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Abyssal circulation change in the equatorial Atlantic: Evidence from Cenozoic sedimentary drifts off West Africa

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Abstract

Seismic profiling in the equatorial Atlantic reveals deep-water (>4500 m) sediment bodies formed by current-controlled deposition near the intersection of large-offset fracture zones with the African margin. A 600 km-long drift accumulation, the Ivory Coast Rise, lies north of the St Paul Transform near 3° N. A smaller drift deposit has been identified along the northern side of the Guinea Transform at 10° N. Antarctic Bottom Water (AABW), which presently enters the eastern Atlantic basins through the Romanche and Vema Fracture Zones, probably played an important role in the development of these features. Proto-AABW may have reached the equatorial region as early as mid-Eocene time, before the establishment of permanent ice sheets in Antarctica. The Ivory Coast Rise existed as a distinct sedimentary drift by the mid-Eocene as a result of deposition from bottom water moving southwards along the African margin and westwards parallel to the St Paul Fracture Zone. This early flow pattern is in the opposite sense to the present movement of deep water in the Sierra Leone Basin. A reversal in abyssal circulation may have been caused by the northward passage of the region across the paleoequator during the Cenozoic.

Keywords: Atlantic; seismic reflection profiles; drift deposits; paleocirculation; Antarctic Bottom Water; fracture zones

1. Introduction

The development of sedimentary bodies in the paths of abyssal currents is important to our understanding of the history of thermohaline circulation in the oceans and the formation of ancient contourite deposits. Most sedimentary drifts in the deep sea can be related to present-day movements of water derived from high latitudes. Examples include the Blake Outer Ridge and Feni Ridge in the North Atlantic (Heezen et al., 1966; Jones et al., 1970; Mountain and Tucholke, 1985), Ewing Drift in the South Atlantic (Flood and Shor, 1988), Davie Drift in the western Indian Ocean (Faugères et al., 1999) and the Eastern New Zealand drifts in the West Pacific (Carter et al., 2004). Seismic profiling has revealed their internal structure (Faugères et al., 1999; Viana, 2001), while drilling and shallow coring have clarified the role of bottom currents in controlling deep-sea sedimentation (e.g. Kidd and Hill, 1987; Arthur et al., 1989; Bianchi and McCave, 2000; Knutz et al., 2002). Using seismic reflection data, bathymetry and oceanographic observations we now consider sedimentary accumulations which have been built up in an area of the equatorial Atlantic where the past flow regime was quite different from that at

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the present time. The deposits are also of interest in their tropical setting because their formation is related to the transfer of polar water across both the equator and the Mid-Atlantic Ridge. Furthermore, the Coriolis deflection of bottom currents in this area, although weak, is highly sensitive to changes in paleolatitude.

Two sedimentary features have been investigated using single-channel seismic reflection profiles recorded by the vessels *Atlantis II*, *Shackleton* and *Vema* in conjunction with recent bathymetric data (Fig. 1). The larger is the Ivory Coast Rise which was included in a reconnaissance seismic survey off West Africa by Emery et al. (1975). It lies in the Sierra Leone Basin, an area that began to develop during the Aptian by sea-floor spreading between the St Paul and Guinea Fracture Zones (Sibuet and Mascle, 1978; Jones et al., 1995). A second and smaller sedimentary feature, here named the Guinea Drift, has been identified in the southern part of the Gambia Basin, which opened in the late Jurassic (Hayes and Rabinowitz, 1975). The drift deposit lies close to the Guinea Fracture Zone, a large-offset transform that meets the African margin along the edge of the Guinea Plateau (Fig. 1).

2. Bathymetric setting

Recent compilations of bathymetric data (IBCEA, 1999) show that the Ivory Coast Rise forms a broad swell

