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*BOTTOM CURRENTS AND CONTOURITES
IN THE NORTH ATLANTIC.*

**COURANTS PROFONDS ET LEURS DEPOTS
DANS LE BASSIN NORD-ATLANTIQUE.**

Mots-Clés : Courants profonds,
Paléocirculation,
Dépôts contourites,
Nord-Atlantique.

Key-Words : Bottom currents,
Paleocirculation,
Contourites,
North Atlantic.

RESUME :

Une étude synthétique sur les courants profonds et leurs dépôts dans le Bassin nord-Atlantique a été réalisée. L'évolution d'une circulation complexe de l'eau profonde était progressive, et elle était modulée par des facteurs climatiques et tectoniques. Quatre événements de la paléocirculation ont caractérisé le Paléogène et Néogène. Au Quaternaire il y avait des différences marquées entre les périodes glaciaires et chaudes.

L'identification certaine des contourites (dépôts des courants profonds) nécessite des évidences combinées : des mesures de courants et des couches néphéloïdes, des caractères morphologiques et une signature sismique, des discontinuités et des lacunes associées et des caractères sédimentaires. Plusieurs exemples des contourites du Bassin Nord-Atlantique sont détaillés, et deux genres sont définis : «muddy contourites» et «sandy contourites». Il est très probable que des identifications anciennes de contourites soient erronées.

ABSTRACT :

A synthesis of our present knowledge of bottom currents in the North Atlantic shows that they have had a pronounced effect on the nature and distribution of sediments throughout the Cenozoic. Deep circulation evolved gradually, but the appearance of each of the main deep-water masses marks a major paleocirculation event, closely related to tectonic and climatic changes. A series of pronounced changes also took place during the Quaternary climatic cycles. It appears that bottom-circulation was much reduced during glacial episodes. More evidence is needed to confirm these first speculations on North Atlantic paleocirculation. At the present day, bottom currents vary greatly in time and space. Tidal, seasonal and irregular periodicities have all been measured, with velocity fluctuations of up to 40 cm/s in the direction of mean flow, as gianteddies or in a reversed sense.

Contourites can **only** be identified with any certainty by using a combination of lines of evidence including : direct measurement of currents and nepheloid layers, characteristic morphological and seismic patterns, associated hiatuses or unconformities, and sedimentary characteristics. Many examples of contourites have been described from the North Atlantic using this kind of evidence. Muddy contourites are homogeneous, bioturbated and with a mixed biogenic/terrigenous composition. They can be very difficult to distinguish from hemipelagic sediments. Sandy contourites occur as thin, irregular, bioturbated, muddy, lag deposits with a mixed broken, iron-stained biogenic and terrigenous composition. Clean, cross-laminated biogenic sands or reworked turbidite sands have been less commonly identified with confidence. Sedimentary criteria **alone** are not yet sufficiently definitive ; and many of the earlier criteria and identifications must be questioned.

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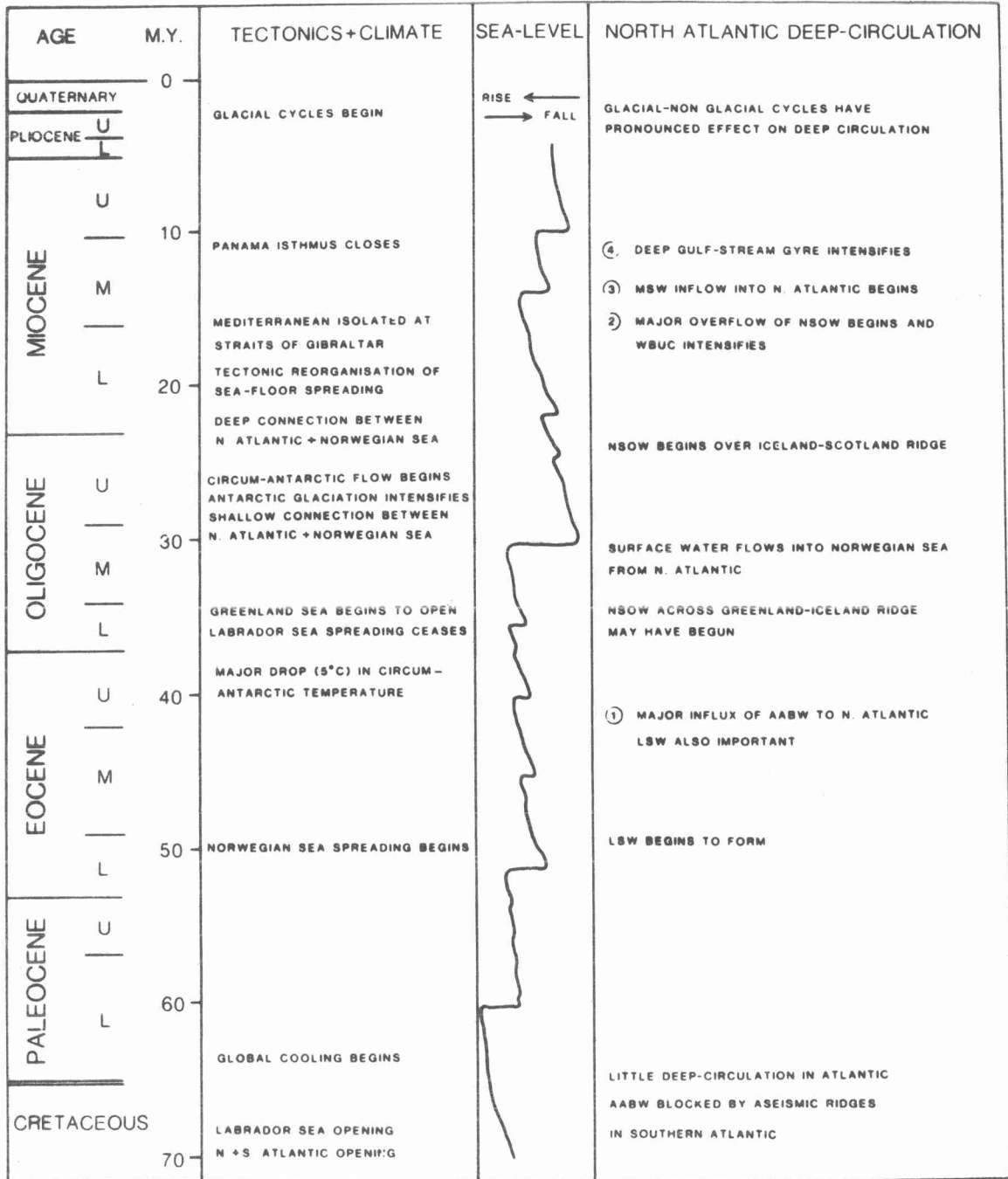


