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Quantitative characteristics of sinuous distributary channels on the Amazon Deep-Sea Fan

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ABSTRACT

Morphometric analysis of meandering channels on the middle and lower Amazon Deep-Sea Fan demonstrates that these channels have definite similarities with meandering subaerial rivers. The relationships between meander wavelength and both channel width and radius of meander curvature for fan channels are similar to those observed for large rivers; however, channel width, depth, and cross-sectional area decrease down a fan channel. Channel slope or gradient, measured along the channel axis, decreases smoothly down fan even though the fan slope (valley slope) which the channel traverses decreases irregularly down fan. Channel sinuosities range from about 1.05 to 2.6 on the fan, and sinuosity along a single channel, especially on the middle fan, appears to increase or decrease locally to compensate for varying fan surface slope (valley slope) to maintain a smoothly decreasing channel slope. This dynamic relationship between valley slope and channel sinuosity suggests that the sinuosities of the Amazon Fan channels have changed (that is, the channels have meandered) to obtain the optimum channel slopes, and the optimum channel slope decreases down fan. It is not possible, however, to determine whether that meandering occurred early in the development of the channel or during or throughout its evolution. Down-channel changes in fan and channel slope and maximum flow thickness (combined with variations in flow density) may produce systematic changes in flow characteristics and channel facies down fan.

INTRODUCTION

The Amazon Deep-Sea Fan is the third largest modern deep-sea fan; it extends from the continental shelf off northeast Brazil for about 700 km to abyssal depths (>4,700 m; Fig. 1). Previous studies have described the mix of sedimentary processes, including channelized turbidity flows, mass-wasting, and hemipelagic sedimentation, that have built the fan (Damuth and Kumar, 1975; Damuth and Embley, 1981; Damuth and Flood, 1984, 1985). The distributary channel system and surface morphology of the fan were recently mapped to about 3,500-m depth, using long-range side-scan sonar (GLORIA; see Laughton, 1981, and references therein, for a description of this system; Damuth and others, 1983a, 1983b). A detailed description of fan anatomy and features observed with GLORIA is presented elsewhere (Damuth and others, unpub. data). This GLORIA survey for the first time allowed us to continuously map entire channel trends and to determine the temporal and spatial relationships between channel-levee systems (Figs. 1 and 2). The GLORIA data, coupled with high-resolution seismic data, provide an adequate data base to conduct quantitative investigations of distributary channel geometry.

The most striking and surprising characteristic of the fan distributary channels revealed by GLORIA is their highly sinuous (meandering) planforms (Figs. 2 and 3), which appear similar to those of nature, meandering river systems on land (for example, the lower Mississippi). These meandering planforms are not easy to explain in light of traditional turbidity current concepts of fan-channel formation; they would seem to require a more continuous type of turbidity-induced flow that has hydrodynamic parameters somewhat similar to those encountered in subaerial rivers (Damuth and others, 1983a, and unpub. data). Clearly, a careful evaluation of fan-channel morphology is required to determine the actual hydraulic processes responsible for their formation. The study reported here is a first attempt to conduct such a quantitative morphological analysis. We used GLORIA side-scan sonar and high-resolution (3.5- to 12-kHz) reflection profiles to measure several parameters of the channels on the middle and lower fan, and we compared the values and relationships observed to those published for terrestrial rivers. Although these data have some limitations (for example, spacing, quality, and so on) that create uncertainties in the measurement of some parameters, the comparison with rivers should lead to a better understanding of the processes responsible for the formation and evolution of channels on the Amazon and other deep-sea fans.

