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Contourite drift types and their distribution in the North and South Atlantic Ocean basins

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ABSTRACT

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Patterns of sediment accumulation under the control of deep bottom currents depend on interacting factors: intensity of the regional deep circulation, morphology of the sea-floor, Coriolis effects, abundance of terrigenous and biogenic supplies, subsequent turbidity of deep nepheloid layers, and depth of the CCD.

Based on many examples of bottom current deposits, from the Atlantic and from other oceans, we recognise three major types of contourite accumulation: (1) giant elongate drifts, (2) contourite sheets, and (3) channel-related drifts. They generally occur in distinct topographic settings and show different geometries, facies and rates of deposition.

In the North Atlantic, strong bottom circulation, an open basin system and high sediment supply have led to the construction of large elongate contourite drifts, which have striking relief (200–1000 m) above the surrounding sea-floor and are composed of muddy contourites, rich in calcareous pelagic material. In the South Atlantic, strong bottom-currents are often trapped in gyre-like circulation patterns around topographically closed basins or are accelerated through deep, narrow, connecting passages. The resulting deposits are mainly extensive contourite sheets, covered by fields of large sediment waves, and channel-related drifts, including "contourite fans" constructed at the downstream exit of deep passages.

Introduction

Many recent oceanographic studies from all parts of the world's oceans have documented the wide range and varied distribution of contourite facies, as well as a variety of different contourite drift types. They have also demonstrated clearly that patterns of sediment accumulation under the control of deep-water bottom currents depend on the complex interaction of several major factors.

In this paper, we first summarise the main controls on contourite accumulation, secondly propose a classification of the major types o contourite drift and, thirdly, discuss the reason for the occurrence of different drift types in th North and South Atlantic Ocean basins.

In addition to our own collective experience o work on modern contourite deposits, we dra heavily on other published material, especiall with regard to the synthesis of drift types (e.g Heezen et al., 1966; Jones et al., 1970; Ewing e al., 1971; Stow and Holbrook, 1984; McCave an Tucholke, 1986; Richardson et al., 1987; Floo and Shor, 1988; Pickering et al., 1989).

Controls on contourite accumulations

The main factors that influence contourite accumulation can be summarised as follow (Fig. 1)

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(1) *Active geostrophic circulation*

Most importantly, there must be a sufficiently active geostrophic circulation in the ocean basins to induce sediment movement. Climate and sea level are both critical in this respect. An adequate temperature differential between equator and poles is required to drive an effective thermohaine geostrophic circulation, such as has been particularly evident during periods prone to polar glacial episodes (e.g. late Palaeozoic and late Cenozoic). The precise correlation between bottom circulation and glacial–interglacial cycles is not known in detail, although there is growing evidence that extensive sea ice during glacial maxima may lessen the production of cold deep water and hence dampen bottom circulation. By contrast, periods of climatic instability or crisis seem to have resulted in enhanced bottom current activity.

Surficial currents can interact with deep bottom currents, particularly in areas of the ocean that are prone to high surface instability as a result of the global oceanic circulation pattern. In these areas, particular atmospheric conditions involving periods of major storms can induce short-duration high-energy events and high bottom current velocities, called "benthic storms" (Hollister and McCave, 1984).

(2) *Sea-floor topography*

Where a strong western boundary current has developed in response to the Coriolis force piling up a moving water mass against the continental margin, then further current intensification and velocity increase will occur against steeper slopes. Major changes in orientation of the slope with respect to the current direction will also result in velocity variation.

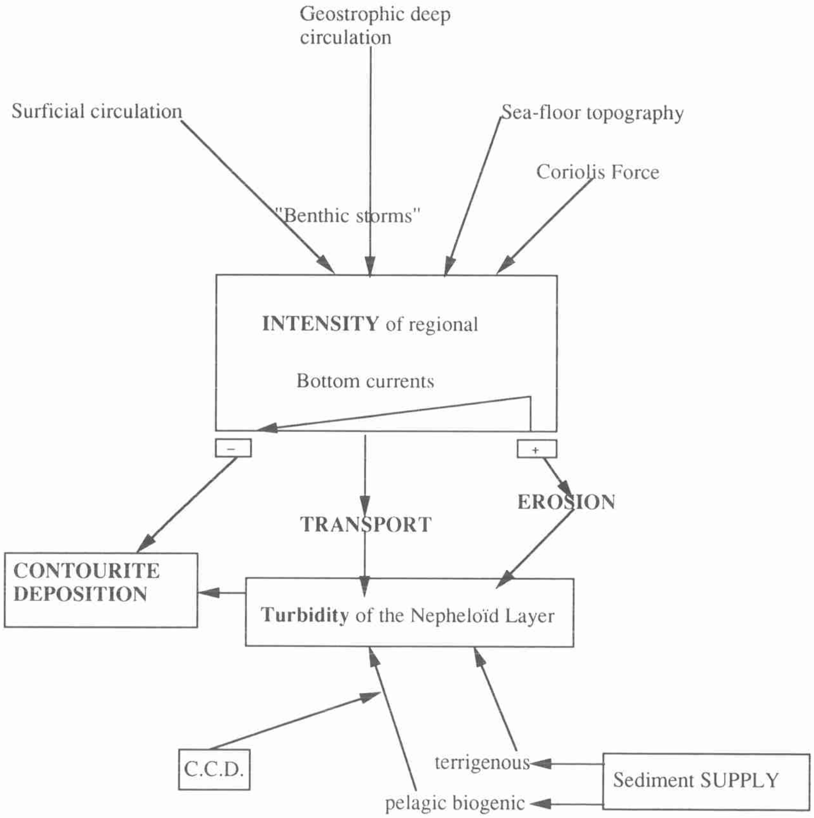


Fig. 1. Main factors that influence bottom current accumulation.

