OCEAN DRILLING PROGRAM

LEG 155 SCIENTIFIC PROSPECTUS

AMAZON DEEP-SEA FAN

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This Scientific Prospectus is based on pre-cruise JOIDES panel discussions. The operational plans within reflect JOIDES Planning Committee and thematic panel priorities. During the course of the cruise, actual site operations may indicate to the Co-Chief Scientists and the Operations Superintendent that it would be scientifically or operationally advantageous to amend the plan detailed in this prospectus. It should be understood that any proposed changes to the plan presented here are contingent upon approval of the Director of the Ocean Drilling Program in consultation with the Planning Committee and the Pollution Prevention and Safety Panel.

ABSTRACT

Deep-sea fans represent an important part of the continental margin sedimentary record, and their deposits contain records of continental climate, ocean circulation, sea level and tectonic activity that can be interpreted in light of a detailed understanding of fan facies and growth pattern. Equatorial South America and the western Equatorial Atlantic Ocean are important areas for understanding past changes in land and ocean climate. The Amazon River and the Amazon Fan (the deep-water sediment deposit formed on the continental margin by the Amazon River since the mid Miocene) have played an important role in preserving these climate records especially during low sea-level stands when the Amazon River discharged its sediment load directly into the deep sea. ODP Leg 155 will sample the sediment facies of the Amazon Fan in order to study its sedimentary response to Pleistocene sea level variations, evolution of Equatorial South American climate, and changes in western Equatorial Atlantic Ocean circulation. The leg will also address general issues of the processes, character and architecture of turbidite deposition.

High-resolution seismic images of the Amazon Fan show that it has been built of a series of distinctive units that are typical of many mud-rich fans. These units include channel-levee systems of the upper and middle fan, reflective units of the lower fan, and large, transparent debris flows. These units stack and overlap to build the fan. Although the morphology of this and other muddy modern fans is often displayed on bathymetric and seismic profiles, the lithologies and ages of the sediments that make up these units, and the relationships between these units and sea-level change, are poorly defined. We will resolve these questions by sampling key acoustic units to determine their lithologies, facies and ages. Since fan sediments are river-derived, analysis of the sediments deposited in the channel levees (e.g., pollen, clay and sand mineralogy, bulk geochemistry, organic matter) should reveal a high-resolution record of equatorial land climate during several glacial-interglacial cycles. Such records are difficult to obtain from continental sites. In addition, the Amazon Fan underlies the western Equatorial Atlantic, and high-quality planktonic records can be obtained from fan sediments when proper care is given to hole placement. Cores recovered from the elevated crests of abandoned levees, especially where shielded from the active levee system, contain high sedimentation-rate records apparently free from the influence of downslope flows. The spatial distribution of $\delta^{18}O$ events provides a record of the interaction of surface circulation and river discharge on a time scale of several thousand years. The integrated analysis of fan architecture and growth pattern, land climate as recorded in fan sediments, and paleocirculation

patterns in the western Equatorial Atlantic will allow us to understand more fully the response of this important equatorial region to glacial-interglacial and other cycles. Secondary objectives of ODP Leg 155 include studies of the degradation of organic matter in sediments, influences of Andean tectonics on fan sedimentation, and more localized fan-tectonic interactions such as the sedimentological effects of continental margin flexure due to the mass of the fan itself.

INTRODUCTION

The Amazon Fan (Figs. 1 and 2) is one of the largest modern submarine fans (or, more generally, turbidite systems) and forms a significant portion of the continental margin off northeastern Brazil. The fan contains much of the material eroded from the continent within the Amazon drainage basin. Large mud-rich fans, such as the Amazon, Mississippi, Indus and Bengal fans, are formed by the long-term localized input of riverine sediments moderated by glacio-eustatic sea-level fluctuations, climate change, and tectonic activity. These large fans are also significant crustal loads and can create bulges at or near the coastline, which, in turn, affect sedimentation patterns. A knowledge of the morphology, structure, and sedimentation of large, muddy fans such as the Amazon Fan is important for understanding processes that control fan growth (including sea level), and also for revealing the record of climate change on land and ocean circulation. Because normal piston cores sample only the upper 10 m of these several-kilometer-thick deposits, an understanding of the sedimentary facies associated with the observed seismic and morphological units, and the age relationships of these units and the climatic record preserved in their sediments, remains poor. Deep, continuous sampling is required to make significant progress toward understanding fan growth and to obtain important and unique climatological records from fan sediments.

The Amazon Fan is a good choice for drilling large, muddy fans at this time, because only the Amazon Fan possesses all four of the following critical characteristics. It is one of the most extensively surveyed, and thus best imaged, of any of the large deep-sea fans, including high-resolution seismic data, swath-mapping bathymetry (SeaBeam) and sidescan sonar (GLORIA). It contains a large number of spatially dispersed, discrete channel-levee sequences at or just beneath the present fan surface and thus is readily accessible with relatively shallow drilling. It is the only well-studied major fan that provides an opportunity to investigate equatorial land climatic changes. It underlies a key area for understanding Equatorial circulation changes during glacial and interglacial periods and during climate transitions. In addition, drilling on the Amazon Fan also complements ongoing studies on Holocene sedimentary patterns on the Amazon Shelf being undertaken by C. Nittrouer (MSRC, SUNY-Stony Brook) and A. Figueiredo (UFF, Niteroi) as part of the NSF-supported AmasSEDS project (Nittrouer et al., 1991a, b). These factors make the Amazon depositional system among the best understood systems in the world and give us unparalleled insights into the overall dynamics of this system.

Our drilling will pursue three major themes: fan processes, facies and growth pattern; the equatorial South Atlantic continental climatic record; and equatorial oceanic dynamics and paleocirculation patterns. Additional themes include the diagenesis of organic carbon, the effect of Andean tectonics on the fan record, and the effects of fan loading on sedimentation patterns.

Deep-Sea Fan Growth Models and Depositional 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 data from hydrocarbon basins. Drilling of a modern deep-sea fan provides an opportunity to integrate these historically divergent approaches.

a) Much of the focus of work in hydrocarbon basins has involved application of the Vail sea level models. Key questions include: What is the relationship of fan architecture to sea level change (Posamentier et al. 1988; Mutti, 1992); can sequence boundaries be recognized on submarine fans, and what is their relationship to channel-levee complexes (cf. Weimer, 1989); are "lowstand lobes" and mid to upper fan deposits synchronous or sequential?

b) 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 hitherto been limited only to the latter part of a glacial cycle. 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 will also provide samples to interpret the initiation and mechanics of debris flows.

c) Flysch sections on land provide information on the lithology and sequence of lithofacies, but commonly lack independent evidence of depositional environment (Mutti, 1992). Drilling will provide "ground-truth" for lithofacies and cycles recognized in ancient rocks; the proposed holes will allow correlation of lithofacies with sea level change and turbidite processes.

Deciphering the Equatorial South Atlantic Continental Climatic Record

Studies of land fauna and Pleistocene geology within the Amazon drainage basin indicate that the climate during glacial cycles may have been vastly different from that of today: during glacials, the vast tropical rain forests shrank and all but disappeared, and semiarid savannahs prevailed (Fig. 3; see Damuth and Fairbridge, 1970). However, the continental record of these changes remains incomplete and poorly known or dated. In particular, the paleotemperature record derived from continents and oceans for the last glacial maximum (LGM) at 18 ka is inconsistent. On the continents, there are records of large temperature decreases; yet there was very little sea surface temperature change at low latitudes, but the reasons for this difference are unknown (Rind and Peteet, 1985). Recent evidence from one locality (paleotemperatures derived from measurements of atmospheric noble gases dissolved in groundwater of a Texas aquifer; Stute et al., 1992) supports the existing continental data. The question of glacial-interglacial temperature difference is a fundamental question of importance for understanding future climate change. Whether or not the ocean was 2°C colder than today at low latitudes has major implications for the hydrological cycle (which in turn controls deep water circulation) and for the temperature gradient from high to low latitudes.

Very little proxy-climate continental data are derived from the Amazon region. Thus, obtaining a record of glacial-interglacial change from pollen and other indicators in the Amazon Fan should be very important, as it will reflect changes in the Amazon drainage basin. Studies of Amazon Fan sediments to date show an interesting although limited record of land climate and its past fluctuations. Damuth and Fairbridge (1970) reported that arkosic sand grains were deposited throughout the Guyana Basin during the last glacial, suggesting an arid Amazon Basin during glacials. However, preliminary studies by R. Kowsmann (personal communication, PETROBRAS, 1987) suggest that not all Amazon sands are arkosic, and thus changes in sand composition may reflect temporal patterns of arid vs. humid climate within the source area. Also, Kronberg et al. (1986) and Nesbitt et al. (1990) note that the uppermost Pleistocene sediments

(~11 to 9.5 ka) have bulk chemical compositions and rare-earth-element enrichment patterns slightly less pronounced than those observed on the Amazon Shelf or River today. These compositional trends reflect severe weathering within the source area, and possibly temporal changes in weathering pattern.

Coring through a sequence of successively older levee deposits will allow us to obtain a nearly continuous, high-resolution section of fine-grained sediments for analysis of temporal changes in pollen, sediment mineralogy, sediment geochemistry and organic carbon. From these records we should be able to construct an important record of land climate extending from at least the last interglacial period (and perhaps back as far as Pliocene times) through the last glacial period to the present Holocene interglacial.

Understanding Equatorial Oceanic Dynamics and Paleocirculation Patterns

In addition to containing an important record of land climate during glacial/interglacial climatic stages and transitions, the Amazon Fan also underlies the western tropical Atlantic water masses (Fig. 4). These water masses and their circulation are particularly important in terms of ocean dynamics and inter-ocean heat transfer. Oceanic currents in this area include the westward-flowing South Equatorial Current (SEC), the northwestward flowing North Brazil Coastal Current (NBCC; Metcalf and Stalcup, 1967; Richardson and Walsh, 1986), and the eastward-flowing North Equatorial Countercurrent (NECC; Fig. 4). The NBCC is the only known cross-equatorial heat transport in the global circulation pattern, and thus is an important link in the present-day climatic regime. 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 back) into the NECC between July and November. Lenses of low-salinity surface water 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 will discharge directly into relatively deep water, and mixing of the river plume into the coastal water may occur more slowly than at present, allowing more extensive freshwater lenses to form.

Planktonic foraminifers are found in sediments of the Amazon Fan, despite the relatively high accumulation rates, especially on the tops of abandoned levees. These high accumulation rates expand the planktonic record making high-resolution time-series studies possible, and small-volume analytical techniques (Showers and Palczuk, personal communication, 1993) have allowed isotopic stratigraphies from these rapidly deposited hemipelagic sediments (confirmed by AMS ^{14}C dates on small quantities of foraminifers) to be constructed for the first time.

Showers and Bevis (1988) and Showers et al. (in press) note that $\delta^{18}O$ stratigraphies show a number of well-developed negative $\delta^{18}O$ deviations during the late glacial/early interglacial that appear to be correlated and are tentatively interpreted as Amazon River paleodischarge events. The apparent occurrence of paleodischarge events ($\delta^{18}O$ spikes) on the eastern portion of the fan but not on the western portion (which lies north of the Amazon River mouth) during certain time intervals suggests that the spikes may 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. Precise dating of these isotopic events and their distribution patterns will allow us to better assess the relationships between these spikes and other events in global circulation. We may thus be able to determine if any leads or lags can be identified, and the likely role of the Equatorial Atlantic in global circulation.

STUDY AREA

Analysis of high-resolution seismic reflection profiles (single-channel and 3.5-kHz); swath-mapping data (GLORIA sidescan sonar, SeaBeam bathymetry), and piston cores from the Amazon Fan have helped to reveal the structure of this complex sediment deposit, and have provided insights as to the kind of sampling strategies that are needed to understand continental margin sedimentation at lateral and temporal scales that are often difficult to approach. These studies suggest that fan growth is in part related to external controls such as sea level fluctuations and in part related to events such as channel avulsions and mass-transport activity that are internal to the fan. Although high-resolution seismic profiles have revealed many aspects of fan architecture, little information is available on the actual sediments that make up the observed acoustic depositional units or on the relative or absolute ages of those units. We propose to drill a series of generally shallow-penetration holes on the Amazon Fan (Fig. 5). These holes will provide critical information on sedimentary facies within different acoustic units, characterize temporal and spatial variations in the mineralogy, palynology and organic matter (and its early diagenesis), determine the ages and deposition rates of critical fan units, and reveal the evolution of fan architecture and its relationships to sea level, climatic, and tectonic events (Andean uplift as well as more localized margin flexure) in the late Pleistocene and perhaps back into the mid-Pliocene.

Fan Morphology and Growth Patterns

The Amazon River has been the major source of terrigenous sediments to the Equatorial Atlantic since Andean uplift in the early Miocene (Castro et al., 1978), and the development of the Amazon Fan was apparently initiated by that event. During the present sea-level high, sediments discharged by the Amazon River (derived in part from the Andes and in part from weathering within the Amazon Basin) are of mixed size grades (silt and clay dominate; Gibbs, 1967), contain organics derived both from within the drainage basin and from upland sources (Hedges et al., 1986; Ertel et al., 1986), and deposit on the shelf in a large subaqueous delta (Kuehl et al., 1982; Nittrouer et al., 1983, 1986). The high-sea-level stand prevents sediment from crossing the shelf; thus the fan has been inactive during the Holocene (Damuth and Fairbridge, 1970; Damuth and Kumar, 1975). Characteristics of the river load are poorly known for previous glacial sea-level lows when the Amazon River crossed the emerged shelf and discharged directly into deep water and onto the fan (Damuth and Fairbridge, 1970; Damuth and Kumar, 1975; Milliman et al., 1975). The few studies of the bulk chemistry of the uppermost Pleistocene fan sediments (ca. 11 ka) suggest that weathering patterns in the source area at that time were broadly similar to those observed today (Kronberg et al., 1986; Nesbitt et al., 1990).

The Amazon Fan (Fig. 1) extends seaward 700 km from the Amazon submarine canyon to abyssal depths and contains sedimentary/acoustic sequences that appear to be characteristic of many large and small modern elongate or mud-rich fan systems (Stow et al., 1985). These characteristics include large, leveed sinuous channels on the upper and middle fan that become smaller and evolve into unleveed channels on the highly reflective lower fan (Fig. 6; Damuth and Kumar, 1975; Damuth and Embley, 1981; Damuth et al., 1983a, b, 1988; Damuth and Flood, 1983/1984, 1985). The unchannelized Demerara Abyssal Plain extends seaward from the base of the fan below a depth of 4800 m. The late glacial sediments of the upper and middle fan are in general muds with scattered thin sand/silt layers, whereas those sediments of the lower fan contain abundant, thicker sandy turbidites (Damuth and Kumar, 1975; Coumes and Le Fournier, 1979; Moyes et al., 1978). The Amazon Fan has been the subject of several studies undertaken by scientists of Lamont-Doherty Earth Observatory (LDEO) (Manley, 1989; C. Pirmez, personal communication, 1993), sedimentological and especially sediment geochemistry studies undertaken by French scientists (expedition ORGON II summarized in Coumbaz and Pelet, 1978), and more recent paleontological studies undertaken by W.J. Showers on LDEO core material in conjunction with a 1991 Meteor cruise (Showers et al., in press). Some of the existing PETROBRAS seismic data for the shelf and upper fan were summarized by Bruno (1987).

Detailed mapping of the fan from high-resolution seismic records (digitally recorded using air and water gun sources), supplemented with swath-mapping data (GLORIA sidescan sonar and SeaBeam bathymetry), has revealed a complex pattern of submarine channels and large debris flows (Damuth et al., 1983a, b; Damuth and Flood, 1983/1984, 1985; Flood and Damuth, 1987; Damuth et al., 1988; Manley and Flood, 1988; Flood et al., 1991). Channels are common from the base of the submarine canyon to about 4000 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 continuing interaction between turbidity current flow and sediment deposition. Although numerous channel segments are recognized on the fan, only one channel is now connected to the Amazon Submarine Canyon (termed Channel 1 or Amazon Channel); all other channels have been disconnected from their upstream source. Amazon Channel is the most recently active channel, and it has been studied in detail from the canyon to 4273 m water depth on the lower fan, where it is too small to be resolved on SeaBeam bathymetry (i.e., <200 m wide).

The sinuous fan channels, including Amazon Channel, are perched on top of lens-shaped, aggradational overbank deposits to form channel-levee systems in the upper and middle fan (Fig. 6a, 6b). On both the upper and middle fan, channel axes are marked by zones of near-vertical, high-amplitude reflections (HAR). Drilling of the youngest channel floor on the Mississippi Fan has demonstrated that these high-amplitude reflections are associated with sands and gravels in the channel axis (Stelting et al., 1985b). The HAR pattern commonly appears to extend deep within the channel-levee system, and its presence and distribution within the levee have been used to map the evolution and meandering of the channel-levee system (e.g., Stelting et al., 1985a; Kastens and Shor, 1986). However, seismic modeling studies suggest that the precise pattern of HAR's within the levees may result, in part, from the plan 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).

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, strong, parallel seismic reflections. As the lower fan is reached, levee deposits and debris flows pinch out to give rise to a sequence of highly reflective, nearly parallel horizons that extend at least to the lower fan (Fig. 6c). Channels on the lower fan are generally less than 20 m deep and have small, reflective levees.

The large number of abandoned channel segments on the fan appear to have been created through the process of avulsion (Damuth et al., 1983b). Avulsion occurs when turbidity currents breach an existing channel wall, and subsequent downslope flows abandon the track of the old channel downstream of the gap to create a new channel segment. With time, overbank deposits from the newly created channel fill the adjacent older channel near the point of avulsion, but the topographic expression of the older channel remains. Because avulsion has occurred many times on the fan, numerous local topographic irregularities are associated with abandoned channel sections at mid-depths on the fan (Fig. 2). Also, the levee deposits of older, abandoned channels can be identified on seismic lines (Fig. 7), and the pattern of these old levees can be determined laterally (Fig. 8) and with depth (Fig. 9). Buried channels appear to exhibit the same meandering patterns (HAR's are present), avulsion patterns, and slopes as the surficial channels.

The abandoned channels that are followed on the fan surface and in subsurface have been assigned numbers (Damuth et al., 1983b) and color names (Manley and Flood, 1988; Figs. 8 and 9). The uppermost seven channels (the surficial channel and six abandoned ones) are, in order of increasing age, Channel 1 (or Amazon Channel), Brown, Aqua, Purple, Blue, Yellow, and Orange. An apparent debris flow, Unit R, underlies these channels, and thus the uppermost seven channels are termed the Upper Levee Complex. Unit R overlies the Red Channel, and in some areas the Red Channel is isolated from the Green Channel by another apparent debris flow. The more deeply buried channels, Green, Gold, Lime, Grey, and Pink, form the Lower Levee

Complex. The Red Channel forms part of the Middle Levee Complex (Figs. 8 and 9). Other channels and possible debris flows are observed deeper in the record, but these have not been mapped in detail.

Topographic analysis of the fan suggests that the sinuous channels appear to approach a graded profile similar to that in a mature river system, because channel sinuosity varies down-fan, apparently to keep the along-channel gradient uniformly decreasing down-fan (Flood and Damuth, 1987). Graded profiles exist on the fan apparently because of the passive margin setting and the large sediment influx. If the channels are at grade, localized changes in channel morphology, such as those caused by an avulsion, will cause the channel to erode rapidly upstream of the avulsion and to aggrade rapidly downstream of the avulsion (Flood et al., 1991; C. Pirmez, personal communication, 1993). Such rapid deposition may create the flat-lying, high-amplitude, lobe-like reflection packets (HARP's) that underlie a channel-levee system in the middle fan (Fig. 7) and that extend down-fan to form part of the lower fan. This interpretation suggests that parts of the seismically identified lower fan are formed concurrently with channel-levee systems. Also, coarse sediments may be transported through the long, leveed channels by repeated cycles of avulsion and downcutting, thus providing a mechanism for transporting coarse material to the deeper, sandy parts of the fan.

Analysis of closely spaced water gun profiles in the vicinity of Amazon Channel show that individual lens-shaped channel-levee systems overlap and coalesce to build levee complexes that also stack and overlap, but that are bounded by large debris-flow deposits (Figs. 6 and 7). The alternation of acoustic facies appears to form a cyclic pattern, but because both channel-levee systems and debris flows can be active at the same time (for example, one of the major near-surface debris flows can be traced upslope to a diapir field), this cyclicity may not necessarily develop as a result of external controls such as sea-level change.

Several approaches have been undertaken to estimate the age of distinctive seismic facies observed on the Amazon Fan to determine the possible relationships between fan activity and sea-level fluctuations. These estimates provide a wide range of possible ages, each having important implications for sea-level control on fan development. Damuth et al. (1983b) estimated, based on sedimentation rates thought typical of surficial Amazon Fan sediments, that the 6 to 10 major levees exposed on the fan surface could all have been deposited within the last 2 to 8 m.y. or about

200,000 yr to perhaps 1.3 m.y. per levee. C. Pirmez (personal communication, 1993) has extrapolated sedimentation rates observed in channel-axis piston cores on Amazon Channel to the base of that channel-levee system and estimates that only the channel-levee systems closely associated with Amazon Channel were deposited during the last glacial lowstand, suggesting that each major levee results from a single lowstand. Manley and Flood (1988) note that nearly all of the exposed channel-levee systems can be traced to the present-day Amazon Canyon, while a more deeply buried channel-levee system seems to be related to a buried canyon system. Thus, all of the exposed levees (actually, the Upper Levee Complex) may have been deposited during the last glacial period. Such a high fan growth rate may require that nearly all of the sediments discharged by the Amazon River during the lowstand be deposited on the fan. Only through deep sampling will we know the precise relationship between fan growth and sea level fluctuations.