FAN MORPHOLOGY AND DISTRIBUTARY CHANNEL PATTERN

The Amazon Fan is divided into three regions (upper, middle, and lower fan; Fig. 1) on the basis of morphologic characteristics (Damuth and Flood, 1984, 1985). The upper fan extends from the shelf break to a depth of 3,000 m (Fig. 1), where the bathymetric contours show a noticeable break in slope. Gradients range from about 25 m/km (1:40) near the shelf break to 10 m/km (1:100) near 3,000 m; the average gradient is 14 m/km (1:70). The Amazon Submarine Canyon extends down the upper fan from the shelf to about 1,400 m. A single central channel, which is perched on a broad levee system, extends down fan from the canyon. This levee system is as much as 50 km wide and 1 km thick, and it rises to as much as 300 m above the surrounding fan surface (Fig. 4a). The channel is the largest on the fan and is as much as 200 m deep and 2.5 km wide. Below 2,000 m, three other large channels are present (Fig. 1 and 2). The middle fan extends from about 3,000 m to 4,000–4,200 m (Fig. 1), where a subtle decrease in gradient occurs. Gradients on the middle fan

Figure 1. Morphometric map of Amazon Fan showing major physiographic boundaries and locations of the fan channels (after Damuth and others, 1983b).

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lower fan is more gently sloping with an average gradient of 2.3 m/km (1:430). Numerous small, unveleved distributary channels cross the lower fan (Fig. 4c). These channels range in depth from 5 to 25 m and average 0.4 km in width; they commonly appear to incise the underlying fan sediments.

The upper and middle fan are composed predominantly of broad, overlapping channel/levee systems. Apparently only one channel/levee system is active at any given time, but events such as flow breaching or slumping of channel walls may cause abandonment of the active channel (avulsion) and the construction of a new channel/levee system down fan from the breach (Damuth and others, 1983b). The GLORIA side-scan data allowed us to identify and map the trends of at least eight distinct channel/levee systems on the present fan surface (Fig. 2; Damuth and others, 1983a); the seismic profiles across these channels then allowed us to establish the relative ages of these channel/levee systems (Fig. 2; Damuth and others, 1983b). Large segments of at least ten older channel/levee systems were also mapped by GLORIA (Fig. 2). Most older channels are known only from the middle fan because, if present, they are too deeply buried on the upper fan to be imaged by GLORIA. Because only a very small part of the lower fan was surveyed with GLORIA, channel trends across this region remain largely uncertain. Below 3,000-m depth, the coalescing and overlapping channel/levee systems form two distinct levee complexes (Western and Eastern; Fig. 1) that diverge down the middle fan (Damuth and others, 1983a, 1983b).

The most recently active and best preserved channel on the fan (no. 1 in Fig. 2) has apparently been inactive since the beginning of the Holocene (about 11,000 yr B.P.) (Damuth and Kumar, 1975; Damuth and Flood, 1984, 1985). All other channel segments on the fan have been cut off and abandoned; subsequently some of these have been partly or totally filled by overbank deposits from adjacent channels and/or slumping of channel walls. Channel 1 is the best preserved, followed by channels 3 and 4.

Figure 3. Side-scan sonar mosaic of channel 4 and nearby channels 1, 3, 5, 6a, 6b, and 6c on the middle fan. Circles show locations of water- and channel-depth measurements made on channel 4, that is, where bathymetric profiles cross the channel. These depth measurements mark the ends of discrete segments (or reaches) along which channel parameters discussed were measured (see text). The sonar records have been corrected for slant-range distortion and variations in ship speed to provide a geometrically correct map of the sea floor, and they have been processed to enhance the sonar return. Location shown in Figure 5.
Following development of channel 3, the Eastern Levee Complex was apparently abandoned, leaving channels 3 and 4 still unburied and well preserved at the fan surface. Although it is older, channel/levee system 4 is larger and better developed than is channel 3. The following quantitative analysis will focus on the parameters of channels 1 and 4 (to 3,900 m), although data from the other channels and from a well-mapped channel segment on the lower fan (6°30’S to 7°30’S; Fig. 2) are also included.

Although relative ages are known, the actual ages of the various channel/levee systems are unknown. Damuth and others (1983b) estimated that the channel/levee systems 1 to 6A, 6B, and 6C (Fig. 2) at the fan surface could have developed in as little as 2 m.y., or about 250,000 yr/system. If more channels developed in 2 m.y. (for example, a total of at least 18, which can be resolved at the present fan surface), we determine a rate of 111,000 yr/system. Sedimentation rates, however, could be much higher than predicted, and thus the channels could have developed more quickly than these estimates suggest. Recent drilling of a comparable channel/levee system on the Mississippi Fan during Deep Sea Drilling Project Leg 96 revealed sedimentation rates of as much as 1,100 cm/1,000 yr (Kohl and others, 1985), which is an order of magnitude higher than the rate of <100 cm/1,000 yr used by Damuth and others (1983b).