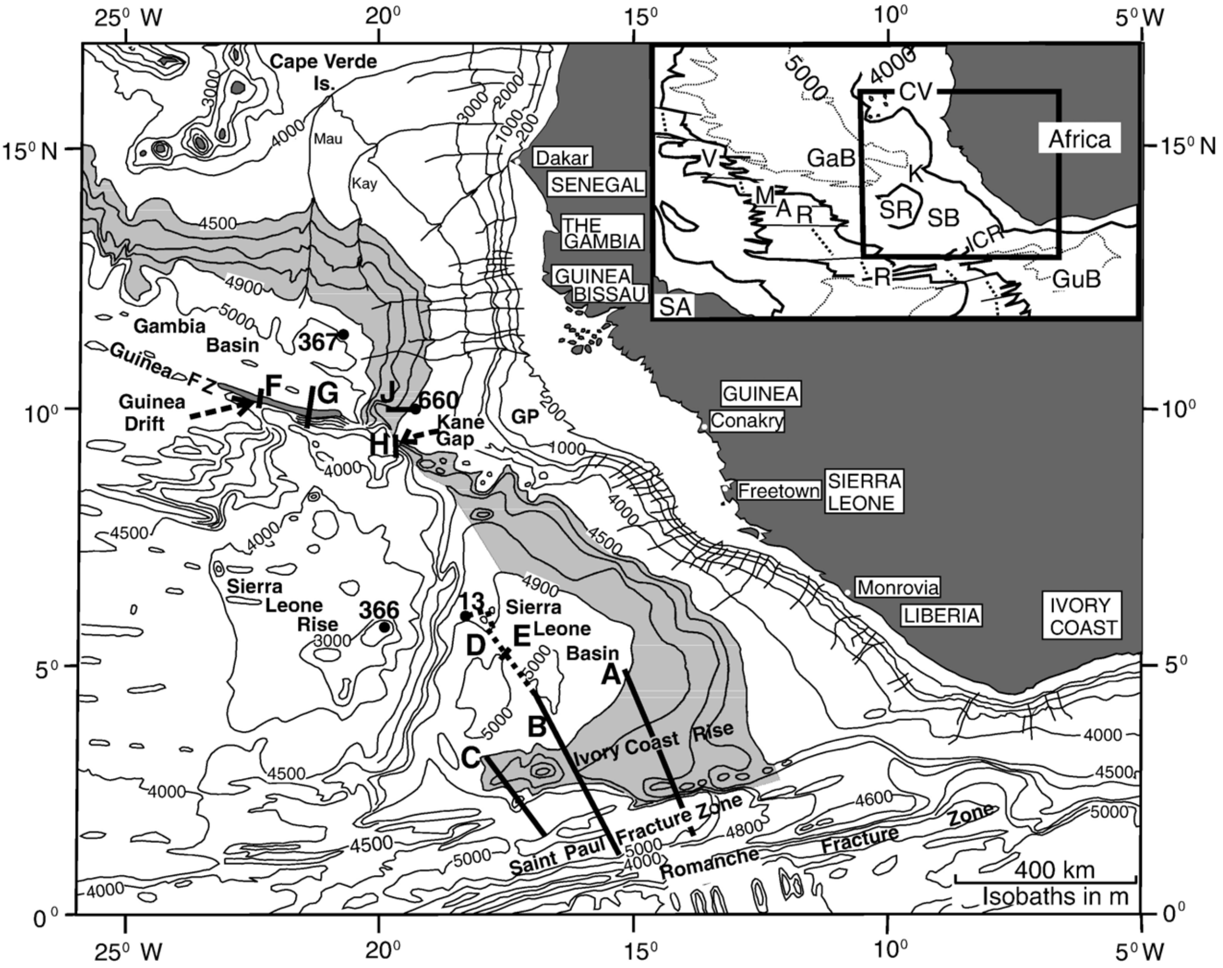


Fig. 1. Bathymetry of the Sierra Leone Basin and environs from IBCEA (1999), with additions from Searle et al. (1982) and Hunter et al. (1983). The continental rise between 4500 m and 4900 m, and the Guinea Drift along the southern margin of the Gambia Basin are shaded. Locations of main canyons on the continental slope and deep-sea channels on the continental rise are shown; Mau — Mauritania Channel, Kay — Kayar Channel. Positions of seismic profiles A–J and DSDP/ODP sites 13, 366, 367 and 660 are indicated. GP — Guinea Plateau. Inset map: CV — Cape Verde Islands, GaB — Gambia Basin, K — Kane Gap, SR — Sierra Leone Rise, SB — Sierra Leone Basin, ICR — Ivory Coast Rise, GuB — Guinea Basin, MAR — Mid-Atlantic Ridge, V — Vema Fracture Zone, R — Romanche Fracture Zone, SA — South America.

that continues westwards from the Liberian continental slope for over 800 km. Defined approximately by the 4500 m and 4900 m isobaths, the elevation occupies much of the southern part of the Sierra Leone Basin. It is situated north of the complex topography associated with the St Paul Fracture Zone and south of a section of the African continental slope which is deeply dissected by canyons. The Ivory Coast Rise presently acts as a barrier to

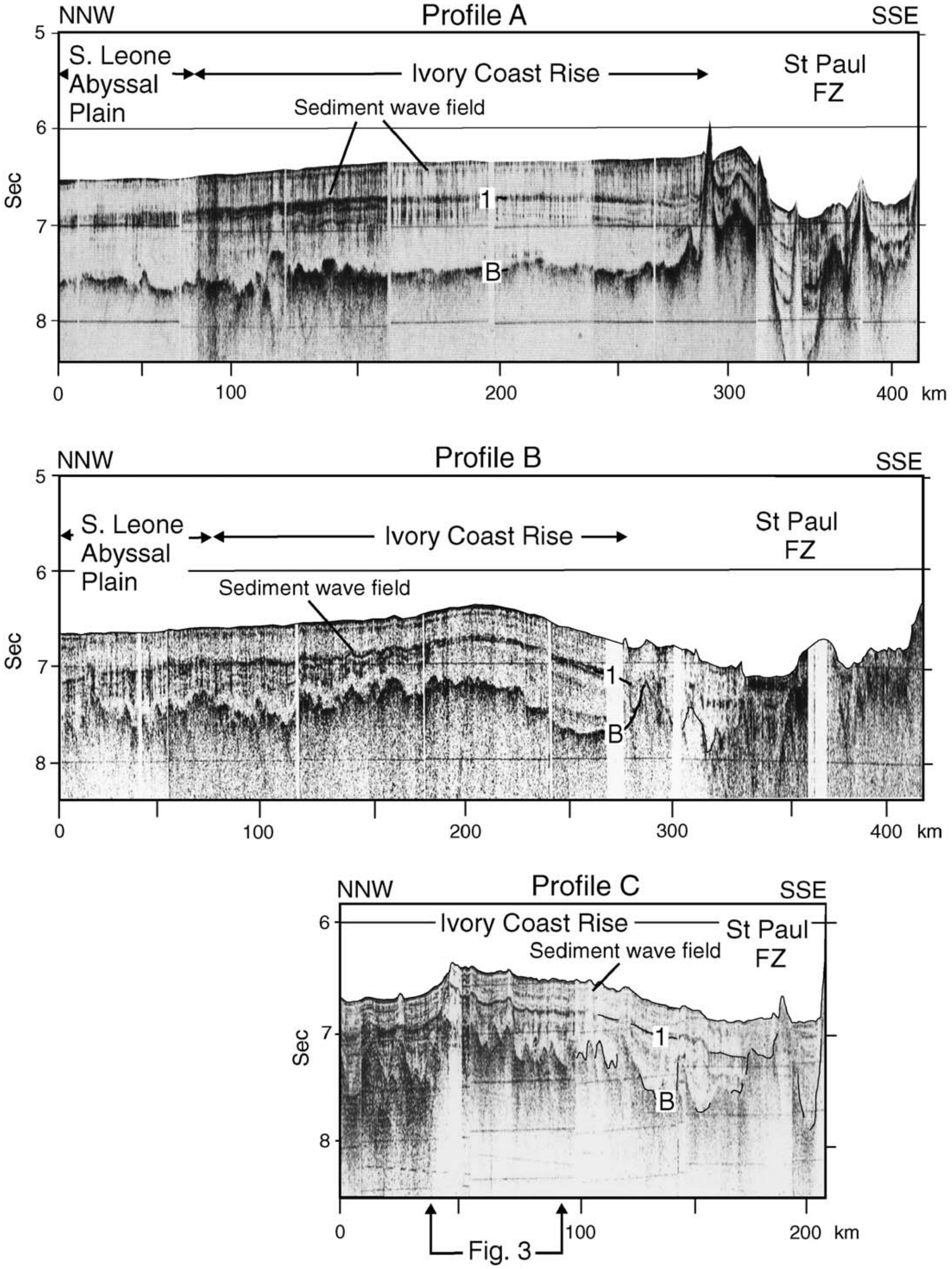


Fig. 2. Seismic reflection profiles A–C across the Ivory Coast Rise, with two-way travel times shown. Vertical exaggeration ~ 62. See Fig. 1 for locations. A tie line to DSDP-13 (Fig. 4) indicates that reflector 1 within the sediment cover is mid-Eocene. Reflector B is the oceanic basement.

southward-flowing turbidity currents from the canyon system off Sierra Leone and Guinea as far as 18° 30′ W (Fig. 1). Between its western termination and the Sierra Leone Rise water depths are great enough to provide access for sediment-laden bottom currents into the main trough of the St Paul Fracture Zone.