Fig. 1 - Résumé des évènements de circulation profonde en Atlantique Nord pendant le Tertiaire et des changements tectoniques, climatiques et du niveau de la mer qui ont pu affecter la paléocirculation. Courbe globale du niveau de la mer d'après Vail et al. (1977).
 Summary of North Atlantic deep-circulation events during the Tertiary and tectonic, climatic and sea-level changes that may have affected paleocirculation. Global sea-level curve from Vail et al. (1977).

INTRODUCTION

Only 30 years ago most geologists believed the oceans were deep quiet basins disturbed by little more than a gentle rain of pelagic organisms. We now know they are the site of dramatic plate construction and destruction, and that their uneven sediment cover is shaped by highly variable currents, winds, geochemical processes, biogenic activity and terrigenous supply. In particular, the importance of deep ocean circulation in determining the nature of the sediment record has become widely recognised.

Most of the deep-sea floor is swept by very slow (< 2 cm/s) thermohaline currents that originate in polar regions by the cooling, freezing and wind-forced convection of surface waters. These currents are intensified in parts of the oceans, particularly on the western margins of topographic basins as a result of the earth's rotation, and in narrow passages between basins by the acceleration of constricted flows. Wind-driven «surface» currents, such as the Gulf Stream, can also impinge on the sea floor at depths of 4000 m and more. Both these types of «normal» ocean currents that are active at depths of more than about 1000 - 2000 m are referred to here as bottom currents.

There is now little doubt that the higher velocity bottom currents are capable of eroding, transporting and depositing a range of fine-grained sediments. Over a long period, strong bottom currents can cause significant erosion or non-deposition and leave a marked hiatus in the sediment record. In parts of the oceans they contribute to the development of ferromanganese nodules and pavements, smooth and sculpture continental rises, or construct large-scale sediment drifts up to several hundred kilometres long, tens of kilometres wide and hundreds of metres thick. Deep-sea sediments that have accumulated under the influence of bottom currents are known as contourites (Hollister and Heezen, 1972). Both muddy contourites deposited from suspended sediment in nepheloid layers, and sandy contourites that have been winnowed and partly transported as bedload, are recognized (Stow and Lovell, 1979), but there is still considerable confusion over the correct identification of contourites both in deep-sea cores and in the ancient record.

This paper attempts to synthesize what we know today of bottom current circulation and contourite characteristics in the North Atlantic ocean, with special reference to the Quaternary. It further identifies some of the key problems and questions that remain to be answered. Important earlier syntheses include those of Davies and Laughton (1972), Hollister and Heezen (1972), Barousseau and Vanney (1978), Stow and Lovell (1979), and Faugères et al. (1979).

DEVELOPMENT OF BOTTOM CIRCULATION

For much of its early history the North Atlantic appears to have been too small and without access to polar-cooled waters for the development of a marked deep circulation (Schnitker, 1980). Wind-driven surface currents may have locally scoured the bottom, and thermal convection from newly-formed ocean crust will have helped overturn basinal water masses. However, the widespread occurrence of organic-rich black shales in early and mid-Cretaceous rocks (Ryan and Cita, 1977) testifies to long periods of restricted circulation prior to the Tertiary.

The North Atlantic gradually developed its deep-water circulation system during the Paleogene and Neogene as a result of plate tectonic reorganisation and climatic changes (Fig. 1). Four main paleocirculation «events» can be identified (Berggen and Hollister, 1974, 1977; Tucholke and Vogt, 1978; Shor and Poore, 1978; Roberts and Montadert, 1979; Schnitker, 1980). Changes in faunal migration patterns and in clay mineral distribution during the Eocene, the widespread mid-Eocene siliceous deposits and the mid-late Eocene erosional event marked by pronounced hiatuses in many deep-sea cores all signal the first major paleocirculation «event». This probably correlates with the beginnings of global cooling throughout the Tertiary and with a sharp temperature drop (about 5°C) in the circum-Antarctic region. Antarctic Bottom Water (AABW) was formed at high southern latitudes and flowed into the North Atlantic. This vigorous bottom circulation was augmented by the development of deep cold Labrador Sea Water (LSW), and, perhaps, by overflow through the Denmark Strait from the newly-formed Norwegian Sea.

The AABW continued to dominate deep circulation through most of the Oligocene, with increasing formation and outflow of LSW as the climate deteriorated. Faunal evidence coupled with the known subsidence history of the Iceland-Faeroes Ridge suggest the establishment of surface-water inflow into the Norwegian Sea Overflow Water (NSOW) began in latest Oligocene but was probably not significant until mid-Miocene. This second paleocirculation «event» was heralded by deposition of the northeast Atlantic sediment drifts and by a major erosional unconformity at the early-mid Miocene boundary.

The third and fourth paleocirculation «events» also took place in the Miocene. Closure of the Tethys in the east was completed by the end of the early Miocene, and the first warm, saline Mediterranean Sea Water (MSW) began to flow out into the North Atlantic. Closure of the Panama Isthmus through the Miocene deflected

the North Equatorial Current to strengthen the Gulf Stream system. Both erosion along the continental margin and deposition of the western North Atlantic sediment drifts date from this period and can be related to the deep Gulf Stream Gyre (GSG) and an intensifying Western Boundary Undercurrent (WBUC).

Thus, by the late Miocene the essential elements of present-day deep circulation in the North Atlantic had been established. Minor changes occurred in the nature of water masses and in the paths of bottom currents, but no major reorganisation took place until the onset of the Plio-Pleistocene climatic cycles.