Piston-core transects guided by SeaBeam bathymetric data were collected across channel and levee deposits at several depths down-fan. Dating of middle-fan turbidites associated with the most recently active Amazon Channel yielded a maximum age of about 13,000 yr (^{14}C dating of coarse organic debris; Flood et al., 1991), suggesting that active levee building continued into the post-glacial sea level rise of the early Holocene. Analysis of cores from along Amazon Channel suggests that the locus of deposition migrated landward during the early interglacial period. At about 9.5 ka, sea level became high enough to prohibit significant river-derived sediment from reaching the fan.

Many of the cores collected from the Amazon Fan contain relatively high organic carbon levels, as is typical for muddy fan sediments. Early sediment diagenesis occurs on the fan, as gas in 10-m piston cores occasionally caused 10-cm gas cracks to develop after the cores were retrieved. This was especially true for cores collected near a recent bifurcation point along Amazon Channel at about 3600 m water depth. Perhaps sediments accumulate rapidly immediately following channel avulsion, allowing organic matter to become incorporated into fan sediments. At least one authigenic carbonate nodule has been recovered from Amazon Fan with a $\delta^{13}C$ value of -52 $^0/_{00}$, consistent with a biogenic methane source (W.J. Showers, personal communication, 1993). R. Kowsmann (PETROBRAS, personal communication, 1991) notes that carbonates on the top of an exposed diapir at about 1500 m water depth have a $\delta^{13}C$ value of -54.6 $^0/_{00}$, also suggesting a potential biogenic source for methane. At high concentrations, methane will form gas hydrates in sediments and shallow sediments on the Amazon Fan are within the hydrate stability field.

The nature of organics and their early diagenesis in different fan environments needs to be studied to understand their sources, the role of fan processes in preserving organic matter, and the paleoclimatic history of the organic material itself. Iron diagenesis also occurs in these sediments, and there appear to be down-core changes in iron chemistry, perhaps related to organic matter diagenesis. A detailed understanding of early diagenesis will require information on the temperature and the compaction/permeability regimes.

These existing bathymetric, seismic, and limited core data provide a partial picture of the distributary channel system and of the fan-growth pattern. A more realistic and detailed understanding of the vertical succession of sediment facies, sediment composition, and relative and absolute ages, and thus a fuller understanding of actual fan growth patterns and processes and their relationships to sea-level fluctuations, will require direct sampling of sediment sequences.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

1. Establishment of the relationship, if any, between the development of fan deposits, sea-level fluctuations, climatic change and uplift of the Andes.

    This will require establishing an absolute chronostratigraphic framework. Rates of accumulation of the fan itself and of discrete fan facies, together with changes in the geochemical character of detritus, will be required to determine fluctuations in rates of continental denudation.

2. Determination of the sediment lithologies characteristic of distinctive acoustic facies and an understanding of the evolution of turbidite facies in relation to fan morphology and flow processes.

    The Amazon Fan provides the first opportunity to characterize facies in a large, mud-rich fan system with excellent seismic control. Issues such as the development of cyclicity in bed thickness, the processes of meander deposition, down-channel evolution of turbidity flows and the dynamics of debris flows will be addressed. The synthesis of the sedimentological, seismic stratigraphic and chronologic data should allow new understanding of the growth processes of a large mud-rich fan and their relationship to allocyclic controls such as sea-level change and climate/discharge variations.

3. Use of the stratigraphic record of the Amazon Fan to better understand climatic change within the Amazon drainage basin, the nature and timing of surface circulation patterns in the western Equatorial Atlantic, and Amazon Basin changes over glacial/interglacial cycles and integration of these into worldwide climatic signals.

   Paleoclimate records will come from climatic indicators preserved in fan sediments. Indicators of continental climate include pollen and spores, chemical weathering patterns of terrigenous mineral grains, and the character of organic carbon. Indicators of oceanic circulation and ocean climate will come from faunal and isotopic analysis of marine organisms incorporated in the sediments. Continental indicators should be best preserved in levee sediments, whereas oceanic indicators should be best preserved on the crests of abandoned levees. Seismic correlation of drill sites will be used to combine these records into an overall paleoclimate framework.

4. Characterization and an understanding of the nature, origin and early diagenesis of organic carbon present in the different fan units.

   Submarine fans can be large reservoirs of organic carbon as a result of high accumulation rates and the close association with land and coastal carbon sources. We need to better understand the sources of that carbon, especially the distinction between modern material and material recycled from the continent, and the maturation, migration and degradation of the organic carbon. Most of the interval to be sampled lies within the zone of methane hydrate stability, and we will use the pressure core sampler to sample these units when found.

DRILLING PLAN/STRATEGY

The drilling strategy requires somewhat different sites to meet the four major objectives. Many of the sites chosen meet more than one of these objectives.

Objective 1 requires adequately sampling the fan to obtain a chronology for the units recognized on seismic profiles, especially for the last major cycle of fan deposition but also for earlier cycles.

Objective 2 requires detailed sampling of representative fan units in both "proximal" and "distal" settings where they are well characterized on seismic records. The objective of understanding turbidite depositional processes and characterizing turbidite facies will require some concentrated sampling in a small number of representative depositional units. In some cases this concentrated sampling may exceed routine sample limits. Whole round samples for geotechnical and other analyses will be needed in some cases in the first or second holes to meet parts of this objective (e.g., dynamics of debris flows).

Objective 3 requires continuous stratigraphic records in many locations to remove the effects of local sedimentary processes in the fan system and would benefit from expanded sections due to high sedimentation rates. Records from different stratigraphic levels will be combined based on seismic correlation. Since accumulation rates in the fan are very high (>1 km/Ma), microfossils are sparse in some lithologies, and many holes may not even penetrate to the last interglacial (stage 5e), our paleontological strategy may include examining fewer core catcher samples and instead concentrating on analysis of critical hemipelagic horizons.

Objective 4 can use sites planned for other purposes, but a second hole may be drilled to provide sufficient samples. Whole round frozen samples for chemical analysis will be needed in some instances in the first or second holes to meet this objective. The pressure core barrel will be used to sample in situ gas/hydrates in a small number of selected cores.

The principal objective for logging is to characterize turbidite sediments, particularly in areas of limited recovery (sands), using the Quad-combo and FMS logs. The potential value of the Geochemical logs in identifying diagenetic features will be evaluated in early holes, as will the applicability of the GHMT log for magnetic susceptibility as a proxy for sediment type and for core-log integration.

Heat flow gradients will be determined from sparse ADARA measurements in spatially distributed holes in order to assess regional hydrate stability fields and diagenetic conditions. In addition, we will look for temperature anomalies in permeable zones as an indicator of fluid flow.

We plan to drill on the eastern levee complex early in the leg in a region where piston cores with good stratigraphic records have been recovered and where an old levee is present near the fan surface. This will permit us to confirm the potential for dating in several fan environments as well as the range of ages to be recovered. Drilling near the recently active channel will occur later in the leg. We expect that biogenic gas will be more common closer to the more recently active channel. As we progress to more difficult drilling environments (e.g., more sand and/or more gas), we will have our earlier drilling experiences to guide us.

Shipboard chronology will be based on the recognition of climatic stage 5e (Ericson W zone) both lithologically and from its biogenic assemblages, particularly the abundance of *G. menardii. P. obliquiloculata* disappears at about 40 ka and may provide a useful horizon. If longer holes penetrate to stage 12 or older, the standard nannofossil zonation can be used. We do not know if we will reach the base of the Brunhes magnetochron in any of the proposed holes. Post-cruise chronology will be based on development of a composite stratigraphic section using the seismic correlations. It is anticipated that glacial-interglacial fluctuations in biogenic (including pollen) assemblages will be correlated with standard climatic records, and that some portions of the isotopic records from the fan will correlate with standard isotopic records. In addition, AMS radiocarbon dates on foraminifers and large seeds can be used for the past 40 - 50 ka. Uranium series dating and thermoluminescence dating may be used to resolve uncertainties in the identification of interglacial stages.

PROPOSED SITES

Channel-levee sequences are one of the basic sedimentary units of large, muddy fans. In particular, the middle fan is built by a large number of these sequences deposited one on top of another, with intercalated large-scale debris flows (Figs. 6-8). A series of APC/XCB sites will penetrate a number of these stacked middle-fan levee sequences, providing a complete stratigraphic sequence for the last major cycle of fan deposition (the Upper Levee Complex of Manley and Flood, 1988; Fig. 10), which may span one or more glacial sea-level lowerings. These APC/XCB sites will be located on the levees of well-imaged channel-levee systems whose relative ages can be deduced from seismic profiles (Damuth et al., 1983b; Manley and Flood, 1988). The record will be considerably expanded (probably with a better pollen and mineralogy record) where the levees are near active channels, and somewhat compressed (probably with a better planktonic stratigraphy) where the thinner parts of active levees are sampled, especially on the tops of abandoned levees. To obtain a complete stratigraphy from both proximal and distal levee environments, sections from more than one channel-levee system will have to be combined. Sites will also be positioned along levee systems in order to determine variations in sedimentation and timing of deposition down-fan. Sampling sites will also include abandoned channel-floor deposits and the reflective, flat-lying HARP units that underlie channel-levee systems in order to characterize the turbidite facies and sequences within these units and their relationships with other acoustic units. Some holes will be deep enough to reach Unit R (the debris-flow deposit) that underlies the Upper Levee Complex and to reach channel-levee systems preserved in the buried Middle and Lower Levee complexes. These deeper holes are necessary to determine the upper age limit of these older levee complexes, to determine the sedimentological nature of the transparent and highly reflective acoustic zones between levee complexes, and to help understand longer-term fluctuations in fan growth that may be related to external influences such as Andean uplift.

Twenty-two sites (17 priority 1, 5 priority 2 and 3) have been identified on Amazon Fan (Fig. 1; Tables 1 and 2). Several of the priority 1 holes have deeper extensions rated as priority 2. Seven holes will penetrate to depths of 100-179 mbsf, seven holes to 226-301 mbsf and three holes to 369 to 417 mbsf. The uppermost parts of many holes will be double APC-cored to ensure recovery of a complete section. While most of the holes will be in relatively fine-grained sediments, some holes will encounter unconsolidated sands. We anticipate logging all holes greater than about 250 m, although selected logs may be run in some shallower holes. We also plan to use the Pressure Core Sampler (PCS) in several holes where gassy (hydrated?) sediments are encountered. Time-to-depth conversions are based on velocities from sonobuoy measurements for the entire fan (Fig. 11); there may be significant deviations from this profile, depending on the nature of the sediments at any site. Correlations between cored sections and the seismic profiles will need to be made rapidly to ensure that the target intervals on the seismic records are being sampled. Selected holes will be logged to improve correlation with seismic records and to better characterize the sediments.

Sites AF-1, AF-2, AF-3, and AF-14 are located on the middle fan and will sample the oldest fan sediments on the leg. Site AF-1 (Priority 2) will penetrate through a sequence of relatively distal levees at a depth where carbonates are expected to be preserved, through a debris-flow deposit, to the Lower Levee Complex. Specific objectives for site AF-2 are the proximal levee of Amazon Channel, the high-amplitude reflectors (HARP's) that underlie this channel-levee system, the debris-flow unit (Unit R), the Red system, and the Gold system (separated from the Red system elsewhere on the fan by a debris-flow unit). Site AF-2 is offset laterally from site AF-1 to sample the Gold system near the top of the levee, where we expect to recover a relatively long hemipelagic sequence, but site AF-1 will penetrate to older sediments. Site AF-3 is offset 50 km downslope and will also sample the top of the levee where the debris-flow unit (Unit R) is beginning to thin. Site AF-14 will sample a similar sequence, although farther upslope on the fan. All these holes will penetrate and sample the distinctive reflective layers that may be sheet sands associated with channel avulsion, to show us the character of the sediments that make up these layers and their likely depositional processes. The up-fan limit of the Brown system (sampled at site AF-13 less than 2 miles from site AF-3) is located between sites AF-1/AF-2 and AF-3, so that we can identify how the levee system upslope of the avulsion responded to the Brown avulsion event. Site AF-22 is located at the down-fan end of the leveed channel at the transition from the middle to the lower fan. This hole will sample the sequence of sediments deposited on the lower fan, which may in part be related to the growth and evolution of leveed channels on the middle fan. Proposed sites AF-4 and AF-5 are located toward the western part of the fan, where much of the morphology is covered by one or more large surficial debris flows. Site AF-4 will sample the proximal parts of the Purple system and the transition to the present Amazon Channel. Site AF-5 will sample the western debris flow to determine the number of flows represented and the source of the material, and also will sample an undated but relatively shallow channel-levee system (2B).

Site AF-6 is located on the levee of Amazon Channel near the location where the channel diverged from the path of the Aqua system. The levee at this site shows several distinctive layers that will be sampled. These may have been formed as part of the response of the channel-levee system to changes in base level due to avulsions. Alternatively, they may represent pelagic intervals deposited during sea-level highstands. Sites AF-12 and AF-15 are to be primarily shallow holes that complement site AF-6 and will sample sediments closely associated with the levee of Amazon Channel and the systems that immediately predate it. Site AF-12 will penetrate through relatively acoustically transparent sediments near the upper fan channel into more uniformly layered sediments below. The recent change in seismic character from acoustically laminated to transparent may signify a change in the kinds of flows that pass through the system and may be related to sea level rise. This site will determine the timing of this change (possibly from ^{14}C dating) and the sediment lithologies and facies. Site AF-15 will penetrate the fill of an abandoned channel meander still attached to Amazon Channel to determine the sedimentary facies in this environment and possibly to estimate the age at which the channel fill started. The meander may have been abandoned as a result of avulsion and downcutting associated with the abandonment of the Brown system. Sites AF-6, AF-12, and AF-15 are in areas of recent rapid deposition, and are aimed at studying early sediment and organic matter diagenesis.

Sites AF-7, AF-8, AF-9, AF-10, AF-11, AF-19, and AF-21 will sample proximal (upper middle fan) levee sediments (along with overlying hemipelagic sections) for the older channel-levee systems within the Upper Levee Complex. Site AF-7 (Priority 2), located on the eastern part of the fan, will penetrate the proximal levee sediments of the Blue, Yellow and possibly 6C systems at a relatively shallow depth (2845 m). Site AF-8 (Priority 2) will sample the proximal levees of the Blue system and system 6C, but at a deeper water depth (3495 m). Site AF-9 will sample the proximal sediments of the Yellow system, distal levee sediments of 6A, an apparent debris flow, and the top of a very large, unnamed levee that may be quite old. This unnamed levee may mark a time of pronounced sediment input, perhaps related to increased Andean uplift. Site AF-10 will sample the proximal levees of system 5 on the far eastern part of the fan, penetrating through this system and a possible debris flow to the underlying levee sediments. Site AF-11 will sample the pelagic sediments overlying 6A and levee sediments of 6A. Site AF-11 also has a lower priority deeper extension, should datable sediments be recovered in the shallower parts of AF-11. Site AF-19 (Priority 2) is close to sites AF-8 and AF-11, and should give a similar record to site AF-11, but should sample a different deep levee. Site AF-21 will sample sediments overlying the crest of the Orange levee system.

Sites AF-2 through AF-12, AF-15 and AF-22 form an important suite of sites designed to recover proximal levee sediments from each of the channel-levee systems in the Upper Levee Complex. This series of sites will provide a nearly continuous record of the material brought to the ocean by the Amazon River and discharged onto the fan.

Sites AF-13, AF-17, AF-18, and AF-20 are designed to sample the primarily pelagic material that is deposited on topographically isolated abandoned levees. Some of the holes have deeper, lower priority continuations. These holes should provide a continuous record of planktonic material, relatively free of downslope transport because of their elevated locations (based on analysis of existing cores from this environment) following channel abandonment. These holes will provide material from the western (sites AF-18, Priority 2, and/or AF-10 at about 3500 mbsl) and central parts (site AF-13 at 3800 mbsl and site AF-14 at 3500 mbsl) of the fan and from the central part of the fan (sites AF-16 and AF-17 at 2800 mbsl). Site AF-20, on the crest of a relatively old levee on the western edge of the fan, should provide a long, high-sedimentation-rate record for the eastern part of the fan to complement the record to be recovered at sites AF-10 and AF-11.

This material will contain a valuable record of river discharge and land climate moderated by the effects of sea level change. High sea level stands recovered at these sites should be clearly identified as pelagic sections that contain interglacial fauna, and thus would allow us to determine the sediments and fan units deposited during a glacial-interglacial cycle.

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Table 1. Primary - Site Time Estimates

Site *in drilling order*	Latitude Deg Min (North)	Longitude Deg Min (West)	Water Depth (m)	Penetration (mbsf)	Drilling Operations (days)	Log Type	Logging Operations (days)	Transit Time (days)
Barbados Port Call								
								3.21
AF - 20	5 44.24	49 7.39	3368	A 180	1.13			
				B 40	0.23			
				C 40	0.38			
								1.51
AF- 10	5 11.52	46 38.95	3550	A 420	2.74	Q, Gc, F, Gh	1.15	
				B 50	0.29			
				C 50	0.46			
								0.10
AF - 9	5 8.09	46 48.99	3407	A 275	1.30			
				B 50	1.09			
								0.32
AF - 21	5 0.73	47 35.63	3128	A 250	1.36			
				B 143	0.69			
								0.17
AF - 6	5 8.60	47 31.73	3195	A 275	2.14	Q, F	0.42	
				B 143	0.75			
								0.11
AF- 14	5 25.63	47 32.02	3488	A 370	2.48	Q, Gc, F, Gh	1.08	
								0.00
AF- 15	5 29.04	47 40.87	3415	A 100	1.18	Q, F, Gc	0.35	
				B 100	0.61			
								0.17
AF - 2	5 38.02	47 40.22	3588	A 350	2.50	Q, F	0.98	
				B 125	0.75			
								0.23
AF- 11	5 12.79	47 2.06	3384	A 275	1.78	Q, F	0.35	
				B 50	0.43			
								0.29
AF- 17	4 35.17	47 11.51	2797	A 133	0.82			
				B 133	0.58			
				C 133	0.68			
								0.18
AF- 16	4 39.60	47 18.82	2811	A 273	1.61	Q, F	0.39	
				B 200-273	0.60			
								0.18
AF- 12	4 43.36	47 30.22	2794	A 100	0.68			
				B 100	0.57			
								0.25
AF - 5	5 22.54	48 2.16	3387	A 225	1.55	Q, F	0.40	
				B 160	0.84			
								0.09
AF - 4	5 21.47	47 50.52	3397	A 179	1.08			
				B 50	0.43			
								0.19
AF- 13	5 56.08	47 44.60	3710	A 125	0.68			
								0.08
AF-3	5 56.19	47 45.30	3715	A 225+	1.49	Q, F	0.42	
				B 143	1.05			
								0.39
AF - 22	6 57.33	47 52.98	4124	A 225	2.35	Q, F	0.46	
				B 225	1.56			
								3.20
Barbados Port Call								
Total					**38.86**		**6.00**	**10.67**

Total Days at Sea = 55.53

Q = Quad-combo, Gc = Geochemical tool, F = FMS, Gh = GHMT (magnetic susceptibility tool)

Table 2. Alternate - Site Time Estimates

Site	Latitude Deg Min (North)		Longitude Deg Min (West)		Water Depth (m)	Penetration (mbsf)	Drilling Operations (days)	Log Type	Logging Operations (days)
AF- 1	5	37.95	47	45.09	3600	724	6.2	Q, Gc, F	1.6
AF-7	4	37.38	47	15.16	2846	568	4.3	Q, Gc, F	1.4
AF-8	5	13.99	47	7.93	3497	273	2.4	Q, F	1.2
AF-18	5	7.90	46	33.85	3520	A 179 B 179	2.6 Total		
AF-19	5	13.53	47	5.54	3434	A 273 B 133	2.0 Total		

Q = Quad-combo, Gc = Geochemical tool, F = FMS, Gh = GHMT (magnetic susceptibility tool)

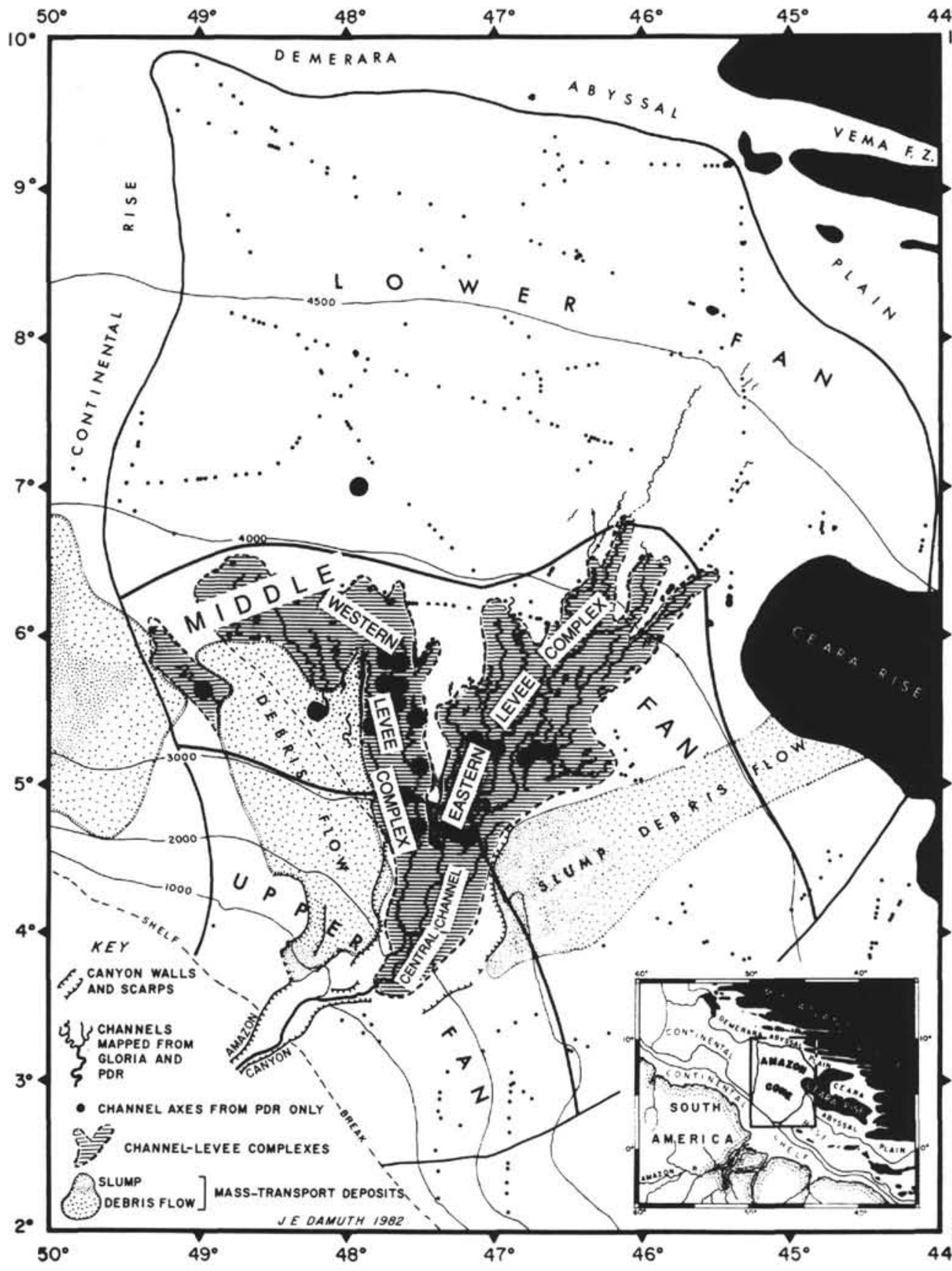


Figure 1. Morphological map of the Amazon Fan, showing locations of surficial channels, levees, canyons and debris flows. Solid black circles show approximate locations of holes AF-1 to AF-22 (see Fig. 5 and Table 1). Inset map shows location of Amazon Fan with respect to South America and the Amazon River. (Adapted from Damuth et al., 1983b.)

