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38. BIOSTRATIGRAPHY AND SEDIMENTATION RATES OF THE AMAZON FAN[1]

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ABSTRACT

Although the Amazon Fan is a complex stratigraphic sequence of mass-transport deposits (MTDs), levee complexes, and hemipelagic oozes, the interpretation of micropaleontological and isotopic data from the Amazon Fan has provided excellent results. Compared to other mega deep-sea fans, the Amazon Fan is highly structured, thus providing an unusual opportunity to investigate the Quaternary evolution of a deep-sea fan.

Biostratigraphic work has been carried out on two of the main sedimentological fan units: (1) the upper Pleistocene/Holocene sediments that cap the entire fan area and are equivalent in age or younger than the paleomagnetic Lake Mungo Excursion of 32 ka; and (2) the interglacial deep-carbonate units that underlie the MTDs and are younger than the *Pseudoemiliania lacunosa* event of 475 ka. Age assignments are primarily based on biostratigraphic analyses of calcareous nannofossils and planktonic foraminifers. Nannofossils are common only in the Holocene calcareous muds and in the deep carbonate units. Foraminifers are common in the same units, but are also present in the glacial levee muds underlying the Holocene calcareous clays. Additional age constraints are provided by interpretation of the paleomagnetic record and accelerator mass-spectrometry ^{14}C dates. Stable oxygen- and carbon-isotope data are used to further refine the biostratigraphic and environmental interpretations.

Biostratigraphy of the cores retrieved during Leg 155 has provided an overall stratigraphic framework for understanding the Quaternary evolution of the Amazon Fan. Biostratigraphic and paleomagnetic data are combined to provide estimates of sedimentation rates, ranging from 5 cm/k.y. during interglacial periods, to over 5000 cm/k.y. during glacial periods. A combination of biostratigraphy, seismic stratigraphy, magnetostratigraphy, and sedimentation rate constraints was used to date the top of both the near-surface MTDs and the deep MTDs. These data suggest that the deep MTDs were last active at ~33 ka and 45 ka, whereas the near-surface MTDs were active during Termination I (11–14 ka).

INTRODUCTION

Deep-sea fans are found offshore from many of the world’s major rivers; for example, the distal part of the Bengal Fan, the Zaire (Congo) Fan, the Mississippi Fan, and the Amazon Fan. Though deep-sea fans may provide unique information on both terrestrial and past marine environments and climates, their deposits are rarely studied because of the rather inhomogeneous and complex nature of sediment structures as compared to open ocean sediments. The Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) have previously drilled the Mississippi Fan (Bouma, Coleman, Meyer, et al., 1986) and the Bengal Fan (Cochran, Stow, et al., 1990). The deepest sediment recovered during DSDP Leg 96 in the Mississippi Fan (515 meters below seafloor [mbsf]) was younger than 275 ka. The Mississippi Fan complex is less structured than the Amazon Fan as its terrestrial sedimentation has been continuous, unlike the “on-off” glacial-interglacial sedimentation on the Amazon Fan. In contrast, the Bengal Fan seems to be constructed entirely by turbidites. The deepest site drilled on the Bengal Fan during ODP Leg 116 bottomed at ~950 mbsf and reached sediments of Miocene age (older than 16 Ma; Gartner, 1990). In comparison, Leg 155 reached a maximum depth of 438 mbsf, the oldest sediment recovered being younger than 475 ka (Flood, Piper, Klaus, et al., 1995).

The Amazon River has created a subaqueous delta that stretches for hundreds of kilometers alongshore and offshore and reaches the shelf where it forms the deep-sea Amazon Fan (Nittrouer et al., 1986) (Fig. 1). There are two distinct phases of Amazon Fan sediment supply during the Quaternary period (Milliman et al., 1975). During high interglacial sea levels, most of the sediment transported by the Amazon River was deposited near the river mouth, and only hemipelagic open-ocean sedimentation took place on the fan. During glacial periods with greatly reduced sea level, most of the Amazon River sediments were channeled directly to the deep sea, forming extensive glacial-stage deposits in the fan area. This “on-off” sedimentation on the Amazon Fan is one of the reasons for it being so structured, thus allowing successful biostratigraphic investigations.

The Amazon Fan complex is composed of several sedimentological units that have been defined by careful analysis of seismic data and sedimentological investigations (Fig. 2; Flood, Piper, Klaus, et al., 1995). The key components of the Amazon Fan are (1) a thin Holocene ooze that caps the entire fan area and includes at its base a time-transgressive iron-rich crust, (2) levee complexes and channel deposits, (3) mass-transport deposits (MTDs), and (4) relatively thin, calcium carbonate-rich interglacial deposits, here termed the “deep carbonate units,” found beneath the MTDs (Fig. 3).

The complex structure of the Amazon Fan is far from an ideal setting for conducting biostratigraphic and stable isotope studies. The purpose of this paper, therefore, is to present biostratigraphic information from the Amazon Fan drilling and to attempt to organize the information into a coherent stratigraphic model in view of the fan’s complicated stratigraphy. We demonstrate that Amazon Fan deposits can provide comprehensive and valuable information when samples and data are carefully selected and interpreted.

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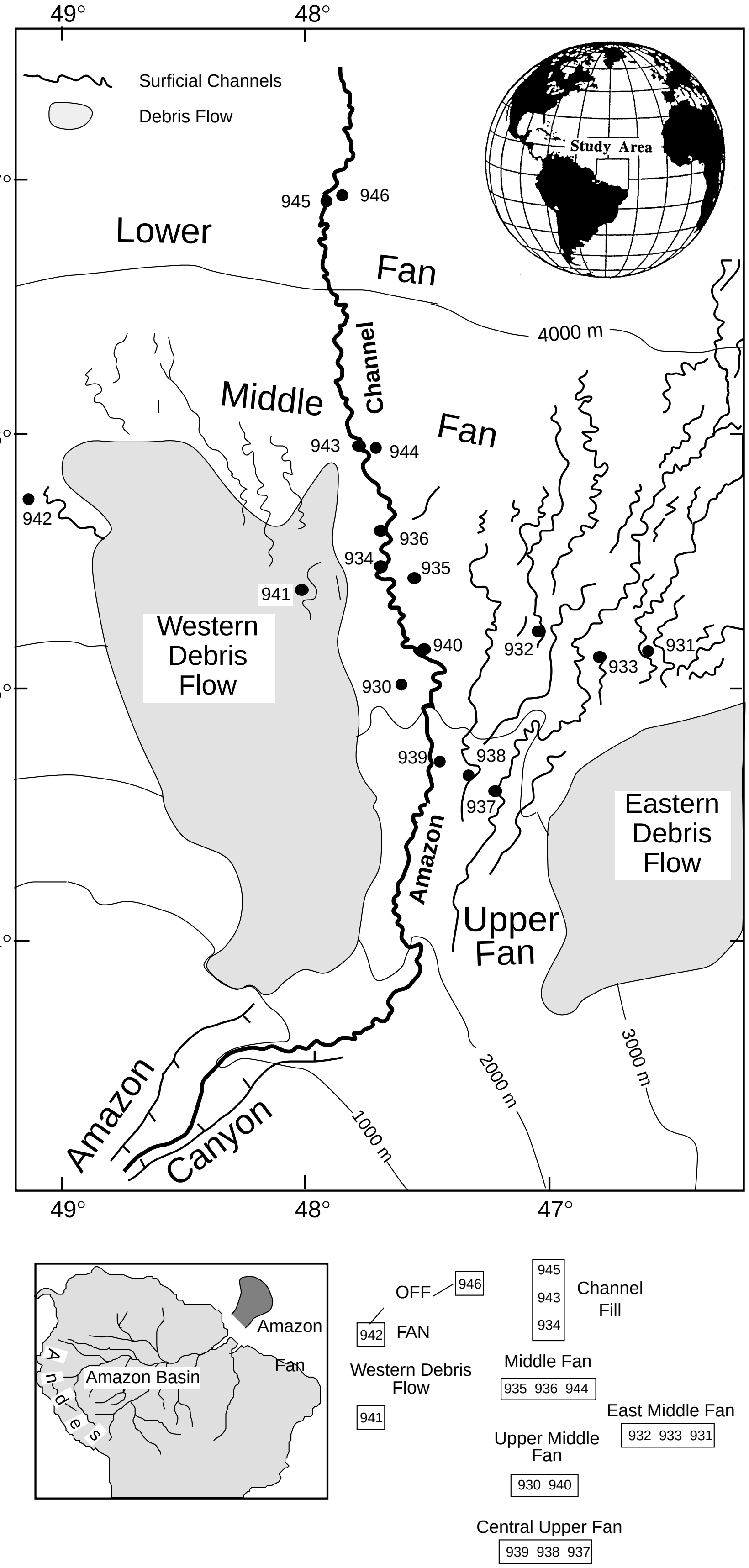

Figure 1. Map of the Amazon Fan and location of Leg 155 sites. Modified from Flood et al., 1995; modified from Damuth et al., 1988, and Manley and Flood, 1988.

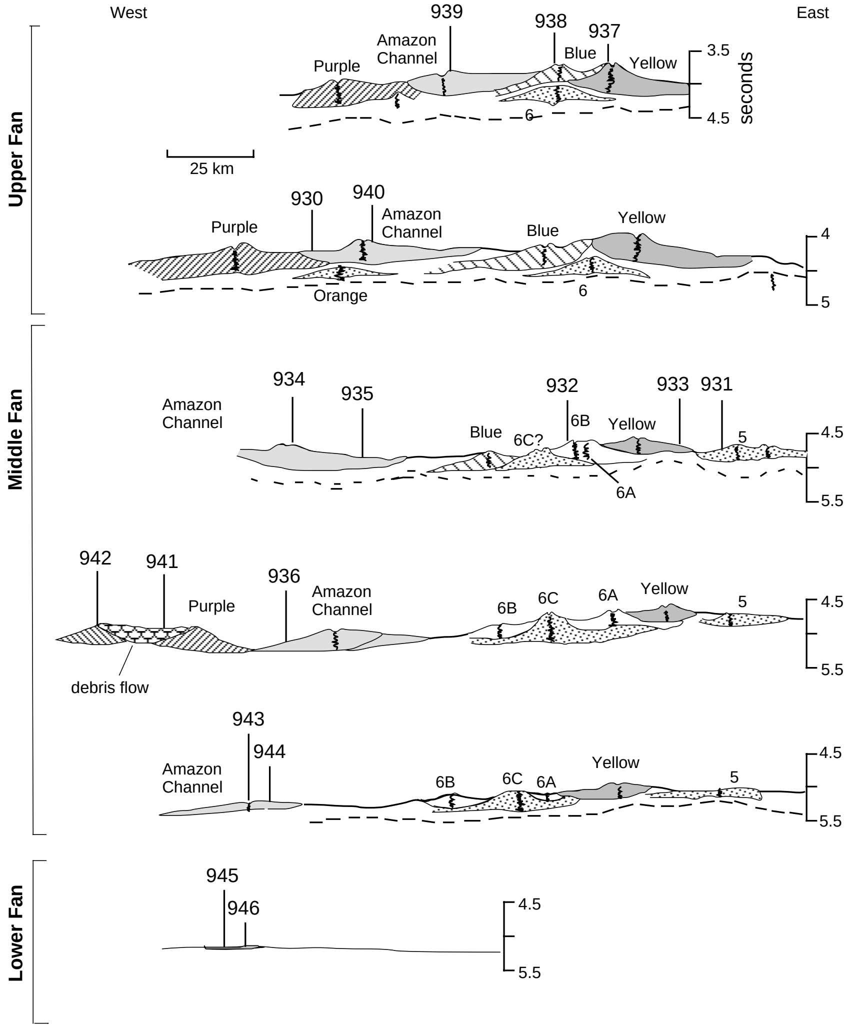

Figure 2. Fan construction. The Amazon Fan is constructed by thick and overlapping channel-levee systems that were formed by periodic channel avulsions. Previous studies have assigned color names and numbers to all the seismically recognized channel-levee systems (Manley and Flood, 1988; Damuth et al., 1983). Individual channel-levees are grouped into four larger levee complexes: the Upper, Middle, Lower, and Bottom Levee (see Fig. 18). All sites are grouped relative to their location on the fan (upper, middle, and lower fan sites).