North of the Ivory Coast Rise the abyssal parts of the Sierra Leone Basin extend as far as the Sierra Leone Rise and Guinea Plateau (Fig. 1). The latter is bounded by the Guinea Fracture Zone, a large-offset transform that continues westwards to form the southern margin of the Gambia Basin. The Guinea Drift lies north of the transform and can be traced for more than 200 km in an ESE direction from 23° W. Situated on the line of the transform east of the Guinea Drift is a narrow deep-water channel known as Kane Gap (Egloff, 1972). This region between the Guinea Plateau and the Sierra Leone Rise has a sill depth of ~ 4570 m and forms a deep-water connection between the Gambia and Sierra Leone Basins. North of Kane Gap the African continental rise broadens to merge with the thick apron of sediments around the Cape Verde Islands. The continental rise is here incised by several long deep-sea channels, the largest being the Mauritania and Kayar (Fig. 1; Egloff, 1972; Hunter et al., 1983).

3. Seismic profiles

Seismic reflection profiles across the Ivory Coast Rise are shown in Figs. 2 and 3. Sections A and B were recorded from *R/V Vema* using a small airgun source (~ 0.4 L) fired at intervals of ~ 40 m along track and the summed output of a short (~ 30 m) towed hydrophone array. Profile C was acquired by *R/V Atlantis II* with a similar airgun and the combined outputs of two 30 m hydrophone arrays towed from port and starboard booms. At the northern end of profile A sediments of the Sierra Leone Abyssal Plain cover smooth oceanic basement located 1 s below the sea floor or at a depth of 1 km, assuming an average seismic velocity of 2 km s^{-1}. Further south the water depth decreases and the sediments are mounded against the rough basement topography of the St Paul Transform. Within the sediments is a prominent seismic reflector labelled 1, which continues across the Ivory Coast Rise into the fracture zone. This reflector delineates a broad sub-surface sedimentary swell that developed on a smooth basement floor to the north of the St Paul Fracture Zone. Profile B shows the central part of the Ivory Coast Rise to be a sedimentary ridge with a southern flank dipping into the St Paul Fracture Zone. The irregular basement topography of the northern transform ridge (~ 300 km, horizontal axis) is deeper on this section and is buried under 0.3 s (300 m) of sediments. A broad sub-bottom swell is clearly defined by reflector 1. Profile C crosses the Ivory Coast Rise near its western termination. It is imaged as a sedimentary ridge covering a basement surface which is more irregular than further east. Reflector sequences indicating migration of the crest of the Rise, non-uniform deposition and the development of large sedimentary waves with wavelengths of 1–3 km are shown in Fig. 3. Reflector 1 is again a prominent seismic horizon within the sedimentary cover.

The nearest deep-water location at which drilling reached reflector 1 is DSDP-13 in the western Sierra Leone Basin (Fig. 1; Maxwell et al., 1970). Profile D (Fig. 4a) shows the continuity of the reflector from the

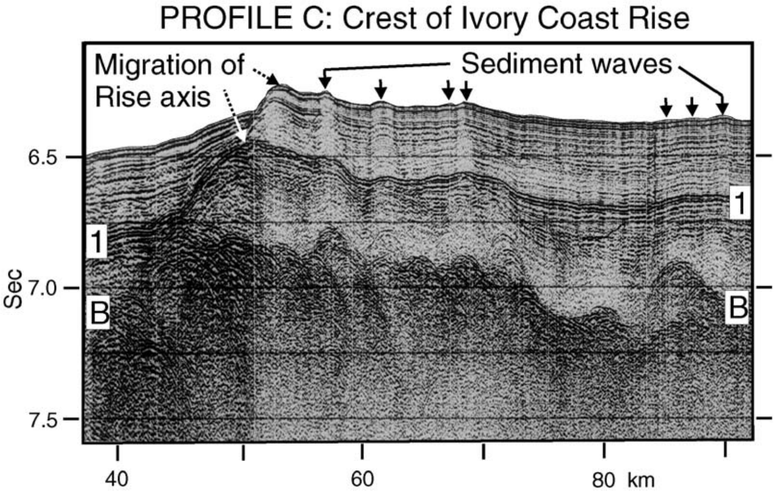


Fig. 3. Enlarged section from profile C (Fig. 2) showing the crest of the Ivory Coast Rise. The mid-Eocene reflector 1 is imaged by strong returns from a depth of ~ 0.3 s below the sea floor. B — oceanic basement.

