REVIEW OF THE TIMING AND CAUSES OF THE AMAZON-FAN MASS TRANSPORT AND AVULSION DEPOSITS DURING THE LATEST PLEISTOCENE

MARK A. MASLIN
Environmental Change Research Centre, Department of Geography, Pearson Building, Gower Street, University College London, London, WC1H 6BT, U.K.
e-mail: mmaslin@geog.ucl.ac.uk

Abstract: The late Pleistocene Amazon deep-sea fan provides a "modern" analogue to ancient fan systems containing sandy hydrocarbon reservoirs. Extensive deposits of sand-rich material are found in the Amazon Fan mass-transport deposits (MTDs) and the base-of-channel avulsed sand bodies which underlie the channel–levee systems. These deposits were drilled as part of ODP Leg 155, the results of which form the basis of this review. The hemipelagic sediment above the MTDs and avulsed sand bodies were dated using primarily AMS radiocarbon dating. The dating provides support for the interpretation that the MTDs and avulsed sand bodies were triggered by relatively small, millennial-scale changes in relative global sea level (± 5–20 m). Equally controversial has been the suggestion that changes in sea level also control the architecture of the channel–levee distributive systems within the Amazon Fan. For example, Maslin et al. (2006) proposed that prior to 22,000 calendar years BP a tripartite channel system existed while afterwards only one active channel–levee system existed. This switch may have been due to the fall in sea level below the shelf break, providing direct access between the canyon and the sediment supplied to and eroded from the shelf-edge delta front. This would have significantly increased the sediment supply to the Amazon Fan at 22 ka, contributing to channel entrenchment involving channel-floor erosion and the growth of levees within the canyon–channel transition area, promoting the development of a single deep, incised channel. If future work confirms that Amazon deep-sea Fan sedimentation is sensitive to relatively small changes in sea level, this will provide support for the central assumption of the theory of sequence stratigraphy, namely that changes in sea level control basin sedimentation and the emplacement of sand-rich, potential hydrocarbon-bearing, deposits. It is hoped that these controversial suggestions reviewed here will stimulate more investigations into the Amazon Fan and other deep-sea fans.

Key words: Amazon Fan, avulsion, slope failure, Pleistocene, sequence stratigraphy

INTRODUCTION

Large submarine-fan systems are one of the most important repositories for continentally derived clastic sediments, and thus, deep-marine hydrocarbon reservoirs (Emery and Myers, 1996). Despite a concerted effort to understand and identify the fundamental controls on growth patterns of these fan systems, the relative roles of internal (autocyclic) vs. external (allocyclic) processes are still debated. The central problem is to identify the degree to which sand deposition is controlled by climate-induced changes, such as sea level and/or sediment supply (allocyclic), or by internal depositional (autocyclic) and/or random dynamics within the fan system (e.g., Flood et al., 1995; Prins and Postma, 2000; Bouma, 2001). I present here a review of the controversial evidence for the correlation between the formation of large MTDs and sand bodies produced by channel-avulsion events and millennial-scale changes in global relative sea level.

OVERVIEW OF THE AMAZON FAN

The Amazon Fan (Fig. 1) is located off the northeast Brazilian continental margin in the equatorial Atlantic Ocean; it is the world's third-largest mud-rich deep-sea fan. The fan extends 700 km down slope from the shelf break with an average gradient of 0.4° on to the Demerara Abyssal Plain at a water of depth of 4,800 m. The fan exhibits an elongated radial pattern covering 330,000 km^2 and has a maximum thickness of 4–5 km, and the total volume of sediment has been estimated as in excess of 700,000 km^3 (Damuth and Kumar, 1975; Damuth and Flood, 1984; Damuth et al., 1988). During interglacials, such as the Holocene, the Amazon river sediment load is transported by longshore currents to the northwest and deposited on the continental shelf, inshore of the shelf break (Milliman et al., 1975; Milliman et al., 1982; Nittrouer and DeMaster, 1986). Deposition of terrigenous sediments was temporarily interrupted on the fan during the Holocene and previous interglacials and pelagic sediments were deposited. Thin intervals of biogenic mud recovered deeper in the fan attest to previous periods of fan inactivity during older interglacials (Flood et al., 1995). These intervals of biogenic mud apparently represent condensed sections equivalent to at least portions of transgressive (TST) and highstand (HST) systems tracts and maximum flooding surfaces (MFS) in the Vail/Exxon conceptual sea-level model. Sedimentation rates of Holocene and previous interglacial Amazon Fan sediments reflect this and are approximately 5–10 cm/kyr (Damuth and Kumar, 1975; Damuth and Flood, 1984; Damuth et al., 1988; Mikkelsen et al., 1997). During glacial periods the terrigenous sediment supply is transported across the shelf break, switching on the sediment supply directly to the fan. During glacial periods as much as one giga tonne (one thousand billion kilograms) of sediment per year, over 80% of which originates in the Andes (Milliman and Meade, 1983; Rimington, 1999) is deposited on the Amazon Fan. Glacial sedimentation rates range from 1 m/kyr to over 50 m/kyr, a 20- to 1000-fold increase compared to Holocene sedimentation rates (Mikkelsen et al., 1997; Piper et al., 1997a).

Prior to ODP drilling in 1994 on Leg 155, architectural elements and the distribution of sedimentary facies within the Amazon Fan were inferred from high-resolution seismic, GLORIA sidescan sonar, SeaBeam swath-mapping, and piston-core data (e.g., Damuth and Kumar, 1975; Damuth and Embley, 1981; Damuth et al., 1988; Damuth and Flood, 1984; Manley and Flood, 1988; Flood et al., 1995; Pirmez, 1994; Pirmez and Flood, 1995). In particular, these

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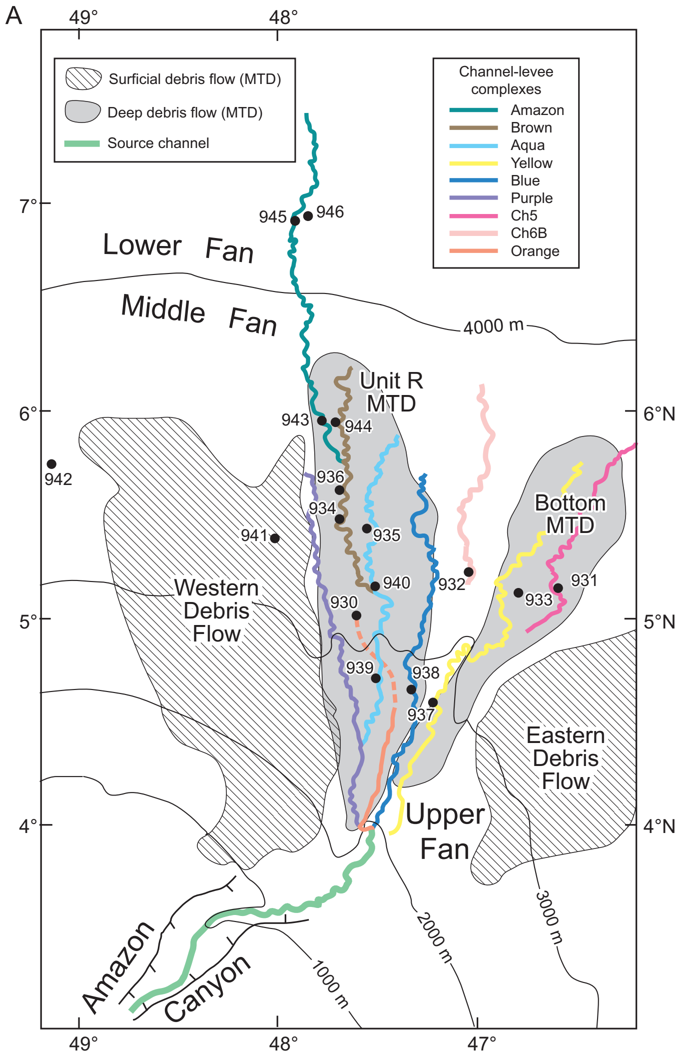