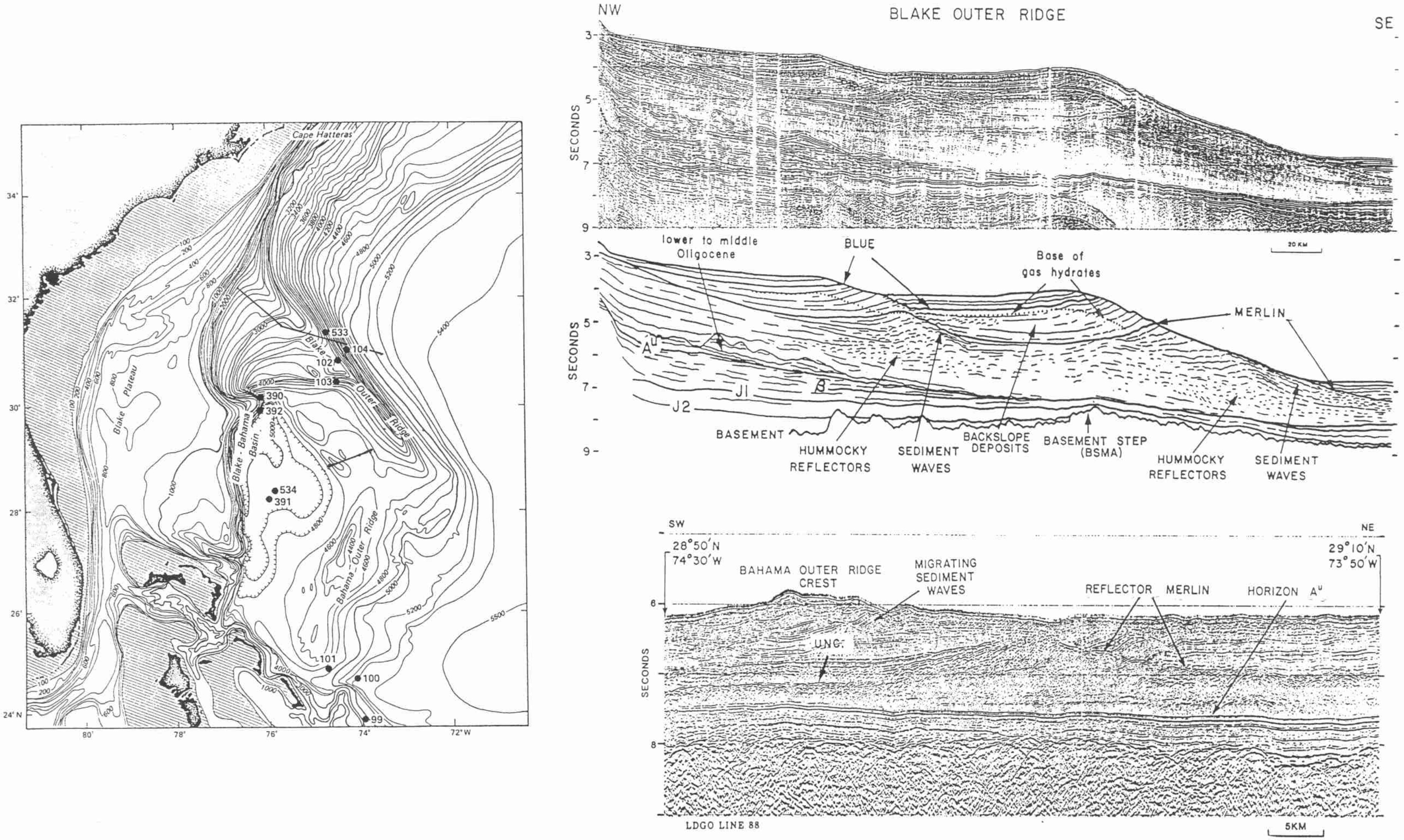


Fig. 2. Blake and Bahama outer ridges; an example of giant elongate drifts from the North Atlantic: location and morphologic and seismic patterns (from Mountain and Tucholke, 1985, and Tucholke and Mountain, 1986).

Narrow passageways through which a water nass is forced to flow, including deep straits etween land masses, valleys across volcanic idges and major fracture zones through the nid-ocean ridge system, are locally responsible or very high current velocities.

Variation in current intensity and velocity (as n (1) and (2) above) will markedly affect the edimentary processes beneath the current sysem; these may vary from strongly erosional, hrough mainly transporting to dominantly depoitional in nature in order of decreasing intensity.

3) Sediment supply

The rate of accumulation of sediment by botom currents also depends on the availability and olume of sediment input. Supply of terrigenous naterial is mainly controlled by geology, tectonics nd climate in the continental source area, by nargin morphology and relative tectonic activity, nd by sea-level variation. Supply of biogenic naterial is closely related to hydrological condiions, climate, productivity and deep-sea dissoluion of shell material. Locally, the direct input of irborne or seaborne volcaniclastic debris may be mportant in increasing rate of accumulation beeath bottom current systems.

4) Nepheloid layer turbidity

The turbidity of deep-water nepheloid layers is function of sediment supply, sea-floor erosion nd transport by bottom currents, and the posiion of the carbonate compensation depth. In eneral, nepheloid layers with a high sediment oad (turbidity) have the potential to effect greater ates of contourite accumulation. However, where he high turbidity is related more specifically to ncreased hydrodynamic energy above the sea-loor, then deposition may not occur.

ajor types of contourite accumulation

From the many examples of bottom deposits lescribed previously from the Atlantic and other ceans, we propose to distinguish three major ypes of contourite accumulation, which can be related to distinct topographic settings and which show different geometry, facies and rates of deposition.

(1) Giant elongate drifts

Giant elongate drifts are very large sediment bodies that have developed an elongated geometry parallel to trend of the bottom current system and hence parallel to the bottom topography (i.e. continental margin, mid-ocean ridge etc.). They are tens to hundreds of kilometres long, tens of kilometres wide, and range from 0.1 to more than 1 km in relief above the surrounding sea-floor. Their accumulated thickness may locally exceed 2 km. They can occur anywhere from the upper slope to abyssal depth, depending on the depth of the current involved in their construction. Some, but not all, are partly covered by large fields of giant sediment waves.

Typically, sedimentation rates are moderately high, averaging between 20 and 100 m/m.y., and the contourite facies relatively fine-grained, including silty muddy and biogenic contourites, with only very rare coarse-grained sandy contourites. In many cases, they are lithologically very similar to hemipelagites (calcareous silty clays) or pelagites (clayey foraminifer/nannofossil ooze).

Giant elongate drifts are particularly common in the North Atlantic Ocean (Figs. 2, 8), where they have been constructed by either the North Atlantic Deep Water (NADW) or by the Western Boundary Undercurrent (WBUC) composed of NADW and Antarctic Bottom Water (AABW). More than fifteen examples have been studied in detail since the first surveys in the mid-1960s (Heezen et al., 1966; Jones et al., 1970; see reviews by Stow and Holbrook, 1984, McCave and Tucholke, 1986). There are also some smaller, less well-developed elongate drifts along the south Iberian margin built by the Mediterranean outflow (Faugères et al., 1984, 1985; Stow et al., 1986), and in the western central Atlantic constructed beneath an outflow from the Caribbean Sea (Mullins et al., 1980).

