated with the Western Boundary Undercurrent (WBUC) (e.g. Shor *et al.* this volume). Over an 8 month period on the continental rise south of Cape Cod, Luyten (1977) demonstrated a mean westward flow of 5 cm/s and velocity pulses of up to 40 cm/s to both east and west. Both long-term and short-term measurements have confirmed bottom velocities beneath the Gulf Stream of 5–15 cm/s at depths of 3600–5000 m, with current eddies of up to 30 cm/s. Generally sluggish currents have been reported from the east central North Atlantic. However, bottom current velocities associated with the MSW are up to 300 cm/s in the Straits of Gibraltar and from 10–80 cm/s along various parts of the south Iberian margin in the Gulf of Cadiz (e.g. Faugères *et al.* 1984; Gonthier *et al.* this volume).

Although the movement of water masses can be generalized in terms of a bottom current system and short-duration current, measurements have yielded the sorts of values outlined above. It is important to note the great variability in time and space of such currents as well as the overall complexities of the circulation pattern. The currents vary from a few kilometres to tens of kilometres in width and flow at different levels within the water column. They flow downslope as well as along-slope, and large competent eddies peel off to move at right angles to the main flow. Insufficient measurements have been made to

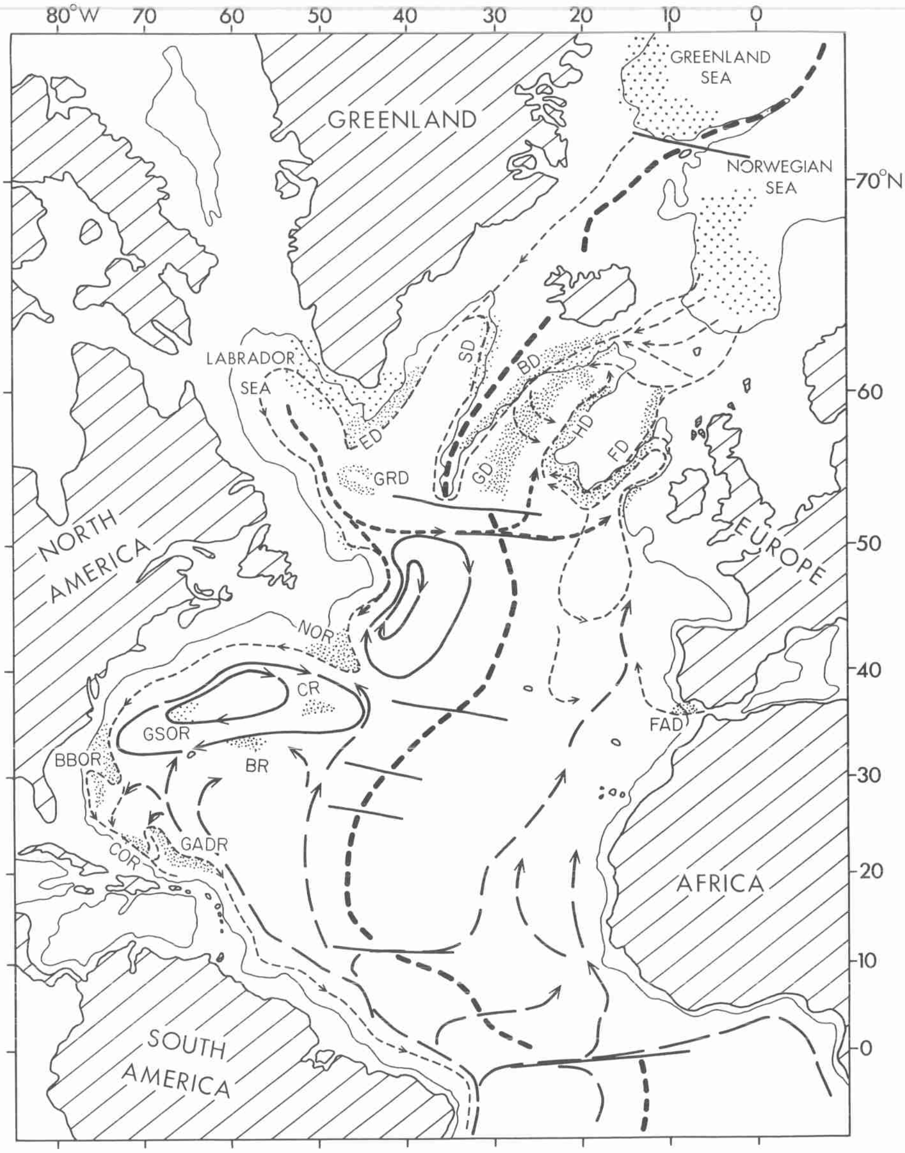


FIG. 1. North Atlantic present-day deep-water circulation (arrows, see text) and the major sediment drifts (close stipple). FAD = Faro Drift, FD = Feni Drift, HD = Hatton Drift, GD = Gadar Drift, BD = Bjorn Drift, SD = Snorri Drift, ED = Eirik Drift, GRD = Gloria Drift, NOR = Newfoundland Outer Ridge, CR = Corner Rise, BR = Bermuda Rise, GSOR = Gulf Stream Outer Ridge, BBOR = Blake Bahama Outer Ridge, GAOR = Greater Antilles Outer Ridge, COR = Caicos Outer Ridge. Areas of bottom water formation shown by wide stipple.

determine any characteristic periodicity in flow velocity, but both seasonal (Shor *et al.* 1980) and tidal (McCave *et al.* 1980) fluctuations have been noted. Velocities decrease from the core to the margin of the current, and reverse flows are commonly measured. It appears that a variable period and variable diameter eddy-like advance is more typical of deep bottom currents than simple uniform unidirectional flow.