FIG. 1.—Map of Amazon Fan and sites drilled during Ocean Drilling Program Leg 155 (adapted from Damuth et al., 1988; Manley and Flood, 1988). The spatial distribution of the different channel–levee complexes is shown with appropriate colors and is reconstructed from Pirmez and Flood (1995). Mass-transport deposits were penetrated at eight sites, and the spatial distribution is reconstructed from Piper et al. (1997b).

studies revealed that distributary channels have highly meandering planforms and are perched on natural levee systems. High-amplitude reflections (termed HARs) observed beneath the channel axes were interpreted as coarse-grained channel-fill deposits. More laterally extensive high-amplitude reflection packets (termed HARPs) at the bases of channel–levee systems were interpreted as coarse sediment deposited either from flows spreading laterally outward from a channel mouth (i.e., depositional lobe) or from flows issuing through a crevasse in a levee during initiation of a channel-avulsion event (i.e. crevasse splays). Although only one channel–levee system was apparently active at any given time, repeated channel avulsion developed groups of overlapping, genetically related channel–levee systems, termed channel–levee complexes, across the upper to middle fan surface. In addition, large, regionally extensive mass-transport deposits (MTDs) were recognized on the modern fan surface (Damuth and Embley, 1981) and buried within the fan between older levee complexes (Manley and Flood, 1988). ODP Leg 155 systematically cored Amazon Fan at 17 drill sites, and excellent continuous sections were recovered from all major submarine-fan elements including: (1) levee/overbank deposits of channel–levee systems of a variety of ages, (2) channel-fill deposits (HAR units), (3) base-of-channel deposits (HARP units or avulsed sand bodies), (4) lower-fan lobes, and (5) surficial and buried mass-transport deposits. Terrigenous sediments constitute the vast majority of the cored intervals and display a number of discrete sandy and muddy facies (see Flood et al., 1995, and Flood et al., 1997, for detailed results). The levee or overbank deposits are mud and clay with interbeds of predominantly silt laminae, with common thin silt and fine sand beds. Sediments cored from HAR units beneath the axis of the modern Amazon Channel are predominantly thick-bedded, fine- to coarse-sand facies. The coarsest and thickest sand beds were cored in the thick, laterally extensive HARP units at the bases of Amazon and other channel–levee systems, and in lower-fan deposits, which represent coalescing depositional lobes (i.e., HARPs) extending down fan from the channel mouths. HARP units contain thick, laterally extensive, medium to coarse sands commonly with mud clasts and rock granules. Wireline and FMS logs suggest that some intervals of little to no core recovery are thick beds of disorganized gravel or sandy gravel (Pirmez et al., 1997). More commonly, HARPs and lower-fan deposits contain medium to thick (up to 12 m) beds of fine to medium sand, with common mud clasts. The HARPs or avulsed sand bodies are up to 20 km wide, 30 km long, and 20–50 m thick in the Pleistocene Amazon Fan (Figs. 1, 2). It has been suggested that the HARP units formed by deposition from turbidity and related gravity-controlled flows that issued from a crevasse in an active channel levee during the beginning of an avulsion event (Flood et al., 1997). The HARP units are laterally restricted by inter-levee topography and progressively prograded downslope in front of the newly forming channel–levee system until it reached the lower fan. The new channel–levee system, which was created by avulsion, progressively built downslope and buried these coarse deposits to form the base-of-channel HARP unit (see graphical representation of these features in Flood et al., 1995). Upon completion of channel–levee development, the coarse sands spread laterally across the lower fan to form an end-of-channel lobe. These HARP units occur on the same scale and in the same depositional context as clastic hydrocarbon reservoirs observed in ancient fan systems (e.g., Mutti and Normark, 1987; Weimer, 1990; Richards, 1996). Hence, the Amazon Fan provides a Pleistocene analogue for the mechanics of the formation of hydrocarbon reservoirs and in particular the controlling influence of climate and sea level. The thick, regionally extensive mass-transport deposits of the fan contain mainly chaotic muddy facies that clearly indicate large-scale sediment failure and mass transport (e.g., slumps, debris flows) down-fan. These deposits consist predominantly of thick intervals (tens of meters) of deformed or chaotic mud with mud clasts and blocks, or discordant, contorted, folded, faulted, and truncated beds. Thick intervals of disorganized pebbly or gravelly mud and sandy mud are common, and intervals of homogeneous, structureless mud (possibly undeformed blocks) also occur (Piper et al., 1997b).

MASS-TRANSPORT DEPOSITS

Eight sites penetrated MTDs on the Amazon Fan, and sediment was recovered from the entire unit of the MTDs and underlying sediment at seven of these sites (Flood et al., 1995). Three of the four late Pleistocene MTDs were drilled, and each cover an area of approximately 200 km downslope and 100 km wide and are about 100–200 m thick (Figs. 1, 2; Damuth and Embley, 1981; Damuth et

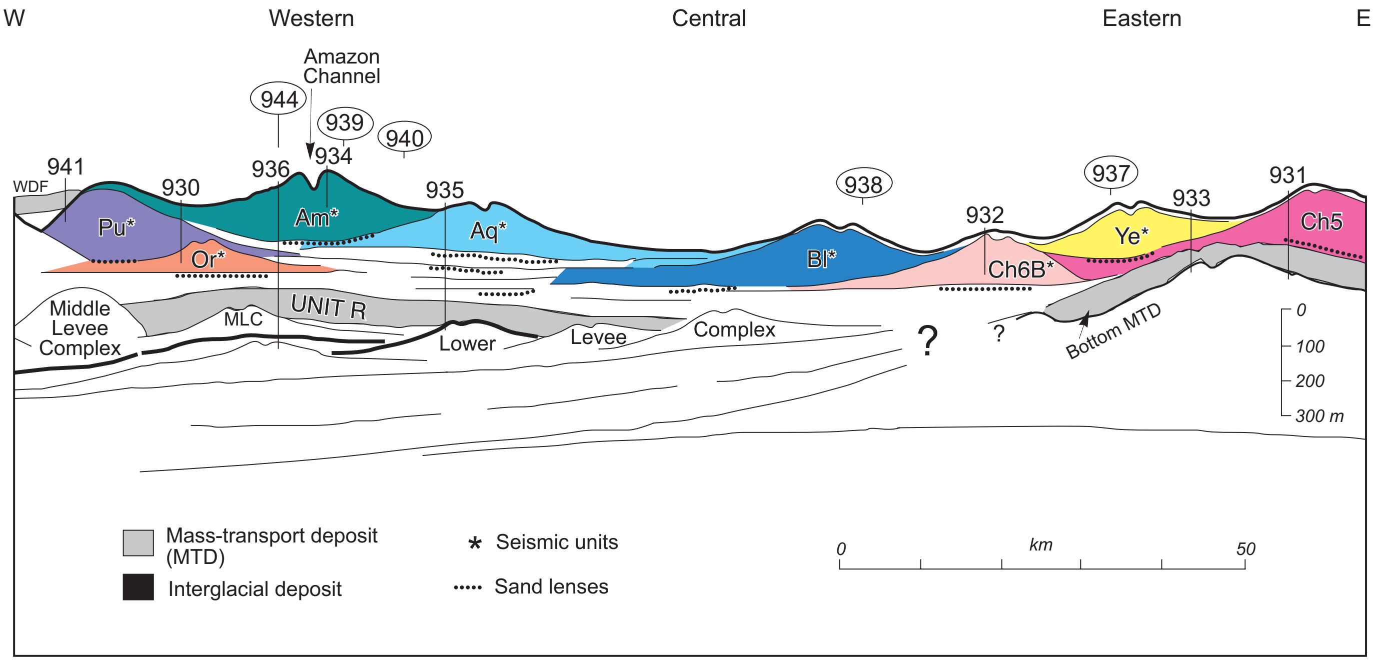

FIG. 2.—Stratigraphic relationships of Amazon Fan architectural units (modified from Flood et al., 1995; Piper et al., 1997a; Piper et al., 1997b; Flood and Piper, 1997; Mikkelsen et al., 1997). Units are based on seismic stratigraphy (Flood et al., 1995), Ye = yellow, Bl = blue, Aq = aqua, Am = Amazon channel, Pu = purple, Or = orange, Ch6B = Channel 6B, Ch5 = Channel 5, and MLC = middle levee complex.

al., 1988; Manley and Flood, 1988; Pirmez and Flood, 1995; Piper et al., 1997a; Piper et al., 1997b; Flood et al., 1997; Maslin and Mikkelsen, 1998). Each of these deposits covers about 15,000 km^2 (approximately the size of Jamaica), with a maximum thickness of 200 m, and contain at least ~ 5,000 Gt of sediment (Owen et al., 2007). This is about half the size of the biggest Hawaiian slide (Moore et al., 1994), five times larger than the Mediterranean "megaturbidite" recorded by Rothwell et al. (1998), and of a size comparable to that of the Nordic Seas Storegga (Bugge et al., 1987) and North Sea (King et al., 1996) slides.

