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Résumé de l'article

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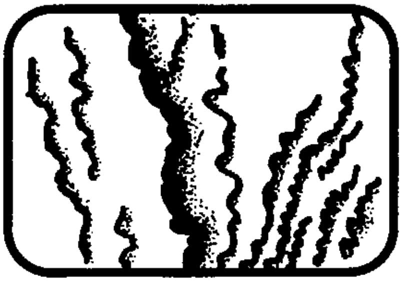

Amazon Submarine Fan Drilling: A Big Step Forward For Deep-sea Fan Models

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SUMMARY

The results of coring on the Amazon submarine fan in 1994 challenge previous ideas about facies architecture and genesis of fan deposits. A shingled set of latest Pleistocene, upward-fining channel-levee units is underlain by, and locally interleaved with, equally voluminous sand-rich deposits. The sands occur as 5-25 m-thick packets, locally rich in semi-consolidated mud clasts. Each sand-rich unit is inferred to have been partly derived from an upfan avulsion site, landward of which entrenchment of the pre-existing channel floor occurred. Sands were distributed into the adjacent inter-channel low, where lack of confinement allowed spreading of turbidity currents to form sheet-like sand-rich bodies. Subsequently, the advance of a new leveed channel over the sheet sands focussed sand transport along the channel axis, with simultaneous accumulation of muddy overbank deposits in the levees. Ancient channel-levee systems atop sheet sands, including those in some oilfields, may have similarly formed during single lowstands of sea level and as a result of repeated cycles of levee progradation and upfan avulsion.

RÉSUMÉ

Les résultats de sondages réalisés sur le cône sous-marin de l'Amazone en 1994 remettent en question les conceptions acceptées concernant l'arrangement structurale et la genèse des dépôts des cônes sous-marins. Les cordons de galets à granoclassement normal présents dans les derniers dépôts pléistocènes, d'unités sédimentaires de levées de rive de chenaux, recouvrent, et s'interstratifient par endroits avec des volumes d'égale importance de dépôts fortement sableux. Ces unités sableuses se présentent en paquets de strates de 5 m à 25 m d'épaisseur comportant par endroits de nombreux clastes de boues. Des indices permettent de supposer que les matériaux de chacune de ces unités sableuses proviennent en partie de sites d'avulsion situés en amont, juste en aval du lit d'anciens chenaux. Les sables ont été étalés dans les dépressions entre les chenaux adjacents où des courants de turbidité ont pu former des couches sableuses de grande continuité, étant donnée l'absence de structures de confinement. Par suite du développement d'un nouveau chenal sur la couche sableuse, le transport des sables s'est concentré le long de l'axe du chenal et, des couches de boues ont été déposées sur les levées. D'anciens systèmes de chenaux à levées reposant sur des unités très étendues de sable, entre autres, ceux de certains bassins pétroliers, ont pu se former durant un seul et même épisode de basse mer, par répétition du cycle de progradation de levées suivie d'avulsions d'amont d'un cône sous-marin.

INTRODUCTION

Models for the interpretation of ancient submarine fans at outcrop and in the subsurface have long suffered a severe deficiency: morphological features have been recognized and classified from modern fans, whereas facies successions have been described largely from ancient deep-water successions (Mutti and Ricci Lucchi, 1972; Normark, 1978; Walker, 1978; Mutti and Normark, 1987, 1991). Acoustic facies and acoustic facies successions are well described from modern fans (*e.g.*, Droz and Bellaiche, 1985; McHargue and Webb, 1986; Weimer, 1991, 1995; Kolla and Schwab, 1995; Flood *et al.*, 1991, Damuth *et al.*, 1995; Normark *et al.*, in press), but are undated and largely uncalibrated by cores. Such uncalibrated acoustic data cannot be used with confidence to guide the interpretation of ancient deep-sea fan deposits.

Unlike modern continental and shallow-marine siliciclastic settings where coring and trenching can easily reveal typical facies successions, modern submarine fans have escaped definitive study of their internal facies architecture because of inaccessibility, difficulty in piston-coring sandy and coarser sediments, and the very large scale of their component morphological elements (Normark *et al.*, 1979). As a consequence, ground-breaking studies of deep-water siliciclastic sedimentation have been dominated by investigations of sediment transport mechanisms (*e.g.*, Middleton, 1966a, 1966b, 1967, 1970; Hay, 1987; Normark and Piper, 1991; Masson *et al.*, 1993; Kneller and Branney, 1995), not predictive facies models.

In 1994, a major step was taken by the Ocean Drilling Program (ODP) to rectify the dearth of ground-truth sediment data from modern submarine fans. ODP Leg 155 raised 4053 m of cores from 34 holes at 17 sites on the Amazon Fan (Fig. 1), one of the largest extant submarine fans (Barnes and Normark, 1984). Penetration ranged from 75 m below sea floor (mbsf) to 435 mbsf, and averaged 235 mbsf. Two goals of Leg 155 (Flood *et al.*, 1995a) were 1) to determine the facies organization of the fan, by drilling proximal and distal muddy levees, sandy channel fills, mass-transport complexes, channel-mouth lobes, and an abandoned channel fill, and 2) to determine the kinds of sediments associated with particular seismic facies. In this paper, we summarize those results relevant to facies architecture and models for submarine fans characterized by widespread channel-levee complexes, including most large open-ocean fans, and smaller fans fed by low-gradient river systems with a high proportion of suspended load.

FACIES SUCCESSIONS OF AMAZON FAN

The uppermost 500-800 m of Amazon Fan consist of three extensive levee complexes (Fig. 2), each formed of a number of laterally shingled channel-levee systems. The youngest of these, the Upper Levee Complex, formed entirely during oxygen isotope stages 2-4 of the latest Pleistocene (Piper *et al.*, in press). A particularly exciting Leg 155 result is the discovery of widespread, medium- to coarse-grained, sheet-like sand units, located beneath, and interleaved with, channel-levee deposits of the Upper Levee Complex. In seismic data (Flood *et al.*, 1991, 1995b; Damuth *et al.*, 1995), the sheet-like sand units correspond to High Amplitude Reflection Packets (HARPs; Figs. 2 and 3), which include both parallel and subtly lens-shaped internal reflections, the latter suggesting the presence of small, unleveed channels. HARPs are broadly contemporaneous with a set of channel-levee units on the upper and middle Amazon Fan (Pirmez, 1994), and with lower fan sandy lobes (Flood and Piper, in press). To characterize these sheet sands, Pirmez *et al.* (in press) generated five detailed bed-by-bed sections for Sites 931, 935, 936, 944 and 946 using shipboard core descriptions and interpretations of downhole logs (mainly gamma-ray) and borehole images obtained using the Formation MicroScanner tool (FMS).