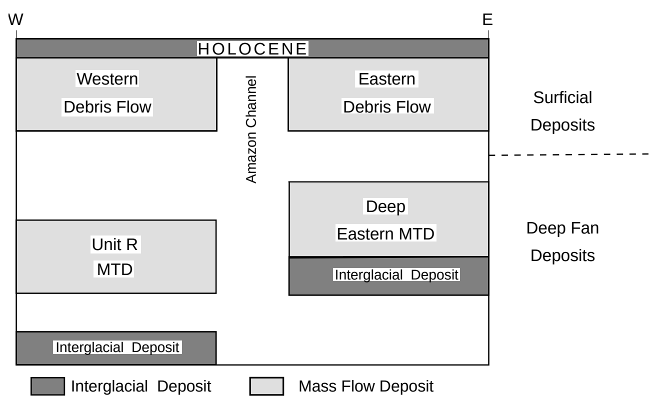

Figure 3. Schematic diagram showing the relationship between the Holocene calcareous clays capping the fan area, the mass-transport deposits (MTDs), and the interglacial hemipelagic deposits (the deep carbonate units) of the Amazon Fan.

BIOSTRATIGRAPHY

Age assignments are based on biostratigraphic analyses of calcareous nannofossils and planktonic foraminifers. Nannofossils and foraminifers are only present in relatively high abundances together in the hemipelagic sediments recovered from the Amazon Fan, whereas biostratigraphically useful foraminifers were also retrieved from the levee muds. Stratigraphic constraint of calcareous nannofossils and foraminifer datums was achieved by analyzing samples with a spacing of less than 0.1 m in the calcareous intervals.

The discontinuous nature of the deeper part of the Amazon Fan underlying the MTDs does not allow for a traditional subdivision of the hemipelagic sediments based either on biostratigraphic datums or on isotope stratigraphy. Nevertheless, based primarily on a correlation between nannofossil zones and a standard oxygen-isotope curve (Fig. 4), and supported by isotope values, the hemipelagic sediments underlying the MTDs have been tentatively placed into an isotope stage framework.

Calcareous Nannofossils

Zonation and Datum Levels

The Quaternary nannofossil biostratigraphy is based on the zonal scheme of Bukry (1973, 1975, 1978) and Okada and Bukry (1980), combined with the high-resolution Quaternary studies of Gartner (1977), Raffi et al. (1993), Weaver (1993), and Pujos and Giraudeau (1993). The Pleistocene/Holocene zonal schemes based on acme episodes (Weaver, 1993; Pujos and Giraudeau, 1993) were better adapted to the disrupted nature of the recovered sequences than the classical first/last appearance datums. However, no complete succession of acme periods as reported from the deep-sea record by Weaver (1993) and Pujos and Giraudeau (1993) has been found in the Amazon Fan. This situation is attributed to a number of factors. The first factor, dis-

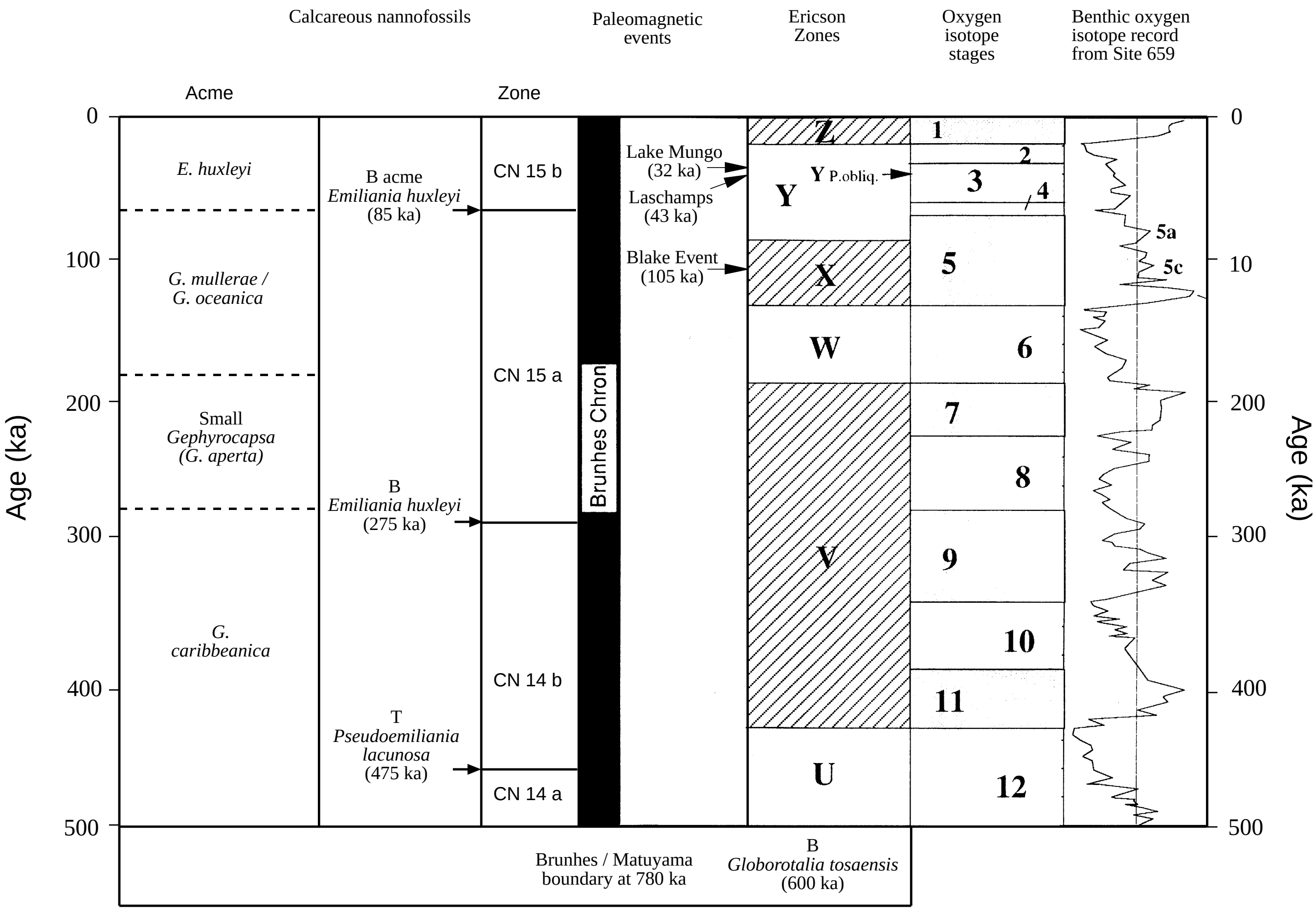

Figure 4. Summary of nannofossil acme zones of Weaver (1993) and Pujos and Giraudeau (1993); nannofossil zones of Okada and Bukry (1980); paleomagnetic events as used for Leg 155 sequences (Cisowski and Hall, this volume); and planktonic foraminifer stratigraphy (Ericson Zones of Ericson and Wollin, 1968; Ericson et al., 1961), all compared to age and the classical oxygen isotope stages (from Tiedemann et al., 1994).

solution, may affect specific taxa like the small *Gephyrocapsa* and thus distort the acme picture. Second, environmental and ecologically controlled conditions linked to the Amazon Fan environment distort the coccolith assemblages both qualitatively and quantitatively, and, therefore, produce atypical assemblages. Third, mixing and reworking, possibly the most important factor, have affected parts of the deposits, thus resulting in a disrupted and often distorted stratigraphic record.

The stratigraphic record recovered during Leg 155 encompasses only two standard nannofossil datums. One is the bottom of the acme of *Emiliania huxleyi*, which defines the base of nannofossil Zone CN15b. This datum, according to Thierstein et al. (1977), is time transgressive, occurring in isotope Stage 4 in transitional waters and in Substage 5b in low latitudes, but is here given an age of 85 ka. The other is the first occurrence of *E. huxleyi*, which defines the base of Zone CN15a at 275 ka. *Pseudoemiliania lacunosa,* which has its last occurrence at 475 ka, was not observed in situ, and all recovered sections are therefore younger than 475 ka. The CN14b/15a boundary was difficult to locate precisely in the Amazon Fan sites because of the reworked and diluted nature of the deposits. The problem locating this boundary may be further accentuated by ecologically controlled abundance fluctuations of the marker species *E. huxleyi* at the base of its first appearance (Gartner, 1972).

Abundant and well-preserved nannofossils are only found in true hemipelagic deposits of the Amazon Fan, that is, in the deep carbonates and in the Holocene calcareous clays that cap the Amazon Fan sequence. A sharp decrease in the abundance and preservation of nannofossils is observed in all Holocene sequences at a level corresponding to the time-transgressive iron-rich crust dated to 9.3 ^{14}C ka by Showers and Bevis (1988), and they are rare and highly corroded in the underlying late glacial sediments. Well-preserved nannofossils are also present in discrete calcareous clasts within the turbidites and other MTDs and thereby provide a means of estimating the maximum ages of these deposits. Thin, discrete white layers within the turbidites are barren of nannofossils and consist of euhedral carbonate rhombs, probably diagenetic siderite (Burns, this volume).

Planktonic Foraminifers

The foraminifer biostratigraphic framework is based primarily on the Ericson Zones (Ericson, 1961; Ericson et al., 1961; Ericson and Wollin, 1968). This ecostratigraphic zonation was defined in the tropical Atlantic Ocean by the presence or absence of *Globorotalia menardii* and *Globorotalia tumida.* In the western equatorial Atlantic, the Ericson Z/Y Zone boundary has been regarded as approximately equivalent to the Holocene/Pleistocene boundary (e.g., Ericson and Wollin, 1968; Damuth, 1977; Prell and Damuth, 1978). For the purpose of biostratigraphic work on Leg 155 materials, the Holocene/upper Pleistocene boundary was defined to be coeval with the Ericson Z/Y boundary or as the reappearance of *G. tumida.* Recent accelerator mass-spectrometry (AMS) ^{14}C dating has shown that *G. tumida* repopulated the Atlantic Ocean from the Indian Ocean 9000 yr ago, whereas *G. menardii* did not reappear until 6250 yr ago (Jones, 1994, unpubl. data). Previous studies show that, in general, in the Amazon Fan, the Z/Y Zone boundary approximately correlates with a change in the type of sediment deposited and is associated with the occurrence of an iron-rich crust. However, this crust is diachronous across the Amazon Fan and adjacent western equatorial Atlantic (McGeary and Damuth, 1973; Damuth, 1977; Damuth et al., 1983). Recent high-resolution studies have also shown that on the Mississippi Fan, the Ericson Z/Y boundary was apparently not associated with shifts in either sedimentology or sedimentation rates (Kolla and Perlmutter, 1993). Changes in sedimentology and sedimentation rate thus are driven by other factors (e.g., sea level), whereas the shifts in abundance of planktonic foraminifers such as *G. menardii* and *G. tumida* are driven by climate and surface-water circulation changes (Pujol and Duprat, 1983; Pflaumann, 1986; Pflaumann et al., 1996). It should be noted that the Ericson Zones do not always correlate with interglacial-glacial climate shifts (e.g., the V Zone spans oxygen-isotope Stages 7–11).

Other Quaternary planktonic foraminifer datums used in the present study are based on those of Pujol and Duprat (1983), Berggren et al. (1985), and Chaisson and Leckie (1993). The first appearances of *Globigerinoides ruber* (pink) and *Globorotalia tumida flexuosa* have been shown to occur within oxygen Stages 16 and 18, respectively, in the eastern equatorial Atlantic (Pflaumann, 1986). These species also show a significant increase in abundance at oxygen-isotope Stage 12 (Pflaumann, 1986). These abundance maxima are also reported in the southwest Atlantic by Pujol and Duprat (1983). Neither of these studies are in the western equatorial Atlantic, but the major tropical and subtropical current systems of the Atlantic link these areas. This suggests that the first appearances and changes in abundance of these species may be coeval between the three areas, allowing them as a first approximation to be used as datums for the western equatorial Atlantic. In the eastern Atlantic, *G. tumida flexuosa* is present in Pleistocene interglacials and peaks in abundance during oxygen isotope Stage 5, especially during Substage 5e (Pflaumann, 1986; U. Pflaumann, pers. comm., 1994). *Globorotalia hexagonus* is also abundant in interglacials. The disappearance of *Pulleniatina obliquiloculata* within the Ericson Y Zone has been placed between 36 and 44 ka in the western tropical Atlantic, and has been defined as the *P. obliquiloculata* datum within the Ericson zonal system (Prell and Damuth, 1978). During Leg 155, the *P. obliquiloculata* datum was assigned an age of 40 ka. *P. obliquiloculata* reappears at 11 ka based on AMS ^{14}C dating (Jones, 1994, unpubl. data). The *Globorotalia truncatulinoides truncatulinoides* Zone was divided into one Holocene subzone (*Globorotalia fimbriata*) and four Pleistocene subzones (*Globorotalia bermudezi, Globigerinella calida calida, Globorotalia crassaformis hessi*, *Globorotalia crassaformis viola*) by Bolli and Saunders (1985). However, because of the extremely young age of the sediments of the Amazon Fan (less than 475 ka), the Ericson Zones and the *P. obliquiloculata* datum were the most useful.