Leg 155 cored two major deep MTDs (Figs. 1, 2). The first, the "Unit R Debris Flow" (Manley and Flood, 1988), underlies the Upper Levee Complex and was recovered at Sites 935, 936, and 944 (Fig. 2). Unit R was found to have levee muds directly below the contact surface, but at Sites 936 and 944 there was an additional sand unit approximately 40 m thick below the levee muds. At Site 935 below the levee muds is an interglacial carbonate-rich unit. On the eastern part of the Amazon Fan, the second MTD, termed the Bottom or Deep Eastern MTD (referred to as Bottom MTD in this review), overlies the crest of the Bottom Levee Complex and was cored at Sites 931 and 933 (Figs. 1, 2). This MTD has interglacial sediments directly below the contact surface. The two near-surface MTDs, termed the Eastern and Western "debris flow" by Damuth et al. (1988), were defined from seismic lines (Fig. 1, 2). Only the Western Debris Flow was cored during ODP Leg 155 at Site 941 and the base was recovered at 130 mbsf (Flood et al., 1995). A full description of all of the units recovered by ODP Leg 155 can be found in Flood et al. (1995).

DATING THE AVULSION EVENTS AND MTD UNITS

Base-of-channel (HARP) sand units formed by avulsion events and MTDs have been identified from both seismic and lithological records (Flood et al., 1995). To radiocarbon date the avulsion events, samples were collected from the hemipelagic sediments in the overlying levee deposits; see Table 1 for exact sample locations. Due to the extremely high sedimentation rates in the base of the channel–levee system a range of material was used to obtain dates, including planktonic foraminifera, marine molluscan fragments, and plant detritus (termed organic matter in Table 1). These were AMS ^{14}C dated at the Leibniz Labor für Altersbestimmung und Isotopenforschung, Kiel University, Germany (Nadeau et al., 1997; Nadeau et al., 1998) (Table 1). We obtained dates for all avulsion events drilled on ODP Leg 155, with the exception of the events initiating the Aqua and Blue channel–levee systems. The high sedimentation rates above these units resulted in extreme dilution of the datable biogenic components. Dates for these units (Sites 935 and 938) were determined by correlating seismic boundaries (Piper et al., 1997a) with paleomagnetic remanent features and oxygen isotope records from adjacent sites 932 and 933 (Cisowski and Hall, 1997; Maslin et al., 1997). It should be noted that a number of other avulsion events have been identified through seismic data but were not drilled by ODP Leg 155 (Pirmez and Flood, 1995). AMS ^{14}C dates were calibrated to calendar years with associated errors using OxCal 3.10 and CalPal SFCP (Weninger et al., 2004; Bronk Ramsey, 2005). Errors on the calibrated ages range from ± 400 to over ± 1000 years. When possible, multiple biogenic components and/or sites were dated for each avulsion event (Table 1).

There are a large number of errors that can occur when using radiocarbon dates to date MTDs and avulsion events, including reworking and selective bioturbation. These errors are discussed in detail by Owen et al. (2007). The most important consideration is that the material above the MTD or avulsed sand body represents the youngest age of that deposit. This is compounded by selective bioturbation within the hemipelagic sediment, whereby younger

TABLE 1.—Stratigraphy of the Amazon Fan avulsion and failure events occurring over the past 50 ky.

Base date of Amazon Seismic Units	Location	Site	ODP Sample code	Radiocarbon dates (C^{14} yr BP)	Material dated	Calendar years Age (yr B.P.) 2 sd quoted§	Dates of Amazon fan avulsion/failure events (calendar yr BP)
Holocene	Eastern Fan Western Fan Central Fan	933A 942C 944A	1H, 1W, 54–56 cm 1H, 1W, 74–76 cm 1H, 1W, 54–56 cm	10,805 ± 55 10,260 ± 50 10,510 ± 70	Foraminifera Foraminifera Foraminifera	12,325 ± 325 11,255 ± 105 11,650 ± 618	~ 11,600 but is not coeval across the Fan
Amazon	Western Fan	940A 944A	8H, 1W, 10–25 cm 13X, CCW, 0–28 cm	13,310 ± 210 13,730 ± 100	Foraminifera Foraminifera	15,150 ± 800 15,825 ± 563	15,700**
Brown	Western Fan	936A 936A	8H, 7W, 14–40 cm 8H, 7W, 14–40 cm	16,250 ± 90 17,780 ± 100	Mollusk Foraminifera	19,075 ± 195 20,575 ± 375	19,700
Aqua	Central–Western Fan	935A					~ 22,000*
Blue	Central Fan	938A					~ 27,000*
Yellow	Eastern Fan	933A	2H, 6W, 100–115 cm	23,000 ± 200	Foraminifera	27,420 ± 520	27,400
Purple	Western Fan	944A 944A	17X, 1W, 34–56 cm 17X, 1W, 72–90 cm	22,740 ± 100 23,220 ± 110	Organic matter Organic matter	27,620 ± 220 28,110 ± 220	27,900**
Channel 5	Eastern Fan	931B	16X, 3W, 72–102 cm	30,200 ± 220	Organic matter	35,540 ± 340	35,500
Orange	Western Fan	936A	18X, 1W, 20–35 cm	34,620 ± 1000	Organic matter	40,280 ± 2120	40,300
Channel 6B	Central Fan	933A	9H, 3W, 40–55 cm	33,840 ± 500	Foraminifera	40,000 ± 1840	40,000
Date of occurrence of Amazon MTDs							
Eastern Debris Flow	Eastern Fan					Correlation to WDF	13,500*** or 14,500 or > 30,000 (see main text)
Western Debris Flow	Western Fan	941			Foraminifera		13,500***
Bottom MTD	Eastern Fan	931, 933			Foraminifera		37,000***
Unit R MTD	Western Fan	935, 936, 944			Foraminifera		41,000***

§The age before present is in calendar years, and radiocarbon dates have been calibrated by using OxCal 3.10 for dates younger than 26 radiocarbon kyr and CalPal SFCP for dates older than 26 radiocarbon kyr (Weninger, et al. 2004; Bronk Ramsey, 1995, 2005). Dates for avulsion and failure events are given to only 3 SF due to the inherent errors.

* Radiocarbon dates were not possible for these seismic boundaries so ages are based on correlating palaeomagnetic remanent features and oxygen isotopes from Sites 935 and 938 to 932 and 933 (Showers et al., 1997; Piper et al., 1997a, 1997b; Maslin et al., 1997).

** These radiocarbon ages have been combined using the baysian-based combine function in Oxcal (Weninger, et al., 2004; Bronk Ramsey, 1995, 2005). An agreement of 60% was used as a rejection threshold for all combinations. Where this is not possible an average has been taken.

*** Estimated ages for the Amazon MTDs are from Maslin et al. (2005).

material is moved downwards. The secondary consideration is whether the datable material above the MTD or HARP has been laterally or vertically reworked from the older material. Due to the extremely high sedimentation rates of the channel–levee system above both the MTD and HARP units, samples for dating were taken some distance away from the boundary to minimize the reworking. For example, a conservative sedimentation rate for the base of the channel–levee system is 20 m/kyr (Piper et al., 1997a; Mikkelsen et al., 1997); thus a sample taken 2 m away from the boundary would have an error of about 100 yr, which is well within the error range of the radiocarbon dating method (± 400 to ± 1,000 years). In addition, when possible multiple samples from different sites and depth were taken (Table 1).

