The Equatorial Atlantic Mid-Ocean Channel: An Ultra High-Resolution Image of Its Burial History Based on TOPAS Profiles

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Abstract. Multibeam bathymetric and ultra high-resolution seismic data reveal that the distal course of the Equatorial Atlantic Mid-Ocean Channel (EAMOC) extends further east and south than was previously known, and is controlled by the presence of morphologic highs related to the Fernando de Noronha Fracture Zone. The distal course of the EAMOC is buried by sediments, and does not have bathymetric expression on the seafloor. The channel fill consists of three seismic sequences, suggesting that the recent geological evolution of the channel is composed of successive phases of decreasing sedimentary activity that finally resulted in its complete burial. Tectonic and volcanic activity related to the Fernando de Noronha Fracture Zone and Ridge, together with the effect of strong pulses of the Antarctic bottom water current during the upper Pliocene are suggested to have contributed to the progressive burial and the final abandonment of the EAMOC.

Introduction

Deep-sea channels represent the oceanic continuation of the sediment transport systems existing on adjacent continental margins. Most of them provide physical links between submarine canyons and abyssal plains, and therefore constitute the last pathway for the sediments transported from the continents to the deep ocean basins. The characteristics of the most important known deep-sea channels were compared by Carter (1988), who showed their many similarities. Most of them head along continental margins and link directly to adjacent deep-sea canyon-fan valley systems. Their most common characteristics include a U-shaped cross section profile, great length (up to 4000 km), variable width (1 to 10 km), and low axial gradient (1:1000 or less) (Carter, 1988). The sedimentary mechanisms dominant within deep-sea channels include turbidity currents, mass-failure, bottom currents, and pelagic processes (Ewing et al., 1953; Lonsdale et al., 1981; Carter, 1988; Carter and Carter, 1988). Though a submarine channel 'sensu stricto' is originally an erosional feature (Carter, 1988), most of them are characterized during their geologic history by the succession of erosional and depositional periods (Carter, 1988; Pickering et al., 1995). Depending on the type of channel and its location with respect to the continental margin, the erosional/depositional periods may be controlled by relative sea-level changes, variations in sediment supply to the canyon heads, or local tectonics (uplift vs. subsidence). The time-varying interplay of such processes finally results in the predominantly erosional or depositional character of some deep-sea channels (Embley et al., 1970). Despite the activity of depositional processes that may eventually lead to their infilling, some known deep-sea channels have been in existence since the Tertiary (Damuth and Gorini, 1976; Carter, 1986) and are still preserved as identifiable features of the present seafloor.

Mid-ocean channels are a special type of deep-sea channels that develop especially in areas where submarine fans are not present, are mainly characterized by their orientation parallel to the margin, and by the absence of a direct link to submarine canyons eroded on the continental margin. The present paper shows newly acquired bathymetric and high-resolution seismic data along the distal end of the Equatorial Atlantic Mid-Ocean Channel. These data can help to solve some uncertainties still existing about the recent sedimentary history of one of the largest deep-sea channels in the Atlantic Ocean.

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Geological Setting

The formerly called 'Equatorial Atlantic Mid-Ocean Canyon' (Heezen et al., 1960) (herein 'EAMOC') is a leveed deep-sea submarine channel (Damuth and Gorini, 1976; Belderson and Kenyon, 1980) located in the western equatorial Atlantic, off NE Brazil (Figure 1). This 1200 km-long and 5–8 km-wide submarine channel trends east–southeastwards, subparallel to the northeastern Brazilian continental rise, crosses the Fernando de Noronha Basin, and ends in the Pernambuco Abyssal Plain. The Fernando de Noronha Basin is limited to the north by the North Brazilian Ridge and the Romanche Fracture Zone, and to the south by the Fernando de Noronha Ridge and Fracture Zone (Figure 1). The sedimentary evolution and geological history of the EAMOC has received little attention in the past, and still remains somewhat uncertain (Damuth and Gorini, 1976; Belderson and Kenyon, 1980). The few published works indicate that the EAMOC is an ancient, probably relict feature that was active during the early Miocene, and constituted the major pathway for terrigenous sediment dispersal along the Fernando de Noronha Basin during that time (Damuth and Gorini, 1976). The genesis of the EAMOC has been related to turbidity-current activity (Damuth and Gorini, 1976; Carter, 1988), and its trend parallel to the Fernando de Noronha Ridge also suggests a structural control (Kenyon and Belderson, 1980; Baraza et al., 1995). The relict character of the EAMOC is suggested by its 75 to 150 km proximal section, which is buried under sediments between 80 and 250 m thick (Damuth and Gorini, 1976). The precise age of the channel, the exact time when it became inactive, and the reasons why its activity ceased, however, have not previously been totally explained (Damuth and Gorini, 1976; Carter, 1988). On the basis of seismic data and sedimentological evidence, the abandonment of the channel is thought to have occurred at some time between the middle Miocene and the late Pleistocene (15–1 m.y. BP) (Damuth and Gorini, 1976). This abandonment and the subsequent burial of the channel occurred when the predominant direction of sediment dispersal from the continental margin shifted northeastward from the Fernando de Noronha Basin towards the adjacent Guiana Basin (Figure 1), probably during the middle or late Miocene (Damuth and Gorini, 1976). The reasons for this change in sediment dispersal direction are still uncertain.

In 1993, the southernmost portion of the EAMOC was surveyed in order to answer some questions concerning the unknown factors about its genesis and later abandonment. This paper shows the newly acquired data and analyzes the most distal channel pathway and morphology and the seismic stratigraphy of the sedimentary fill and levees of the distal channel. The final objective of the paper is to interpret the recent sedimentary history and abandonment of the EAMOC.

Methodology

The following interpretation is based on new bathymetric data and ultra high-resolution seismic profiles obtained on board the Spanish R/V Hesperides during the CAMEL '93 cruise. A bathymetric mosaic was obtained using a multibeam SIMRAD EM 12 swath bathymetry echosounder, with full coverage of the study area (Figures 2 and 3). This system transmits 81 acoustic beams to the seafloor with a total beam angle of 90º, covering a sector of the seafloor whose width equals twice the water depth. This operating mode resulted in approximately 10.5 km-wide corridors covered during each of the 8 tracklines, which provided a total coverage area of about 10300 km^2. Ultra high-resolution seismic profiles were obtained with a TOPAS (TOpographic PArametric Sonar) system developed by Bentech Subsea A/S (Figure 2). The TOPAS system is a hull-mounted seabed and subbottom echosounder based on a parametric acoustic array, which operates using the non-linear acoustic properties of the water (Dybedal and Bøe, 1994). The system transmits two acoustic signals with slightly different frequencies (primary frequencies 16 to 20 kHz) that interact within the water column, generating a secondary signal with a frequency between 0.5–5 kHz (secondary frequency), but retaining the same beam width as the primary pulse. The system is thus capable of operating at relatively low frequencies, achieving penetration similar to that of boomers and sparkers, while retaining a narrow beam and giving high horizontal and vertical resolution (Kuhn and Weber, 1993; Webb, 1993). The above-mentioned advantages over other conventional echosounder systems all result in a very good resolution of the seafloor morphology, good lateral resolution, and relatively high penetration. During the CAMEL '93 cruise, 30 ms long, FM sweep (chirp) signals with secondary frequencies ranging from 2 to 4 kHz were generated, and realtime filtering and deconvolution was applied. Under these conditions, the system proved to be capable of obtaining ultra-high resolution profiles of the subseafloor at full oceanic depths (5300 m water depth) revealing an impressive, highly detailed image of the structure and stratigraphy of the sediment column, generally within the upper

