Morphology, Sedimentation Processes, and Growth Pattern of the Amazon Deep-Sea Fan

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Abstract

The Amazon Deep-Sea Fan began to form in the Early Miocene and is characterized by a highly meandering distributary channel system. On the middle fan, these leveed channels coalesce to form two broad levee complexes. Older, now buried levee complexes are also observed within the fan. These levee complexes grow through channel migration, branching, and avulsion. Probably only one or two channels are active at any given time. Sediments reach the fan only during glacio-eustatic low stands of sea level. Coarse sediments largely by-pass the upper and middle fan via the channels and are deposited on the lower fan.

Introduction

The Amazon Fan (or Amazon Cone) is the third largest modern deep-sea fan and extends from the continental shelf off northeast Brazil to depths in excess of 4700 m (Figures 1 and 2). The morphology, sedimentation processes, age, and structure of the fan were first examined in detail [1, 2] using conventional seismic and sediment data. Additional studies have indirectly addressed some aspects of the fan age and development in less detail [3–10]. More recently, a new series of Amazon Fan studies has been initiated which utilizes more sophisticated, state-of-the-art oceanographic instruments and techniques (e.g., side-scan sonar, bathymetric swath mapping) to address problems of sedimentation processes and growth pattern of the fan that could not be resolved using the conventional geologic/geophysical techniques and data of previous studies. The first of these new studies was a survey of the upper and middle fan using the GLORIA long-range side-scan sonar [11]. The GLORIA enabled mapping of entire trends and bifurcation patterns of individual channels for the first time. This study revealed much new information about channel morphology (e.g., highly meandering) [11] and relative age relationships [12]. It also raised a number of new problems that must be addressed during upcoming studies. Below, we briefly summarize the present state of knowledge of the morphology, sedimentation processes, and growth pattern of the Amazon Fan.

Regional Setting

The Foz do Amazonas is the sedimentary basin that underlies the Amazon River mouth, continental shelf, and upper Amazon Fan. Sediments range from Middle Cretaceous to Quaternary in age; thicknesses range from 5 km onshore to possibly 14 km at the shelf edge and under the upper fan [10]. The Amazon Fan extends downslope from the shelf break for as far as 700 km (Figures 1 and 2) and has an average gradient of 6.6 m/1000 m (~1:15 or 0.4°). The fan is about 250 km wide at the shelf break, but it quickly widens downslope to a maximum width of approximately 650 to 700 km. This elongated radial pattern covers approximately 330,000 km². The maximum thickness of the fan is 4 to 5 km [10], and the total volume of sediments in the fan is probably in excess of 700,000 km³.

Fan Morphology

We divide the Amazon Fan into three morphologic divisions (upper, middle, and lower) based on morphologic and acoustic characteristics. The upper fan extends from the shelf break
to about 3000 m (Figure 1) where the bathymetric contours show a noticeable break in slope (Figure 2). Gradients range from about 25 m/1000 m (1:40 or 1.4°) near the shelf break to 10 m/1000 m (1:100 or 0.6°) near 3000 m; the average gradient is 14 m/1000 m (∼1:70 or 0.8°). The upper fan surface is often rugged, and steep scarps of up to a few hundred meters relief are observed (Figures 1 and 3, Profile WX). The major morphologic features of the upper fan are the Am-

Figure 1. Morphology of Amazon Fan. Distributary channels on upper and middle fan were mapped from GLORIA side-scan sonographs (uncorrected for slant range) [11] and conventional PDR echograms [1,2]. Small channels on lower fan are mapped from PDR only. Numbers 1 through 6 beside major distributary channels indicate relative ages of channels in order of increasing age (see text).
azon Submarine Canyon and a large leveed central distribu-
tary channel that divides into four prominent leveed distribu-
tories between 2000 and 3000 m (Figures 1–3, 4A).