The Amazon channel/levee systems thus may have formed much more rapidly than predicted in the conservative approach described above.

MEASUREMENT OF FAN-CHANNEL PARAMETERS

Channel segments in water depths shallower than about 2,000 m were not resolved well enough on GLORIA sonographs to permit channel widths or sinuosities to be measured. This poor channel resolution is due in part to the narrower sea-floor swath that can be mapped in shallower water as well as the fact that a larger proportion of the sonar record is disrupted by artifacts, especially sound refraction by internal waves, at shallower water depths. In addition, channel structure appears to be more complex on the upper fan, as walls are often composed of multiple, step-like scarps (compare Fig. 4a with Figs. 4b and 4c). Sonar echoes from these complex structures are not as easily interpreted as are echoes from the simpler channel walls deeper on the fan.

The GLORIA side-scan sonar records were geometrically corrected (slant-range corrected and merged with navigation) in order to plot the
Figure 4. Bathymetric (3.5-kHz) profiles showing examples of distributary channels on the Amazon Fan: (A) large, leveed central channel of upper fan, (B) leveed middle fan channel (channel 4), and (C) unveeied lower fan channels. Locations in Figure 5. Horizontal and Vertical scales approximate.

channels and other sonar targets in their correct positions on the fan and to preserve the correct geometry of the channel meanders (Fig. 3). Water depths (sea level to channel floor) and channel depths (or reliefs) were measured on all bathymetric profiles (3.5–12 kHz) that cross channels (Figs. 3 and 5). We define the segments between bathymetric crossings of the channels (Fig. 3) as reaches, along which we measured channel parameters. A total of 84 channel reaches, ranging from 4 to 100 km long, were delimited. All seven channel parameters defined below, however, could be measured along only 48 of these reaches because of gaps in sonar coverage or channel discontinuities. The mean length of the 48 reaches is 20.7 ± 12 km.

Seven channel parameters were measured for the Amazon Fan channels: (1) channel width, (2) channel depth (average vertical relief from axis of channel floor to levee crest), (3) water depth (depth of channel axis below sea level), (4) meander radius of curvature, (5) meander wavelength, (6) valley length (the straight line distance down fan between ends of a channel reach), and (7) channel length (distance between ends of a channel reach measured along the channel axis). An additional three parameters were calculated: (8) channel slope (the average gradient along the channel axis), (9) valley slope (the average gradient along the valley length), and (10) sinuosity (the ratio of channel length to valley length. River channels with sinuosities greater than 1.5 are termed meandering (Leopold and Wolman, 1957).

The term “valley” is defined here as the general trend of a channel segment or reach down the fan. Specifically, valley describes the path of a channel reach as a straight-line between two points where channel width and depth are measured (bathymetric crossings; for example, circles in Fig. 3). Although technically the channel/levee systems of the fan are not confined in valleys as are subaerial river systems, the terms “valley length” and “valley slope” defined here are parameters equivalent to valley slope and length measured from subaerial rivers (Schumm, 1977).

Channel width and meander radius of curvature were measured on the GLORIA records at or near the start of the channel reach (Fig. 3). Meander wavelength, also measured on the GLORIA records, was determined by counting the number of meanders along the reach and dividing by the valley length. Channel depth and water depth were measured on bathymetric profiles at the start of the reach, and channel and valley lengths were measured on a large-scale map of fan channels constructed from the GLORIA records (Fig. 1). Channel width was measured as the width of the high-reflectivity channel patterns on the GLORIA records (Fig. 3). Detailed study of channels mapped by GLORIA from both sides along different ship tracks, along with comparisons with bathymetric profiles, confirms that this high-reflectivity zone represents only the area between the steep channel walls, that is, the channel floor (Damuth and others, unpub. data). Channel sinuosity was calculated for a channel reach by dividing the channel length by the valley length. Slopes were calculated both along the channel axis (channel drop divided by channel length) and along the valley (channel drop divided by valley length).