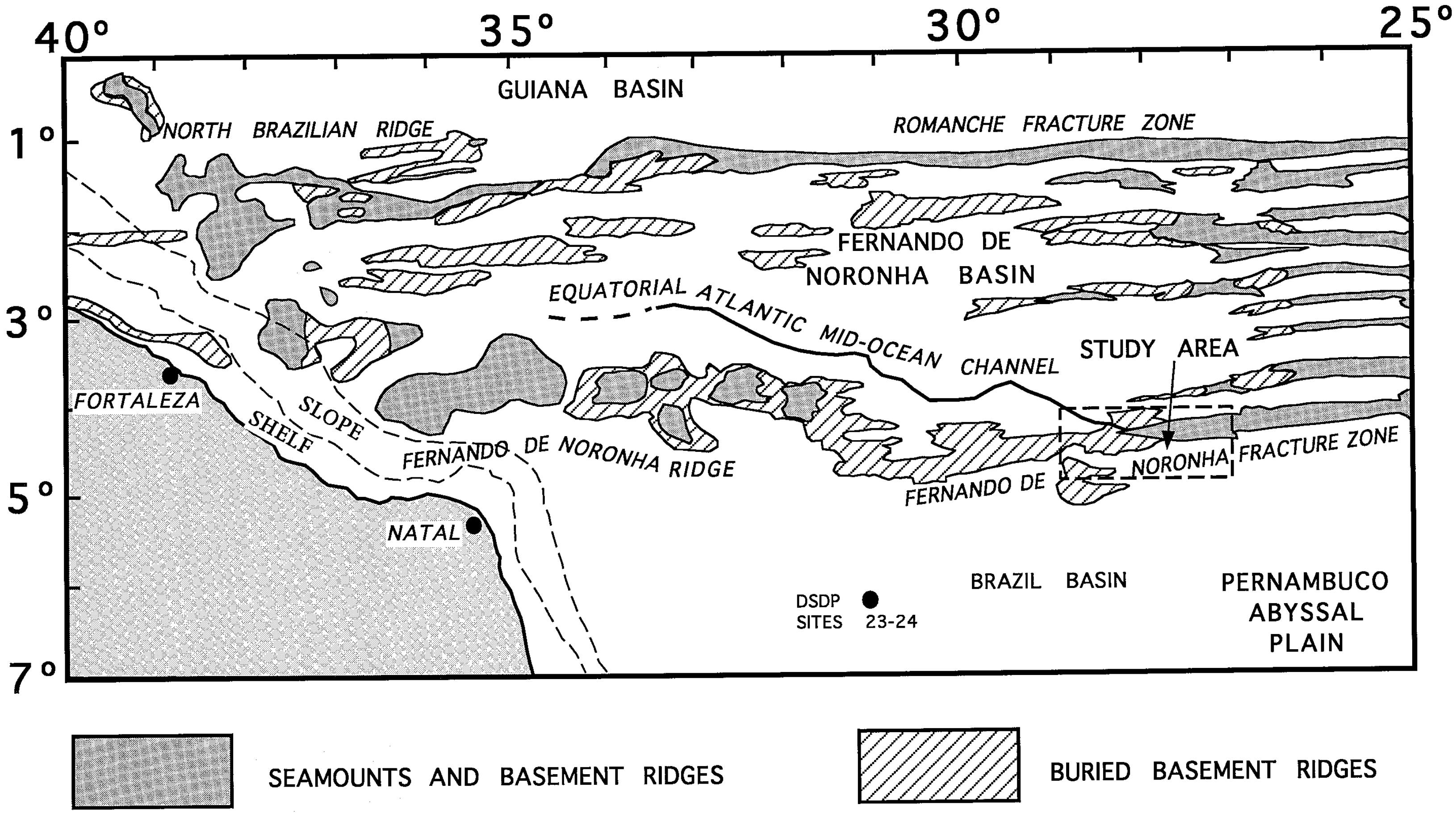

Fig. 1. Physiographic sketch-map of the EAMOC (modified from Damuth and Gorini, 1976) showing relationship with fracture zones and sedimentary basins. Study area is denoted by dashed rectangle.

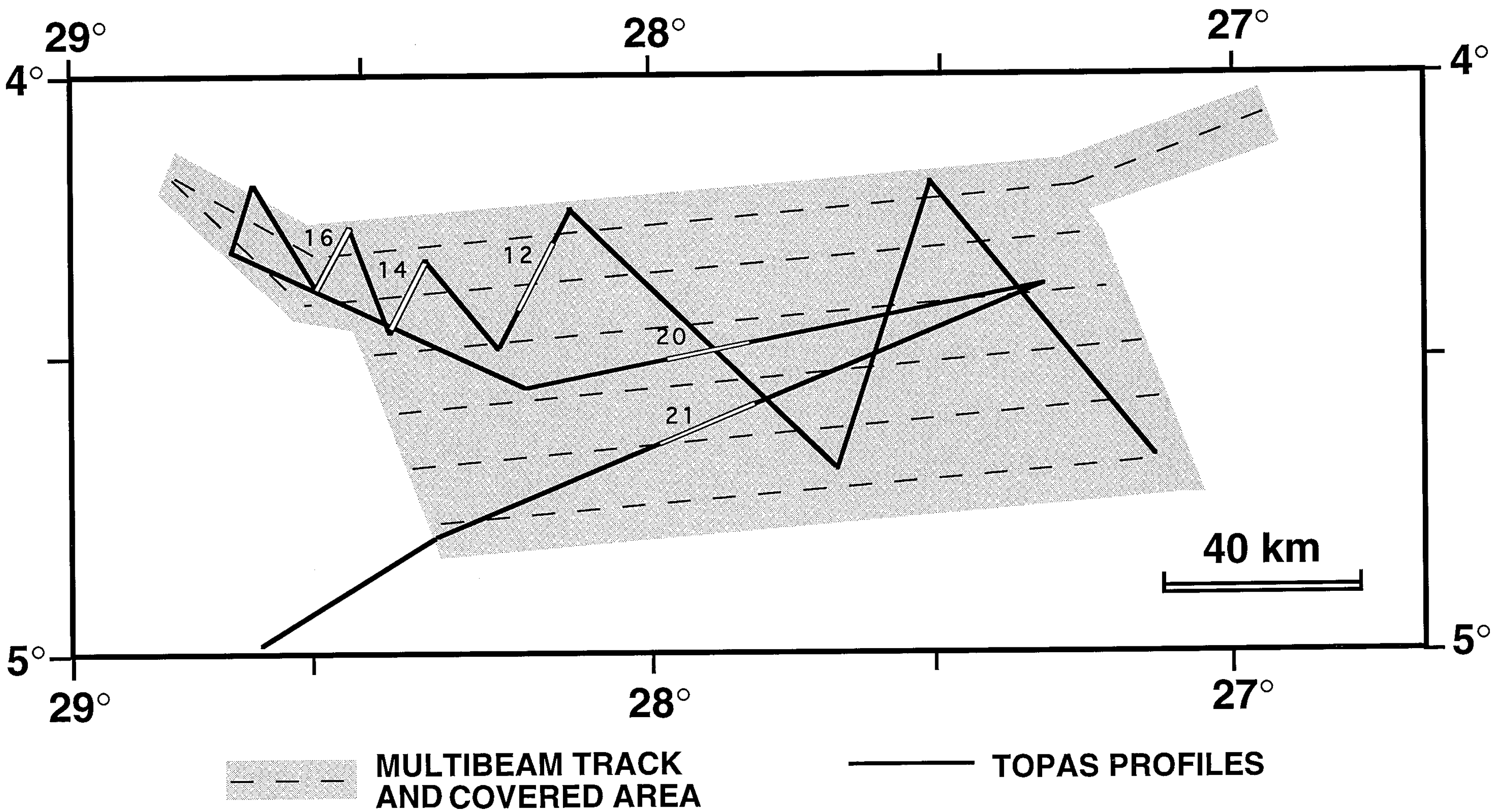

Fig. 2. Multibeam bathymetry and TOPAS tracklines obtained during CAMEL ’93 cruise. Shaded area shows total bathymetry coverage. Thick white segments represent TOPAS line sections used to construct Figure 4. Sections 12, 14 and 16 are shown in Figures 6–8. Area of figure located in Figure 1.

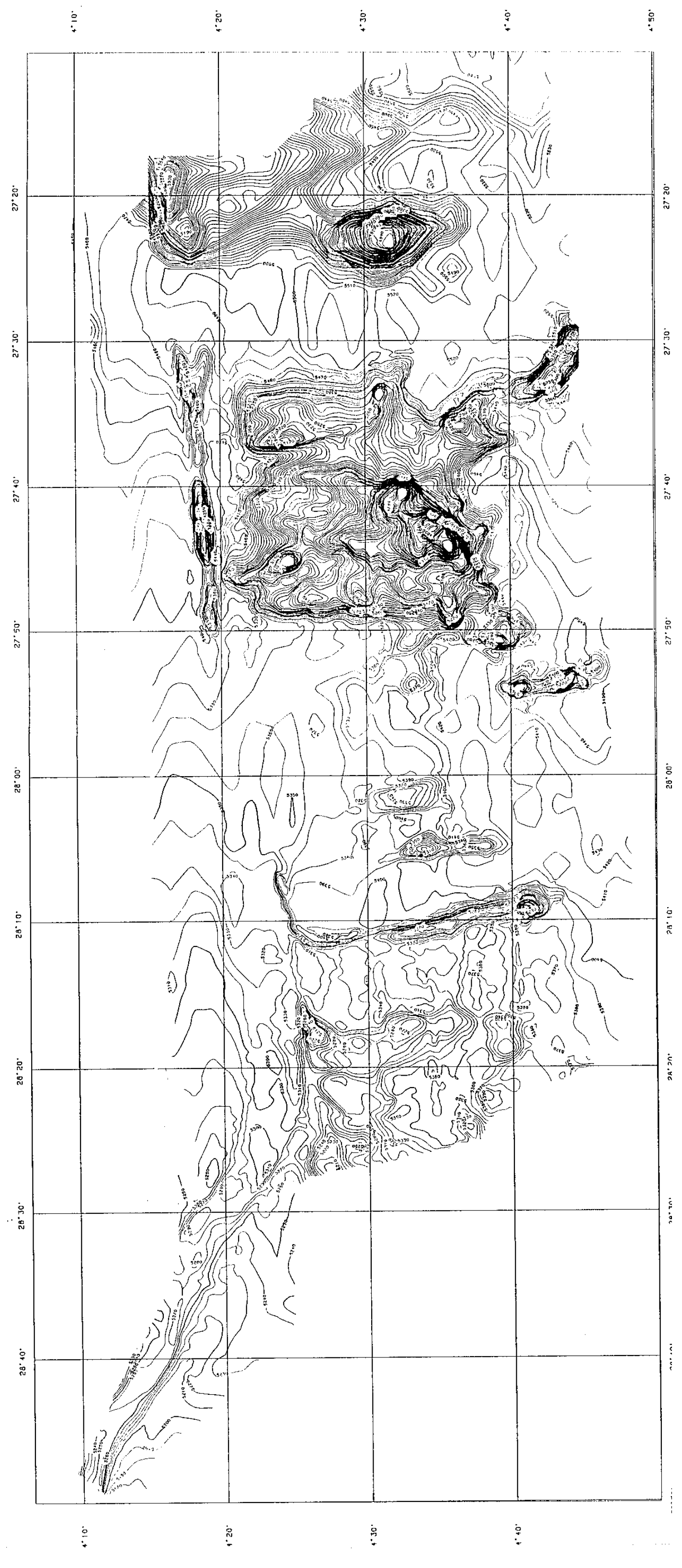

Fig. 3. Bathymetry of the studied area obtained from multibeam data. Contour interval 10 m. Location in Figure 1.

50–90 m. Seismic methods and concepts based on publications by Sangree and Widmier (1977), Mitchum et al. (1977), Sangree et al. (1978), and Brown and Fisher (1980), have been applied for the present seismic stratigraphic analysis and further geological interpretation. Two-way travel distance in miliseconds within the sediments measured on the TOPAS profiles has been converted to meters using an average velocity of 1600 ms^{-1}. In the following descriptions, right and left channel walls always refer to downchannel-looking observations.