The FMS (Schlumberger tradename) is a four-pad micro-electrical resistivity device that allows detailed investigation of vertical and lateral variations of resistivity near the borehole wall (Serra, 1989). The vertical resolution of the tool is of the order of 2.5 cm, similar to that of shipboard core descriptions and many outcrop studies. Examples of FMS images from the Amazon Fan, and a complete set of the bed-by-bed sections derived from these images, are available in Pirmez *et al.* (in press). Here, we base our analysis on gamma-ray profiles (Fig. 4) and a restricted set of representative bed-by-bed sections from either shipboard core descriptions (see site chapters and backpocket plates 1 and 2 in Flood *et al.*, 1995a) or FMS interpretations (Pirmez *et al.*, in press). Core recovery in HARP sand facies was poor (Fig. 4), sufficient to support the interpretations of grain size derived from logs, but not adequate to determine the characteristics of typical beds. Numerous core photographs of levee facies are available in Flood *et al.* (1995a); detailed photographs of HARP sand facies are very few because of the poor recovery (Flood, Piper *et al.*, 1995a, p. 329-330, 662-665, 668).

Thick-bedded to very thick-bedded intervals of sand, 5-25 m thick, characterize HARPs (Fig. 5). Mud clasts are common in the thicker sand beds, which are up to 10 m thick. The HARPs onlap an angular-erosional unconformity at the base of each channel-levee system. Most sands in the HARP units are bounded by thin-bedded, bioturbated, silty-clays below, and show an abrupt decrease in bed thickness and grain size above. The sand beds are organized into either a single group of thick beds, or into a number of packets (*i.e.*, bed clusters), each a few tens of metres thick. The packets generally have sharp basal contacts and fairly sharp tops; locally, the bases of packets are gradational. Some packets contain almost no mud interbeds (Fig. 5D), whereas others have numer-

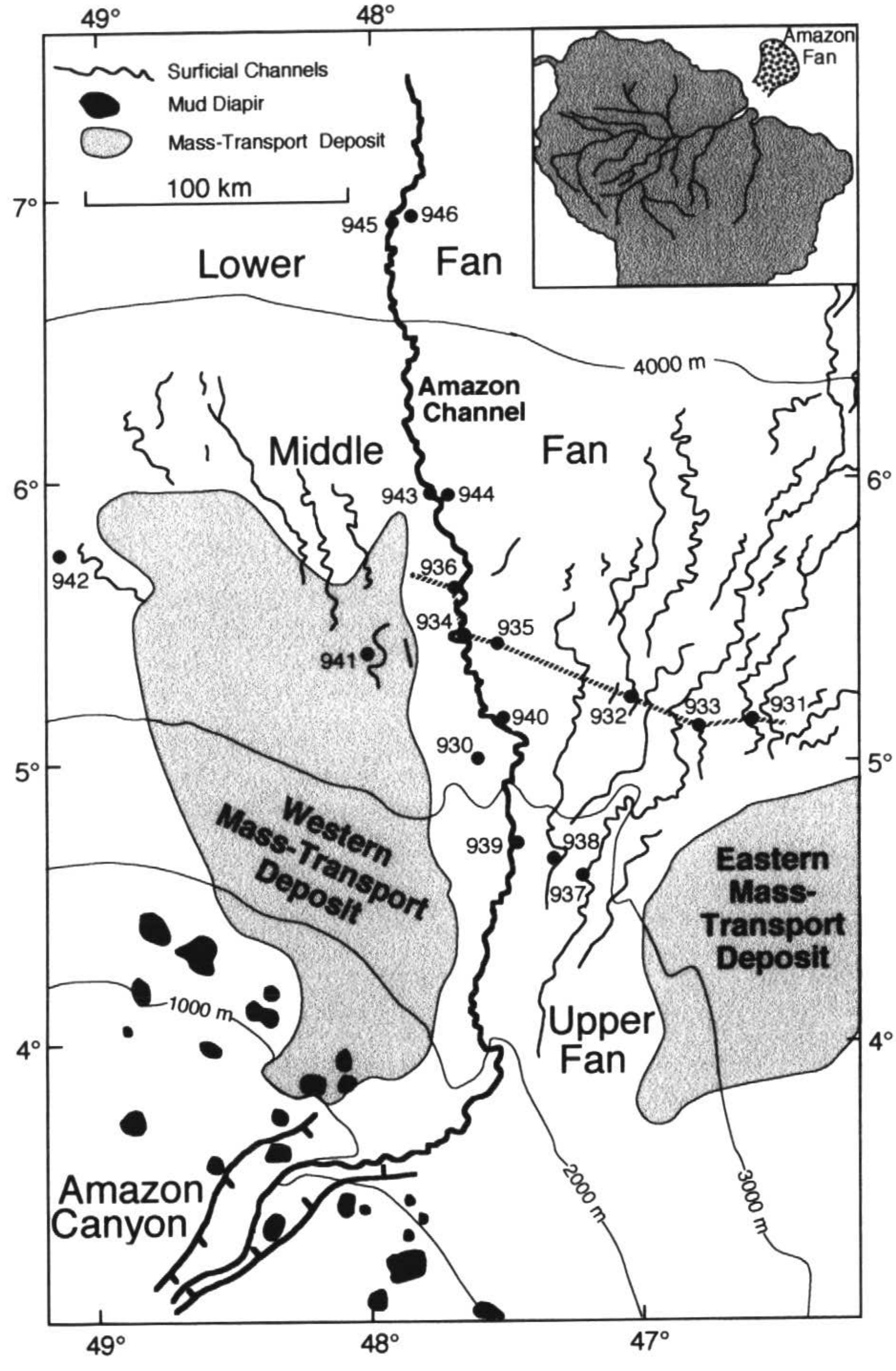

Figure 1 *Location of the Amazon Fan off South America (inset map), the mapped meandering channels on the fan surface (the youngest, Amazon Channel, is drawn with a thicker line), the regionally extensive eastern and western mass transport deposits (debris flow deposits), and the 17 sites (930 to 946) drilled on ODP Leg 155. Dashed line is position of Figure 2 cross section.*

ous mud beds <50 cm thick (Fig. 5A and B). Visual inspection and statistical analysis (Chengsheng Chen, pers. comm, 1996) reveal no significant bed-thickness trends in the sand packets.

The overlying overbank deposits are characterized by thin-bedded turbidites composed primarily of silt and clay. Except for the lower fan Site 946, all of these levee sequences have a 10-25 m thick, fine-grained cap deposited during the latest Pleistocene to Holocene sea-level rise. Below this cap and down to about 50 mbsf, interbedded and inter-laminated sand, silt, and mud turbidites represent the overspill record from the adjacent channel (Hiscott *et al.*, in press). Silt beds through fine-grained sand beds are generally thinner than 5 cm; rarely thicker than 10 cm. The laminated mud beds may be tens of centimetres thick. Average sedimentation rates during active growth phases of the Amazon Channel levees can be estimated using biostratigraphic data and identification of paleomagnetic excursions and secular-variation cycles. These rates are extremely high at 1-2.5 cm·a^{-1} (Flood *et al.*, 1995a, p.18), suggesting a recurrence interval for overspilling turbidity currents of perhaps one to a few years during the Pleistocene. The levee successions fine upward, although they may contain alternating more silt-rich and more mud-rich bedsets (Fig. 6) deposited over time scales of a few hundreds of years.