Sediment drifts

We also show in Fig. 1 the sediment drifts in the North Atlantic that owe their origin largely to the system of bottom currents that has been developing since the early Tertiary. Most of these drifts have been at least sparsely sampled with piston and gravity cores or Deep Sea Drilling Project drill cores. We summarize below brief descriptions of the sediments recovered, together with the supporting evidence that allows their interpretation as contourites. In some of these examples there are intervals of interbedded slumps, debrites and turbidites. This list is based on that compiled by Stow (1982) with certain recent additions.

Feni Drift (Pujol *et al.* 1974; Faugères *et al.* 1979, 1981; Dingle *et al.* 1981)

Sediments: calcareous silts, clays and oozes; gradational contacts between beds, homogeneous; fine-grained; mixed biogenic and terrigenous; sedimentation rate 6–12 cm/1000 yrs.
Other evidence: inferred bottom currents, drift morphology, sediment waves, seismic characteristics.

Hatton Drift (Laughton *et al.* 1972; Shor & Poore 1978; Roberts & Montadert 1979; Montadert *et al.* 1979; McCave *et al.* 1980)

Sediments: calcareous muds, oozes and chalk, diatomaceous chalk; mainly homogeneous and bioturbated, also wavy and contorted lamination (paper-thin lamination and other microstructures in diatomaceous chalk?); fine-grained with foram sand fraction; mixed biogenic and terrigenous; sedimentation rate 2–5 cm/1000 yrs. One sandy contourite identified, with 35–70% foram sand.
Other evidence: measured bottom currents and nepheloid-layer, drift and small-scale morphology, seismic characteristics, hiatuses.

Gardar Drift (Shor 1980: Faugères *et al.* 1979; McCave *et al.* 1980)

Sediments: calcareous muds; homogeneous; mixed biogenic and terrigenous; sedimentation rates 25–40 cm/1000 yrs. Sandy contourites identified, muddy sands 1–10 cm thick; bioturbated and burrowed, no primary structures; fine sand-sized, poorly sorted, positively skewed; mixed biogenic and terrigenous, broken and iron-stained foram tests; sedimentation rate 2 cm/1000 yrs.
Other evidence: measured bottom currents and nepheloid-layer, drift and small-scale morphology, seismic characteristics, hiatuses.

Bjorn Drift (Laughton *et al.* 1972; McCave *et al.* 1980)

Sediments: muds and calcareous muds; homogeneous, bioturbated, rare thin laminae; fine-grained; biogenic and terrigenous, foram sand fraction; sedimentation rate 12 cm/1000 yrs.
Other evidence: inferred bottom currents, drift morphology, seismic characteristics.

West Reykjames Ridge (Luydendyk *et al.* 1978; Shor & Poore 1978)

Sediments: calcareous ooze and chalk, siliceous chalk; homogeneous, bioturbated, rare thin irregular coarse laminae; dominantly biogenic, some terrigenous.
Other evidence: inferred bottom currents, drift morphology, seismic characteristics.

Eirik Drift (Chough 1978; Latouche & Parra 1979; Chough & Hesse, in press)

Sediments: calcareous muds; intensely bioturbated and mottled, rare wavy parallel lamination, rare laminated coarse layers; fine-grained, poorly-sorted; biogenic and terrigenous.
Other evidence: measured bottom currents, drift morphology, seismic characteristics.

Gloria Drift (Laughton *et al.* 1972)

Sediments: calcareous muds; homogeneous, bioturbated; fine-grained; biogenic and terrigenous.
Other evidence: measured bottom currents, drift morphology, seismic characteristics.

Newfoundland Ridge (Auzende *et al.* 1970; Pastouret *et al.* 1975; Latouche & Parra 1979)

Sediments: calcareous mud; mainly homogeneous, some more sandy and silty intervals; fine-grained; biogenic and terrigenous.
Other evidence: measured bottom currents and nepheloid-layer, drift morphology, seismic characteristics.

Bermuda Rise and Corner Rise (Peterson & Edgar 1968; McGregor *et al.* 1973; Silva *et al.* 1976; Laine & Hollister 1981)

Sediments: calcareous muds; homogeneous and bioturbated; fine-grained with coarse biogenic debris; biogenic and terrigenous.
Other evidence: measured bottom currents and nepheloid-layer, non-uniform drift morphology.

Blake-Bahama Outer Ridge (Heezen *et al.* 1966; Hollister *et al.* 1972; Klasik & Pilkey 1975; Flood 1981; Flood & Hollister 1980; Gradstein *et al.* 1981)

Sediments: calcareous clays and muds and marls; homogeneous, bioturbated, mottled, rare thin ungraded coarse layers, no other primary structures; mainly fine-grained, some with up to 20% foram sand, moderately poorly sorted; biogenic and terrigenous, carbonaceous in parts, cyclic vertical variations in composition in parts, alongslope compositional variation in parts.
Other evidence: measured bottom currents and nepheloid-layer, large-scale drift and wide range small-scale morphological features, seismic characteristics, hiatuses.

Greater Antilles Outer Ridge (Bader *et al.* 1970; Tucholke 1973, 1975; Tucholke & Ewing 1974)

Sediments: calcareous muds and silty clays; homogeneous, mottled, rare concentrations of biogenic material in irregular layers; fine-grained, minor biogenic sand; biogenic and terrigenous, cyclic variations in carbonate content, carbonaceous in parts.
Other evidence: measured bottom currents and nepheloid-layer, drift and small-scale morphology, seismic characteristics.

Gilliss Seamount (Taylor *et al.* 1975)

Sediments: calcareous muds and marls; homogeneous, structureless; fine-grained with foram sand fraction; biogenic and terrigenous, numerous broken foram tests; sedimentation rate 1 cm/1000 yrs.
Other evidence: inferred bottom currents, drift morphology on flanks of seamount, seismic characteristics.

Great Meteor Seamount (Von Stackelberg *et al.* 1979)

Sediments: calcareous oozes; bioturbated, rare lamination; fine-grained with nannofossil silt and foram sands; mainly biogenic, minor terrigenous.
Other evidence: inferred bottom currents, drift morphology on flanks of seamount.