In the South Atlantic (Le Pichon et al., 1971a; Flood and Shor, 1988), there are three major contourite drift complexes, which are related to a rather complicated gyre-pattern of AABW circulation around the deep Argentine Basin (Fig. 3). The most prominent is the Zapiola drift in the south, with a star-like form of crescentic to irregularly shaped elongate drifts. The sharp crests rise up to 1 km above the surrounding sea-floor giving a total thickness of accumulation that in places exceeds 3 km. Much of the complex is covered by giant sediment waves. The Argyro complex is a series of elongate drifts across the western part of the Argentine Basin, whereas the Ewing drift is a very large and complex arcuate construction that extends discontinuously from the lower Argentine continental rise in the north to the southeastern part of the basin where it merges in the Zapiola drift. Whereas the Ewing and Argyro drifts are fairly similar to the giant drifts of the North Atlantic, the Zapiola drift

Fig. 3. The Argentine Basin; examples of giant drift complexes and wavy contourite sheets. (Top) Drifts and sheet distribution and AABW flows (after Flood and Shor, 1988). (Bottom) W–E seismic line across the northern field of contourite waves (from Barker et al., 1977); profile length about 300 km; sediment thickness 1 cm ≃ 800 m.

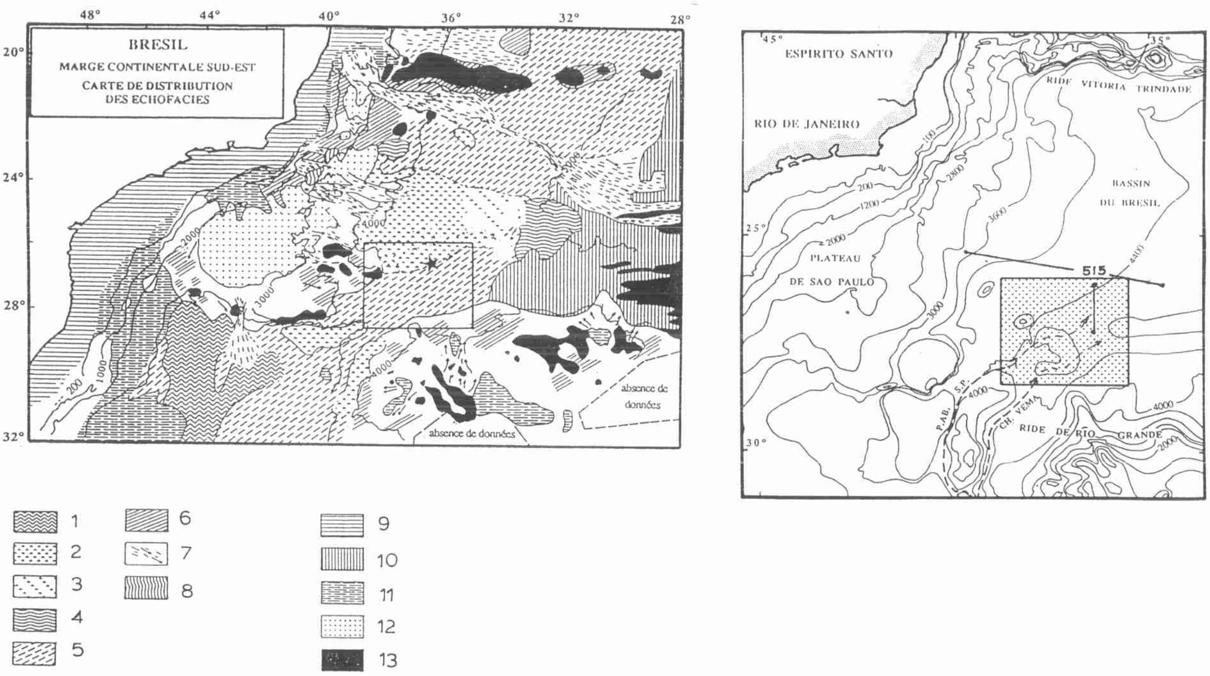


Fig. 4. The southeast Brazilian Basin. (Left) An example of South Atlantic drifts, waves and sheets, illustrated by echofacies distribution (after the Remac project, Cherkis, 1983). (Right) Vema Channel exit drifts and seismic line location. Deposition by contour currents: *1* = large-scale standing sediment waves (1 km $< \lambda <$ 5 km); numerous subbottom parallel reflectors; *2* = medium-scale sediment waves ($\lambda <$ 1 km); numerous subbottom parallel reflectors; *3* = medium-scale sediment waves ($\lambda <$ 1 km); non-parallel subbottom reflectors; *4* = bottom current main pathway with migrating sediment waves; echo with hyperbolae and subbottom reglectors; *5* = flow axis of bottom currents; hyperbolae reaching the bottom and subbottom reflectors. Deposition by gravity processes: *6* = sliding, slump; *7* = turbidity currents; *8* = migrating sediment waves on turbiditic levees (0.5 km $< \lambda <$ 4 km). Other patterns: *9* = continental shelf; *10* = abyssal hills; *11* = regular topography (echo with parallel subbottom reflectors); *12* = irregular topography (São Paulo Plateau); *13* = irregular topography (rocky outcrops). For the boxed areas see Fig. 8.