Morpho-Structural Analyses

Channel pathway and morphology

The study area extends from 4º10′ to 4º50′ S latitude and 27º10′ to 29º W longitude, approximately 450 km east of the Fernando de Noronha Archipelago, and about 800 km offshore NE Brazil (Figure 1). Previous studies on the most distal part of the EAMOC (Damuth and Gorini, 1976; Belderson and Kenyon, 1980) locate its eastern termination at about 4º23′ S, 28º16′ W. These authors suggest that the channel either comes to an end at this point, or bends sharply to the south to pass over a low point in the Fernando de Noronha Fracture Zone, although this latter possibility was found to be highly unlikely (Damuth and Gorini, 1976). The newly obtained bathymetric map (Figure 3) shows the final 51 km of the EAMOC and the westernmost sector of the Fernando de Noronha Fracture Zone. The distal trace of the channel follows a relatively smooth, sinuous course with a NW–SE (av. N135º) general trend that at 4º22′ S, 28º25′ W turns sharply to a W–E direction, at about 5300 m water depth. After this point, the channel runs for about 33 km parallel to the edge of some seafloor morphologic highs of up to 100 m in height, and continues eastward until its trace is finally lost at 4º24′ S, 28º08′ W at approximately 5330 m water depth (Figures 3 and 4).

The exposed portion of the channel is U-shaped in cross section with asymmetric walls, and shows a step-like longitudinal profile (Figure 3). In the westernmost sector of the study area the channel floor is 2–3 km in width, with a central, deeper part between 1.4 and 1.9 km wide (Figure 4, line 16). Slope gradients within the channel range from 1.5º to 4.5º on the left and right walls respectively, and up to 0.50º on the channel floor, although higher slopes (up to 1.25º) may be found locally. The maximum width between the levee crests ranges from 4 to 6 km, and the maximum relief between these and the channel floor varies between 37 and 75 m, always being higher on the left wall. Differences in the height of the levees across the channel can be the result of the Coriolis effect, or due to the sinuous character of the channel: the higher and steeper levee always develops close to the external margin of the channel loop (Figures 3–5). The entire channel becomes wider downcourse, where the channel floor reaches between 4 and 7.8 km wide, and the distance between the levees also increases, ranging from 4.8 to 10 km (Figures 3 and 4). In this sector, the channel walls gradually decrease in height and the channel cross section becomes more subdued (maximum height between 8.2 and 53 m) (Figure 4, lines 12 and 16). Slope gradients decrease to 0.5º and 3.5º in the channel walls, and to 0.25º in the channel floor. Beyond the point where the EAMOC loses its morphological expression on the seafloor and apparently disappears (Figures 3 and 4, lines 20 and 21), the TOPAS profiles have revealed the existence of a buried paleo-channel course whose pathway can be easily followed (Figure 5). The pathway of the paleo-channel continues in a W–E direction until 4º20′ S and 27º55′ W, at 5360 m water depth. Beyond this point the paleo-course turns southward through almost 90º, and apparently continues following a nearly N–S (N190º) direction across the entire area covered by the existing seismic profiles (Figure 5).

Morphologic highs

A group of morphologic highs, many with clear linear geometry, are identified from the bathymetry (Figures 3 and 5). These linear highs show two well-defined orientations, 80º and 170º–180º, and appear to be structurally controlled. The linear highs oriented 80º appear in the vicinity of the area where the channel turns eastwards and begins to lose its bathymetric expression (4º24′ S, 28º08′ W, Figure 5), and near the NE limit of the study area. These highs consist of escarpments and ridges of up to 54 km length, 2 to 7 km width and 150 to 400 m height. Most of the linear highs oriented 170º–180º are located near the area where the EAMOC finally disappears and the buried channel course takes a sharp southward bend. These highs are especially concentrated in the SW sector of the studied area. The highs form ridges of 11 to 30 km length, 1.5 to 4 km width, and 250 to 400 m height (Figures 3 and 5). Larger and geometrically more complex morphologic highs which seem to result from the coalescence of several individual ones, occur south and east of the exposed channel and occupy an area of about 900 km^2. These complex

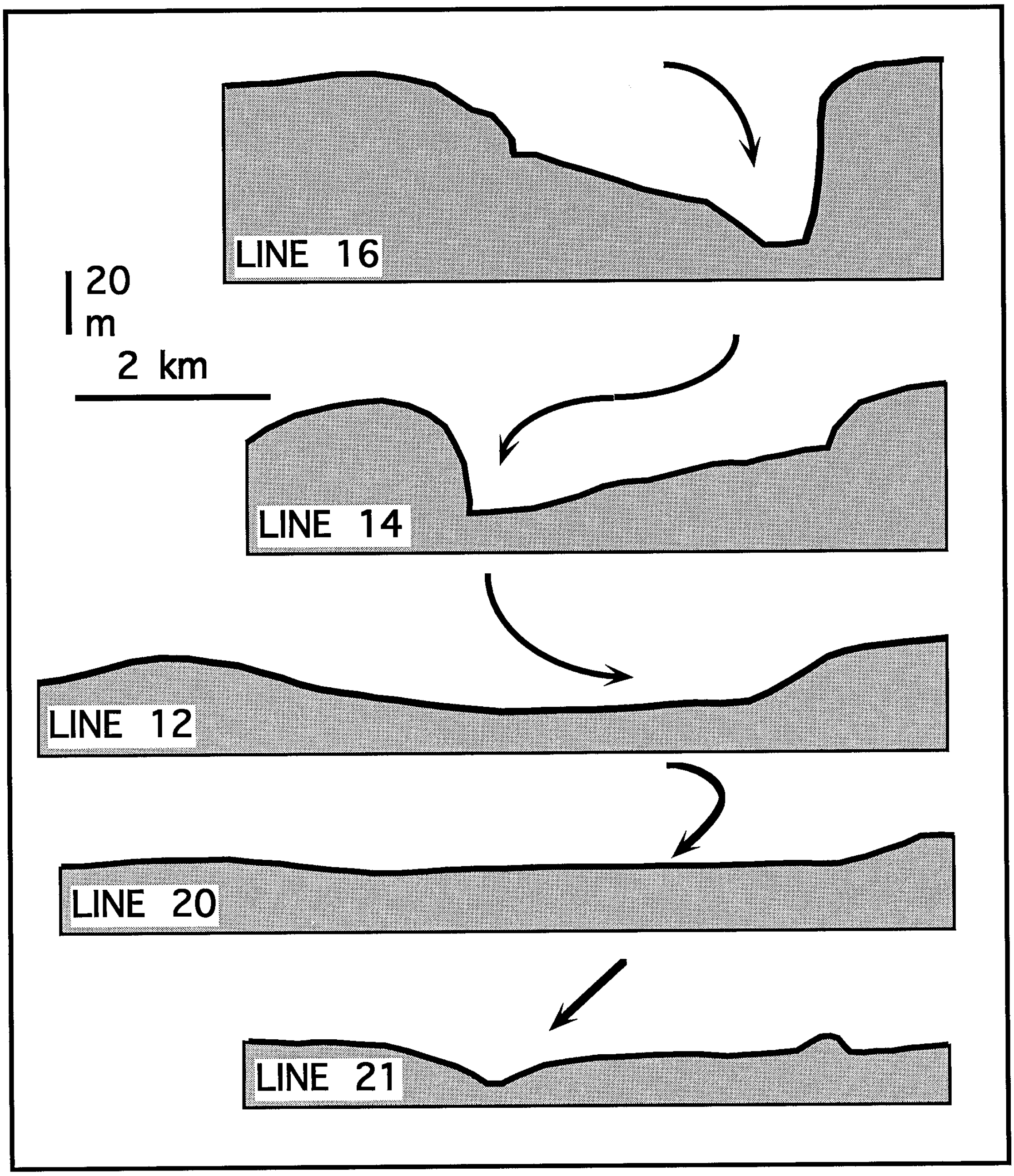

Fig. 4. Bathymetric cross sections of the EAMOC traced from TOPAS records, showing the progressive attenuation of channel relief downcourse. Arrows give an indication of channel course trend between sections. Location of profiles shown in Figure 2.

morphologic structures are bounded locally by escarpments up to 200 m in height oriented parallel to the linear highs. Within them, several cone-shaped morphologies having up to 700 m in height are identified, which can be attributed to volcanic edifices belonging to the Fernando de Noronha Ridge (Figures 3 and 5).