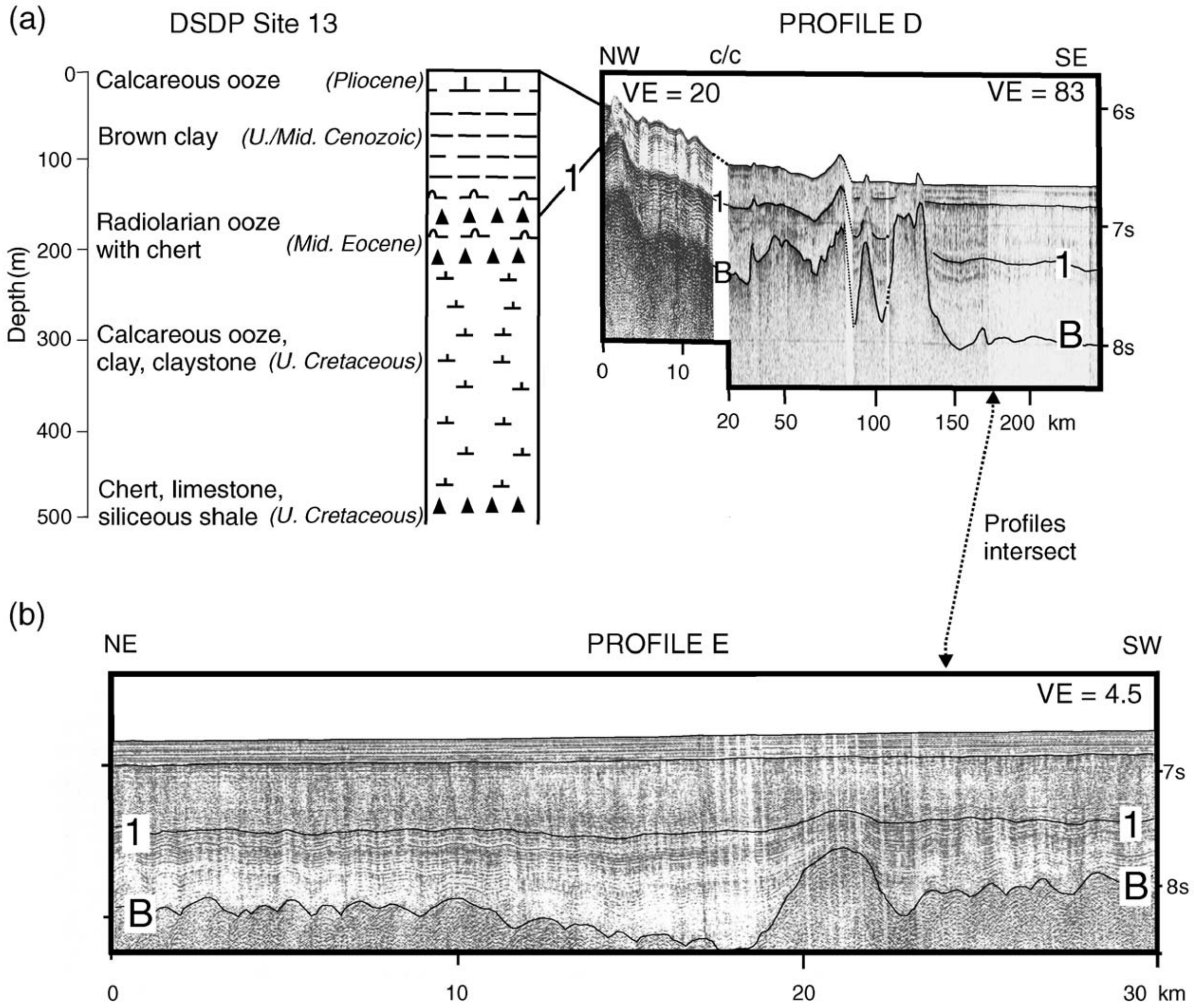


Fig. 4. (a) Profile D compiled from single-channel sections recorded by *R/V Vema* and *RRS Shackleton* which link DSDP-13 to the northern end of profile B (Fig. 2). See Fig. 1 for location. Summary of drilling results is taken from Maxwell et al. (1970). Seismic reflector 1 is associated with a chert-rich sequence of mid-Eocene age. B — oceanic basement. VE — vertical exaggeration. c/c — course change. (b) Abyssal plain sediments on reflection profile E which crosses profile D at km 175. See Fig. 1 for track position.

northern end of profile B to the drill-site where strong seismic returns come from a sequence of mid-Eocene cherts of high acoustic impedance interbedded with clays. Reflector 1 in relation to the structure of the abyssal plain sediments is recorded on a cross-line (profile E; Fig. 4b). Mid-Eocene siliceous sediments are associated with the same seismic horizon at DSDP-367 and ODP-660 in the Gambia Basin (Fig. 1; Lancelot et al., 1977b; Ruddiman et al., 1988) and DSDP-366 on the Sierra Leone Rise (Lancelot et al., 1977a). The gentle sub-bottom sedimentary swell marked by reflector 1 on profiles A–C (Fig. 2) suggests that the Ivory Coast Rise had begun to develop as a distinct sedimentary feature by mid-Eocene time.

The pronounced westward extension of the sedimentary apron off Africa to form the Ivory Coast Rise might be explained by preferential transport of material by turbidity currents from the adjacent Liberian continental margin. However, the distribution of canyons on the continental slope indicates that the main transport routes from the coastal areas to the deep sea were further north and directed into the Sierra Leone and Gambia abyssal plains (Fig. 1). The presence of extensive sediment wave fields both in the deep sub-surface and near the sea floor on the Ivory Coast Rise (Jacobi and Hayes, 1992) the migration of its axis (Figs. 2, 3) and a general broadening of the lower continental rise across most of the southern half of the Sierra Leone Basin (Fig. 1) suggest that bottom currents have played an important role in shaping the feature. The Ivory Coast Rise bears close similarities in its topography and structure to the sheet-like abyssal contourite drifts of the Argentine Basin (Ewing et al., 1971; Flood and Shor, 1988) and Labrador Sea (Jones et al., 1970; Egloff and Johnson, 1975). These form a cover of almost uniform thickness over a wide area, with a slight decrease in thickness near their margins. Surface and subsurface sediment wave fields are extensive and internal seismic reflectors are usually of low amplitude so the sediments are almost acoustically transparent (Faugères et al., 1999). The seismic transparency of much of the sedimentary cover of the Ivory Coast Rise, while not diagnostic of contourite deposits (Faugères et al., 1999), contrasts with the highly reflective turbidites of the Sierra Leone Abyssal Plain (Fig. 4b) and also with the acoustically reverberant sediments beneath the continental rise seaward of the continental slope canyons further north (Jones and Mgbatogu, 1982; Rossi et al., 1992).

Profiles F and G recorded from *RRS Shackleton* across the margin of the Gambia Basin west of Kane Gap (Fig. 5) image the Guinea Drift as a deposit that is clearly differentiated from the sediments of the Gambia Abyssal Plain. Unlike the Ivory Coast Rise, the drift is not connected to the African continental margin but terminates close to Kane Gap. Drilling at DSDP-367 shows that the flat-lying and highly reflective abyssal plain sediments consist of foraminiferal marls interbedded with sand and silt beds deposited by turbidity currents. Evidence of redeposition of material of shallow water origin is shown by the common occurrence of microfossils of Mesozoic and Cenozoic age in the turbidite units (Lancelot et al., 1977b). Reflector 1 lies at a depth of 0.35–0.45 s (350–450 m) beneath the abyssal plain. Other seismic profiles recorded north of profiles F and G (Uchupi et al., 1976: Jones, 1987) show that reflector 1 can be traced to DSDP-367 (Fig. 1) where it correlates with a sequence of mid-Eocene siliceous sediments (Lancelot et al., 1977b).