There are two sets of MTDs on the Amazon Fan. The near-surface MTDs are referred to as Eastern and Western debris flows (Damuth et al., 1988) which in part overlie the older MTDs referred to as Unit R and Bottom MTD. Three of the MTDs have been directly dated. The Unit R MTD (Manley and Flood, 1988), which underlies the upper levee complex, has been dated to approximately 41 calender ka BP (Maslin et al., 1998; Maslin et al., 2005) (Fig. 3). The second MTD, which on the eastern fan is the Bottom MTD, overlies the crest of a lower older levee complex and is dated to 37 ka BP (Maslin et al., 1998; Maslin et al., 2005). There are also two near-surface MTDs, termed the Eastern and Western debris flows (Damuth et al., 1988). The Western debris flow has been dated to approximately 13.5 calendar ka BP (Maslin et al. 1998, 2005). The date of the Eastern Debris Flow has been estimated at either > 30 ka (Piper et al., 1995a) or approximately the same as the Western Debris Flow (Maslin et al., 1998; Maslin et al., 2005). This is because the age has to be obtained by correlating oxygen isotope records between sites on either side of the Amazon Fan. This is further complicated by a disturbed section occurring on top of the Eastern Debris Flow (Damuth et al., 1988). Maslin et al. (1998) and Maslin et al. (2005) suggested that there was a disturbed section, and thus the most likely age was approximately 13.5 ka due to a fully intact Holocene section on top of the Eastern Debris Flow; however, this is far from conclusive.

ORIGIN OF THE SEDIMENT WITHIN THE MTDS

The benthic foraminifera found in the MTDs provide a unique means of estimating the origin of the sediment in the MTD. The low abundance and diversity of benthic foraminifera along with the evidence that the tests are frequently small, abraded, and brown are characteristics of sediment that has been transported and reworked. The occurrence of the most abundant species is shown in Figure 4, based on the work presented by Maslin et al. (2005). The buliminids and species such as *Cassidulina laevigata*, *Globocassidulina subglobosa*, *Stainforthia complanata*, *Brizalina aenariensis*, *Pseudononion atlanticum*, *Q. lamarckiana*, and *Uvigerina peregrina* were found in the Bottom MTD, the Unit R MTD, and the Western Debris Flow. Buliminids, cassidulinids, and uvigerinids characterize bathyal environments (see references in Maslin et al., 2005). This has been confirmed for the Brazilian margin, because *C. laevigata*, *G. subglobosa*, and species of *Bulimina* are commonly encountered in sediments of the Amazon upper and middle slope (e.g., Vilela, 1995, 1998). Figure 4 shows the current and Holocene depth habitat of these indicator species. The species found in the MTDs come predominantly from the shelf and slope. Maslin et al. (2005) therefore suggested that the sediments in the MTDs originated in the upper–middle bathyal environments, with another possible secondary source area on the shelf. They speculated that the shelf species could have been transported onto the slope and then carried onto the fan via the catastrophic failure and the formation of the MTDs. In addition, sea level was about 100 m lower during the last glacial and the region constituting the present shelf was exposed. Consequently, increased subaerial weathering may have contributed more shelf species to the slope.

CORRELATION OF AVULSION AND MTD EVENTS WITH SEA-LEVEL CHANGES

Figure 5 compares the dated avulsion sands and MTD deposits with a composite global relative sea-level curve based on both coral and Red Sea planktonic-foraminifera oxygen-isotope data (Fairbanks, 1989; Bard et al., 1998, Chappell, 2002; Cutler et al., 2003; Siddall et al., 2003; Rohling et al., 2004). Note that the dating of the formation of the Purple, Blue, and Yellow channel–levee system and the Orange and Ch6B channel–levee system cannot be distinguished due to the associated errors and thus must be treated as coeval. Maslin et al. (2006) suggested from these data that a correlation existed between avulsion and slope-failure events and changes in relative sea level and thus suggested a causal link. In support of this theory they cited the observation that there is continuous channel–levee deposition with no failure or avulsion events when there is little or no change in global relative sea level, i.e., between 26–22 ka and 27–33 ka. Moreover, they suggest that every significant millennial-scale change in global relative sea level seems to be mirrored by an avulsion or failure event on the Amazon Fan.

The avulsion events appear to coincide with millennial-scale rises (Orange, Channel 6B, Channel 5B, and Brown) and falls (Purple, Blue, Yellow, and Aqua) in global relative sea level on the order of 5 to 20 m (Fig. 5). For example, the avulsion event which initiated the Brown unit appears to be associated with the 10 m rise in sea level at about 19 ka, documented by Yokoyama et al. (2000). The deeper MTDs also seem to correlate with 5 m to 25 m falls in sea level. In contrast, the near-surface Western Debris Flow and possibly the Eastern Debris Flow coincide with a rapid 20 m rise in sea level at 13.5 ka (MWP 1a; Fairbanks, 1989; Bard et al., 1998). The fundamental finding of the Maslin et al. (2006) study was that, even considering the errors in dating, every major change in Amazon Fan architecture over the last 50 kyr was related to a significant change in relative global sea level.

DISCUSSION

Origin of the MTDs

The benthic foraminifera microfaunal evidence complied by Vilela and Maslin (1997), Vilela (1998), and Maslin et al. (2005) discussed above suggests that the sediment in the MTDs drilled by ODP Leg 155 must have originated at water depths of between 200 and 600 m, i.e., on the upper continental slope. The mass-transport deposits must have travelled laterally more

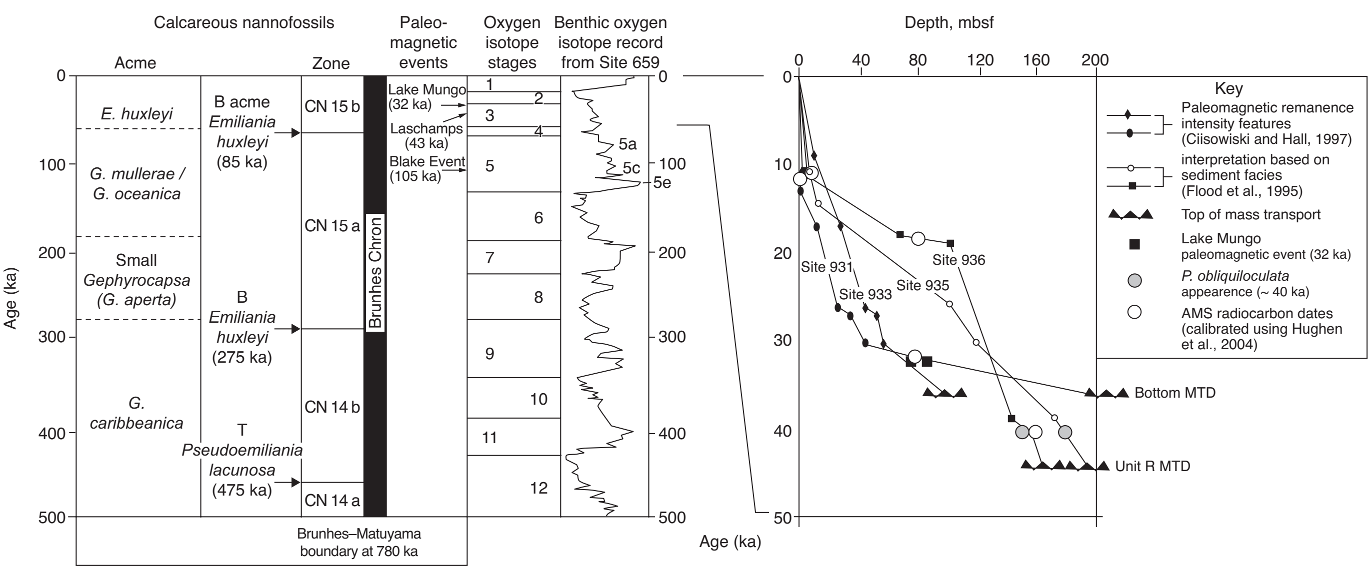

FIG. 3.—Stratigraphic data used to reconstruct stratigraphy of the Amazon Fan (Mikkelsen et al., 1997) compared with a benthic foraminifera oxygen isotope record (Tiedemann et al., 1994) and the age models for key Leg 155 sites. Calcareous nannofossils zonal scheme confirms that all the sediment recovered, except that in the mass-transport deposits, was younger than 460 ka, inasmuch as *Pseudoemiliania lacunosa* was not observed. The age models of Sites 931, 933, 935, and 936 were constructed using biostratigraphy, magnetic stratigraphy, AMS radiocarbon dates, and sedimentation-rate constraints (see Maslin et al., 2005, for full details).