The middle fan extends from about 3000 m to 4000–4200 m (Figure 1) where a subtle change in gradient occurs (Fig-
ure 2). Gradients range from 10 m/1000 m to 4 m/1000 m
(1/250 or 0.2°); the average gradient is about 5 m/1000 m
(1:200 or 0.3°). The middle fan is characterized by numer-

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**Figure 2.** Bathymetry of Amazon Fan. Contours in corrected meters. Heavy lines WX and YZ show loca-
tions of seismic profiles in Figure 3; lines A to D show locations of 3.5-kHz echograms in Figure 4. Box outlines location of GLORIA sonograph in Figure 5.
ous large, leveed distributary channels (Figures 1–3, 4B, and 4C). The individual levee systems coalesce to form two large, distinct levee complexes (the Western and the Eastern complexes, Figure 1) whose downslope ends define the boundary between the middle and lower fan.

The lower fan is smooth and very gently sloping with an average gradient of 2.3 m/1000 m (1:430 or 0.1°). Numerous small, unveleed distributary channels cross the lower fan (Figures 1 and 4D). On low-frequency seismic records, the lower fan is acoustically distinct (Figure 3). The upper and middle fan are characterized by acoustically transparent to semitransparent sediment wedges and prisms that are recognizable as buried channel-levee systems and former fan surfaces (Figure 3). In contrast, the lower fan uniformly returns a highly reflective, conformably stratified pattern (Figure 3, Profile WX). Transparent channel-levee systems are not observed.

**Distributary Channel System**

The distributary channel system of the Amazon Fan radiates outward from the Amazon Submarine Canyon (Figures 1 and 2). The canyon is up to 600 m deep and extends from the outer shelf (40-m contour) to at least 1400 m. Near 1400 m, the canyon abruptly widens, and a large, leveed central channel or fan valley arises (Figures 1 and 2). The levee system associated with this channel is up to 50 km wide, 1 km thick, and rises up to 300 m above the surrounding fan surface; the channel itself is perched atop this levee system and is up to 250 m deep and 2500 m wide (Figure 4A). This central channel trends downfan (gradient ~8.5 m/1000 m) to about 2200 m, where GLORIA sonographs show that it bifurcates; the deeper (up to 200 m) main branch curves sharply northwestward, whereas the shallower (40 to 60 m) eastern branch curves northeastward (Figure 1).

Using GLORIA sonographs and PDR echograms, we identified and mapped six major distributary channels (1 through 6 in Figure 1) and their associated branches on the upper and middle fan [12]. Channels 1 and 3 arise from the bifurcation of the central channel. Channels 2 and 4 arise between 2500 and 2800 m, apparently from bifurcation of channels 1 and 3, respectively (Figure 1). Below 3000 m, the trends and branching patterns of the observed channel segments (including 5 and 6) are less certain because most appear as discontinuous segments on GLORIA sonographs. Although some of these discontinuities are due to small gaps in GLORIA coverage (e.g., directly beneath ship or the absence of slant-range correction), many others appear to represent channel cutoff and abandonment with subsequent partial burial or destruction of channel segments (Figure 1).

Each distributary channel on the upper and middle fan is perched atop a wide levee system (e.g., Figure 4B) that builds upward and laterally by overbank spilling [1,11,12]. Individual levee systems appear as thick (up to 1 km), semitransparent, wedge-shaped deposits on seismic profiles (Fig-
Figure 4. The 3.5-kHz echograms of distributary channels that show examples of channel size and morphology at various locations downfan (locations shown in Figure 2). A. Leveed central channel (1) on upper fan. B. Leveed meandering channel (4) typical of middle fan. Average gradients on backsides of such levees are generally 15 m to 40 m per 1000 m (~1° to 2°); locally gradients range up to 166 m/1000 m (9.5°). C. Small channels with low levees characteristic of the middle-to-lower fan transition. Small debris flow is from a nearby basement knoll. D. Small channels (CH) less than 20 m deep that are typical of lower fan.

Figure 3. High-amplitude reflectors are commonly observed beneath the channel axis in each levee deposit and may be reflected from coarse sediments deposited in the channel floor as the levee sequences built upward. Numerous older, now buried channel-levee systems are observed on seismic profiles (Figure 3).