OTHER DATING METHODS

Other stratigraphic tools were used to support and extend the biostratigraphy, primarily paleomagnetism, AMS ^{14}C dating, and isotope stratigraphy. Three short geomagnetic features were used for regional correlations: the Lake Mungo Excursion (32 ka), Laschamps (43 ka), and the Blake Event (105 ka; Cisowski, 1995; and Cisowski and Hall, this volume). Cisowski and Hall (this volume) successfully identified 12 intensity features in the Amazon Fan sediments of which only the six most prominent features were identified in several sites and given an estimated age in calendar years (Cisowski, 1995).

Three samples were AMS ^{14}C dated at the new Leibniz Labor für Altersbestimmung und Isotopenforschung, Kiel University, Federal Republic of Germany. The ages are given as "conventional" ^{14}C ages using a 5568 yr "Libby half-life," and the results corrected for sample preparation contamination by subtracting the activity measured in Eemian foraminifers processed in the same way. A general ocean reservoir correction of -400 yr has been made, although it is noted that this may differ because of both location and changes in the rate of deep-water ventilation in the past. The first sample (Sample 155-932A-1H-1, 19–24 cm, 0.19 mbsf) chosen to date the top of Hole 932A, consisted of 2000 *G. trilobus* tests in the >350-µm size range and gave an age of 3970 ± 90 yr. This sample confirms that a significant part of the Holocene was recovered at Site 932. The second sample (Sample 155-933A-1H-1, 70–74 cm, 0.70 mbsf) was chosen to date the top of Hole 933A. This sample consisted of 1500 *G. trilobus* tests in the >250 µm-size range and gave an age of 11,910 ± 90 yr. The third sample (155-932A-3H-6, 20–24 cm, 23.20 mbsf) was chosen to confirm the dating and identification of the Lake Mungo Excursion in Hole 932A. The sample consisted of a mixture of 1350 tests of *Neogloboquadrina dutertrei* and *G. truncatulinoides* in the >250-µm-size fraction and gave an age of 32,730 + 320/-300 yr. Despite the low number of tests and the necessity of using more than one species, the AMS ^{14}C date does confirm that the Lake Mungo Excursion (24.9 mbsf) has been correctly identified.

Traditional isotope stratigraphic work has been attempted on the youngest sediments and on undisturbed sediments overlying the MTDs (Showers et al., this volume; Maslin et al., this volume). In the disrupted hemipelagic sequences beneath the MTDs, isotope data were used to confirm glacial-interglacial interpretations and to document reworking (Maslin and Mikkelsen, this volume).

STRATIGRAPHY OF AMAZON FAN SITES

The Amazon Fan sites are grouped into generically related units that reflect their location on the fan and their mode of origin (see Figs. 1, 2, 5–12). Below, each site is shortly discussed separately, and reference to the location of the sites is given in Table 1 and Figure 1. Detailed information recording the relationship between the Amazon Fan seismic units and the Leg 155 sites is presented in Figure 2, and additional biostratigraphic data are given in Flood, Piper, Klaus, et al. (1995).

Site 930

Site 930 (Fig. 6) is located in the upper fan area on the crest of the buried Orange Channel-levee System, 10 km west of the active Amazon Channel in a slight topographic low formed between the Purple and Amazon Channel-levee Systems (Figs. 1, 2). The overall abundance of nannofossils is low with the exception of the Holocene sequence and a few clasts in the debris flow in the bottom of Hole 930B.

Planktonic foraminifers are rare. The site has a poorly defined Ericson Zone Z/Y boundary, and a questionable *P. obliquiloculata* datum at 137.41 mbsf. This site has a good Lake Mungo Excursion (85.2–87.5 mbsf; Cisowski, 1995), and six paleomagnetic remanence intensity features were identified (Cisowski, 1995).

Site 931

Site 931 (Fig. 7) is located in the middle fan area on a flat terrace on the western levee of Channel 5 (Figs. 1, 2). It is the most easterly site drilled on the Amazon Fan. The site penetrated the deep eastern MTD (EMTD) and recovered an underlying interglacial deep carbonate unit (Fig. 7).

Abundant nannofossils are found only in the Holocene sediments and in the deep carbonate units underlying the deep EMTD. In the hemipelagic sediments of Core 155-931B-38X, nannofossil abundance varies greatly and includes in certain horizons reworked Neogene species and clastic material. The interval spanning 349.1–351.3 mbsf (Samples 155-931B-38X-4, 15–20 cm, to 931B-38X-5, 140–144 cm) is referred to Zone CN15a. The underlying sequence (Samples 155-931B-38X-7, 87–92 cm, to 155-931B-39X-1, 42 cm) is

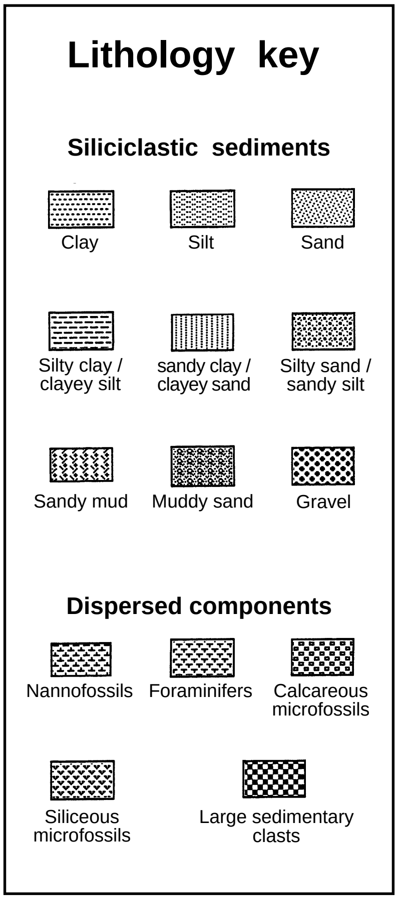

Figure 5. Sedimentological key for Figures 6–12 (adapted from Flood, Piper, Klaus, et al., 1995).

characterized by a high abundance of *G. caribbeanica,* which, however, is not a characteristic acme and is therefore referred to the CN14b/15a boundary. *G. caribbeanica* becomes increasingly abundant in the lowermost part of the deep carbonate section (Sample 155-931B-39X-1, 42–47 cm), which may represent the CN15a–14b transition or the very upper part of Zone CN14b. A tentative correlation to the isotope stratigraphy refers the deep carbonate interval of Site 931 to isotope Stage 7 and possibly Stage 9.

Based on foraminifers, the site has a poorly defined Ericson Zone Z/Y boundary. No *P. obliquiloculata* datum was found above the deep EMTD, but the paleomagnetic Lake Mungo Excursion was located at 76.5 mbsf (Cisowski, 1995), together with six paleomagnetic remanence intensity features.

Site 932

Site 932 (Fig. 7) is located on the eastern part of the middle Amazon Fan, 200 m east of the crest of the western levee of the abandoned Channel-levee System 6B (Figs. 1, 2). Nannofossils are found in high abundance only in the Holocene sequence above the iron-rich crust (0.61 mbsf), and they are rare to absent in the underlying bioturbated glacial muds. The Ericson Zone Z/Y boundary was defined on the basis of detailed planktonic foraminifer assemblage data, and the *P. obliquiloculata* datum was identified at 44 mbsf.

It was possible to obtain a detailed isotope-stratigraphic record for the section younger than 32 ka at this site. Furthermore, a good paleomagnetic record with the Lake Mungo (32 ka) and Laschamps Excursions (24.9–25.9 mbsf and 27.5 mbsf; Cisowski, 1995; Cisowski and Hall, this volume) has been identified and confirmed by AMS ^{14}C dating (Maslin et al., this volume). A detailed age model for this site is presented in Maslin et al. (this volume). Based on the good late glacial-Holocene isotope record and ^{14}C data, this site can be used as a reference site for stratigraphic correlation of the younger parts of the Leg 155 sites.

Site 933

Site 933 is located on the eastern part of the middle Amazon Fan, on the eastern flank of the Yellow Channel-levee System, (Figs. 1, 2). The site penetrated the crest of the Bottom Levee Complex and the deep EMTD (Fig. 7), both also sampled at Site 931.

Nannofossils are abundant and well preserved only in the Holocene calcareous clay capping the site. The hemipelagic ooze underlying the deep EMTD provides poorly preserved nannofossil assemblages, often accompanied by clastic material and alternating with barren samples. The entire deep carbonate sequence is referred to the lower part of nannofossil Zone CN15a based on assemblage composition. The sequence is tentatively referred to isotope Stage 7.

The site has a poorly defined Ericson Zone Z/Y boundary. Stable-isotope data and a single AMS ^{14}C date at the top of Hole 933A suggest that very little Holocene material was recovered from Site 933 compared with the other Leg 155 sites. No *P. obliquiloculata* datum was found above the deep EMTD. The paleomagnetic Lake Mungo Excursion (81.5–83.0 mbsf; Cisowski, 1995) and six paleomagnetic remanence intensity features were identified (Cisowski, 1995).

Site 934

Site 934 (Fig. 8) is located in a cut-off meander bend in the main Amazon Channel (Figs. 1, 2). The abundance of nannofossils and foraminifers is low overall, below the thin Holocene clay cover. This site has a well-defined Ericson Zone Z/Y boundary at 0.9 mbsf. Neither the *P. obliquiloculata* datum nor the paleomagnetic Lake Mungo Excursion was found at this site, which is consistent with the relatively young ages (<32 ka) of the Amazon Channel deposits.

Site 935

Site 935 (Fig. 9) is located on the flank of the Aqua Channel in the middle fan area (Figs. 1, 2). The site was drilled to investigate the development of the levees of the Amazon Channel and to study the underlying sediment units.

Two distinct hemipelagic intervals are found below the Holocene calcareous clay: a hemipelagic interval at 223–225 mbsf (Core 155-935A-25X) and the interglacial deep carbonate deposits at 276–286 mbsf (Core 155-935A-31X). Moreover, random clasts of calcareous clay are found within the Unit R Mass Flow Deposit.

The hemipelagic interval at 225–228 mbsf (Core 155-935A-25X) is stratigraphically located within the lowest part of a mass-transport unit (Flood, Piper, Klaus, et al., 1995). In the upper part of the interval (Samples 155-935A-24X-CC to 155-955A-25X-5, 59–64 cm), highly diverse nannofosssil assemblages similar to those found in isotope Stage 5 sediments of Site 942 are present. The carbonate-rich lower part of the hemipelagic interval (Sample 155-935-25X-CC), however, has assemblages similar to those of the underlying deep carbonate deposits (Core 155-935A-31X).