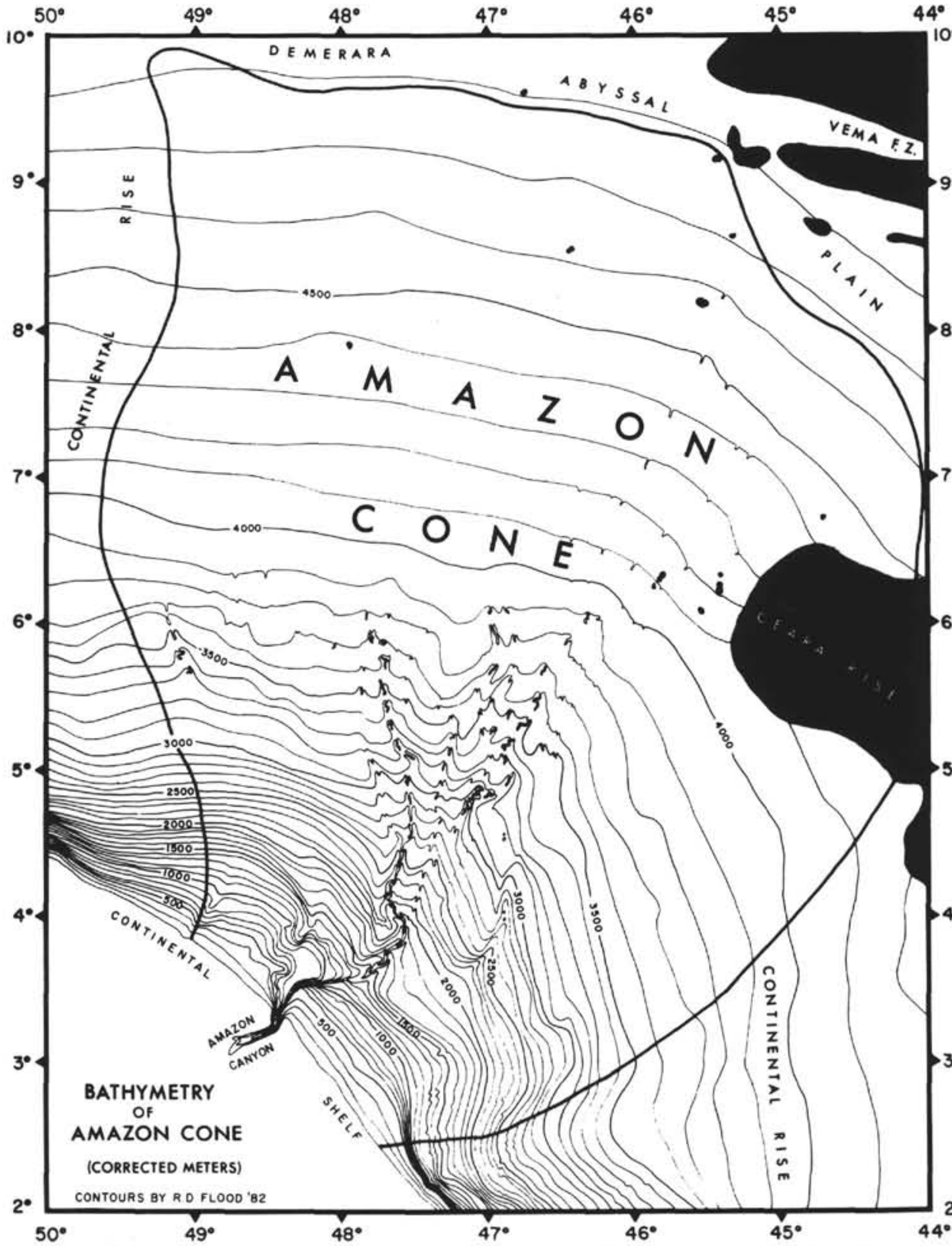


Figure 2. Regional bathymetry (in meters) of the Amazon Fan. (Adapted from Damuth et al., 1988.)

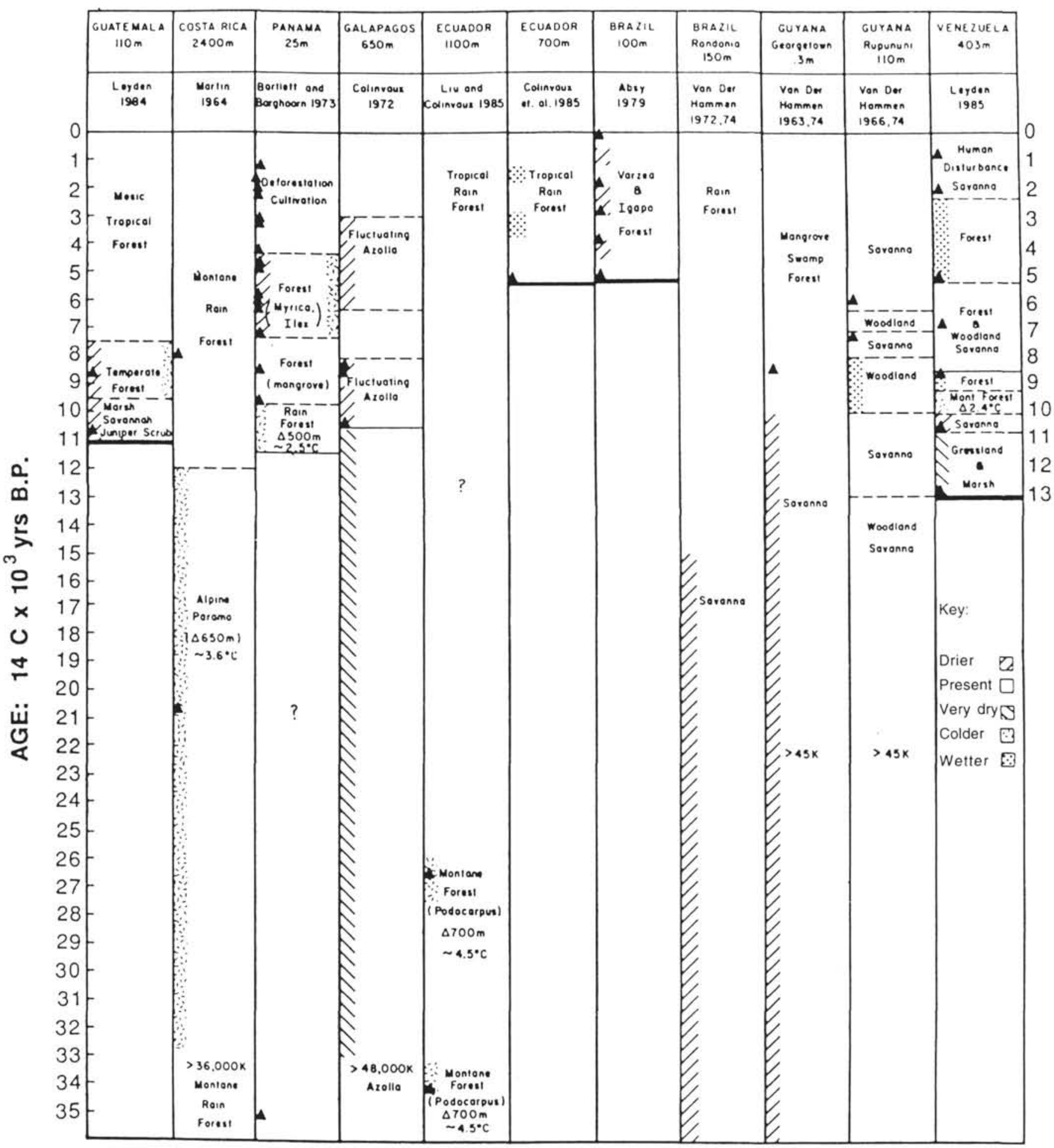


Figure 3. Correlation of pollen records indicating vegetational change in Central and South America. Triangles indicate radiocarbon dates within the stratigraphy. Climatic interpretations are derived from the individual authors. The available records from montane regions surrounding the Amazon Basin indicate a depression of vegetation zones, associated with a cooler and/or drier climate during the late Pleistocene. Little information is available from the lowlands within the Amazon Basin extending back to the late Pleistocene, but the few records available from the basin (e.g. #8) suggest vegetation changes interpreted to represent a drier climate. Figure adapted from Peteet (1986).

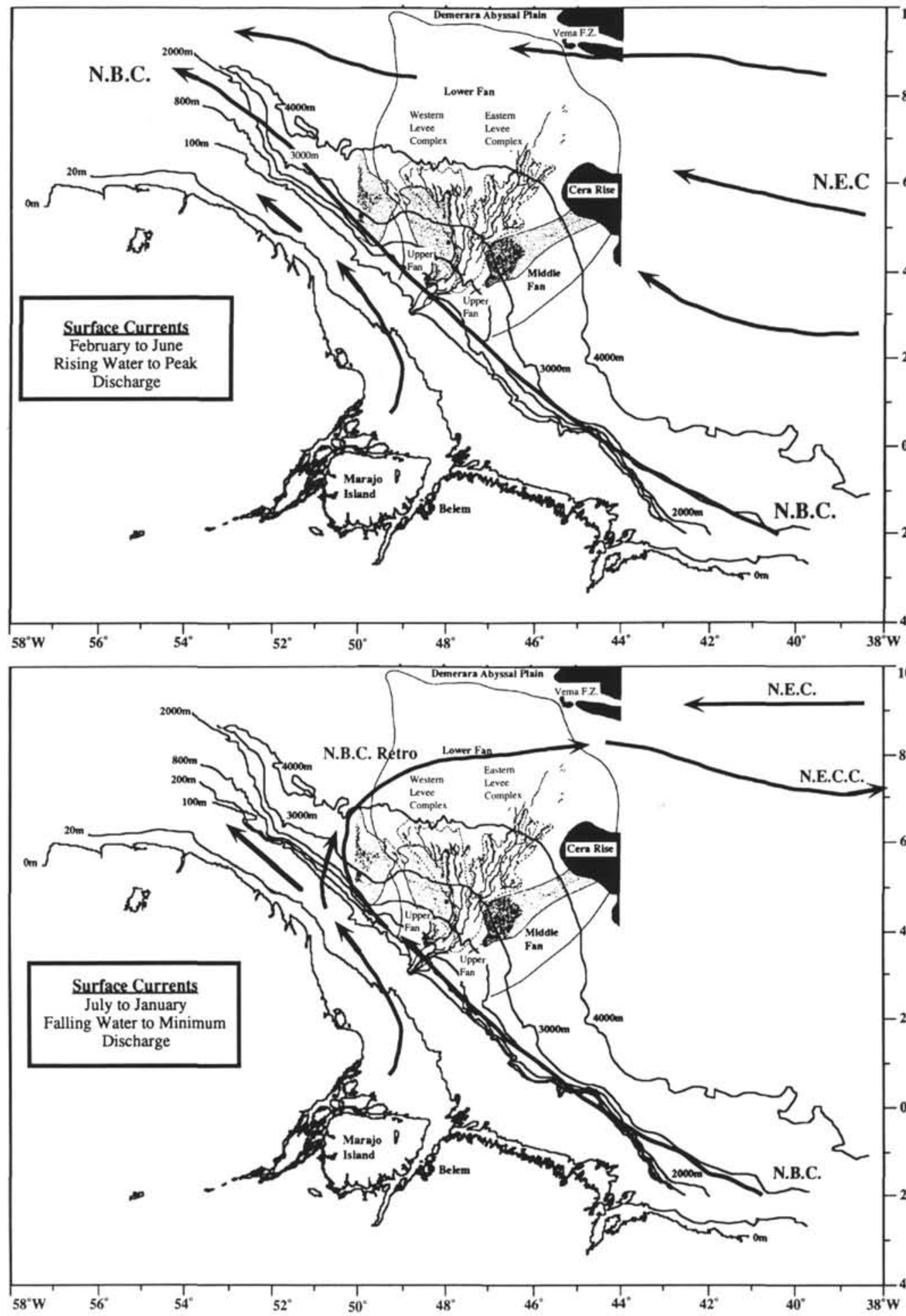


Figure 4. Sketch map showing the seasonal variation in surface circulation in the western Equatorial Atlantic. From July to January, a portion of the North Brazil Current (NBC) turns eastward to flow into the Equatorial Atlantic, whereas from February to June there is no retroflection. The Amazon Fan underlies the present-day retroflection. During low sea-level stands, the coastline was near the 100-m contour, and river sediments discharged directly onto the fan. The pattern of surface currents in this area is poorly known for that time. Temporal variations in the strength of the NBC may affect northward transport of heat and flux. High-resolution planktonic records associated with temporal variations in the position of the retroflection should be preserved in carefully selected fan environments (primarily on abandoned levees).

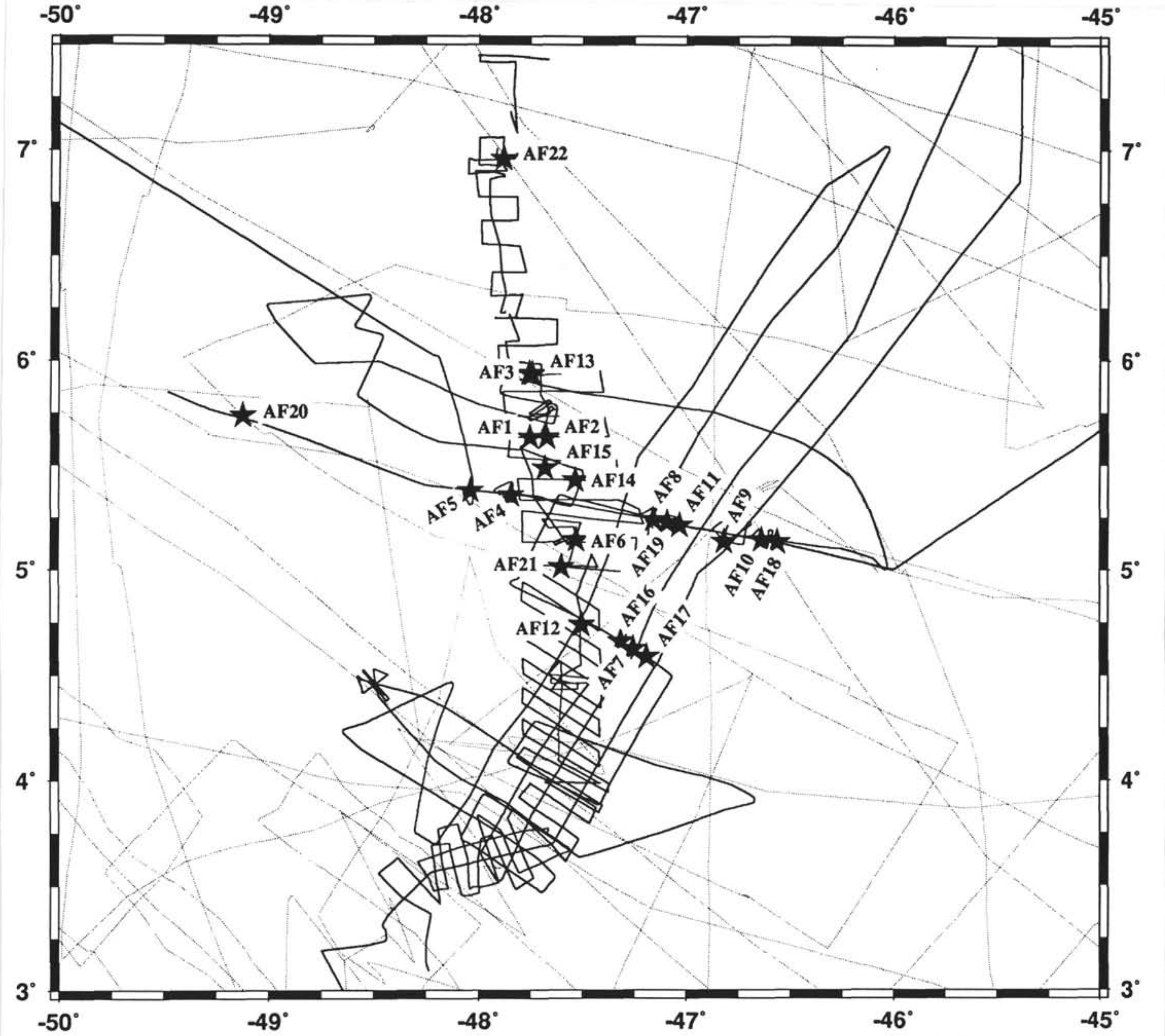


Figure 5. Locations of proposed Amazon Fan drill sites, digitally recorded seismic lines (bold lines), and analog seismic lines (dotted lines). Note that regional lines exist both across the shelf break and on the lower fan that can be tied to our high-resolution seismic grid.

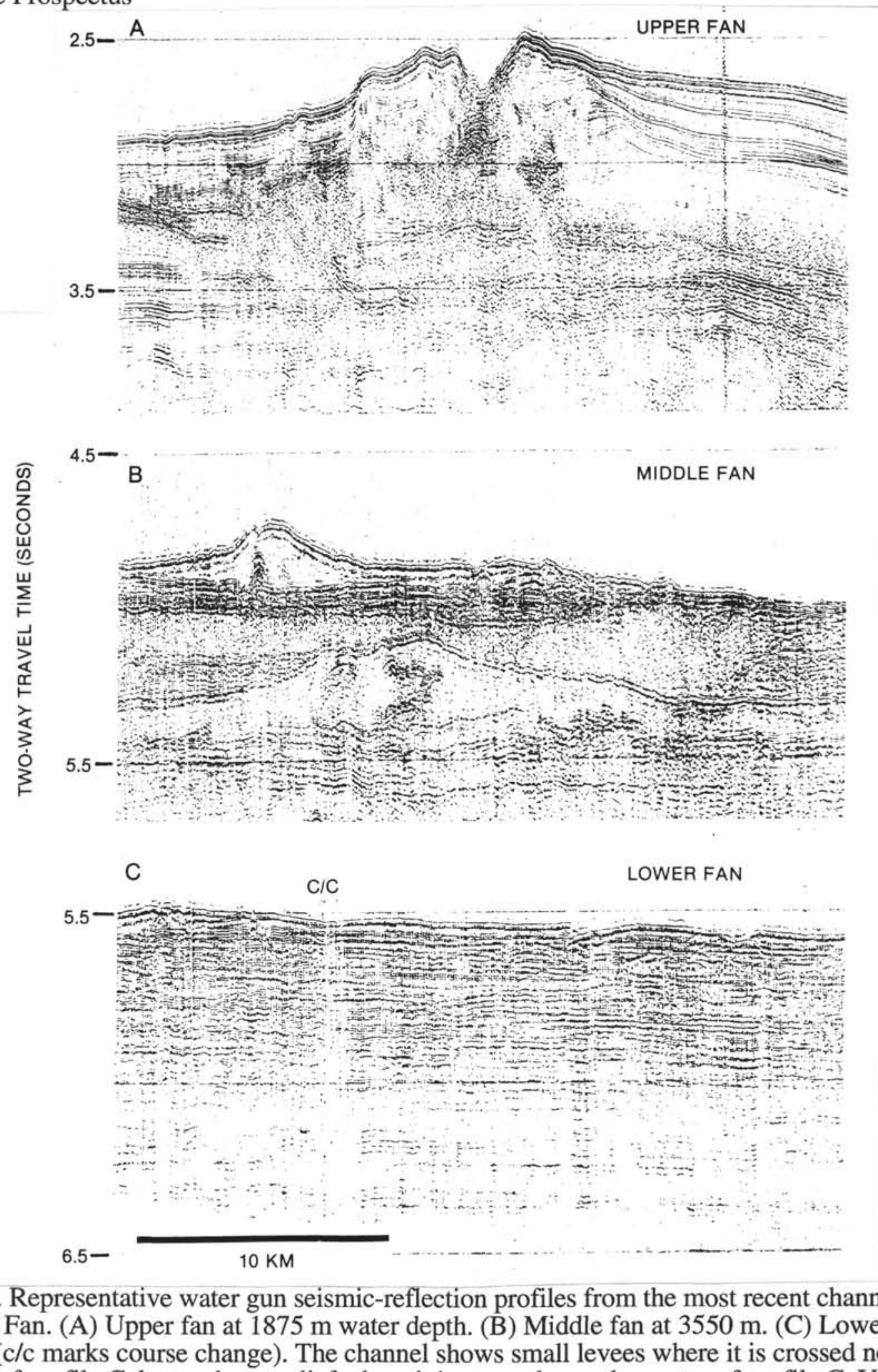


Figure 6. Representative water gun seismic-reflection profiles from the most recent channel on the Amazon Fan. (A) Upper fan at 1875 m water depth. (B) Middle fan at 3550 m. (C) Lower fan at 4125 m (c/c marks course change). The channel shows small levees where it is crossed near the left side of profile C, but no levee relief where it is crossed near the center of profile C. Vertical Exaggeration is 13:1. Acoustic facies are well defined and well resolved on these high-resolution profiles.

