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

Shipboard Scientific Party[2]

INTRODUCTION

Drilling of 17 sites (Sites 930–946) on the Amazon Fan has revealed the nature of the lithologic units that build the fan and has shown that major glacial to interglacial changes in sea level and climate are reflected in the architecture and lithology of turbidite deposits. At this time, immediately following the cruise, we seek to summarize some of our shipboard observations in a way that will better link the results of individual sites. We anticipate that post-cruise studies will refine our stratigraphic and lithologic characterization of the wide range of fan environments studied.

CORRELATION AND CHRONOLOGY

Lithostratigraphy and Acoustic Stratigraphy

The stacked lenticular channel-levee systems observed in seismic-reflection profiles provide a basic stratigraphic context for the sites that were drilled. Relative ages have been assigned to these channel-levee systems based on their overlap stratigraphic relationships observed on seismic profiles (Pirmez and Flood, this volume; "Introduction" chapter, this volume). Sites 931, 933, 935, 936, 944, and 946 sampled the section below the Upper Levee Complex, providing a basic stratigraphic framework for the fan (Figs. 1, 2, and 3). Sites 932, 937, 938, and 942 were primarily intended as biostratigraphic reference sites in the slower sedimentation-rate sections above abandoned levees. Sites 939, 930, 940, 935, 936, 944, and 946 provided sections through the levee of the Amazon Channel from the upper to the lower fan (see back-pocket foldout). Sites 934, 943, and 945 sampled sediments within channels; Site 941 investigated a near-surface debris flow.

The levee crests of abandoned channel-levee systems had bioturbated mud. Levees built by active channels consist of mud with abundant thin beds of silt and sand. They have prograded over thick medium sand beds deposited at the end of an active channel. Mass-transport deposits of slides and debris flows, up to 120 m thick, consist of contorted blocks of mud, with dimensions from centimeters to many meters, generally with little matrix material. The surface meter of sediment on the fan is a calcareous mud; a similar lithology was found on top of some of the deeply buried levees.

Figure 3 provides a detailed synthesis of shipboard lithofacies interpretation and acoustic stratigraphic correlation. Key biostratigraphic and magnetostratigraphic markers are also shown, demonstrating the high rates at which the fan was built. We are aware of some minor inconsistencies in these correlations, which will be refined by shore-based study. Detailed sedimentological logs of the upper parts of most sites are presented in the back-pocket foldout.

Biostratigraphy and Chronology

The combination of seismic profiles and strategically located holes allowed us to develop a consistent stratigraphic framework. Several stratigraphic tools provided shipboard age control. Additional age evidence will come from shore-based studies, including stable isotopes and ^{14}C dating. Planktonic foraminifers and calcareous nannofossils provided useful age markers at about 6, 9, 11, 40, 85, 130, and 260 ka. The channel-levee systems of the Upper Levee Complex other than the Channel 6 and Orange channel-levee systems are younger than 40 ka.

Calcareous clays containing interglacial foraminifers are interpreted as analogs of the Holocene calcareous clay that covers the entire fan and has a sedimentation rate of <0.1 m/k.y. Such calcareous clays form when nearly all Amazon River sediment is advected northwestward along the inner continental shelf. This occurs only during glacio-eustatic highstands of sea level. Three such calcareous clay beds at Site 942 are interpreted as dating from isotopic Stage 5: the middle clay contains a paleomagnetic excursion (the Blake Event, 105 ka). Calcareous clays that immediately overlie the top of the Lower Levee Complex (Sites 935, 939, and 944) and the Bottom Levee Complex (Sites 931, 933 and ?946) (Fig. 1) have nannofossil

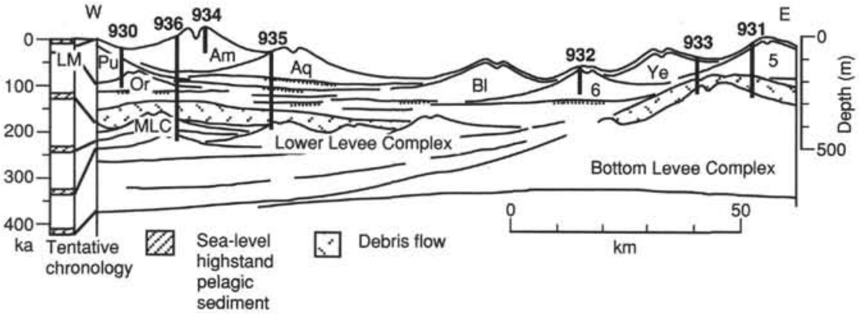

Figure 1. Schematic cross section of the upper Quaternary sediments of the Amazon Fan. Stacked channel-levee systems result from aggradation by turbidity currents flowing down channels, followed by abrupt switching of the channel to a new path. Each system has prograded across sand beds deposited at the downstream end of the channel. Groups of stacked channel-levee systems make up levee complexes (MLC = Middle Levee Complex). Am, Aq, Pu, Bl, Ye, 5, Or, and 6 signify successively older channel-levee systems of the Upper Levee Complex. LM = Lake Mungo Excursion (30 ka).