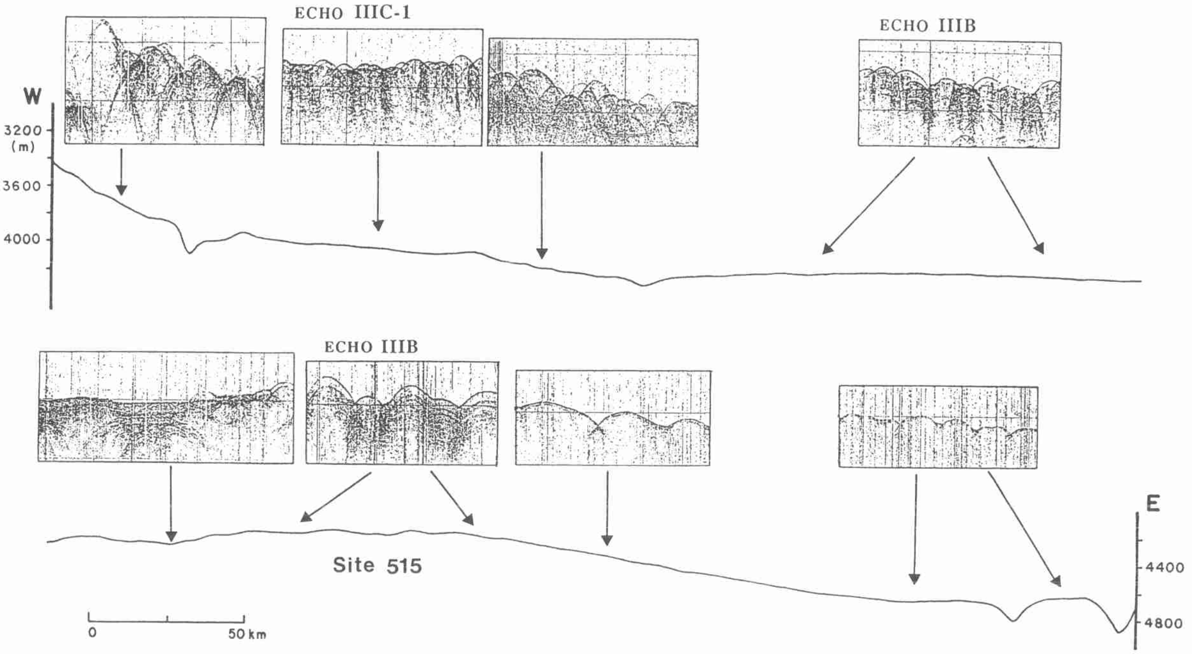


Fig. 5. 3.5 kHz profile (oriented W–E) across the southeast Brazilian Basin and showing various types of sediment waves (location on Fig. 4b).

differs in its morphology and mid-basin location without any linkage with a margin or a volcanic relief.

(2) Contourite sheets

Much less known than elongate mounded drifts are extensive low-relief accumulation, or contourite sheets, that form abyssal basin fills or are plastered against parts of the continental margin. In parts of the Argentine Basin (Fig. 3), flat fields of sediment waves occur over large areas (about 1,000,000 km^2); the waves typically have amplitudes of 10–80 m, wavelengths of 1–10 km, and show a steady migration (normally up-current) with time. The Zapiola, Argyro and Ewing drift complexes described above rise with a distinct mound-like form from this extensive contourite sheet.

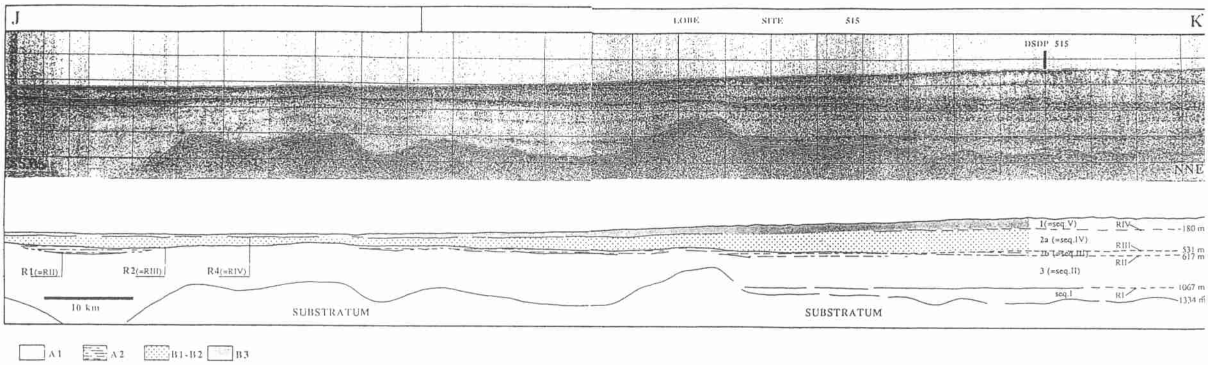
A similar, wave-covered contourite sheet system occurs in the south Brazilian Basin across the continental rise and onto the abyssal plain, in a broad area swept by the AABW (Damuth and Hayes, 1977; Mello, 1988; Mézerais, 1991) (Figs. 4, left and 5). The sedimentation rate on the rise averages 2–3 cm/1000 years, where the deposits are silty clays with low carbonate contents and cyclic variations in silt content. The rates of deposition decrease at greater depths, with a progressive change towards carbonate-free manganiferous brownish-coloured clays (Massé et al., 1991).

Seismic profiles in this area (Figs. 4, right an 6) record bottom current activity since the Earl Oligocene, in the form of three sequence bounded by well-marked unconformities corresponding to the onset of AABW flow and period of enhanced circulation (Gamboa et al., 1983 Barker et al., 1983). Seismic facies with regula undulating reflectors and, locally, channel-relate chaotic reflectors provide additional evidence o bottom current activity. The post-Miocene deposits (above RIV, DSDP hole 515, Gamboa e al., 1983) show an eastward thickening from abou 150 to 300 m, suggesting current-controlle progradation in this direction.

(3) Channel-related drifts

The third type of contourite deposit we identify is related to deep channels or passage through which the bottom circulation is constrained such that flow velocities are markedl increased. Such deposits have been describe from deep passages in the Atlantic, Indian an Pacific oceans (e.g. Kane Gap, Samoan Passage Almirante Passage etc.), and three different type can be recognised. These are irregular, discontinuous sediment bodies on (a) the floor of th channel, (b) the flanks, and (c) at the down-current exit of the channel.

One of the best documented passages is th Vema Channel through the Rio Grande Rise (L



PROFIL JK

Fig. 6. A seismic profile in the southeast Brazilian Basin showing three sequences (III, IV and V) bounded by the majo discontinuities RII, RIII et RIV and corresponding to drift accumulation since the onset of AABW flow, during the Earl Oligocene. *J–K*: profile oriented S–N and located on Fig. 4b (from Mézerais et al., 1993).

ichon et al., 1971b; Barker et al., 1983; Gamboa t al., 1983), which connects the Argentine Basin nd the Brazilian Basin and allows the northward low of AABW beneath the southward flowing ADW (Auffret et al., 1975; Johnson et al., 1976; eid et al., 1977; Hogg et al., 1982; Richardson et l., 1987, among others) (Figs. 7 and 8).