The rapid onset of sand deposition at the base of HARPs is attributed to upslope avulsion (= channel-switching) which diverts sand-laden, effectively unconfined turbidity currents into a former interchannel low (Fig. 7A and B; Flood *et al.*, 1991). The presence of abundant mud clasts in the thicker sand beds points to an increased availability of clasts from eroded and undercut levee muds at the avulsion site. Many of the clasts recovered in the cores and observed in the FMS images are partly compacted (resistive in the images), suggesting that this material probably was buried and subsequently exhumed by erosion. Pirmez (1994) and Pirmez and Flood (1995) present evidence for significant entrenchment of the pre-existing channel, both around and upslope of the knickpoint produced at the site of channel bifurcation. Entrenchment along part of the pre-avulsion channel taps previously deposited channel-floor sand and moves it farther downfan into a new sheet-like HARP unit. Adjustments in channel depth around the knickpoint eventually return the channel centreline to a graded longitudinal profile (Pirmez, 1994).

Formation of a succession of sand packets within the HARPs results from rapid lateral switching of the depocenter to produce stacked, subtly lens-shaped bedsets of sand. Thicker intervals of thin-bedded silty clays that commonly overlie these sand clusters probably are distal overbank deposits from channels elsewhere on the fan surface (*e.g.*, Purple Channel distal levee interrupting HARP sands at Site 936 at about 100 mbsf, Figs. 3B and 4). It is unreasonable to suggest a sealevel control for development of the sand packets (*e.g.*, Mutti and Normark, 1987, 1991), because the entire Upper Levee Complex, with its 10 or more individual channel-levee units (Damuth *et al.*, 1983; Manley and Flood, 1988) and many tens of sand packets, accumulated during a single lowstand of sea level (*i.e.*, oxygen isotope stages 2-4; Piper *et al.*, in press).

The contrast in grain size observed across the upper boundary of HARP units does not require that the sediment load of turbidity currents changed rapidly to silt and clay as levees began to develop. Instead, Hiscott *et al.* (in press) demonstrate that Amazon Fan channel-levee units are probably produced by mixed-load turbidity currents carrying sand low in the flow and mud near the flow top. Sand can only escape confinement within the channel when levees are absent or low. After each avulsion event, levees apparently build rapidly downfan from the avulsion point, much as the levees of the distributaries of river-dominated deltas advance seaward (Wright, 1977). Once the levee tips reach and then pass over a site, the lower parts of the mixed-load turbidity currents become increasingly confined to the channel axis, and spillover deposits become finer grained until few silts and mostly mud

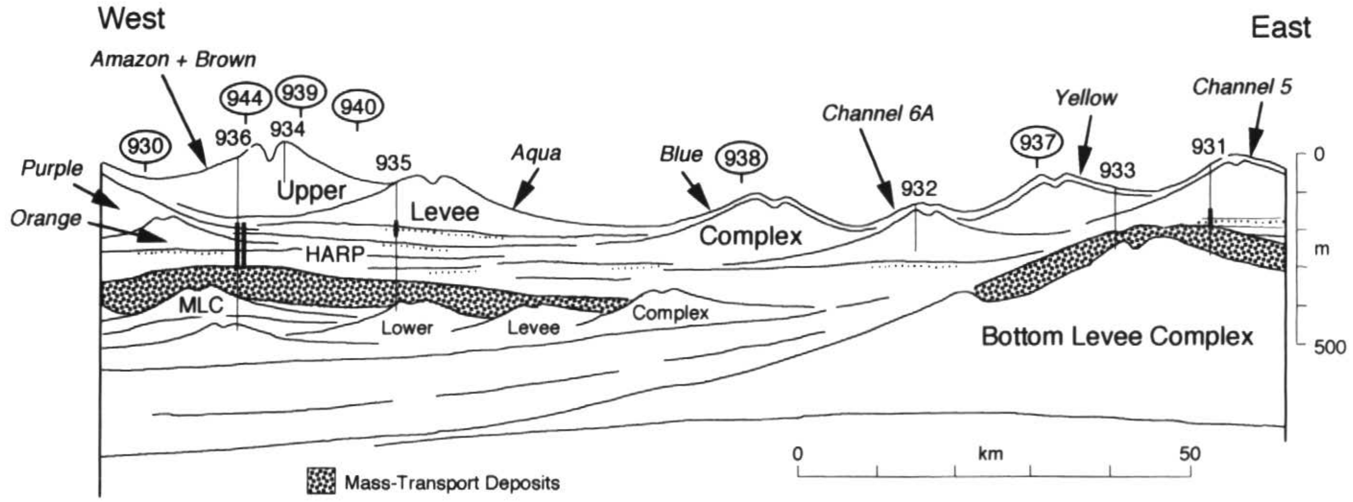

Figure 2 *Schematic cross section, located on Figure 1, of the upper Quaternary sediments of Amazon Fan at about the 3500 m bathymetric contour (based on Manley and Flood, 1988). Sites 936, 934, 935, 932, 933, and 931 are along this cross section; depths of penetration at these sites are shown (bold parts of each borehole = location of FMS-based sections of Pirmez* et al., *in press). The other sites (circled site numbers) are projected into this cross section from farther upfan or downfan* (e.g., *Site 944), and are placed so as to accurately reflect the channel-levee system that was penetrated. Stacked channel-levee systems of the Upper Levee Complex are labelled from youngest to oldest according to an established colour code: Amazon, Brown, Aqua, Purple, Blue, Yellow, Channel 5, Orange, Channel 6A. MLC = Middle Levee Complex. Site 946 is too far downfan to be projected into this cross section.*