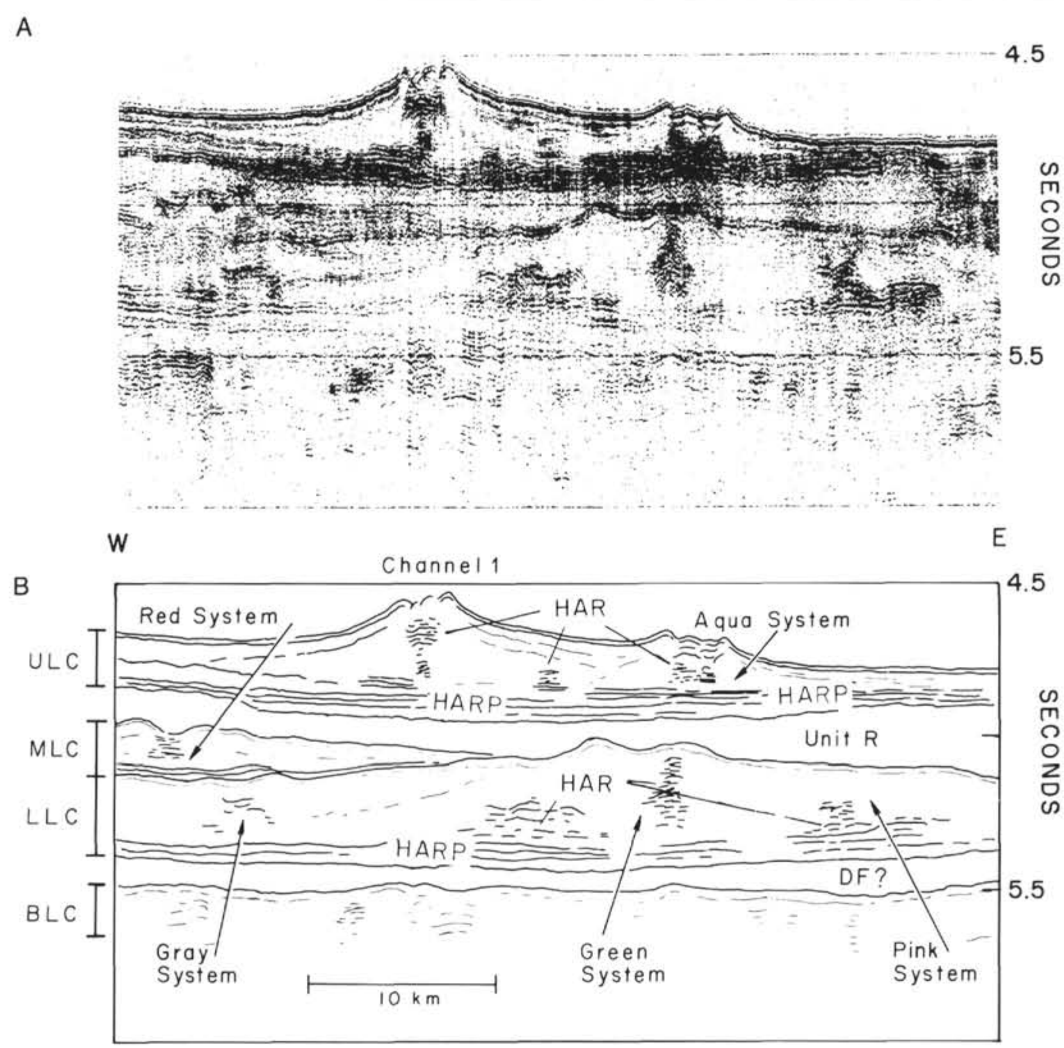


Figure 7. Original water gun seismic-reflection profile (A) and interpretation (B) from the middle fan at 3450 m, showing the relationship between the different seismic facies observed on the fan. Note the high-amplitude reflections (HAR) within the levee of Channel 1 (Amazon Channel) and the flatter lying high-amplitude reflection packets (HARP) that lie beneath the channel/levee system. Similar acoustic facies are also observed associated with other channel-levee systems (color names as given by Manley and Flood, 1988) both at the fan surface and at depth. Unit R, which separates the Upper Levee Complex (ULC) from the Middle and Lower Levee complexes (MLC and LLC), appears to be a debris-flow deposit. An inferred debris-flow deposit (marked DF?) separates the LLC from the more deeply buried Bottom Levee Complex (BLC). The paths of the buried (color named) channel-levee systems are shown in Figure 8. While surficial and buried channel-levee systems and other acoustic facies are well resolved, we do not have a very good understanding of the actual relationships between sedimentation pattern and sea level. (Adapted from Flood et al., 1991.)

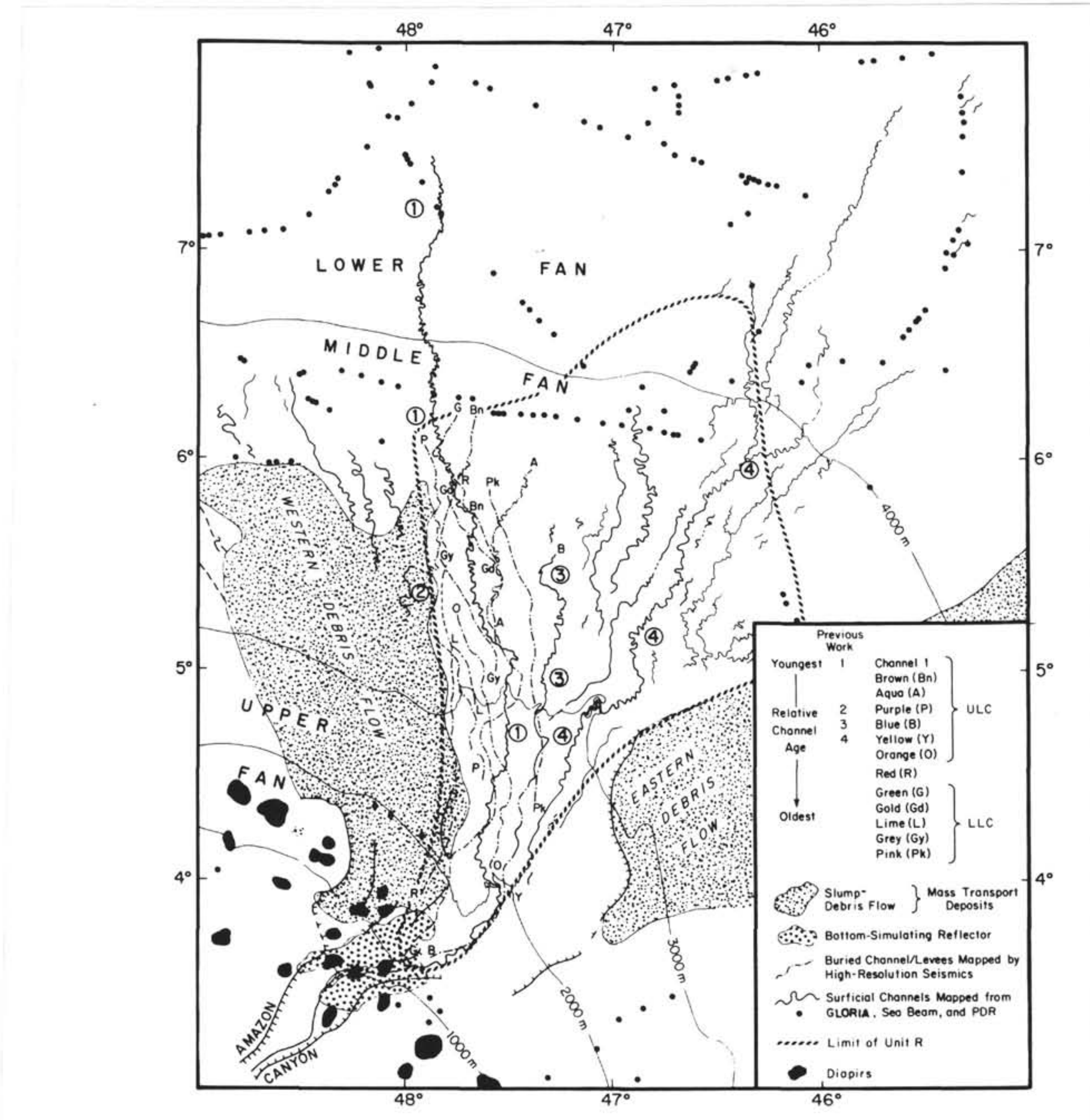


Figure 8. Detailed map of the Amazon Fan showing locations of surficial (thicker lines) and buried (thinner lines) channel axes. Channels are ranked in terms of age following Damuth et al. (1983b; numbers) and Manley and Flood (1988; colors). Buried channels can be subdivided into an Upper Levee Complex, a Middle Levee Complex and a Lower Levee Complex (see also Fig. 6). Also shown are the locations of the major surficial and buried debris flow units, the locations of diapirs, and the extent of a bottom-simulating reflector. (Adapted from Manley and Flood, 1988.)

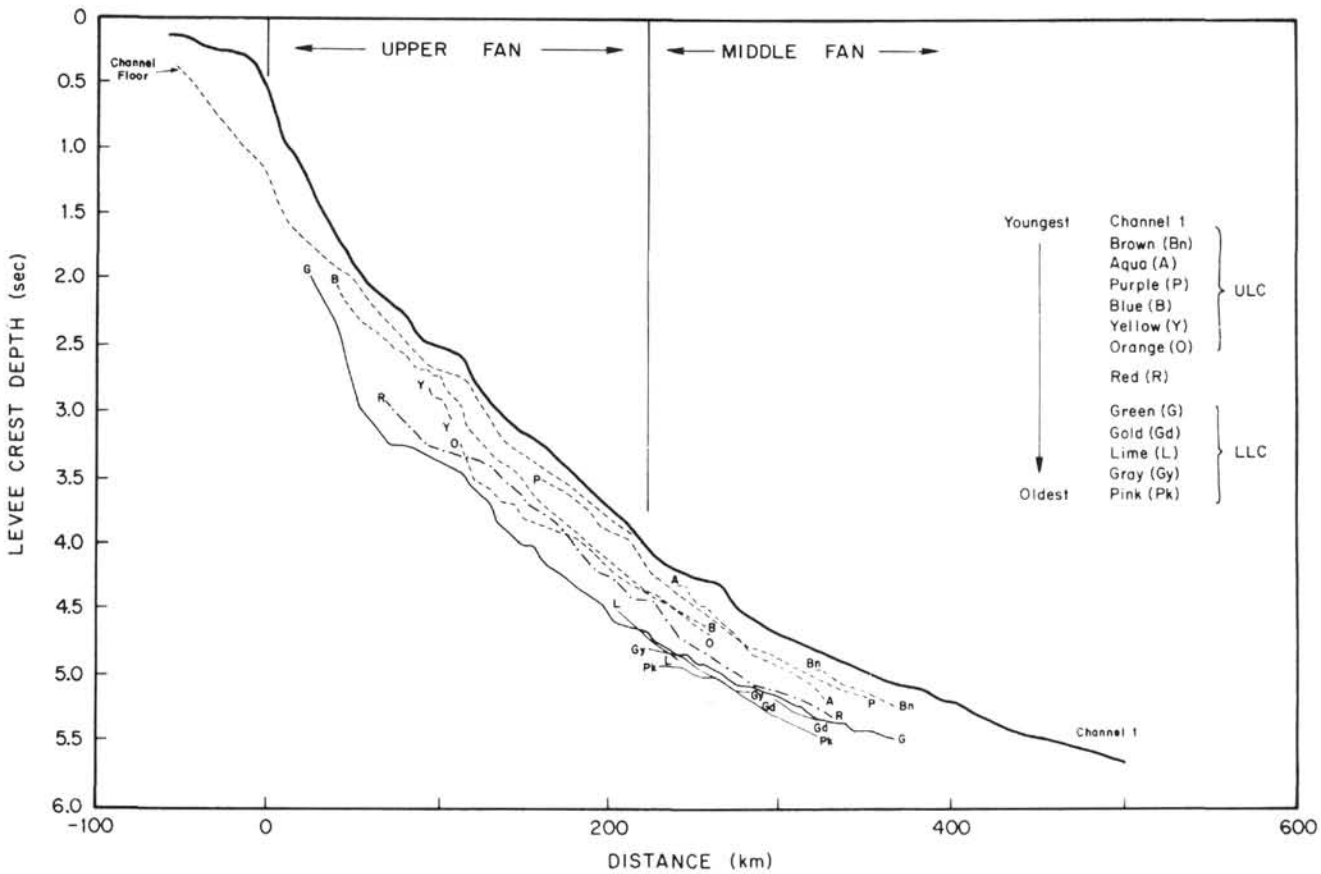


Figure 9. Plot of depth to top of levee vs. distance from canyon for all buried channels mapped from seismic data (see Fig. 6). The crests of all channels exhibit slopes about the same as the Amazon Channel (Channel 1). (Adapted from Manley and Flood, 1988.)

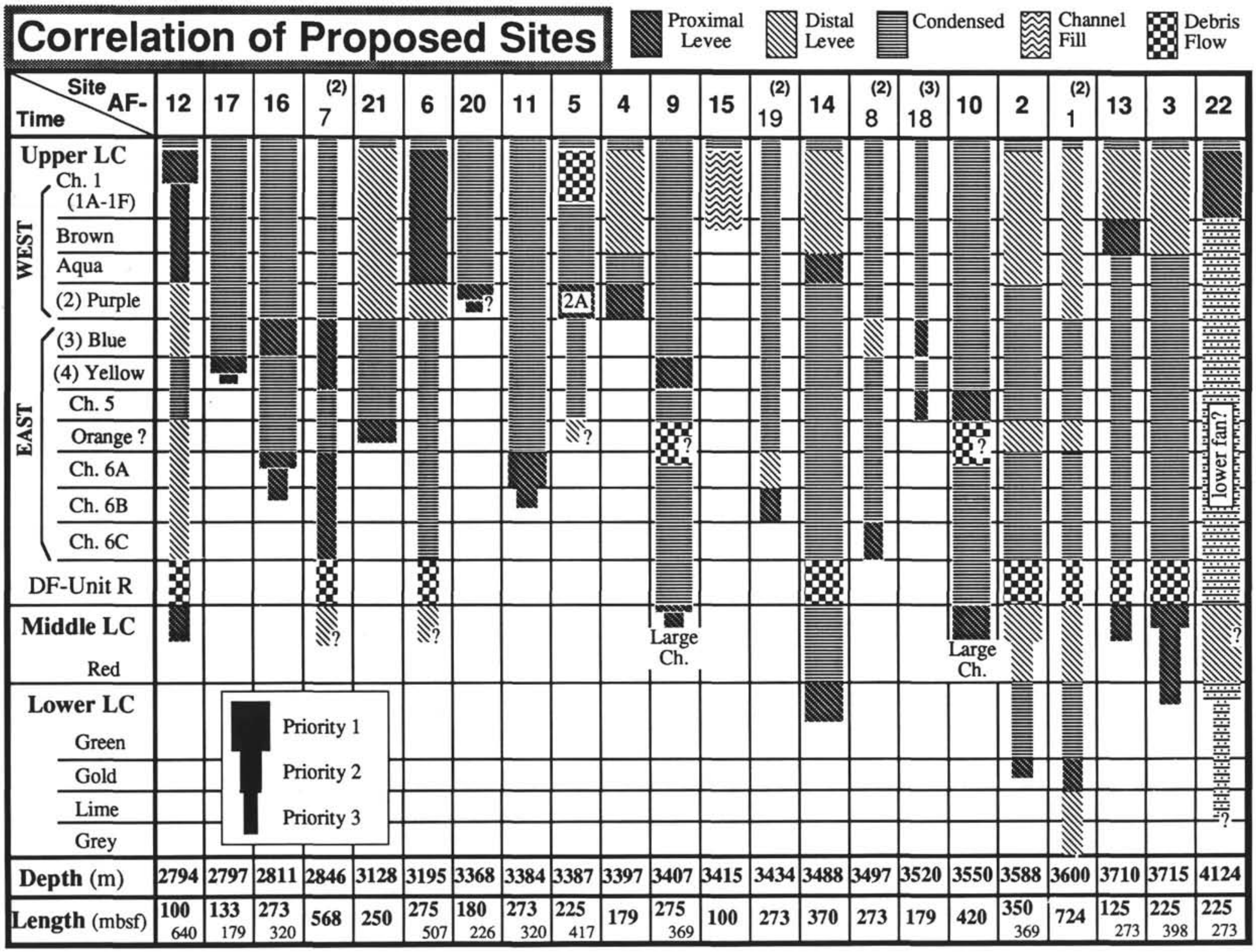


Figure 10. Schematic illustration of the overall relationship between proposed drill sites and the acoustic stratigraphy of the Amazon Fan. Seismic profiles at sites show more precisely the relationships observed. Sites arranged in order of increasing water depth.

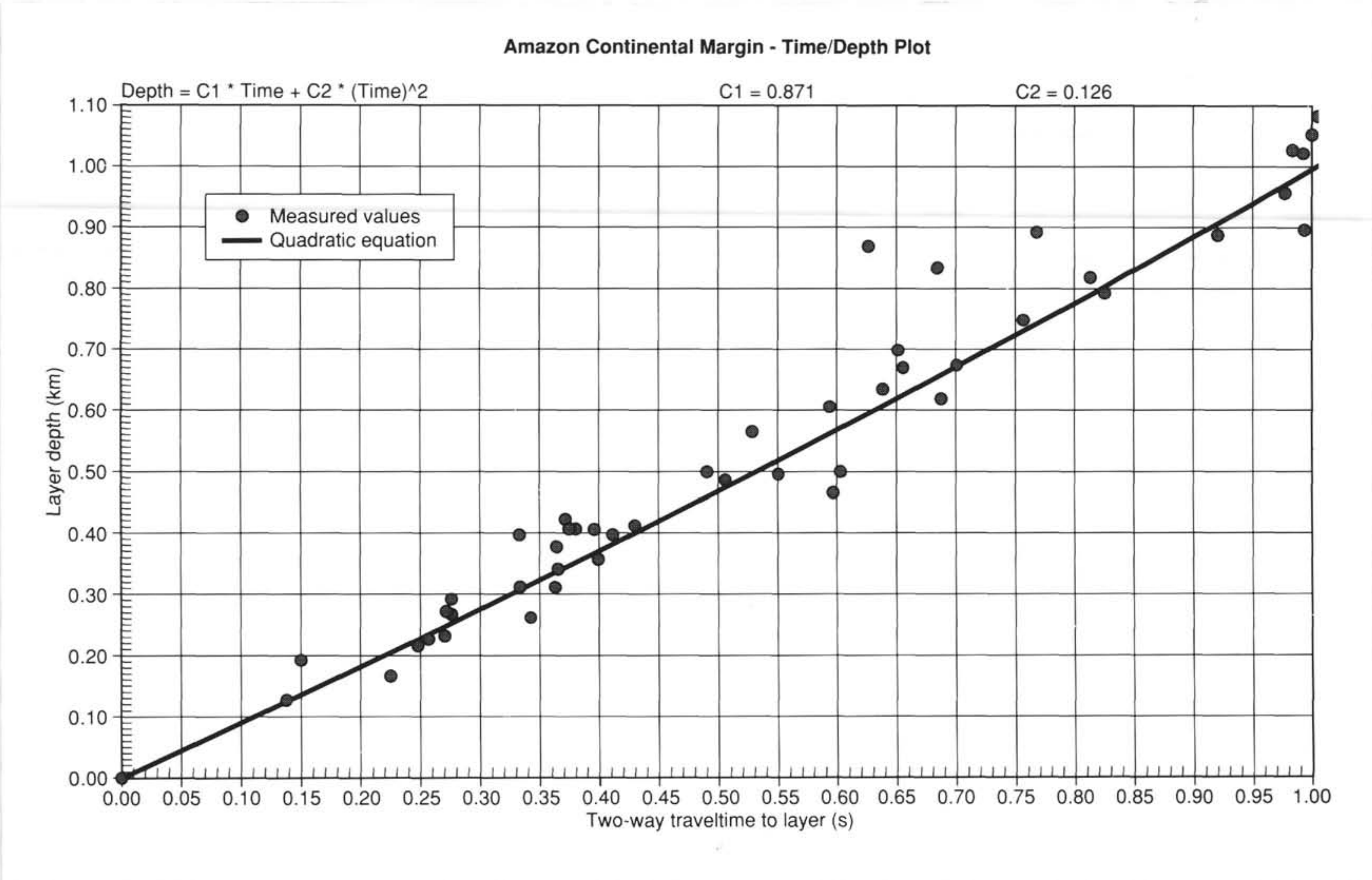


Figure 11. Time-depth plot from sonobuoy data on the Amazon Fan. Some local variation from this plot is expected depending on the sediments at each particular site.