QUATERNARY CIRCULATION

There is much evidence from paleontology (Schnitker, 1974, 1979a, b, 1980 ; Kellogg, 1977) and sedimentology (Hughes et al., 1977 ; Faugères et al., 1979, 1981 ; Latouche and Parra, 1979 ; Volat et al., 1980) for major changes in surface and deep circulation related to glacial-interglacial climatic cycles in the Quaternary. These recent studies, as well as earlier theoretical work (Weyl, 1968), indicate a reduction in the intensity of bottom currents during glacial episodes and, perhaps, the replacement of NSOW, NADW and AABW with a single water mass formed in a subpolar gyre at about 50°N. There was also a marked overprint by turbidites and glacially derived sediments at times of glacial maxima and lowered sea-levels, so that detailed changes in the record of bottom circulation have been partly obscured.

At the present day several different water masses are involved in the North Atlantic deep circulation (Fig. 2). The deepest, coldest water mass is the 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 NSOW mixes partially with LSW formed south of Greenland and with AABW to form the North Atlantic Deep Water (NADW). Warmer saline MSW flows out of the Straits of Gibraltar and spreads out at intermediate levels to both north and south.

Bottom currents associated with the movement of these water masses have now been measured in many parts of the ocean (Table 1 in Stow and Lovell, 1979) mainly with short-duration current meters, and the complex circulation shown in Fig. 3 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

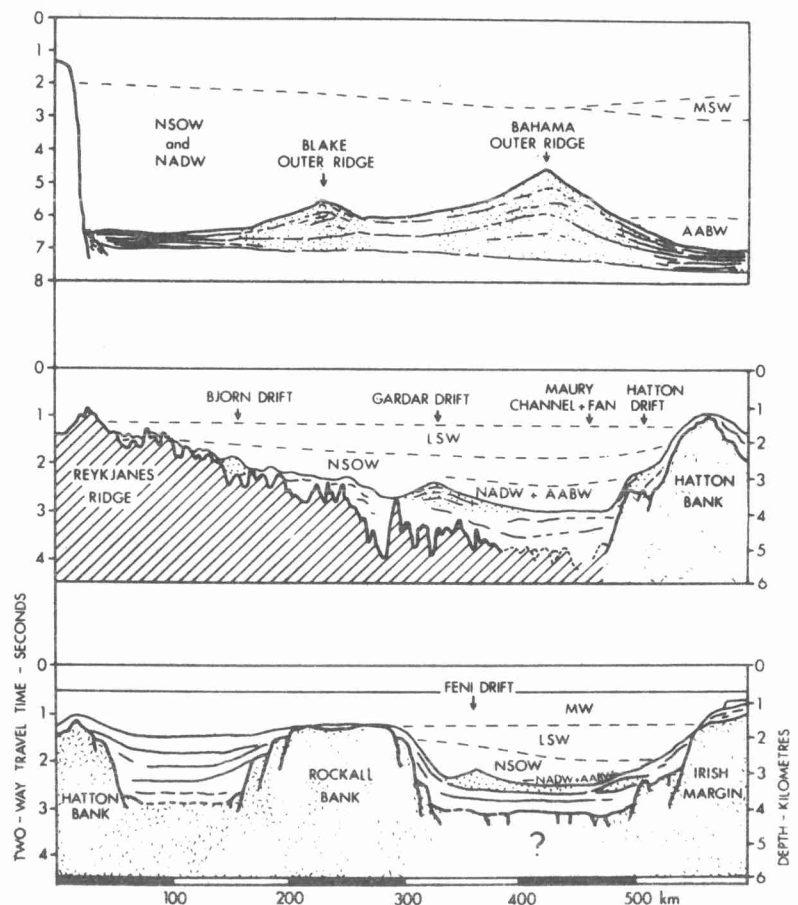


Fig. 2 - Coupes géologiques et océanographiques montrant les déplacements des sédiments et les marnes d'eaux profondes. Voir fig. 7 et 8 l'emplacement des coupes. AABW eau antarctique de fond ; LSW eau de la mer de Labrador ; MSW eau de la mer Méditerranée ; NADW eau profonde Nord-Atlantique ; NSOW eau de débordement de la mer de Norvège. Geological and oceanographic cross-sections showing sediment drifts and deep-water-masses. See Figures 7 and 8 for location of sections. AABW, Antarctic Bottom water ; LSW, Labrador Sea water ; MSW, Mediterranean Sea water ; NADW, North Atlantic Deep water ; NSOW, Sea Overflow water.

mean seasonal velocities of 0.8 cm/s and a 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 south-westerly currents of 5-20 cm/s associated with the WBUC. 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.

With respect to the geological effects of these bottom currents it is important to note their great variability in time and space 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 determine any characteristic periodicity in flow velocity, but both seasonal (Shor et al., 1980) and tidal (Mc Cave et al., 1980) fluctuations have been noted. Velocities decrease from the core to the margin of the current, and reverse flows are commonly measured.