The deep carbonate unit at 276–286 mbsf (Core 155-935A-31X) does not contain any clear stratigraphic succession of nannofossil assemblages, but rather a random distribution of assemblages representative of Zone CN14b and CN15a. The assemblages between Samples 155-935A-31X-1, 11–13 cm, and 155-935A-31X-6, 50–52 cm, alternate between *G. caribbeanica* and small *Gephyrocapsa*/*Gephyrocapsa oceanica*-dominated assemblages. Considering that the total coccolith abundance on average is high, and that dissolution does not seem to have altered the assemblages in any significant way, the random distribution of coccolith assemblages from different zones points to a partially reworked sequence. Moreover, the coccolith-barren samples found within the sequence may represent small turbidites

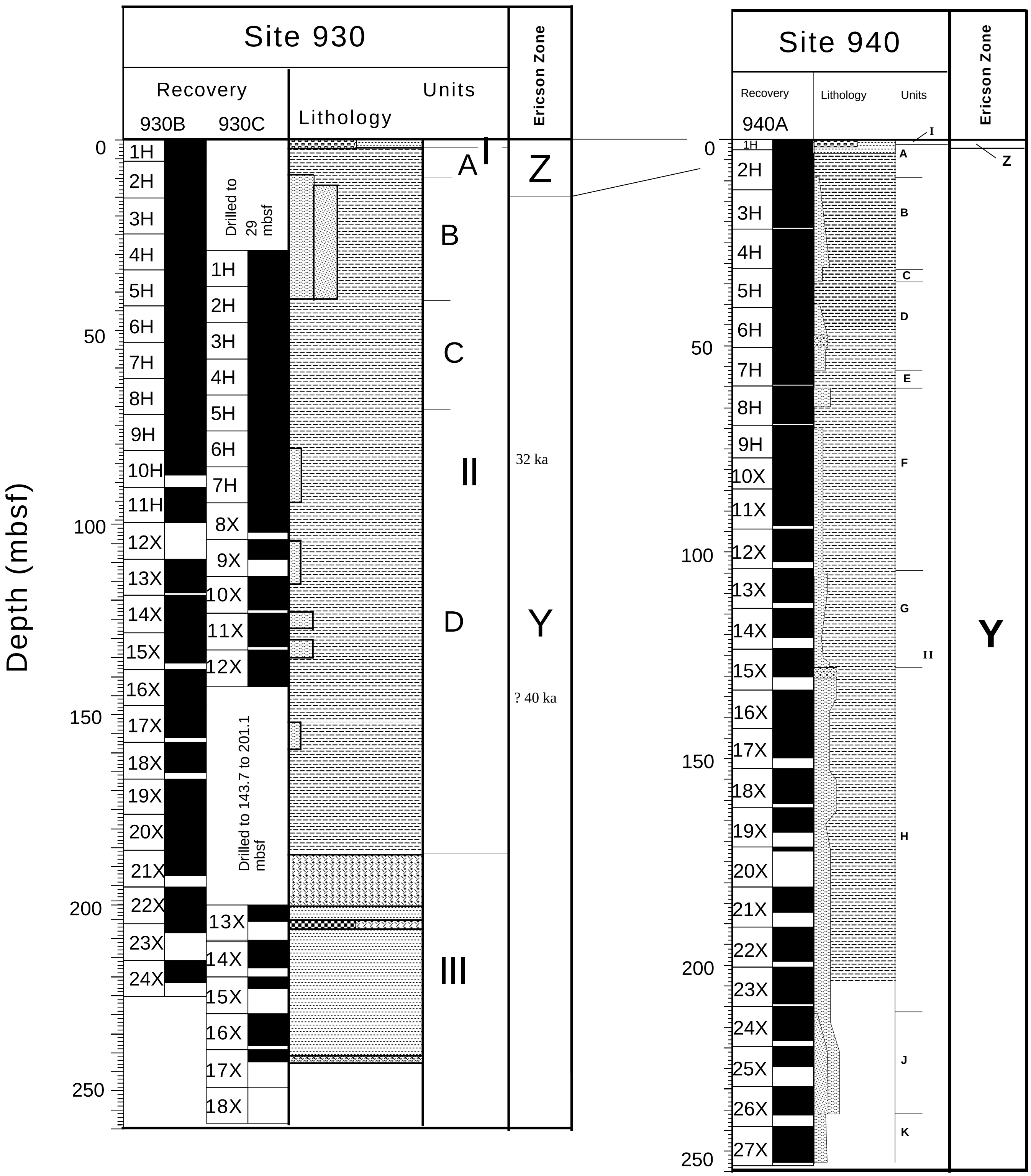

Figure 6. Correlation of upper middle fan Sites 930 and 940. For sedimentological key see Figure 5.

as has been reported from Site 942 (Showers et al., this volume). The deep carbonate sequence of Site 935 is, therefore, a mixture of sediments representing isotope Stages 7, 9, and possibly 11, but may also represent an isotope Stage 7 deposit with reworked Stage 9 and 11 sediments.

The site has a poorly defined Ericson Zone Z/Y boundary. The *P. obliquiloculata* datum was found at 178 mbsf, but no paleomagnetic excursions or paleomagnetic remanence intensity features were identified.

Site 936

Site 936 (Fig. 9) is located on the middle fan on the western levee of the Amazon Channel (Figs. 1, 2). It was drilled to assess the devel-

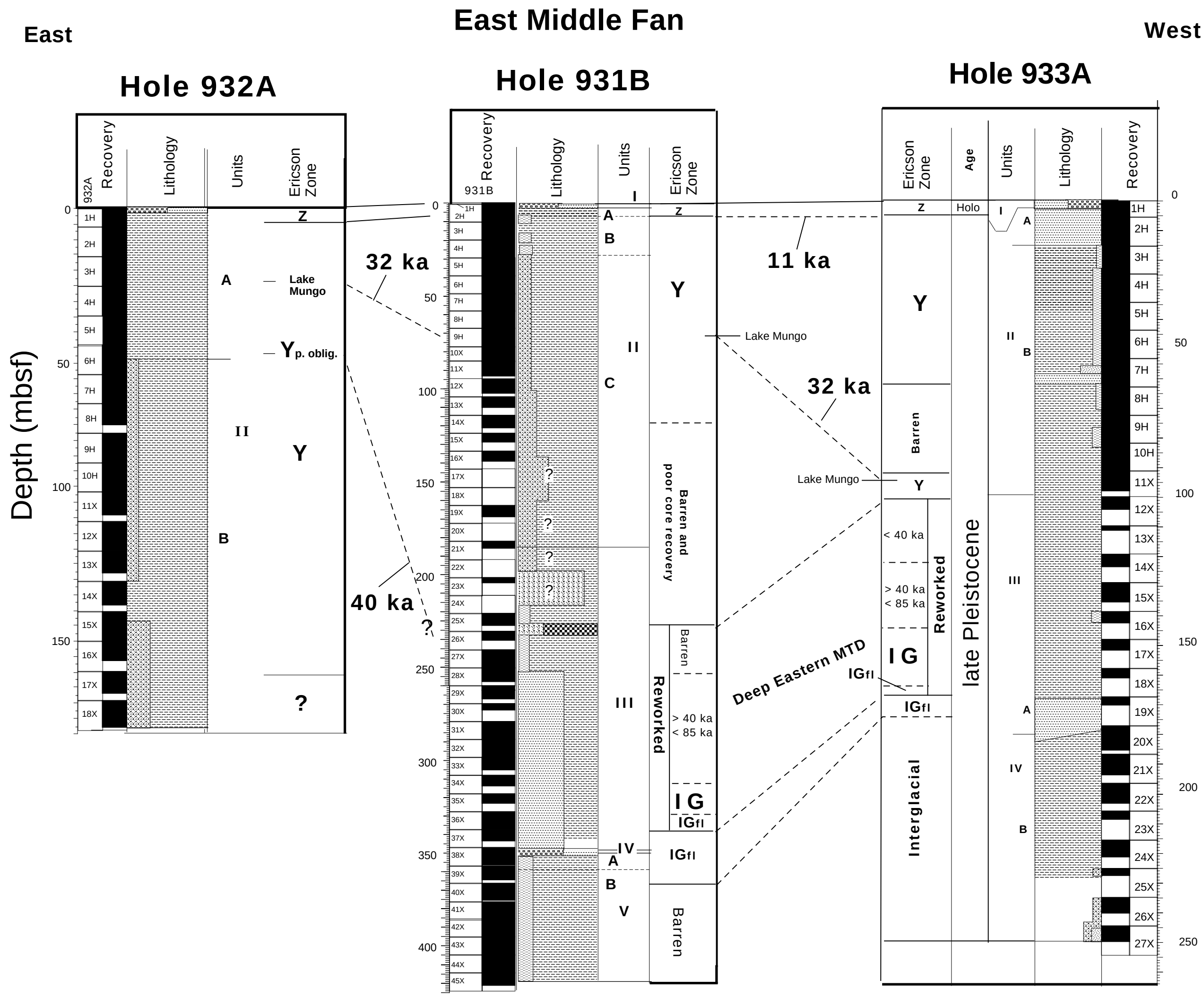

Figure 7. Correlation of east middle fan Holes 932A, 931B, and 933A. For sedimentological key see Figure 5.

opment of the most recently active channel levee system and to date the Unit R MTD, the Middle Levee Complex, and the Gold levee of the Lower Levee Complex.

At this site, two distinct interglacial highstand deposits were identified below the Holocene calcareous clay (Flood, Piper, Klaus, et al., 1995): a <1-m-thick highstand clay at ~387 mbsf (Core 155-936A-42X) that may represent a reworked block (Flood, Piper, Klaus, et al., 1995) and the hemipelagic deep carbonate sequence at ~405–415 mbsf (Section 155-936A-44X-1 through 45X-1).

In the upper part of the hemipelagic deposits of Core 155-935A-42X, acmes of small *Gephyrocapsa* from Zone CN15a dominate the sequence, but are intercalated by CN14b assemblages dominated by *G. caribbeanica*. Samples barren of nannofossils are also found within this succession and may represent small turbidites. It is therefore likely that the upper part of the deep carbonate interval represents a reworked sequence. It may, however, have been formed during isotope Stage 7 with reworked Stage 9 and possible Stage 11 components. The fossiliferous section of Core 155-936A-42X is underlain by a sequence barren of nannofossils from 395 to 399 mbsf (upper part of Core 155-936A-43X, down to and including Sample 155-936A-43X-3, 57–61 cm). In the remaining part of the deep carbonate unit (Samples 155-936A-43X-7, 111–116 cm, to 44X-CC), abundant and well-preserved acmes of *G. caribbeanica* typical of Zone CN14b are present, whereas the underlying Cores 155-936A-45X and 46X are barren of nannofossils.

The nannofossil-bearing sequence of Core 155-936A-44X is tentatively referred to isotope Stage 9. A high abundance of small *Gephyrocapsa* in the bottom of the deep carbonate sequence (Samples 155-936A-44X-2, 81–84 cm, to 44X-3, 11–16 cm) may even indicate that it is the lower part of isotope Stage 9. Pujos and Giraudeau (1993) therefore have shown that the base of Stage 9 in tropical areas is characterized by a short acme episode of small *Gephyrocapsa.*

Site 936 has a well-defined Ericson Zone Z/Y boundary located between 0.52 and 0.1 mbsf. The *P. obliquiloculata* datum was found at 148.79 mbsf. No paleomagnetic excursions or paleomagnetic remanence intensity features were identified.