Gibbs Fracture Zone (Faugères *et al.* 1979; Shor *et al.* 1980)

Sediments: foram sands.
Other evidence: measured bottom currents, drift and erosional morphology.

Faro Drift (Mougenot & Vanney 1982; Faugères *et al.* 1984; Gonthier *et al.* this volume).

Sediments: calcareous muds, silty muds, silts and very fine sands; homogeneous, mottled, and remnants of primary structures; mostly intensely bioturbated; fine clay to fine sand-size, poor to moderately sorted; mixed planktonic/benthonic biogenic and terrigenous composition; regular horizontal variations and irregular vertical 'sequence' of facies noted.
Other evidence: measured bottom currents and nepheloid-layer, drift morphology, bottom photographs of current-induced structures, seismic characteristics.

Continental rise contourites

Along much of the western North Atlantic continental margin, as well as along parts of the eastern margin, it appears that contourites are closely interbedded with resedimented and hemipelagic facies on the continental rise. The contourites described by Pastouret *et al.* (1978), Stow (1979) and Stanley *et al.* (1981) from these settings are closely comparable with those of the sediment drifts outlined above. However, other authors have interpreted a facies comprising silt and fine-sand laminae and thin cross-laminated beds interlayered with mud as being of contourite origin (e.g. Heezen *et al.* 1966; Hollister & Heezen 1972; Bouma & Hollister 1973; Barrusseau & Vanney 1978).

The distinction of facies types on the continental rise is still a matter of some controversy and is the subject of detailed study in an area of the Nova Scotian continental rise (HEBBLE study area, Shor *et al.*, this volume). Until this problem is resolved we base our sedimentary characteristics of contourites on the less equivocal sediment drift examples.

Sedimentary characteristics

The following is a synthesis of the sedimentary characteristics of contourites based on numerous descriptions of sediment drift samples (references as for individual drifts), and on previous syntheses by Stow & Lovell (1979), Lovell & Stow (1981) and Stow (1982). It does not apply to the gravel-lag contourites of narrow passages and straits which have only rarely been sampled.

Contourite facies (Fig. 2)

Muddy contourites (silt and clay grade), sandy contourites (mainly fine sand grade) and gravel-

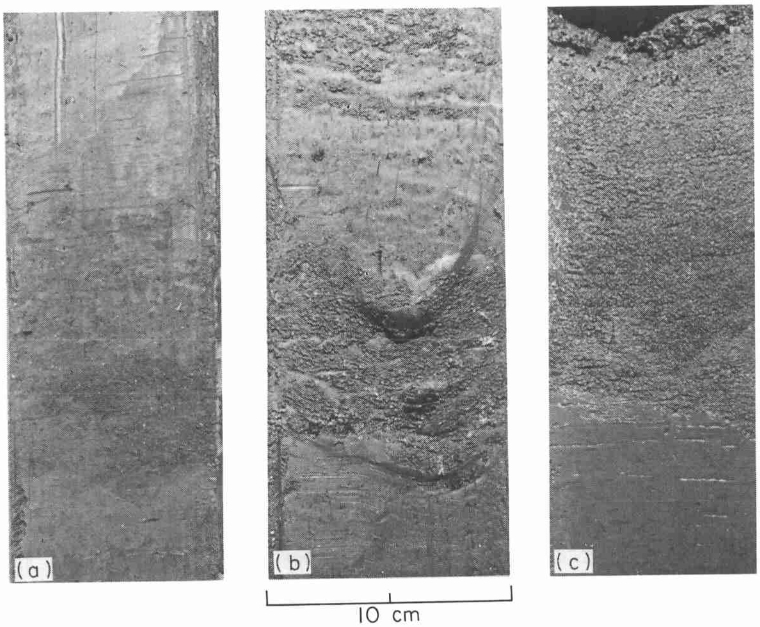


FIG. 2. Photographs of typical contourite facies: (a) muddy contourite, (b) mottled silty-muddy contourite, (c) sandy contourite (lower part). All from Faro Drift, Gulf of Cadiz. Core width approximately 10 cm.

lag contourites (coarse sand and gravel grade) can be distinguished. These form a continuum from purely depositional fine-grained facies to purely erosional coarse lag deposits. Other facies divisions that have been used are mottled silts and muds and silty contourites.

Bedding style and thickness (Figs 2 & 3)

Muddy contourites commonly occur in thick monotonous sections (from a few centimetres to tens of metres) with poor or absent bedding. Where silty or sandy contourites occur, they form thin irregular distinct to gradational layers (commonly <3 cm thick), or thicker often distinct beds (commonly 10–30 cm).

Facies 'sequences' (Fig. 3).

A characteristic succession of muddy, silty and fine sandy facies in positive and negative gradational sequences has been observed. These sequences are highly variable in thickness (<10 cm to >100 cm) and often incomplete in the range of facies and structures present. A typical coupled negative-positive sequences is shown in Fig. 3 (from Gonthier *et al.*, this volume).

Primary sedimentary structures (Figs 2 & 3)

Irregular coarser (often shelly) concentrations, silty lenses and laminae occur in all facies types. Wavy or wispy lamination is commonly noted in parts of the muddy and silty-mud facies; regular horizontal lamination is rare. Silt and fine-sand facies are commonly massive (bioturbated), or more rarely with internal horizontal and cross-lamination. Layer contacts between facies can be entirely gradational, sharp and flat, irregular or erosive. Both tops and bottom of layers show these contact types with equal regularity; the same contact can vary in nature across the width of a core.

