

Papers

A high sinuosity, laterally migrating submarine fan channel-levee-overbank: results from DSDP Leg 96 on the Mississippi Fan, Gulf of Mexico

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DSDP Leg 96 drilled four sites in a channel-levee-overbank system on the Mississippi Fan, Gulf of Mexico, approximately 300 km from the present Mississippi River Delta in water depths of about 2500 m (Sites 617, 620, 621 and 622). Apart from the uppermost 20–25 cm of Holocene marly foraminiferal ooze in most of the drilled sites, the entire cored intervals are in the Pleistocene Ericson Y Zone. Eight sedimentary facies are recognized: (1) biogenic oozes and muddy oozes; (2) calcareous muds; (3) clays and muds; (4) silty muds and muddy silts; (5) silt-laminated muds; (6) silts and sands; (7) muddy gravels and pebbly muds, and (8) gravels. Sediment accumulation rates on this part of the fan during the Wisconsin glaciation were as much as 11 m/1000 yrs, although most of the sediments probably accumulated from discrete, geologically instantaneous events. Site 621 and Site 622 are located within a prominent channel, Site 617 on an adjacent levee, and Site 620 in overbank deposits approximately 18 km northeast from the channel sites. In this part of the fan, there is one prominent high sinuosity channel, asymmetric in cross section and flanked by levees with probable ridge-and-swale topography. Near these drill sites, the channel width is 3–4 km and its bathymetric relief ranges from 25–45 m. Downfan, the dimensions of the channel decrease. Site 617 (to 191.2 m sub-bottom) and Site 620 (to 422.7 m sub-bottom) mainly comprise fine-grained, thin-bedded turbidites, with Site 617 tending to be slightly coarser grained and showing considerably more evidence of wet-sediment deformation. Site 621 (to 214.8 m sub-bottom), in the channel axis near the deepest part of a meander, contains mainly muds with a downhole increase in the silt content above 195 m sub-bottom, where pebbly muds overlie clean gravel that was obviously washed during core-retrieval and probably was a sandy gravel or gravelly sand. Site 622 (to 208 m sub-bottom) shows similar lithologies to Site 621 although the sediments generally contain more silt, and towards the base of the hole become thoroughly laminated silts and sandy silts: pebbles within muds and silts occur at 199 m sub-bottom. Based on overall grain size trends over tens of metres, the channel sites show ill-defined fining-upward sequences, whereas the levee and overbank sites show coarsening-upward sequences, although the upper part of Site 617 is a fining-upward sequence. Biogenic components of sediments at the channel sites are dominated by shallow-water benthic foraminifera derived from the continental shelf, with the coarser grained clastic intervals containing reworked late Cretaceous planktonic foraminifera and radiolaria from the Upper Mississippi River Valley. The levee and overbank sites have a larger percentage of Quaternary radiolaria, pelagic algal cysts, and more planktonic foraminifera than the channel sites. Seismic reflection profiles across this most recent fan channel show high-amplitude reflectors in the lower part of the channel fill, thought to correspond to the coarsest grained channel lag deposits. Isopach maps show that the lag deposits are up to 6.5 km wide, slightly more than 200 m thick, and that the northernmost meander belt has migrated about 2 km laterally, 1.2 km downfan, and has climbed 175 m stratigraphically (Kastens and Shor, 1985; Sterling *et al.*, 1985). Evolution of the meander belt shows features common to point-bar migration in high sinuosity fluvial systems. While the location of Sites 617, 620, 621 and 622 have been drilled within a middle fan environment, the width/depth ratios and the fact that this channel is a single conduit in this part of the fan, perhaps suggest a more appropriate comparison with many inner or upper fan environments that have been described in the literature.

Keywords: Sinuosity; Laterally-migrating; Facies; Sequence; Channel-levee-overbank

Introduction

The Mississippi Fan, in the northeastern Gulf of Mexico (Figure 1) is a large arcuate pile of clastic sediments with a radius varying from 330–380 km. The fan sediments were derived primarily from the

ancestral Mississippi River drainage basin. The middle fan as defined by Bouma *et al.* (1984) has up to 500 m of relief above the surrounding fan surface with a generally smooth, slightly convex-upward surface, and high-resolution seismic reflection profiles locally reveal areas of hummocky topography, probably