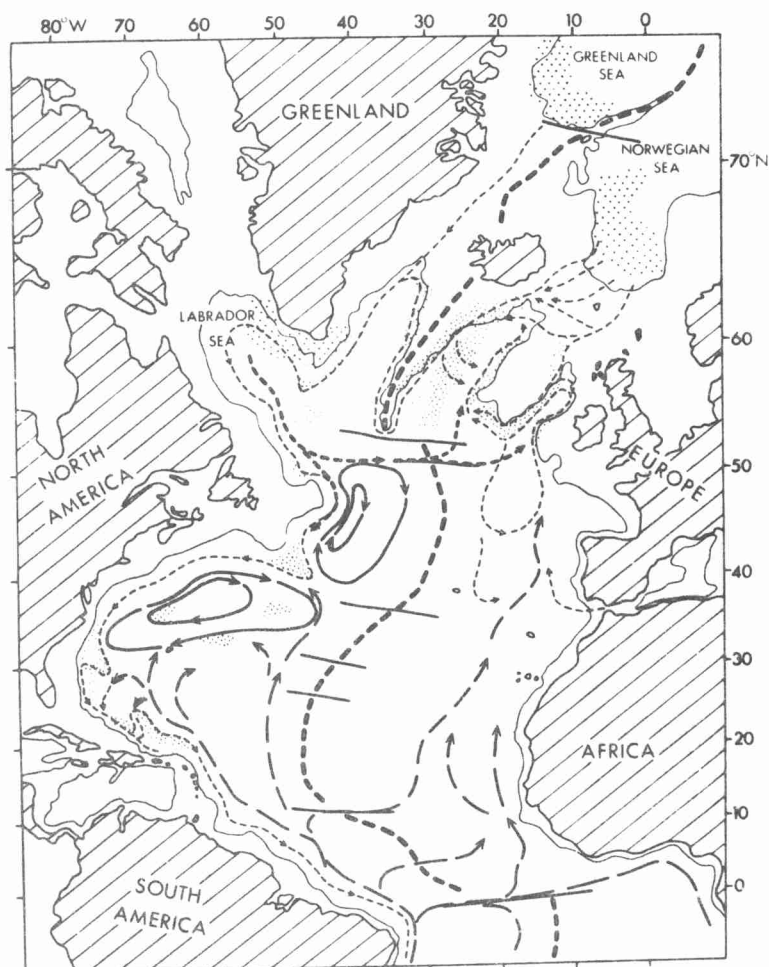


Fig. 3 - Circulation actuelle des eaux profondes en Atlantique Nord et déplacements des sédiments (pointillés serrés). Zones de formation d'eau de fond montrées par des pointillés larges. WBUC : Gyre du Gulf-Stream ; NAG : Gyre de l'Atlantique Nord-Est. Voir fig. 2 pour les autres courants. Contour à 2000 m.
North Atlantic present-day deep-water circulation and sediment drifts (close stipple). Areas of bottom-water formation shown by wide stipple. WBUC : Western Boundary Undercurrent ; GSG : Gulf Stream Gyre ; NAG : Northeast Atlantic Gyre. See fig. 2 for other currents. Contour at 2.000 m.

RECOGNITION OF CONTOURITES

There are several different but related processes of sedimentation in the deep sea. These include debris flows, high and low-concentration bottom currents, hemipelagic and pelagic deposition and ice-rafting. It is not easy to distinguish contourites from the gradational continuum of deposits that result from these processes, and it is therefore essential that a wide spectrum of evidence is collected before a firm contourite identification can be made. Many examples of contourites described in recent literature must be treated with considerable caution when the interpretations are based on insufficient evidence.

For north Atlantic Quaternary contourites the following criteria are useful (Barrusseau and Vanney, 1978 ; Stow and Lovell, 1979) :

- (1) **Bottom currents.** There should be direct current measurements or very strong evidence (hydrographic, photographic, etc.) for competent bottom currents in the region (Fig. 3). Clearly, post-glacial or interglacial circulation systems are not applicable to the glacial episodes (see previous discussion).