(a) *The channel-floor deposits* consist of irregular patches of unconsolidated sediment and manganiferous clays and silts. The manganese nodules (millimetric to centimetric in size) may constitute more than 80% of these sediments, which merge into a broad manganese pavement covering most of the sea-floor surface (Melguen and

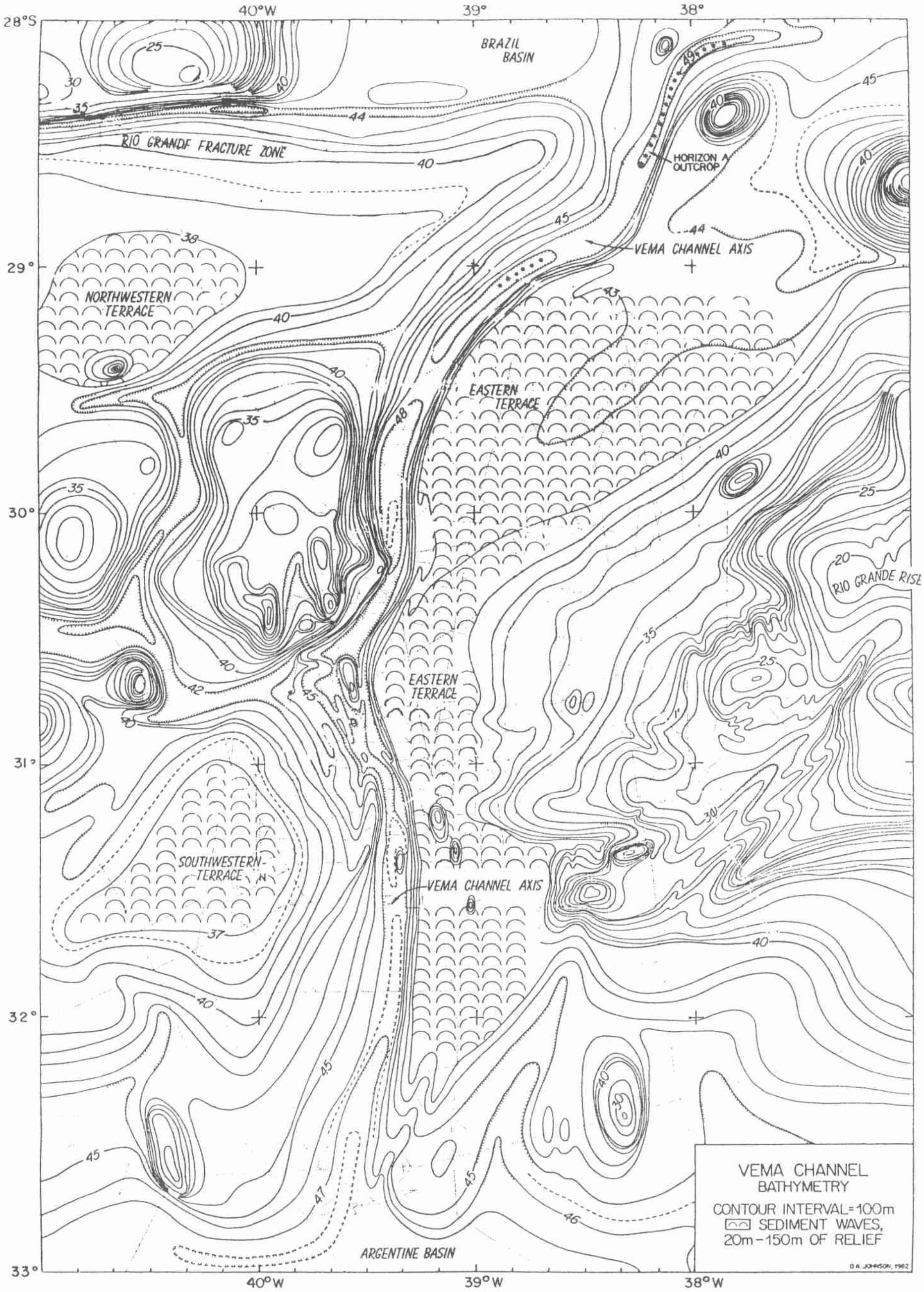


Fig. 7. The Vema Channel (Johnson, 1984): example of channel-related drifts on terraces located on both flanks of the valley.

Thiede, 1974, 1975; Chamley, 1975; Johnson et al., 1977; Ledbetter et al., 1978; Debrabant and Maillot, 1978; Melguen et al., 1978; Johnson, 1984), especially at the northern end of the channel (Mézerais, 1991).

(b) *The channel-flank deposits* occur on terraces located on both margins of the channel and at various heights above the channel floor (Johnson, 1984). These terraces are ornamented with sediment waves; the sediments are silty clayey muds with low carbonate contents (less than 15%) and accumulation rate of about 2–3 cm/1000 years.

(c) *The channel-exit deposits* occur as a cone-shaped sedimentary body built up at the northern exit of the channel (Figs. 4, right, 8) (Mézerais, 1991; Mézerais et al., 1993). It has been built between two main deep channels which cut through the Rio Grande Rise. The accumulation is 250 m high and 100 km wide and gently slopes down toward the NE where it is bordered by a shallow crescent-shaped depression that connects the two channels. Its maximum thickness since its initiation in Oligocene time is about 300 m. The Quaternary sediments consist of alternating greenish detritic silty clayey muds and yellowish manganiferous silty clays. Both facies are free of carbonate or with very low carbonate contents. The Quaternary sedimentation rate is generally high, variable across the accumulation, and difficult to assess on account of common erosional surfaces throughout the recovered core sections (3–4 cm/1000 years). 3.5 kHz echofacies and seismic lines shed some light on the sedimentary body building processes and its hydrological context: it is interpreted as deposition of the material