Bioturbation (Figs 2 & 3)

One of the most characteristic features of contourites is their extensive bioturbation throughout. This bioturbation was clearly a continuous process, in many cases with several superimposed episodes, that has modified or destroyed much of the primary sedimentary structure, partially or completely altered the nature of the contacts, and is probably responsible in large part for the melange of silt, sand and mud that is commonly observed. Bioturbational mottling occurs at a μm, mm and cm scale together with iron sulphide mottles and filaments (mycelia). Distinct burrow types are also recognized, including *Chondrites, Planolites, Scolicia, Teichichnus* and *Zoophycos*. There appears to be a relationship between burrow and mottle size and type and the grain-size of the sediment (Faugères *et al.* 1984).

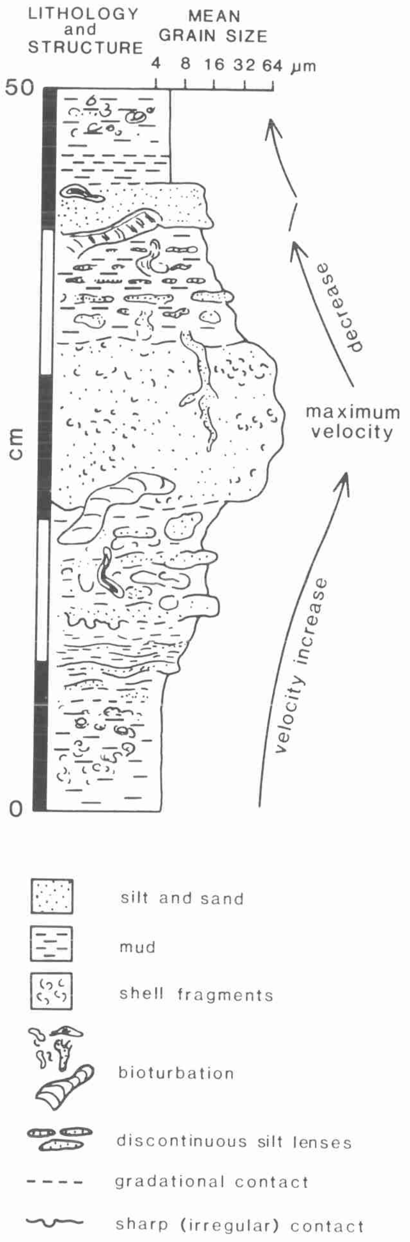


FIG. 3. Typical vertical succession or 'sequence' of contourite facies over 50 cm of section (from Faugéres *et al.*, 1984, Faro Drift). Muddy, mottled silt and mud, and silty/free sandy contourite facies shown. Note variations in grain-size, sedimentary and bioturbational structures through the section.

Texture (Fig. 4)

In nearly all the samples studied to date there is a spectrum of grain-sizes from fine silt and clay grade (mean 8 µm) to coarse silt/fine sand-size (mean 40–70 µm). They are mostly poorly sorted; some silts and fine sands are moderately well sorted. The shape of the cumulative frequency grain-size curves (following the terminology of Rivière 1977) are commonly parabolic-hyperbolic (coarse and fine tails) for the silts and sands, more or less hyperbolic (fine tail) for mixed silty-muddy facies, and close to logarithmic (uniform size distribution) for the finer muddy contourites. Progressive increase or decrease in grain-size (i.e. both positive and negative grading) is common in all facies on a small-scale, over a few centimetres, as well as over 50–100 cm of section.

Composition (Fig. 5)

Composition depends very much on the material available to the bottom current for transport and deposition. In the North Atlantic contourite drifts, there appear to be three end-member compositions: biogenic, terrigenous and volcanogenic. The pure end-member types are relatively rare, although pure foraminiferal sands and volcanogenic silty muds have both been described. Most commonly, there is a mixture of benthonic and planktonic biogenic tests with terrigenous and/or volcanogenic material. Part of the material may be far travelled (over 1000 km) and part may be derived locally, either *in situ* benthonic or overlying planktonic organisms. Current transport and long residence times on or near the bottom, causes fragmentation of biogenic tests and iron staining of grains. Organic carbon contents are commonly low (about 0.5%) Diagenetic minerals, especially iron sulphides and clays, are commonly present in small amounts.

Fabric

There have been few systematic fabric studies to date. Preliminary results suggest that elongate silt or fine sand grains and the anisotropy of magnetic susceptibility both probably parallel the bottom current direction. However, it is not clear what overall orientation pattern is attained by grains deposited from a bottom current that shows large eddies and reversals of direction. Limited scanning electron microscope studies indicate that the contourite mud fabric may be characterized by small particle clusters and individual clay plates relatively well aligned, parallel to bedding. How-