Reflectors within the Guinea Drift reveal similar sedimentary features to those making up the elongate mounded drifts described by Faugères et al. (1999). Both seismic profiles over the drift show rapid changes in sediment thickness due to non-uniform deposition and erosion. Indications of the early effects of bottom currents are apparent from sediment waves between reflector 1 and

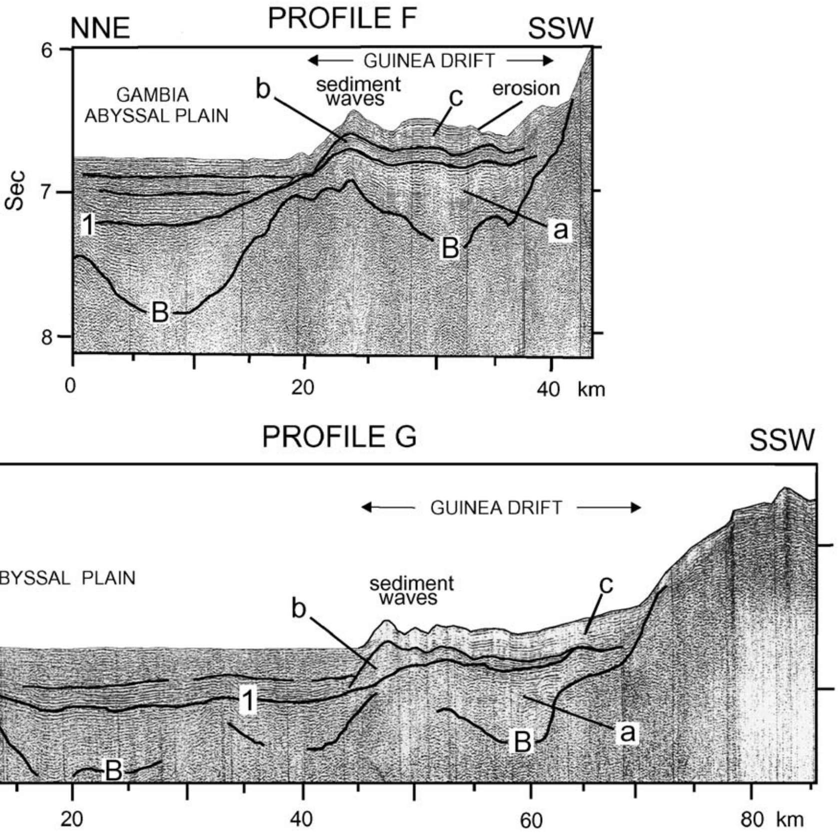


Fig. 5. Reflection profiles F and G over the Guinea Drift along the southern margin of the Gambia Basin. Both were recorded by *RRS Shackleton* using a 1.6 L airgun and the summed output of a 50 m hydrophone array. See Fig. 1 for track positions. 1 — mid-Eocene reflector. B — oceanic basement. Sedimentary units labelled a–c are discussed in the text.

the oceanic basement (unit a, Fig. 5). Current-controlled deposition is clear above reflector 1, with the deposition of two distinct drift units designated b and c. Recent erosion of the uppermost sequence has occurred on the southern side of the drift near km 33 on profile F.

Profile H (Fig. 6) over the shallowest part of Kane Gap shows a seabed which is strongly reverberant along most of the section. A nearby seismic profile (line J; Fig. 6) which crosses ODP-660 (Fig. 1) shows that the highly reflective sea floor is the southern continuation of the strongly reflective mid-Eocene siliceous sequence recovered at the drill-site (Ruddiman et al., 1988). In Kane Gap it is clear that the post-mid-Eocene sedimentary cover is thin or absent. Seismic reflector 1 appears to be exposed at the seabed and is underlain by the continuation of the seamount basement imaged at the southern end of the section (B: Fig. 6). Erosion or non-deposition has also been reported in this area by Hobart et al. (1975). The thinness or absence of the post-mid-Eocene sediment cover in a region so close to the African margin contrasts markedly with the thick sediments forming the Ivory Coast Rise further south, a difference emphasised by recently compiled bathymetry (IBCEA, 1999; Fig. 1).

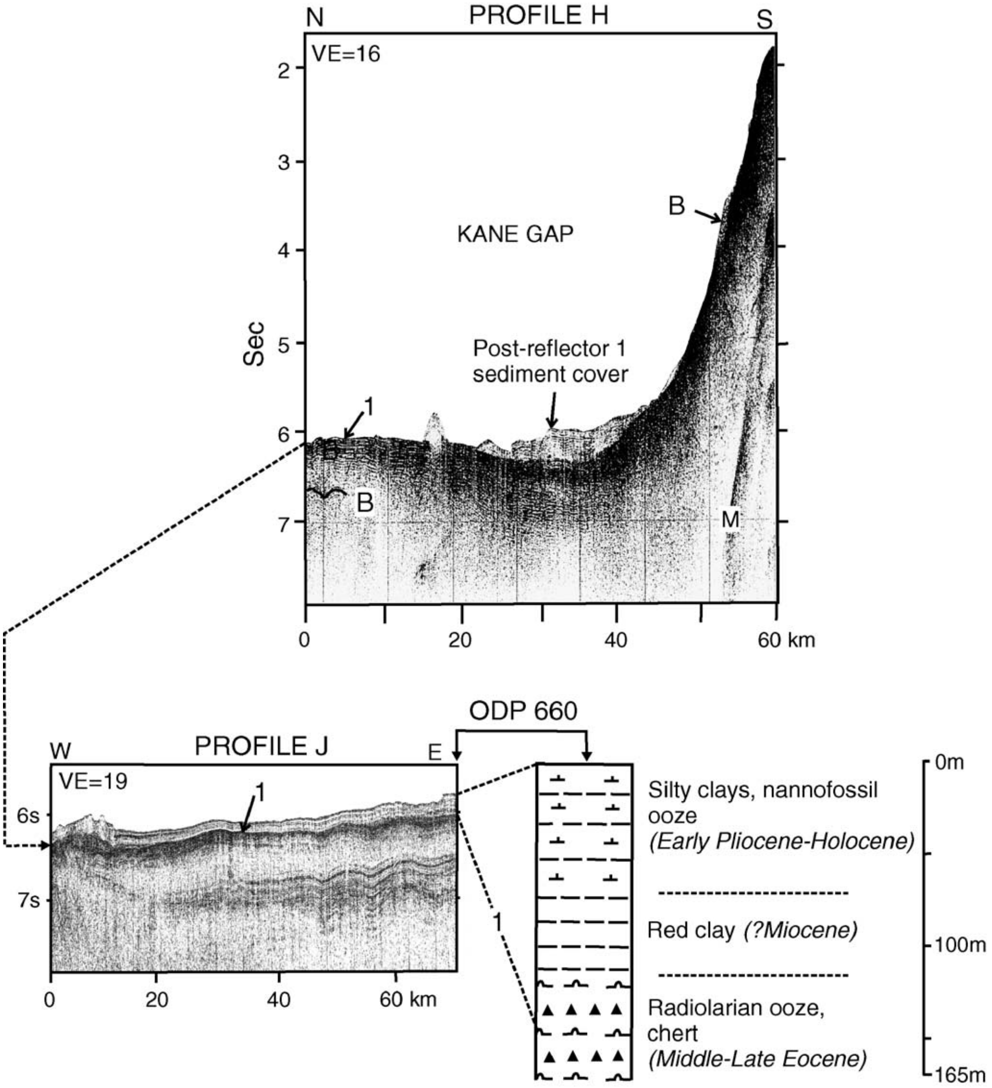


Fig. 6. Profile H across Kane Gap. This *Shackleton* section runs over the shallowest part of the sill between the Gambia and Sierra Leone Basins (Fig. 1) where reflector 1 lies at or within a few metres of the sea floor. The nearby profile along line J (Fig. 1) passes through ODP-660. At this drill-site reflector 1 lies within a section of mid-late Eocene chert-bearing siliceous ooze (Ruddiman et al., 1988). B — oceanic basement. M— seabed multiple reflection.