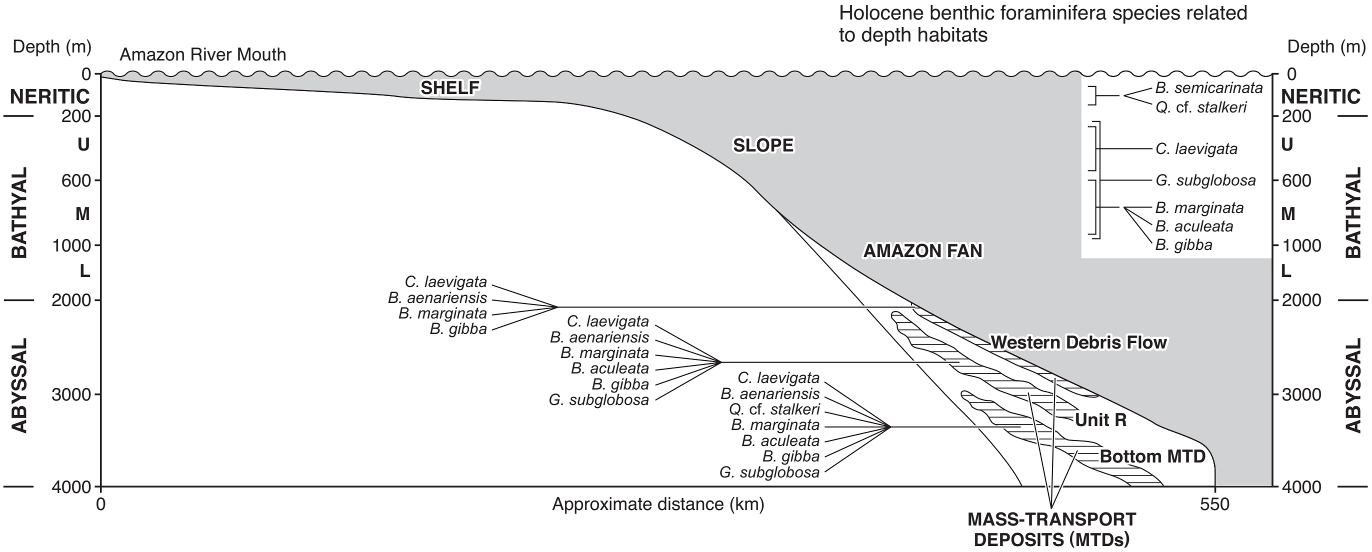

FIG. 4.—Modern bathymetric distribution of benthic foraminiferal species compared with the occurrence of species in the MTDs (adapted from Maslin et al., 2005).

than 200 km and bathymetrically down at least 1500 m to have reached their current locations. This is supported by the discrete clasts found in the MTDs which contain either Pliocene or Miocene nannofossil assemblages which can have originated only from the exposed Pliocene and Miocene sections on the Brazilian upper continental slope. This may, however, not be true of the Eastern Debris Flow, inasmuch as Damuth and Embley (1981) suggested that it originated at 2500–3200 m and unpublished seismic lines show that it may have originated from the side of a channel–levee system (Damuth, personal communication, 2007).

The strong consistent internal structure of the mass-transport deposits drilled on ODP Leg 155 shown by both sedimentological and biostratigraphic evidence (Flood et al., 1997; Normark et al., 1997; Mikkelsen et al., 1997; Vilela and Maslin, 1997) and relatively low angle of the slope traversed (< 1°) indicate that these are slump deposits; in contrast, the mud clasts and blocks suggest that they are debris flows. This suggests that the Amazon Fan MTDs are probably slump–debris-flow deposits in terms of process. Catastrophic slump/debris flow events may be caused by either rapid dissociation of gas hydrates (e.g., Kayen and Lee, 1991; Haq, 1993, 1995, 1998; Rothwell et al., 1998; Dillon et al., 2001; Owen et al., 2007) or by overburdening of the sediment column (e.g., Weaver and Kuijpers, 1983; Roberts and Cramp, 1997; Nisbet and Piper, 1998), submarine earthquakes (e.g., Nisbet and Piper, 1998; Rothwell et al., 1998; Owen et al., 2007) or simply the influence of gravity (Owen et al., 2007).

There are two sets of Amazon MTDs: two near-surface and two deep MTDs. Because of their different relationship to global relative sea level, two different causes have been suggested; see the following section. The deep MTDs appear to have been deposited as sea level was falling, and the near-surface occurred as it was rising. The deep MTDs are discussed first, because there is more evidence for their timing and sedimentological structure.

As suggested above, the initiation of the two deep glacial mass-transport deposits corresponds to periods of rapidly falling sea level (Fig. 5). Two causes have been suggested: *in situ* slumping and gas hydrate release due to sea-level lowering. *In situ* slumping of the channel–levee deposits was suggested by Piper et al. (1997a) based on seismic data and the presence of carbonate-rich interglacial deposits at the bases of the units. These sediments would be deformed and slumped *in situ*. However, there is evidence from lithology and foraminiferal contents (Piper et al., 1997a; Piper et al., 1997b; Vilela and Maslin, 1997; Maslin et al., 1998) for distinct blocks or subunits in the MTDs, which occur in both depth and lateral domain. By considering the original climatic conditions under which the sediment in the MTDs was formed, inferred from their planktonic foraminiferal assemblages (Vilela and Maslin, 1997) suggested that these blocks have different sources of material. In the Bottom MTD there are three distinct blocks positioned one on top of another. In the Unit R the same unit has different blocks at different sites across the fan (Vilela and Maslin, 1997). The benthic foraminiferal assemblage data indicate a more distal source. Moreover, Maslin and Mikkelsen (1997) suggested that the structurally weaker carbonate-rich interglacial deposits may have acted as slip planes for the MTDs. In such a case, inclusion of interglacial material in the bases of the MTDs would be expected. However, the presence of separate blocks within each of the MTDs does raise the question of whether the MTDs were single or multiple failure events. At the moment the assumption for dating these events has been that they are single events. The dating of hemipelagic sediments directly on top of the MTD represents the youngest age of the event. If these are multiple events, then this date represents only when the last event occurred. Dating material within the MTDs does not help because of the erosional nature of these deposits. For example, material in the Western Debris Flow showed a clear dating reversal with a date of 20,870 radiocarbon years 14 m above a date of 18,270 radiocarbon years.

