Flood, R.D., Piper, D.J.W., Klaus, A., et al., 1995
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1. INTRODUCTION[1]

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Continental margin environments are important repositories of information about the Earth's history. Sediments deposited in this environment, although sometimes difficult to decipher, contain records of sediment flux to the oceans (related in part to sea-level changes), ocean circulation, and land and ocean climate. Margin environments are of particular importance because sedimentation rates are usually high (thus allowing for high-resolution records), and they are located where environmental gradients are steep and where the marine and terrestrial records interfinger. Interpreting this record requires a detailed understanding of sediment processes and distribution patterns.

The study of margin sediments is particularly rewarding in regions of submarine fans. Submarine fans form the largest deep-water sediment bodies on continental margins, and the record of sediment flux to submarine fans can provide important information about the effects of land climate, sea-level and tectonic activity in the source area. Several sedimentary environments may be present at any one time in fan deposits, and each environment can provide a different record of paleoclimate. However, our understanding of the growth patterns of submarine fans and of the relative roles of processes internal and external to the fan in creating the sediment body is limited. Many of the materials that accumulate on fans originate on land, and their composition (both inorganic and organic) contains important information about the climate and erosional history of the source area. During marine lowstands, the levee of an active channel contains materials delivered by rivers to the continental slope with minimal time delay. The biota of the ocean, and associated organic materials, can be preserved in those fan environments where downslope transport is minimized, such as local topographic highs including abandoned levee crests. Sedimentation rates in these environments are, nevertheless, higher than in pelagic environments, so that an expanded sequence is expected and age control is possible.

Normal piston cores only penetrate the upper 10 m or so of these thick sedimentary deposits and thus sample only the most recent time intervals. As a result, our overall understanding of the sedimentary facies associated with seismic and morphological units, the age of these units and their relationships to one another, and the climatic record preserved in their sediments remain poor. Deep, continuous sampling in morphologically well-defined areas is required to make significant progress toward understanding the depositional patterns and growth of deep-sea fans. This information can then be applied to the interpretation of ancient turbidite basins.

The Amazon Fan, at the mouth of the Amazon River, provides an opportunity to investigate a large, muddy fan and the climatic records that it contains. The Amazon Fan is one of the largest modern submarine fans and forms a significant proportion of the continental margin off northeastern Brazil (Fig. 1). The fan contains much of the material eroded from the continent within the Amazon drainage basin. Large fans, such as the Amazon, Mississippi, Indus, and Bengal fans, are formed by the long-term localized input of fluvial sediments moderated by glacio-eustatic sea-level fluctuations, climate change, and tectonic activity.

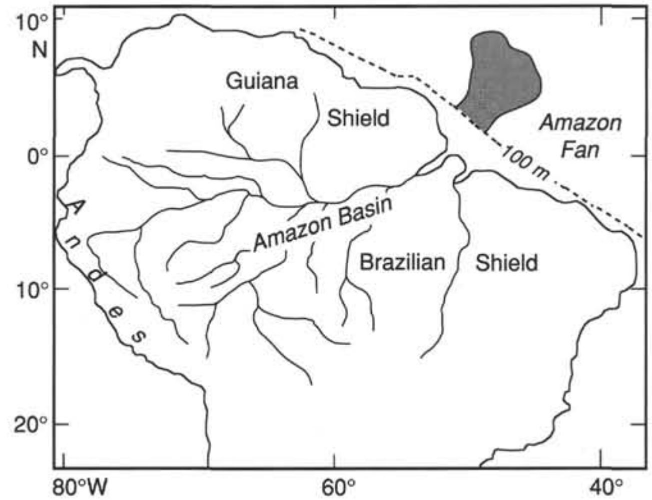

Figure 1. The Amazon River drains the Andes and the Guiana and Brazilian shields as well as the Amazon Basin. During times of lowered sea level, much of the material transported by the Amazon River is deposited on the Amazon Fan.

The record of land climate in equatorial South America, the source region of the Amazon River, is of critical importance to our understanding of Quaternary climatic history. Equatorial regions play a pivotal role in the atmospheric transport of heat to higher latitudes. Land climate records in such regions are short. For the Amazon Basin, few records extend back to the last glacial maximum, so climatic conditions at that time are poorly known. Materials eroded by the Amazon River are deposited on the Amazon Fan during times of lowered sea level. We will attempt to determine a detailed record of land climate through study of the terrestrial (organic and inorganic) components of fan sediments.

The Amazon Fan also underlies the western tropical Atlantic water masses. These water masses and their circulation patterns are particularly important in terms of ocean dynamics and inter-ocean heat transfer. During glacial times, equatorial circulation patterns may have been different due to, for example, changing wind patterns. Reduced flow of the North Brazil Coastal Current (NBCC) across the equator would reduce cross-equatorial oceanic heat and salt transport, both of which are important components of the global ocean circulation pattern. If this were the case, then circulation patterns of the glacial western tropical Atlantic could at times have been very different from the modern-day circulation regime. Understanding the changes in ocean properties and ocean circulation that have occurred will contribute to the understanding of global circulation dynamics.

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A number of sites have been drilled on the Amazon Fan during Leg 155 to meet four main objectives:

1. To determine the relationship between the development of fan deposits, sea-level change, and climatic and possibly tectonic changes in the Amazon Basin.
2. To determine the sediment lithologies characteristic of distinctive acoustic facies and sedimentary processes.
3. To use the stratigraphic record of the Amazon Fan to better understand climatic change within the Amazon drainage basin and the overlying western equatorial Atlantic.
4. To characterize and understand the nature, origin, and early diagenesis of organic carbon present in different fan units.

GEOLOGY OF THE AMAZON FAN

The Amazon River has been the major source of terrigenous sediments to the equatorial Atlantic since Andean uplift in the Miocene (Castro et al., 1978) initiated the development of the modern Amazon Fan. Sediment discharged at present by the Amazon River (derived in part from the Andes and in part from weathering within the Amazon Basin) is dominated by silt and clay (Gibbs, 1967), contains organic matter derived both from within the lowland basin and from upland sources (Hedges et al., 1986; Ertel et al., 1986), and is deposited on the shelf in a large subaqueous delta (Kuehl et al., 1982; Nittrouer et al., 1983, 1986). The present high sea-level stand prevents sediment from crossing the shelf, and thus the fan has been inactive during the Holocene. During glacial sea-level lowstands, the Amazon River crossed the emerged shelf and discharged sediments directly into deep water, into the head of the Amazon Canyon, thereby actively building the fan (Damuth and Fairbridge, 1970; Damuth and Kumar, 1975). Characteristics of the river load are poorly known for these earlier times (Milliman et al., 1975) but the modern river transports sand with a high proportion of rock fragments and few feldspars (Franzinelli and Potter, 1980). Bulk chemistry of the uppermost Pleistocene fan sediment (about 11 ka) is broadly similar to that observed today (Kronberg et al., 1986; Nesbitt et al., 1990).

The Amazon Fan (Fig. 2) extends seaward 700 km to abyssal depths and contains morphological and acoustic characteristics that appear to be typical of many modern elongate or mud-rich fan systems (Stow et al., 1985). A feeder submarine canyon, the Amazon Canyon, is incised into the continental slope, and large, sinuous channels with high levees cross the upper and middle fan with both levee and channel size decreasing down-fan (Fig. 3A and 3B). On the sandy lower fan, both channels and their levees become quite small (Fig. 3C; Damuth and Embley, 1981; Damuth et al., 1983a, b, 1988; Damuth and Flood, 1984, 1985). Seaward of the lower fan, the flat Demerara Abyssal Plain reaches a water depth of more than 4800 m.