Site 937

Site 937 (Fig. 10) is located on the eastern part of the upper Amazon Fan, on the crest of the western levee of the abandoned Yellow Channel-levee System (Figs. 1, 2). Overall, nannofossil abundance is very low, and planktonic foraminifers are rare. This site has a poorly defined Ericson Zone Z/Y boundary and exhibits a strong reworking of Holocene planktonic foraminifers down to 17 mbsf. No *P. obliquiloculata* datum, paleomagnetic excursions, or remanence in-

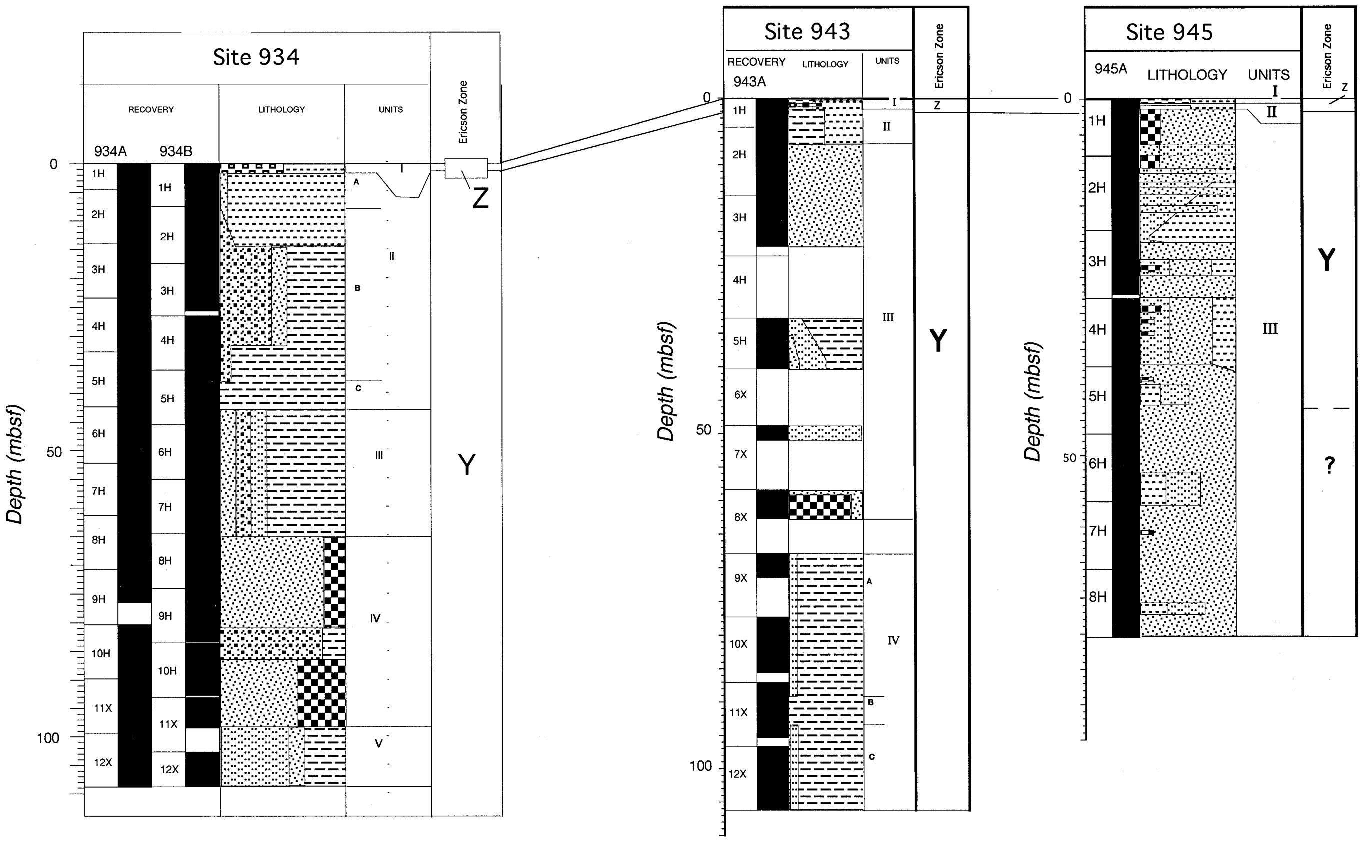

Figure 8. Correlation of channel fill Sites 934, 943, and 945. For sedimentological key see Figure 5.

tensity features were identified. This suggests that the deepest sediment recovered at 180 mbsf is no older than 32 ka.

Site 938

Site 938 (Fig. 10) is located on the eastern part of the upper Amazon Fan on the flank of the western levee of the abandoned Blue Channel-levee System (Figs. 1, 2). The nannofossil abundance is generally low and represents Zone CN15b. Planktonic foraminifers are also rare, and the site has a poorly defined Ericson Zone Z/Y boundary. The *P. obliquiloculata* datum is placed at 148.9 mbsf and the paleomagnetic Lake Mungo Excursion at 144.4–146 mbsf (Cisowski, 1995), thereby giving an age of less than 85 ka for the deepest part of the site.

Site 939

Site 939 (Fig. 10) is located ~1–1.5 km east of the crest of the eastern levee of the Amazon Channel on the upper Amazon Fan (Figs. 1, 2). Overall, the nannofossil abundance is very low and represents Zone CN15b. Rare specimens of the cold-water species, *Coccolithus pelagicus*, are present in the glacial sediment of Site 939. Planktonic foraminifers are rare, but the site has a well-defined Ericson Zone Z/Y boundary at 0.82 mbsf. No *P. obliquiloculata* datum, paleomagnetic excursions, or remanence intensity features were identified. This suggests that the deepest sediment recovered at 103 mbsf is younger than 32 ka.

Site 940

Site 940 (Fig. 6) is located on the flank of the eastern levee of the Amazon Channel ~3 km from the levee crest (Figs. 1, 2). The nannofossil abundance is low overall, whereas planktonic foraminifers are relatively abundant. The site has a poorly defined Ericson Zone Z/Y boundary and no *P. obliquiloculata* datum. No paleomagnetic excursions or remanence intensity features were identified, which suggests that the deepest sediment recovered at 248 mbsf is younger than 32 ka.

Site 941

Site 941 (Fig. 11) is located on the western side of the middle Amazon Fan (Fig. 2) on the Western Debris Flow. One of the drilling aims at this site was to provide an age for the emplacement of the Western Debris Flow. In addition, this site provides a near-surface debris flow to compare with the deep MTDs recovered at Sites 931, 933, 935, and 936.

No *P. obliquiloculata* datum, paleomagnetic excursions, or remanence intensity features were identified. This agrees with the assumption that the Western Debris Flow occurred during Termination I (11–14 calendar ka; Maslin and Mikkelsen, this volume), but is slightly younger than the interpretation by Piper et al. (Chapter 6, this volume) for emplacement during the last glacial maximum. Within the Western Debris Flow, a succession of repeated biounits identified on the basis of foraminiferal assemblages could be used for interhole correlation at the site (Fig. 11).

Site 942

Site 942 (Fig. 12) is located on the crest of an abandoned levee to the west of the main part of the Amazon Fan, and therefore is under less direct influence of the Amazon River discharge than other Leg 155 sites (Figs. 1, 2).

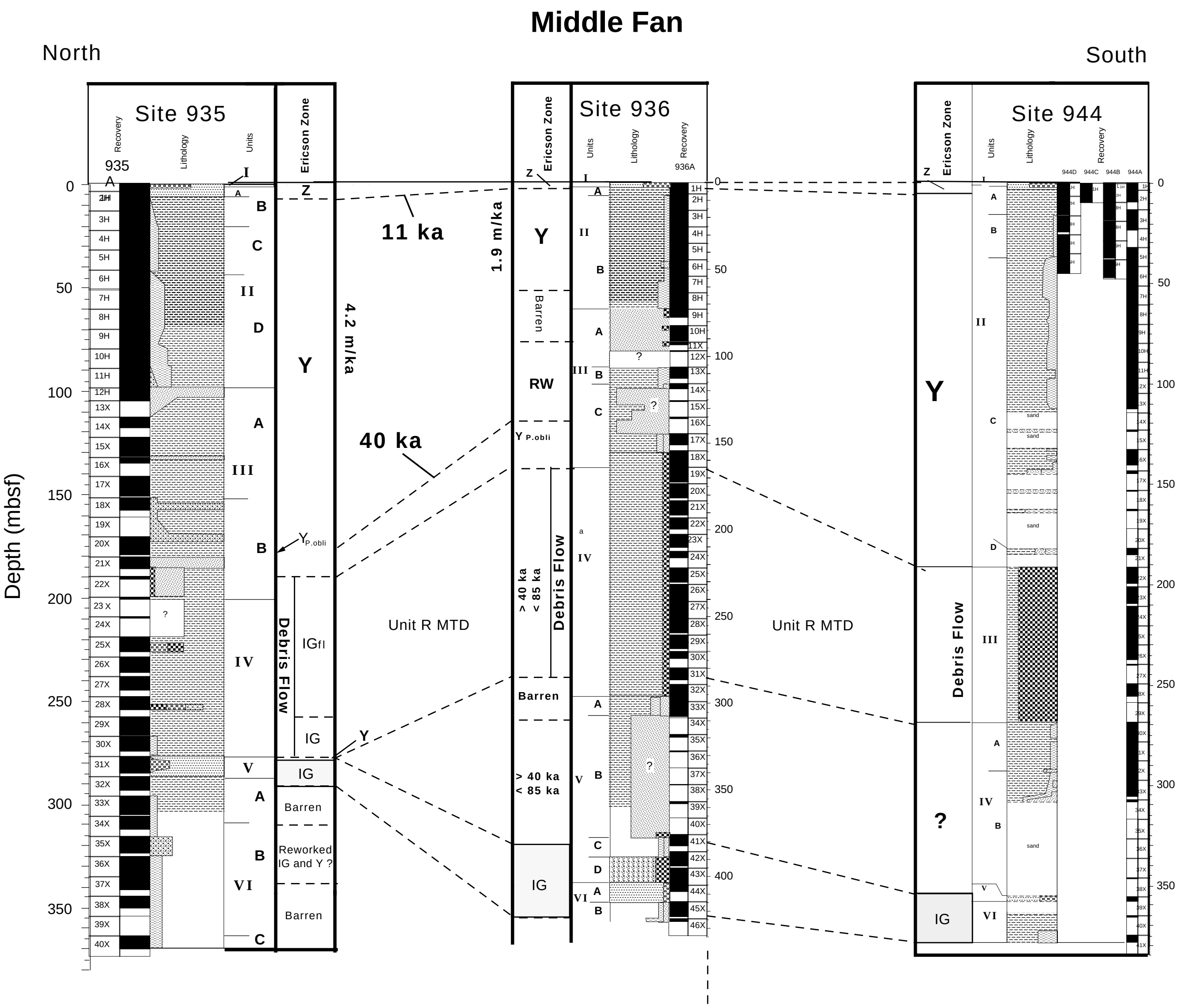

Figure 9. Correlation of middle fan Sites 935, 936, and 944. For sedimentological key see Figure 5.

Overall, the abundances of nannofossil and planktonic foraminifers are high, especially in the three distinct hemipelagic intervals below the Holocene iron-rich crust: at 28 mbsf (interval 155-942A-4H-4, 80–150 cm), at 41 mbsf (Section 155-942A-5H-7 through 6H-1), and at 65 mbsf (Section 155-942A-8H-3 through 8H-4).

Nannofossils are generally abundant and well preserved in all three carbonate horizons and display diversified assemblages. However, all intervals also furnish poorly preserved nannofossils with a high content of clastic material. The first carbonate interval is referred to Zone CN15b because of a dominance of *E. huxleyi*. The second and third carbonate intervals contain acmes of small *Gephyrocapsa* and are referred to Zone CN15a.

Site 942 has a well-defined Ericson Zone Z/Y, Y/X, and X/W boundaries. The *P. obliquiloculata* datum was found at 14.5 mbsf. The paleomagnetic Lake Mungo Excursion (Hole 942A, 9–10 mbsf; Cisowski, 1995), Laschamps Excursion (Hole 942A, 14 mbsf; Cisowski and Hall, this volume), and Blake (Hole 942A, 41–42.2 mbsf; Cisowski, 1995) Event, as well as six paleomagnetic remanence intensity features, were identified. A detailed age model based on high-resolution oxygen-isotope records was produced for this site by Showers et al. (this volume).

Site 943

Site 943 (Fig. 8) is located in the main Amazon Channel on the central part of the Amazon Fan (Figs. 1, 2). Apart from the Holocene cover, Site 943 is almost barren of nannofossil and planktonic foraminifers. The site has a poorly defined Ericson Zone Z/Y boundary located between 2.7 mbsf and 0.5 mbsf. No *P. obliquiloculata* datum, paleomagnetic excursions, or remanence intensity features were identified at the site.

Site 944

Site 944 (Fig. 9) is located on the middle of the Amazon Fan, on the eastern levee of the Amazon Channel ~2 km from the channel axis and outside of a meander bend (Figs. 1, 2). It was drilled to sample the Unit R MTD, the Middle Levee Complex, the Lower Levee Complex, and the interglacial deep carbonates below the MTD.