On the lower fan, PDR echograms and seismic profiles show numerous, small (5 to 25 m deep) distributary channels (black dots, Figure 1) that have little or no associated levee development (Figure 3, Profile WX and Figures 4C and 4D). GLORIA sonographs show these channels to be highly meandering. One 20 m deep channel was traced continuously from 4100 m to 4450 m (Figure 1).

On the middle fan (3000 to 4200 m), two distinct, separate levee complexes, each composed of several individual, coalescing channel-levee systems, diverge down the middle fan (Figure 1). These were designated the Western Levee Complex and the Eastern Levee Complex [11,12]. On the upper fan, these two complexes merge, and only one large levee complex is associated with the central channel and its two branches (1 and 3). Beneath the present levee complexes, older buried levee complexes consisting of ancient channel-levee systems are observed on seismic records (e.g., "buried levees" in Profile YZ, Figure 3).

The most striking characteristic of the distributary channels revealed by GLORIA [11] is their extensive and intricate meander patterns (Figures 1 and 5). Nearly all channels deeper than 2500 m exhibit high sinuosity (1.5 to 2.5) with well-developed, recurving meanders; channels shallower than 2500 m have lower sinuosities of 1.0 to 1.5. In addition, cutoffs, abandoned meander loops (oxbows) and scars, and other floodplain-like features are observed on the GLORIA
sonographs [11]. The sinuosity, meander patterns, and associated morphologic features of these channels appear to be quite similar to meander patterns and associated floodplain features of mature fluvial systems on land. For example, the dimensions of these features on the middle fan (e.g., meander wave length, amplitude, and frequency; channel and levee dimensions) are equal to or larger than those of similar features of the lower Mississippi River [11].

The GLORIA sonographs show channel bifurcation or branching at several locations, and other bifurcations can be inferred even though they are not directly observed (Figure 1). At most locations, bifurcation appears to result from breaching of channel walls and levees, especially on the outside curves of meander loops [11]. Bifurcation apparently does not occur as frequently as predicted by previous studies [1,2], and many channels extend for long distances down the fan without apparent bifurcation (Figures 1 and 5). However, discontinuous channel segments are also observed that have no apparent up-slope connection (Figure 1) and thus may be abandoned segments. At present, we are unable to determine with certainty the nature of most of the observed bifurcations. In some cases, both channel branches may remain active whereas in others the original channel may be abandoned as a result of channel avulsion. Certainly avulsion might be expected where bifurcation is caused by breaching of a meander loop. No evidence of channel braiding has been observed.

**Sedimentation Processes**

**Mass-Transport Deposits**

The distributary channel system on the upper and middle fan is bounded on either side by large slump and debris-flow deposits that cover at least 46,000 km² or about 14% of the fan's surface [2] (Figure 1). The upslope portions of these deposits consist of hummocky slump or slide deposits that are generally bounded by scarps. Downslope from these hummocky zones, the deposits consist of thin (10 to >50 m), acoustically transparent debris flows. These debris flows have traveled down the fan for distances of up to 300 km on slopes with gradients as low as 2.5 m/1000 m (0.14°). The total amount of fan sediments displaced may exceed 2500 km³. Piston cores show zones of disturbed, contorted bedding and suggest that the age of these mass movements is probably Late Wisconsin [2].

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**Figure 5.** GLORIA long-range side-scan sonograph mosaic showing examples of meandering distributary channels on the middle Amazon Fan (location in Figure 2). Reflective areas are black. The processing routines corrected for slant range, ship speed, and beam pattern; a time-varying gain was applied and the data were contrast stretched. Ship tracks are along the white bands down the center of each sonograph. The 10-km scale bar applies to distance along ship track as well as distance laterally from track.
Sediments

Forty-four sediment cores have been collected from the Amazon Fan by Lamont-Doherty [1,2,4] and French scientists [9]. Unfortunately, only six of these cores were raised from the channel-levee complexes of the upper and middle fan, and only one is from a channel floor. Seven cores have been taken in the Amazon Submarine Canyon. The rest of the cores are from the lower fan, the slump-debris flow complexes, and areas peripheral to the fan.