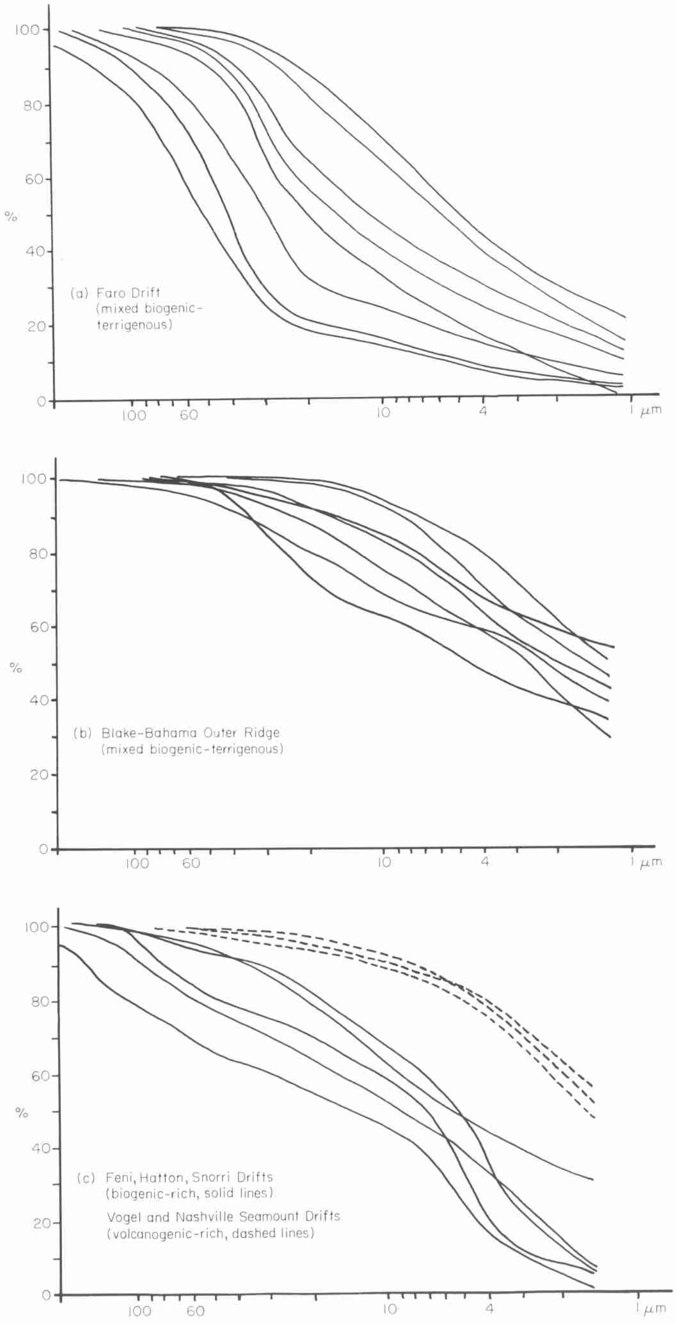


FIG. 4. Cumulative frequency grain-size distribution curves for North Atlantic contourites; semi-logarithmic plots. Examples from: (a) Faro Drift, (b) Blake-Bahama Outer Ridge and (c) NE Atlantic Drifts and Seamounts. (sources: Gonthier *et al.*, this volume; Stow & Holbrook, unpublished data; Chough & Hesse, in press).

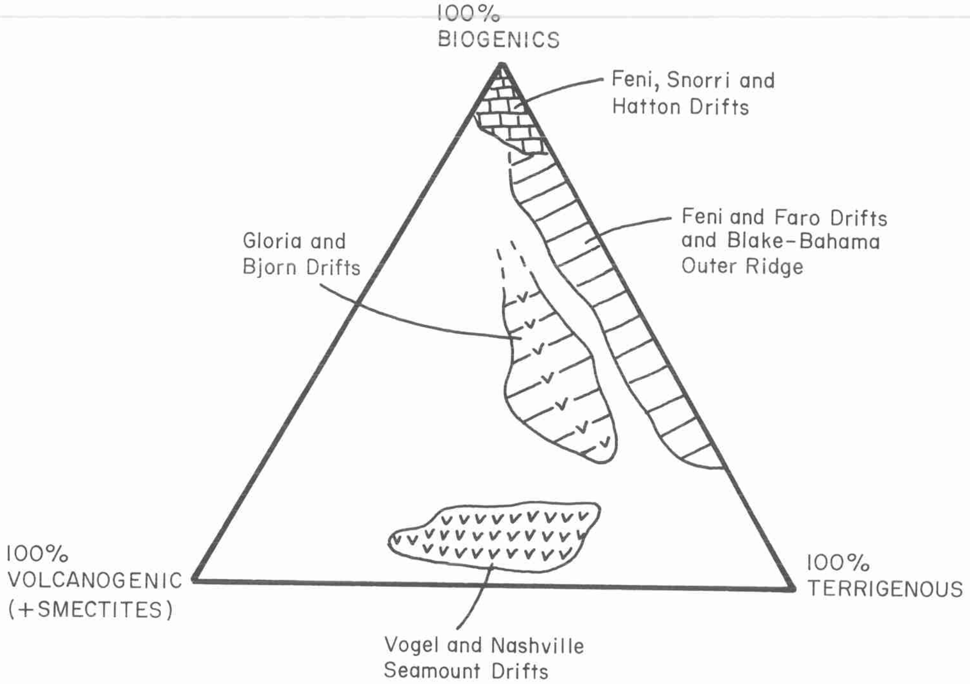


FIG. 5. Composition of North Atlantic contourites. Generalized triangular plot of three main components: biogenic debris, terrigenous material and volcanogenic material (including smectite clays). Based on smear slide estimates, and sand-fraction grain mounts and X-ray diffraction data (Stow & Holbrook, unpublished data).

ever, this may depend to some extent on the pre-flocculated nature of suspended materials introduced to the bottom current from different sources. Both silt and mud fabrics will clearly be disturbed by subsequent bioturbation.

Sedimentation rate

The rates of accumulation of many North Atlantic contourite drifts have been determined from either carbon 14 or micropalaeontological dating of cored sections (Davies & Laughton 1972; Hollister *et al.* 1972; Klasik & Pilkey 1975; Sheridan, Gradstein *et al.* 1981). These rates, mainly for Pliocene to Recent sections, mainly lie between about 5 cm and 10 cm/1000 yrs, ranging from as little as 1 cm/1000 yrs to around 15 cm/1000 yrs. Similar values are obtained from estimates of seismic thickness and stratigraphic age for certain drifts, and for contourites of the continental rise (e.g. Stow & Lovell 1979).