[1]Flood, R.D., Piper, D.J.W., Klaus, A., et al., 1995. *Proc. ODP, Init. Repts.,* 155: College Station, TX (Ocean Drilling Program).
[2]Shipboard Scientific Party is as given in the list of participants in the contents.

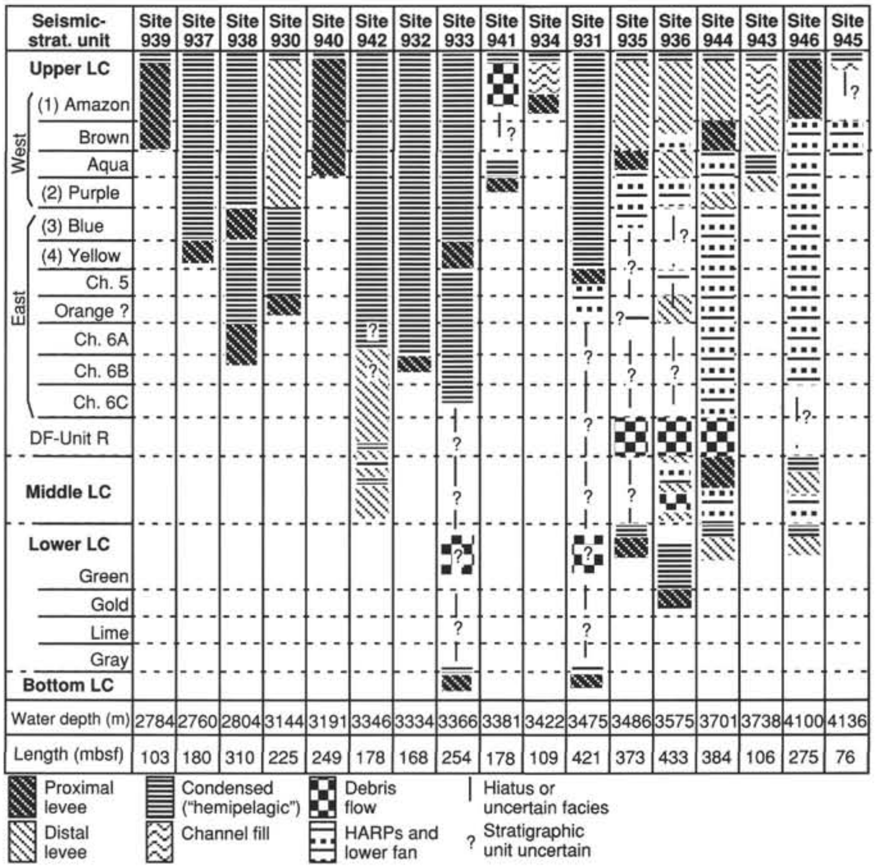

Figure 2. Summary of the relationship between facies drilled at each site and their acoustic stratigraphy.

assemblages different from those at Site 942. Our shipboard interpretation is that isotopic Stage 9 rests on the Lower Levee Complex, and isotopic Stage 11 on the Bottom Levee Complex. Isotopic Stage 5 appears to overlie the Middle Levee Complex, but in many areas it has been removed by the overlying Unit R Debris Flow. Isotopic Stage 7 may be present at Site 936 below the Middle Levee Complex.

Magnetostratigraphy

Paleomagnetic studies provided two unexpected techniques for dating and correlating sites: a widespread and distinctive paleomagnetic excursion that appears to be the Lake Mungo Excursion (ca. 30 ka) and oscillations in magnetic declination, inclination, and intensity interpreted as geomagnetic secular variation. These are reviewed in Cisowski (this volume).

Sedimentation Rates

Glacial-age sedimentation rates on the fan are measured in meters per thousand years and are quite variable between sedimentary environments. The levee crests of abandoned channels, which stand above all but the thickest turbidity currents, had "low" sedimentation rates of 1–3 m/k.y., and despite dilution by terrigenous sediment contain continuous foraminiferal records suitable for isotope stratigraphy. The levees built by active channels accumulated at rates of 10–25 m/k.y., and sandy lobes deposited downstream from channels at rates averaging 2 m/k.y. In contrast, calcareous clays deposited across the fan during sea-level highstands accumulated at rates of only 0.1 m/k.y.