Nearly all Amazon Fan cores have an upper meter or less of light-brown pelagic foraminiferal ooze or marl of Holocene age. The Pleistocene–Holocene boundary is generally marked by a rusty-colored iron-rich crust [1,2,4,13]. The remainder of each core is latest Wisconsin in age and consists of gray hemipelagic clay, often with interbedded silt–sand turbidites [1,4]. The hemipelagic sediment is silty terrigeneous clay with abundant organic detritus (organic carbon content = 0.5 to 0.75% [13]) and was apparently deposited slowly but continuously throughout the latest Wisconsin by gravity-controlled bottom flows [1,4]. Minimum sedimentation rates exceed 15 to 40 cm/10^3 yr and may reach 100 cm/10^3 yr [1]. The interbedded turbidites are less than 1 cm to a few meters thick and consist mainly of silt to medium sand; however, grain sizes from clay to fine gravel are observed. Quartz (>60%) and feldspar (>30%) are the dominant minerals. Organic detritus (wood and leaf fragments) is commonly disseminated throughout the silt/sand and occasionally forms discrete beds.

Sediment Distribution and Cycles

The pelagic Holocene sediments indicate that the Amazon Fan has been temporarily inactive during the last 11,000 years; the high sea-level stand traps Amazon River sediments on the inner continental shelf [1,2,4,5]. Presumably the fan was also inactive during previous interglacial sea-level stands. In contrast, sea-level lowering during the Wisconsin and previous glacial periods permitted the Amazon River to discharge sediments directly into the Amazon Canyon, hence sediments could easily be transported to the fan by turbidity flows via the canyon and distributary channels.

The sediment cores reflect the dispersal patterns of coarse terrigenous sediment across the fan during latest Wisconsin [1]. Cores from the upper and middle fan contain little or no bedded silt/sand. When present, beds are generally <5 cm thick and are often only laminae. In contrast, cores from the lower fan and the adjacent Demerara Abyssal Plain contain numerous, thick (20 cm to >5 m) beds of silt-to-gravel-sized particles [1]. This distribution pattern of coarse sediments is further evidenced by variations in 3.5-kHz echo character across the fan [1,3]; the upper and middle fan generally return distinct echo troughs with continuous parallel subbottoms (indicative of little or no coarse sediment), whereas the lower fan and adjacent abyssal plains generally return indistinct prolonged echos with no subbottoms (indicative of abundant coarse sediment).

The apparent absence of abundant or thick silt/sand beds from the upper and middle fan implies that most coarse sediment by-passes these regions, presumably via the distributary channels, and is deposited across the lower fan and adjacent abyssal plains by turbidity flows. Zones of high-amplitude reflectors are generally observed directly below each channel axis on low-frequency seismic records (Figure 3) and may represent residual coarse sediment trapped in the channel axis as the channel and associated levees built upward through time.

Age, Thickness, and Average Sedimentation Rate

Damuth and Kumar [1] estimated an age of 8 to 15 m.y. (Middle to Late Miocene) for the Amazon Cone by extrapolating the age (2.2 m.y.) of a prominent acoustic reflector on the Ceara Rise that can be traced into the fan; calculating an average sedimentation rate (~100 cm/10^3 yr) for the fan sediments above this reflector; and then extrapolating this rate to the maximum thickness of the fan (9.7 to 13.7 km) as calculated from sonobuoy, seismic refraction, and sediment-compaction data. Kumar [8] subsequently revised the age to approximately 22 m.y. (Early Miocene) when DSDP drilling revealed the prominent reflector to be 6 m.y. old. More recently PETROBRAS scientists ([10] and Kowsmann, personal communication, 1983) have established an age of 16.5 m.y. (Early Miocene) for the fan by correlation of seismic facies beneath the Foz do Amazonas and upper fan with borehole data from the shelf and Amazon estuary. These studies suggest that the maximum thickness of the upper fan may be only about 4.2 km. This yields an average sedimentation rate of 25 cm/10^3 yr.