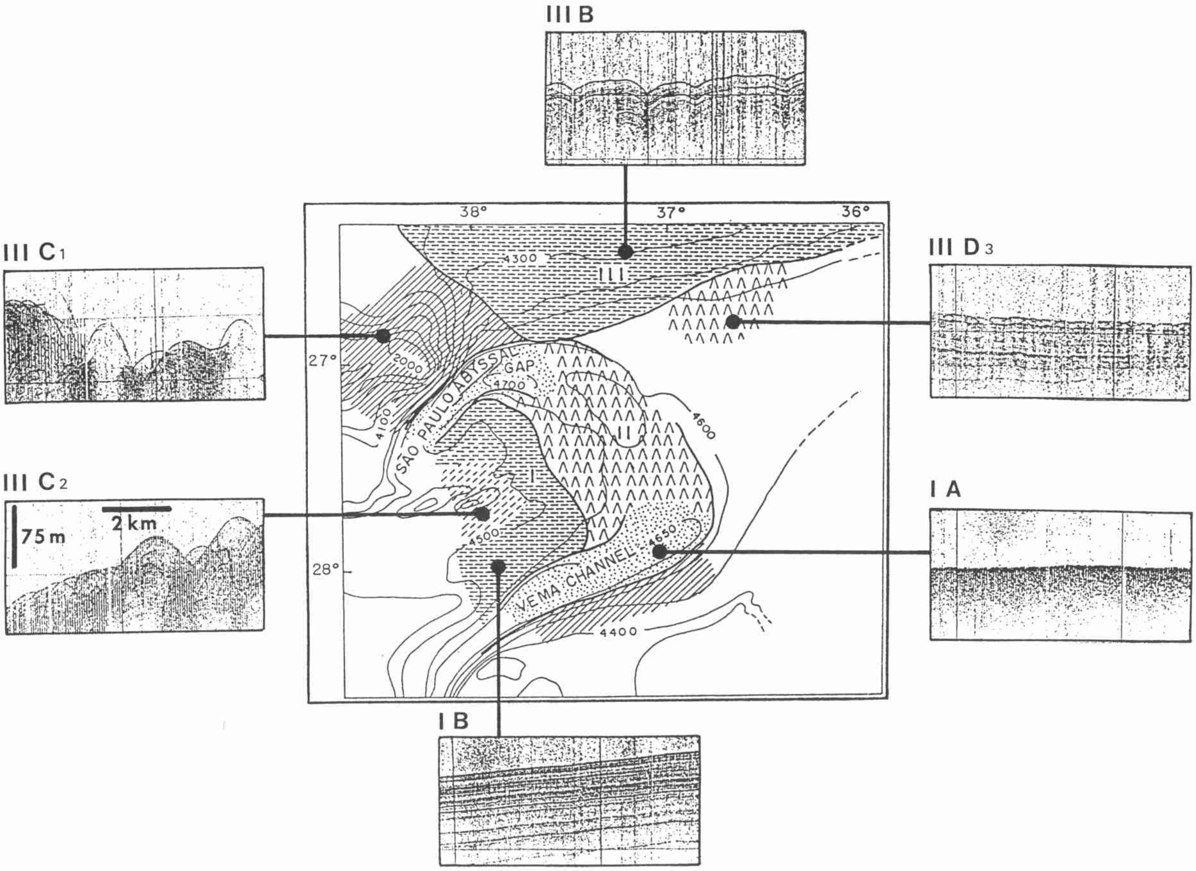


Fig. 8. Vema Channel exit drift (NE Vema Channel, located Fig. 3): distribution of echofacies linked to gravity processes (*IIIC1*), bottom current processes of high (*IA*), moderate (*IIID3, IIIB*) and low (*IB*) energy, and interaction between both processes (*IIIC2*). "Contourite fan": *I* = area of high deposition; *II* = depression bordering the accumulation, lower deposition. "Contourite sheet" on the rise: *III* = field of sediment waves, moderate deposition (see Fig. 5).

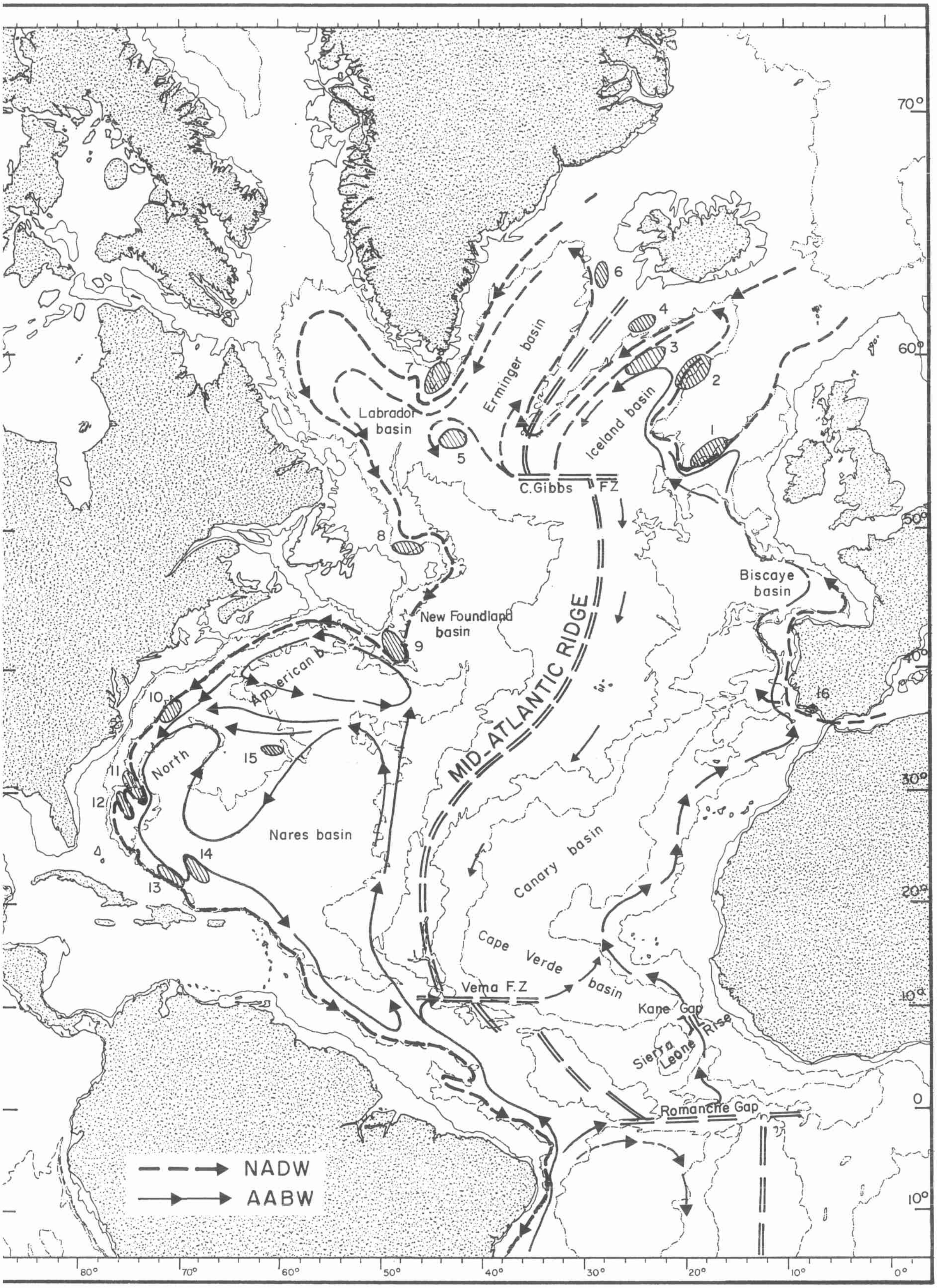


Fig. 9. North Atlantic Ocean sub-basins and circulation patterns (after McCave and Tucholke, 1986). The numbers refer to the “giant contourite drifts”. *1* = Feni; *2* = Hatton; *3* = Gardar; *4* = Bjorn; *5* = Gloria; *6* = Snorri; *7* = Eirik; *8* = Sackville spur; *9* = New Foundland; *10* = Hatteras; *11* = Blake; *13* = Caicos; *14* = Greater Antilles; *15* = Northern Bermuda; *16* = Faro.

