The Equatorial Mid-Ocean Canyon: A relict deep-sea channel on the Brazilian continental margin

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ABSTRACT

The Equatorial Mid-Ocean Canyon is an erosional-depositional deep-sea channel which was formed by turbidity-current activity, was active during the Miocene, but is now a relict feature. The canyon parallels the Brazilian continental rise between $3^\circ$-$5^\circ$S and $33^\circ$-$15^\circ$W and descends eastward for at least 1,200 km with a gradient of $1:1,000$. The canyon is 5 to 8 km wide and as much as 200 m deep. Although the bathymetric expression of the canyon on the sea floor begins at about $33^\circ$-$15^\circ$W, the canyon has been traced westward (up-slope) from this longitude in subsurface for at least 75 to 150 km. The trend of this buried portion of the canyon indicates that originally the head of the canyon was on the upper continental rise. The stratigraphic relationship between the canyon and a lower Miocene acoustic reflector of widespread regional extent suggests that the canyon formed during the late early Miocene period. Piston cores from the canyon floor, walls, and levees consist largely of pelagic foraminiferal marls and brown clays which indicate that the canyon has been inactive for at least the past million years. The exact time when the canyon became inactive is still uncertain, but it was probably middle to late Miocene. When active, the canyon channeled terrigenous sediments southeastward along the trend of the Fernando de Noronha Basin. The canyon apparently was abandoned and subsequently buried when the predominant direction of sediment dispersal shifted from southeastward along the Fernando de Noronha Basin to northeastward into the adjacent Guiana Basin, thus making the canyon path obsolete. Key words: marine geology, continental margin, deep-sea channels, mid-ocean canyons, equatorial Atlantic.

INTRODUCTION

Most deep-sea channels have trends perpendicular to the continental margin. Occasionally, however, a channel is discovered on a remote region of the ocean floor which seems to have no connection or relationship to the continental margin. Such channels have been termed "mid-ocean canyons" (Heezen and others, 1959; Heezen and Menard, 1963) and have been reported from the North Atlantic (Heezen and others, 1959, 1969), the equatorial Atlantic (Heezen and others, 1960), the Gulf of Alaska (Heezen and others, 1969), and the Hikurangi Trench east of New Zealand (Heezen and Hollister, 1971). Since their discovery, the origin of these features has been uncertain because (1) they are apparently confined to abyssal provinces, (2) they show no connection to channels on the continental margin, and (3) their trends are generally parallel (rather than perpendicular) to the adjacent continental margin. Turbidity currents, tectonism, and thermohaline circulation have all been suggested as possible mechanisms of formation (Ewing and others, 1953; Dietz, 1958; Heezen and others, 1960; Heezen and Laughton, 1963; Shepard and Dill, 1966; Heezen and others, 1969).

The present study is concerned with the origin of the Equatorial Mid-Ocean Canyon, which is located east of Fortaleza, Brazil (Fig. 1). Heezen and others (1960) first surveyed the canyon in 1956 and 1957 (Fig. 2, dotted lines) and reported that it paralleled the base of the continental rise for at least 650 km. The canyon did not appear to extend west of about $33^\circ$-$10^\circ$W, and no connection with channels on the adjacent continental rise was found. Heezen and others (1960) concluded that although the morphology and sediments of the canyon suggested a turbidity-current origin, the parallelism of the canyon with the continental margin and the Mid-Atlantic Ridge suggested tectonic control.

Because no seismic reflection profiling system was available during these early surveys, the relationship of the canyon to subsurface sediments and structures could not be studied. Between 1957 and 1974, however, seismic reflection profiles were obtained during several random crossings of the canyon (Fig. 2; crossings 3, 5, 22, 25, 28, 29, and 36). Crossing 5 (Fig. 2, V24) proved to be the key to understanding the origin of the canyon. Although the 3.5-kHz echogram showed no evidence of the canyon, the seismic reflection profile (Fig. 3) revealed a buried canyon-like feature which suggested that the canyon was present west of $33^\circ$-$10^\circ$W as a buried feature.