Detailed mapping of the margin with seismic-reflection profiles, long-range side-scan sonar (GLORIA) and SeaBeam multibeam bathymetry has shown a complex pattern of submarine channels and large debris flows on the fan (Figs. 2 and 3) (Damuth et al., 1983a, b; Damuth and Flood, 1984, 1985; Flood and Damuth, 1987; Damuth et al., 1988; Manley and Flood, 1988; Flood et al., 1991). Amazon Canyon is incised up to 500 m into the continental slope, which is underlain by flat-lying sediments, a "bottom-simulating reflector" (BSR), and mud diapirs. Channels are common from the lower end of the submarine canyon to about 4300 m water depth. These channels are remarkably sinuous, with length scales and sinuosities similar to those of terrestrial rivers, suggesting that the channels have been formed through a continuous interaction between turbidity currents and sediment deposition (Flood and Damuth, 1987). Although numerous channel segments are recognized on the fan, only one channel (Amazon Channel) is now connected to Amazon Submarine Canyon; all other channels have been disconnected from their upstream source.

The sinuous fan channels, including Amazon Channel, are perched on top of lens-shaped, aggradational overbank deposits forming channel-levee systems in the upper and middle fan (Figs. 4 and 5). On seismic-reflection profiles, channel axes are marked by stacked sets of high-amplitude reflections (HAR; Figs. 4 and 6). Drilling of the youngest channel floor on the Mississippi Fan suggests that these high-amplitude reflections are typically associated with sand and gravel in the channel axis (Stelting et al., 1985).

As the down-fan limit of the middle fan is approached, semi-transparent levee deposits and transparent debris-flow deposits begin to interfinger with units composed of multiple, high-amplitude, parallel seismic reflections. As the lower fan is reached, levee deposits and debris flows pinch out to give rise to a sequence of high amplitude, nearly parallel horizontal reflections (HARP; Figs. 4 and 6). Channels on the lower fan are generally less than 20 m deep and have low, acoustically reflective levees.

The numerous abandoned channel segments on the fan appear to have been created through the process of avulsion (Damuth et al., 1983b). Avulsion occurs when an existing channel wall is breached (Fig. 6). Subsequent downslope flows abandon the path of the old channel downstream of the breach to create a new channel segment. With time, overbank deposits from the newly created channel will fill the adjacent older channel near the point of avulsion (Fig. 6). The topographic expression of the older channel, however, remains preserved for a relatively long time. Because avulsion has occurred many times on the fan, there are numerous local topographic highs associated with abandoned channel sections in the middle part of the fan.

Detailed topographic analysis of the fan suggests that the along-channel gradient decreases uniformly down-fan and channel sinuosity varies down-fan apparently to maintain this gradient (Flood and Damuth, 1987; Pirmez, 1994). If this is the case, localized changes in channel depth, such as that caused by an avulsion, will cause the channel to cut down rapidly upstream and to aggrade rapidly downstream of the avulsion point (Flood et al., 1991; Pirmez, 1994; Pirmez and Flood, this volume). Such rapid deposition may create the flat-lying, lobe-like, high-amplitude reflection packets (HARPs) that underlie channel-levee systems in the middle fan and that extend down-fan to form part of the lower fan (Fig. 4).

The abandoned channel-levee systems seen in seismic sections can be grouped into larger complexes that are separated by zones of acoustically incoherent and transparent sediment interpreted as debris-flow deposits and hemipelagic sediments (Flood et al., 1991). Upper, Middle, Lower, and Bottom Levee complexes have been distinguished. Other channel-levee systems and possible debris-flow deposits are observed deeper in the seismic profiles.

Analysis of piston cores has shown that the late glacial sediment of the upper and middle fan is in general gray mud with occasional thin sand/silt layers, whereas sediment of the lower fan contains abundant, thicker sandy turbidites (Damuth and Kumar, 1975; Coumes and Le Fournier, 1979; Moyes et al., 1978; Damuth et al., 1988). Organic detritus is common. Sediment is commonly stained black by iron-sulfide minerals including abundant hydrotroilite ($FeS \cdot nH_2O$), which is formed post-depositionally by heterotrophic bacteria acting on organic substances, and which rapidly oxidized in contact with air (Ericson et al., 1961). Other iron-sulfide minerals including greigite, mackinawite, and marcasite are also present. Radiocarbon dating of coarse organic matter and foraminifers in middle-fan turbidites from piston cores near Amazon Channel suggests accumulation rates as high as 168 cm/k.y. in the late glacial period from 14.3 ka to 16.0 ka, with somewhat lower rates in the overlying sediment (W.J. Showers, pers. comm., 1993). In contrast to these gray sediments deposited during the late glacial, the upper few tens of centimeters of sediment in piston cores comprise tan to brownish pelagic calcareous clay to ooze resting on a diagenetic iron-rich crust that can be correlated throughout the Amazon Fan and adjacent Guiana Basin (Damuth and Fairbridge, 1970; McGeary and Damuth, 1973; Rich-