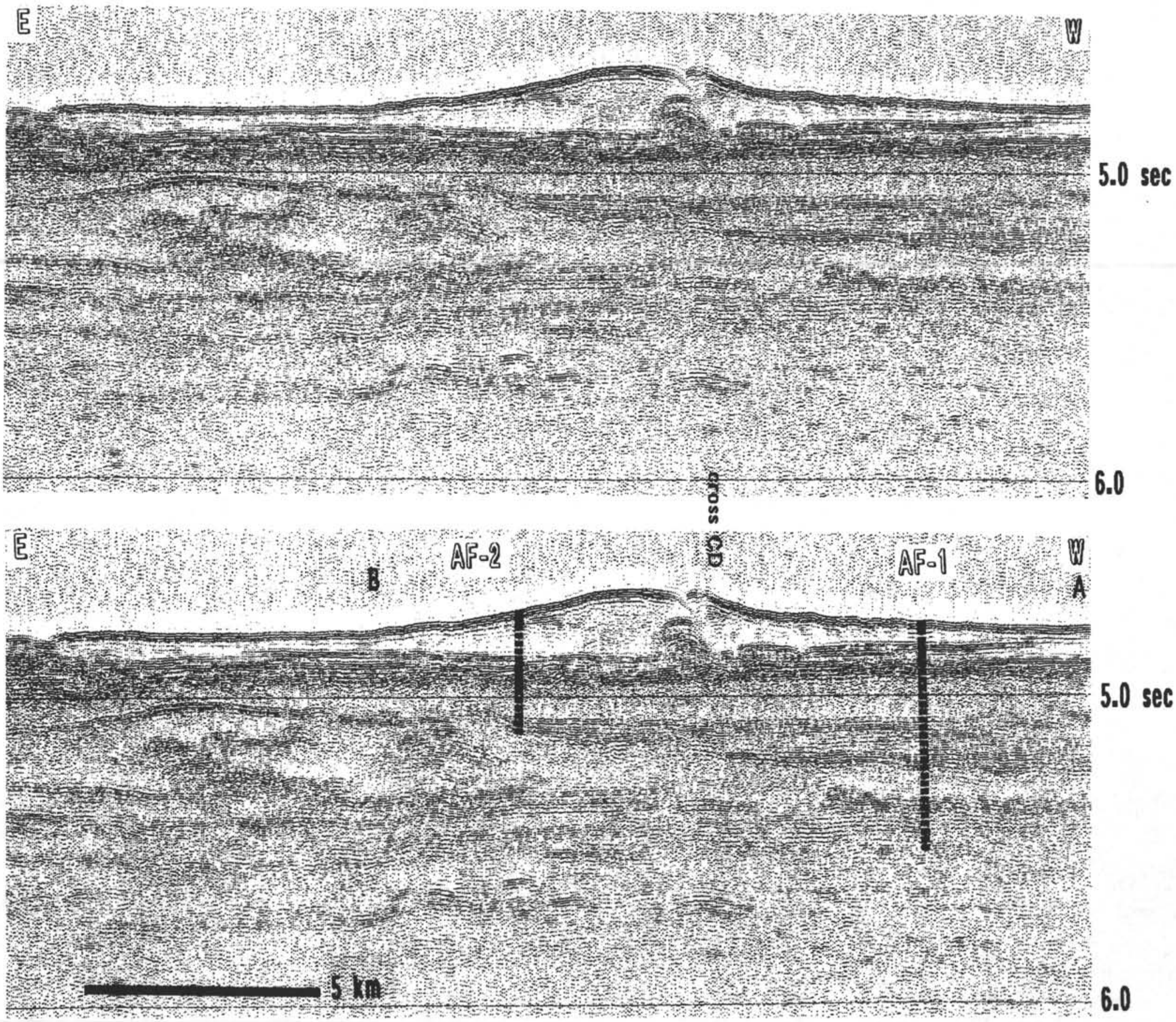
Site: AF-1
Priority: 2
Position: 5°37.95'N, 47°45.09'W
Water Depth: 3600 m
Sediment Thickness: 4000 m
Seismic Coverage: SCS C2514 1124 hrs 12/03; C2415 0450 hrs 12/16 (projected 1 mi)

Objectives: To recover a section through relatively distal levee deposits, penetrating the Lower Levee Complex at about 400 m sub-bottom. Potential objectives that would give it a higher priority are (a) its potential as a stratigraphic hole to reach the older sediments, should proposed sites AF-2 and AF-3 be unsuccessful, should sediment accumulation rates prove exceptionally high or low, or should there be high-quality paleontological dates in similar settings in previous holes, (b) its potential, from the upper part of the hole, to provide information on lateral variability of Amazon Channel and Brown levee sediments, which might prove important to interpret the response of levee sediments to avulsion (objective (c) of proposed sites AF-2 and AF-3).

Drilling Program: Hole A: APC/XCB to total depth . Possible Hole B: RCB if APC/XCB can't penetrate to total depth in Hole A.

Logging and Downhole Operations: Core orientation, Adara/WSTP. Full suite of logs if conditions permit.

Nature of Rock Anticipated: Silty clay with scattered sand layers.


E
W
5.0 sec
6.0
cross CD
E
B
AF-2
AF-1
W
A
5.0 sec
5 km
6.0

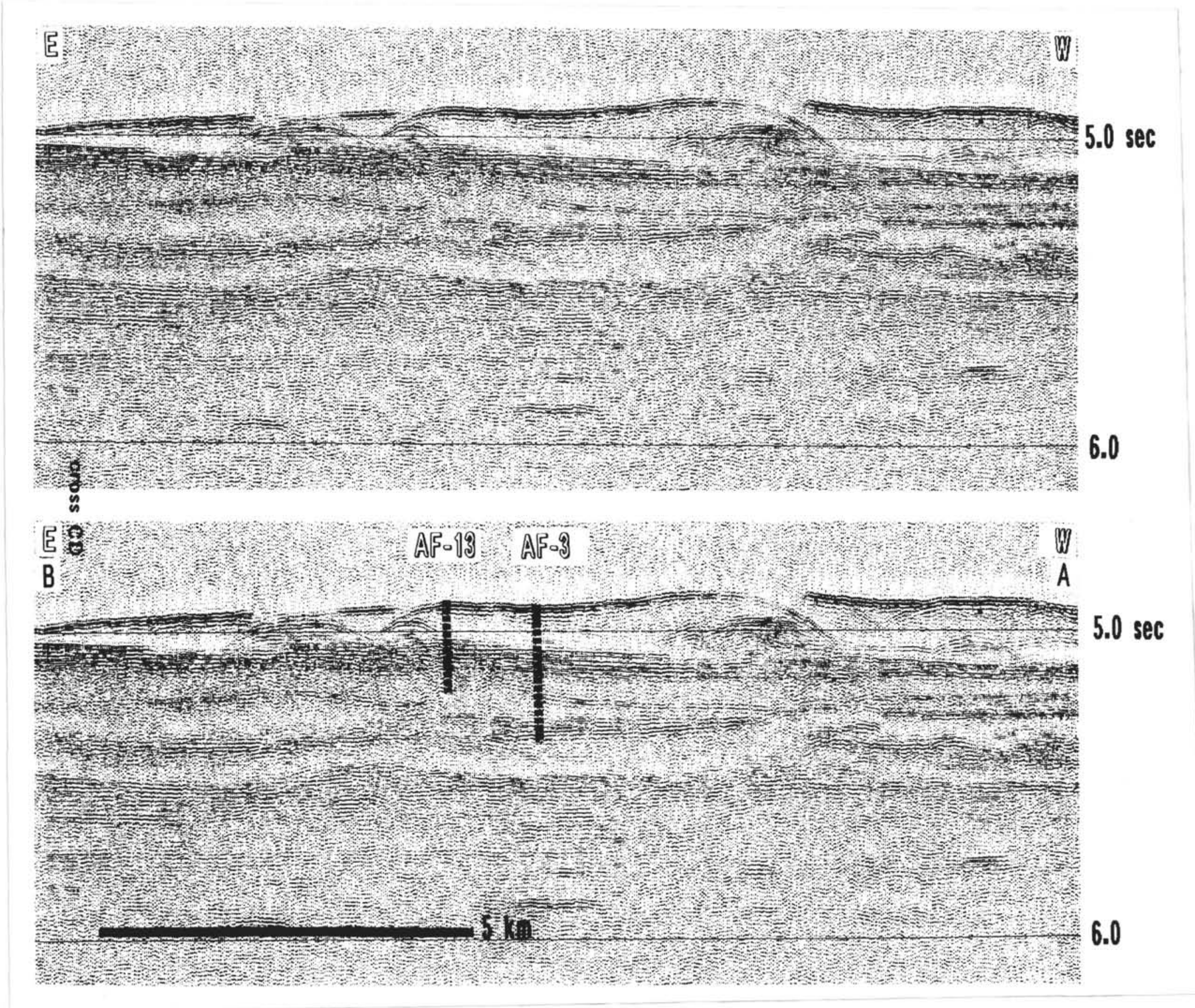
Site: AF-2
Priority: 1
Position: 5°38.02'N, 47°40.22'W
Water Depth: 3588 m
Sediment Thickness: 4000 m
Seismic Coverage: SCS C2514 1200 hrs 12/03; C2415 0515 hrs 12/03 (projected 2 mi.)

Objectives: To sample the proximal levee of the Amazon Channel and the Brown system, the underlying HARP's that may represent end-of-channel deposits, the Unit R debris flow, the Red levee and the Gold levee near its crest. Drilling at this site, together with proposed site AF-3, will allow us to (a) sample the possible stage 5 interval and the underlying Green and Gold systems, and determine age and mineralogical character of these older sediments; (b) characterize the nature of HARP's interpreted as sheets associated with channel avulsion; and (c) establish the response of levee immediately upslope from the Brown avulsion event. Secondary objectives include an investigation of the downslope behavior of debris flow and the contact between Channel 1 and underlying levees, and sampling of levees of modern channel. Some whole-round samples for organic geochemistry and geotechnical testing may be necessary.

Drilling Program: Hole A: APC/XCB into Gold levee (~350 mbsf). Hole B: APC/XCB to base of Brown levee (~125 mbsf).

Logging and Downhole Operations: Core orientation is high priority. Adara/WSTP is moderate priority. Quad-combo and FMS logs.

Nature of Rock Anticipated: Silty clay with scattered sand layers, particularly 125-200 mbsf, and debris flow.


E
W
5.0 sec
6.0
cross CD
E
B
AF-13
AF-3
W
A
5.0 sec
5 km
6.0

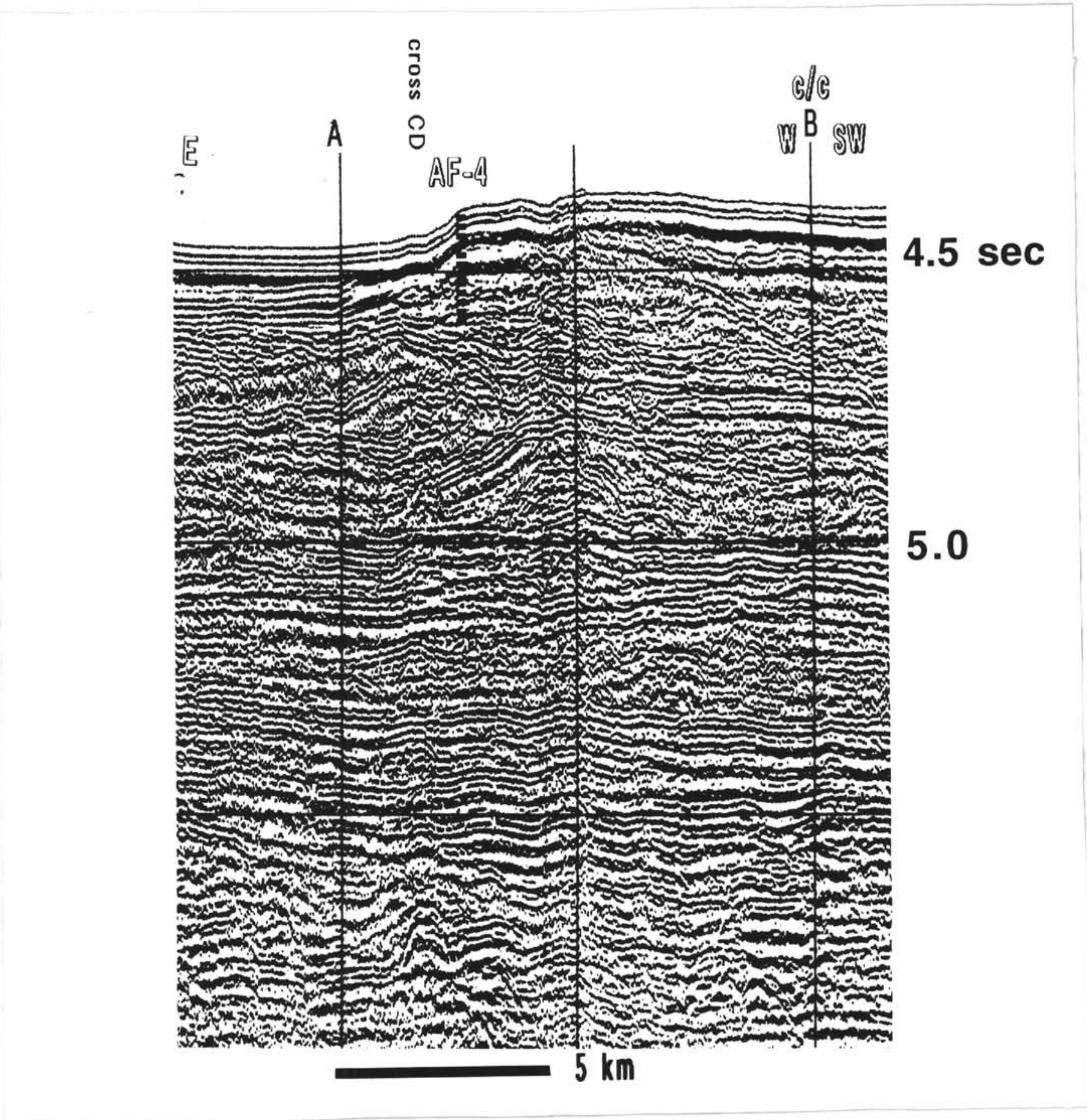
Site: AF-3
Priority: 1
Position: 5°56.19'N, 47°45.30'W
Water Depth: 3715 m
Sediment Thickness: 4000 m
Seismic Coverage: SCS C2514 0545 hrs 12/04; C2415 1405 hrs 12/16 (projected 3 mi.)

Objectives: To sample the levee flank of the Amazon Channel and the Brown levee, the Unit R debris flow, and through the ?Red levee to the Green levee. Objectives are similar to those for proposed site AF-2.

Drilling Program: Hole A: APC/XCB to target depth within Unit R debris flow (225 mbsf), possible lower priority extension to total depth at the flank of Green levee depending on results of prior sites. Hole B: APC/XCB to ~143 mbsf to achieve complete/duplicate section of active channel facies.

Logging and Downhole Operations: Core orientation is high priority. Adara/WSTP is high priority. Probable Quad-combo and FMS logs.

Nature of Rock Anticipated: Silty clay with scattered sand layers.


cross CD
c/c
E
A
AF-4
W
B
SW
4.5 sec
5.0
5 km

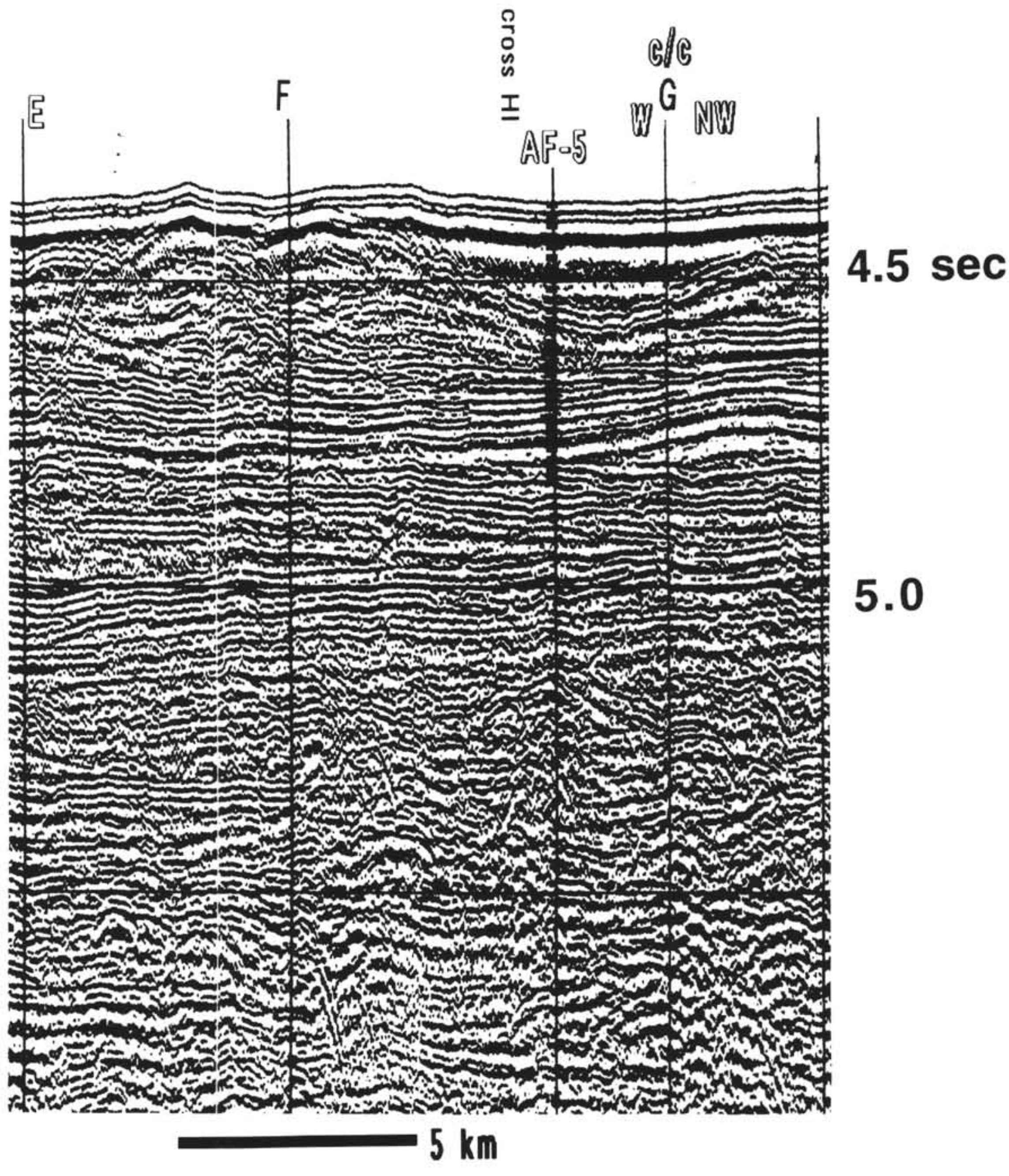
Site: AF-4
Priority: 1
Position: 5°21.47'N, 47°50.52'W
Water Depth: 3397 m
Sediment Thickness: 4000 m
Seismic Coverage: E9209 1915 hrs 09/21

Objectives: This site and proposed site AF-5 are located toward the western part of the fan, where much of the morphology is covered by one or more surficial debris flows. At this site, we aim to sample the Purple levee, overlying interfingering debris flows and levee flank sediments of the Amazon Channel to show their relative timing. The primary objective is to stratigraphically sample and date the Purple levee interval. Secondary objectives include the interpretation of debris flow frequency, the characterization of levee flank sediments from the Amazon Channel, and the recovery of a record of post-Purple pelagic sediment. Partial reason for the second hole is for obtaining whole round samples to characterize debris flow deposit properties.

Drilling Program: Hole A: APC/XCB to target depth at base of Purple levee (~179 mbsf). Hole B: APC/XCB to ~50 mbsf.

Logging and Downhole Operations: Core orientation is high priority. Adara is low priority. No logging.