In May 1974, the upslope end of the canyon was surveyed during Vema Cruise 31 (Fig. 2) in order to establish the continuity and trend of the buried part of the canyon. We have combined the data from this survey with all data collected between 1956 and 1974 in order to describe the morphol-

Figure 1. Location map for the equatorial Mid-Ocean Canyon. Outlined areas are maps A and B of Figure 2. Black areas are basement ridges (redrawn from maps by Gorini and others, 1974; and Gorini and Bryan, 1974).

EQUATORIAL MID-OCEAN CANYON

EXPLANATION

SEAMOUNTS & BASEMENT highs

EQUATORIAL MID-OCEAN CANYON

BURIED EXTENSION OF CANYON

CRUISE TRACKLINES

3.5 kHz PDR & SEISMIC REFL. PROFILES

12 kHz PDR & SEISMIC REFL. PROFILES

12 kHz PDR ONLY

* PISTON CORES

METERS

FORAMINIFERAL MARL
B BROWN CLAY
N NANNOSPORE & Ooze
S Silt/Sand Bed (10 cm Thick)
G Graded Terrigenous Silt/Sand
D Graded Biogenic (Foram-Nannossil) Silt/Sand

Figure 2. Map of the Equatorial Mid-Ocean Canyon (areas A and B in Fig. 1), showing cruise tracklines, locations, and lithologic logs of piston cores and locations of bathymetric and seismic profiles (numbers 1 through 42) discussed in the text and shown in following figures. Cruises are indicated by number (for example, V31); V is R/V Vema and RC is R/V Conrad. Piston cores are indicated by cruise and core number (for example, V9-11). Letters to the right of core V9-11 indicate climatic zones determined by Ericson and Wollin (1968).

MORPHOLOGY OF THE CANYON

The Equatorial Mid-Ocean Canyon has continuous sea-floor expression for at least 1,275 km (Fig. 2). The canyon has no bathymetric expression west of about 33°35'W (Fig. 4). The canyon's course eastward of profile 42 is also uncertain (Fig. 2). Along the easternmost cruise track line (Fig. 2, V22), no canyon is observed either on the sea floor or in the subsurface. A large basement ridge with up to 400 m of relief occurs near 4°30' to 5°S along the V22 track and between 27°30' to 28°W along the V12 track (Fig. 2). The canyon does not run to the north or west of this ridge. It is possible that the basement ridge is not continuous between the V22 and V12 tracks and that the canyon follows a southeastward course through a gap in the ridge. In any case, the canyon is not observed along any portion of the V22 track and thus must terminate at some point between crossing 42 and 27°30'W.

The canyon is 5 to 8 km wide and has a relief of as much as 200 m (Figs. 4 and 5). The axial gradient along the canyon floor is relatively smooth and averages 1:1,040 (Fig. 6, top line). Slightly steeper gradients occur between 450 to 550 km and 1,000 to 1,100 km and correspond to sharp southward bends of the canyon (Fig. 2, 31°W and 29°03'W). The canyon has natural levees...
(for example, the north wall in crossing 10; see Fig. 5); in 20 out of the 35 bathymetric profiles (Fig. 4, crossings 7 through 41), the north canyon wall is higher than the south wall by as much as 25 m. The south wall is higher in only 4 of the 35 profiles.

The difference in levee heights across a deep-sea channel can generally be attributed to the effects of the Coriolis and (or) the centrifugal forces which act on the sediment-laden currents flowing down the channel (Buffington, 1952; Menard, 1955; Komar, 1969). In the southern hemisphere, channelized currents are tilted upward from right to left by the Coriolis force. Thus the left levees of channels (looking in a downslope direction) should be higher than the right levees. The facts that the north levee of the Equatorial Mid-Ocean Canyon is the left levee (looking downslope) and is often higher than the south levee may indicate preferential deposition on the north levee under the influence of the Coriolis force, even though the Coriolis force is relatively small at this low latitude (3° to 5°S). On the other hand, the higher north levee may simply result from the centrifugal force acting on the sediment-laden currents as they follow the meanders of the canyon. However, this does not explain why, within the random distribution of more than 40 crossings, the north levee is higher in 60 percent of the crossings, whereas the south levee is higher in only 10 percent of the crossings.