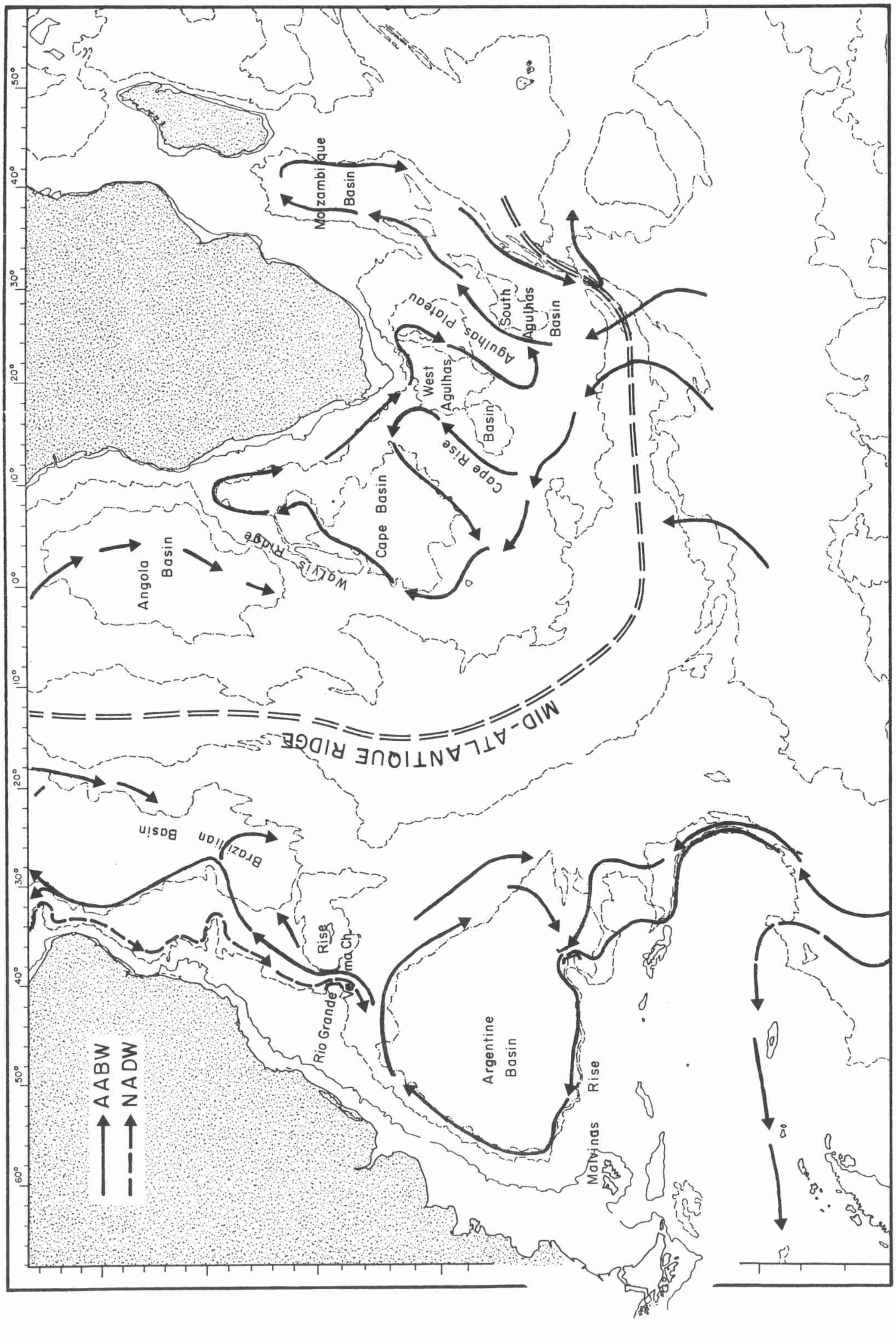


Fig. 10. South Atlantic Ocean sub-basins and circulation patterns.

ransported by the AABW below the shear zone aking place between the two branches of the deep circulation. The name of “contourite-fan” is proposed for this type of accumulation deposited at the exit of a deep channel (Mézerais, 1991). It has a cone-like form, seismic units which indicate a channel–levee system of deposits, seismic geometry showing superimposed units that migrate aterally and downstream, so that it mimics turbiditic deep-sea fans but has been built by conour currents.

Distribution of contourite accumulation in the Atlantic Ocean

The distribution of different types of conourite accumulation reveals a significant difference between the North and the South Atlantic. With certain exceptions, giant marginal elongate drifts are the prominent contourite bodies in the North Atlantic, whereas contourite sheets and channel-related drifts are more typical of the South Atlantic. How can one explain such a disribution?

North Atlantic Ocean (Fig. 9)

The North Atlantic Ocean is composed of numerous sub-basins of limited geographic extension, named Sierra Leone, Cape Verde, Canary, Iberian, Rockall, Iceland basins in the Eastern Ocean, and Guyana, North America, Newfoundand, Labrador, Erminger basins in the Western Ocean. In fact, these sub-basins are largely open and interconnected, and grouped in the two maor basins elongated N–S on each side of the mid-oceanic ridge: the East and the West North Atlantic basins. Communication between these two main basins is restricted to narrow passages along the transform fracture zones, whereas, within the East and West basins, the deep circuation may move without encountering any major topographic barriers.

This circulation is mainly derived from the Norwegian Sea Water, as cold, dense currents overflowing the Scotland–Iceland–Greenland sills and are then deflected against the margins of the Northern basins. They flow generally south and westward as well as through the deep valleys of the Charlie Gibbs Fracture Zone, which connects the NE and NW Atlantic basins.

The AABW-derived currents occur mainly throughout the southern part of the NW Atlantic basin (Fig. 9), with fairly complex and still partly unknown circulation paths (McCave and Tucholke, 1986). Schematically they flow northward along the mid-oceanic ridge, then southward where they combine with the NADW and form the Western Boundary Under Current (WBUC).

In such an hydrological and morphological context, deposition of giant marginal drifts is the result of major sediment inputs from multiple sources. Terrigenous supplies are derived from the adjacent continents and islands (notably Iceland) where fluvial and glacial erosion and transport of sediment are very active. Biogenic production of skeletal material is equally important and the calcareous particles well-preserved as the sea-floor is most often above the CCD. In addition, it has been demonstrated that the energy of major surficial currents (e.g. the Gulf Stream) may directly enhance bottom current energy and therefore contribute to the process of sedimentation (Hollister and McCave, 1984). Such conditions coincide with a high-turbidity nepheloid layer (e.g. off Cape Hatteras margin, Biscaye and Eittreim, 1977) which favours rapid deposition (McCave and Tucholke, 1986).