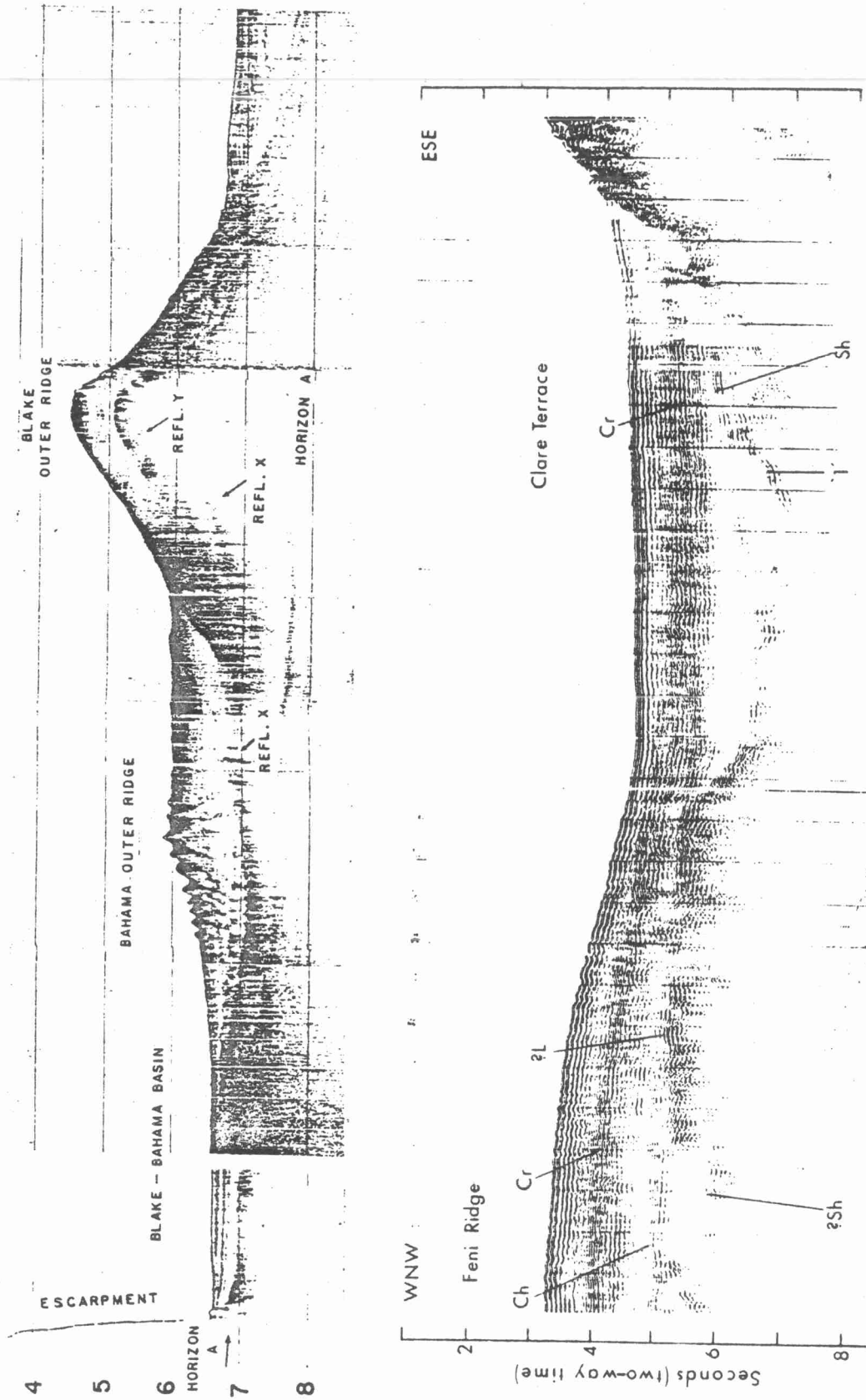


Fig. 5 - Lignes de sismique réflexion à travers les rides extérieures Blake Bahama (Markl et al. 1970) et Feni (Dingle et al. 1981).
Seismic reflection lines across Blake-Bahama Outer Ridge (Markl et al., 1970) and Feni Drift (Dingle et al., 1981).

- (2) **Nepheloid layers.** Well-developed nepheloid layers are commonly associated with high-velocity bottom currents, and provide evidence that sediment transport is taking place. Nepheloid layers are also present due to resuspension of sediment at the shelf-slope boundary, and within submarine canyons.
- (3) **Morphology.** A wide range of morphological features can be detected on the sediment surface, using photographic, side-scan sonar or shallow seismic techniques, that result from erosion, transport or deposition by bottom currents (Fig. 4). These include large-scale sediment drifts or outer ridges, giant sediment waves, smaller-scale dunes, waves and ripples, faint lineation, coarse lag or drift in the lee of small obstacles, and smoothed sediment surfaces. Erosion can create deep moats, large and small-scale furrows, and minor sediment scour. These various features are also commonly produced by turbidity currents, up and down-slope canyon currents and by deep tidal action.
- (4) **Seismic characteristics.** Thick contourite accumulations can be recognized on seismic records from their geometrical configuration, internal character and surface reflections. They occur as projections from the continental rise, as isolated ridges detached from the continental margin, or as mid-ocean drifts piled against pre-existing topography (McCave et al., 1980). They form a non-uniform drape over the sea floor, and are commonly related to major acoustic basement features such as seamounts or ridges, as well as to bottom current circulation (Dingle et al., 1981). Commonly, they are acoustically transparent lensoid packages similar to pelagic deposits, although in some cases they show a faint internal layering or discontinuous crenulated lamination (Fig. 5). Surface reflections from contourite drifts may show a variety of hyperbolic echo types, migrating sediment waves or a smooth sediment surface. All of these echo-characters can be produced by turbidity currents as well as by bottom currents (Damuth, 1978, 1980).
- (5) **Hiatuses.** Unconformities, hiatuses and, to a lesser extent, condensed sequences in the deep-sea sediment record result from erosion, non-deposition or reduced deposition. At great depths, far from land and in areas of low biological productivity, there is simply an absence of material to be deposited. However, in other areas and particularly along continental margins a break in the sediment record implies non-deposition or active removal of sediment by downslope slumps and gravity flows or by bottom currents. The hiatuses found in many cores from the North Atlantic during the mid-late Eocene and early-mid Miocene (Fig. 6) most probably result from the initiation or intensification of deep circulation associated with the AA-BW and NSOW respectively (see earlier discussion). The sediments adjacent to such hiatuses may represent accumulation under the influence of weaker bottom currents.

- (6) **Sediment characteristics.** As more and more contourites are recognised and described it becomes increasingly evident that their characteristics are not unique, and that sedimentary criteria alone cannot be used for positive identification. Stow (1979) and Stow and Lovell (1979) pointed out the severe pro-

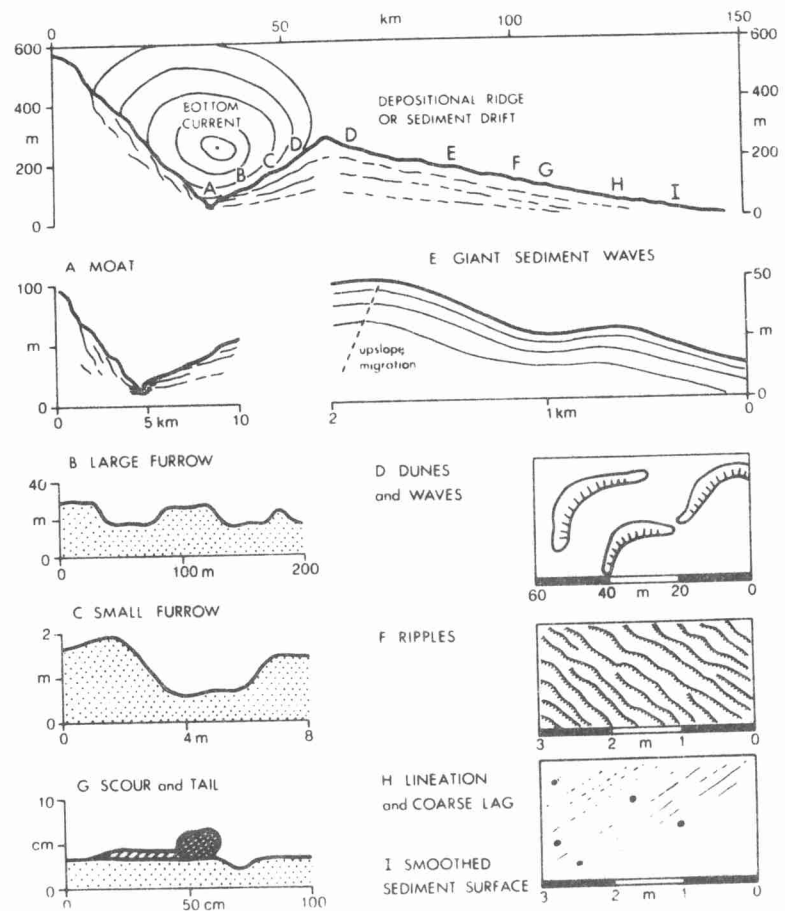


Fig. 4 - Schémas des caractéristiques d'érosion et de dépôts de courant profond.
 Sketches of bottom-current erosional and depositional features.

blems that existed with earlier criteria that had been proposed for the recognition of contourites (Hollister and Heezen, 1972 ; Bouma and Hollister, 1973). However, there have now been numerous descriptions of sediments from the North Atlantic that can be identified as contourites on the basis of their morphological and seismic character and on direct evidence of bottom currents, nepheloid layers and associated hiatuses. These examples will be reviewed in the following section.