FAN SEDIMENTATION PROCESSES

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. Studies of ancient fans often focus on regions with good outcrop exposure but little information about the morphological setting in which the sediments accumulated. Studies of modern marine fans have good morphological data but little information on the sediments deposited below the reach of standard piston cores (ca. 10 m). We are beginning to bridge this gap by characterizing the sediments in a range of settings on a large, muddy fan (see back-pocket foldout). Similar studies will be needed to characterize smaller, sand-rich fans.

The drilling results from Leg 155, integrated with previous seismic-reflection studies, show that the Amazon Fan has aggraded as a result of rapid deposition in channel-levee complexes that have prograded across medium- to coarse-grained sands deposited at the downstream ends of channels. Rare pebbles are found in sands at 3500-m water depth. Channel termination sands are thick bedded, and some occur in coarsening-upward sequences. We achieved high core recoveries when APC-coring coarse channel sands, which formed beds up to 18 m thick (see back-pocket foldout). The medium and coarse sand is concentrated within shoestring bodies (channels and channel termination zones) within the predominantly muddy middle fan. Some levees form fining-upward sequences of mud with beds of silt and fine sand.

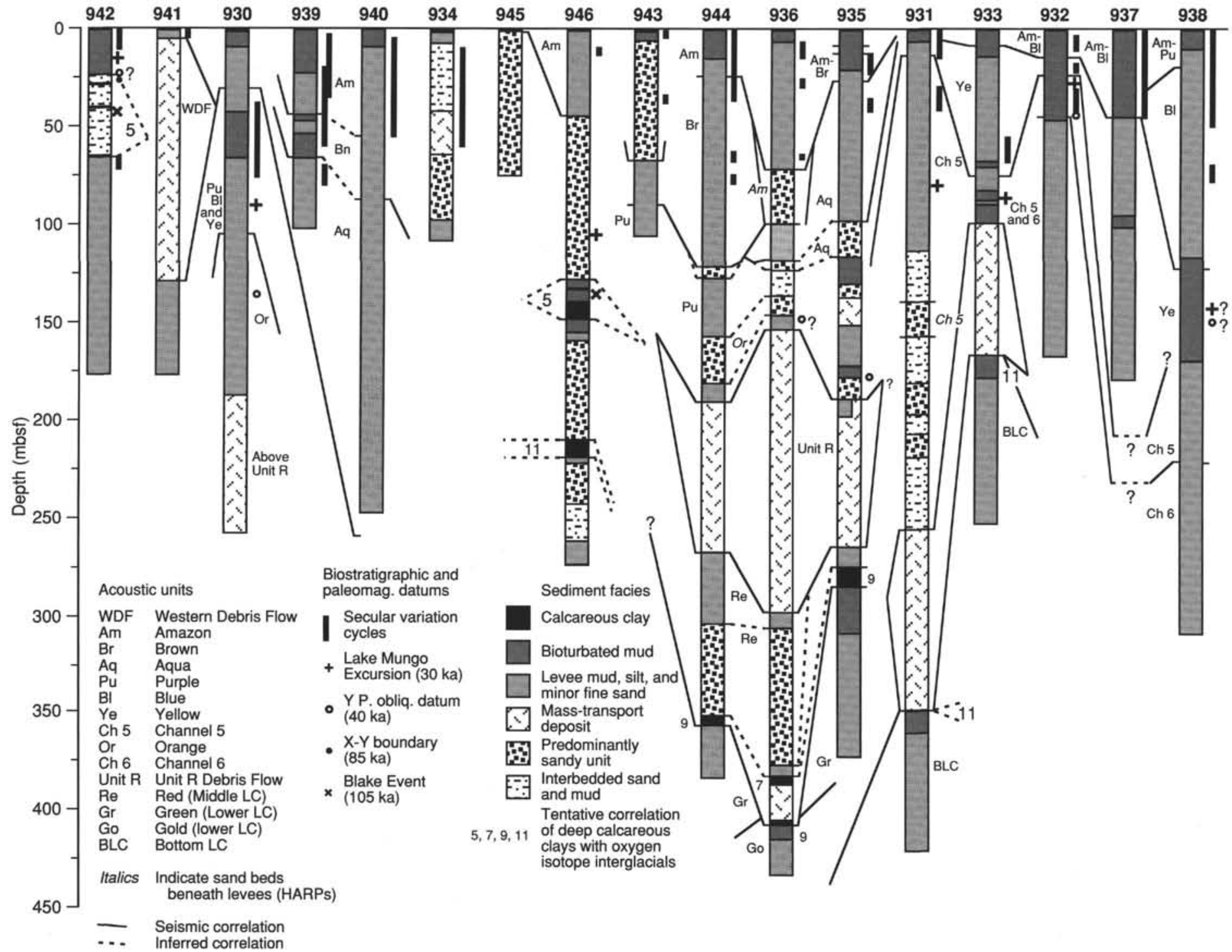

Figure 3. Preliminary correlation diagram of the Leg 155 sites, showing sediment facies from cores and logs, magnetostratigraphic and biostratigraphic datums, and seismic reflection correlation.

Our preliminary chronology shows that the major shifts in channel position by avulsion on the upper fan took place every 5 to 10 k.y. in the late Pleistocene. These avulsion events are expected to have a pronounced effect on sedimentation along the length of the channel (Pirmez and Flood, this volume). Many individual channel-levee systems show fluctuations in the abundance of overbank silt on a scale of 0.5 to 1.5 k.y., which suggests that controls in addition to sea-level change affect sediment supply to the deep sea. Shore-based isotopic chronology should allow us to correlate such changes across the fan and to relate them to sea-level and climate history. On a longer time scale, initial results suggest that each major levee complex of the Amazon Fan corresponds to a glacial stage (Fig. 1).

Debris-flow deposits more than 100 m thick occur near the present seafloor over more than half the middle fan, and others are intercalated with older levee deposits (Fig. 1). The lower parts of these debris-flow deposits appear to be large slide blocks, whereas the upper parts resemble muddy debris flows. No clear relation between debris-flow activity and sea level has yet emerged.

CLIMATE CHANGE AND OCEANIC CIRCULATION