Seismic Analysis

Acoustic facies

Three types of acoustic facies have been differentiated on the TOPAS profiles within the channel fill and the levees: (i) transparent, (ii) stratified, and (iii) chaotic

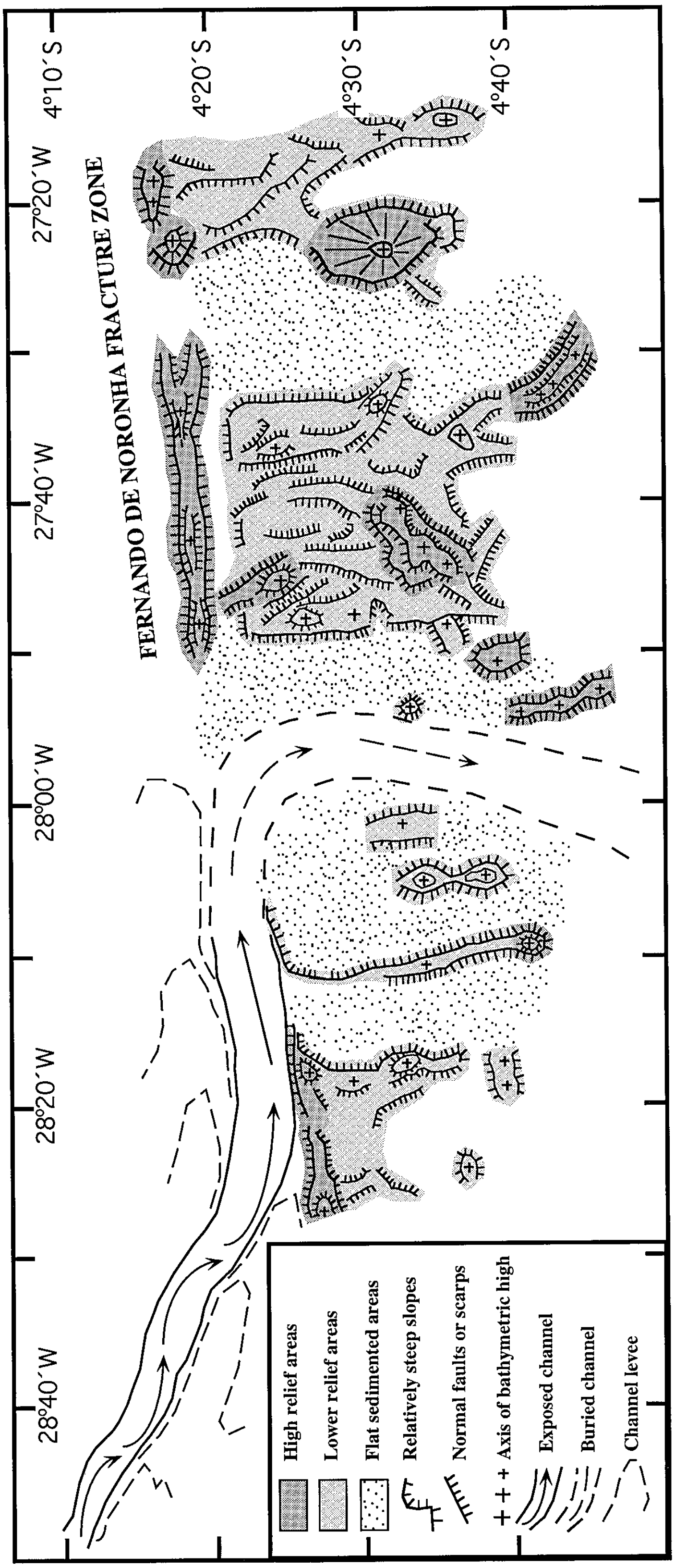

Fig. 5. Physiographic interpretation based on bathymetry and TOPAS profiles. Location in Figure 1.

(Figures 6A, 7A and 8A). The transparent facies (i) is characterized by the lack of acoustic reflections, and forms sedimentary bodies which are bounded by irregular or hummocky surfaces of high acoustic amplitude. The stratified facies (ii) is defined by reflections with a high lateral continuity and a generally uniform frequency. This facies shows a wide range of acoustic amplitudes which are generally uniform along each seismic reflection, although sharp lateral changes are also observed. The stratified facies shows three different configurations: sigmoidal, onlap and parallel. The chaotic facies (iii) is composed of prolonged echoes without discrete reflections, although traces of hyperbolic reflections are sometimes observed, occurring as irregular-shaped bodies within the stratified facies.

Seismic characteristics of channel fill and levees

On the basis of their distinct acoustic response on the TOPAS profiles, three seismic sequences separated by unconformities – ‘a’, ‘b’ and ‘c’ from older to younger – have been differentiated within the channel fill and levees (Figures 6–8).

Seismic Sequence ‘a’

Seismic sequence ‘a’ is composed of several discordant sedimentary packages with transparent acoustic facies, each bounded by highly reflective, irregular surfaces. These packages are tabular, wedge- or mound-shaped in transverse and oblique channel sections, and their across channel extension and thickness are quite variable, ranging from 3.5 to 5 km across, and from 5.5 to 20 m thick (Figures 6–8). The seismically transparent packages are vertically stacked, and form units that abut the sides of the channel, generally displaying an onlap fill configuration along most of the channel course. Near the area where the EAMOC loses its bathymetric expression, however, the lower transparent packages onlap a gently sloping surface towards the right wall of the channel, forming a preferential depocenter in the opposite left margin of the channel (Figure 7). Upwards within seismic sequence ‘a’, the onlapping transparent packages gradually reach the right wall of the channel. The overlying units, separated by irregular surfaces, occupy the entire channel floor and finally onlap both margins of the channel (Figure 7). Due to the limitation of penetration of the TOPAS system (max. reached: 90 m), the lower boundary of seismic sequence ‘a’ in the channel fill has not been determined. The upper boundary of seismic sequence ‘a’, however, is an irregular or hummocky surface of high reflectivity suggesting an erosive character (Figures 6–8). The presence of high-amplitude reflections that completely absorb the seismic energy also produces limitations in the seismic penetration below 65 m in the levees and surrounding areas. Therefore, it is difficult to correlate the entire seismic sequence ‘a’ between the channel fill and the stratigraphy of the levees, and only the lateral relationships of the upper part of seismic sequence ‘a’ are easily observed. On the levees and further away off the channel, seismic sequence ‘a’ is defined by a series of parallel stratified reflections of alternating high and low amplitude, some of which decrease in thickness and pinchout from 3 to 4.5 km away from the channel, showing a convergent-like configuration (Figures 6–8). Close to the channel course, the stratified reflections are intercalated with a relatively thick (9.5 m) tabular level with transparent acoustic facies whose acoustic character is similar to that observed within the correlative channel fill (Figure 7). Small lenticular bodies made of transparent acoustic facies and bounded by highly reflective, probably erosional, sometimes hyperbolic surfaces, appear locally within seismic sequence ‘a’, especially in the uppermost section of the levees (Figure 7).

Seismic Sequence ‘b’

Seismic sequence ‘b’ is composed of stratified acoustic facies with reflections of high amplitude displaying mainly sigmoidal, but also onlap and parallel configurations (Figures 6–8). In cross-channel sections the sigmoidal configuration is 1.5 to 3 km long, with curved lenses about 4 m thick, dipping towards the right wall of the channel. These are initially confined to locations close to the left channel wall, downlapping the pre-existing channel floor topography, but upwards in the sequence the sigmoidal lenses progressively occupy the entire channel floor (Figures 7 and 8). This type of configuration is not clearly identified in sections oblique to the channel, where the seismic response of the channel fill forms an even-layered pattern. The onlap configuration is locally restricted to the sedimentary filling of the small scale troughs existing on the previous channel floor, especially near the left wall of the channel. The parallel configuration is mainly represented in the stratified deposits that constitute the upper section of seismic sequence ‘b’, especially close to the area where the channel loses its bathymetric expression (Figure 7). There is a vertical succession from onlap, then to sigmoidal, and finally to parallel configurations within the stratified facies (Figures 6–8). The stratified facies may be locally interrupted by sedimentary bodies with lenticular or irregular geometry and transparent or chaotic facies, bounded by erosive surfaces and similar to those described for seismic

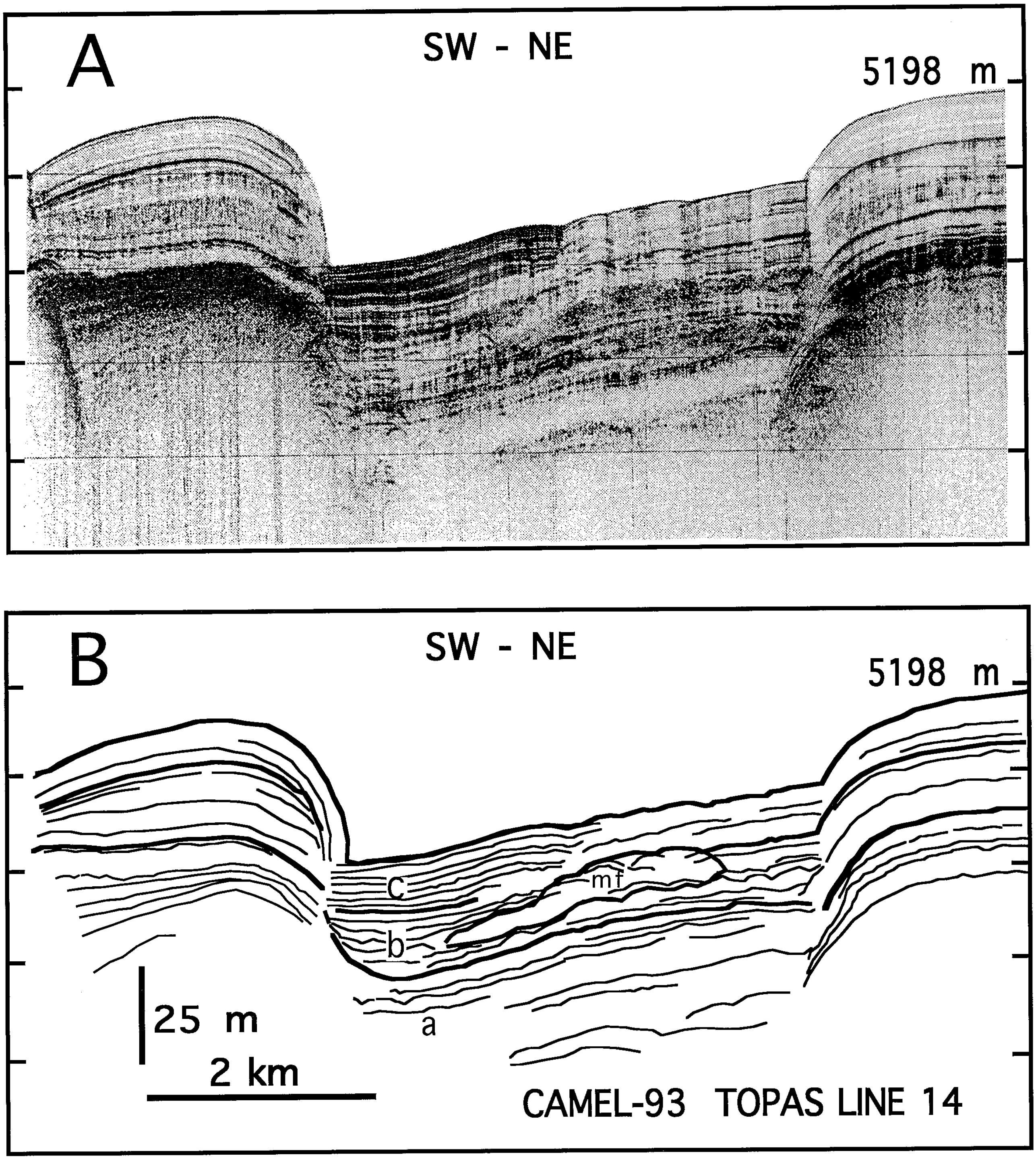

Fig. 6. TOPAS seismic profile (A) and line drawing (B) of the exposed EAMOC section showing the three seismic sequences, 'a', 'b' and 'c', identified within the channel fill and levees. Note mass-flow deposit (mf) within seismic unit 'b'. Location of profile shown in Figure 2.

sequence ‘a’ (Figures 6 and 8). These transparent or chaotic sedimentary bodies are up to 2 km long and 17.5 m thick, and are more abundant and have greater thickness upstream in the channel.