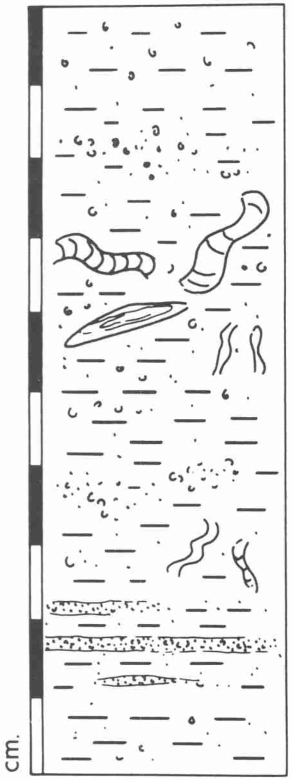
Discussion

Processes

Bottom currents have an important effect on the nature and distribution of sediments in the North Atlantic Ocean at the present day. Bottom circulation is complex, involving several different water masses, large areas of the ocean where flow is negligible, and other areas where flow velocity can reach over 100 cm/s for short periods of time. Long-term current measurements show that bottom currents vary greatly in time and space, having tidal, seasonal and irregular periodicities, current reversals and an eddy-like flow advance.

Many bottom currents are capable of eroding, transporting and depositing fine-grained sediments (up to about fine or medium sand-size), of reworking medium and coarse-grained sands, and of winnowing finer material away from coarser-grained sandy and gravelly sediments. Bottom currents transport fine suspended material (average size about 12 μm) in thin to thick (110 m to over 1500 m?), very low concentration (0.01 to 0.3 mg/l), bottom nepheloid-layers, in some cases transporting the finest material over thousands of kilometres. Suspended sediment enters the nepheloid-layer from bottom current erosion, from sediment resuspension due to burrowing organisms, internal tides, etc. from the fine tails of turbidity currents, and from the vertical settling of hemipelagic and pelagic material through the water column. A relatively weak bottom current will only slightly effect this material during its

MUDDY CONTOURITES: CHARACTERISTICS



Structure:

HOMOGENEOUS
BEDDING POOR OR ABSENT
IRREGULAR WINNOWED CONCENTRATIONS
RARE PRIMARY SILT LAMINAE
BIOTURBATED AND BURROWED

Texture:

DOMINANTLY SILTY-MUD
0-15% SAND-SIZED
POORLY-SORTED

Composition:

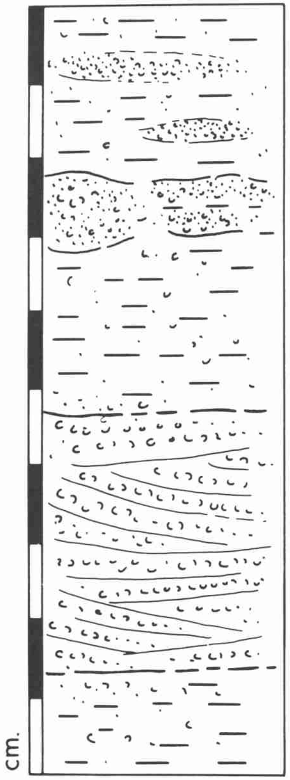
COMBINATION OF BIOGENIC AND
TERRIGENOUS (ie. HEMIPELAGIC)
PART MAY BE FAR-TRAVELLED
ORGANIC CARBON (av. 0.3-1.0%)
CARBONATE (COMMONLY HIGH)
ABSENCE OF SHALLOW-WATER BIOGENICS

Fabric:

MAGNETIC ANISOTROPIC FABRIC MAY
PARALLEL BOTTOM CURRENT
SMALL CLAY-PARTICLE CLUSTERS
(?) WITH PREFERRED ORIENTATION

FIG. 6. Muddy contourites: sedimentary characteristics (after Stow 1982).

SANDY CONTOURITES: CHARACTERISTICS



Structure:

THIN IRREGULAR LAYERS (LAG
CONCENTRATIONS)
MORE RARELY, HORIZONTAL AND
CROSS-LAMINATION PRESERVED
COMMONLY BIOTURBATED

Texture:

SILT-SAND SIZE, RARELY GRAVEL LAG
POORLY-SORTED, MUDDY OR
WELL-SORTED, CLEAN
±SLIGHT NEGATIVE SKEWNESS

Composition:

CONCENTRATION OF COARSE FRACTION
AT SEDIMENT SURFACE
COMMONLY LOCAL ORIGIN
BIOGENIC+TERRIGENOUS SANDS MIXED
IRON-STAINED+BROKEN BIOGENIC DEBRIS

Fabric:

GRAIN ORIENTATION MAY PARALLEL
BOTTOM CURRENT DIRECTION
ALSO DISTURBED-RANDOM ORIENTATIONS
DUE TO BIOTURBATION+REWORKING

FIG. 7. Sandy contourites: sedimentary characteristics (after Stow 1982).

passage to the sea floor, and so in many cases the depositional process must be considered intermediate between bottom current and pelagic, hemipelagic or turbiditic, depending on the main mode of sediment supply. Stronger bottom currents will have a more marked effect on the sediment during its deposition.

Facies

Given the complexity of bottom current flow and the common interaction of several different depositional processes in the deep sea, it is hardly surprising that there is a gradation of contourite facies as well as gradations between contourite and pelagic, hemipelagic or turbidite facies.

Two main contourite facies can be identified as resulting from *deposition* by bottom currents: muddy contourites and sandy contourites (Figs 6 & 7). *Muddy contourites* are fine-grained, mainly homogeneous or structureless and thoroughly bioturbated, more rarely having irregular layering, lamination and lensing. They range from finer-grained homogeneous muds to siltier mottled silts and muds. Their composition varies with the primary source material, but is most commonly mixed biogenic and terrigenous. They most closely resemble hemipelagites. *Sandy contourites* occur as thin irregular layers (<1 to 5 cm) or thicker beds (5–25 cm), that are either structureless and thoroughly bioturbated or with some primary horizontal and cross-lamination preserved. They can show both negative and positive grading, or both, and have sharp or gradational bed contacts. Grain-size is commonly fine sand, more rarely medium sand, with poor to moderate sorting. In many cases the mean grain-size is the coarse silt grade and the facies may be more accurately termed 'silty to fine sandy' contourites. The composition is variable, commonly mixed terrigenous and biogenic. The facies may sometimes be confused with fine-grained turbidites. Muddy and sandy contourites commonly occur together in sediment drifts in irregular vertical 'sequences'.