A very prominent acoustic reflector (marked by arrows) occurs at 0.1 to 0.4 sec below the sea floor in the vicinity of the canyon (Fig. 7). The canyon cuts this reflector in profiles 25, 29, 34, and 36. The reflector appears to crop out on some of the canyon walls (Figs. 5, 7, and 8). A thin sequence of transparent sediment up to 0.1 sec thick overlies the reflector within the canyon (Figs. 7, 8). In profiles 22, 15, 10, and 7 (Fig. 7), the relief of the canyon decreases progressively in the up-canyon direction, whereas the sequence of transparent sediment between the present canyon floor and the prominent acoustic reflector progressively thickens upslope (0.15 sec to 0.3 sec).

The upslope (western) end of the canyon was surveyed between 33° and 33°45'W (Fig. 2, crossings 1, 2, 4, 6) to determine the

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**Figure 3. Seismic reflection profile along crossing 5 (V24).** Large arrow points to buried Equatorial Mid-Ocean Canyon. Small arrow points to the prominent lower Miocene reflector discussed in text.

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**Figure 4. Bathymetric profiles traced from PDR records of crossings 1 through 42 (Fig. 2).** North is to the left. Scale to right of each profile is in uncorrected fathoms. Arrows indicate axis of buried canyon in crossings 1 through 6.
Figure 5. Echograms (3.5 kHz) of the Equatorial Mid-Ocean Canyon. Profile locations are indicated by number in Figure 2. Arrows in profile 29 point to prominent lower Miocene reflector discussed in text.

subsurface trend of the canyon west of crossing 7. In each profile, the canyon is clearly visible as a subsurface feature with well-stratified levels. The prominent acoustic reflector apparently forms the canyon floor. The canyon and levels are buried beneath as much as 0.35 sec of relatively transparent sediment. The buried canyon extends at least 75 km westward (upslope) of its westernmost sea-floor expression along a trend that is upslope and more or less perpendicular to the continental margin. In addition, a seismic profile along the RC15 track suggests that the buried canyon may extend westward as far as 34°20’W (Fig. 2). However, more seismic profiles between crossing 1 and the RC15 track are needed to confirm the continuity of the buried canyon westward to this location. The burial of the westernmost 75 to 150 km of the canyon by younger continental-rise sediments suggests that the canyon is a relict feature.

An axial profile along the subsurface canyon floor at the top of the prominent acoustic reflector indicates that downslope from about 400 km (approximately 31°30’W), the gradients of this subsurface floor (1:1.150) and the present canyon floor (1:1.110, upper line) are about equal (Fig. 6). The buried floor is consistently 60 to 80 m below the present floor. However, upslope from about 400 km, the average gradient of the present canyon floor (1:840) is steeper than the gradient of the buried canyon floor (1:1,300) (Fig. 6). The thickness of sediments between the buried canyon floor and the present floor increases progressively upslope from about 80 m at 400

Figure 6. Top line (solid) is an axial profile of deepest soundings along the present floor of the Equatorial Mid-Ocean Canyon. Solid circles are depths at crossings 7 through 42 (Figs. 2 and 4). Solid triangles are depths at additional crossings (Fig. 2). Solid squares are crossings 1 through 6 (Figs. 2 and 4) and show depths of sea floor over the axis of the buried portion of the canyon. Lower line (dashed) is an axial profile along the buried floor of the canyon (Figs. 3, 7, 8, 9). Locations of profiles are shown by number in Figure 2. Depths to the buried canyon floor were calculated using a seismic velocity of 1.8 km/sec which is consistent with sonobuoy data from this region.

Figure 7. Seismic reflection profiles of the Equatorial Mid-Ocean Canyon. Locations are indicated by numbers in Figure 2. Arrows point to prominent lower Miocene reflector discussed in text.

Figure 8. Two seismic reflection profiles of the Equatorial Mid-Ocean Canyon and corresponding 3.5-kHz echograms across the south canyon wall. Lower profile is along crossing 28 (Fig. 2), whereas upper profile is along V31 trackline (crossing not numbered in Fig. 2) at its intersection with crossing 28. Arrows point to the prominent lower Miocene reflector discussed in text.
km to about 260 m at ~75 km. This suggests that the upper end of the canyon is being progressively filled downslope by younger sediments.