To summarize, we observe that giant marginal elongate drifts of the North Atlantic Ocean occur along margins of relatively open basins, swept by active bottom currents that are not trapped in gyre-like recirculation, and that contourite sedimentation is locally enhanced by increased surficial current energy, and where there is an abundant terrigenous and/or biogenic supply.

South Atlantic Ocean (Fig. 10)

The sea-floor morphology of the South Atlantic is very different from that of the North Atlantic Ocean. On both sides of the mid-oceanic ridge, the sea-floor is compartmentalised into several well-delineated and nearly closed sub-basins. This topographical pattern is due to the presence of prominent E–W topographic barriers of volcanic origin.

In the Western South Atlantic, the Vittoria Trindade chain separates the North and South Brazilian basins, the Rio Grande Rise separates the Argentine and the South Brazilian basins, the Falkland Rise–North Scotia Ridge separates the Argentine and Scotia basins, and the South Scotia Ridge separates the Scotia and the Weddell Sea basins.

In the Eastern South Atlantic, a similar pattern emerges in the Cape Rise between the Cape and Agulhas basins, the Walvis Ridge between the Cape and Angola basins and the Sierra Leone Rise between the Angola and Cape Verde basins. Only very few deep erosional valleys that cut through the sedimentary cover of the volcanic rises, connect these basins, including the Falkland Gap, the Vema Channel, the Kane Gap, and other narrow passages across the Cape Rise and in the Agulhas Basin.

A deep circulation system is active in the South Atlantic Ocean, especially in the southernmost basins and along the western continental margins. This circulation is supplied by the AABW, dominantly formed in the Weddell Sea. As a result of the morphological background, the bottom currents are (a) partly trapped in the basins and move in a gyre-like circulation pattern, and (b) locally restricted in narrow channels that provide the only means of connection between basins.

The Argentine Basin provides a good example of these morpho-hydrological conditions. The AABW currents flow from the Weddell Sea toward the Sandwich Trench and Orcadas Rise and then into the Argentine Basin through the Falkland Fracture Zone. In the basin itself, the currents are deflected toward the west against the Falkland Rise, then move along the Argentine margin, the south flank of the Rio Grande Rise and then the west flank of the Mid-Atlantic Ridge. Detailed reconstruction of the current pathways reveals an even more complex circulation pattern, documented by numerous bottom photographs, 3.5 kHz records (Flood and Shor, 1988), and grain-size studies of the deposits (Klaus and Ledbetter, 1988).

Whatever the detail of this circulation, it is evident that a major part of the AABW is trapped in the basin and moves in an anticyclonic gyre. Only a minor part of this water escapes from th basin and flows into the Brazilian Basin throug the Rio Grande Gap where high-velocity current have been recorded. About 10% of the AABW introduced into the Argentine Basin along th Falkland escarpment exits the basin northwar through the Vema Channel.

A similar pattern of gyral circulation has bee described for the southeastern Atlantic basin (Tucholke and Embley, 1984) as well as for th Brazilian Basin, at least in its southern part.

As a direct result of these morphological an hydrological characteristics, bottom current sedimentation patterns are, not surprisingly, differen from those of the North Atlantic, both in contourite drift morphology and lithology. There ar no giant-marginal elongate drifts in the Sout Atlantic, apart from the rather complex patter of elongate drifts in the central and souther Argentine Basin. Instead, contourite sheet widespread fields of sediment waves an channel-related deposits are typical. The Zapiol drift with its star-like form and bifurcated crest is best explained by secondary gyres of the basinal recirculation pattern.

A further influence on the style of contourit deposited in the South Atlantic is a generally lo sediment supply due to low continental input and a shallow (4000–4500 m) position of th CCD which results in extensive carbonate dissolution. These factors may help explain the lack development of giant elongate drifts on the Sout Brazilian continental rise, for example, where th Neogene sedimentation rates are about thre times lower than over the North Atlantic margina drifts. Still more drastic conditions occur on th margins of the Cape and Agulhas basins wher erosion and transport processes are prominent a the combined result of sediment starvation an active contour currents (Tucholke and Emble 1984).

However, in other regions where terrigenou inputs are fairly abundant, a different limitin factor for bottom current deposition may be invoked, namely the occurrence of high sea-surfac energy. This occurs along the Argentine cont nental margin where the surficial circulatio (Malvinas and Brazilian currents) creates ver igh surface energy which, in turn, leads to very igh-energy conditions at the bottom and consequent non-deposition and/or erosion on the deep ca-floor despite the high turbidity of the nephloid layer. This part of the continental margin isplays a generally concave shape, as a result of rosion and transport away from the area, and as a very low average sedimentation rate.

onclusions

The morphological pattern of Atlantic basins ppears to be a major controlling factor in the tyle of contourite accumulation. In the North tlantic, the basins are largely open without sigificant topographic barriers, the strong currents ow without impediment and are continually fed y both terrigenous and biogenic material. The ost frequent contourite accumulations are of e form of giant elongate drifts which are conructed along the continental margins and along e flanks of the mid-oceanic ridge. However cally, partial enclosure of the bottom current stem, as in the distal part of the Erminger asin, results in a complex of low-amplitude rifts, contourite sheets and large sediment waves, ery similar to the contourite drifts in the Argenne Basin. Parts of the continental margins are lso covered by thin contourite sheets, probably here sediment supply to the bottom is rericted.

In the South Atlantic, the deep circulation is qually active with strong currents of AABW, but ther factors result in a somewhat different style f contourite accumulation compared to that of e North Atlantic Ocean. The deep South Atntic is composed of nearly closed basins of mited extent (Argentine, Brazilian, Cape, Agulas) instead of the large, open East and West orth Atlantic basins. In some cases, these basins e only connected by deep channels that form mpulsory pathways for the main flow. As a nsequence, the AABW is first confined against e western margins, then partly trapped on the ttom of the southern basins moving in large ockwise gyres before escaping towards the north rough the deep channels. Furthermore, the sedent inputs are rather low and deposition occurs ostly beneath the CCD.

In this context, no large well-developed contourite drifts have been constructed at the foot of the basin margins. Instead, erosional surfaces and moats (SW South African Basin) and depressions due to low sedimentation rates (western border of the Argentine Basin) are observed. In the basins themselves, deposits constitute widespread contourite sheets covered by long-wavelength sediment waves (Argentine, Brazilian and Cape basins) sometimes associated with complex giant drifts, and cone-shaped sedimentary body that are deposited downstream of channel exits, for example the "contourite fan" NE of the Vema Channel.

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