There are several potential sources of error in this analysis. Uncertainties may come from errors in track and channel position and from possible difficulties in measuring the depth of channels when they are obscured by side echoes. All of the ship tracks used here were positioned by transit satellite navigation; thus we expect navigation errors to be less than about 1 km. In addition, the GLORIA sonar and bathymetric profiles have been closely studied in order to produce a sonar mosaic and bathymetric map, and the earlier bathymetric tracks have been slightly adjusted to minimize bathymetry errors at crossing and to agree with the side-scan sonar data. We thus expect any resulting navigation errors to be much less than 1 km. Bathymetric
profiles of the channels are often obscured when side echoes from the channel walls intersect above the channel floor (see, for example, Fig. 4c). These side echoes occur because the bathymetric profiler used has a wide beam angle. Side echoes are more common in the middle and lower fan where water depth is greater and the channels are narrower. An echo from the channel floor, however, can generally be identified below the intersecting side echoes (Fig. 4c, left side; see also Krause, 1962). Overall errors in measuring channel depth are therefore probably small and on the order of 10 m.

In addition to these measurement errors, the use of channel reaches of arbitrary length may cause an undersampling of channel parameters by averaging over distances which are long compared to the scale of variability. As the reaches contain an average of four meanders, however, measurements along those reaches should not undersample the major variability of the fan channels. The bathymetric measurements are, by necessity, made on the present-day fan topography. As the flow activity which created the channels occurred during glacial periods, it is possible that later sedimentation, such as would occur during a sea-level rise, may have altered the topographic expression of the channels. Although some channels have been partially obscured by later sedimentation, several channels are quite fresh in appearance on the sonar and sub-bottom profile records.

**QUANTITATIVE RELATIONSHIPS BETWEEN CHANNEL PARAMETERS**

**Meander Wavelength versus Channel Width and Meander Radius of Curvature**

Investigators of meandering river systems have noted a strong correlation between certain dimensions of meander systems, specifically meander wavelength, channel width, and meander radius of curvature. In particular, log-log plots of meander wavelength versus either channel width or meander radius of curvature show straight-line relationships which indicate that channel meandering is a fundamental characteristic of rivers and of other flow systems (Leopold and Wolman, 1960; Leopold and Longbein, 1966). Plots of meander wavelength versus channel width (Fig. 6, top) and meander wavelength versus radius of curvature (Fig. 6, bottom) show relationships quite similar to those observed for subaerial rivers. The range of values observed for the fan channels is 2 to 15 km for meander wavelength, 0.3 to 1.4 km for channel width, and 0.5 to 7 km for meander radius of curvature. These values are similar to those observed for large meandering rivers, including the Arkansas, Sacramento, Coosa, Megan, Red, Kansas, Colorado, Missouri, and Mississippi Rivers in the United States (values reported by Leopold and Wolman, 1960).

Meander wavelength and radius of curvature show little or no systematic change down slope. The range of wavelength observed remains approximately constant with depth, although there is considerable scatter. Radius of curvature shows a slight decrease with water depth (from 1 to 2 km at 2,500 m to 0.5 to 1 km at 4,000 m). Because channel width was measured as the width of the highly reflective zone associated with the channel on GLORIA sonographs, some systematic error could exist in those measurements. Although we can demonstrate that the reflective zone corresponds approximately to the channel width, the true accuracy of this measurement is uncertain. For example, processes such as slumping could alter channel width along some reaches, making the channels somewhat wider than when they were formed. Improved bathymetric information gained from swath-mapping (for example, Sea Beam) could be used to determine channel width (and depth) more precisely.