Erosion into the prominent acoustic reflector by the canyon seems to be progressively deeper in the downslope direction. East of about 31°30'W, the canyon clearly cuts the reflector (Figs. 7 and 8); west of 31°30'W, the canyon either cuts the reflector only slightly (Fig. 7) or else the canyon floor is at the top of the reflector (Fig. 9). This relationship indicates that the canyon either (1) formed and was active during deposition of the reflector or (2) formed a short time after deposition of the reflector. The absence of former levels of the canyon floor below the reflector suggests that the canyon did not exist before the reflector was deposited (however, the high reflectivity of the reflector may obscure such underlying structures). The reflector appears to contain natural levees which border the canyon (for example, profiles 29 and 36 shown in Fig. 7). Such levees suggest that the canyon was active during deposition of the reflector. Taken together, these observations suggest that canyon formation must have been contemporaneous with or just slightly after deposition of the prominent acoustic reflector.

SEDIMENTS OF THE CANYON

Eight piston cores have been raised from the Equatorial Mid-Ocean Canyon (Fig. 2). Core V9-11 (4,236 m) is from the north levee approximately 5 km from the canyon wall and consists entirely of light-brown pelagic foraminiferal marl. A biostratigraphic curve based on the frequency of abundance of foraminifera of the Globorotalia menardii complex (Ericson and Wollin, 1968) indicates that the core is continuous back to the lowest T zone, or approximately 900,000 yr B.P. Core V9-12 (4,219 m) is from the north wall of the canyon approximately 27 m above the canyon floor and consists of light-brown pelagic sediments (Fig. 2). A climatic curve (Ericson and others, 1964) suggests that this core is continuous back to at least 600,000 yr B.P. The core does contain two thin (5 to 10 cm) turbidites of brown volcanic glass and foraminifera which were probably derived from the Fernando de Noronha Ridge to the south (Fig. 1). Core V9-14 (4,801 m) was raised from the canyon floor and consists of light-brown pelagic foraminiferal marl and brown clay (Fig. 2). This core is continuous back to about 700,000 yr B.P. (Ericson and others, 1964; D. B. Ericson, personal communication). The absence of terrigenous beds (turbidites, hemipelagic sediments, and so on) in these three cores indicates that at least some parts of the canyon’s floor and levees received no terrigenous sediment during the last 600,000 to 900,000 yr.

In contrast to the previous cores, RC16-162 (4,412 m), which was raised from the canyon floor, consists of a single turbidite which grades downward from fine sand to fine gravel (Fig. 2). The sand consists of quartz, feldspar, and mica and includes abundant foraminifera of latest Pleistocene age (Wisconsinan). Core V31-130 (5,000 m) was also raised from the canyon floor and contains redeposited beds which consist of graded foraminiferal sand (Fig. 2). No terrigenous sediment is present, although volcanic glass forms a minor component. The foraminifera range from Pliocene (or older) to latest Pleistocene in age. These beds are clearly turbidity-current deposits which were probably derived from nearby seamounts.

Cores V12-85 (5,058 m) and V30-31 (5,142 m) are from the canyon levees at locations a few hundred metres from the south wall (V12-85) and about 2 to 3 km from the north wall (V30-31). The cores consist almost entirely of pelagic brown clay; however, V12-85 contains a thin bed of foraminiferal marl of late Pleistocene age. Core V31-129 (5,415 m) is from the canyon floor at the southeasternmost crossing (42, Fig. 2) and also consists of pelagic brown clay. Because the sedimentation rate for brown clay in the western equatorial Atlantic during the Quaternary was about 1 cm/10^6 yr (Damuth, 1973), these three cores indicate that terrigenous sediment has not reached the floor or levees of the lower canyon during at least the last 900,000 to 1,200,000 yr.