Shipboard studies have shown that cores can be used to infer the climatic history of the Amazon Basin; however, care is being used, because deep-sea fans are mostly built of reworked sediment. Pollen is much more abundant at low sea-level stands than in Holocene and interglacial sediments. Cerrado (grassland) species are well represented in samples from the last glacial maximum. Although proportions of clay minerals are influenced by grain-size effects, kaolinite appears more abundant during inferred isotopic Stages 2 and 6 than at other times, possibly reflecting changes in weathering in the Amazon Basin. Shore-based studies of organic geochemistry, pollen, and mineralogy and geochemistry of terrigenous detritus should provide important information on the climatic history of the Amazon Basin and surrounding highlands.

The western equatorial Atlantic Ocean, above the Amazon Fan, is important in the Earth's heat budget, because the Northeast Brazil Current is the only major current to cross the equator. Shore-based isotopic and paleontological work will be necessary to interpret our high-resolution records of oceanic circulation, temperature, and productivity.

EARLY DIAGENESIS

The diagenetic environment on the Amazon Fan is unusual for its combination of high sedimentation rates (typically 3–8 m/k.y.), abundant supply of carbon of terrestrial origin, and iron-rich terrigenous detritus ($\approx$8 wt% Fe_2O_3). Sulfate reduction is complete by 10 mbsf, and almost uniformly high concentrations of methane are found below this level, with organic carbon decreasing from 1% in near-surface levee mud to 0.8% at sub-bottom depths of several hundred meters. Excessive gas expansion, honeycomb-like structures in mud, and wireline-log data all suggest that gas hydrates may occur locally. Pore-water phosphate peaks at about 6 mbsf, and iron at 14 mbsf. Iron appears to be precipitated first as sulfide and then at greater depth as vivianite (an iron phosphate), which forms small diagenetic nodules throughout the cores. Detailed understanding of the diagenesis of organic matter awaits shore-based study. There is considerable geographic variation in geothermal gradients (Fig. 4). This is in part due to the wide range in sediment types, and to the high and variable rates at which the fan has accumulated. Variation also may be a result of different temperature measurement depths at different sites.

MARGIN DRILLING—CHALLENGES AND OPPORTUNITIES

Leg 155 has shown that continental-margin sediments with a considerable proportion of sand can be successfully cored if holes are carefully chosen. Continental margins contain a high-resolution record of paleoclimatic events on both the adjacent continent and the overlying ocean. A well-designed drilling program can answer important questions about the processes by which continental-margin sediment bodies accumulate, and the nature of early diagenesis in a high-sedimentation-rate environment.