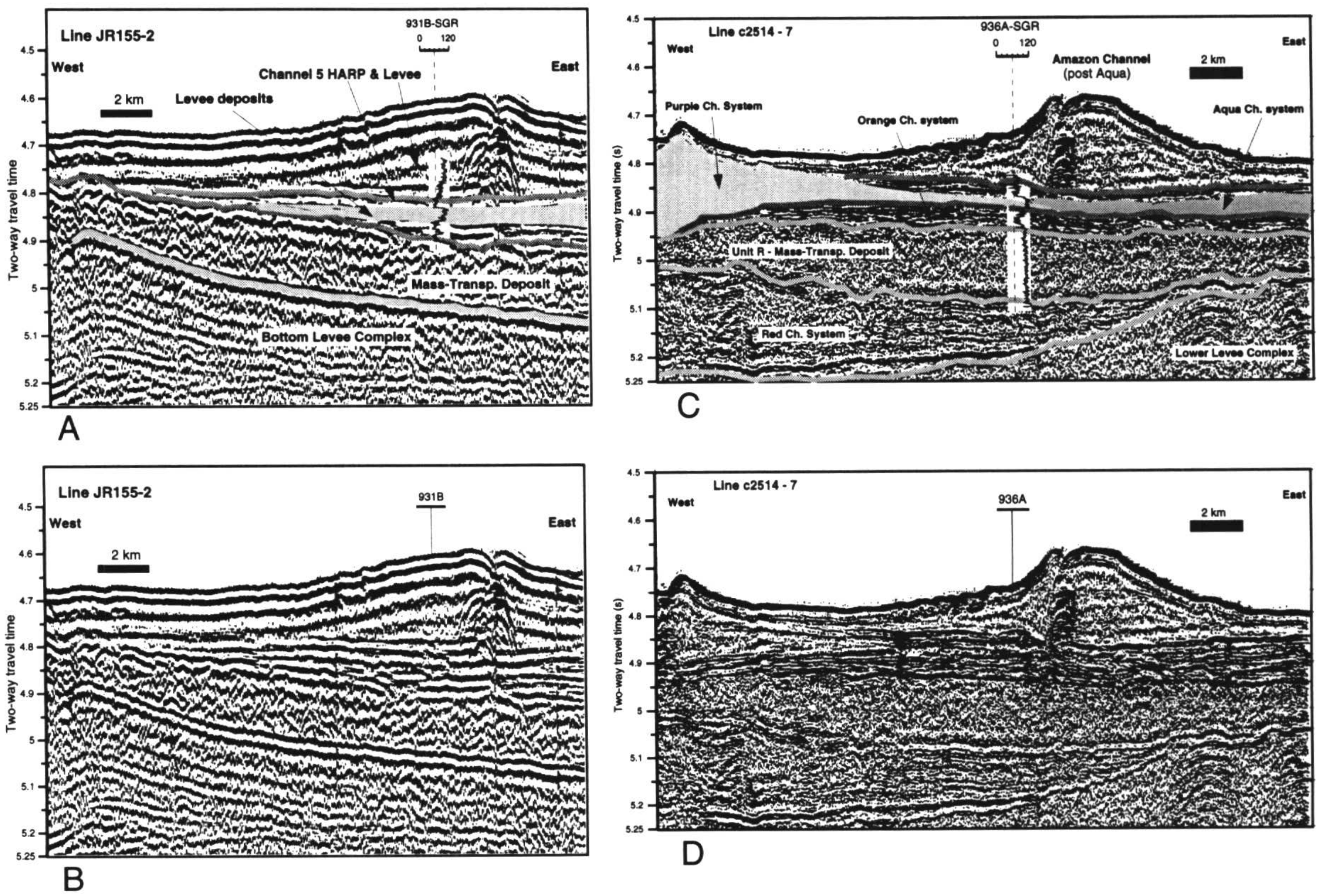

Figure 3 *Seismic character and stratigraphic position of High Amplitude Reflection Packets (HARPs) around Site 931 (A = interpreted; B = uninterpreted) and Site 936 (C = interpreted; D = uninterpreted). In both cases, the HARP intervals underlie acoustically transparent levees. Three units onlap the underlying mass transport deposit near Site 931 (A/B): the Channel 5 HARP, levee deposits of an unnamed channel which was located to the east of Site 931, and an underlying unnamed HARP (Pirmez* et al.*, in press). Three units also separate the Amazon Channel levee from the underlying Unit R Mass-Transport Deposit at Site 936 (C/D): the Brown system HARP, undifferentiated distal deposits of the Orange/Purple/Aqua levees (Fig. 2), and the Orange system HARP, just above the mass-transport deposit. Integration of gamma-ray traces with seismic data is based on the respective synthetic seismogram matches, and travel time derived from sonic logs. These same gamma-ray traces are shown at a larger scale in Figure 4.*

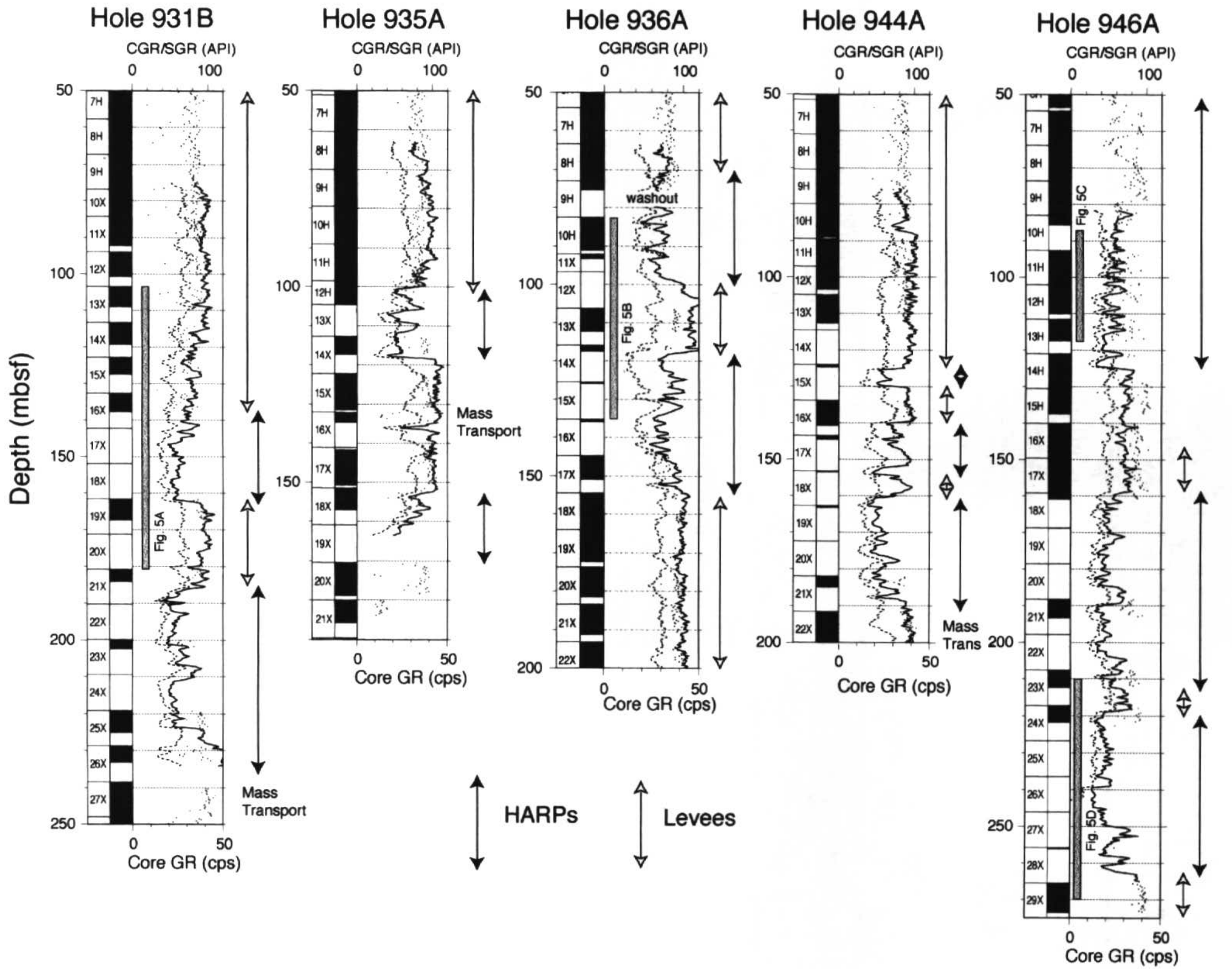

Figure 4 *Downhole gamma-ray logs for Holes 931B, 935A, 936A, 944A and 946A. Dots represent measurements on core material, in counts per second (cps). HARP intervals and the location of bed-by-bed sections reproduced in Figure 5 are indicated by labelled (e.g., Fig. 5A) shaded vertical bars. In the white/black core-recovery column, black = recovery, and white = no recovery. Note that recovery in sandy HARPs was poor. mbsf = metres below the seafloor. SGR = [K + U + Th] gamma readings in API units (solid curve). CGR = [K + Th] gamma readings in API units (dashed curve).*