The lower boundary of seismic sequence ‘b’ is a downlap surface, although the downlapping is so gradual that it is sometimes not evident. The upper boundary is an erosional truncation and/or toplap surface for the sigmoidal reflections, and a concordant surface where the parallel configuration predominates (Figures 6–8). The thickness of seismic sequence ‘b’ varies from 16 to 22.5 m, but small relative depocenters develop locally, resulting from the pre-existing topography inherited from seismic sequence ‘a’ (Figures 7 and 8). There is a clear lateral continuation between the reflections within the channel fill and the reflections of the levees within seismic sequence ‘b’. In the levees and surrounding areas, this sequence is represented by well-stratified parallel reflections of a generally low amplitude. The relief of the levees for this seismic sequence is relatively low (about 14.5 m), and its thickness in the levees and surrounding areas decreases downchannel, from 26.5 to 19 m (Figures 6–8).

Seismic Sequence ‘c’

Seismic sequence ‘c’ is characterized by parallel stratified facies. The amplitude of reflections within this sequence is generally low along most of the channel, although sharp lateral changes to high amplitude occur in the upstream sections, especially close to the channel walls (Figures 6–8). The lower and upper sequence boundaries are flat, concordant surfaces, and the seismic sequence displays a layered sheet geometry with a relatively constant thickness of about 16 m along most of the study area (Figures 6–8). Locally, slight variations in thickness occur upstream in the channel, with the maximum thickness (25.5 m) covering the deepest sector of the channel floor (Figure 6). This sector of greater thickness coincides with the area where seismic sequence ‘c’ shows more numerous lateral variations in seismic amplitude. Seismic sequence ‘c’ is easily correlatable between the channel, levees and surrounding areas, given that its seismic character does not show significant variations over the entire study area (Figures 6–8). This seismic sequence is represented in the levees and further away from the channel by a package of stratified facies of low amplitude, showing high lateral continuity in thickness and in the acoustic character of the reflections.

Sedimentological Interpretation

Sequence and processes of channel infill

The succession of facies observed in the sedimentary record of the channel-fill and levees of a relict deep-sea channel would be expected to reflect the progressive dominance of deposition over transport and erosion, finally leading to channel abandonment. If this abandonment takes place gradually, the architecture of the sedimentary fill will consist of a vertical succession of facies reflecting the progressive decrease in activity of the channel. Such a decrease in the energy of the depositional environment is recognized on TOPAS seismic profiles mostly by changes in the seismic facies, stratal architecture and the nature of the limiting surfaces. Seismic facies change from transparent or chaotic to stratified; the stratal arrangement from sigmoidal to plane-parallel; and the bounding surfaces change from erosional truncations to smooth depositional surfaces (Figures 6–8). This is the proposed succession of seismic characteristics for the EAMOC, which would represent its progressive evolution from an active channel phase, in which high-energy sedimentary processes (turbidity currents, mass flows, etc.) were dominant, to a phase of channel inactivity, in which the slow deposition from low-density currents or pelagic suspensions prevailed. Similar succession of seismic facies has been recognized in the sedimentary fill of ancient submarine canyons off Africa (Rasmussen, 1994), and a comparable infill model has been recently proposed for turbidite channels (Pickering et al., 1995).

The following sedimentological interpretation is based on the acoustic facies, internal configuration and geometry of seismic sequences ‘a’, ‘b’ and ‘c’. The evidence presented shows that the infill of the EAMOC took place during three main phases, which can be correlated with the identified seismic sequences.

Phase I

This Phase I correlates with the deposition of seismic sequence ‘a’ when the channel was a high-energy, active and open sediment transport pathway (Figure 9). This is indicated by the transparent acoustic character of the sedimentary bodies, their wedge- or mound-shaped geometry, and the irregular, probably erosive character of their boundaries (Figures 6–8). All these characteristics suggest coarse-grained sediment gravity flow deposits, most probably sandy turbidites, mass flows, and/or slump-derived debris. These sediments would have been transported through the channel by means of high-energy, probably turbulent flows, mixed with sediments eroded or slumped from the channel

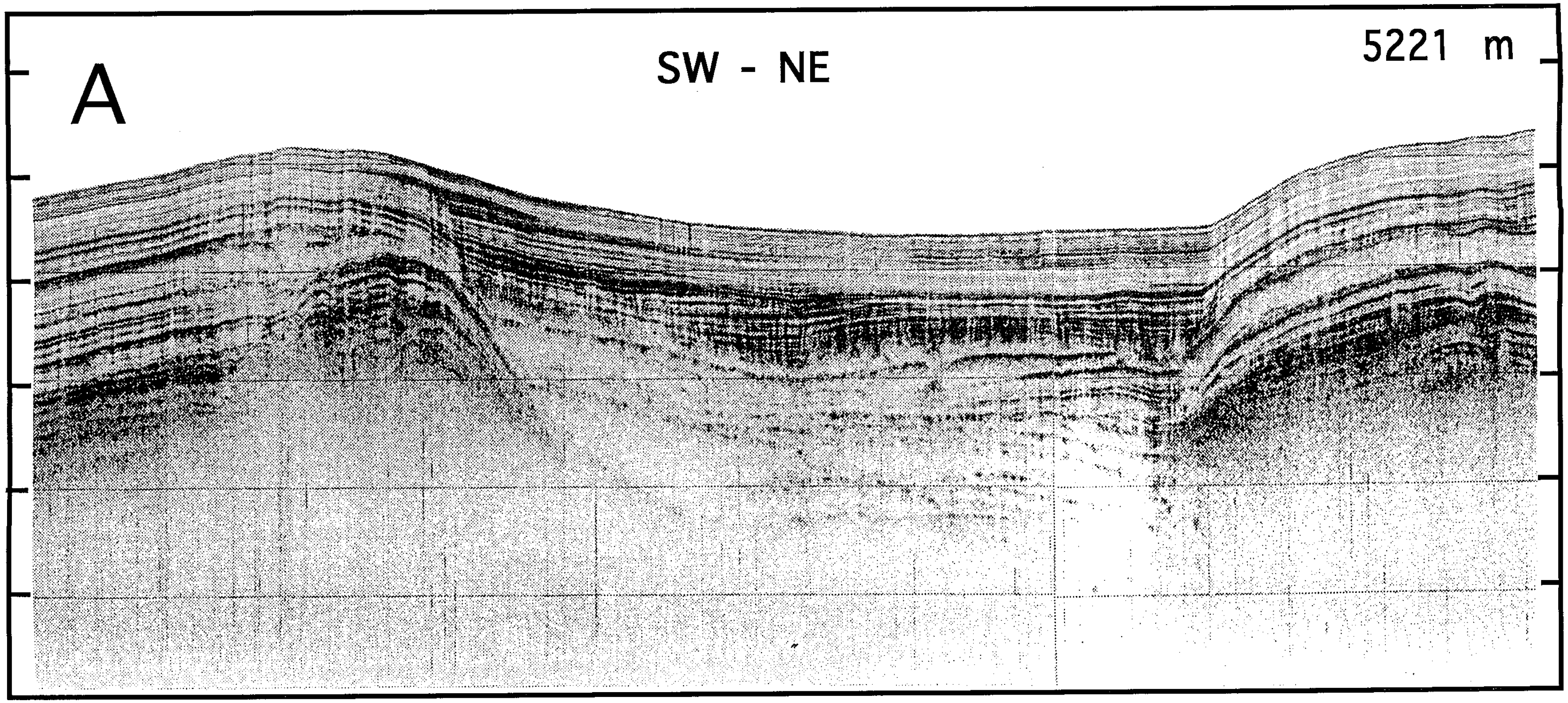

Fig. 7. TOPAS seismic profile (A) and line drawing (B) of the EAMOC near the area where it loses its bathymetric expression, showing the three seismic sequences, ‘a’, ‘b’ and ‘c’, identified within the channel fill and levees. Within seismic sequence ‘a’, tabular seismically transparent level (T) and lenticular seismically transparent body (L) are indicated on the left and right levees, respectively. Location of profile shown in Figure 2.