The effects of *winnowing* and *reworking* by bottom currents can result in contourite facies with rather different characteristics. Thin, irregular, poorly-sorted, structureless, mixed-composition, iron-manganese coated, coarse-sandy and *gravel-lag contourites* are formed by the winnowing and removal of all fines from a coarse-grained sediment by powerful bottom currents. The more or less *in situ* reworking of sandy turbidites can result in a bottom current modified turbidite sand. These are believed to be common on continental slopes and rises.

Ancient contourites

We now have a relatively well-documented suite of sedimentary characteristics for contourites, based mainly on data from present-day sediment drifts but which we believe is applicable to contourites from other depositional settings. In theory, therefore, we should be able to recognize contourites with some degree of confidence from ancient rocks on land or in drill-cores from the oceans. In practice, however, these sedimentary criteria are not always definitive and may be partially lost during burial and diagenesis. The cautious triple-scale approach proposed by Lovell & Stow (1981) should still be followed in any identification of ancient contourites.

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References

Auzende, J.M., Olivet, J.L. & Bonnin, J. 1970. La marge du Grand Banc et la fracture de Terre Neuve. *C.R. Acad. Sci. Paris*, **271,** 1063–66.

Bader, R.G. *et al.* 1970. Site 28. *In*: Bader, R.G. *et al., Init. Repts. DSDP*, **4.** US Govt. Print. Off., Washington, DC. 125–43.

Barusseau, J.P. & Vanney, J.R. 1978. Contribution à l'étude du modèle des fonds abyssaux. Le rôle géodynamique des courants profonds. *Revue Géog. phys. Géol. dyn.*, **20,** 59–94.

Berggren, W.A. & Hollister, C.D. 1974. Palaeogeography, palaeobiogeography and the history of circulation in the Atlantic Ocean. *In*: Hay, W.W. (ed.), *Studies in Paleoceanography*. Soc. econ. Paleo. Min. Spec. Pub. 20, 126–86.

—— 1977. Plate tectonics and palaeocirculation – commotion in the ocean. *Tectonophysics*, **38,** 11–48.

Bouma, A.H. & Hollister, C.D. 1973. Deep ocean basin sedimentation. *In:* Middleton, G.V. & Bouma, A.H. (eds.), *Turbidites and Deep Water Sedimentation*. 79–118.

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

—— & Hesse, R., in press. Contourites from the Eirik Ridge, south of Greenland. *Sed. Geol.*

Davies, T.A. & Laughton, A.S. 1972. Sedimentary processes in the North Atlantic. *In*: Laughton, A.S. Berggren, W.G. *et al.* (eds), *Init. Repts. DSDP*, **12,** US Govt. Print. Off., Washington, DC. 905–34.

Dingle, R.V., Megson, J.B. & Scrutton, R.A. 1981. Acoustic stratigraphy of the sedimentary succession west of Porcupine Bank, NE Atlantic Ocean: a preliminary account. *Marine Geol.*, **47,** 17–35.

Ellett, D.J., Dooley, H.D. & Hill, H.W. 1979. Is there a northeast Atlantic shore current? *ICES, CM 1979*, **C:35,** 11 pp.

Faugeres, J.C., Stow, D.A.V. & Gonthier, E., 1984. Contourite drift moulded by deep Mediterranean outflow. *Geology*.

—— *et al.* 1979. Evolution de la sédimentation profonde au Quaternaire récent dans le Bassin nord-atlantique: corps sédimentaires et sédimentation ubiquiste. *Bull. Soc. géol. Fr.*, **21(5),** 585–601.

——, Gonthier, E., Grousset, F. & Poutiers, J. 1981. The Feni Drift: the importance and meaning of slump deposits on the eastern slope of the Rockall Bank. *Marine Geol.*, **40,** M49–M57.

Flood, R.D. 1981. Longitudinal triangular ripples in the Blake-Bahama Basin. *Marine Geol.*, **39,** M13–M20.

—— & Hollister, C.D. 1980. Submersible studies of deep-sea furrows and transverse ripples in cohesive sediments. *Marine Geol.*, **36,** M1–M9.

Gradstein, F.M., Sheridan, R.E. *et al.* 1981. Leg 76: Western North Atlantic Ocean. *Joides Journal*, **VIII,** 29–35.

Heezen, B.C., Hollister, C.D. & Ruddiman, W.F. 1966. Shaping of the continental rise by deep geostrophic contour currents. *Science*, **152,** 502–8.

Hollister, C.D. & Heezen, B.C. 1972. Geologic effects of ocean bottom currents: western North Atlantic. *In*: Gordon, A.L. (ed.), *Studies in Physical Oceanography*, **2,** 37–66.

—— Ewing, J.I. *et al.* 1972. *Init. Repts. DSDP*, **11,** US Govt. Print. Off., Washington, DC.

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

Klasik, J.A. & Pilkey, O.H. 1975. Processes of sedimentation on the Atlantic continental rise off the southeast United States. *Marine Geol.*, **19,** 69–89.

Laine, E.P. & Hollister, C.D. 1981. Geological effects of the Gulf Stream system on the northern Bermuda Rise. *Marine Geol.*, **39,** 277–310.

Latouche, C. & Parra, M. 1979. La sédimentation au Quaternaire Récent dans le 'Northwest Atlantic Mid-Ocean Canyon' – apport des données minéralogiques et géochimiques. *Marine Geol.*, **29,** 137–64.

Laughton, A.S., Berggren, W.A. *et al.* 1972. *Init. Repts. DSDP*, **12,** US Govt. Print. Off., Washington DC.

Lovell, J.B.P. & Stow, D.A.V. 1981. Identification of ancient sandy contourites. *Geology*, **9,** 347–9.