Causes of the MTDs

Maslin et al. (1998) and Maslin et al. (2005) suggested release of gas hydrates as the most likely cause of failure. The sea-level drops which correlate with the MTDs are indeed very rapid. McGuire et al. (1997) estimated rates between 15–25 m/kyr (Figure 6), which would be sufficient to reduce the hydrostatic pressure enough to destabilize gas-hydrate reservoirs on the

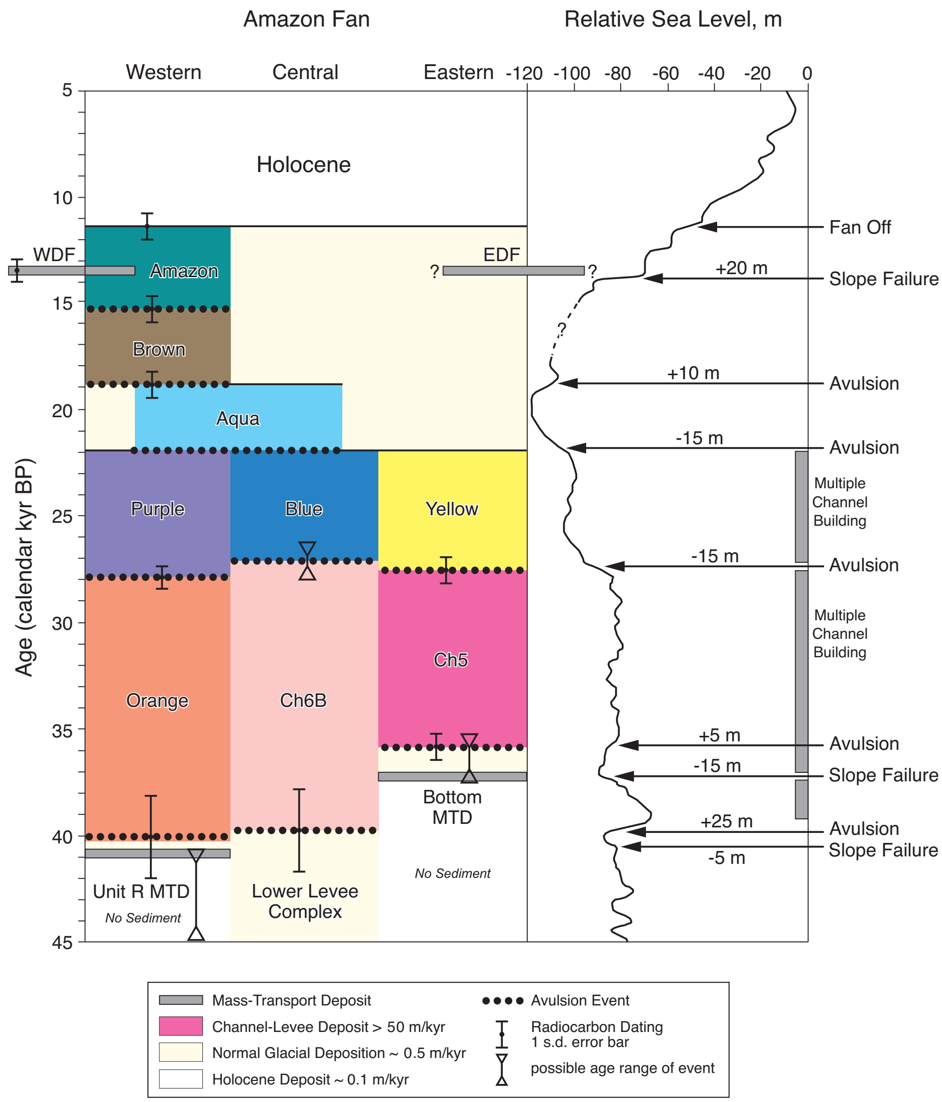

FIG. 5.—Comparison between the global relative global-sea-level curve and the avulsion events on the Amazon Fan. The channel–levee systems are color coded and named, and their spatial and lateral extent can be seen in Figures 1 and 2. Note that when sea level is relatively constant there are no avulsions or failure events and channel–levee systems accumulated over a 3,000–8,000 year period. Moreover at 22 ka there was a shift from a tripartite to a single channel–levee system, which is discussed in the text. The composite global relative-sea-level curve based on both coral (Fairbanks, 1990; Bard et al., 1998, Chappell, 2002; Cutler et al., 2003) and Red Sea planktonic foraminifera oxygen isotope data (Siddall et al., 2003; Rohling et al., 2004) data. WDF = Western Debris Flow, EDF = Eastern Debris Flow, MTD = mass-transport deposit. (Adapted from Maslin et al., 2006.)

continental slope (e.g., Kvenvolden, 1993; Haq, 1993, 1995; Kennett et al., 2003; Owen et al., 2007). Maslin et al. (1997), Maslin et al. (1998), and Maslin et al. (2005) speculate that it was the rapidity of the release of pressure below a critical sea level that caused the dissociation of clathrate and thus mass failure of the North Brazilian continental slope. The origin of the mass-transport deposits at water depths of between 200 and 600 m supports this hypothesis, because this is where the most sensitive gas-hydrate reservoir is located. Bottom-simulating reflectors (BSR) are characteristic of the phase shift between solid hydrate and free gas (Dickens et al., 1997). The BSR has been observed in acoustic data of the Amazon Fan and the Brazilian continental slope, indicating the presence of gas hydrates (Manley and Flood, 1988; Flood et al., 1995). In addition, Soh (1997, figure 11) showed the location of the BSR above the Western Debris Flow. The presence of gas hydrates has been reported in other deep-sea fans such as the Congo Fan (Uenzelmann-Neben and Spiess, 1996). Other foot-of-the-slope slides, slumps, and megaturbidites that have been attributed to gas-hydrate dissociation are interpreted on the Norwegian margin (Bugge et al., 1987), the New Jersey margin (Dickens et al., 1997), the Gulf of Mexico (Haq 1993, 1995), and the Balearic Abyssal Plain (Rothwell et al., 1998).

Additional evidence for the possible catastrophic release of gas hydrates is the extreme negative excursions in the planktonic foraminifera carbon isotope records from sites on the Amazon Fan (Maslin et al., 2005) (Fig. 7). Gas hydrate contains highly depleted methane with a carbon isotope signature of between –40‰ and –100‰ (average is thought to be about –60‰; e.g., Dickens et al., 1997; Kvenvolden, 1993; Dickens, 2001; Maslin and Thomas, 2003). If this depleted carbon is released into the water column, some of it oxidizes to highly depleted carbon dioxide and is incorporated into the calcium carbonate tests of planktonic foraminifera. The planktonic foraminifera *N. dutertrei* carbon isotope record from Site 932 (Fig. 7) plot against the age model developed by Haberle and Maslin (1999) clearly shows major carbon isotope excursions of up to 2‰ associated with both the occurrence of Unit R MTD and Bottom MTD. These excursions are also found in the other four planktonic foraminifera records measured for this site and also at Site 933 (Maslin et al., 1997). The presence of these negative excursions in the sediments coeval with the occurrence of the MTDs strongly suggests that methane was released either just before or during the slope failures. However, the presence of gas hydrate does not mean that it was the cause, because it could just be the effect of the slope failures. For example, if a random submarine earthquake occurred on the continental shelf it may have caused sediment to fail between 200 and 600 m water depth. This would have led to a combination of slump and debris flow, resulting in the MTD. The removal of material from the continental shelf would have removed weight from the underlying sediments and resulted in depressurization of any gas hydrate trapped there. For the Maslin et al. (2005) suggestion that gas hydrates were the cause of the slope failures to be correct, then the dating of the MTDs is critical, inasmuch as the link to changing sea level is the only piece of evidence which suggests a nonrandom cause.