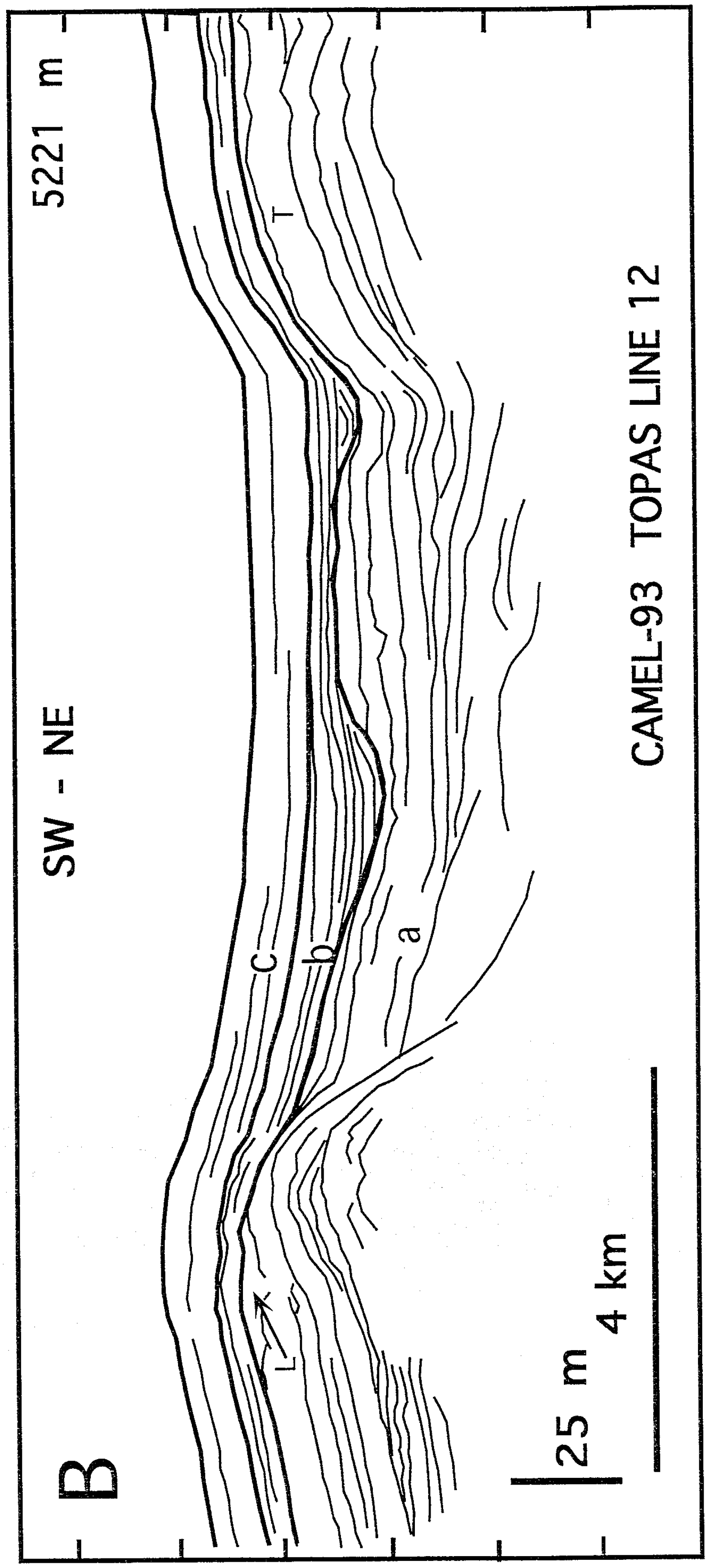

Fig. 7B

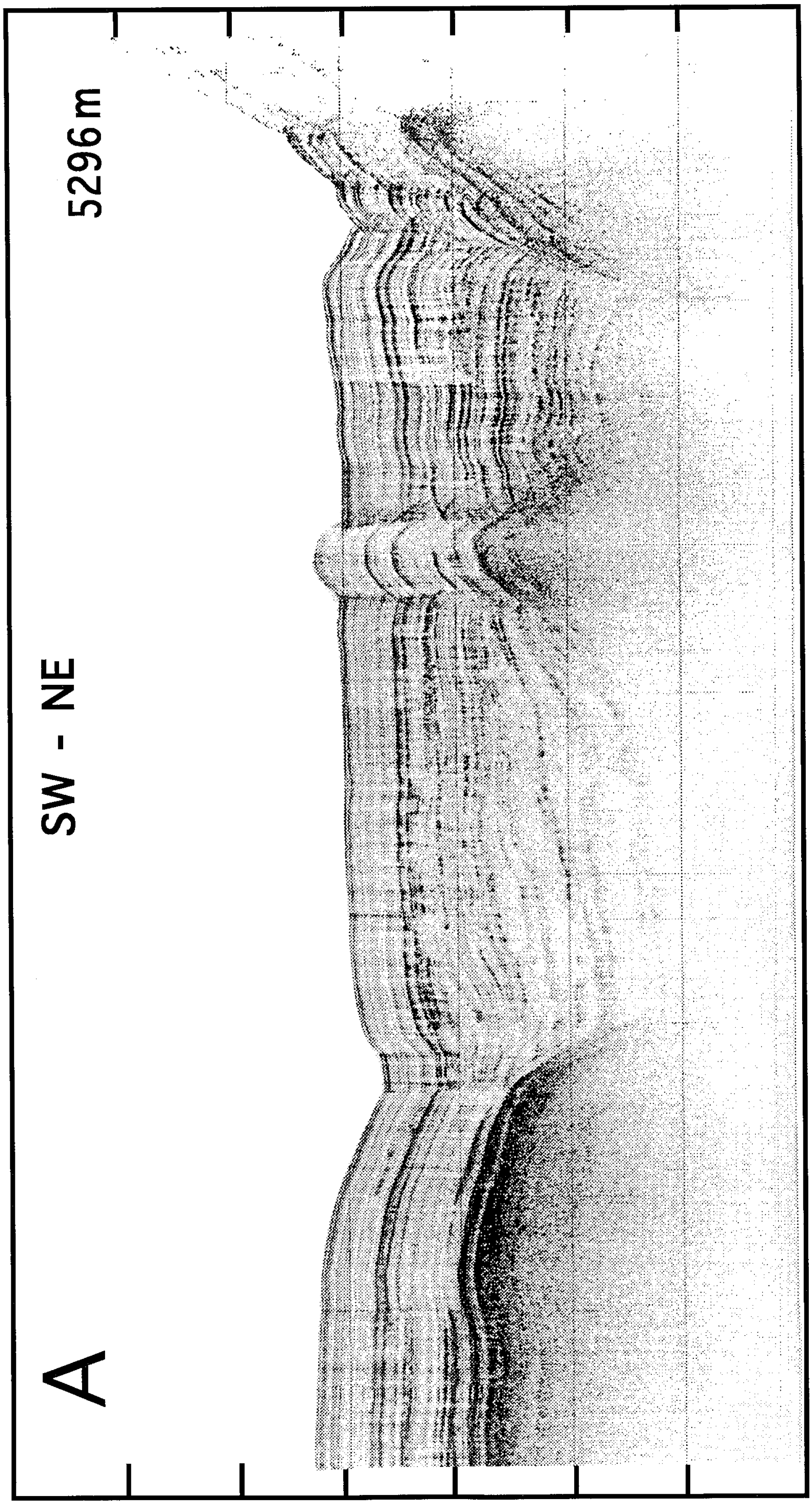

Fig. 8. TOPAS seismic profile (A) and line drawing (B) of the buried part of the EAMOC showing the three seismic sequences, ‘a’, ‘b’ and ‘c’, identified within the channel fill and levees. Note mass-flow deposit (mf) within seismic sequence ‘b’. Location of profile shown in Figure 2.