Figure 5. Bathymetric tracklines (3.5 kHz–12 kHz) used in determining channel depths. All tracks were satellite navigated. Those rare crossings showing major inconsistencies in channel locations with the side-scan records were not used. Heavy lines A, B, and C denote locations of 3.5-kHz profiles in Figure 4; dotted box shows location of sonar mosaic in Figure 3.
Channel Width, Depth, and Cross-Sectional Area versus Water Depth

Channel width and depth vary systematically down fan (Fig. 7). The youngest channel (channel 1) exhibits greatest channel depth in water depths of less than 1,000 m where it is actually the erosional Amazon Submarine Canyon. Canyon depth increases with water depth to a maximum of 585 m in 850-m water depth (Fig. 7, top). When the leveed channel is encountered, channel depth decreases rapidly to 200 m at 1,400 m water depth. Channel depths of channel 1 and all other channels continue to decrease down fan until they range between 15 and 40 m at 4,500-m water depth. Depths of some abandoned channels are anomalously shallow (because of subsequent filling) compared to those of younger or better-preserved channels.

The widest channels generally occur in the shallower water depths (upper fan). Although channel width cannot be accurately measured from GLORIA records for depths less than 2,000 m, standard bathymetric profiles suggest that channel width ranges from about 4 km in the Amazon Canyon to about 1 km at 2,000-m depths. Channel width decreases slightly with increasing water depth from 600 m at 2,200-m water depth to 400 m at 4,000-m water depth (Fig. 7, middle). Some channels, however, appear to be abnormally wide at several locations. For example, channel 6C has a width of 1.4 km from 3,300- to 3,500-m water depth, whereas other channels at this depth are generally 0.5 km wide. This abnormal width of channel 6C may result from its long period of inactivity during which it was filled by overbank deposition from nearby channels 6A and 6B. This may have resulted in a different acoustic signature on GLORIA sonographs.

Cross-sectional areas of the measured channels decrease dramatically, although somewhat irregularly, down fan from about 100,000 m² at 2,000-m depth to 10,000 m² at 4,500-m depth (Fig. 7, bottom). This tenfold decrease occurs along a distance of about 500 km down fan (about 900 km measured along the channel axis). The cross-sectional area is approximated here simply as the product of width and depth. Because the channel is clearly not rectangular, the actual cross-sectional areas will differ from those calculated. A decrease in cross-sectional area, however, occurs regardless of how the calculation is made. Abnormally large or small cross-sectional areas appear to be typical of poorly preserved channels, although similar variability also occurs in some well-preserved channels.

The down-fan decrease in channel depth (as well as levee size) suggests a progressive down-fan decrease in the maximum thickness of the turbidity currents which flow down the channel. The decrease in channel cross section suggests that the total volume of channelized turbidity-current flow also decreases down fan. This is in contrast to subaerial rivers where the discharge generally increases downstream as tributaries contribute more water. The most likely route for portions of a turbidity flow to leave the fan channel is through over-bank spilling, especially at sharp channel bends and meanders (for example, “flow stripping”; Piper and Normark, 1983) or at low points or crevasses in the levees (Kastens and Shor, 1985). Because the sediment entrained in the upper part of a turbid flow is finer than that in suspension at the bottom, overbank spilling will cause the portion of the flow remaining within the channel to become progressively coarser down fan (Piper and Normark, 1983). Sediment deposited in the channel floor by the turbidity flow will generally be the coarsest fraction transported. The net effect may be that channel deposits tend to become progressively better sorted down fan as both the coarser and finer fractions are removed.

Valley Slope, Channel Slope, and Sinuosity versus Water Depth

Valley slopes generally decrease down fan, but along many reaches, valley slopes actually increase with increasing water depth (Fig. 8, top). The channel slopes, measured along the axes of the meandering channels, also decrease down fan (Fig. 8, middle); however, the decrease is much smoother than for valley slope, and far fewer local down-fan increases in channel slope occur. In the Amazon Canyon (shallower than 1,400 m), the valley slopes range from 7 to 16 m/km, but they are typically 10 to 13 m/km. On the upper fan (1,400 to 3,000 m) valley slopes range from 8 to 12 m/km, and decrease slightly down fan. No data are available on channel slopes shallower than 2,000 m. Between 2,000 and 3,000 m, channel slopes range from 4 to 8 m/km with no apparent down-fan trend. On the middle fan (3,000 to 4,000 m) valley slopes show a pronounced decrease down fan, ranging from 7 to 11 m/km at 3,000 m to 2 to 4 m/km at 4,000 m. Channel slopes decrease along this same interval from 5 to 7 m/km to 1 to 3 m/km. On the lower fan (deeper than 4,000 m) the valley and channel slopes remain approximately constant and are about the same as those of the lower part of the middle fan; data are insufficient to determine whether a down-fan trend in channel slopes exists in this region.