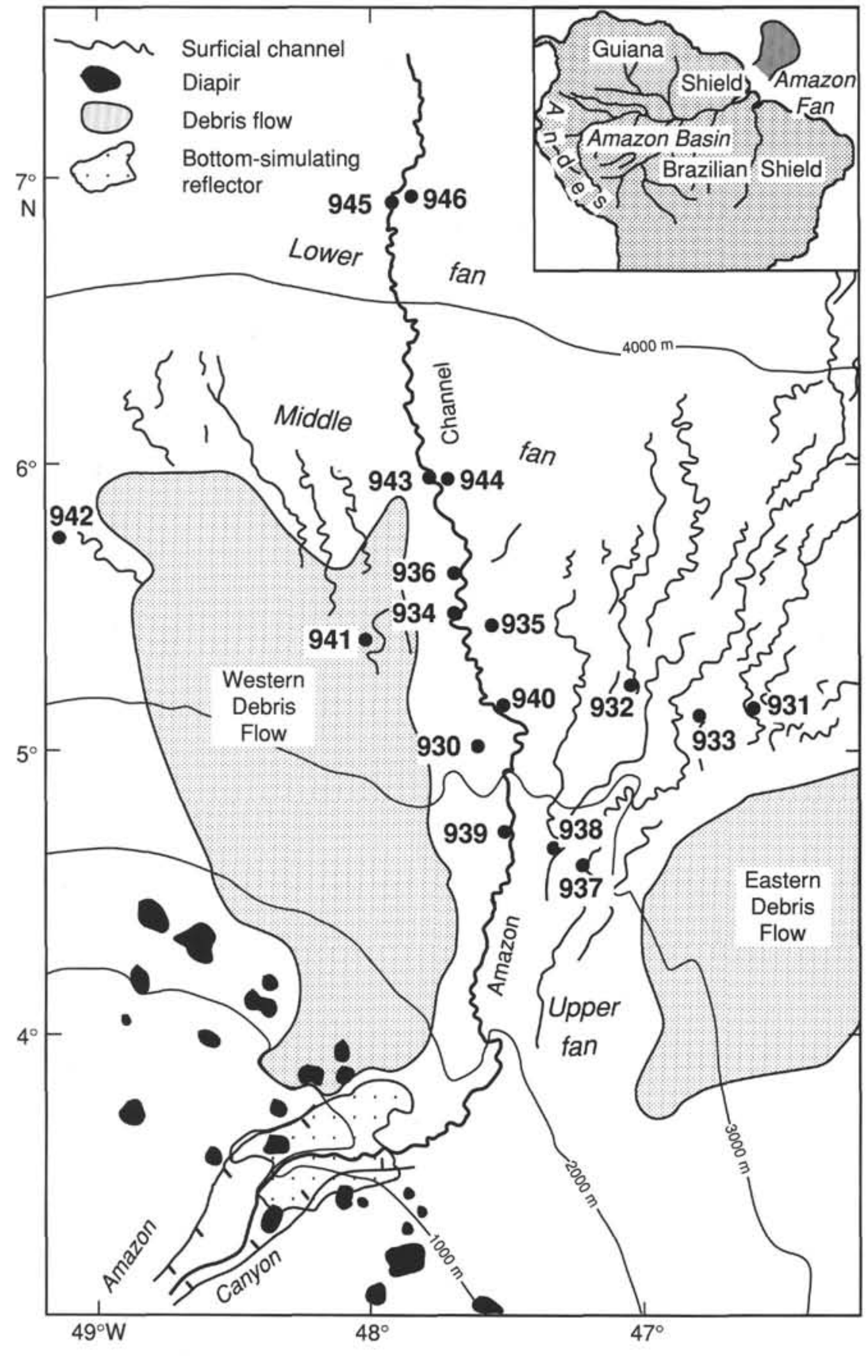

Figure 2. Generalized map of the Amazon Fan showing location of sites in relation to surficial channel systems and debris flows. The Amazon Channel is the most recently active channel on the Amazon Fan.

ardson, 1974; Damuth, 1977). The sediment containing this crust has been dated as 9.3 ka by Showers and Bevis (1988), but crust formation is apparently diachronous across the Guiana Basin (~8–15 ka, Damuth, 1977). The brownish calcareous surface sediment marks the cessation of rapid supply of terrigenous material as the mouth of the Amazon River retreated across the continental shelf, and active levee building ceased in response to Holocene sea-level rise. Initiation of rapid coastal retreat approximately corresponds to a "global" sea level of about –40 to –45 m (using the curve of Fairbanks, 1989).

Extrapolation of these radiocarbon dates and estimates of sediment flux suggests that only the channel-levee systems closely associated with Amazon Channel 1 were deposited during lowered sea level of the last glacial (Manley and Flood, 1988; Flood et al., 1991). This may mean that each major levee complex is associated with a single glacial phase lowstand. Manley and Flood (1988) note that nearly all of the exposed channel-levee systems of the Upper Levee Complex can be traced to the present-day Amazon Canyon, whereas more deeply buried channel-levee systems seem to be related to a different buried canyon system. This suggests that at least portions of these complexes might have formed during different sea-level lowstands. The preferred hypothesis of several investigators before the beginning of this leg was that the Upper Levee Complex corresponded to oxygen isotopic Stages 2–4 and the Middle Levee Complex to Stage 6, whereas others considered that these upper sediment units were a little older.

Many of the cores collected from the Amazon Fan contain relatively high organic-carbon contents, as is typical for muddy fan sediments. Early diagenesis produces methane gas, which is common in

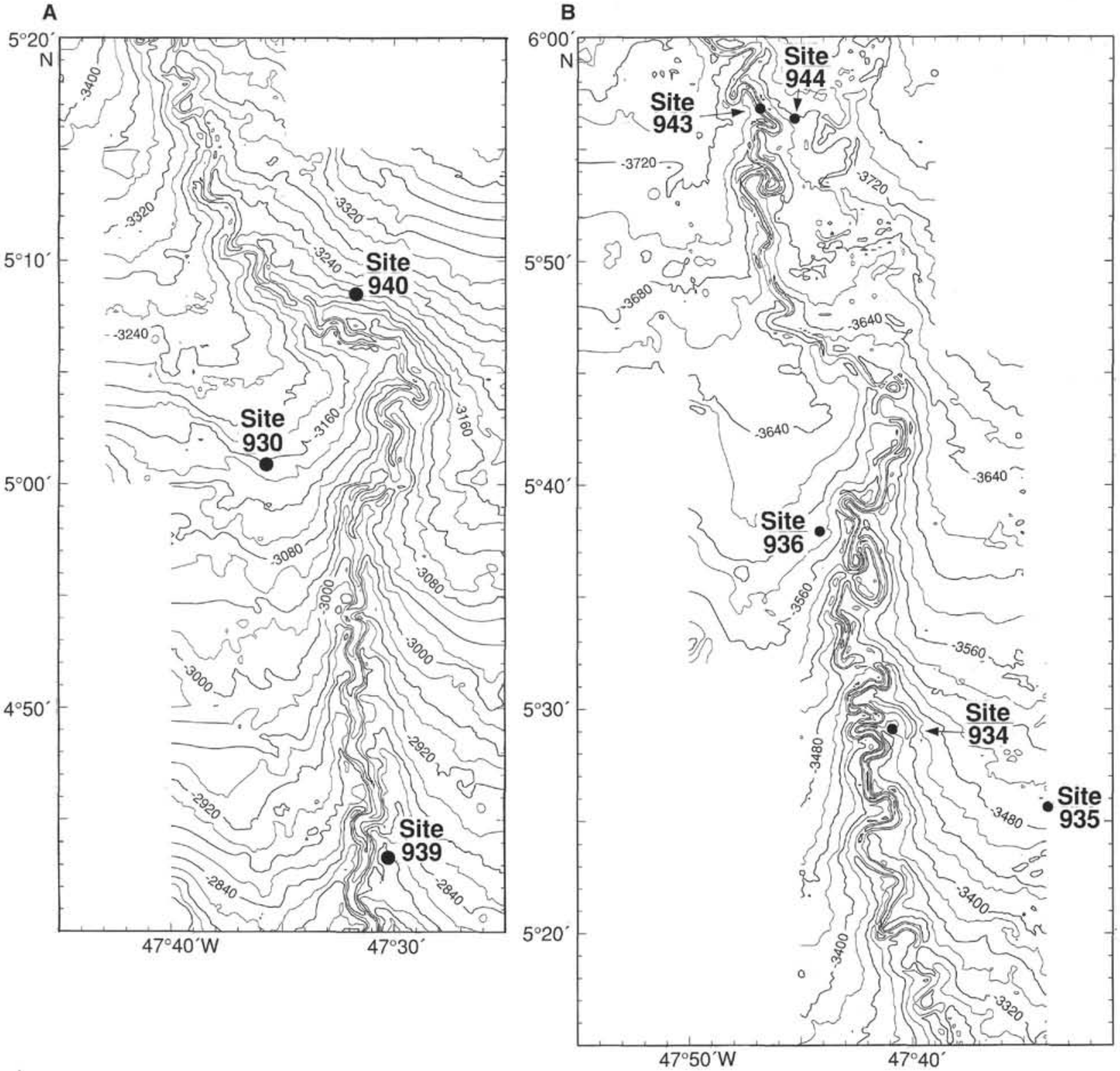

Figure 3. Bathymetric maps of central part of Amazon Channel with nearby sites shown. **A.** Upper fan Sites 930, 939, and 940. **B.** Middle fan Sites 934, 935, 936, 943, and 944. **C.** Lower fan Sites 945 and 946. Base map is gridded SeaBeam multibeam bathymetry.

some 10-m-long piston cores, particularly those in areas of high sediment accumulation. An authigenic carbonate nodule recovered from the Amazon Fan yielded $\delta^{13}C$ of –52‰, consistent with a biogenic methane source (W.J. Showers, pers. comm., 1993). The bottom simulating reflectors on the upper fan and slope (Manley and Flood, 1988) suggest the presence of gas hydrates. Estimated temperature and pressure conditions are suitable for the formation of hydrates on the fan.