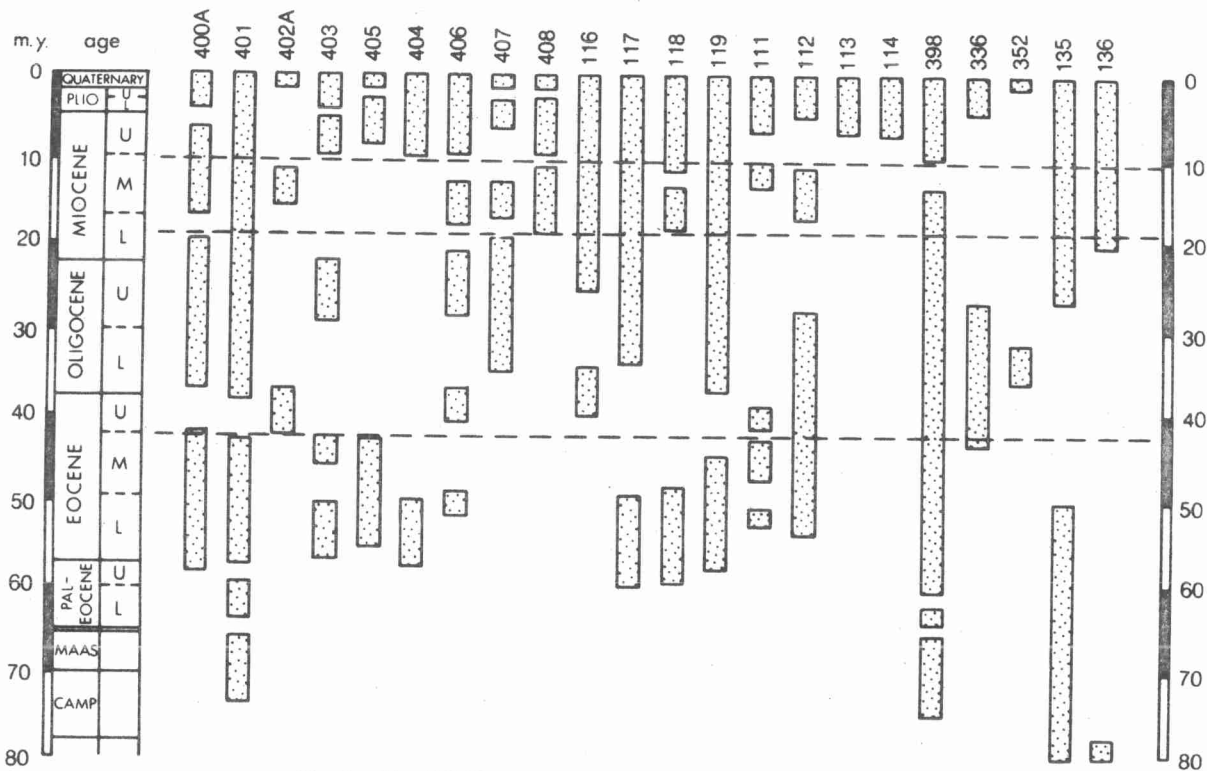


Fig. 6 - Sites DSDP en Atlantique Nord et principaux hiatus tertiaire.
North Atlantic DSDP sites and principal Tertiary hiatuses.

NORTH ATLANTIC CONTOURITES

Most of the sediment drifts or outer ridges in the North Atlantic (Figs. 7 and 8) have been at least sparsely sampled with piston and gravity cores or at DSDP drill sites. The sediments recovered are detailed below together with the supporting evidence that allows their interpretation as contourites.

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 years.

Other evidence : inferred bottom currents, drift morphology, sediment waves, seismic characteristics.

Hatton Drift (Laughton, Berggren et al., 1972 ; Shor and Poore, 1978 ; Montadert, Roberts 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 years. 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 years. 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 years.

Other evidence : measured bottom currents and nepheloid layer, drift and small-scale morphology, seismic characteristics, hiatuses.

Bjorn Drift (Laughton, Berggren 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 years.

Other evidence : inferred bottom currents, drift morphology, seismic characteristics.

West Reykjanes Ridge (Luyendyk, Cann et al., 1978 ; Shor and 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 and Parra, 1979).

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, Berggren 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 and 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.