4. Present-day abyssal circulation

Before examining the paleoceanographic implications of current-controlled deposition close to the St Paul and Guinea Transforms it is pertinent to consider present abyssal circulation in the eastern equatorial Atlantic (Fig. 7). The deep circulation (Warren, 1981) is dominated by the movement of North Atlantic Deep Water (NADW) and the underlying Antarctic Bottom Water (AABW). The former flows towards the equator at levels of 1400–4400 m and is characterised by potential temperatures of 2.4–4.7 °C (Friedricks and Hall, 1993). Speer and McCartney (1991) define lower NADW as flow between 2900 m and 4400 m. Abyssal dunes and other current-controlled sedimentary features in this depth range have been mapped at and close to the seabed by Jacobi and Hayes (1992) using high-resolution 3.5 kHz echo-sounder data. More deeply penetrating seismic profiles recorded by Rossi et al. (1992) and Westall et al. (1993) have delineated slope-parallel sediment drifts, erosional features and current-mounded sediment waves with wavelengths of ~ 0.5–2 km and heights of 100 m in the path of NADW at depths of 1500–4250 m along the southern transform margin of the Guinea Plateau. Profiles from a local survey of the Romanche Fracture Zone near 17° 30′ W on the Equator (Westall et al., 1993) also reveal ponded and mounded sediment bodies in the paths of AABW and NADW.

An extensive study by Wüst (1933) established that AABW reaches the tropical Atlantic through the western basins of the South Atlantic and enters the eastern equatorial Atlantic through the Romanche Fracture Zone (Fig. 7). In spreading northward from Antarctica the potential temperature of bottom water, θ_B, increases from values of less than −0.8 °C to +0.6 °C at the equator. Low values of θ_B in the eastern equatorial Atlantic led Wüst (1933) to conclude that a component of AABW passes eastwards through the Romanche Fracture Zone and then into the Sierra Leone Basin to the north and the Guinea Basin to the east. The passage of AABW through the Romanche Fracture Zone was later confirmed by Metcalf et al. (1964) who demonstrated that the sill depth is no deeper than 3750 m. Near-bottom potential temperatures show that it moves northwards into the Sierra Leone Basin and eastwards to the Guinea Basin, while mixing with NADW (Fig. 7; Mantyla and Reid, 1983; McCartney et al., 1991; Ferron et al., 1998; NODC, 2001). Westerly dipping isotherms and salinity gradients below 4500 m on hydrographic transects along latitudes 7° 30′ N and 5° 30′ N (Fuglister, 1960; Arhan et al., 1998; Sokov et al., 2002) indicate a northerly flow of bottom water over the African continental rise.

AABW also enters the eastern equatorial Atlantic through the Vema Fracture Zone near 10° N (Fig. 7; Heezen et al., 1964; Eittreim et al., 1983). From changes in θ_B along the fracture zone Heezen et al. (1964) identified a sill at a depth of ~ 4500 m near 41° W, which was later mapped in detail by multibeam bathymetric surveys (Vangriesheim, 1980). More recent oceanographic observations of McCartney et al. (1991) showed that after

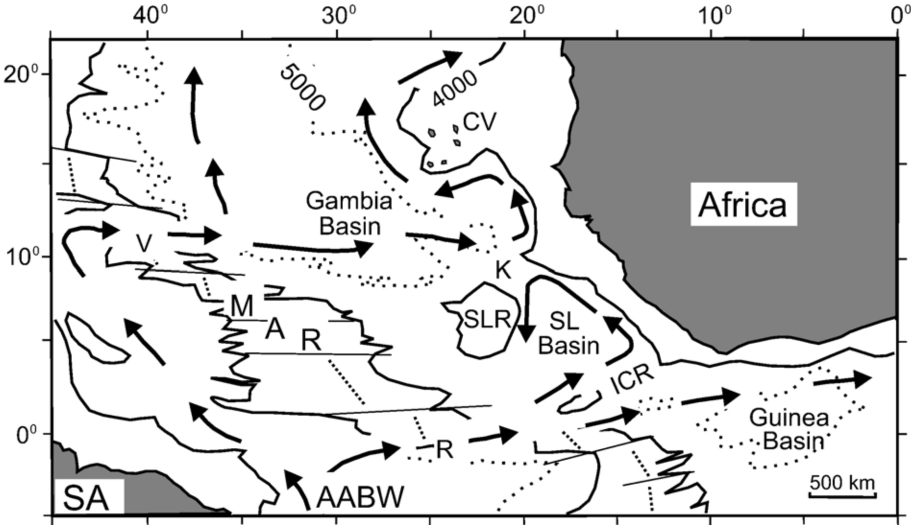


Fig. 7. Present-day paths of Antarctic Bottom Water (AABW) in the equatorial Atlantic. CV — Cape Verde Islands, K — Kane Gap, SLR — Sierra Leone Rise, ICR — Ivory Coast Rise, MAR — Mid-Atlantic Ridge, V — Vema Fracture Zone, R — Romanche Fracture Zone, SA — South America.

flowing through the deep valley of the Vema Fracture Zone the AABW bifurcates. One component passes along the southern side of the Gambia Basin until it is deflected towards the north by the African margin before flowing westwards off the Cape Verde Islands. A second branch spreads northwards as a deep boundary current along the flanks of the Mid-Atlantic Ridge. Estimates of volume transport are $\leq 1.0 \times 10^6$ m^3 s^{-1} and 1.8–3.9×10^6 m^3 s^{-1}, respectively. Temperature, salinity and nutrient measurements indicate negligible net transfer of AABW between the Gambia and Sierra Leone basins through Kane Gap (McCartney et al., 1991; Oudot et al., 1998; Lux et al., 2001). Bottom water thus circulates in two distinct counter-clockwise flow patterns in the Sierra Leone and Gambia Basins (Fig. 7).