GROWTH PATTERNS OF DEEP-SEA FANS

The scientific understanding of turbidites and deep-sea fans has resulted from work with three types of data: ancient flysch sequences on land, modern deep-sea fans, and principally seismic-reflection data from hydrocarbon basins. Because of the differences in tools used to investigate each type of data and the differences in scale, it is commonly difficult to relate the three types of data (Normark et al., 1993). For example, "lobes" recognized in industry seismic profiles may be quite different from those inferred from ancient outcrops. In general, outcrop geology lacks information on morphological setting at the time of deposition, and seismically imaged modern deep-sea fans and hydrocarbon basins lack detailed information on lithologies. Drilling of a modern deep-sea fan provides an opportunity to integrate these historically divergent approaches through the characterization of lithology in different morphological settings. This data set will allow correlation of the various lithofacies and cyclic patterns that are recognized in ancient rocks (Mutti, 1992), in outcrop, boreholes and seismic-reflection profiles.

Studies of modern fans have been used to understand the relationship of recent turbidity currents to fan morphology (Flood and Damuth, 1987; Normark and Piper, 1991), but have been limited to only

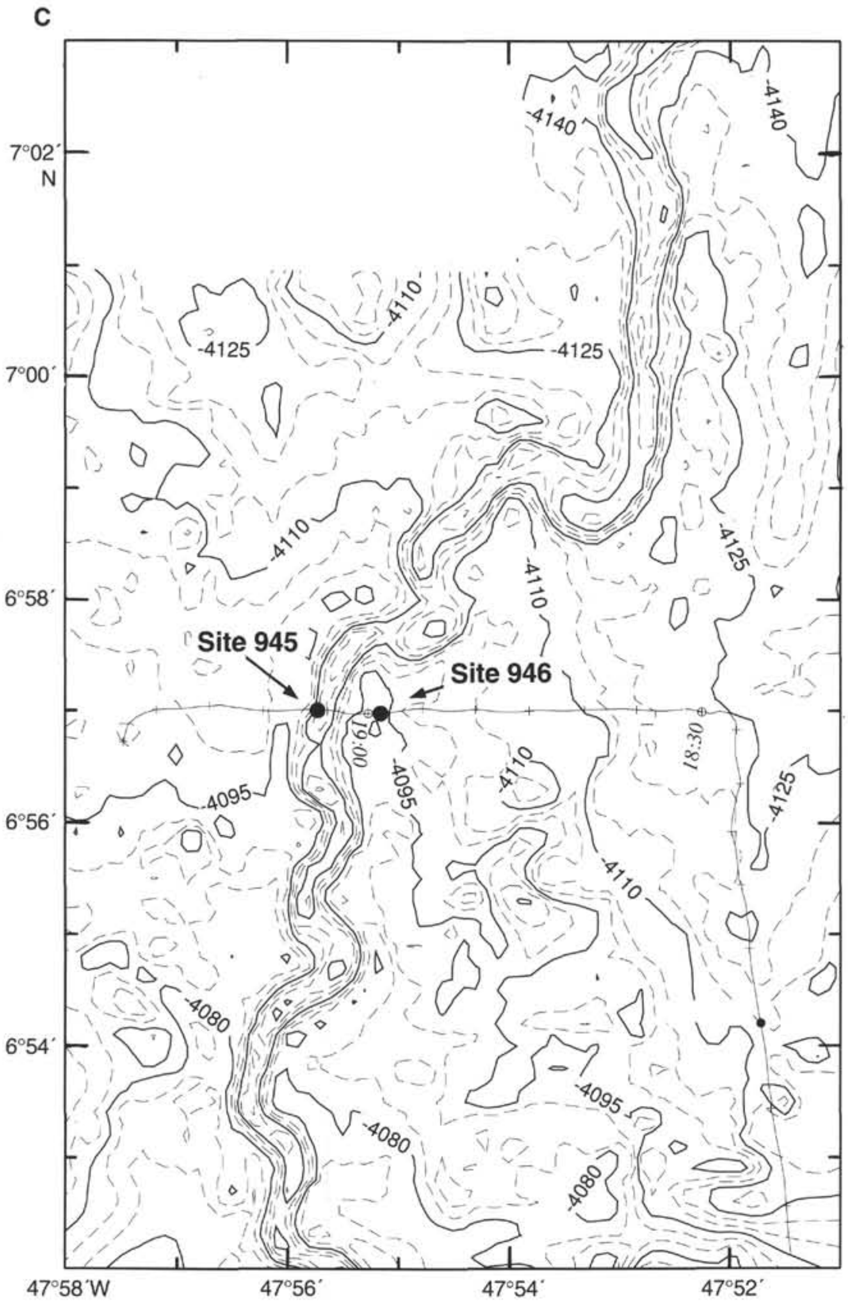

Figure 3 (continued).

the latter part of the last glacial cycle because of the absence of long cores. The behavior of individual turbidity currents depends strongly on their overall volume and the type of sediment load, which are influenced both by sediment supply and by initiation mechanism, as well as on gradient and seafloor morphology. Drilling provides an opportunity to define the relationship between changes in sediment supply during glacial-interglacial cycles, turbidity-current flow processes inferred from channel morphology, and the resulting deposits. Drilling also will provide samples to help understand the initiation and mechanics of debris flows.

Much of the focus of work in hydrocarbon basins has involved application of sea-level models, especially the conceptual sequence-stratigraphic model developed by P.R. Vail and his Exxon co-workers (e.g., Posamentier and Vail, 1988; Vail et al., 1991). The various models predict that the relative rise and fall of sea level can control development of fan subenvironments and sediment facies in a systematic, predictable manner (Mitchum, 1984; Mutti, 1985; Posamentier et al., 1988; Posamentier and Vail, 1988). For example, the current Vail conceptual model predicts that the sand-rich lower fan (lobe) subenvironment forms in response to the incision and erosion of the continental shelf and upper slope by the submarine feeder canyon and its associated fluvial valley during the initial relative fall and downward acceleration of sea level. The resultant mound-shaped, unchannelized sand-rich deposit downlaps onto the previous sequence boundary and is termed the "basin-floor fan" (van Wagoner et al., 1988; Vail et al, 1991). As the rate of sea-level fall slows and the lowest sea level is reached, erosion decreases and a more muddy middle- to upper-fan subenvironment composed of channel-levee systems,