The tools needed for continental-margin drilling are different from those used successfully for the study of ocean history at bluewater sites. High sedimentation rates and 1% organic carbon lead to an abundance of biogenic methane that extends to sub-bottom depths of hundreds of meters. Expanding methane disturbs the physical properties of cores, so that detailed sedimentological descriptions, magnetic characteristics, well logs, and high-resolution seismic-reflection profiles are the best tools for correlating between holes. Detailed sedimentological features are largely revealed by ephemeral colors that disappear within a few hours as a result of oxidation. Sampling of sediment, pore fluids, and gases at in-situ pressures will be essential for understanding the record preserved in the depressured cores. Improved technology is also needed to ensure sand recovery, particularly in sediment in which the APC is inappropriate. The scientific problems addressed on this leg were not accessible by techniques other than by ocean drilling.

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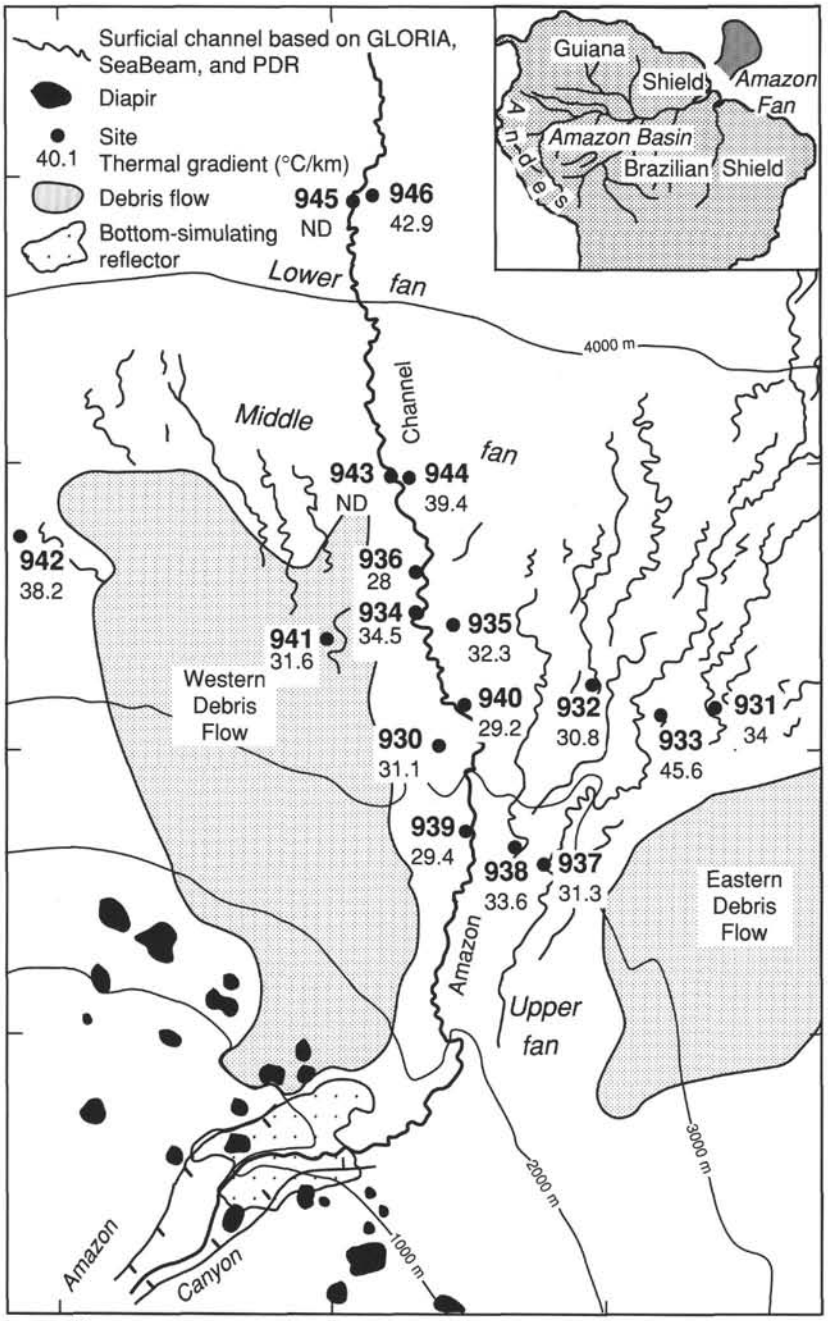

Figure 4. Summary of thermal gradient measurements during Leg 155. These are average thermal gradients measured in the upper 50–150 m. ND = not determined.