Two hemipelagic intervals were recovered: the Holocene calcareous clay and the hemipelagic deep carbonate unit, which unfortunately, was highly affected by drilling disturbances. In the poor core-recovery sequence of the hemipelagic sediments (355.4–357.5 mbsf),

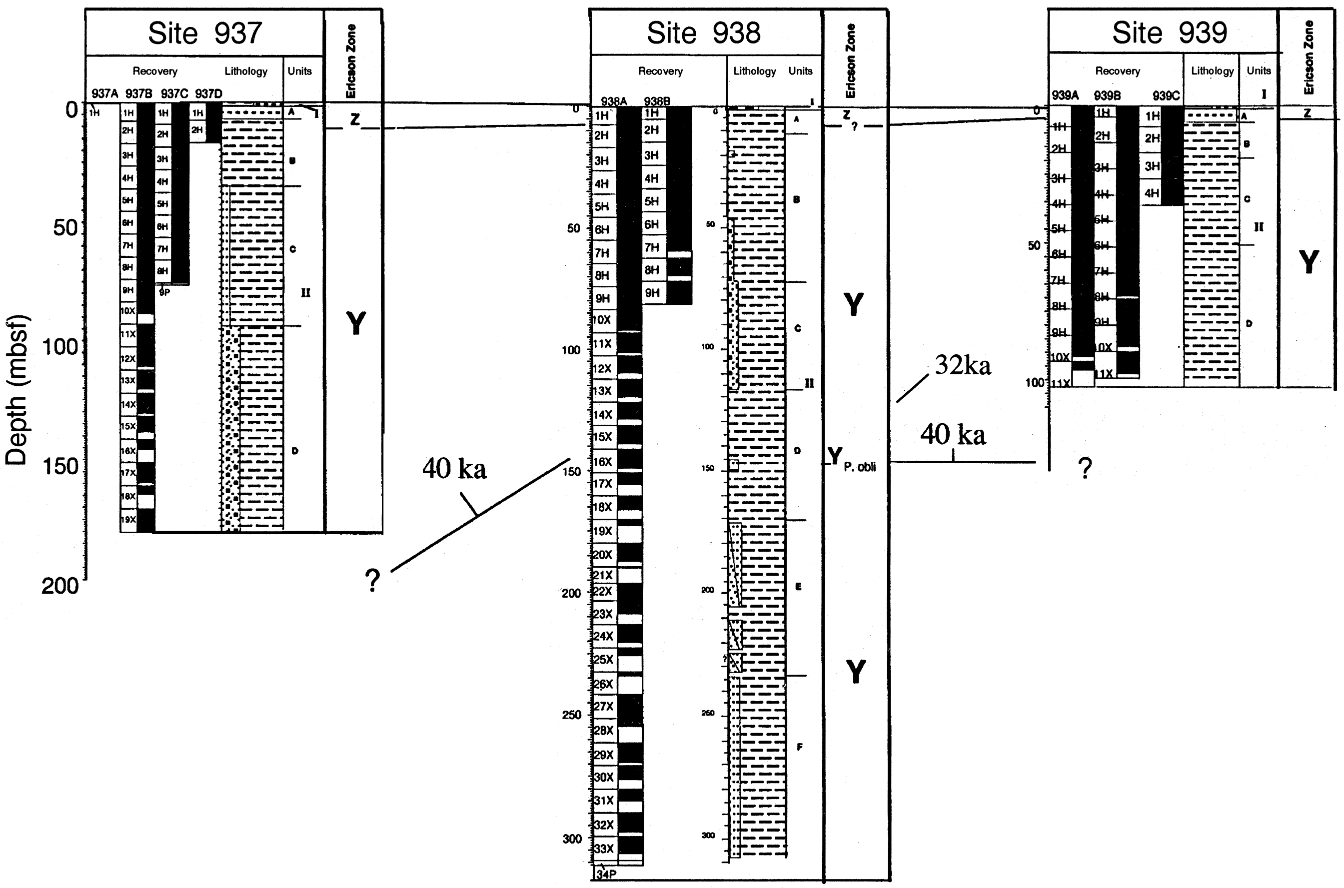

Figure 10. Correlation of central upper fan Sites 937, 938, and 939. For sedimentological key see Figure 5.

a rich nannofossil assemblage of Zone CN15a is present in the upper part (Samples 155-944A-39X-1, 8–9 cm, to 39X-1, 144 cm). Acmes of *G. caribbeanica* representing Zone CN14b appear in the lower part (Samples 155-944A-39X-2, 14 cm, to 39X-2, 59 cm). The deep carbonate unit is tentatively referred to as isotope Stages 7 and 9, based on a correlation between biostratigraphy and isotope chronology (Fig. 4).

Site 944 has a poorly defined Ericson Zone Z/Y boundary and no *P. obliquiloculata* datum. No paleomagnetic excursions or paleomagnetic remanence intensity features were identified in the younger sequences overlying the MTDs.

Site 945

Site 945 (Fig. 8) is located in the main Amazon Channel of the Amazon Fan, near the transition from the middle to the lower fan (Figs. 1, 2). Apart from the Holocene sediment, Site 945 is almost barren of nannofossils and planktonic foraminifers. This site has a poorly defined Ericson Zone Z/Y boundary located between 2.7 and 0.5 mbsf. No *P. obliquiloculata* datum, paleomagnetic excursions, or remanence intensity features were identified, suggesting an age of less that 40 ka for the base of the site.

Site 946

Site 946 (Fig. 12) is located near the transition from the middle to lower Amazon Fan (Figs. 1, 2). This site has a poorly defined Ericson Zone Z/Y boundary (0–6.95 mbsf), but a reasonably well-defined Y/X boundary at 130.5 mbsf. Possible Ericson Zones W and V were identified in the deepest sections of Site 946 (Flood, Piper, Klaus, et al., 1995). No *P. obliquiloculata* datum was found. Although the paleomagnetic Lake Mungo Excursion (101.5–101.8 mbsf) and Blake Event (132.2–134.0 mbsf; Cisowski, 1995) were identified, no paleomagnetic remanence intensity features could be recognized.

Nannofossils are abundant in the Holocene section and in two prominent carbonate intervals at depths of 130.25–130.75 mbsf (Core 155-946A-15X) and 211–220 mbsf (Cores 155-946A-23X and 24X). In the first thin hemipelagic interval (in Core 155-946A-15X), the nannofossil assemblages are highly diverse and represent the acme of *Gephyrocapsa oceanica/mullerae* from Zone CN15a. In the deep carbonate unit, nannofossil-rich samples alternate with barren or very poorly preserved assemblages. The upper part of the interval (Samples 155-946A-23X-3, 120 cm, to 24X-1, 112–113 cm) is within Zone CN15a, whereas the lower part, with typical *G. caribbeanica*, is within Zone CN14b. The CN15a/14b boundary is placed between Samples 155-946A-24X-1, 112–113 cm, and 24X-1, 133 cm. A tentative correlation between the biostratigraphy and the isotope stratigraphy would place the deep carbonates in isotope Stages 7 and 9.

Sedimentation Rates

Age models and estimated sedimentation rates for Leg 155 sites with good stratigraphic control are shown in Figures 13–17. The age models are constructed using biostratigraphy (this study), the paleomagnetic events (32 ka, 43 ka, and 105 ka; Flood, Piper, Klaus, et al., 1995), paleomagnetic remanence intensity data (Cisowski, 1995), and AMS ^{14}C dates for Sites 932 and 933 (Maslin et al., this volume). These data were used together to compile a model of the overall stratigraphy of the MTDs and the interglacial deep carbonates drilled on the Amazon Fan (Fig. 18).

The selected sites may be divided into two end-member groups based on sedimentation rates (Fig. 13): low sedimentation-rate sites

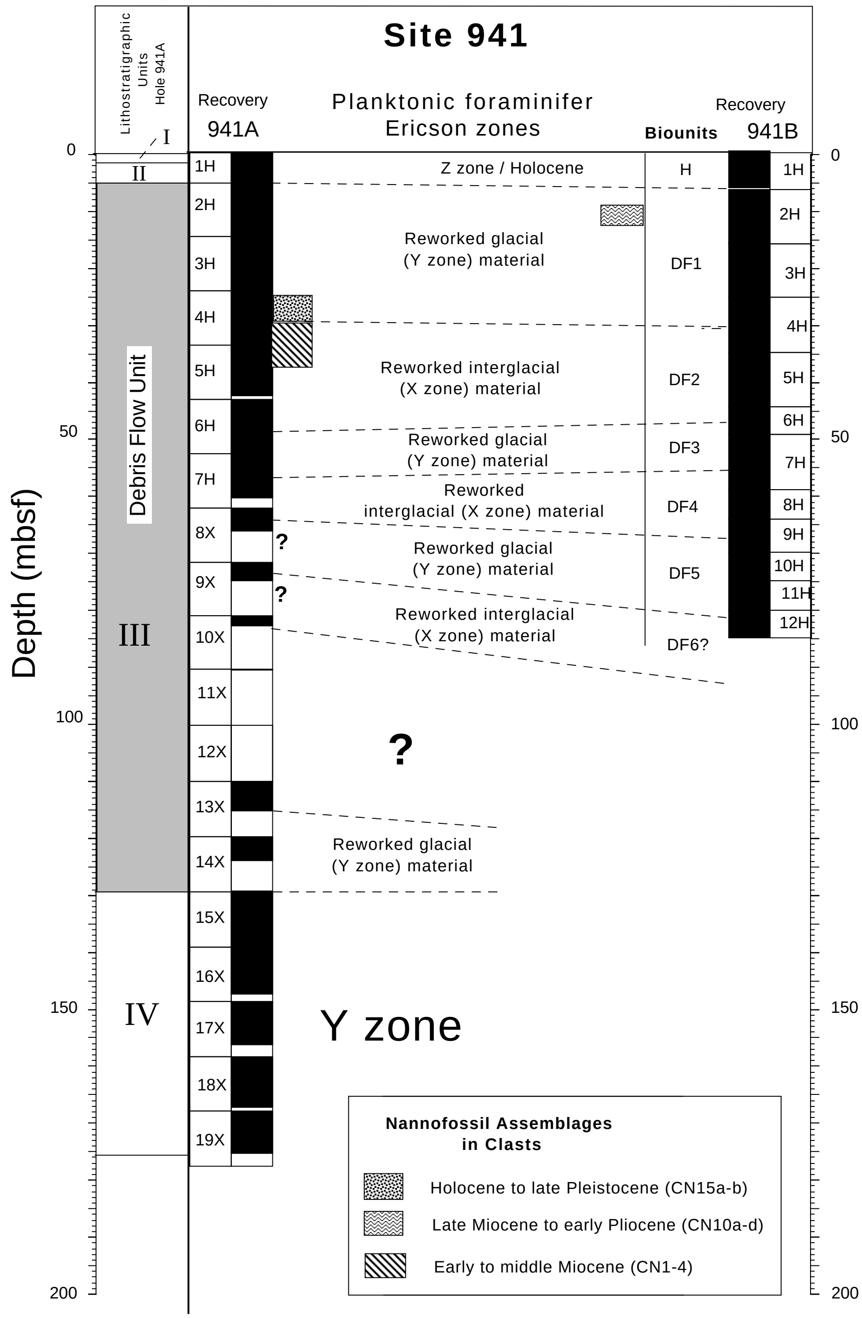

Figure 11. Within the Western Debris Flow at Site 941, a succession of repeated "biounits" was identified based on foraminifer assemblages and used for hole correlation. Two distinct planktonic foraminifer assemblages are identified: (1) material from Ericson Zone Y, but dated as between 40 and 85 ka because of the occurrence of *P. obliquiloculata,* and/or Zone W; and (2) material from Ericson Zone X and/or V containing relatively high abundances of *G. menardii, G. tumida,* and *G. tumida flexuosa.* The occurrence of *G. tumida flexuosa* suggests a significant interglacial sediment source. The correlation of Holes 941A and 941B seems to indicate that within the Western Debris Flow there are alternating sediment sources.

(Sites 932 and 942) and high sedimentation-rate sites (Sites 930, 938, and 946). Within the latter group, Site 946 is characterized by lower sedimentation rates prior to 32 ka, in contrast to Sites 930 and 938. This is because the most recently active Amazon Fan channel fed a significant amount of sediment to Site 946 after ~30 ka, whereas Sites 930 and 938 were less affected by the channel.

The sedimentation rates calculated from the age-depth plots for Sites 932, 942, and 946 are shown in Figure 15. Two of these sites, Sites 942 and 946, are located off the fan and therefore receive less sediment from the main Amazon Fan discharge. This explanation, however, does not apply to the top of Site 946 or to Site 932, which is located within the middle fan area. Because of the building of the Channel-levee System 6B and its subsequent abandonment (Fig. 2), Site 932 has become a topographic high compared to the surrounding area (Flood, Piper, Klaus, et al., 1995). Reduction in terrestrial sedimentation following the abandonment of the Channel-levee Complex is reflected in the sedimentation rates, whereby the underlying abandoned Channel-levee System 6B has rates over 18 m/k.y. (Figs. 13, 15), whereas the overlying sediments average less than 1 m/k.y.