The near-surface Eastern and Western Debris Flows, if coeval, occurred at 13.5 ka, during Termination 1A, when sea level was rising rapidly (Fig. 5). Maslin et al. (1998) and Maslin et al. (2005) suggest that these debris flows could not have been caused by gas-hydrate release, because the increase in hydrostatic pressure, as sea level rose, would have stabilized the hydrate deposits. It could be speculated that a rapid rise of intermediate water temperature could have overcome this increase in hydrostatic pressure. This is unlikely, because the transmission of temperature changes from the sediment–ocean interface to the base of the stability zone is extremely slow due to the low thermal diffusivity of marine sediment (Clennell et al., 1999). In addition there is no evidence for such a rapid "threshold"-like rise in intermediate water temperatures over the Amazon Fan. Hence more likely the Eastern and Western Debris Flows may have failed due to overburdening of the continental-slope sediment column because of an increase and/or a redistribution of the Amazon River sediment discharge. An increase in sediment discharge could have been caused by the deglaciation of the Andes (Thompson et al., 1995). This suggestion is supported by evidence of a massive ten-fold increase in sedimentation rate observed at ODP Site 942 between 13.5 and 13 ka (Maslin et al., 2000). In addition there is evidence that at the end of this high sedimentation rate the depocenter for the Amazon River sediment discharge shifted. Hence the Western and Eastern Debris Flow could have been caused by either an increase in sediment deposition due to flushing of the Amazon

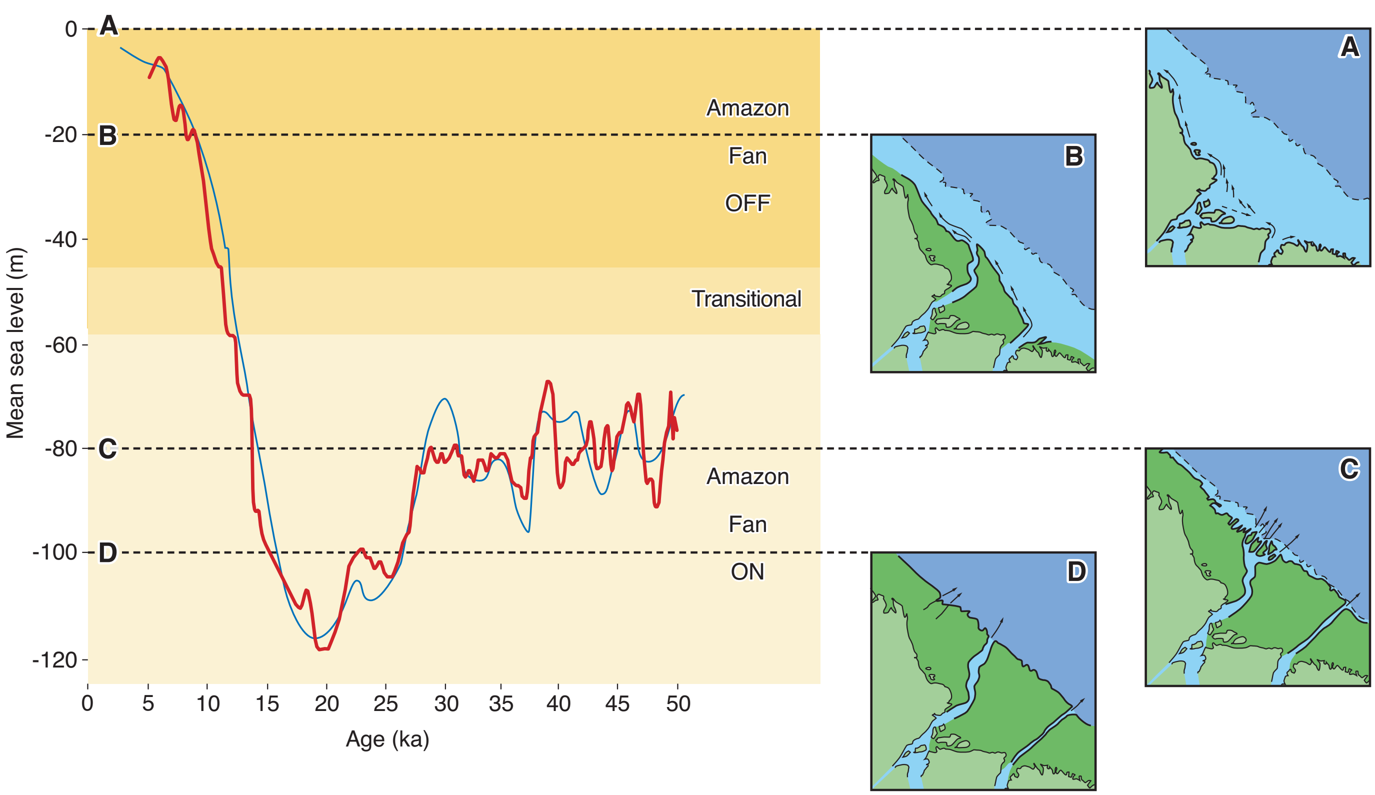

Fig. 6.—Comparison of the composite global relative-sea-level curves with the Milliman et al. (1975) theoretical model of changing morphology of the continental shelf and Amazon delta with lowering sea level. Red (thick) sea-level curve is a composite of coral and Red Sea data shown in Figure 5, and for comparison the blue (thin) curve is a composite coral and benthic oxygen isotope record (McGuire et al., 1997). When relative global sea level is below about 50 m compared with today, this study suggests that small changes in sea level can significantly change the sediment supply to the fan. This results in either channel-floor aggradation or channel-floor erosion and thus an avulsion event. (Adapted from Maslin et al., 2006.)

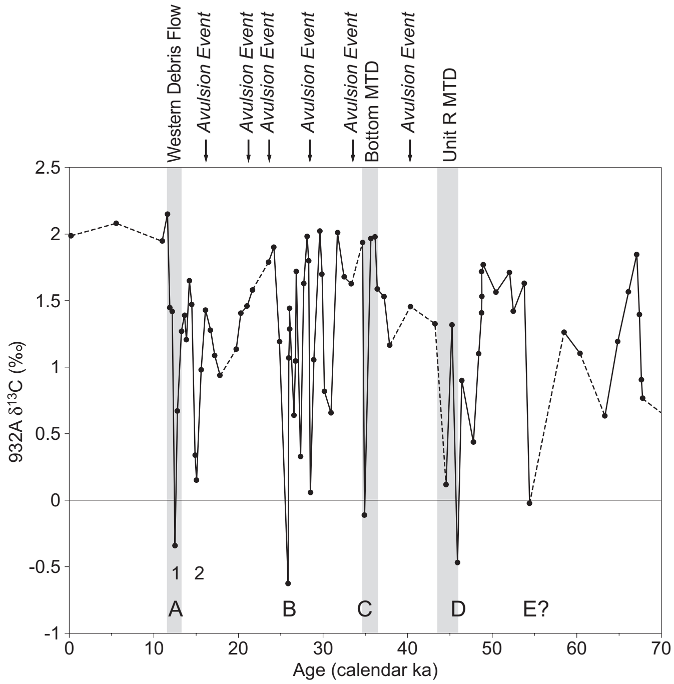

FIG. 7.—Planktonic foraminifera *N. dutertrei* carbon isotope record from Site 932 plot against the age model developed by Haberle and Maslin (1999) compared to the timing of the MTDs. Note that there is a strong correlation between extreme negative excursions in the carbon isotope record and the MTDs. This could have been due to the catastrophic release of very negative gas hydrate methane into the water column during each collapse. Note the double peak between 13 and 15 ka, which may suggest that the Eastern and Western Debris flows occurred at slightly different times. (Adapted from Maslin et al., 2005.)

Basin by deglaciation of the Andes or the shifting of the sediment depocenter to the continental shelf. The most likely scenario could be that the two mechanisms may have worked in tandem so that enhanced sediment supply and relocation of the sediment deposition onto the continental slope, causing it to overburden and to fail catastrophically. This raises the question whether if the Western Debris Flow was caused by a changing sedimentation regime, could not the same be true for the deeper MTDs? Because both Unit R and the Bottom MTD occurred when sea level dropped (Fig. 5), it could be argued that there was an increase in sediment load directly into the Amazon Fan; this could have led to a rapid increase in the overburden and slope failure. The evidence for gas hydrates concurrent with these events would then be an effect and not the cause, which is contrary to the suggestion of Maslin et al. (2005).