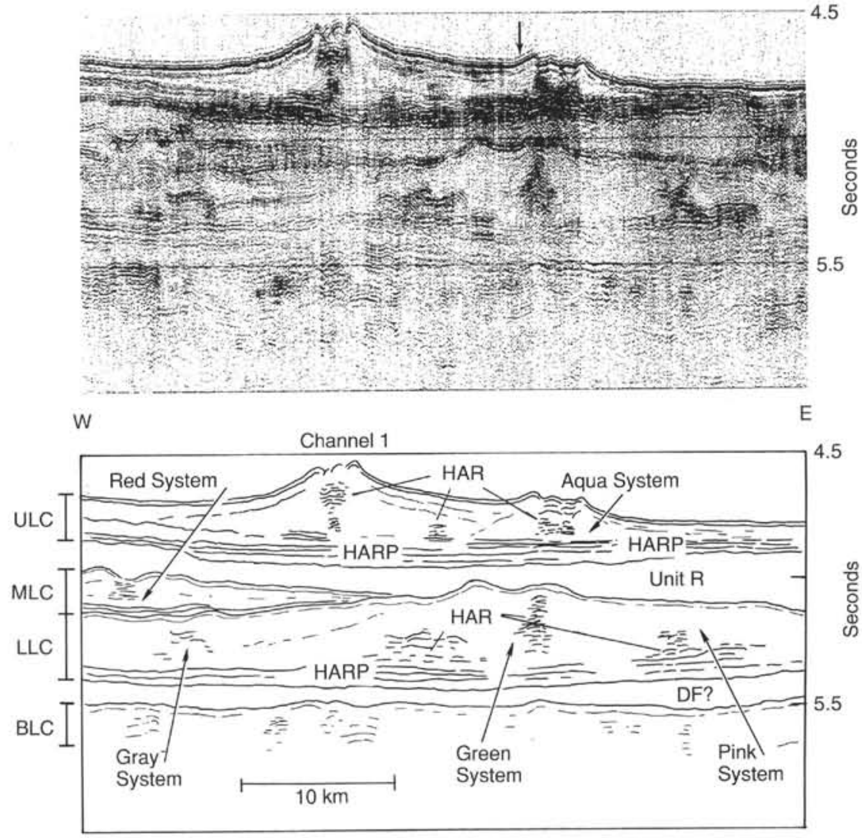

Figure 4. Seismic section and line drawing showing acoustic facies and stacked channel-levee systems (after Manley and Flood, 1988; Flood et al., 1991). HAR = high-amplitude, nearly vertical reflection sets beneath channels. HARP = high-amplitude reflection packet beneath levees. ULC = Upper Levee Complex; MLC = Middle Levee Complex; LLC = Lower Levee Complex; BLC = Bottom Levee Complex. DF = debris flow. The projected location of Site 935 is shown on the seismic profile by the arrow.

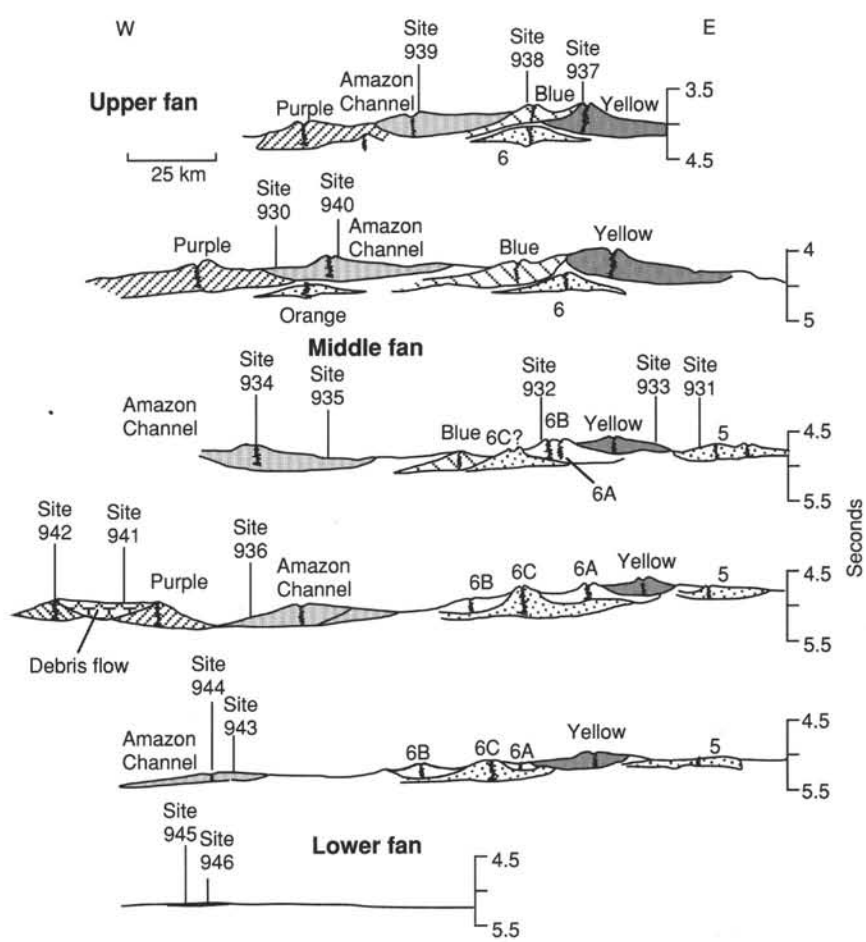

Figure 5. Series of schematic cross sections showing the surficial expression of channel-levee complexes of the Upper Levee Complex and the Western Debris Flow and the general location of Leg 155 sites (after Damuth et al., 1983b).