The age-depth plots for sites penetrating MTDs are shown in Figure 14. Age models for Sites 935 and 936 are not well constrained, as only the Holocene/glacial boundary and a possible *P. obliquiloculata* datum (40 ka) were identified. It is therefore difficult to estimate the age of the sediment above the Unit R MTD. Using the average glacial sedimentation rate of these sites (5 m/k.y.), Maslin and Mikkelsen (this volume) have nevertheless suggested that the Unit R MTD was last active ~45 ka. Better constrained age models are available for Sites 931 and 933, which have good paleomagntic records. The glacial sedimentation rates at these sites vary between 2 m/k.y. and 8 m/k.y. Based on sedimentation rate estimates, Maslin and Mikkelsen (this volume) suggest that the deep EMTD drilled at Sites 931 and 933 was last active about 33 ka.

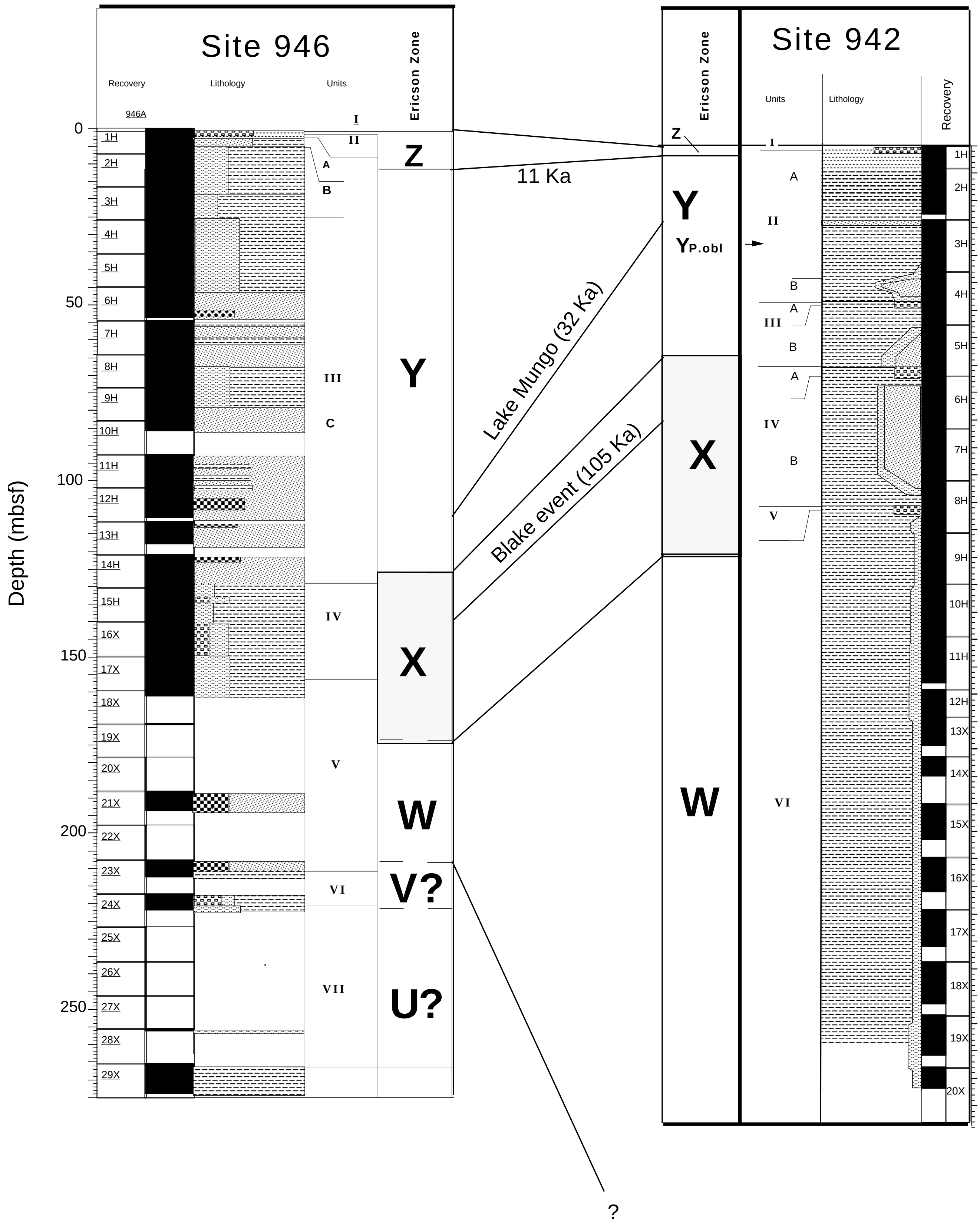

Figure 12. Correlation of off-fan Sites 946 and 942. For sedimentological key see Figure 5.

A number of sites revealed sections where no glacial biostratigraphic datums or paleomagnetic ages were found. These sites were mainly drilled to investigate sedimentological processes within the fan complex. The sequences at these sites were dominated by sand and/or levee muds with significant amounts of silt and fine sands. To provide an estimate of the minimum sedimentation rates of these sites, the deepest sediment recovered was estimated to be no older than 75 ka (the last interglacial/glacial transition, i.e., the boundary between oxygen-isotope Stages 5a and 4). This assumption was based on the presence of distinct sedimentological, geochemical, and isotope anomalies across this boundary within Sites 942 and 946 (e.g., Flood, Piper, Klaus, et al., 1995; Goñi, this volume; Showers et al., this volume). At each of these sites, the sedimentation rates estimated in this manner must have been at least 1 m/k.y. or greater (Fig. 17). The differences in the minimum estimated sedimentation rates are controlled by how deep each site was drilled. In reality, the sedimentation rates are presumably extremely high, and in the case of the sandy units, much of the sedimentation may have occurred very rapidly or even instantaneously (Flood, Piper, Klaus, et al., 1995; Cramp et al., this volume).

In summary, the sedimentation rates of the Leg 155 sites range from <0.05 m/k.y. to >50 m/k.y., a range of 3 orders of magnitude. A number of factors influence sedimentation rates on the Amazon Fan. The first is "on-off" glacial-interglacial variation of the terrigenous sediment supply to the fan. During interglacial periods, nearly all the Amazon River sediment is deposited on the shelf, thereby allowing pure-pelagic sedimentation on the fan. Sedimentation rates increase dramatically during the glacials as terrigenous sediment is funneled via the Amazon canyon directly onto the fan. At present, the annual sediment discharge of the Amazon River is just under one gigaton per year (Milliman and Meade, 1983), the third largest river-sediment discharge in the world. This indicates the size of the increase in sediment supply to the Amazon Fan expected during glacial periods.

The channeled glacial input of terrigenous sediment onto the fan is not distributed evenly, however, because it is transported via channel-levee systems. The second factor controlling Amazon Fan sedimentation rates is the formation and abandonment of the channel-levee systems. Evidence from the Amazon Fan suggests that the highest sedimentation rates occur at sites directly underlying the channel-system. Relatively high sedimentation rates also occur within the vicinity of an active channel-levee system caused by extensive

Table 1. Location and drilling information of all sites from Leg 155 Amazon Fan.

Site	Latitude	Longitude	Water depth (m)	Deepest sediment (mbsf)	Oldest sediment recovered
930	5°0.9′N	47°35.7′W	3155	259	late Pleistocene ?
931	5°8.5′N	46°37.9′W	3476	421	middle Pleistocene
932	5°12.7′N	47°1.8′W	3344	168	late Pleistocene
933	5°5.8′N	46°48.7′W	3376	254	middle Pleistocene
934	5°29.0′N	47°40.8′W	3421	108	late Pleistocene
935	5°25.6′N	47°33.9′W	3486	372	middle Pleistocene
936	5°37.9′N	47°44.1′W	3575	434	middle Pleistocene
937	4°35.8′N	47°12.4′W	2951	180	late Pleistocene
938	4°39.5′N	47°18.7′W	2804	310	late Pleistocene
939	4°43.3′N	47°30.2′W	2784	103	late Pleistocene
940	5°8.6′N	47°31.7′W	3191	248	late Pleistocene
941	5°22.4′N	48°1.7′W	3381	178	Holocene*
942	5°44.6′N	49°5.5′W	3346	178	middle Pleistocene
943	5°56.8′N	47°46.8′W	3739	67	late Pleistocene
944	5°56.3′N	47°45.5′W	3701	384	middle Pleistocene
945	6°57.0′N	47°55.7′W	4136	76	late Pleistocene
946	6°56.9′N	47°55.2′W	4100	275	middle Pleistocene

Notes: A tripartite division of the Pleistocene has been used following Harland et al. (1990). The boundary between the late and middle Pleistocene is placed at the beginning of isotope Substage 5e, and the boundary between middle and early Pleistocene at the Matuyama-Brunhes magnetic polarity reversal. * = debris flow contained material as old as Miocene, but the oldest sediment in place was from the early Holocene.

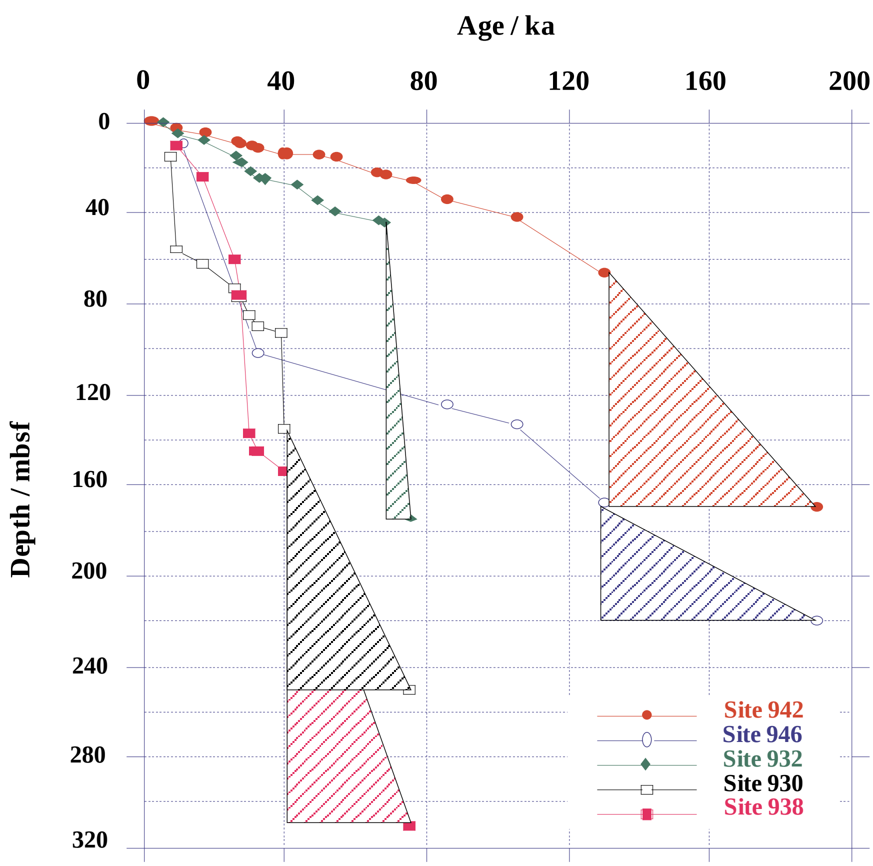

Figure 13. Age-depth plots for Sites 930, 932, 938, 942, and 946.