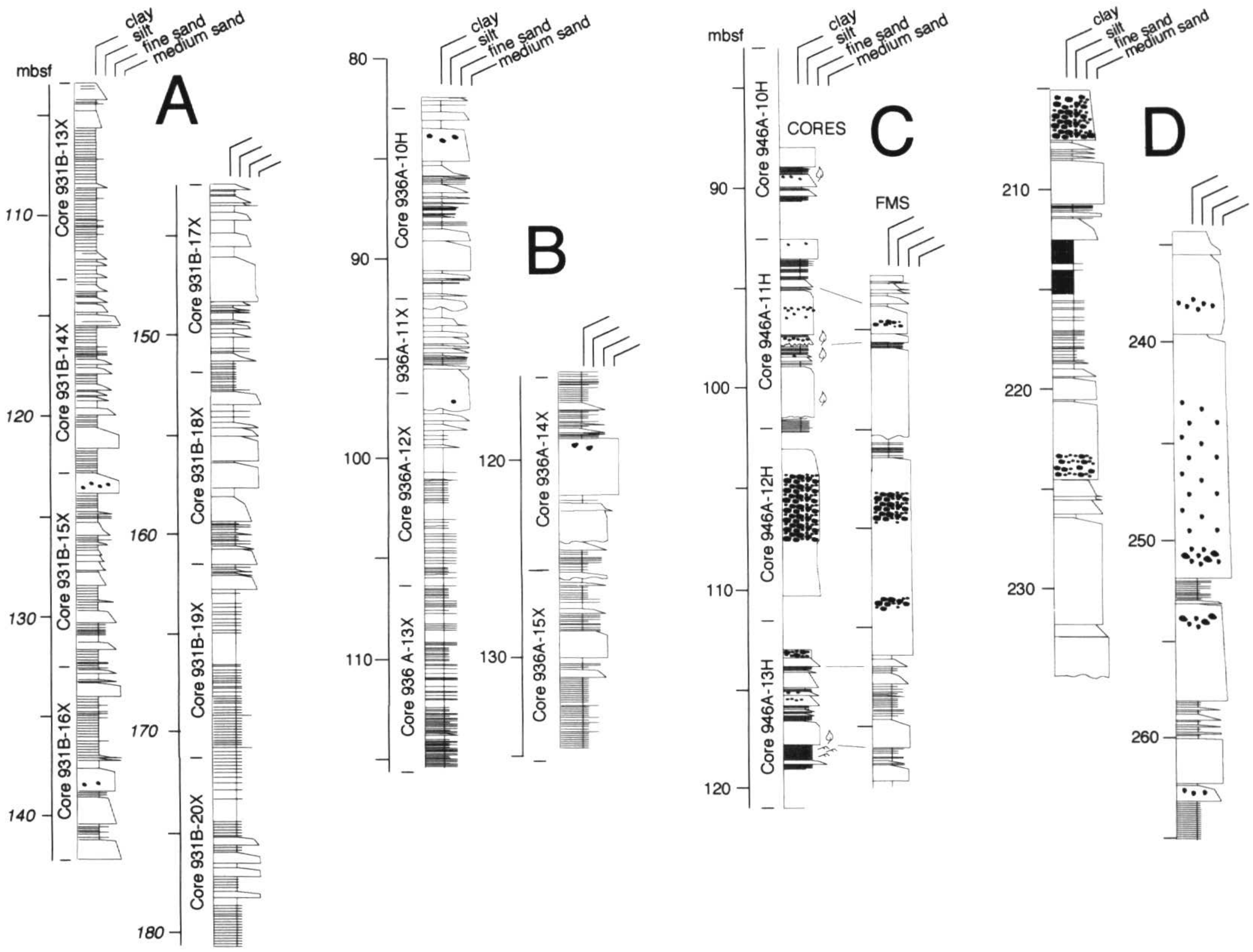

Figure 5 *Representative bed-by-bed sections from HARPs, stratigraphic locations shown in Figure 4. Note the grouping of sand beds (white) into packets. These sections are all based on interpretation of FMS images, calibrated to available cores, except C, which is based equally on cores (left column) and FMS images (right column) from the same depth at Site 946; the two columns do not match precisely because of sand disturbance during coring and locally poor FMS image quality in sands close to the top of the hole. A = Hole 931A; B = Hole 936A; C and D = Hole 946A. In all sections, symbols set to the right of the columns are either leaves where plant debris is present, or ripple bedforms. Elliptical black symbols within thick sand beds are mud clasts. In D, the muds shown with a superimposed brick pattern (212.5-215 mbsf) are highstand carbonate-rich hemipelagic sediments.*

characterize the crests of high levees (Flood *et al.*, 1995a; Hiscott *et al.*, in press).

As summarized in Figure 7C, the facies succession of Amazon Fan channel-levee units begins with a broad platform of sand, commonly disposed in a stacked set of 5-25 m-thick packets extending many tens of kilometres laterally (Fig. 3) and hundreds of kilometres downfan (Pirmez *et al.*, in press). Sand accumulation begins abruptly as a consequence of upfan avulsion (Fig. 7A), and stops rapidly because upward- and downfan-growing levees soon confine the sand-rich basal parts of transiting turbidity currents to a narrow channel axis (Fig. 7B). At outcrop and reservoir scale, such sand units would appear to be sheets, although at basin scale they are limited, in the proximal area, to a single interchannel low and widen downfan until they coalesce to form a sandy apron on the lower fan. The sandy HARP units are overlain by and/or interfinger at their top with predominantly silt/mud overbank deposits. These fine upward, although small-scale fluctuations in silt and sand content are present.