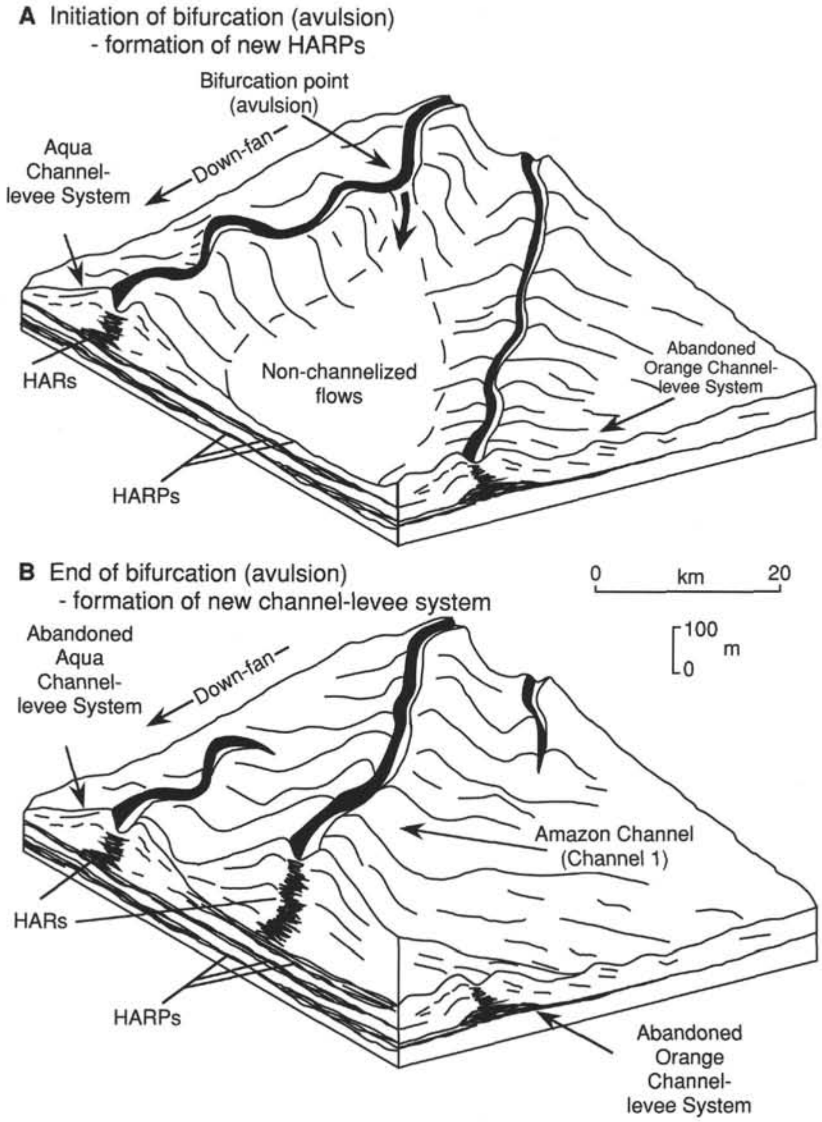

Figure 6. Schematic block diagram illustrating the development of channel-levee systems and the formation of HARPs following avulsion (from Flood et al., 1991).

called the "slope fan," is deposited over and downlaps onto the "basin-floor fan." Vail et al. (1991) and Mitchum (1984) consider the "basin-floor fan" to be equivalent to the sandy lower fan subenvironment (depositional lobes) identified on modern fans and the "slope fan" to be equivalent to the muddy channel-levee systems of the middle- to upper-fan subenvironments on modern fans.

In most studies where sea-level models have been applied to turbidite basins, precise and independently dated correlation between changes in sea level and basin sedimentation has been lacking. The relationship is best understood from outcrop studies (e.g., Mutti and Sgavetti, 1987), but in such cases, information on paleo-morphology is lacking. Thus the relationship of fan architecture to sea-level change (Posamentier et al. 1988; Mutti, 1992) remains rather speculative. It is uncertain whether sequence boundaries can be traced off the shelf onto submarine fans at the base of channel-levee complexes, as proposed by Weimer (1989) for the Mississippi Fan. On the Amazon Fan and some other modern fans (e.g., Mississippi, Indus), latest Pleistocene sediment in piston cores indicates that the sandy lower-fan subenvironment ("basin-floor fan" of van Wagoner et al., 1988) and the muddy middle- to upper-fan subenvironment ("slope fan" of van Wagoner et al., 1988) form contemporaneously, at least throughout a period of rising sea level (Damuth and Kumar, 1975; Damuth et al., 1988; Kolla and Macurda, 1988; Flood et al., 1991).

We wanted to correlate Amazon Fan stratigraphy with "global" sea-level variations to answer the following questions related to current sea-level models:

- –Is there a relationship between channel-levee formation and sea-level fluctuation (i.e., do new channel-levee systems form as a result of auto-cyclic channel avulsion processes or are they initiated by changes in sediment supply)?
- –What relationships are there between debris flows and sea-level change?
- –What seismic reflectors correlate with sequence boundaries on the shelf?
- –What is the relationship of channel-levee systems to sequence boundaries and flooding surfaces?
- –Do the high-amplitude reflections at the base of channel-levee systems represent condensed sections during maximum flooding surfaces, so that the erosional surfaces at the bases of chan-

nel-levee systems are sequence boundaries (Weimer, 1989), or are they of autocyclic origin?

–What is the temporal relationship of lower-fan deposits (depositional lobes) to middle- and upper-fan deposits (channel-levee systems)?

One advantage of investigating fan evolution since 0.2 Ma is that the history of sea-level change is known more precisely than at any other time in geological history. The standard "global" (SPECMAP) oxygen isotopic curve (Martinson et al., 1987) is a first-order approximation of sea-level change (Chappell and Shackleton, 1986; Shackleton, 1987). These changes in "global" (eustatic) sea level, driven by changes in ice volume, are approximately equal throughout the world. In glaciated or tectonically active areas, however, relative sea level using a terrestrial datum may vary substantially between areas as a result of tectonic and glacial isostatic effects. Gravitational and isostatic effects due to water loading mean that "eustatic" sea-level changes may vary by up to 10 m even in tectonically stable areas remote from past ice sheets (Farrell and Clark, 1976). For these reasons, and because of the isotopic shifts due to melting ice sheets and variations in bottom water temperature, the global isotopic curve varies in detail from geologically determined past sea levels.

Analysis of geologically determined sea levels and the global eustatic curve suggests the following sea-level history for the late Pleistocene (Fig. 7). Since 0.2 Ma, only two major transgressive events have shifted shorelines completely across continental shelves, during Stages 6 to 5e and Stages 2 to 1, with sea level generally quoted as 6 m higher than present in Stage 5e (Bloom and Yokenura, 1985). Sea-level change since the last glacial maximum is well defined from local geological studies (e.g., Fairbanks, 1989) and has a resolution greater than that applicable for a "global eustatic" curve. Raised coral reefs, such as those on the Huon Peninsula and Barbados, have provided information on the magnitude and approximate age of highstands through oxygen isotopic Stages 3 to 5 (Bloom and Yokenura, 1985, summarized by Wellner et al., 1993), although there is considerable uncertainty in dating and whether rates of tectonic uplift are constant. Marine lowstands are less well defined from geological data, but most authors estimate lowstands of no lower than –80 m during Stages 3–5, compared with –115 m for Stage 2. The Huon Peninsula data suggest three main highstands in Stage 3 that range from –20 to –40 m elevation (Bloom and Yokenura, 1985), and comparison with uplifted terraces worldwide suggests ages of 36 ka, 50 ka, and 60 ka for these highstands (Smart and Richards, 1992). The intervening lowstands fell to below –60 m (≈40 ka) and below –70 m (≈55 ka; Chappell, 1974). The magnitude of sea-level lowering during Stage 4 (65 ka) is poorly constrained, but is estimated to be lower than –35 m in Barbados (Steinen et al., 1973) and below –50 m in Huon (Chappell, 1974). Highstands early in Stage 5 at 80–85 and 100–105 ka are well defined in coral reef data and correlate well with the oxygen isotopic curve. Estimated elevations for these highstands are, respectively, –10 m and +1 m (Bloom and Yokenura, 1985; Toscano and York, 1992). Intervening lowstands are estimated at about –50 m on the Huon Peninsula, but coastal data elsewhere suggest a lowering to –20 m (Stage 5b) and –28 m (Stage 5d; Piper and Perissoratis, 1991; Toscano and York, 1992).