Luyten, J.R. 1977. Scales of motion in the deep Gulf Stream and across the Continental Rise. *J. mar. Res.*, **35,** 49–74.

Luyendyk, B.P., Cann, J.R. *et al.* 1978. *Init. Repts. DSDP*, **49,** US Govt. Print. Off., Washington DC.

McCave, I.N., Lonsdale, P.F., Hollister, C.D. & Gardner, W.D. 1980. Sediment transport over the Hatton and Gardar contourite drifts. *J. sed. Petrol.*, **50,** 1049–62.

McGregor, B.A., Betzer, P.R. & Krause, D.C. 1973. Sediments of the Atlantic Corner Seamounts: control by topography, palaeowinds and geochemically directed modern bottom currents. *Marine Geol.*, **14,** 179–90.

Mougenot, D. & Vanney, J.R. 1982. Les rides de contourites Plio- Quaternaires de la pente continentale sud-Portugaise. *Bull. Inst. Geol. Bassin d'Aquitaine*, **31,** 131–9.

Montadert, L., Roberts, D.G. *et al.* 1979. *Init. Repts. DSDP*, **48,** US Govt. Print. Off., Washington DC.

Pastouret, L., Auffret, G.A., Hoffert, M., Melguen, M., Needham, H.D. & Latouche, C. 1975. Sedimentation sur la Ride de Terre-Neuve. *Can. J. Earth Sci.*, **12,** 1019–35.

——, Auffret, G.A. & Chamley, H. 1978. Microfacies of some sediments from the western North Atlantic: palaeoceanographic implications (Leg 44 DSDP). *In*: Benson, W.E., Sheridan, R.E. *et al.*, *Init. Repts. DSDP*, **44,** US Govt. Print. Off., Washington DC. 477–501.

Peterson, M.N.A. & Edgar, T.N. (eds) 1968. *Init. Repts. DSDP*, **2.** US Govt. Print. Off., Washington DC.

Pujol, C., Duprat, J., Gonthier, E., Peypouquet, J.C. & Pujos-Lamy, A. 1974. Résultats préliminaires de l'étude effectuée par l'Institut de géologie du Bassin d'Acquitaine concernant la mission Faegas dans l'Atlantique nord-est. *Bull. Inst. Geol. Bassin Acquitaine*, **16,** 65–94.

Riviere, A. 1977. *Méthodes Granulométriques: Techniques et Interprétation.* Masson, Paris. 170 pp.

Roberts, D.G. & Montadert, L. 1979. Margin palaeoenvironments of the northeast Atlantic. *In*: Montadert, L., Roberts, D.G. *et al.* (eds), *Init. Repts. DSDP Leg 48*, US Govt. Print. Off., Washington DC. 1099–118.

Schnitker, D. 1980. Global palaeoceanography and its deep water linkage to the Antarctic glaciation. *Earth Sci. Rev.*, **16,** 1–20.

Sheridan, R.E., Gradstein, F.M. *et al.* 1982. Early history of the Atlantic Ocean and gas hydrates on the Blake Outer Ridge: results of the DSDP Leg 76. *Bull. geol. Soc. Am.*, **93,** 876–85.

Shor, A.N. 1980. *Bottom Currents and Abyssal Sedimentation Processes South of Iceland.* Ph.D. Thesis, Woods Hole Oceanographic Institution. 246 pp.

Shor, A.N. & Poore, R.Z. 1978. Bottom currents and ice rafting in the North Atlantic: interpretation of Neogene depositional environments of Leg 49 cores. *In*: Luyendyk, B.P. & Cann, J.R. *et al.*, *Init. Repts. DSDP*, **49,** US Govt. Print. Off., Washington DC. 859 pp.

Shor, A.N., Lonsdale, P., Hollister, C.D. & Spencer, D. 1980. Charlie-Gibbs fracture zone: bottom-water transport and its geologic effects. *Deep-Sea Res.*, **27A,** 325–45.

Silva, A.J., Hollister, C.D., Laine, E.P. & Beverly,

B. 1976. Biotechnical properties of deep-sea sediments: Bermuda Rise. *Mar. Geotechnol.*, **1,** 195–232.

STANLEY, D.J., SHENG, H., LAMBERT, D.N., RONA, P.A., MCGRAIL, D.W. & JENKYNS, J.S. 1981. Current-influenced depositional provinces, continental margin off Cape Hatteras, identified by petrologic method. *Marine Geol.*, **40,** 215–35.

STOW, D.A.V. 1979. Distinguishing between fine-grained turbidites and contourites on the deep-water margin off Nova Scotia. *Sedimentology*, **26,** 371–87.

—— 1982. Bottom currents and contourites in the North Atlantic. *Bull. Inst. Geol. Bassin d'Aquitaine*, **31,** 151–66.

—— & LOVELL, J.P.B. 1979. Contourites: their recognition in modern and ancient sediments. *Earth Sci. Rev.*, **14,** 251–91.

SWALLOW, J.C., FOULD, W.J. & SAUNDERS, P.M. 1977. Evidence for a poleward eastern boundary current in the North Atlantic Ocean. *ICES, CM 1977*, **C:32,** 21 pp.

TAYLOR, P.T., STANLEY, D.J., SIMKIN, T. & JAHN, W. 1975. Gillis seamount: detailed bathymetry and modification by bottom currents. *Marine Geol.*, **19,** 139–57.

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

—— 1975. Sediment distribution and deposition by the Western Boundary Undercurrent: The Greater Antilles Outer Ridge. *J. Geol.*, **83,** 177–207.

—— & EWING, J.I. 1974. Bathymetry and sediment geometry of the Greater Antilles Outer Ridge and vicinity. *Bull. geol. Soc. Am.*, **85,** 1789–1802.

VON STACKELBERG, U., VON RAD, U. & ZOBEL, B. 1979. Asymmetric sedimentation around Great Meteor Seamount (North Atlantic). *Marine Geol.*, **33,** 117–32.

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