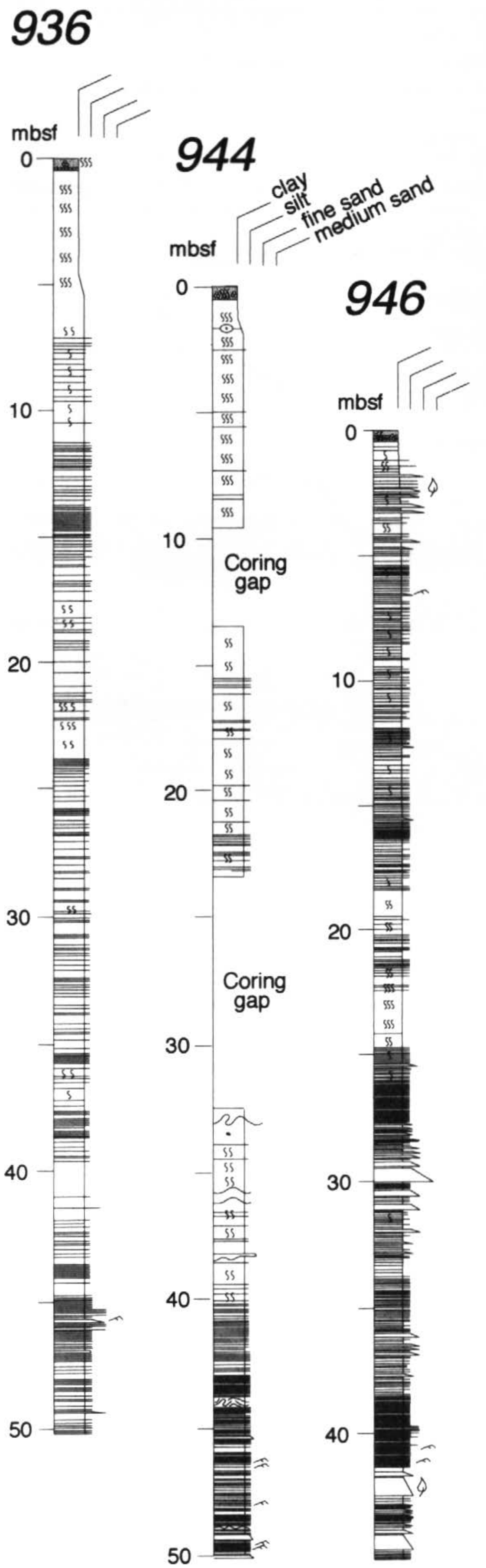

Figure 6 *Representative bed-by-bed sections from levees, all shallower than the logged intervals in Figure 4. These sections are based entirely on shipboard core descriptions. In all sections, symbols set to the right of the columns are either leaves where plant debris is present, or ripple bedforms. S-shaped symbols within the mud columns indicate intensity of burrowing (S = slightly burrowed, SSS = bioturbated).*

PREDICTIVE FEATURES OF AMAZON FAN CHANNEL-LEVEE SUCCESSIONS

The following features stand out:

1) Although apparently formed in part of intimately shingled, small-scale lenses, the lowermost sandy units (HARPs) are laterally extensive, whereas each of the uppermost muddy units (levees) has a gull-wing shape and limited lateral extent (Fig. 2).

2) Sandy facies are as volumetrically important in the channel-levee complexes as are the levee muds. These sands (and some gravel: Shipboard Scientific Party, 1995a) are carried hundreds of kilometres beyond the shelf edge, at times in unconfined flows following avulsion events and at other times in the lower parts of efficient turbidity currents flowing through the meandering channels of Amazon Fan (Hiscott *et al.*, in press).

3) The primary control on sand transfer to interchannel areas is upfan avulsion, which occurs on time scales of a few thousand years, much shorter than Pleistocene sea-level fluctuations. A significant proportion of the sand in HARPs and lower-fan lobes may have moved down the fan in a series of steps, being mobilized by channel entrenchment upfan of avulsion sites, and spending in-

tervening periods in the shallow surface deposits of the fan.

4) Statistically significant numbers of packets displaying asymmetric vertical trends in bed thickness are absent within the sandy HARP deposits (Chengsheng Chen, pers. comm., 1996).

POSSIBLE OILFIELD ANALOGUES

The essential features recognized in channel-levee complexes of the Amazon Fan may be used elsewhere to infer an origin linked to channel-levee dynamics (*i.e.*, periodic avulsion, progressive flow confinement by advancing levees, stacked cycles of avulsion → entrenchment → levee-progradation during single sea-level lowstands). Although submarine fans span a wide range of scales (Barnes and Normark, 1984), those constructed by mixed-load, efficient turbidity currents commonly contain channel-levee units that are scaled-down versions of the Amazon Fan channel-levee systems. For example, the following fans, all with radius less than about 300 km (half the size of Amazon Fan), contain aggradational, commonly sinuous, leveed channels that have periodically shifted their position on the fan surface because of channel avulsion: Astoria Fan (Nelson, 1984), Delgada Fan (Normark and Gutmacher, 1984), Magdalena Fan (Kolla *et al.*, 1984), Rhône Fan (Droz and Bellaiche, 1985) and Var Fan (Savoye *et al.*, 1993). These and other systems of similar scale might have experienced avulsions and HARP → channel-levee depositional cycles like those of the Amazon