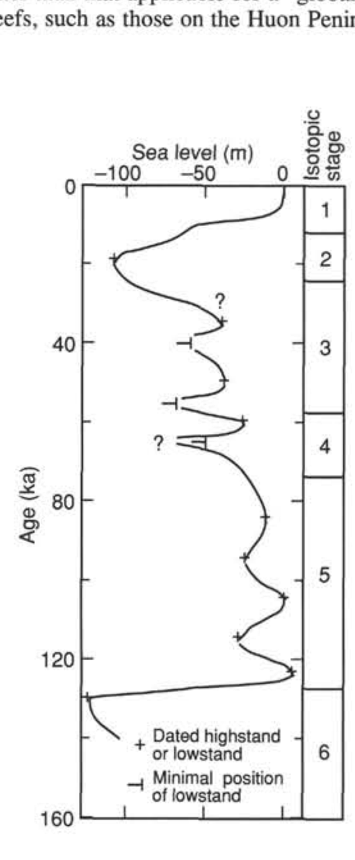

Figure 7. "Eustatic" variations in sea level in the late Pleistocene (for explanation of sources, see text). We expect sedimentation on the Amazon Fan to be responding to changes in sea level of this general magnitude and timing.

CLIMATIC RECORD OF THE AMAZON BASIN AND THE EQUATORIAL SOUTH ATLANTIC

Interpretation of the marine foraminiferal record (CLIMAP Project Members, 1976) suggests that during the last glacial maximum, ocean temperatures in equatorial regions were slightly warmer or similar to those found at present. Paradoxically, most paleoclimatic studies of land areas indicate substantial cooling at equatorial latitudes during glacial intervals (e.g., Rind and Peteet, 1985; Peteet, 1986; Stute et al., 1992). Confirming the validity of these inferences is important to understand global climatic conditions during glacial periods.

Studies of land fauna and Pleistocene geology within the Amazon drainage basin suggest that during glacial intervals, the vast tropical rain forests shrank and semi-arid savannahs probably prevailed over much of the eastern Amazon (Colinvaux, 1989). However, the continental record of these changes remains sparse and incomplete (Absy et al., 1991; Liu and Colinvaux, 1988). The pollen record in marine sediments from piston cores off northern Brazil suggests that savannah was an important type of vegetation in the Amazon Basin during the last glacial maximum and that mangroves expanded along the coast in response to rising sea level during the transition from the last glacial to the present full interglacial (Holocene; Caratini and Tissot, 1976; Caratini et al., 1978).

The circulation of the western tropical Atlantic water masses that overlie the Amazon Fan (Fig. 8) has an important effect on world ocean dynamics and inter-ocean heat transfer. This is because the North Brazil Coastal Current (NBCC) is the only known cross-equatorial heat transport in the global circulation pattern (Metcalf and Stalcup, 1967; Richardson and Walsh, 1986). From December to June, the NBCC may extend into the Guyana Current and link with the Caribbean Current when wind stress variation causes increased transport in the NBCC (Picaut et al., 1985; Philander and Pacanowski, 1986). However, the NBCC turns eastward (retroflects) into the eastward-flowing North Equatorial Countercurrent (NECC) between July and November. Lenses of low-salinity surface water resulting from dilution of the Amazon plume occasionally become detached and can move seaward, perhaps also as a result of weakening of trade winds, NECC eddies, or variations in Amazon River discharge (Nittrouer and DeMaster, 1986). During low sea-level stands, the river would have discharged directly into relatively deep water, and mix-

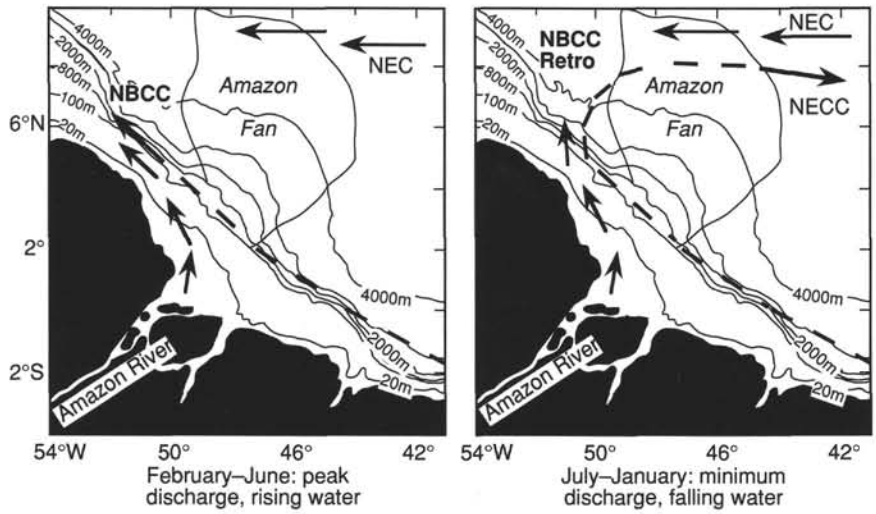

Figure 8. Sketch map showing present-day seasonal variation in surface circulation in the western equatorial Atlantic. Similar changes, which may have occurred for extended periods of time during past intervals, may be part of worldwide changes in ocean circulation and heat flux. NBCC = North Brazil Coastal Current; NEC = North Equatorial Current; NECC = North Equatorial Countercurrent. Retro = retroflection of the NBCC.

ing of the river plume into the coastal water might have occurred more slowly than at present, allowing more extensive fresh-water lenses to form.

Planktonic foraminifers are found in sediments of the Amazon Fan despite the relatively high sediment accumulation rates, which have the beneficial effect of expanding the planktonic record, making a high-resolution time series possible. Showers and Bevis (1988) and Showers (pers. comm., 1993) show that a number of well-developed negative $\delta^{18}O$ deviations during the late glacial/early interglacial on the eastern part of the fan appear to correlate and are tentatively interpreted as Amazon River paleo-discharge events. Such deviations are less common on the western fan, suggesting that the spikes might alternatively be due to reduced activity of the NBCC. Such isotopic events would also mark periods of reduced cross-equatorial oceanic heat and salt transport, important components of the global circulation pattern. If this is the case, then circulation patterns of the glacial western tropical Atlantic could at times have been very different from the modern-day circulation regime.

SHALLOW SEISMIC STRATIGRAPHY OF AMAZON FAN AND SUMMARY OF SITE SETTINGS

The shallow sediments on Amazon Fan have been deposited principally as prograding channel-levee systems. Channels have at times experienced avulsion, and there has been more variation in channel position on the middle fan than on the upper fan. Channel-levee systems have been assigned numbers (Damuth et al., 1983b) and color names (Manley and Flood, 1988; Figs. 5 and 9; Table 1). Their relative ages have been assigned based on their stratigraphic (onlap) relationships to one another on seismic profiles. The uppermost seven channel-levee systems on the western fan (the most recently active channel and six abandoned ones) are, in order of increasing age, Amazon Channel, Brown, Aqua, Purple, Blue, Yellow, and Orange. Abandoned channel-levee systems on the eastern fan are Channel 5 (poorly constrained in age but thought to be between Yellow and Orange) and Channels 6A, 6B, and 6C (below Channel 5 and probably below Orange). All these channel-levee systems compose the Upper Levee Complex, which is separated by an apparent debris flow, Unit R, from the Middle Levee Complex. In the central portion of the fan where high-resolution seismic data are available, the Middle Levee Complex consists of only the Red Channel. In some areas, the Red Channel is separated from the underlying Green Channel by another apparent debris-flow deposit. The more deeply buried channel-levee systems (Green, Gold, Lime, Gray, and Pink) form the Lower Levee Complex.