5. Paleoceanography and sedimentation

The thick deposits of the Guinea Drift and Ivory Coast Rise point to the long-term influence of bottom-water movements on sedimentation in the eastern basins of the equatorial Atlantic. The lack of continuity between the Guinea Drift and the extensive sedimentary apron along the continental margin (Uchupi et al., 1976; Jones and Mgbatogu, 1982) suggest that transport of material directly from African sediment sources did not play a major role in the development of the drift. Bottom water probably came from the west as part of a counter-clockwise flow in the Gambia Basin. At the present time AA BW enters the area through the Vema Fracture Zone which acts as an important conduit for bottom water from the western Atlantic. Sarnthein and Faugères (1993) have earlier concluded from the presence of mounded mid-Eocene radiolarian contourites at the level of reflector 1 at ODP-660 (Figs 1, 6) that AABW was an important element in mid-Eocene circulation. This implies production of dense bottom water off Antarctica during the period of global cooling following the early Eocene climatic optimum documented by Zachos et al. (2001). Furthermore, it indicates the entry of proto-AABW into the eastern equatorial Atlantic and the build-up of equatorial drift deposits before the establishment of permanent Antarctic ice sheets during the early Oligocene (Fig. 8). A recent analysis of geophysical data in the Weddell Sea and surrounding area by Livermore et al. (2005) indicates that crustal extension and subsidence led to the development of a mainly shallow (<1000 m) seaway between the Pacific and South Atlantic during the mid-Eocene, which they suggest contributed to global cooling at this time. The introduction of proto-AABW into the equatorial Atlantic may be linked to the initiation of this major oceanographic gateway (Fig. 8). The development of pre-Oligocene contourite drifts in the path of modern AABW has also been reported much further south in the Cape Basin by Schut and Uenzelmann-Neben (2005).

Whether sediment accumulation from AABW took place throughout the depositional history of the Guinea Drift is open to debate, since drilling results from the Weddell Sea and South Atlantic indicate that the Antarctic region may not have been the primary source of Atlantic bottom water during parts of the Paleogene (Kennett and Stott, 1990; Sher and Martin, 2004). Arctic water began to enter the Atlantic over the Scotland–Greenland Ridge in early Oligocene time (Tucholke and McCoy, 1986; Davies et al., 2001) and so would not have influenced early drift deposition in the equatorial region. While its contributions to bottom water in the deep parts of the eastern equatorial basins are small at present (McCartney et al., 1991), influx of Arctic water deflected by Coriolis force along the eastern side of the Mid-Atlantic Ridge may have affected patterns of sedimentation during post-Eocene time. It has been suggested by Kennett and Stott (1990) that the Tethyan seaway was an important source of Atlantic bottom water during the early Cenozoic, producing Warm Saline Deep Water (WSDW) that reached as far south as the Weddell Sea. However, Bice and Marotzke (2001) conclude from recent numerical modelling of ocean circulation during Paleocene–Eocene time that it is unlikely that such a water mass would have been dense enough to penetrate the deep parts of the Atlantic basins. In spite of warm subtropical temperatures in the Tethyan region, they find the maximum surface densities at high latitudes, which thus provided bottom water for the deep Atlantic and other oceans.

The marked widening of the Liberian continental rise towards the south and its extension seawards as the Ivory Coast Rise suggest deposition from bottom water moving equator-wards off Africa and westwards parallel to the elevated topography of the St Paul Fracture Zone, a clockwise flow which is in the opposite direction to prevailing deep currents (Fig. 7). Sub-surface wave fields and a broad sedimentary swell marked by reflector 1 that extends over 100 km north of the St Paul Fracture Zone (Figs 2, 3) indicate the activity of clockwise-flowing bottom currents in the region of the Ivory Coast Rise during the mid-Eocene when contourites were being deposited at ODP-660. At this time the Sierra Leone Basin was situated immediately south of the paleoequator (Smith and Briden, 1977). A reversal of deep-water movement to the present-day pattern in the Sierra Leone Basin may thus have been a response to the later northward motion of the area across the paleoequator.

Schematic circulation patterns that would result from the introduction of bottom water into the eastern

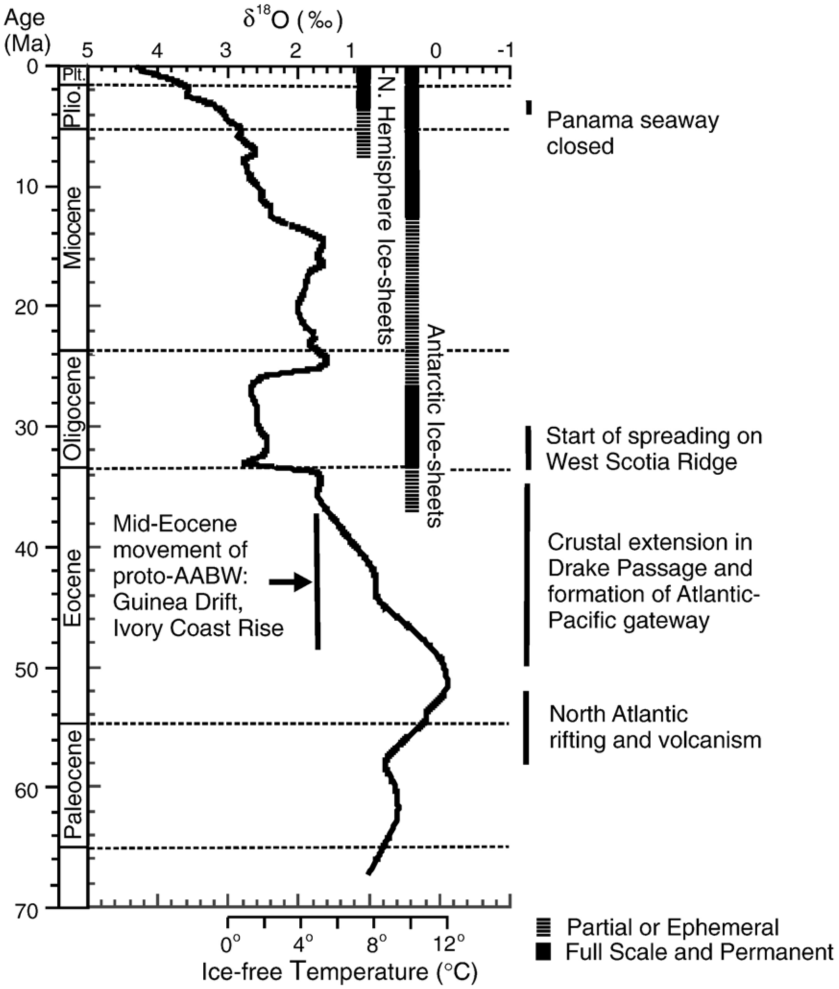
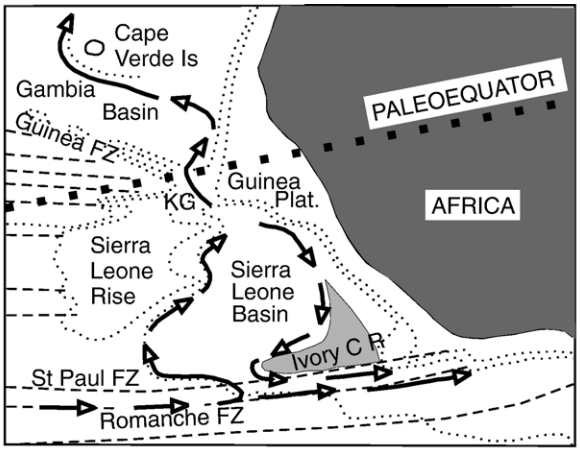