Whatever the cause of these two near-surface MTDs, there is evidence that they caused a secondary effect of releasing significant amounts of gas hydrates. First there is evidence for significant quantities of gas hydrates within the Amazon Fan MTDs (e.g., Figueiredo et al., 1996; Soh, 1997). For example, Soh (1997) demonstrates clearly from X-ray computed tomography (CT) and pore-water chemistry the presence of gas hydrate in the Western Debris Flow sediments recovered at Site 941. Using CT, Soh (1997) showed that the gas hydrate content reached ~ 10 vol% (or ~ 17% of the pore space) of the fluidized sediment, which is equivalent to the highest content of gas hydrate above the bottom-simulating reflectors (BSRs) reported from other gas-hydrate regions, e.g., ~ 18% of the pore space at the Chile Triple Junction (Bangs et al., 1993) or ~ 8.4% of the pore space at Site 997 on Blake Outer Ridge, Leg 164 Scientific Party (Paull et al., 1996). Second, the planktonic foraminifera carbon isotope records from Sites 932 (Fig. 7) and 933 (Maslin et al., 1997) clearly show a negative peak at 13–13.5 ka, which could indicate the massive release of gas hydrates. Interestingly, there is an earlier negative peak at 14–14.5 ka, which led Maslin et al. (2005) to speculate that the Eastern Debris Flow may not have been coeval with the Western Debris Flow and may have occurred up to a thousand years earlier.

Causes of the Avulsion Events

The AMS ^{14}C chronology and synthesized geological data suggest that global relative sea level may have had an important control on the general architecture of the Amazon Fan as well as the formation of the MTDs. Maslin et al. (2006) controversially speculated that when relative global sea level was between –50 and –100 m the Amazon Fan functioned as a tripartite system with three independent channel–levee systems operating in the western, central, and eastern parts of the fan (Fig. 3). This conclusion was reached because the dates of the channel–levee systems were so close. For example Purple, Blue, and Yellow cluster around ~ 28 ka and the Orange and Ch6B at ~ 39 ka. If these channel–levee systems were formed consecutively, then the oldest would have had less than 500 years to form while the youngest would have had thousands of years to develop. Maslin et al. (2006) suggested that when sea level fell below –100 m the Amazon Fan system switched to a single channel–levee system (Fig. 3; Aqua to Brown to Amazon, which started at ~ 22 ka). Sediment was supplied to both systems via the Amazon Canyon. Then, when sea level rose above –50 m, following a rapid rise of 15 m at ~ 13 ka, sedimentation over the fan switched off and reverted to carbonate-rich pelagic–hemipelagic muds.

Maslin et al. (2006) suggested that these observed changes in fan sedimentation, including the avulsion events, were triggered by rapid marine transgression and regression across the continental shelf due to changing global relative sea level. During interglacial highstands, such as the Holocene, the Amazon Fan is dormant because the shelf morphology induces longshore drift and the sediment of the Amazon and Tocantins rivers is deposited in a continental-shelf delta (Fig. 6). As sea level falls the Amazon coastline evolves from a shelf delta to a shelf-edge delta (Milliman et al., 1975; Milliman, 1982). Results from previous studies suggest that longshore drift deposition ceased with a fall of global relative sea level of greater than -50 m (Maslin et al., 2000). Unlike shelf deltas, which are set back from the continental edge, shelf-edge deltas feed sediment directly to the deep-water sediment system (Emery and Myers, 1996). Sediment load to the Amazon Fan would have increased with the encroachment of the coastline to the edge of the continental shelf and the head of the Amazon Canyon. The progression of the coastline, with falling sea level, from a shelf delta to a shelf-edge delta (Fig. 6) coincided with increased sedimentation rates in the Amazon Fan (Mikkelsen et al., 1997) and may be responsible for the switch from tripartite to single channel–levee distributary systems. There is evidence from the Amazon Fan to support this controversial suggestion. For example the tripartite channel–levee system does seem to have originated during intervals of relatively low sedimentation rates (40–28 ka equates with ~ 1–2 m/kyr and 27–22 ka equates with ~ 2–10 m/kyr; Mikkelsen et al., 1997) compared to the single channel–levee system (see below). The channel branching also occurs on the low-gradient slope of the canyon–channel transition area (Fig. 1). Maslin et al. (2006) suggested that channel-floor aggradation or deposition occurred at the expense of the levees so that a single channel was unable to completely contain density flows transported down the fan. The flows were, therefore, distributed through branching (avulsion) of two major overspill channels at nodes along a main channel. Maslin et al. (2006) suggested that this theory was supported by the location of the different branches (Fig. 1) and that they occurred at slightly different times (Fig. 5). However, the latter is true only if it is assumed that the slight difference in age of the deposits is real and not due to the large errors associated with radiocarbon dating. They also attributed the trigger of the branched tripartite systems to increases in the sediment supply associated with 10–20 m changes in global relative sea level (Fig. 5). Similar simultaneously active, secondary channel–levee branches within a turbidite channel system have been found in the Tertiary succession off the West African continental slope (Fonnescu, 2003). These tripartite systems may be analogous to the mechanism observed in smaller-scale anastomosed and braided fluvial channel complexes (Kneller, 2003; Bridge, 2003).

The change from a tripartite distributive system to the single channel–levee system coincides with increased sedimentation rates (from 5 to > 30 m/kyr between 22 and 11.5 ka; Mikkelsen et al., 1997). This difference in sedimentation rate between the channel–levee systems is probably one of the strongest pieces of evidence for multiple active channel–levee systems prior to 22 ka, if we assume that approximately the same amount of sediment entered the Amazon Fan during the last glacial period. If only one channel–levee system was active at any one time, then they should have similar sedimentation rates. As it is, there is a significant difference between those channel–levee systems prior to and after 22 ka. In fact the sedimentation rates of Purple, Blue, and Yellow channel–levee systems together are equivalent to the Amazon channel–levee system. Maslin et al. (2006) suggested that this significant increase in sediment supply to the Amazon Fan at 22 ka contributed to channel entrenchment, involving channel-floor erosion and the growth of levees within the canyon–channel transition area. This regime promoted the development of a single deep, incised channel, which was able to fully contain the turbidity-current flows and extended down fan via a series of mid-fan avulsions. The increase in sedimentation rates coincides with the fall in sea level below the shelf break at 22 ka, which provided direct access between the canyon and the sediment supplied to and eroded from the shelf-edge delta front. The initiation of the single channel–levee system and avulsion events on the mid-fan correspond with millennial-scale falls and rises in global relative sea level (Fig. 5). The system was probably maintained during sea-level rise (Fig. 5) by significant erosion of the shelf edge (Galloway, 1989; Emery and Myers, 1996).

In summary, Maslin et al. (2006) speculated that avulsion events occurred as a result of channel-floor aggradation by sea-level change induced either by a process of backfilling and downstream blockage (Schumm et al., 1987) or by a process of aggradation and blockage at meander bends in response to sea-level-induced increases in sediment supply (Kneller, 2003).

CONCLUSIONS

Recent papers on the Amazon Fan challenge the current view of the structure and sedimentary evolution of a deep-sea fan system. First, it is proposed that millennial-scale sea-level fluctuations caused both slope failure and avulsion events on the Amazon Fan (Maslin et al., 1995; Maslin et al., 1998; Maslin et al., 2005; Maslin et al., 2006). Second, the formation of MTDs led to a significant release of gas hydrates (Maslin et al., 1998; Maslin et al., 2005). Third, three channel–levee systems operated and were stable at the same time (Maslin et al., 2006). Fourth, the avulsion events occurred when sediment supply to the fan was enhanced during rising and falling sea level. For example, large sandy deposits of up to 1 x 10^9 m^3 (1 km^3) can form in a deep-sea muddy fan with sea-level changes as little as ± 10 m (Maslin et al., 2006). If this is found to be true, it supports one of the central assumptions of sequence stratigraphy, namely that relatively global sea level has a central role in determining continental-slope deposition. However, there are still a number of unanswered questions, which need to be addressed if the new theories are to be properly tested. First, the dating of the occurrence of the MTDs and base-of-channel (HARP) sand units formed by avulsion events needs to be improved to confirm if there is any link to changes in global relative sea level. Second, more investigation into the Eastern Debris Flow and other undated avulsion events is required, particularly recovery of new material either by giant piston coring or ultimately ocean drilling. Third, modeling is required to ascertain whether a tripartite channel–levee system can theoretically be stable for between 5 and 10 thousand years. Fourth, similar investigations should be encouraged on other deep-sea fan system to seek confirmation of these new suggestions.

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