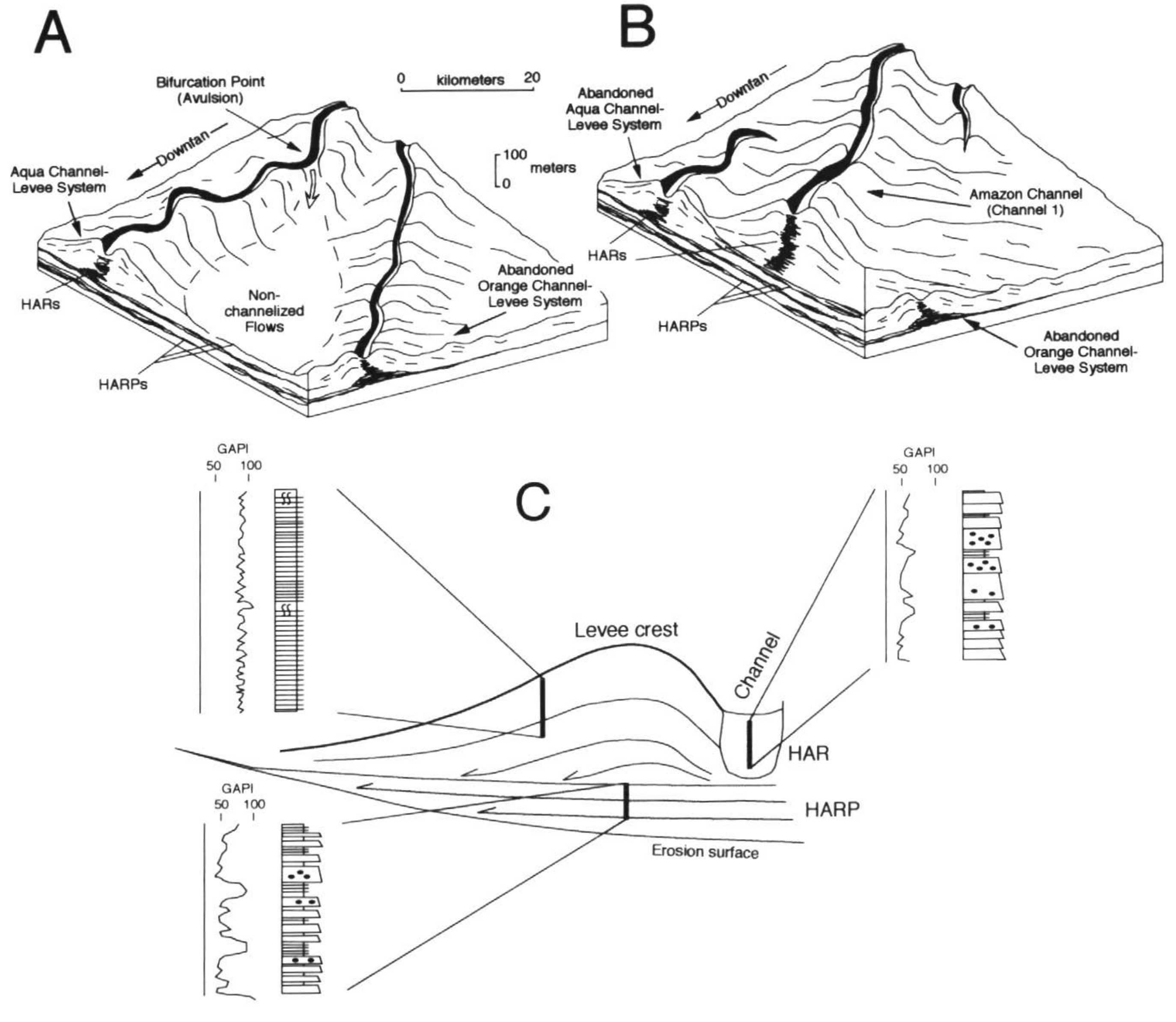

Figure 7 *HARP formation, and geometry, stratigraphy, lithofacies, and gamma-ray signature of components of Amazon Fan channel-levee systems.* (**A**) *example of HARP formation, initiated when a breach in the levee of the Aqua Channel permits diversion of sand-laden turbidity currents into an interchannel low, forming sheet-like deposits.* (**B**) *growth of the Amazon Channel levee over the HARP formed in part A, leading to sand confinement to the new channel axis and burial of older levees.* (**C**) *typical facies architecture of Amazon Fan channel-levee systems, including the sheet-like HARP succession onlapping pre-existing topography (lower left), downlapping mud/silt deposits of an aggrading and prograding levee (upper left), and aggrading channel-floor sands of the new channel segment (HAR, upper right). Each column represents about 30-50 m of section. Gamma-ray values, in API units (GAPI), reflect the range of Leg 155 data (Fig. 4). Parts A and B from Flood* et al. *(1991).*

Fan (Fig. 7).

In oilfield examples of deep-sea fans, interpretations commonly invoke the former presence of channel-levee complexes. Based on Amazon Fan experience, these might have formed in response to an autocyclic (*e.g.*, channel avulsion) rather than a sea-level control. Two subsurface examples are briefly described to illustrate this point. It would, of course, be preferable to match the scale of the ancient or oilfield example by thoroughly coring a modern fan of similar size. However, long cores are unavailable for most modern fans. Until this deficiency is rectified, the Leg 155 results will continue to provide an important template against which to compare other deposits, even those of smaller scale, so long as they are composed of similar architectural elements.

Pliocene "J" Sands, Green Canyon 65 Field, Gulf of Mexico

The Green Canyon area is about 150 km southwest of New Orleans in the Gulf of Mexico, on the margin of a salt-withdrawal mini-basin (Holman and Robertson,1994). There are four interconnected sand packets (J1 through J4), each 15-30 m thick, separated by slump/debris-flow deposits, 10-15 m thick (Fig. 8). Within the J1 through J4 interval, grain size and extent of channeling increase upward to a number of unconformities, at and above which there is a thick interval of channel-levee complexes. The sand-packet and channel-levee deposits both accumulated during one Pliocene glacio-eustatic lowstand. Sediment presumably was supplied by a coastal plain river carrying a mixed sand-mud load.

The gamma-ray profile (Fig. 8), reflecting the lithofacies contrast between sandy and muddy deposits in the Bullwinkle mini-basin, is remarkably like the Amazon Fan profiles (compare Figs. 4 and 8). The upward coarsening within the sandy part of the succession might reflect seaward advance of a new leveed channel following an upsystem avulsion event. In the Green Canyon area, relief created by salt tectonics is superimposed on the broader depositional setting, possibly explaining the thin debris-flow deposits between sand packets. Mass-flow deposits thinner than 30 m are present beneath HARP sands at Amazon Fan ODP Sites 935 (120-150 mbsf, Fig. 4) and 936 (390-405 mbsf, Shipboard Scientific Party, 1995a). These may form as slopes are readjusted (by erosion, failure, and deposition) to new channel configurations after avulsions. Much thicker mass-transport deposits within the Amazon Fan (*e.g.*, Unit R and Western Debris Flow, Shipboard Scientific Party, 1995b) must record more catastrophic failure events on the fan and adjacent slope.

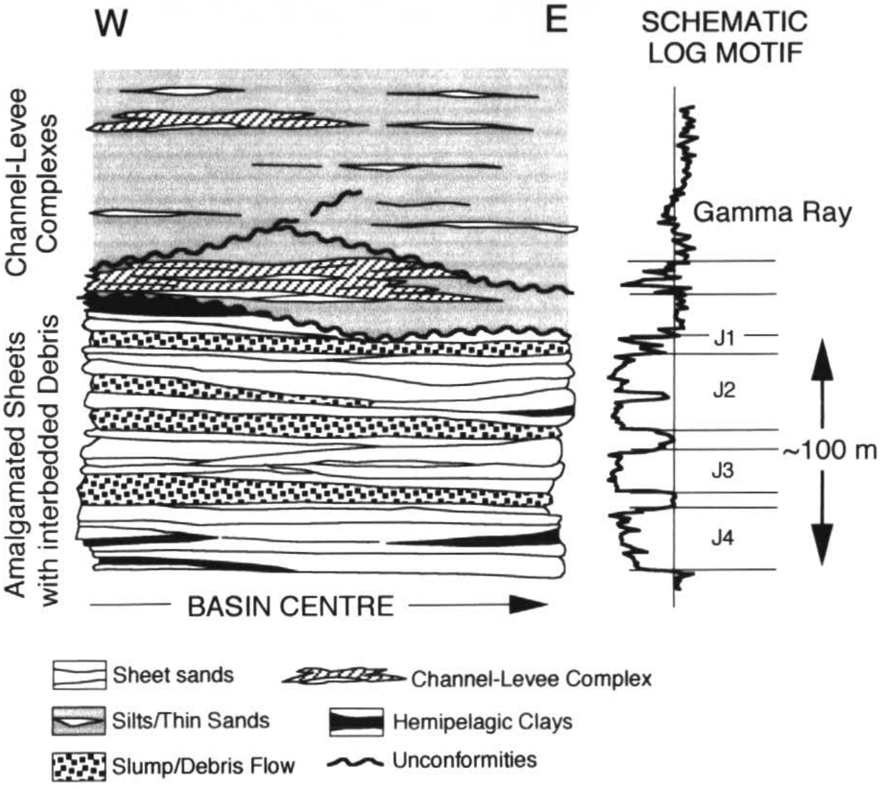

Figure 8 *Schematic gamma-ray profile and inferred two-dimensional facies panel through sheet-sands and levee deposits at and immediately above the "J" interval, Bullwinkle mini-basin (rimmed by salt diapirs), Gulf of Mexico. Redrawn from Holman and Robertson (1994).*