Nature of Rock Anticipated: Silty clay and interspersed debris flow deposits.


cross HI
c/c
E
F
G
W
NW
AF-5
4.5 sec
5.0
5 km

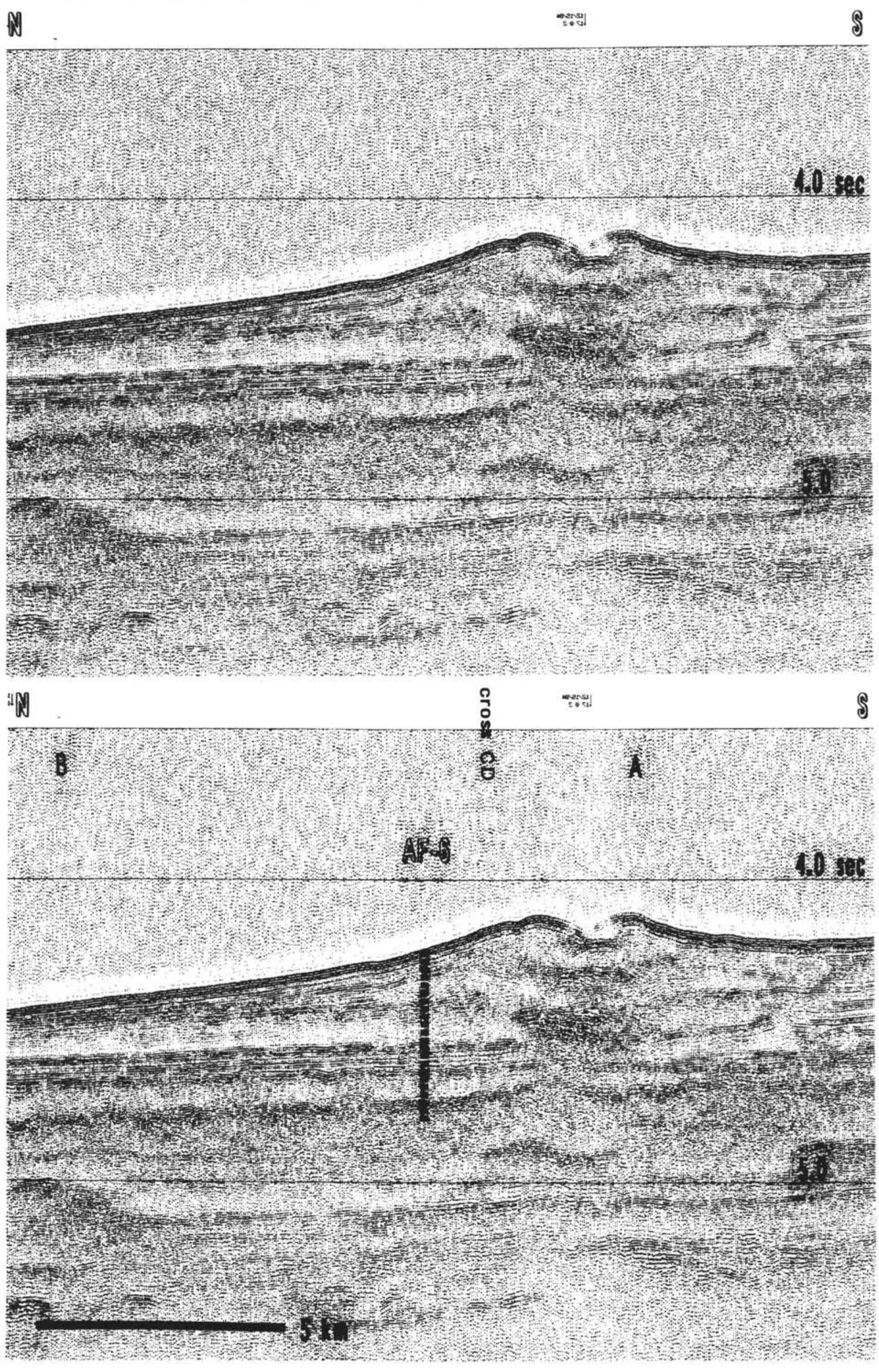
Site: AF-5
Priority: 1
Position: 5°22.54'N, 48°02.16'W
Water Depth: 3387 m
Sediment Thickness: 4000 m
Seismic Coverage: E9209 2330 hrs 09/21

Objectives: Drilling at this site will penetrate the western debris flow, levee 2A (Purple), a HARP and a deeper undated levee interval. Primary objectives are (a) to determine the number of debris flow events in the Western Debris Flow, and their source(s), (b) to obtain stratigraphic and mineralogical samples of the undated underlying levee sequences, and (c) to obtain a pelagic section that lies beneath the debris flow and overlies the Purple levee from the western sector of the fan. Partial reason for the second hole to ~160 mbsf is for obtaining whole round samples to characterize debris flow deposit properties.

Drilling Program: Hole A: APC/XCB to target depth (~225 mbsf) at old undated levee beneath debris flow. Hole B: APC/XCB to ~160 mbsf.

Logging and Downhole Operations: Core orientation is high priority. Adara is moderate priority. Quad-combo and FMS logs.

Nature of Rock Anticipated: Silty clay with scattered sand layers and debris flows.


N
S
4.0 sec
5.0
N
S
B
cross CD
A
AF-6
4.0 sec
5.0
5 km

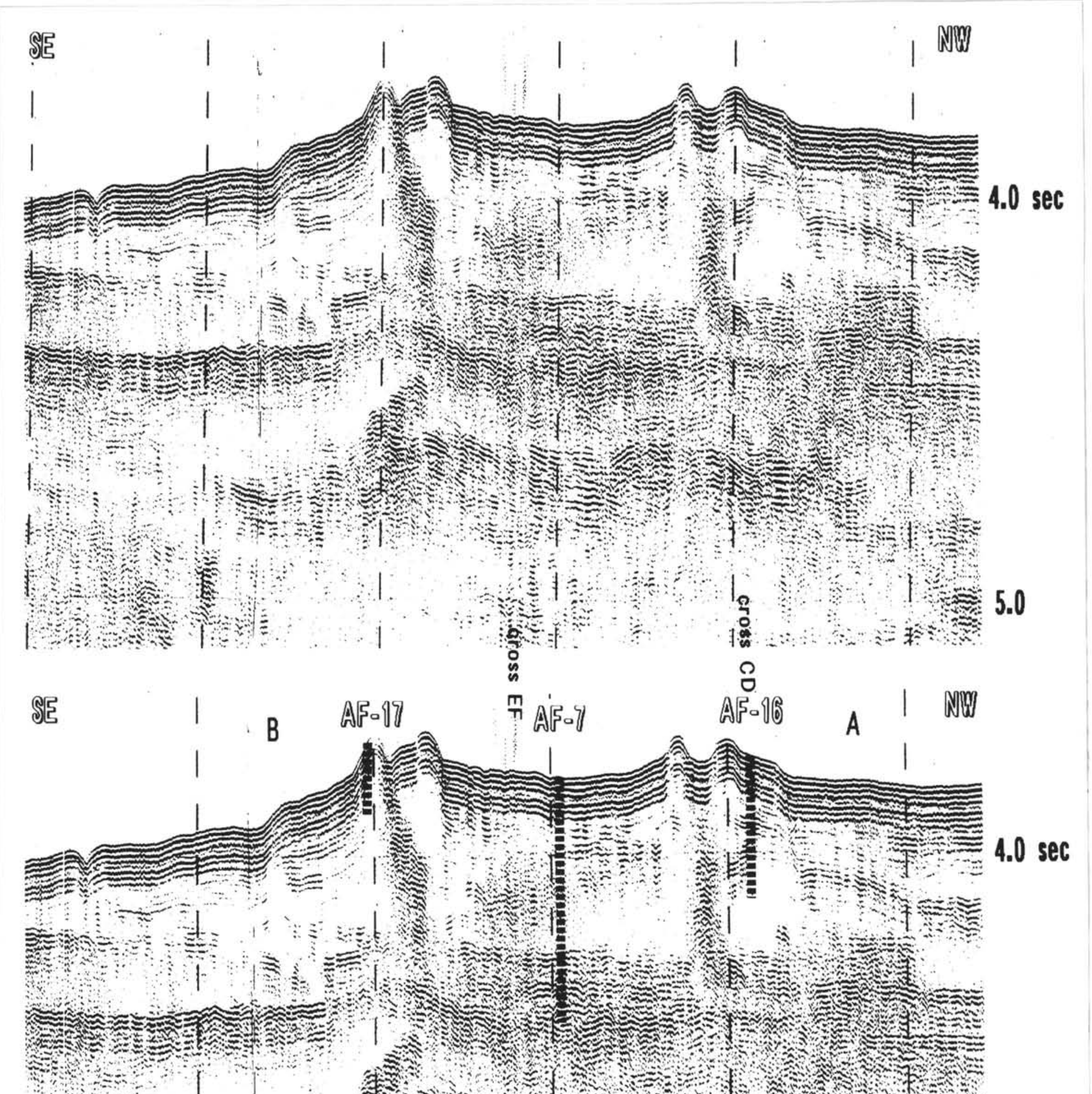
Site: AF-6
Priority: 1
Position: 5°08.60'N, 47°31.73'W
Water Depth: 3195 m
Sediment Thickness: 4000 m
Seismic Coverage: C2514 1716 hrs 12/15; C2514 0950 hrs (projected 0.8 mi)

Objectives: This site is located on the levee of Amazon Channel near the site immediately above where the channel diverged from the path of the Aqua system. At this site, we aim to sample the Amazon, Brown, Aqua and earlier levee deposits, with a HARP at the Priority 1 penetration depth of 300 m. Deeper penetration would allow us to sample the Unit R debris flow and an earlier levee deposit. Primary objectives are (a) to identify the character of prominent reflectors, to understand if they reflect changes in flow processes (e.g., avulsions) or are pelagic intervals, (b) to integrate findings with data gathered from proposed sites AF-2, AF-3, AF-12, AF-15, and AF-22 to understand the flow processes and facies variation along the length of a levee system, (c) to integrate findings with data gathered from proposed sites AF-12 and AF-15 to study early sediment and organic matter diagenesis in an area of rapid modern sedimentation. Secondary objective of an extended hole would be to sample and date the older part of the sediment section around the R debris flow. Partial reason for the second hole is for obtaining whole round samples for analyses to characterize organic origin and diagenesis.

Drilling Program: Hole A: APC/XCB to penetrate base of levees (~275 mbsf). Time permitting, extend to ~507 mbsf (secondary priority). Hole B: APC/XCB to ~143 mbsf.

Logging and Downhole Operations: Core orientation is high priority. Adara/WSTP is moderate priority. Quad-combo and FMS logs (unless >400 mbsf, then full suite of logs).

Nature of Rock Anticipated: Silty clay with scattered sand layers.


SE
NW
4.0 sec
5.0
cross EF
cross CD
SE
B
AF-17
AF-7
AF-16
A
NW
4.0 sec
5.0
5 km

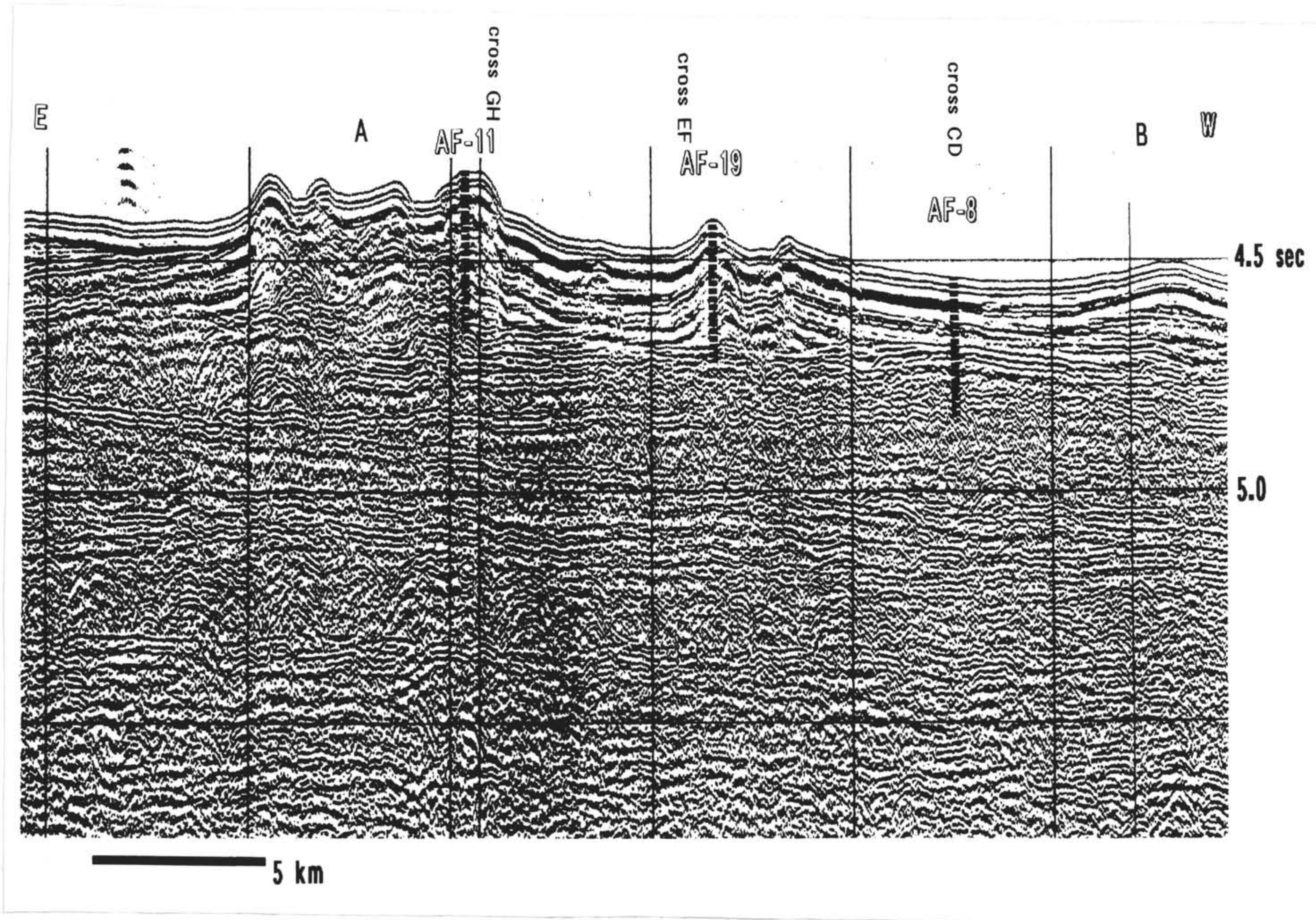
Site: AF-7
Priority: 2
Position: 4°37.38'N, 47°15.16'W
Water Depth: 2846 m
Sediment Thickness: 4000 m
Seismic Coverage: FR815 0831 1/12; FR815 0330 hrs 1/07 (projected 1 mi)

Objectives: At this site, we aim to sample proximal levee sediments of the Blue and Yellow systems and overlying hemipelagic sediments. The base of the hole at this site will penetrate the system 6 feeder channel and underlying sediment. The relatively shallow water means that carbonate preservation should be good. Similar objectives will be met at proposed sites AF-16 and AF-17. Part, or all, of the hole might be drilled if proposed site AF-16 or AF-17 is unsuccessful.

Drilling Program: Hole A: APC/XCB to total depth. Possible Hole B: Depending on Hole A penetration, RCB at deep levee flank.

Logging and Downhole Operations: Core orientation, Adara/WSTP. Full suite of logs if conditions permit.

Nature of Rock Anticipated: Silty clay with scattered sand layers.


E
A
AF-11
cross GH
cross EF
AF-19
cross CD
AF-8
B
W
4.5 sec
5.0
5 km

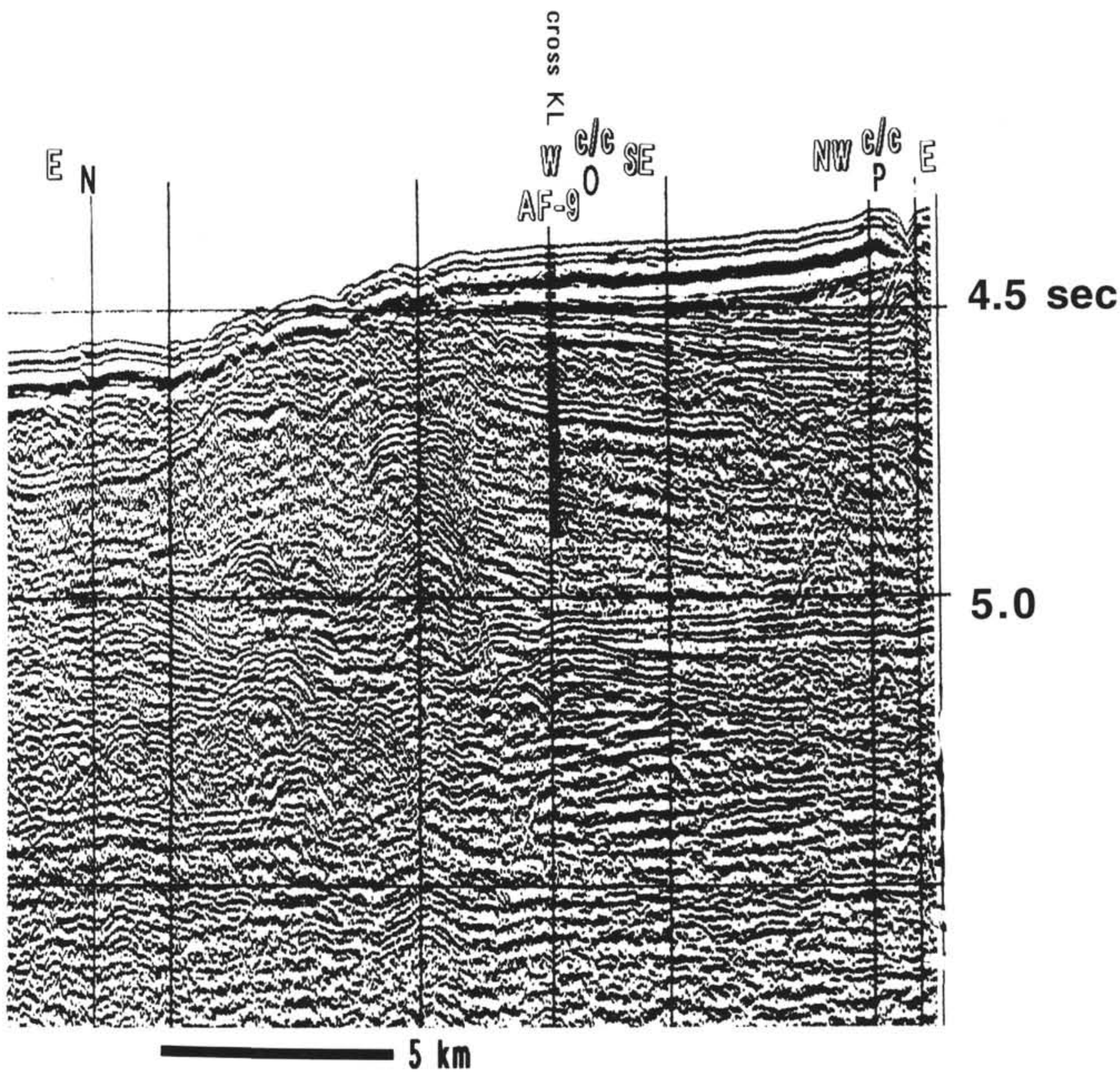
Site: AF-8
Priority: 2
Position: 5°13.99'N, 47°07.93'W
Water Depth: 3497 m
Sediment Thickness: 4000 m
Seismic Coverage: E9209 0730 hrs 09/21; E9209 0930 hrs 09/21

Objectives: At this site, we aim to sample proximal levees of the Blue system and system 6C. Because of the greater water depth, the planktonic record will not be as good as at proposed sites AF-7, AF-16, and AF-17. The hole at this site complements proposed site AF-11 and might be drilled if the shallower water stratigraphic holes experience hole-control problems or if we expect along-channel changes in sediment facies.

Drilling Program: APC/XCB to refusal or target depth. Deeper target is 6C levee.

Logging and Downhole Operations: Core orientation, Adara/WSTP. Full suite of logs if conditions permit.

Nature of Rock Anticipated: Silty clay with scattered sand layers.


cross KL
E
N
W
c/c
O
SE
AF-9
NW
c/c
P
E
4.5 sec
5.0
5 km

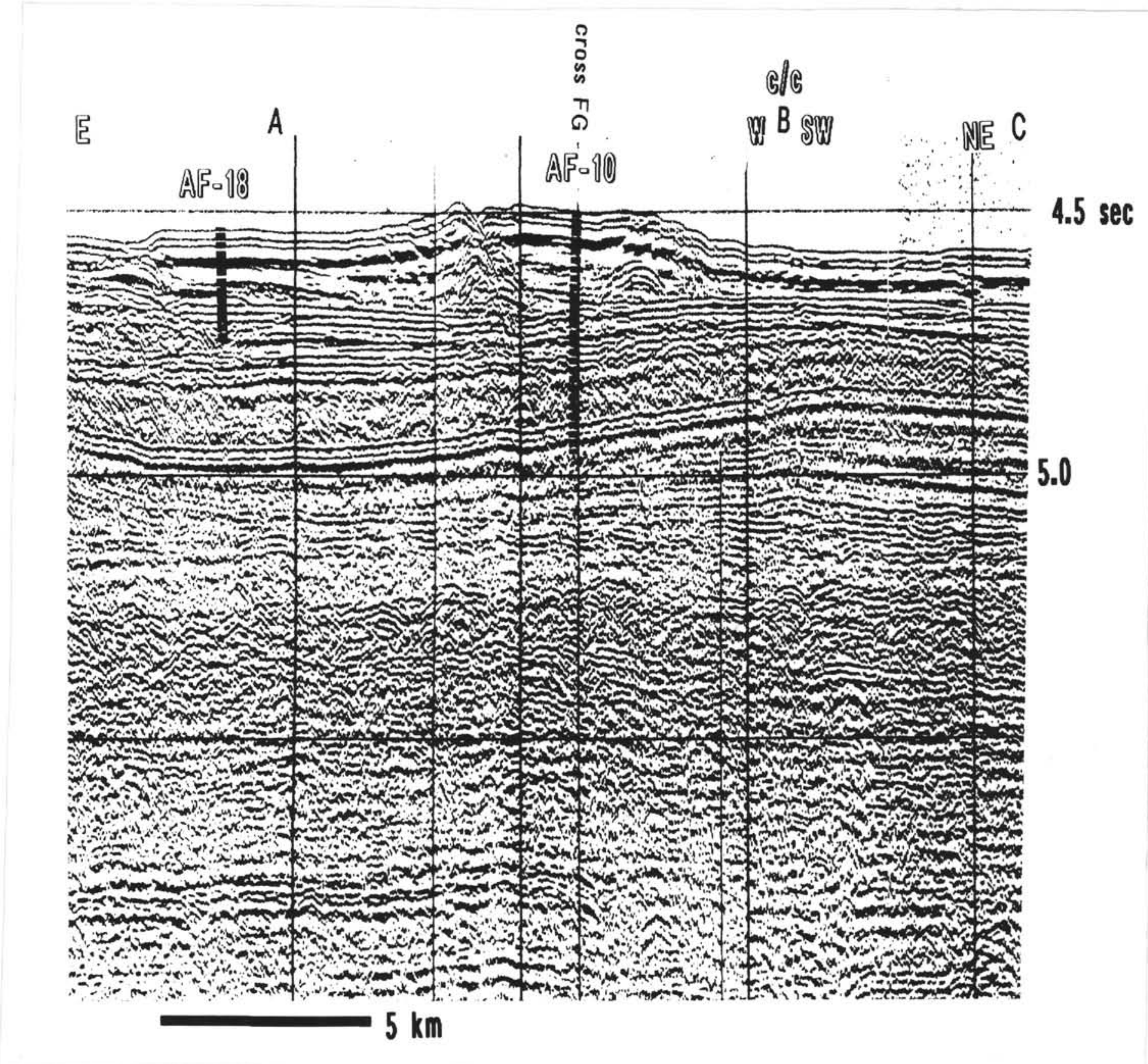
Site: AF-9
Priority: 1
Position: 5°08.09'N, 46°48.99'W
Water Depth: 3407 m
Sediment Thickness: 4000 m
Seismic Coverage: E9209 0415 hrs 09/21; E9209 0022 hrs 09/21

Objectives: At this site, we aim to penetrate the proximal part of the Channel 4 levee (Yellow system), distal levee sediments of Channel 6A, a possible debris flow, and the crest of a deep, unnamed levee. The primary objective is to sample stratigraphically the Channel 4 levee and the deep unnamed levee. A secondary objective would be to duplicate the objectives at proposed site AF-10, although better dating is expected at site AF-9 because of the paleotopographic expression.