The absence of terrigenous sediment from most of the cores indicates that levee construction did not take place and that turbidity currents did not reach most parts of the canyon floor during the last million years. Thus the canyon has been inactive during at least the late Quaternary. Two cores from the canyon floor do contain turbidity-current deposits; however, the facts that (1) the upper 75 to 150 km of the canyon is buried and (2) the other cores indicate an inactive canyon suggest that the turbidity currents entered from downslope locations along the middle and lower portions of the canyon. Thus, these deposits did not contribute to construction of the canyon, but rather to its burial. No evidence was seen in any of the cores or in bottom photographs from the coring sites for erosion or sediment redistribution within the canyon by geostrophic bottom currents (contour currents).

AGE AND ORIGIN OF THE CANYON

The stratigraphic relationship between the canyon and the prominent acoustic reflector (Figs. 7, 8, and 9) suggests that the canyon formed during or just slightly after deposition of the reflector. The regional distribution of the reflector is not restricted to the Fernando de Noronha Basin; it extends southward into the Brazil Basin (Figs. 10 and 11). Northward, however, the reflector apparently does not extend across the low topographic sill between the North Brazilian Ridge and Romanche Fracture Zone (Figs. 11 and 12).

Fortunately, the age of the reflector was determined during Leg IV of the Deep Sea Drilling Project at a drill site (DSDP sites 23 and 24) which was approximately 275 km south of the Equatorial Mid-Ocean Canyon (Figs. 10 and 11). The reflector consists of turbidites of fine to medium terrigenous sand which are interbedded with gray silty clay. The age of the reflector is early Miocene (~15 to 23 m.y. B.P.) (Bader, Gerard, and others, 1970). The reflector can be continuously traced from the drill site northward to the canyon (Fig. 10). Because the canyon formed contemporaneously with or just after the reflector, the age of formation of the canyon must have been approximately late early Miocene or earliest middle Miocene.

The time of abandonment of the canyon is less certain. No datable acoustic reflectors occur above the lower Miocene.
reflector, and piston cores reflect only the last million years of canyon inactivity. If the 60 to 80 m of transparent sediment overlying the lower Miocene reflector in the lower canyon consist entirely of pelagic brown clay deposited at rates consistent with those observed in the piston cores (1 cm/10^4 yr; Damuth, 1973), then the canyon has been inactive for at least 6 to 8 m.y. At present, however, all that can be stated with certainty is that the canyon became inactive at some time before the late Pleistocene period (1,000,000 yr B.P.).

The course of the canyon is eastward along the trend of the Fernando de Noronha Basin and parallel to the Fernando de Noronha Ridge (Fig. 11). This parallelism suggests that the canyon's course was structurally controlled by the ridge. When considered in this tectonic setting, it is apparent that the canyon does not parallel the continental margin as originally reported (Heezen and others, 1960) but has a trend more or less perpendicular to the margin (Fig. 11).

If the lower Miocene reflector is of consistent lithologic composition, then its areal distribution records the pattern of terrigenous-sediment dispersal throughout the Fernando de Noronha Basin during the early Miocene period. This pattern indicates that sediment dispersal was predominantly southeastward along the trends of the basin and the canyon. Because the lower Miocene reflector apparently records a period of extremely widespread terrigenous sedimentation, it is quite possible that the Equatorial Mid-Ocean Canyon developed in response to this increased terrigenous influx and was a major dispersal route for the sediment.

In contrast to the southeastward dispersal of terrigenous sediment during early Miocene time, the predominant direction of sediment dispersal during the late Quaternary (shown by arrows in Fig. 11) has been northeastward toward the Guiana Basin. At present, the direction of steepest gradient on the continental rise between 33° and 37°W is northeastward (parallel to profile B in Fig. 11). In addition, the modern deep-sea channels in this region have northeastward trends (parallel to arrows in Fig. 11) which converge on the gap between the North Brazilian Ridge and the wall of the Romanche Fracture Zone (Damuth, 1973). The dashed line in Figure 11 shows the approximate eastward limit of terrigenous sediment dispersal during the late Quaternary. All cores from west of this line consist of gray hemipelagic silty clay and redeposited terrigenous beds; all cores from east of the line are composed of light-brown pelagic foraminiferal marls and brown clays. Thus, at least during late Quaternary time, the bulk of terrigenous sediment has either moved northeastward through the topographic gap and into the Guiana Basin or was ponded against the wall of the Romanche Fracture Zone (as shown by the arrows in Fig. 11). Very little terrigenous sediment has been dispersed southeastward along the trend of the basin. Consequently, almost no terrigenous sediment reaches the vicinity of the Equatorial Mid-Ocean Canyon.