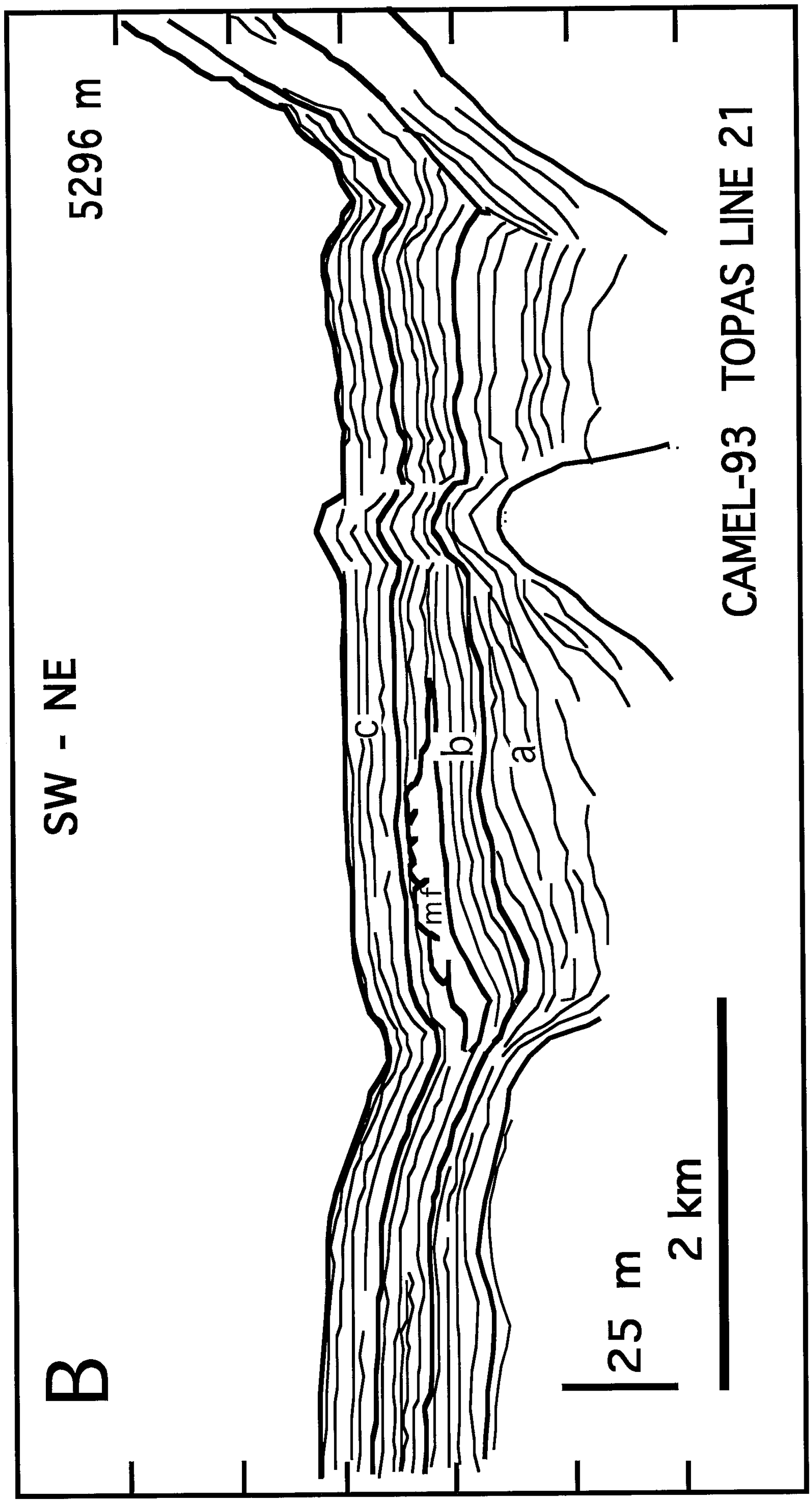

Fig. 8B

walls, and deposited as series of overlapping, tabular, mounded or wedge-shaped bodies (Figure 9). The onlap internal configuration of these deposits towards the right wall of the channel may simply be the result of deposition within the asymmetric channel, but it could also be an indication of synsedimentary deformation of the channel floor by basement movements (Figure 7), as the pathway of the channel begins to be controlled by the high reliefs of the Fernando de Noronha Ridge (Figures 5 and 7).

The levees of the channel show high relief (up to 50 m) (Figures 6–8), and the reflections within them display good lateral continuity and high amplitude, indicating that they result from high energy flows that overbank the channel. The identification of erosive surfaces truncating these reflections, and the presence of horizontal levels and lenticular bodies with transparent acoustic facies that interrupt the stratified reflections, corroborate the episodic occurrence of high-energy overbank flows. The above mentioned relatively high relief of the levees during Phase I probably results from the repetitive occurrence of these overbank events.

Phase II

The second phase corresponds to seismic sequence ‘b’, and was characterized by the predominance of depositional over erosional processes (Figure 9). This phase represents the initiation of the infilling of the EAMOC. Sediments deposited during this phase are initially characterized by a sigmoidal internal configuration and show a progradational seismic pattern (Figures 6–9). Progradation of channel-fill deposits contributed to the levelling of the pre-existing irregular trough morphology of the channel inherited from Phase I. Later, sedimentation continued with a minor lateral accretion, and aggradation prevailed within the channel fill (Figure 9). The high amplitude and relatively low lateral continuity of the sigmoidal stratified facies suggest the deposition of interbedded, coarse- and fine-grained sediments (Figures 6–8). This deposition was episodically interrupted by high-energy, probably turbulent flows similar to those predominant during Phase I, or perhaps corresponding to small-scale slides or slumps produced in the steep channel walls (Figure 9). These processes originated local erosion of the channel floor, and the deposition of sedimentary bodies with lense or mound-shaped geometry, and chaotic or transparent acoustic facies (Figures 6–9).

According to McHargue and Webb (1986), a sigmoidal configuration within a channel fill, similar to that which developed during Phase II, suggests three possible mechanisms of formation: a) slumping of the channel walls; b) point bar deposits related to the sinuous course of the channel; and c) the greater provenance of sediments from one of the channel margins, due to lateral sediment fluxes that spill over into the channel. Although slumping of channel walls was not uncommon during this phase, this first mechanism is not likely to be responsible for the sigmoidal configuration in the EAMOC because of the well-stratified character of seismic unit ‘b’, in which the signs of instability-related processes (i.e. chaotic or disorganized beds) are only identified locally (Figures 6–8). The mechanism of point bar-like sedimentation can explain the sigmoidal configuration of seismic sequence ‘b’ observed in the sinuous part of the EAMOC. However, this explanation cannot justify the similar configuration observed in the W–E oriented linear portion of the channel (Figures 3 and 5), unless the flow within the straight channel was sinuous. In the new detailed bathymetry there are no signs of a sinuous thalweg existing within the channel course (Figure 3), nor is it observed on the TOPAS profiles. Nevertheless, from the bathymetry and geomorphic map (Figures 3 and 5) we see that the straight sectors of the channel are always surrounded by morphologic highs, which leads us to consider the lateral influx of sediment as another possible explanation. The large number of highs and seamounts located nearby between the EAMOC and the Romanche and Fernando de Noronha Fracture Zones (Figure 1) can be tentatively considered as sources for sediments contributing to the infilling of the channel in the form of turbidity currents. Piston cores recovered from the channel floor consist of turbidites having volcanic glass as a minor component, which suggests their provenance from the nearby volcanic seamounts (Damuth and Gorini, 1976), and may corroborate the influence of lateral sediment sources to the infilling of the channel.

The levees of the channel that developed during Phase II also show the relative decrease in activity of the channel and the prevalence of low-energy or pelagic sedimentary processes in the nearby areas. The levees during this phase are constituted by stratified facies with parallel configuration, and most of the reflectors within the channel fill can be followed laterally to the levees and beyond without major changes in their seismic character (Figures 6–8). This may indicate that a continuity existed between the dominant sedimentary processes within the channel course and outside of it, and that seismic sequence ‘b’ partially results from the accretion of sediments that begin to be deposited in the form of a pelagic drape. The relatively low relief (av. 14.5 m) and thin sedimentary cover (av. 17.5 m)

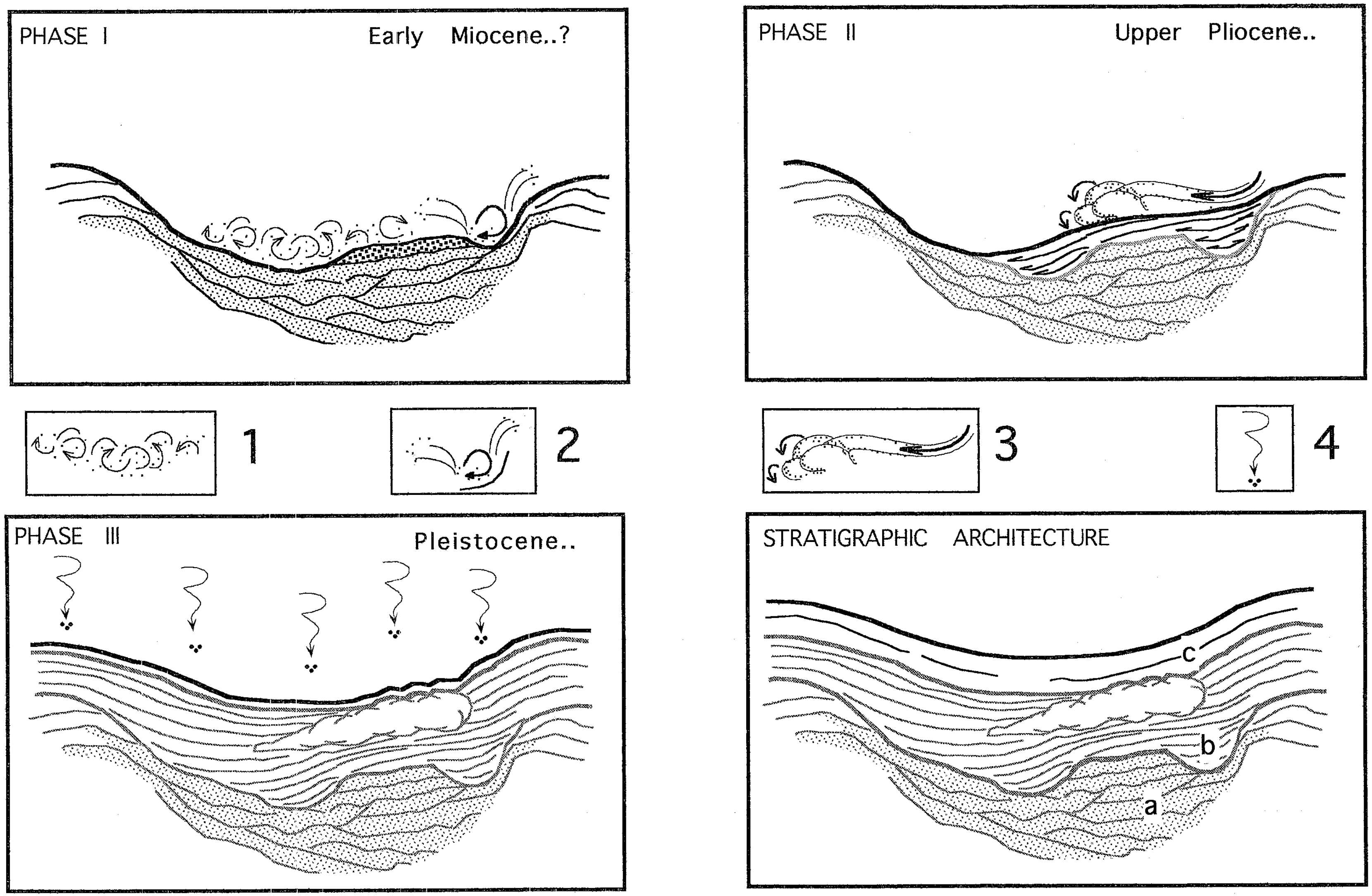

Fig. 9. Schematic diagram showing the sedimentary processes, corresponding phases of activity, chronology suggested for the sequence of infilling of the EAMOC, and resulting stratigraphic architecture of the channel fill. 1: High-energy, turbidite sand/mass flow deposition; 2: Scour and erosion; 3: Onlap fill and slumping; 4: Pelagic sedimentation.

of the levees (Figures 6–8) also suggest a decreasing importance of channel overbank processes.