Drilling Program: Hole A: APC/XCB to refusal or target depth at flank/crest of old levee (~275 mbsf). Possible extension to 370 mbsf. Hole B: APC/XCB to 50 mbsf, possible extension to ~225 mbsf.

Logging and Downhole Operations: Hole A: Core orientation is moderate priority. Adara/WSTP is low priority. No logging.

Nature of Rock Anticipated: Silty clay with scattered sand layers.


cross FG
c/c
E
A
W B SW
NE C
AF-18
AF-10
4.5 sec
5.0
5 km

Site: AF-10
Priority: 1
Position: 5°11.52'N, 46°38.95'W
Water Depth: 3550 m
Sediment Thickness: 4000 m
Seismic Coverage: E9209 1737 hrs 09/20; E9209 0181 hrs 09/20; E9209 2014 hrs 09/20

Objectives: At this site, we aim to sample the Channel 5 levee (?Yellow system) and the flank of a deep unnamed levee. The primary objectives are to (a) sample hemipelagic section above the Channel 5 levee as a biostratigraphic reference, (b) characterize facies in the proximal part of the levee, and (c) stratigraphically sample the Channel 5 levee and the deep unnamed levee. This will be the first hole to provide some experience in the problems associated with drilling in HARP's and the possible character of a deep hyperbolated interval (debris flow?).

Drilling Program: Hole A: APC/XCB to refusal or target depth (~420 mbsf). Hole B: APC/XCB to ~50 mbsf. Possible Hole C: APC/XCB to ~50 mbsf.

Logging and Downhole Operations: Core orientation is moderate priority. Adara/WSTP is high priority. Full suite of logs if conditions permit. Possible GHMT log.

Nature of Rock Anticipated: Silty clay with scattered sand layers.

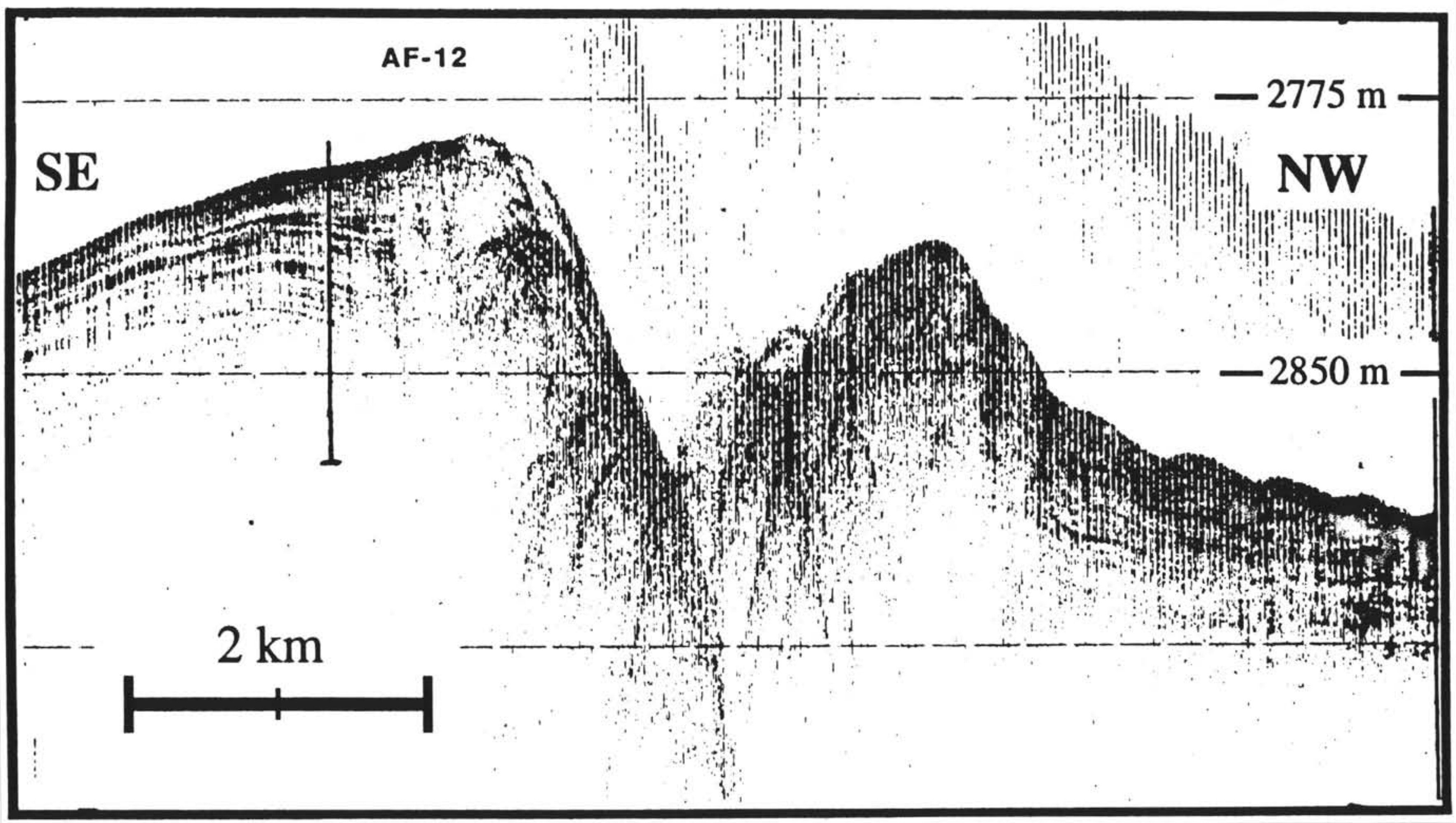
Site: AF-11
Priority: 1
Position: 5°12.79'N, 47°02.06'W
Water Depth: 3384 m
Sediment Thickness: 4000 m
Seismic Coverage: E9209 0635 hrs 09/21; E9209 1150 hrs 09/21

Objectives: At this site, we aim to penetrate relatively proximal sediments of levee 6A and possibly an underlying HARP. The primary objectives are to (a) stratigraphically sample the Channel 6A levee, and (b) obtain a long (expanded) levee sequence to examine sedimentological and detrital trends.

Drilling Program: Hole A: APC/XCB to refusal or target depth at base of levee (~275 mbsf). Possible second priority extension to HARP's (~320 mbsf) depending on results of site AF-10. Hole B: APC/XCB to at least 50 mbsf.

Logging and Downhole Operations: Core orientation is moderate priority. Adara/WSTP is moderate priority. Probable Quad-combo and FMS logs.

Nature of Rock Anticipated: Silty clay.


AF-12
SE
NW
2775 m
2850 m
2 km

Site: AF-12
Priority: 1
Position: 4°43.36'N, 47°30.22'W
Water Depth: 2794 m
Sediment Thickness: 4000 m
Seismic Coverage: C2514 0837 hrs 12/08

Objectives: The hole at this site complements proposed site AF-6 and we will sample acoustically transparent over acoustically layered sediments in the Amazon Channel levee at a shallower depth than at proposed site AF-6, probably corresponding to a perhaps sea-level induced change from a straight to a sinuous channel. If a deep hole is drilled, at about 254 m, we should pass into levee deposits of the Blue, Orange, and Channel 6 systems that overlie the upslope equivalent of the Unit R debris flow. The primary objectives of a short hole are to (a) date, characterize, and understand the change from transparent to stratified sediment on the levees, and (b) complement objectives (b) and (c) at proposed site AF-6. The primary objectives of drilling the deeper part of the hole are to (c) obtain a stratigraphic section of the Blue, Orange, and Channel 6 systems, and (d) determine the character of the R debris flow in the most proximal area where it will be sampled. Partial reason for the second hole is for obtaining whole round samples for analyses to characterize organic origin and diagenesis.

Drilling Program: Hole A: APC/XCB to target depth ~100 mbsf. Possible extension to ~640 mbsf. Hole B: APC/XCB to target depth ~100 mbsf.

Logging and Downhole Operations: Core orientation is high priority. Possible Adara/WSTP (low priority). Full suite of logs only if deep extension is drilled.

Nature of Rock Anticipated: Silty clay in short hole with scattered sand layers in extension.

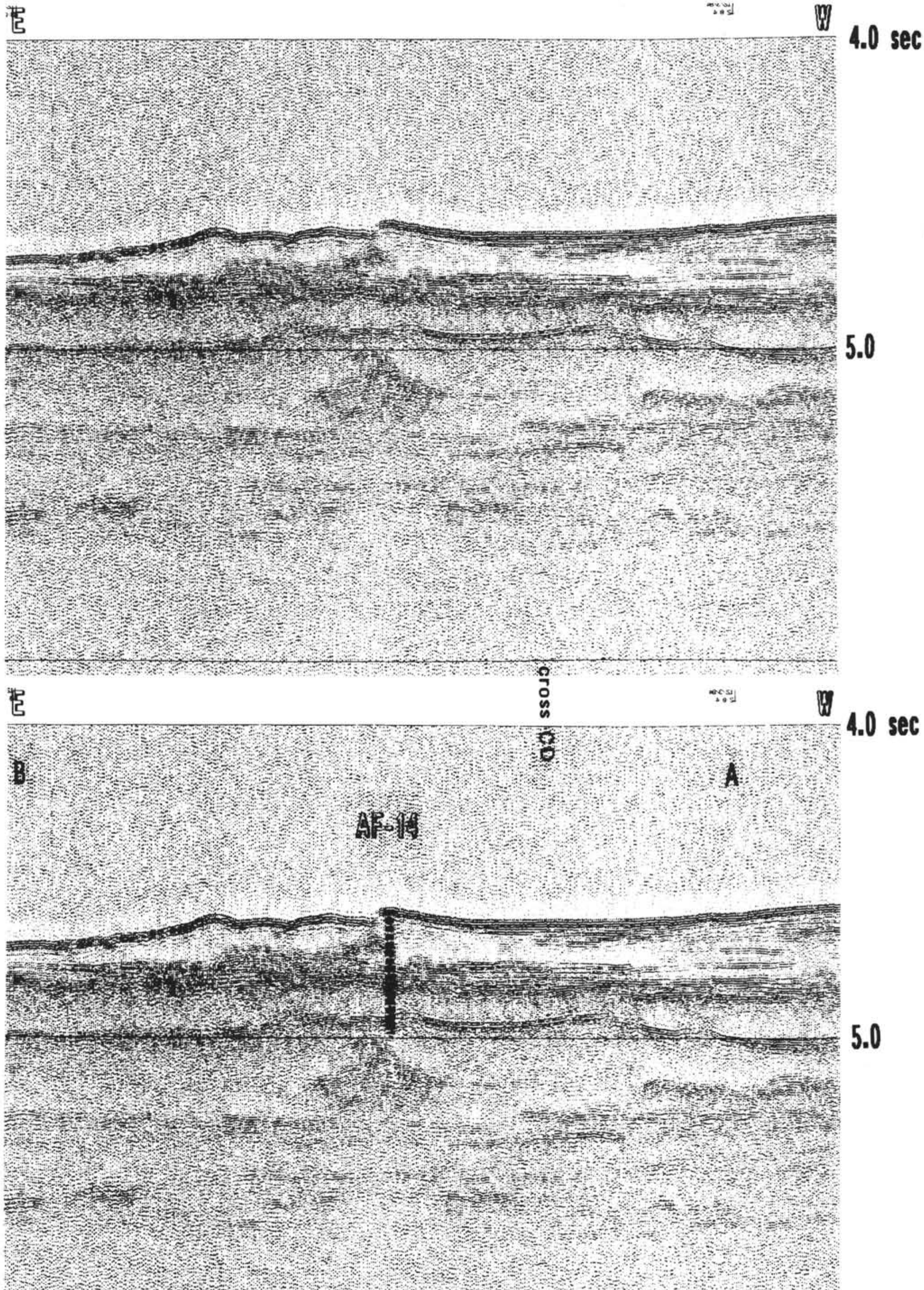
Site: AF-13
Priority: 1
Position: 5°56.08'N, 47°44.60'W
Water Depth: 3710 m
Sediment Thickness: 4000 m
Seismic Coverage: C2514 0537 hrs 12/04

Objectives: At this site, we aim to sample very young pelagic sediment above the Brown levee, and then the Brown HARP's, the Unit R debris flow, and the top of the Red levee. The primary objectives are to (a) sample post-Brown pelagic sediment and to characterize sediments during Brown abandonment, and (b) characterize the HARP's (in conjunction with data from proposed sites AF-2 and AF-3). Secondary objectives include a further understanding of downslope behavior of debris flow and the sampling of the Red interval.

Drilling Program: Hole A: APC/XCB to base of Brown HARP at ~125 mbsf. Second priority extension to ~273 mbsf if Red levee is not previously recovered.

Logging and Downhole Operations: Core orientation is high priority. Adara is low priority.

Nature of Rock Anticipated: Silty clay with scattered sand layers.


E
W
4.0 sec
5.0
E
cross CD
W
4.0 sec
B
A
AF-14
5.0
5 km

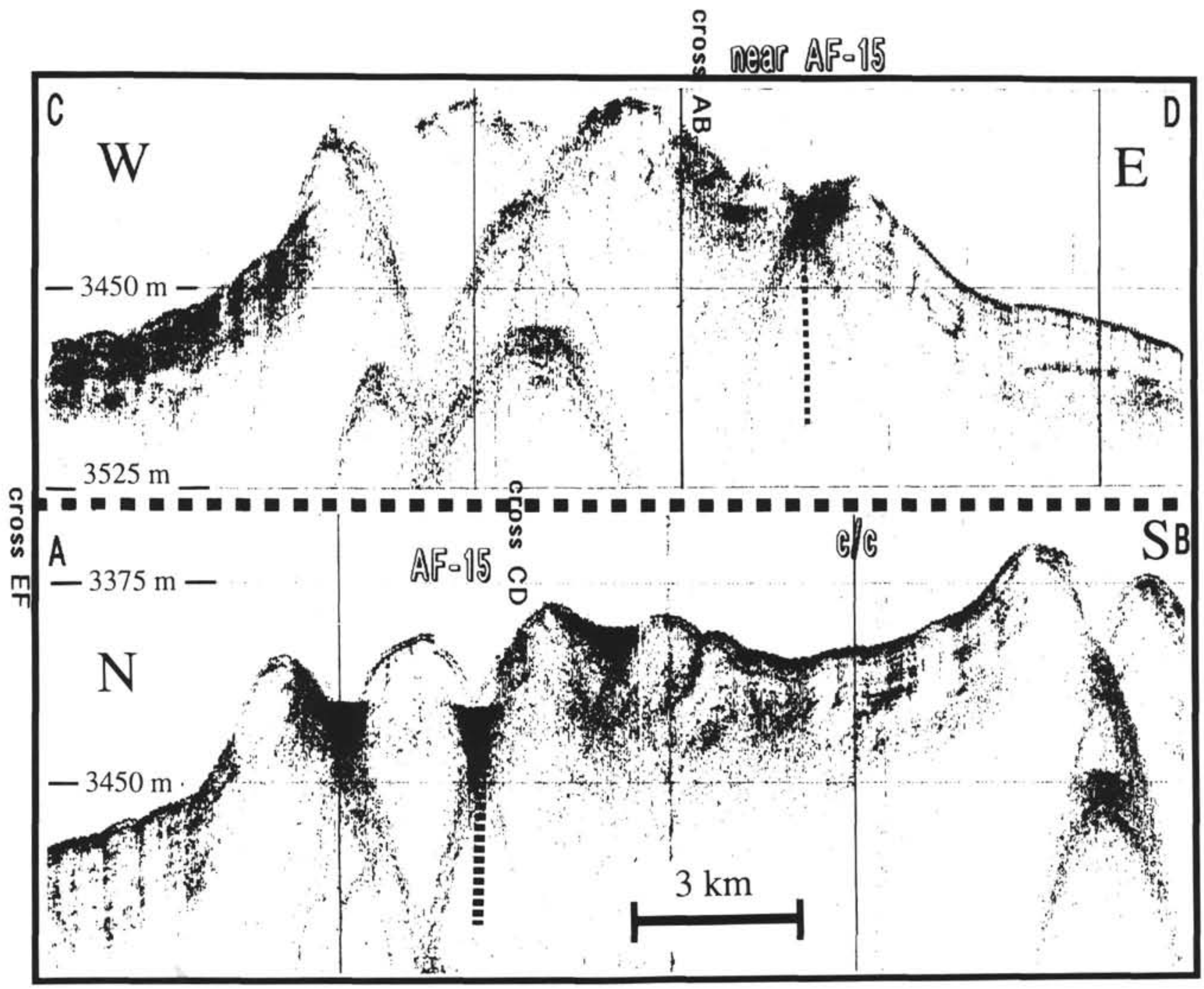
Site: AF-14
Priority: 1
Position: 5°25.63'N, 47°32.02'W
Water Depth: 3488 m
Sediment Thickness: 4000 m
Seismic Coverage: C2514 0230 hrs 12/03; FR815 0400 hrs 1/15 (projected 3 mi)

Objectives: At this site, we aim to sample young pelagic sediment above the Aqua levee, then the Aqua HARP, an earlier HARP, the Unit R debris flow, and the top of the Green levee. Objectives are similar to those at proposed site AF-13. The primary objective is to sample post-Aqua pelagic sediment in relationship to post-Brown sediment and Channel 1 sediment. Secondary objectives include a further understanding of downslope behavior of the Unit R debris flow, further characterization of HARP's through sampling units in space and time, and sampling the Green interval and the possible paleontological record on top of the Green levee.

Drilling Program: Hole A: APC/XCB to top of Green levee (~370 mbsf).

Logging and Downhole Operations: Core orientation is high priority. Adara is high priority. Full suite of logs and GHMT if conditions permit.

Nature of Rock Anticipated: Silty clay with scattered sand layers and debris flow.


cross AB
near AF-15
C
D
W
E
— 3450 m —
3525 m
cross EF
cross CD
A
AF-15
c/c
S
B
— 3375 m —
N
— 3450 m
3 km

Site: AF-15
Priority: 1
Position: 5°29.04'N, 47°40.87'W
Water Depth: 3415 m
Sediment Thickness: 4000 m
Seismic Coverage: C2514 2234 hrs 12/06

Objectives: At this site, we aim to penetrate the fill of an abandoned channel meander still attached to Amazon Channel. The meander may have been abandoned as a result of avulsion and downcutting associated with the abandonment of the Brown system. The primary objectives are to (a) determine the age of the meander cut-off, so that it can be related to other channel processes, (b) characterize sediment type and sequence in the cut-off, and (c) complement objectives (b) and (c) at proposed site AF-6. Partial reason for the second hole is for obtaining whole round samples for analyses to characterize organic origin and diagenesis.

Drilling Program: Holes A and B: APC/XCB to target depth (~100 mbsf).

Logging and Downhole Operations: Core orientation is high priority. Adara/WSTP is moderate priority. Logging, if at all possible, with Quad-combo, FMS, and then geochemical logging in the pipe.

Nature of Rock Anticipated: Silty clay with scattered sand layers. Sand particularly abundant below 50 mbsf.

Site: AF-16

Priority: 1

Position: 4°39.60'N, 47°18.82'W

Water Depth: 2811 m

Sediment Thickness: 4000 m

Seismic Coverage: FR815 0904 hrs 1/12; FR815 2236 hrs 1/07 (projected 0.2 mi)

Objectives: Proposed site AF-16 is located on an elevated section of the Blue levee. At this site, we aim to penetrate post-Blue pelagic sediment, the Blue levee, and the Channel 6 levee. Primary objectives are to (a) obtain a pelagic stratigraphic section, to complement that at proposed site AF-17, above the Blue levee, (b) to obtain possibly pelagic sediments between the Blue and Channel 6 levees, and (c) stratigraphically sample the Blue and Channel 6 levees.

Drilling Program: Hole A: APC/XCB to target depth at buried Channel 6 levee crest (~273 mbsf). Possible Hole B: targeting deep pelagic section (~200-273 mbsf).

Logging and Downhole Operations: Core orientation is moderate priority. Adara/WSTP is high priority. Probable Quad-combo and FMS logging.

Nature of Rock Anticipated: Silty clay.