Because avulsion tends to occur in the middle and lower reaches of channels, several channel-levee systems tend to become coincident toward the upper part of the fan. Thus, for example, at Site 930 (Fig. 3A), which is upstream from the point at which avulsion separated the Amazon Channel from the Aqua Channel, the Aqua, Brown, and Amazon channel and levees are the same.

Levee crests are typically 50–100 m above the channel floor on the middle part of the Amazon Fan, and most individual levee sequences have maximum thicknesses of 200 to 300 m. Levee thicknesses at the crests adjacent to the channels are typically three times greater than thicknesses on the flanks some 10 km away. Aggrading channel axes are marked by high-amplitude reflections (HARs) on seismic profiles. Seismic modeling studies suggest that the precise pattern of HARs within the levees may result, in part, from the plan form geometry of the highly reflective channel floor and, thus, does not always indicate the distribution of more deeply buried sand within the levee (Flood, 1987). Flat-lying, lobe-like, high-amplitude reflection packets (HARPs) underlie channel-levee systems in the middle fan and extend down-fan to form part of the lower fan (Fig. 4). They are thought to be formed by sand deposition following avulsion and are eventually overlain by prograded levee deposits.

From seismic reflection profiles, the following acoustic facies have been distinguished (Fig. 4):

1. Levee crests, with extremely high sedimentation rates.
2. Levee flanks, with high sedimentation rates.
3. HARs possibly marking the aggradation of channels.
4. HARPs at the base of levee sequences.
5. Debris flows, which tend to fill topography.
6. Although not directly resolvable on seismic profiles, from core studies, abandoned levees are interpreted to be the locus of accumulating "condensed" mud-dominated sequences with fewer turbidites.

Sites have been selected to penetrate a series of stacked, overlapping channel-levee systems. The existing extensive seismic correlation of units means that many seismic units can be drilled where the section is highly expanded on levee crests, less expanded on levee flanks, and where it is represented by "condensed" muddy sediments on abandoned levees. Also, because the channel-levee systems are offset laterally on the fan, sites do not have to penetrate all younger levees to reach an older one; older levees can be sampled where they are relatively near the surface. The sites were planned to provide a complete stratigraphic sequence for the Upper Levee Complex. Some holes were planned to reach Unit R (the debris-flow deposit) that underlies the Upper Levee Complex and to reach channel-levee systems

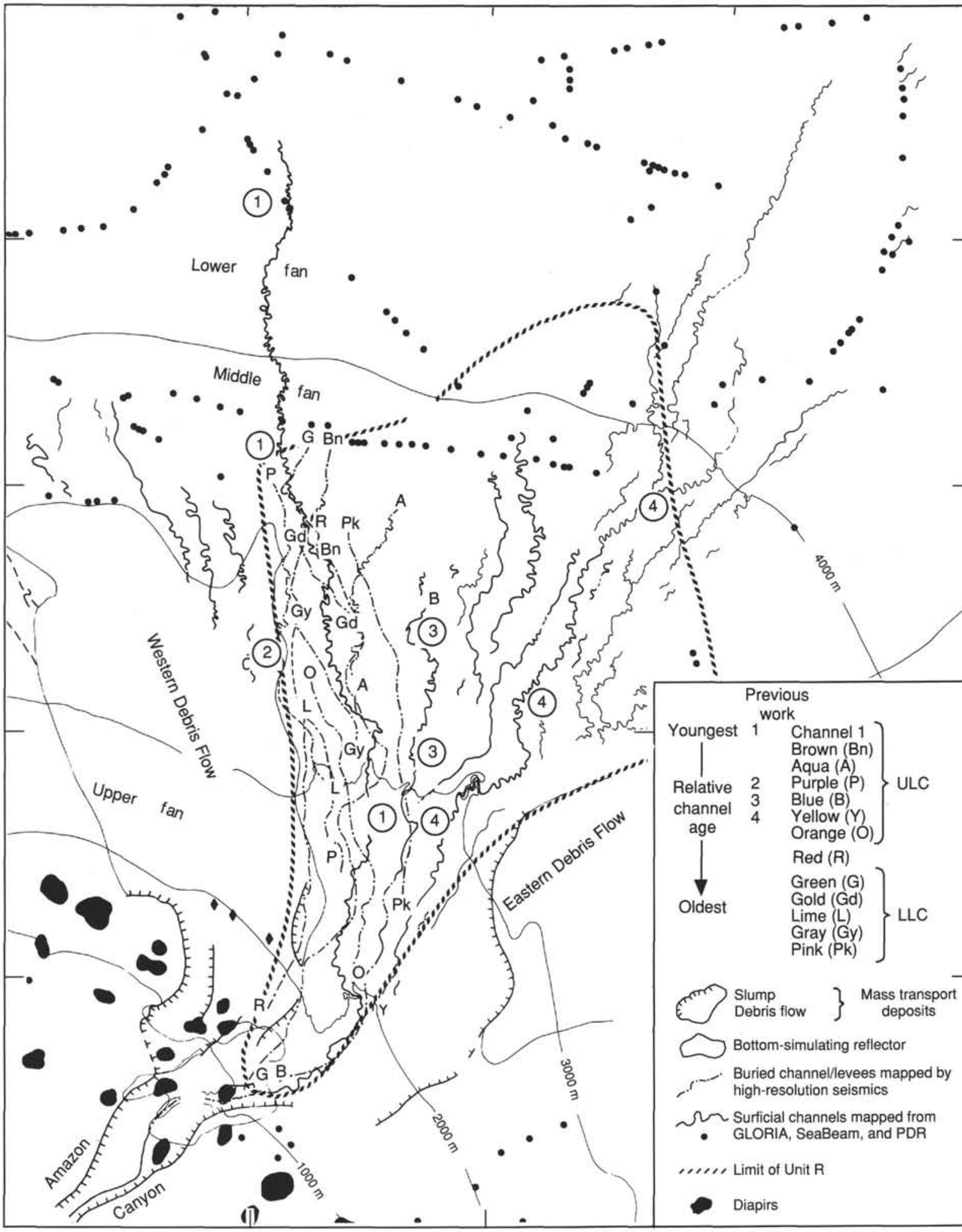

Figure 9. Detailed map of surficial and buried channels on the Amazon Fan (after Manley and Flood, 1988). Also shown are surface features and the apparent lateral extent of buried debris flow "Unit R."

Table 1. Summary of acoustic stratigraphic nomenclature of channel-levee systems on the Amazon Fan, after Damuth et al. (1983b) and Manley and Flood (1988).

	Western fan[+]	Central fan	Eastern fan
Upper Levee Complex			
		Amazon Brown Aqua	(=1)
	Purple (= 2)		
		Blue (= 3) Yellow (= 4)	
			Channel 5*
		Orange*	
			Channel 6A* Channel 6B* Channel 6C*
Unit R Debris Flow			
Middle Levee Complex			
	Red		
Debris flow			
Lower Levee Complex			
		Green Gold Lime Gray	
Debris flow			
Bottom Levee Complex			

Notes: [+]High-resolution seismic data are not available from most of the western fan.
*The age relationship between Orange and Channels 5 and 6A, 6B, and 6C has not been clearly delineated from seismic profiles.

preserved in the buried Middle and Lower Levee complexes. Other sites have been selected to recover high-resolution biostratigraphic records, to sample distinctive acoustic facies, and to track proximal to distal changes along the Amazon Channel system.

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