Growth Pattern

Seismic-reflection profiles (for example Profile YZ in Figure 3) across the upper and middle fan reveal that the individual levee systems associated with each major channel (1 through 6, Figure 1) stratigraphically overlie one another and are thus of relatively different ages [12]. For example, channel 4 in Profile YZ (Figure 3) clearly overlies the flank of channel 6, and is thus stratigraphically younger. By determining the stratigraphic succession of the major channel-levee systems in this manner, a tentative age relationship has been established [12]; the major channels are labeled 1 through 6 in order of increasing age (Figures 1 and 3). Channel 1 on the Western Levee Complex is the youngest channel. Channel 3 is the youngest on the Eastern Levee Complex but is older.
than channels 1 and 2. Channels 2, 4, 5, and 6 are apparently older, now abandoned channels.

These relationships suggest that for each levee complex (Western and Eastern) only one major channel was active at any given time [12]. This active channel deposits a large levee sequence that eventually partially or completely buries the flanks of adjacent levees (e.g., Figure 3). Eventually this active channel is abandoned, probably by avulsion, and a new channel segment develops at the edge of the levee complex where gradients are steeper. Through time, the formation and abandonment of a succession of channel-levee systems builds a levee complex (such as the Western Levee Complex) that grows laterally and downslope.

Occasionally, the course of a newly established channel may be so far from the previous channel that the entire levee complex is abandoned, and a new, separate levee complex begins to develop. This appears most likely to take place when a channel is abandoned well upslope near its head where gradients are highest and the channel can diverge well away from other channels as it builds downfan [12]. For example, the formation of channels 1 and 2 apparently resulted in abandonment of the Eastern Levee Complex and establishment of the Western Levee Complex (Figure 1).

The formation of a succession of discrete, commonly overlapping levee complexes (such as the Western and Eastern Complexes), each composed of several abandoned channel-levee systems, gradually builds the fan upward and radially outward downslope. Additional evidence for this type of growth pattern is observed deeper within the fan on seismic profiles that show older, buried levee complexes beneath the present Western and Eastern Complexes (e.g., the series of "buried levees" beneath the western flank of the Western Levee Complex in Figure 3, Profile YZ).

The growth pattern for Amazon Fan described here and in [12] is not entirely certain because it is possible that two or more channels on a levee complex, or even two or more levee complexes are active simultaneously. For example, GLORIA sonographs of the bifurcation point of the central channel into channels 1 and 3 (~2000 m, Figure 1) appear to show branching, with possibly both channels remaining open. Thus it is possible that during fan growth more than one major channel, and, possibly, even more than one levee complex, may have been active simultaneously. Further detailed studies will be required to resolve this problem and thus verify the growth pattern proposed here.

Conclusions

Amazon Fan studies to date, especially the recent GLORIA survey, have provided important new information on the distribution and morphologic characteristics of the various features of the upper and middle fan, including individual distributary channels and associated levee systems, broad coalescing levee complexes of several channel-levee systems, mass-transport deposits, and the Amazon Submarine Canyon. We are now beginning to understand the growth pattern and sedimentation processes of the fan as well as the details of distributary-channel anatomy (e.g., meander pattern, bifurcation pattern, etc.). However, these studies have also raised important new problems. For example, the discovery of high-sinusity meandering channels and associated floodplain-like features (Figure 5) has important ramifications for the type, volume, and continuity of the turbidity flow that forms, maintains, and modifies such channels. Such meander formation may require hydrodynamic conditions within channels similar to those of fluvial channels on land. Possibly flows through the fan channels must be relatively steady, long term, and high volume, rather than short, intermittent, sporadic flows generally associated with traditional turbidity current events [11]. On the other hand, how could such fluvial-like traction flow transport coarse sediments (presumably as bed load) for hundreds of kilometers down a fan channel, then deposit these sediments in the form of classic turbidites as observed on the lower fan? Our future studies with Sea Beam, high-resolution seismics, midrange side-scan sonar, and close-interval coring during the upcoming years will be aimed at solving these and similar critical problems by focusing on more detailed and quantitative studies at critical locations on the fan.

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