Site: AF-17
Priority: 1
Position: 4°35.17'N, 47°11.51'W
Water Depth: 2797 m
Sediment Thickness: 4000 m
Seismic Coverage: FR815 0758 hrs 1/12; FR815 0320 hrs 1/07 (projected 3.5 mi)

Objectives: Proposed site AF-17 is located on an elevated section of the Yellow levee, and we expect to penetrate primarily pelagic material. The primary objective is to obtain a pelagic stratigraphic section above the Yellow levee. Secondary objectives include stratigraphic sampling and sedimentological characterization of the Yellow levee.

Drilling Program: Holes A and B: APC/XCB Yellow levee crest (~133 mbsf). Probable Hole C: APC/XCB to total depth.

Logging and Downhole Operations: Hole A: Core orientation is low priority. Adara/WSTP is low priority. No logs.

Nature of Rock Anticipated: Silty clay.

Site: AF-18
Priority: 3
Position: 5°07.90'N, 46°33.85'W
Water Depth: 3520 m
Sediment Thickness: 4000 m
Seismic Coverage: E9209 1555 hrs 09/20

Objectives: This priority 3 site has similar objectives to those at proposed site AF-10, sampling the pelagic record on the eastern part of the fan and the Channel 5 levees overlying a HARP.

Drilling Program: Hole A: APC/XCB to refusal or target depth (~179 mbsf). Hole B: APC/XCB to ~179 mbsf.

Logging and Downhole Operations: Core orientation, Adara/WSTP. Full suite of logs if conditions permit.

Nature of Rock Anticipated: Silty clay with scattered sand layers.

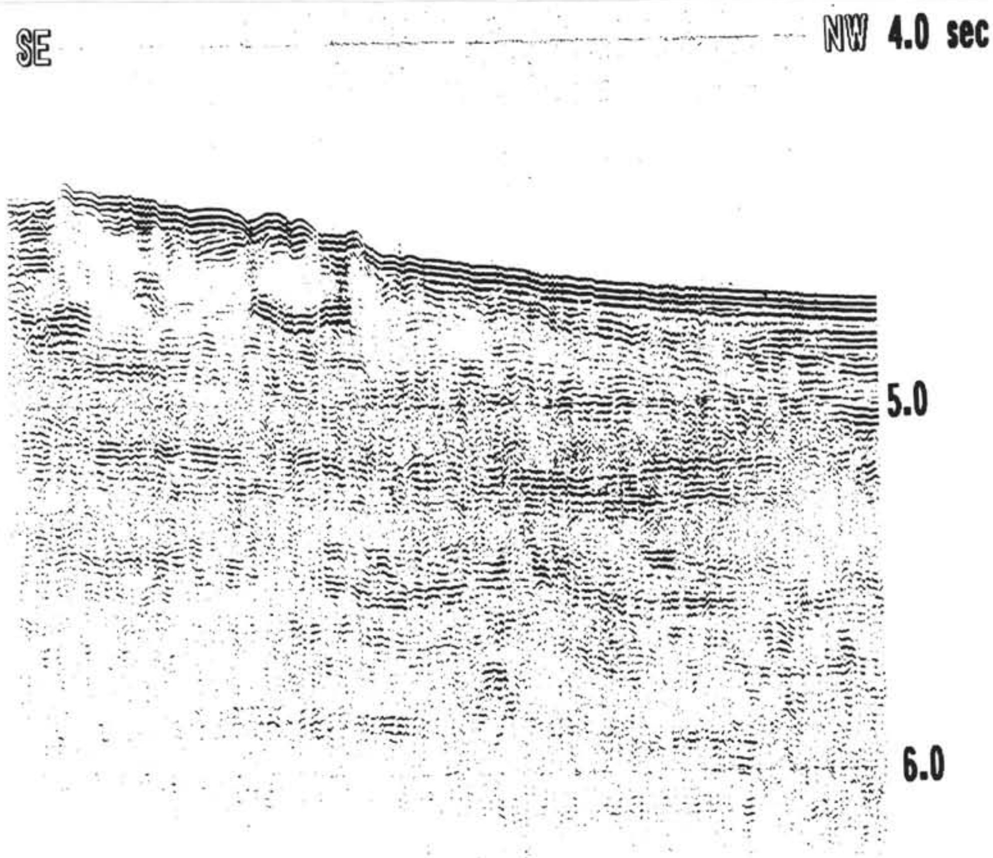
Site: AF-19
Priority: 2
Position: 5°13.53'N, 47°05.54'W
Water Depth: 3434 m
Sediment Thickness: 4000 m
Seismic Coverage: E9209 0708 hrs 09/21; E9209 1045 hrs 09/21 (projected 0.5 mi)

Objectives: At this site, we aim to sample proximal levee sediments of system 6B and the overlying hemipelagic sediments. It is close to proposed sites AF-8 and AF-11 but suffers from the same problem of uncertain preservation of carbonate.

Drilling Program: Hole A: APC/XCB to target depth (~133 mbsf). Possible extension to ~273 mbsf. Hole B: APC/XCB to ~133 mbsf.

Logging and Downhole Operations: Core orientation, Adara/WSTP. Full suite of logs if conditions permit.

Nature of Rock Anticipated: Silty clay.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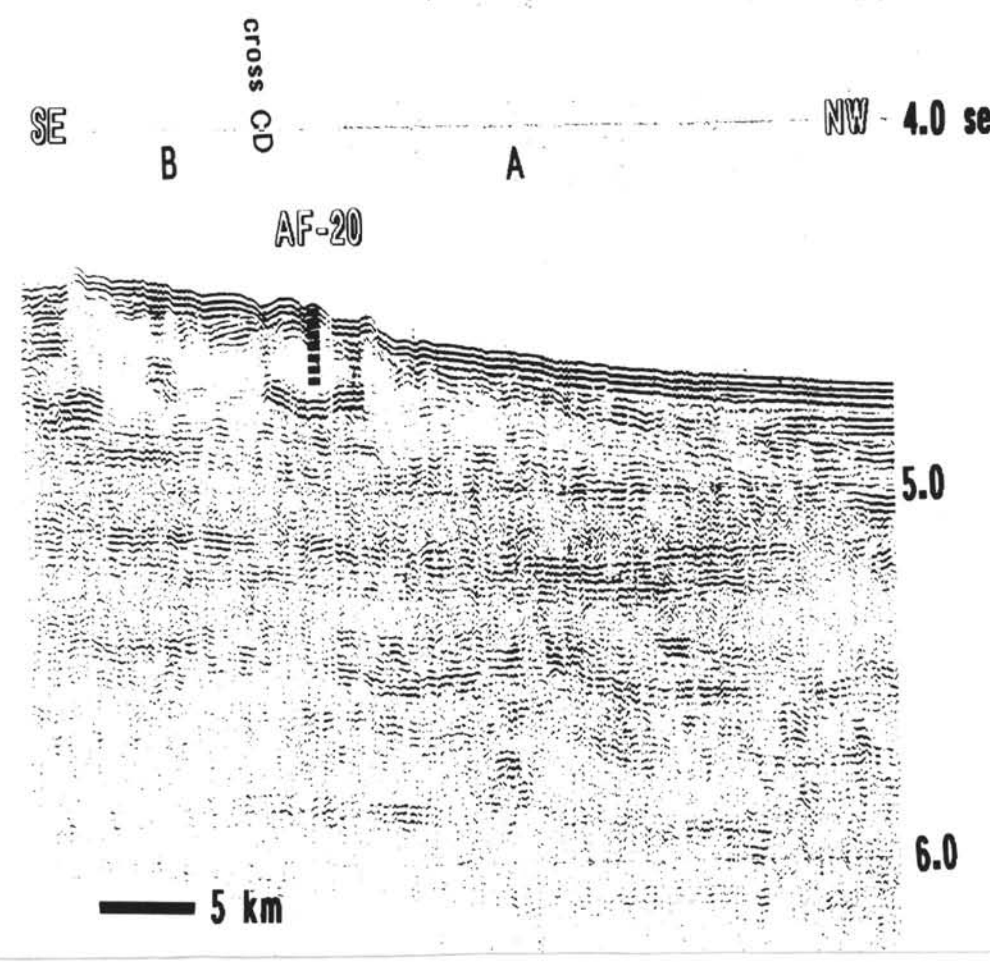
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B
A
AF-20
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5 km

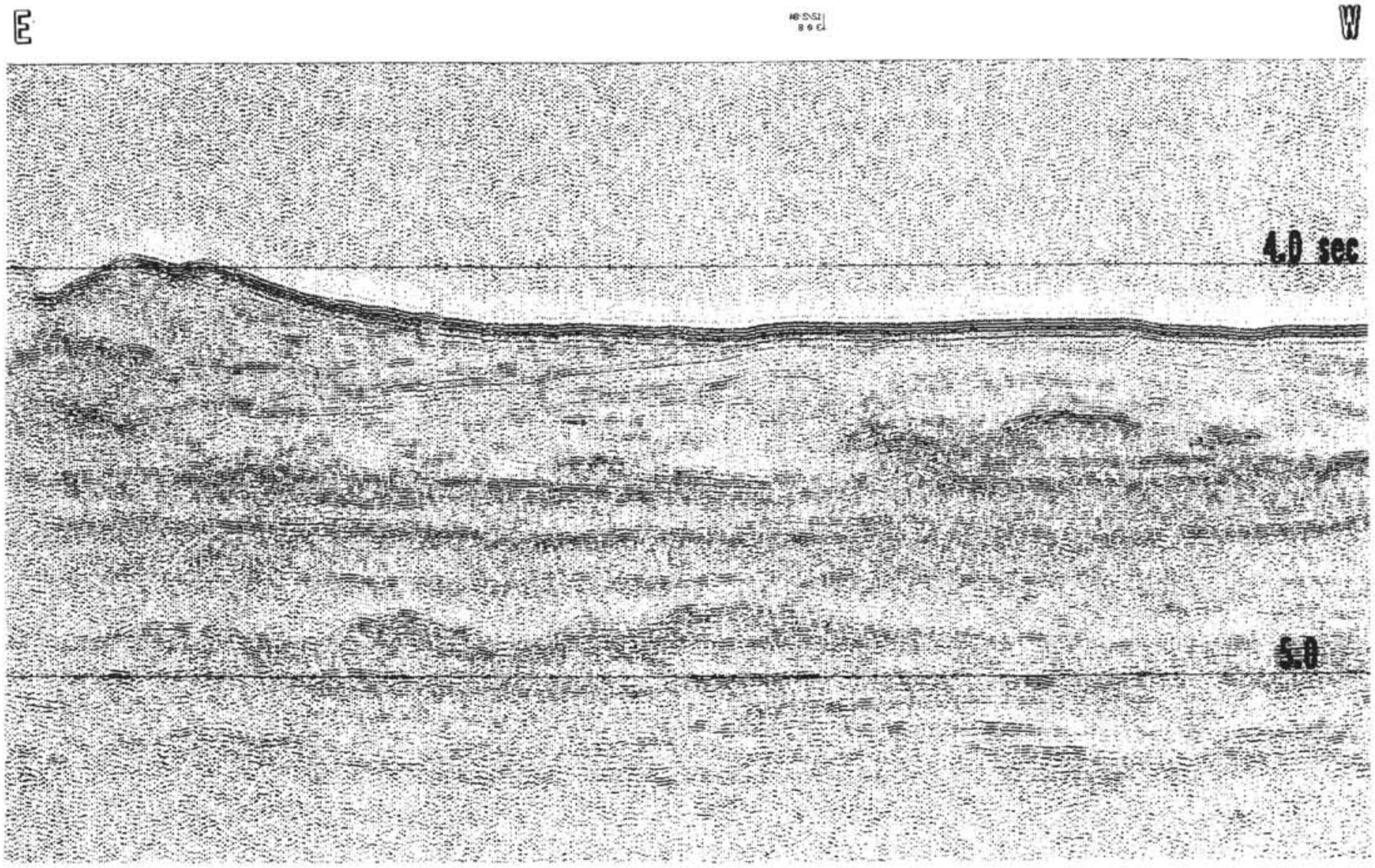
Site: AF-20
Priority: 1
Position: 5°44.24'N, 49°07.39'W
Water Depth: 3368 m
Sediment Thickness: 4000 m
Seismic Coverage: C1612 1925 hrs (1625 on profile) 7/26; FR815 1810 hrs 1/15 (projected 1 mi)

Objectives: This site is located on an old levee on the western edge of the fan. Some debris-flow deposits will be interfingered with the levee-crest hemipelagic record. The primary objective is to obtain a pelagic record to complement that at proposed site AF-17 on the eastern part of the fan, thus together providing a record of surface circulation changes. Whole-round samples for geochemistry may be needed in the A hole.

Drilling Program: Hole A: APC/XCB to target depth (~180 mbsf). Hole B: APC/XCB to ~40 mbsf, depending on results of Hole A. Probable Hole C: same as Hole B.

Logging and Downhole Operations: Core orientation is moderate priority. Adara/WSTP is high priority. No logging.

Nature of Rock Anticipated: Silty clay with scattered debris flow deposits.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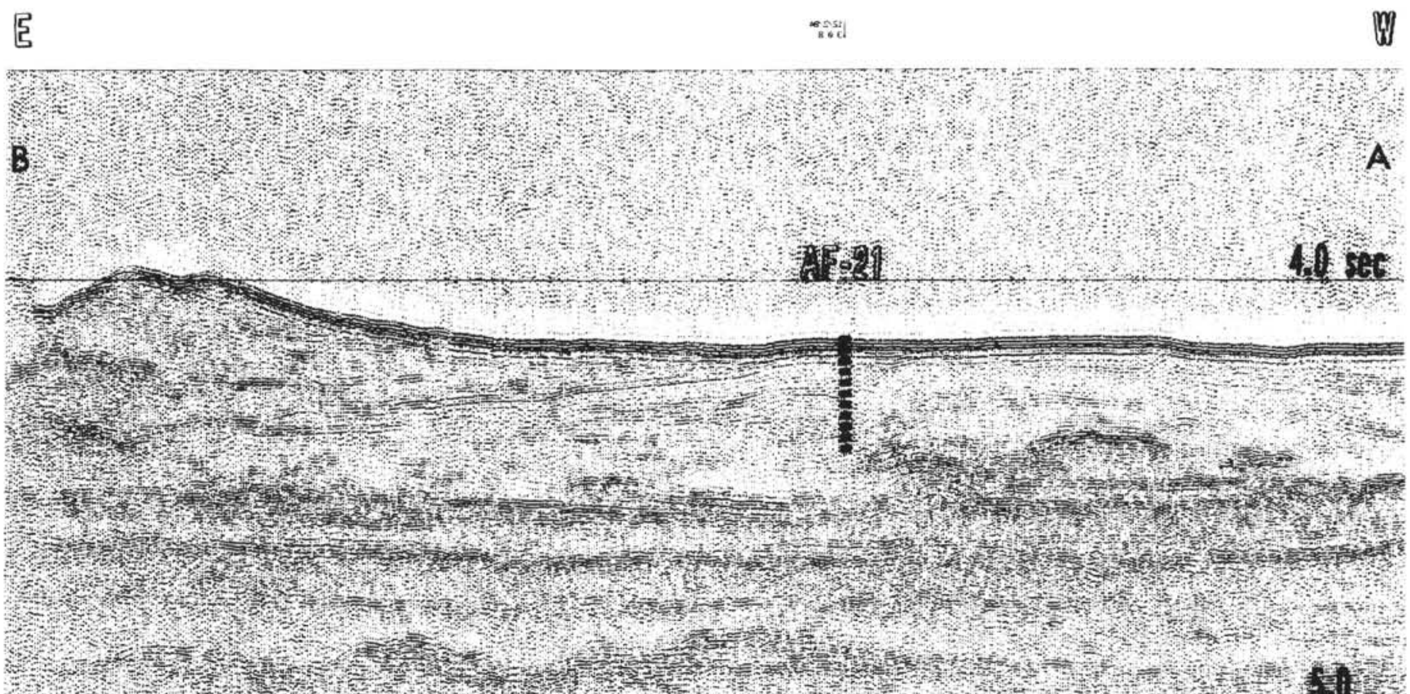

E
W
B
A
AF-21
4.0 sec
5.0
5 km

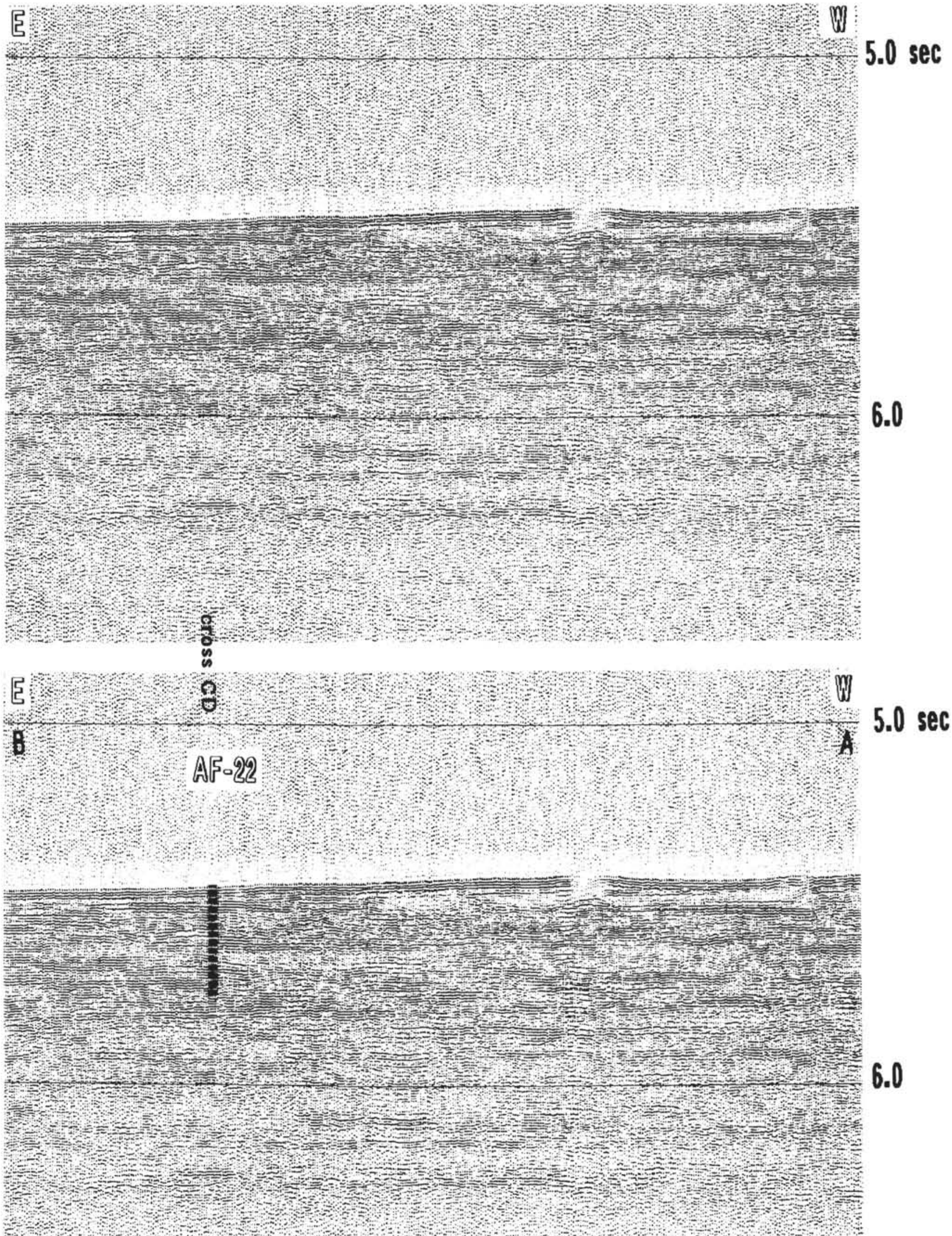
Site: AF-21
Priority: 1
Position: 5°00.73'N, 47°35.63'W
Water Depth: 3128 m
Sediment Thickness: 4000 m
Seismic Coverage: C2514 0300 hrs 12/02; C2514 2335 hrs 12/01 (projected 5 mi)

Objectives: At this site, we aim to sample the levee flank of the Amazon levee, the flank of the Purple levee, and into the crest of the Orange levee. The primary objective is to sample the unit stratigraphically at the top of the Orange levee. Secondary objectives include the sedimentological characterization of three levee flank sequences and the sedimentological comparison of levee crests and flanks in the Amazon Channel.

Drilling Program: Hole A: APC/XCB into crest of Orange levee (~250 mbsf). Hole B: APC/XCB to top of Orange levee (~143 mbsf).

Logging and Downhole Operations: Core orientation is moderate priority. Adara is moderate priority. No logging.

Nature of Rock Anticipated: Silty clay.


E
W
5.0 sec
6.0
cross CD
E
W
5.0 sec
B
A
AF-22
6.0
5 km

Site: AF-22
Priority: 1
Position: 6°57.33'N, 47°52.98'W
Water Depth: 4124 m
Sediment Thickness: 4000 m
Seismic Coverage: C2514 0151 hrs 12/18; C2514 1626 hrs 12/17

Objectives: This site is the most distal of the proposed sites and we aim to sample 35 m of Amazon levee overlying a thick HARP sequence that probably represents channel termination zone deposits and is acoustically similar to the lower fan. The primary objectives are to (a) characterize channel-termination zone deposits, and (b) recover distal levee sediments to complement objective (b) at proposed site AF-6. A secondary objective is to characterize and date the older levee sequence underlying the HARP package. Partial reason for the second hole is for obtaining whole round samples for analyses to characterize organic origin and diagenesis.

Drilling Program: Holes A and B: APC/XCB to ~225 mbsf.

Logging and Downhole Operations: Core orientation is high priority. Adara/WSTP is high priority. Quad-combo and FMS logs.

Nature of Rock Anticipated: Silty clay with sand layers, particularly 35-180 mbsf.

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