The sinuosity of individual channels also changes down fan (Fig. 8, bottom). Between 2,000 and 3,000 m (upper fan), sinuosities are relatively low, ranging from 1.05 to 1.7. Sinuosities are the highest between 3,000 and 4,000 m (middle fan), where they range from about 1.2 to at least 2.6, although occasional lower values are observed. Deeper than 4,000 m (lower fan)
the sinuosity decreases slightly to values of 1.4 to 2.0, and less scatter is apparent. The most extensive and intricate meandering of channels thus occurs on the middle fan, whereas channels on the upper fan show the least meander development.

Although the fan-channel widths and sinuosities are equivalent to those observed in large meandering river systems, their gradients are much larger than those of the large meandering rivers. For example, the fan channel gradients are about 50 times larger than those of the lower Mississippi River system (Fig. 9). Many smaller meandering rivers, however, can have gradients equivalent to those of the fan channels (Lewin, 1984; Edgar, 1984). Steeper fan-channel gradients are expected because the density difference between a turbidity current flowing under clear water is smaller than for water flowing under air.

**Relationship between Sinuosity, Channel Slope, and Valley Slope**

Sinuosity, the ratio of channel length to valley length, is also the ratio of the valley slope to the channel slope. Channel slope, valley slope, and sinuosity are interrelated, and so the low scatter and almost uniform down-fan decrease in channel slope observed in the middle fan occur because of rapid inverse variations in valley slope and sinuosity. The channel may adjust its sinuosity by meandering in order to maintain an optimum slope as it traverses varying regional slopes. The optimum slope is presumably one that is suitable to accommodate the volume of flow and sediment load which the channel must transport. Initial down-fan changes in valley slope are due to pre-existing topography (such as older channel levees systems which the channel must flow across or around), and aggradation will cause channel gradients to change with time.

Investigators of meandering river systems on land have noted a similar correlation between valley slope and sinuosity in both field and laboratory studies (Schumm and Khan, 1972; Schumm and others, 1972), and this geomorphic approach to channel stability has been used to understand the behavior of man-modified meanders on land (Schumm and Beathard, 1976; Schumm, 1985). The correlation between valley slope and sinuosity observed in these studies is summarized in Figure 9. Schumm's (1977, p. 143) explanation for the relationship observed for an idealized river flowing at constant discharge along a variable alluvial valley slope (Fig. 9, top) is paraphrased as follows: when the valley slope is very low, the channel will be straight if it has just sufficient velocity to transport its sediment load. At this flow level, a decrease in channel slope, which would occur if the channel sinuosity increased, would cause aggradation. If the valley slope were to increase through a certain threshold point (which varies for each channel system), the channel would start to meander in an attempt to regain the channel slope it had before the valley gradient increased and to reduce the flow velocity to that just necessary to transport its load. The sinuosity is small for low valley slopes, because only a limited amount of meandering is necessary to reduce the channel slope; however, if the valley slope is greater, the channel sinuosity must also increase to keep the channel gradient as near its former value as possible (Fig. 9, top). For even larger valley slopes, a second threshold is reached where meandering cannot maintain the ideal channel slope. At this threshold, the meandering channel changes to a braided channel (Fig. 9, top).

This relationship between valley slope and channel sinuosity has been demonstrated in laboratory experiments by Schumm and Khan (1972; Fig. 9, top) and observed in the lower Mississippi River (Schumm and others, 1972; Fig. 9, middle) and in other river systems (see, for example, Edgar, 1984). In natural rivers, however, the scatter of data is higher than in the laboratory environment, primarily because of local effects within each river segment (Schumm and others, 1972).