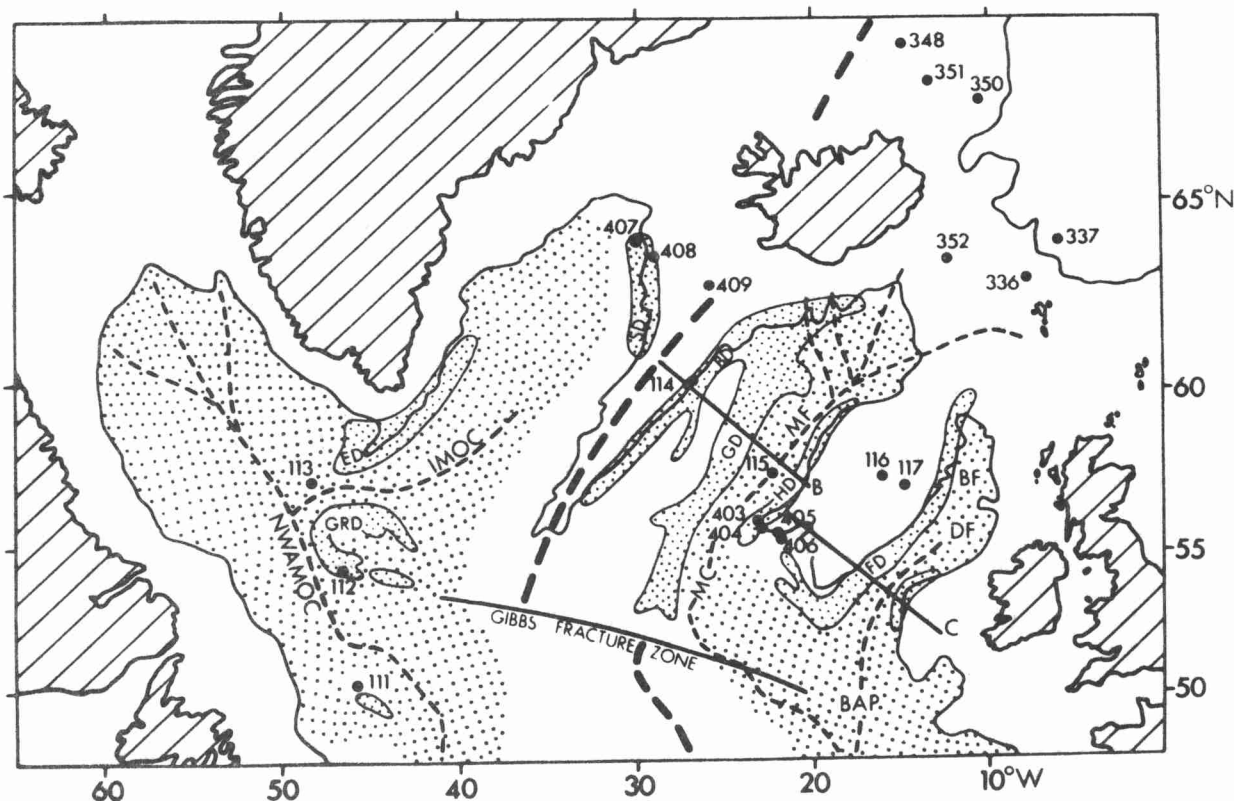


Fig. 7 - Atlantique Nord-Est montrant les sites SDDP, les accumulations sédimentaires (pointillés serrés) et les zones de prédominance d'une sédimentation turbiditique (pointillés larges). FD : Ride Feni ; HD : Ride Hatton ; GD : Ride Gardar ; BD : Ride Bjorn ; SD : Ride Shorri ; ED : Ride Eirik ; GRD : Ride Gloria ; BF : Eventail sédimentaire de Barra ; DF : Eventail sédimentaire de Donegal ; MF : Eventail sédimentaire de Maury ; MC : Chenal de Maury ; IMOC : Chenal médio-océanique d'Imarssuak ; NWAMOC : Chenal médio-océanique de l'Atlantique Nord-Est ; BAP : Plaine abyssale du Golfe de Gascogne. Contour à 2000 m.

Northeast Atlantic showing DSDP sites, sediment drifts (close stipple) and areas of predominantly turbidite sedimentation (wide stipple). FD : Feni Drift ; HD : Hatton Drift ; GD : Gardar Drift ; BD : Bjorn Drift ; SD : Snorri Drift ; ED : Eirik Drift ; GRD : Gloria Drift ; BF : Barra Fan ; DF : Donegal Fan ; MF : Maury Fan ; MC : Maury Channel ; IMOC : Imarssuak Mid-Ocean Channel ; NWAMOC : Northwest Atlantic Mid-Ocean Channel ; BAP : Biscay Abyssal Plain. Contour at 2000 m.

Bermuda Rise and Corner Rise (Peterson and Edgar, 1968 ; McGregor et al., 1973 ; Silva et al., 1976 ; Laine and 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, Ewing et al., 1972 ; Klasik and Pilkey, 1975 ; Flood, 1981 ; Flood and Hollister, 1980 ; Gradstein, Sheridan 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 and 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-foram tests ; sedimentation rate 1 cm/1000 years.

Other evidence : inferred bottom currents, drift morphology on flanks of seamount, seismic characteristics.

Great Meteor Seamount (Von Stackelberg, 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.

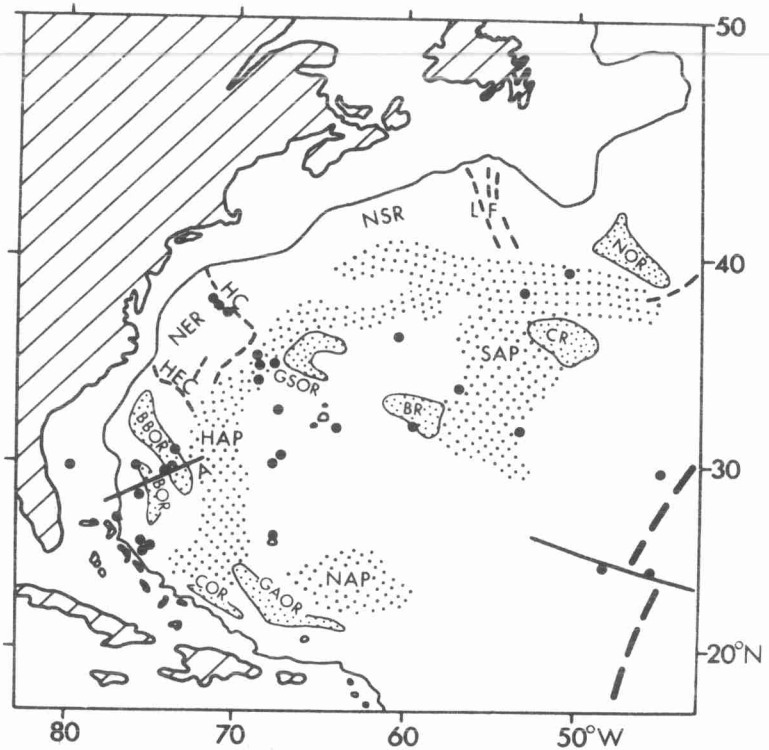


Fig. 8 - Atlantique Nord-Ouest montrant les sites SDDP (cercles non marqués), les rides sédimentaires (pointillés serrés) et les plaines abyssales (pointillés larges). NOR : Ride Outer de Newfoundland ; CR : Ride Corner ; BR : Ride Bermuda ; GSOR : Ride extérieure du Gulf Stream ; BBOR : Ride extérieure de Blake-Bahama ; BOR : Ride extérieure de Bahama ; COR : Ride extérieure de Caicos ; GAOR : Ride extérieure des Grandes Antilles ; SAP : Plaine abyssale de Sohm ; HAP : Plaine abyssale d'Hatteras ; NAP : Plaine abyssale de Nares ; LF : Eventail sédimentaire du St Laurent ; NSR : Ride de Nouvelle-Ecosse ; HC : Canyon de l'Hudson ; HEC : Canyon Hatteras ; NER : Ride de Nouvelle Angleterre.