Phase III

Phase III of channel infill corresponds to seismic sequence ‘c’ and confirms the ceasing of activity of the EAMOC and the exclusive occurrence of pelagic-type sedimentation throughout the entire area (Figure 9). The sediments deposited during this phase extend in the form of a drape over the channel floor, levees, and surrounding areas and contribute to the progressive levelling of the valley morphology in the exposed, sinuous section of the channel, or to its complete infilling in the terminal part (Figures 4–8). These deposits are seismically characterized by constant thickness (16 m) and parallel stratified reflections with low amplitude and high lateral continuity, suggesting laterally homogeneous, pelagic sedimentation (Figures 6–9). The lack of terrigenous sediment transport within the EAMOC during Phase III is supported at the distal end of the channel and levees by the presence of pelagic foraminiferal marls that currently cover many of the previously outcropping seamounts (Damuth and Gorini, 1976). This confirms that the EAMOC is at present a relict feature, and that no evidence of any type of terrigenous sediment flow has been recently recorded along the channel. However, the lateral variations from low to high amplitude reflections observed locally within seismic sequence ‘c’ in the upper channel (Figures 6 and 7), suggest that relatively high-energy processes are still active, although they are of secondary importance and may be related to sporadic lateral input of sediment rather than to more continuous, longitudinal flows along the channel.

Chronology of infilling episodes

The sedimentary fill of the EAMOC shows a clearly developed succession of episodes. The chronology proposed here is based on the correlation of the TOPAS profiles with published sedimentation rates calculated from piston cores recovered from the channel floor and levees of the distal part of the EAMOC (Damuth, 1973; Heezen et al., 1960; Damuth and Gorini, 1976), together with sedimentation rates from Sites 23 and 24 of the DSDP (Leg IV) located about 250 km south of the EAMOC in the Brazil Basin (Benson et al., 1970). The thickness of the transparent facies of seismic sequence ‘a’ has not been determined due to limited penetration of the TOPAS system. Seismic sequence ‘a’ represents the period of greatest activity of the channel, characterized by the predominance of high-velocity turbidity currents and mass flows (Figure 9). Previous authors (Heezen et al., 1960; Damuth and Gorini, 1976), propose a minimum age of late Early Miocene (23–15 myr BP) for the initiation of the channel. The cut-off of the EAMOC from its main terrigenous source in the continental margin is not still clearly understood, but it is thought to have occurred between the middle Miocene and the late Pleistocene (15–1 myr BP) (Heezen et al., 1960). At that time, the predominant direction of sediment dispersal shifted more to the northeast towards the Guiana Basin, and/or paralleled the south face of the Romanche Fracture Zone, with the result that almost no terrigenous sediments reached the vicinity of the EAMOC (Damuth, 1975). Consequently, the channel activity ceased, and the westernmost 75 to 150 km of the EAMOC were buried by a fill sequence 60 to 260 m thick (Damuth and Gorini, 1976). The resulting change in the depositional nature of the EAMOC is represented by seismic sequence ‘b’, whose thickness in the study area is between 16 and 26.5 m, and corresponds mainly to low-energy turbidity currents (Figure 9). Turbidites drilled on Site 24 of the DSDP yielded sedimentation rates between 50 and 100 mm/kyr (Benson et al., 1970). Assuming a similar order of magnitude for turbidite sedimentation rate in the Fernando de Noronha Basin, seismic sequence ‘b’ may tentatively represent a cumulative sedimentation over a period of up to 500,000 years.

Finally, seismic sequence ‘c’ represents the confirmation of the total cessation of activity of the EAMOC, and the beginning of purely pelagic sedimentation (Figure 9). There are quite relevant differences between the published sedimentation rates for pelagic clays in this area. Based on DSDP Leg IV results, Benson et al. (1970) calculated a sedimentation rate of about 5 mm/kyr, whereas Damuth (1973) calculated a sedimentation rate of up to 1 cm/kyr based on piston cores from within the channel course. This latter value has been used by later authors in their discussions about the abandonment of the EAMOC (Damuth and Gorini, 1976). Using this value over the very constant thickness (16 m) of the pelagic drape deposits above the easternmost EAMOC, seismic sequence ‘c’ began to deposit at about 1.6 myr BP, and its age is therefore Pleistocene to recent. Therefore, if we assume that there are no breaks in sedimentation between seismic sequences ‘b’ and ‘c’, as suggested by the TOPAS profiles, we calculate the beginning of the Phase II of channel infill, or the moment when the EAMOC began to become inactive, at about 2.0 to 1.8 myr, therefore within the uppermost Pliocene.

Hypothesis for the Abandonment of the EAMOC

The sediment infill and later abandonment of relatively small submarine canyons eroded on the slopes of continental margins have sometimes been related to local or regional changes in sediment supply rates, or to relative variations of sea-level (Rasmussen, 1994; Druckman et al., 1995). By contrast, one can expect that the complete burial and abandonment of a large and long persistent deep-sea channel could be the consequence of first-order tectonic processes or oceanic-scale changes, and its abandonment therefore represents a first-order basin-scale event.

The hypothesis we propose about the abandonment of the EAMOC puts the emphasis on the effects of major tectonic changes along the valley course due to the activity of the nearby fracture zones. However, the effects in the deep-sea sedimentation caused by paleoceanographic changes related to the global circulation in the southern Atlantic Ocean are also considered. Tectonics is considered by some authors as the main cause for the abandonment of the EAMOC (Damuth and Gorini, 1976). Differential movements related to the tectonic and/or volcanic activity in the region were especially important between 12 to 1 myr BP (Almeida, 1955; Cordani, 1970), and may have been responsible for the shift in the direction of sediment dispersal across the NW Brazilian margin that occurred before the late Pleistocene (Damuth and Gorini, 1976). The progressive emplacement of the volcanic ridge of Fernando de Noronha could have also caused a change in the local base-level of the EAMOC, contributing to a gradual cessation of its activity.

However, marine geologists have recognized for over two decades the important role of deep, thermohaline current systems in controlling the depositional record in the deep South Atlantic (Berggren and Hollister, 1974; Johnson, 1983, 1984). When observed on a general bathymetric map of the Atlantic (Cherkis et al., 1989), one of the most intriguing characteristics of the EAMOC is its southeast-trending course. This is unique among the majority of the larger deep-sea channels in the central and southern Atlantic Oceans, which have northwestward trends compatible with the present deep oceanic circulation, largely controlled by the Antarctic Bottom Current (AABW). The hypothesis we consider here is that a weakly active, SE trending deep-sea channel – such as the EAMOC – will show a progressive loss of activity if there is a relatively strong bottom current with an opposite N–NW trend. This may occur because the weak flows along the distal channel will tend to slow down and deposit their sediment load upslope, compared to its naturally expected position. A change in sedimentation in the more distal sectors of the channel would then occur, and turbidites would progressively be replaced by pelagics. This argument has also been suggested to explain the contact between green turbidites and red clays encountered in DSDP Leg IV, Site 23 (Benson et al., 1970). The relevant changes that occurred during the upper Pliocene in the deep oceanic circulation of this sector of the south Atlantic (Johnson, 1983; Hodell et al.,1985) are suggested here as a second factor responsible for the gradual ceasing of activity and abandonment of the EAMOC. These changes are mostly related to the onset of strong AABW flow pulses in the Brazil Basin mainly through the N–NE trending Vema Channel (Johnson, 1984).

Conclusions

Multibeam bathymetric and high-resolution seismic data on the most distal sector of the Equatorial Atlantic Mid-Ocean Channel (EAMOC) have shown that its course extends further east and south than was previously known, although its final part is buried and does not at present have a bathymetric expression on the seafloor. The distal course of the EAMOC exhibits changes in trend that result from the interaction of the channel pathway with basement highs and outcrops controlled by the Fernando de Noronha Fracture Zone and related faults. The channel course seems to interact and get trapped within the fracture zone relief, following the same direction as the fracture zone for 55 km, and finally escaping through a gap in the basement highs. Its course is then controlled by the presence of morphologic highs and continues trending roughly perpendicular to the direction of the fracture zone.

The distal course of the EAMOC is filled and covered by sediments with contrasting seismic facies and configurations, which result from the stacking of three main seismic sequences. The sedimentological interpretation of the seismic stratigraphy of the channel-fill and levees of the EAMOC suggests that the recent sedimentary history of the channel is defined by the succession of three main phases of decreasing sedimentary activity. Phase I took place when the EAMOC funnelled large quantities of terrigenous sediments to the Fernando de Noronha Basin, and both erosive and depositional processes occurred. This phase represents the last expression of activity of the channel as an active sediment transport agent. During the upper Pliocene, about 1.8 to 2.0 myr BP, the EAMOC experienced a gradual cessation of activity as a conduit for sediment transport to the deep ocean, and the sedimentary infilling of the channel, in a strict sense, began. This moment defines the beginning of Phase II, during which depositional processes within the channel became progressively less energetic, but erosive processes still occurred occasionally. Phase III represents the total cessation of activity of the EAMOC, the complete filling of the channel course, and the covering of the channel and surrounding areas with a continuous pelagic drape. The channel floor of the EAMOC, levees and surrounding areas are at present covered by a 16 m thick pelagic drape which confirms that the channel is currently inactive and must be considered as a relict feature on the present Atlantic seafloor. New ultra-high resolution seismic profiles suggest that the channel has been totally inactive at least since the Pleistocene, at about 1.6 Myr BP. The occurrence of these three phases in the channel fill indicates the gradual death of the Equatorial Atlantic Mid-Ocean Channel as an active sediment transport pathway for sediments originating in the nearby Brazilian continental margin.

Tectonic activity related to the Fernando de Noronha Fracture Zone, or to the volcanic emplacement of the Fernando de Noronha Ridge, may have acted as the main cause for the cessation of activity of the EAMOC. But we also suggest that major changes in the deep oceanic circulation in the South Atlantic, mainly by the effect of strong pulses of the AABW during the upper Pliocene, could have also contributed to the progressive burial and the final abandonment of the EAMOC.

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