The termination of the lower Miocene reflector against the buried portion of the North Brazilian Ridge (Fig. 12, profile B) indicates that terrigenous sediment apparently was unable to move northeastward through the gap and into the Guiana Basin until sometime after early Miocene time.

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**Figure 10.** Seismic reflection profile along line A, Figure 11. Arrows point to the prominent lower Miocene reflector which was drilled at DSDP sites 23 and 24.

**Figure 11.** Structural setting of the Equatorial Mid-Ocean Canyon (redrawn from maps by Gorini and others, 1974; and Gorini and Bryan, 1974). Dashed line indicates the approximate eastward limit of terrigenous sedimentation during late Quaternary time. Arrows indicate the predominant paths of terrigenous sediment dispersal during the late Quaternary.

**Figure 12.** Seismic reflection profile along line B, Figure 11. Acoustic reflectors and basement have been enhanced to make them visible in the photograph. Arrows point to the prominent lower Miocene reflector discussed in text.
Thus the shift in the direction of sediment dispersal occurred sometime after the early Miocene and before the late Pleistocene. The cause of this directional shift is uncertain. The change was probably a normal consequence of the geometry of basin filling in this region. However, rocks from the Fernando de Noronha islands indicate that volcanic activity occurred on the Fernando de Noronha Ridge between 1 to 12 m.y. B.P. (Almeida, 1955; Cordani, 1970; Gorini and others, 1974). Tectonic movements associated with this volcanism may have steepened continental-rise gradients in the northeastern direction. Regardless of the cause and timing, it appears that this change in the predominant direction of sediment dispersal may have caused the Equatorial Mid-Ocean Canyon to become inactive and led to the subsequent burial of the upslope end of the canyon.

SUMMARY AND CONCLUSIONS

Our data suggest the following history for the Equatorial Mid-Ocean Canyon. During the early Miocene, a high influx of sediment from Brazil was dispersed predominantly southeastward along the trend of the Fernando de Noronha Basin, and it formed the prominent lower Miocene acoustic reflector which occurs throughout the region (Fig. 11). The Equatorial Mid-Ocean Canyon probably developed during the late early Miocene in response to this high terrigenous sediment influx. The canyon was a depositional-erosional channel formed by turbidity-current activity and was probably the major pathway for terrigenous sediment to the Fernando de Noronha Basin. The trend of the canyon was structurally controlled by Fernando de Noronha Ridge (Fig. 11). The canyon may have been the major dispersal path for much of the terrigenous sediment which formed the lower Miocene reflector.

Some time after early Miocene time, the direction of terrigenous sediment dispersal shifted from southeastward to northeastward toward the Guiana Basin (arrows in Fig. 11). Large quantities of terrigenous sediment no longer reached the canyon. The canyon became inactive, and the upslope section was subsequently buried by younger sediment. The exact timing of the abandonment of the canyon is uncertain. It could have occurred at any time between the beginning of the middle Miocene (15 m.y. B.P.) and the beginning of the late Pleistocene (1 m.y. B.P.). Terrigenous sediment was probably able to cross the sill in the North Brazilian Ridge, however, and enter the Guiana Basin shortly after the early Miocene period. The fact that the canyon is buried under 60 to 250 m of sediment suggests that the canyon has been inactive for several million years. Thus, the directional change in sediment dispersal and subsequent abandonment of the canyon probably occurred during the middle or late Miocene.

The Equatorial Mid-Ocean Canyon is simply an ancient analogue of modern deep-sea channels which extend for several hundred kilometres across the continental margin to abyssal regions. For example, the canyon is quite similar in size, length, morphology, and physiographic setting to the Cascadia Channel on the northeast Pacific margin (Griggs and Kulm, 1970, 1973; Griggs and others, 1969; Nelson and Kulm, 1973). The only apparent difference between these two features is that the Cascadia Channel is a modern, active feature, whereas the Equatorial Mid-Ocean Canyon is an ancient, relic feature.

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