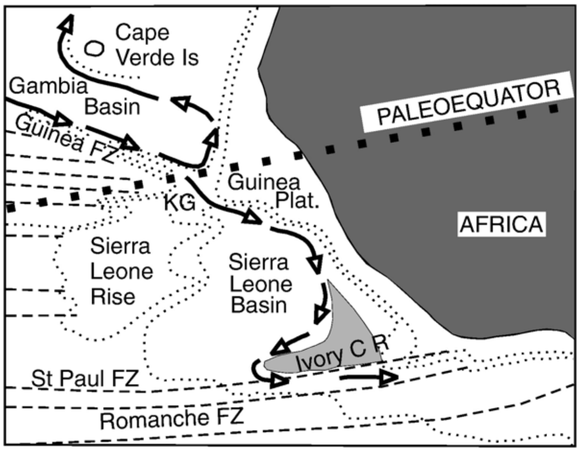
Fig. 8. Movement of proto-AABW in the equatorial Atlantic shown in relation to the deep-sea oxygen isotope record compiled for the Cenozoic by Zachos et al. (2001). The establishment of polar ice sheets and the opening of oceanographic gateways are taken from Zachos et al. (2001), Livermore et al. (2005) and references therein.

equatorial Atlantic through the Romanche and Vema Fracture Zones are shown separately on an Eocene reconstruction of the region in Fig. 9. In Fig. 9a proto-AABW originating from the Antarctic area before the establishment of permanent ice sheets (Fig. 8) enters from the Romanche Transform and is subject to an initial Coriolis deflection to the west. It is then confined by topography to flow northwards as a geostrophic current along the margin of the Sierra Leone Rise and then southwards off Africa. If a component of the polar water crosses the paleoequator through Kane Gap a weak Coriolis deflection leads to a northerly current along the African margin in the Gambia Basin and westerly flow off the Cape Verde platform.

Proto-AABW passing through the Vema Fracture Zone would be constrained by Coriolis deflection and topography to follow the present counter-clockwise circulation pattern in the Gambia Basin (Fig. 9b). It should be noted that a similar path would be taken by bottom water introduced along the eastern side of the Mid-Atlantic Ridge from the north. Any overflow across Kane Gap into the southern hemisphere is subject to an easterly deflection and thus moves southwards along the African margin, a direction opposite to present-day abyssal flow. While there is presently negligible transfer of deep water between the Sierra Leone and Gambia Basins (McCartney et al., 1991), vigorous interchange during the Cenozoic is supported by the lack of a continuous sediment cover on reflector 1 and evidence of seabed erosion in Kane Gap (profile H, Fig. 6; Hobart et al., 1975). Further indications of past water transfer come from high growth rates of hydrogenetic



(a) Proto-AABW: Flow from Romanche F.Z.



(b) Proto-AABW: Flow from Vema F.Z.

Fig. 9. Proposed paths of proto-AABW in the Sierra Leone Basin and environs shown on an Eocene reconstruction of the eastern equatorial Atlantic based on Smith and Briden (1977) and Jones et al. (1995). The bottom water enters the region through the Romanche Fracture Zone in (a) and through the Vema Fracture Zone in (b). KG — Kane Gap.

ferromanganese in deposits of Miocene age outcropping near the axis of the sill (Hartmann et al., 1989).

With the Sierra Leone Basin positioned south of the paleoequator entry of bottom water through the equatorial fracture zones from the Antarctic region or introduced along the eastern flank of the Mid-Atlantic Ridge from northern latitudes provides a means of transporting sedimentary material southwards along the African continental margin and westwards on to the Ivory Coast Rise (Fig. 9). A later reversal of deep-water flow off Africa and the establishment of the present counter-clockwise gyre (Fig. 7) would be consequences of northward motion of the area across the paleoequator. Reversals in abyssal currents may be a feature of regions where deep-sea deposition has been influenced by inter-hemispheric water transfer and plate motions.

6. Conclusions

Seismic profiling in the equatorial Atlantic has revealed the presence of sedimentary drifts near the intersection of the Guinea and St Paul fracture zones with the African margin. The Guinea Drift near 10° N has been formed in the path of bottom water circulating in a counter-clockwise direction in the Gambia Basin, south of the Cape Verde Islands. At the present time the flow is made up of AABW which has passed through the Vema Fracture Zone from the western Atlantic. Results from drilling in contourite deposits at ODP-660 east of the Guinea Drift led Sarnthein and Faugères (1993) to conclude that bottom water originating in the Antarctic region moved through this area during mid-Eocene time. If this is so, then the production of proto-AABW began before the establishment of permanent ice sheets in Antarctica (Fig. 8). Warm Saline Deep Water (WS DW) may also have formed Atlantic bottom water for parts of the Paleogene (Kennett and Stott, 1990) and may have influenced sediment deposition. However, recent numerical modelling of Atlantic paleo-circulation (Bice and Marotzke, 2001) suggests that WSDW would not have reached the deeper levels of the equatorial basins.

Current-controlled deposits also make up the Ivory Coast Rise, which extends as a tongue of thick sediments north of the St Paul Fracture Zone. The geometry of this sedimentary body indicates that it developed in the path of bottom water moving clockwise in the Sierra Leone Basin. This direction of circulation is opposite to the present motion of AABW entering the area from the Romanche Fracture Zone. It is suggested here that the flow reversal is a result of the oceanic lithosphere moving north of the paleoequator in post-Eocene time.

Changes of abyssal circulation in this transitional region between the North and South Atlantic and their relation to water movements at shallower levels of the ocean could be determined by drilling the Ivory Coast Rise. Drilling here and on the Guinea Drift is likely to reveal much about the early history of the inter-hemispheric flow of polar water and the role of equatorial plate motions in bottom circulation.

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