Holman and Robertson (1994) ascribed the decrease in grain size at the transition into channel-levee deposits to sea-level rise. Instead, as on Amazon Fan, this lithofacies change may represent the progradation of leveed channels over interchannel sheet sands (HARPs), all during a sea-level lowstand. Using the Leg 155 results as a guide, deposits emplaced during sea-level rise and the subsequent highstand are predicted to be quite thin and calcareous.

Miocene Mount Messenger Formation, Kaimiro Field, New Zealand

King *et al.* (1994) described outcrop and subsurface upper Miocene deposits of the Mount Messenger Formation, New Zealand, as about 300-400 m of "basin-floor fans" overlain by 150-300 m of channel-levee deposits (Fig. 9). The inferred basin-floor fans return high-amplitude seismic reflections, and thus can be described as HARPs. The entire succession was deposited in 1-2 m.y. Sand packets in proximal areas are underlain by slump deposits. Each of several sand packets in the sand-dominated part of the succession is inferred to overlie a sequence boundary which formed during a fourth-order low-stand of sea level. In coastal outcrops, the inferred sequence boundaries are separated by 50-100 m.

As in the Green Canyon area of the Gulf of Mexico, the lithofacies and gamma-ray profiles for boreholes through the Mount Messenger Formation are strikingly like those from the Amazon Fan (compare Figs. 9 and 4), although the Mount Messenger HARP unit is thicker than the cored succession from Amazon Fan (Fig. 2). It therefore seems possible that the Mount Messenger "basin-floor fans," rather than each representing a separate lowstand deposit, might have formed during a single lowstand event as a result of one or more avulsion events on a submarine fan characterized by long but shifting leveed channels, each of which grew rapidly but was then abandoned.

THE WAY FORWARD IN SUBMARINE-FAN RESEARCH

The insight provided by a single 2-month leg of scientific drilling on Amazon Fan demonstrates that similar dedicated coring will be needed to properly understand the dynamics of sedimentation in other deep-water siliciclastic settings. Renewed interest in facies analysis in such settings has been catalyzed by oil companies interested in deep-water plays (*e.g.*, numerous papers in Weimer *et al.*, 1994; Pickering *et al.*, 1995).

In particular, dedicated coring is required to ground-truth facies predictions for the small sand- and gravel-rich fans found in tectonically active basins like the California borderland (*e.g.*, Piper *et al.*, submitted). Such fans are more like most ancient submarine fans than is Amazon Fan.

In cases where piston or gravity coring of thick sand or gravel is expected to be fruitless, dating may be achieved by coring correlative surfaces in adjacent basinal areas, traced using high-resolution seismic-reflection profiles. For example, Normark *et al.* (in press) successfully used ODP Leg 167 results from Site 1015 in Santa Monica Basin to date development of the adjacent sand-prone Hueneme Fan. Special techniques such as logging-while-drilling, borehole imaging with wireline tools, and perhaps coring systems such as percussion coring will be required to fully characterize the facies successions.

The contemporaneous accumulation of sand sheets and muddy levees on Amazon Fan during a single lowstand period calls into question the hypothesis (Mutti, 1985; Posamentier *et al.*, 1991) that sheet sands (so-called "basin-floor fans") accumulate earlier in sea-level cycles than channel-levee complexes (so-called "slope fans"). Instead, high accumulation rates and multiple abandonments and re-establishments of leveed channels, with downcutting and sand-sheet development immediately following avulsion events, can produce such contrasting deposits. The extent to which levee growth and sand-lobe deposition may be broadly synchronous on sand-rich and sand-mud fans (*sensu* Reading and Richards, 1994) needs to be tested by deep coring of Quaternary fans. Controls on facies development through time (*e.g.*, sand packeting, upward fining trends) can only be evaluated once the chronology and the linkages between events on different parts of a fan have been firmly established using biostratigraphy, magnetostratigraphy, and isotope stratigraphy.

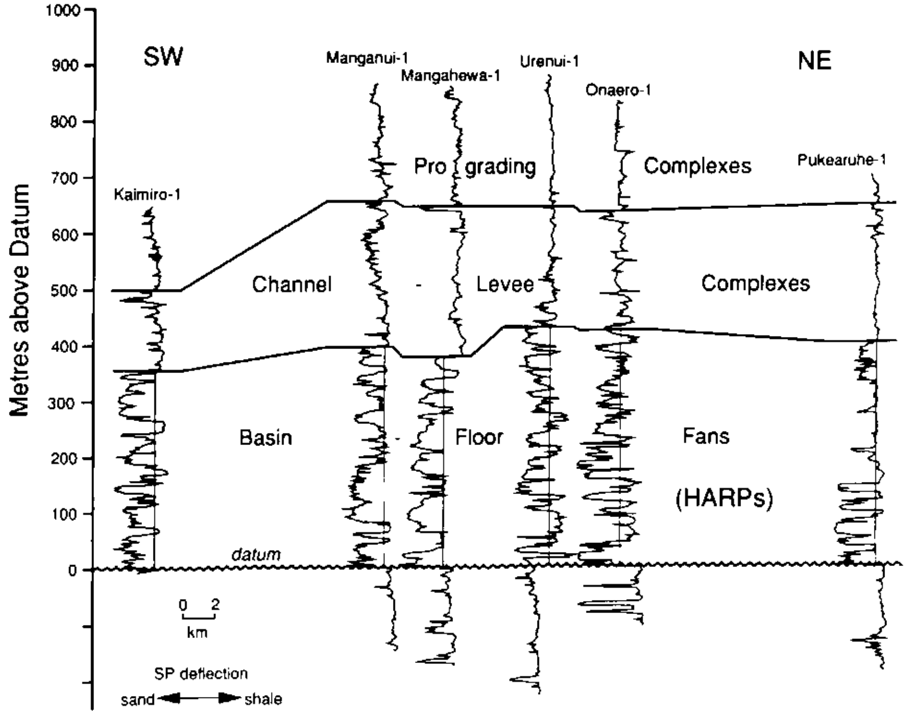

Figure 9 *Spontaneous potential (SP) profiles from six wells located along a SW-NE transect through the Miocene Mount Messenger Formation, Kaimiro Field, Taranaki Penisula, New Zealand. Redrawn from King* et al. *(1994). "Basin Floor Fans" are equated with the HARPs recognized in the Amazon Fan.*

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