When sinuosity is plotted as a function of valley slope for the Amazon Fan channels (Fig. 9, bottom), we observe that channel sinuosity in the middle fan increases with increasing valley slope in a fashion similar to that observed for rivers. Comparing this plot with those of Schumm and co-workers (Fig. 9, top and middle) suggests that the Amazon data points do not follow or cluster around a single line. For the flume studies and the Mississippi River, the range of slopes observed was large enough to
encompass the straight, meandering, and braided fields. On the fan, only meandering channels are present, which suggests that valley-slope values necessary to force a transition from a meandering to a straight or a braided regime probably do not exist on the fan. We therefore cannot scale the curves of Schumm and co-workers to fit the Amazon Fan data. In fact, we do not know if braided channels can even exist in the deep-sea environment (although Belderson and others, 1984, reported possible braided fan channels off Barbados). Possibly some other kind of channel morphology develops when fan-valley slopes are too steep to allow meandering. Along a fan channel, however, the local relationship of increasing sinuosity with increasing valley slope is generally observed, especially for reaches in water depths greater than 3,000 m. A single curve on the slope-sinuosity plot may not be adequate to describe a fan channel, because there may be significant changes in flow volume, sediment load, and so on, along a fan channel (Edgar, 1984). These parameters may be more constant along large segments of a meandering river on land or in a laboratory flume than along a fan channel.

In spite of these complexities, the Amazon Fan–channel parameters do appear to follow the general relationship established for river systems at or near grade: local changes in channel sinuosity occur because of changes in the valley slopes which the channels must traverse. Because this relationship exists throughout a wide portion of the middle fan, in an area where the channel slope decreases with increasing water depth, the ideal gradient which the channel wishes to maintain apparently also decreases down fan.

**DISCUSSION AND CONCLUSIONS**

The intricately meandering distributary channels discovered on the Amazon Fan, as well as those subsequently observed on other major deep-sea fans (Bellaiche and others, 1983; Droz and Bellaiche, 1984; Garrison and others, 1982; Kastens and Shor, 1985, 1986), appear in some aspects quite similar to river systems on land. In addition to planform similarities, several other similarities, including levees, cutoff meanders, and crevasse splays, have also been noted (Damuth and others, 1983a; Kastens and Shor, 1985, 1986). Our measurements of Amazon Fan channels show that the scale of meandering, as indicated by meander wavelength, meander radius of curvature and channel width, is similar to that observed in large terrestrial river systems. Channel width, depth, and cross-sectional area, in contrast to rivers, decrease down the fan channels, suggesting a decrease in maximum flow thickness and volume along the channel. The relationship observed between valley slope and sinuosity on the middle and lower fan is also similar to that observed for rivers: local increases in valley slope appear to be compensated by increases in sinuosity to maintain a relatively constant channel slope. Changes in sinuosity thus allow the channel slope to decrease slowly and uniformly down fan by compensating for abrupt changes in the fan surface (valley) slope which the channel must traverse. Valley slope, however, is not the only parameter which can affect channel sinuosity. Changes in flow volume and sediment load can also have dramatic effects on the river width and sinuosity (Schumm, 1977), and changes in these parameters with time and distance down fan are undoubtedly also important on submarine fans.

Because channel morphology appears to have responded to its environment in a dynamic fashion, it is likely that the meander pattern has evolved through many relatively small increments made during a series of flows. Channel sinuosity can increase with time as meander loops grow larger (Brice, 1974) and decrease with time through either gradual channel straightening or meander cutoffs. Meander cutoffs and the breaching of meander walls probably occur suddenly, perhaps during single large flows. The breaching or slumping of a channel wall may cause a new channel to form down fan of the breach, and the channel, to entrench above the breach. Channel modifications may occur quickly during such entrenchment. Furthermore, many fan channels can be abandoned after only short periods of activity. The breaching of channel walls and the formation of new channels down fan may cause local increases in channel and valley slope and thus increase the channel sinuosity, unless the new slope is so large that the channel is forced out of the meander field.