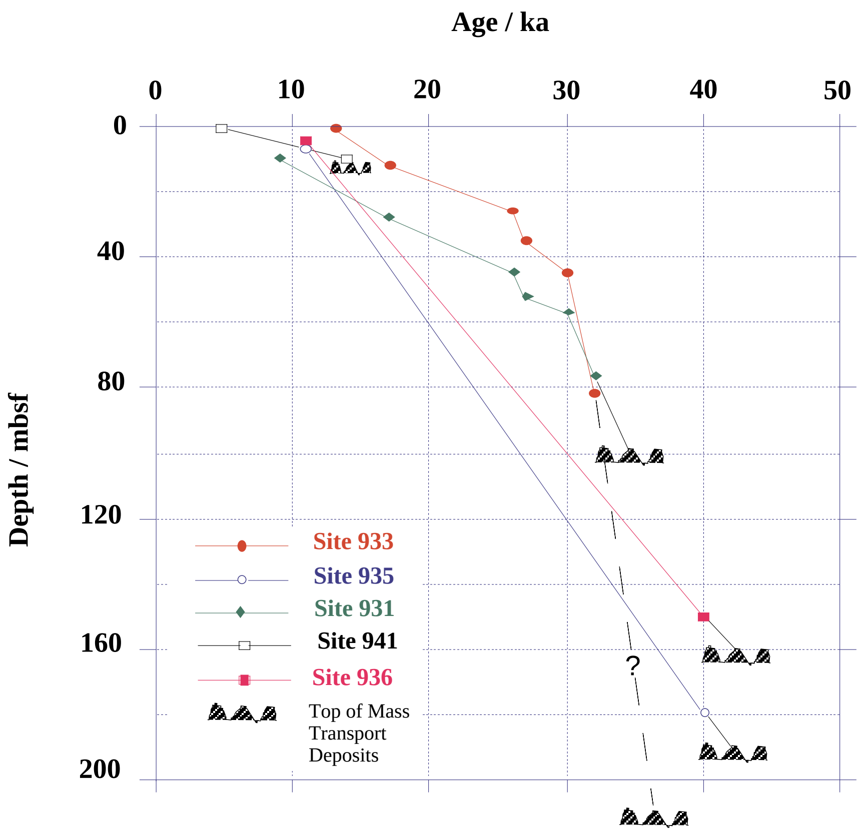

Figure 14. Age-depth plots for Sites 931, 933, 935, 936, and 941.

nonchannelized flows. Piper et al. (Chapter 39, this volume) in their site correlation synthesis show when these different channel-levee systems were active. For those with clearly dated beginnings and terminations, the duration of the channel-levee systems varies between a maximum of 3 k.y. (Amazon System) to a minimum of 1 k.y. (Blue System). Another consideration is that once a channel-levee system has been abandoned it can leave a local topographic high. This greatly reduces the sediment accumulation on the top of the high, as it is less affected by nonchannelized flows. An example of this is Site 932.

What actually controls the fluctuations of the channelized sediment is far from explained. Two main processes have been suggested: either climate change and/or associated sea-level changes, which influence the amount of sediment transported to the fan complex, or auto-cyclic channel avulsion processes (Flood et al., 1991).

SUMMARY AND CONCLUSIONS

1. This preliminary study has shown that despite the problematic nature of making any sensible biostratigraphic analyses of fan deposits, micropaleontological investigations of the Amazon Fan sediments have provided an overall biostratigraphic framework. This framework has been used to help unravel the late Quaternary evolution of the Amazon Fan complex.
2. Biostratigraphic data, combined with other key stratigraphic tools, have provided an overall picture of the extreme range of sedimentation rates found in the Amazon Fan (5 to >5000 cm/k.y.).
3. Biostratigraphy, especially the analysis of nannofossils, has provided the means of estimating the age of the deep interglacial deposits. These deposits underlie the MTDs and are discontinuous.
4. Biostratigraphy, combined with paleomagnetism and sedimentation rate constraints, has provided age estimates of the last activity of both the deep and shallow MTDs recovered from the Amazon Fan.

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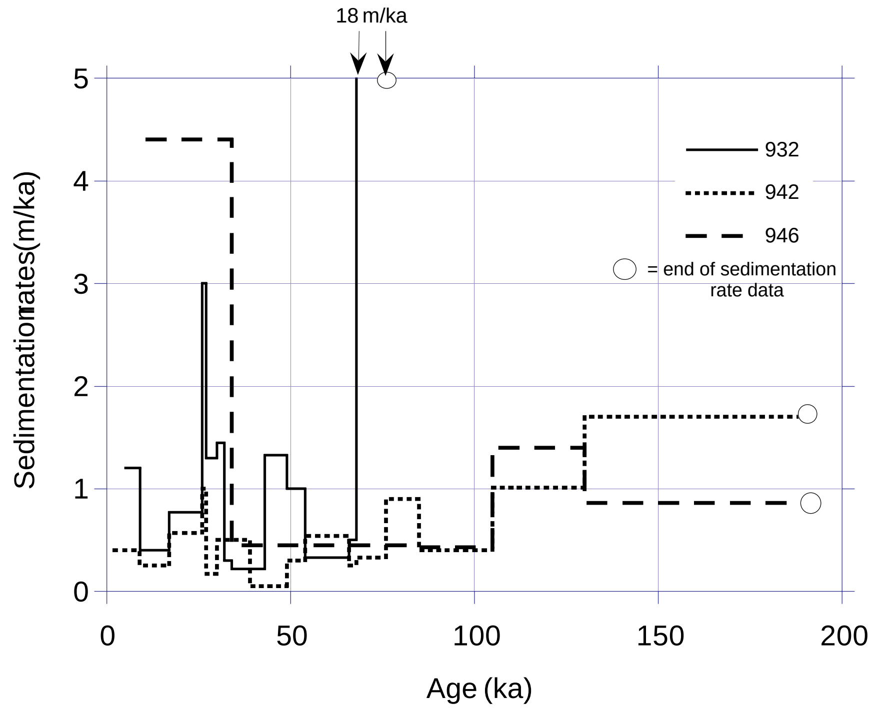

Figure 15. Sedimentation rate plots for Sites 932, 942, and 946.

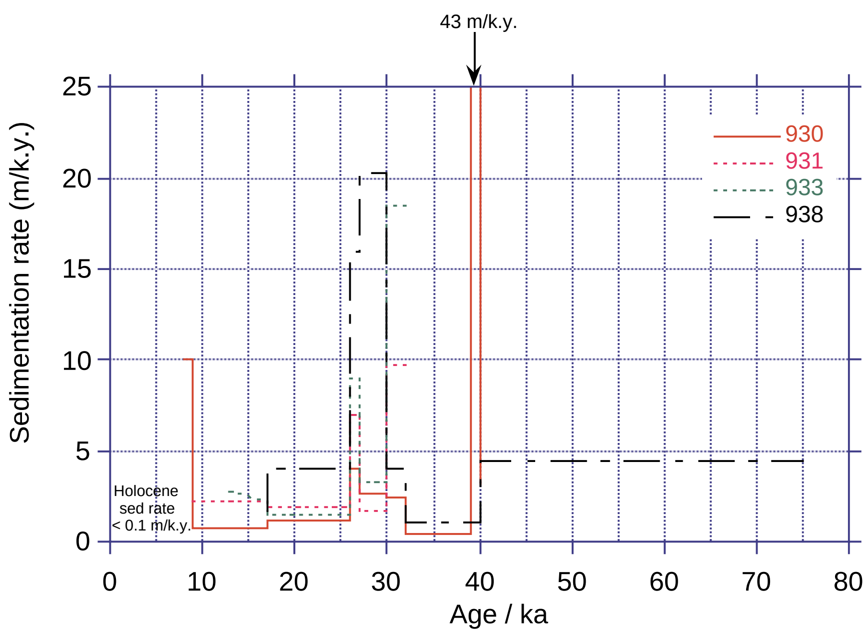

Figure 16. Sedimentation rate plots for Sites 930, 931, 933, and 938.

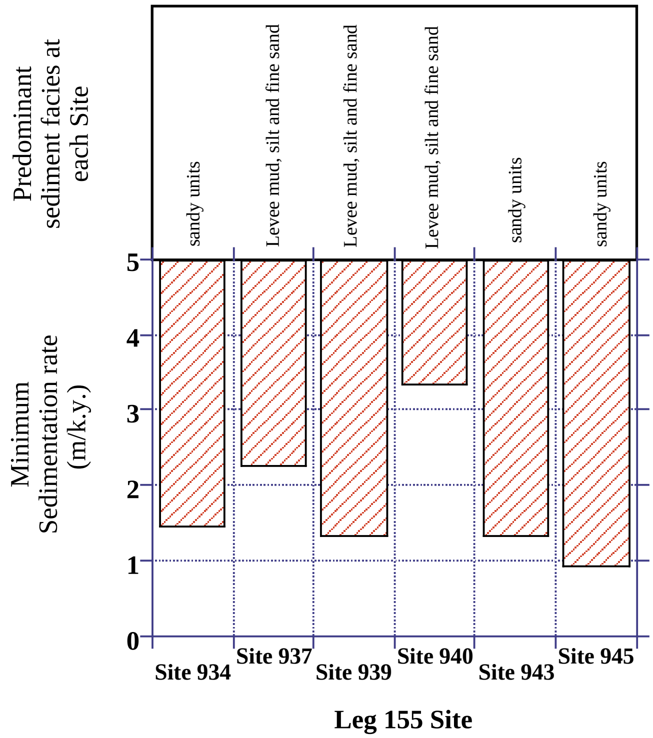

Figure 17. Minimum sedimentation rate plots for Sites 934, 937, 939, 940, 943, and 945.

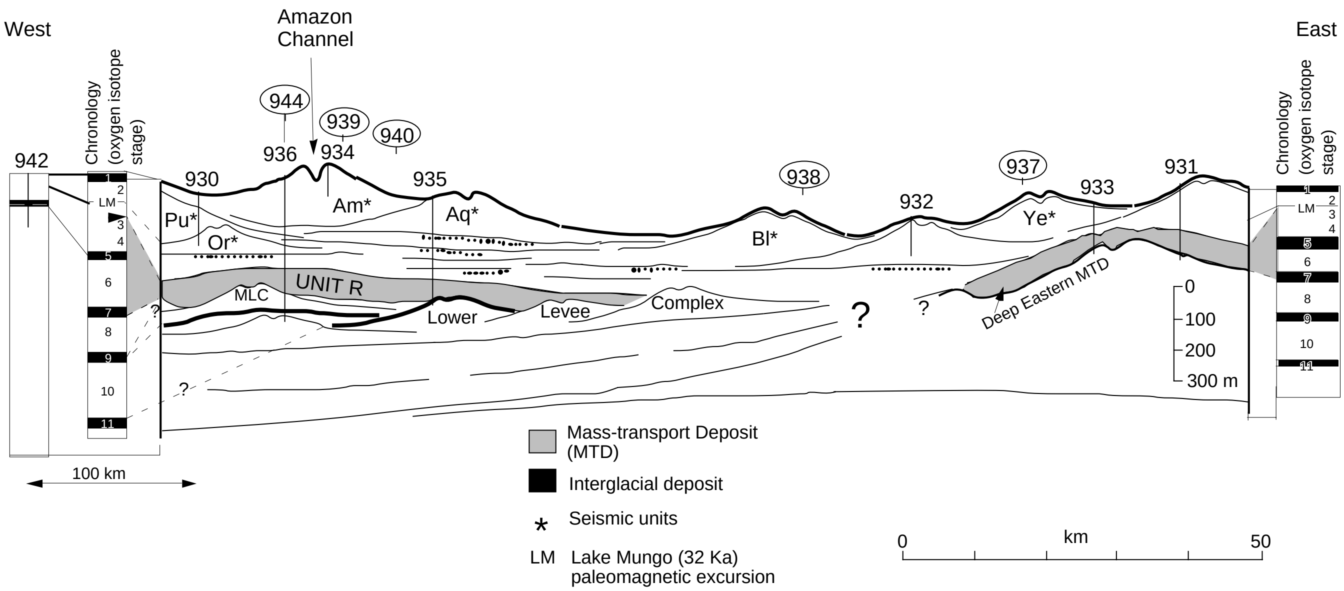

Figure 18. Theoretical model of the overall stratigraphy of the mass-transport deposits (MTDs) and interglacial deep carbonates drilled on the Amazon Fan. Initial unit correlations are based on seismic stratigraphy (Flood, Piper, Klaus, et al., 1995). One of the key biostratigraphic successes of Leg 155 was the characterization and dating of the huge MTDs. It is suggested that the deep EMTD was last active at approximately 33 ka, the Unit R MTD at 45 ka, and the near-surface Western and Eastern Debris Flows during Termination I (Maslin and Mikkelsen, this volume).