Western North Atlantic showing DSDP sites (circles, unmarked), sediment ridges (close stipple) and abyssal plains (wide stipple). NOR : Newfoundland Outer Ridge ; CR : Corner Rise ; BR : Bermuda Rise ; GSOR : Gulf Stream Outer Ridge ; BBOR : Blake-Bahama Outer Ridge ; BOR : Bahama Outer Ridge ; COR : Caicos Outer Ridge ; GAOR : Greater Antilles Outer Ridges ; SAP : Sohm Abyssal Plain ; HAP : Hatteras Abyssal Plain ; NAP : Nares Abyssal Plain ; LF : Laurentian Fan ; NSR : Nova Scotian Rise ; HC : Hudson Canyon ; HEC : Hatteras Canyon ; NER : New England Rise.

In many of the examples of contourites drifts detailed above there are intervals with turbidites, slumps or debris flow deposits. Along much of the western North Atlantic continental margin it appears that turbidites and contourites are closely interbedded, and the distinction between the two types of deposit has been a matter of some controversy. The contourites identified by Pastouret et al. (1978), Stow (1977, 1979) and Stanley et al. (1981) in these settings are most closely comparable with those of the sediment drifts. In the author's opinion, the «classical», thinly-bedded, cross-laminated, contourites of Hollister and Heezen (1972) that have subsequently been reported from many parts of the North Atlantic and other ocean margins are, in most cases, distal turbidites.

The sedimentary criteria that can best assist in the recognition of contourites are summarized in Figs. 9 and 10 for both muddy and sandy contourites. These are essentially those suggested by Stow and Lovell (1979) with minor modifications in the light of recent examples. It is important to stress that such criteria are **not** definitive and may be extremely difficult to apply to the ancient record (Lovell and Stow, 1981).

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

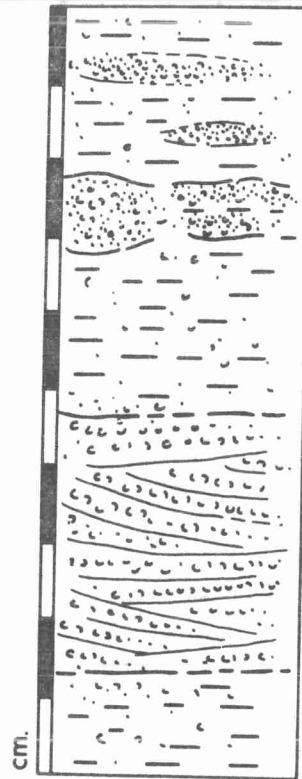
Fig. 9 - Contourites boueuses : caractéristiques sédimentaires.
Muddy contourites : sedimentary characteristics.

SUMMARY AND PROBLEMS

- (1) Bottom currents have had a major effect on the nature and distribution of sediments throughout the Cenozoic development of the North Atlantic. During the Quaternary, deep circulation was apparently much reduced in glacial episodes. However, we need more and firmer evidence for accurate reconstruction of paleocirculation patterns.
- (2) Bottom currents vary greatly in time and space. Tidal, seasonal and irregular periodicities have all been recorded, with velocity fluctuations of up to 40 cm/s in the direction of mean flow, in a reversed sense, or as large eddies peeling off from the flow margins. Narrow strong bottom currents can flow adjacent to essentially still water masses. More long-term measurements and a more extensive coverage of both margins of the North Atlantic are required before we begin to understand bottom current variability.
- (3) Other currents due to surface circulation and internal tides, up and down canyon flow and turbidity currents can all effect the sediment surface at great depths. Such currents can produce depositional bed-forms (waves, ripples, etc...), scour and winnow sediment in the same way as bottom currents. Particularly in the ancient record, it is difficult to distinguish between these various processes.
- (4) The nature and mechanism of deposition and erosion by bottom currents remains a problem. What type of sediment is deposited or eroded and from which part of the bottom current ? Some of the controls that must be considered in this respect are : current variability, current interaction with other currents, existing and developing topographies, sediment types and input into the bottom current system.

- (5) It is important to be able to distinguish between deposits of bottom currents, turbidity currents and other processes operating in the deep sea. We must also recognize that a gradation probably exists between the various processes and their deposits. The point at which thermohaline bottom currents act as density currents and low-concentration low-velocity turbidity currents act as bottom currents may provide important information on the physical parameters of both.
- (6) Contourites can only be identified with any certainty by using a combination of lines of evidence. These should include direct measurement of bottom currents and nepheloid layers, the presence of both large-scale and small-scale current-related morphologies, characteristic seismic signatures, associated hiatuses or unconformities in the sediment record, and characteristic sediment types.

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. 10 - Contourites sableuses : caractéristiques sédimentaires.
Sandy contourites : sedimentary characteristics.

- (7) Contourites have now been described from many parts of the North Atlantic ocean. Muddy contourites are fine-grained, homogeneous, bioturbated sediments with a mixed biogenic and terrigenous composition, that are difficult to distinguish from hemipelagic sediments. Sandy contourites have been less commonly recognised with any degree of confidence. They can occur as thin, irregular, bioturbated lag deposits with a mixture of broken, iron-stained biogenic debris and terrigenous grains ; primary structures may be preserved as in clean cross-laminated foraminiferal sands or in reworked tops of turbidite sands. However, sedimentary criteria **alone** are not yet sufficiently definitive ; many of the earlier criteria and identifications appear now to be inaccurate.

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