Although the relationship between sinuosity and valley slope suggests that the channel meanders are similar in function to those observed in river systems, few constraints are placed on the time scales of meander formation or evolution. There are at least two possible time scales for meander formation. First, the meander pattern may have developed quickly during the early evolution of a channel levee system, and that meander pattern (except for small lateral movements and possible meander cutoffs) could be preserved during the later development of the channel levee system. Alternatively, the meander pattern could have evolved slowly as the channel levee system evolved. Since the thickness of the channel levee system varies only slowly down fan, the initial and final valley gradients are similar, and it is difficult to determine from the present data whether the observed channel patterns were in equilibrium with the initial or final channel slopes.

The seismic evidence for the timing of meander evolution is contradictory. Kastens and
Shor (1986) and Stelting and others (1985) have suggested, on the basis of a detailed seismic survey of a channel meander on the Mississippi Fan, that channel sinuosity increased as the channel/levee system evolved. However, Flood (in press) noted from combined seismic and detailed bathymetric data on the more sinuous channels of the Amazon Fan that seismic data may be contaminated with side echoes from the nearby channel floor and thus contain little evidence of channel migration. Much of the meandering could thus occur early in the evolution of the channel/levee system.

If the channel evolves in a sequence of small changes, we might expect to find sedimentary sequences in fan channels that are similar to those in river systems. In particular, we might expect to find some type of point-bar–like deposit associated with the fan channel meanders (Kastens and Shor, 1985). If, however, most of the channel meandering occurred early in the evolution of the channel/levee system, the point-bar–like deposit would be restricted to the deeper layers of the channel/levee system rather than distributed throughout the levees.

The apparent continuity of the most recent sinuous fan channel suggests that at least some turbidity currents are capable of traversing much of the channel system. Measured along the sinuous channel, the lower fan channels are about 1,000 km from the canyon. Down-fan variations in flow thickness (reflected in part by channel depth), flow volume (reflected in part by channel cross section), sediment load (especially flow density), sediment size, and channel slope will alter the speed of a turbidity current as it flows down the channel (Middleton, 1966a, 1966b; Komar, 1977; Bowen and others, 1984).

The down-fan decrease in channel depth may lead to a down-fan decrease in the thickness of turbidity-current flow, because the portions of the turbidity current which extend far above the levee crests will become quickly disassociated from the current which remains in the sinuous channel (the flow stripping of Piper and Normark, 1983). Piper and Normark (1983) and Bowen and others (1984) have suggested that some sandy flows may be too thin to fill the channel. If these flows, however, thicken down fan due to entrainment, they may grow until they overtop the levees; thus, even with thin flows, channel depth may eventually control turbidity current thickness. The down-fan decrease in maximum flow thickness and channel slope both suggest a down-fan decrease in turbidity-current velocity. Such a downslope decrease in turbidity-current velocity has long been recognized (Heezen and Ewing, 1952, 1955).

Bowen and others (1984) calculated flow parameters from a Holocene muddy turbidite on Navy Fan and suggested that the density of that turbidity current was small; they predicted that the speed of the channelized flow decreased quickly down fan because the upper parts of the flow were stripped off at channel bends. Fukushima and others (1985), however, have suggested that turbidity currents, even ones flowing at relatively slow speeds, can erode material from the channel and accelerate down channel. Bowen and others (1984) suggested that sandier turbidity currents, which have higher densities and are relatively thin and fast, could traverse much of the relatively small Navy Fan system. Komar (1973, 1977) studied possible flows in the 500-km-long Cascadia Deep-Sea Channel and suggested (assuming bank-full flow conditions) that an initial flow thickness of 50 m and speed of about 8 m/sec would be able to traverse much of that channel length. Few data are available to constrain possible turbidity currents of the long Amazon Fan channels. The sinuous nature of the channels suggests that the channels have been traversed by many smaller flows rather than by fewer larger ones, and rapid flows may not be able to negotiate the intricate fan meanders. At least some of these turbidity currents, however, must be capable of flowing great distances.

The Amazon Fan channels clearly have important similarities to meandering river systems. If, in addition to the morphological relationships observed, the fan channels also follow hydrodynamic relationships similar to those found between meander wavelength, channel width, and discharge for fluvial systems on land (Carlston, 1965), we may ultimately be able to use these or similar relationships to estimate frequency, discharge, flow velocity, and sediment load of the turbidity currents which form, maintain, and modify deep-sea fan channels.

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