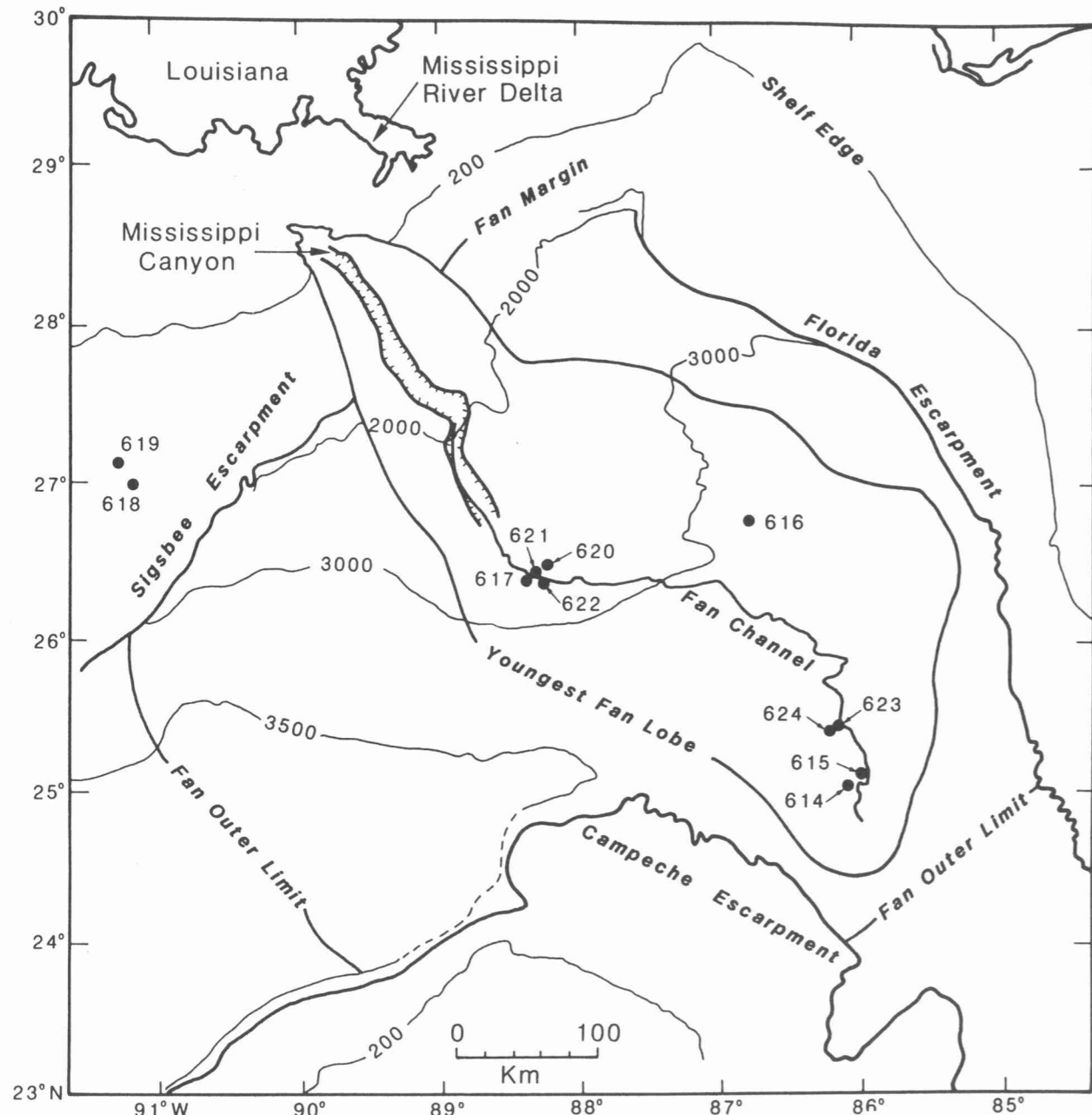


Figure 1 Map of the Mississippi Fan showing DSDP Leg 96 sites and general bathymetry

associated with abandoned main and distributary channels, together with sediment slides (Moore *et al.*, 1978). Gradients typically range from 0.5-0.25 degrees (1:120 to 1:250). The middle fan occurs between water depths of about 1900 m to the 3000 m contour where it merges with the lower fan (Moore *et al.*, 1978; Bouma *et al.*, 1985).

The most recent Pleistocene fan sedimentation is associated with a prominent sinuous channel flanked by well-developed levees and occasional crevasse splays. The main channel follows the axis of the thickest part of the youngest 'upper-middle-lower' fan depositional unit, henceforth termed a 'fan-lobe' to distinguish it from lower fan lobes. Seismic reflection profiles suggest that the channel course has remained essentially constant throughout the fan-lobe development (Garrison *et al.*, 1982). This youngest fan-lobe, overlying seismic horizon '20', is lenticular in cross section with a maximum thickness of about 400 m and a maximum width of about 200 km. At least seven

distinct fan-lobes are recognized (Stelting *et al.*, 1985).

The purpose of this paper is to document the sedimentology and seismic stratigraphy for the most proximal four sites associated with the channel-levee-overbank system drilled on the Deep Sea Drilling Project Leg 96, the last leg of the ocean drilling programme using R/V 'Glomar Challenger'. Leg 96 was the first opportunity to drill a large submarine fan, to complement detailed seismic records, and to make the data publically available. Therefore the results of this cruise (29th Sept. to 8th Nov. 1983) provide a unique opportunity to test some of the models developed from the study of ancient fan systems. The four sites drilled in the leveed channel system during DSDP Leg 96 are: (1) Site 617 in levee sediments; (2) Site 620 in relatively distal overbank sediments; (3) Site 621 in the axial part of the channel floor, and (4) Site 622 in the inner bank of a channel meander (Figure 2).

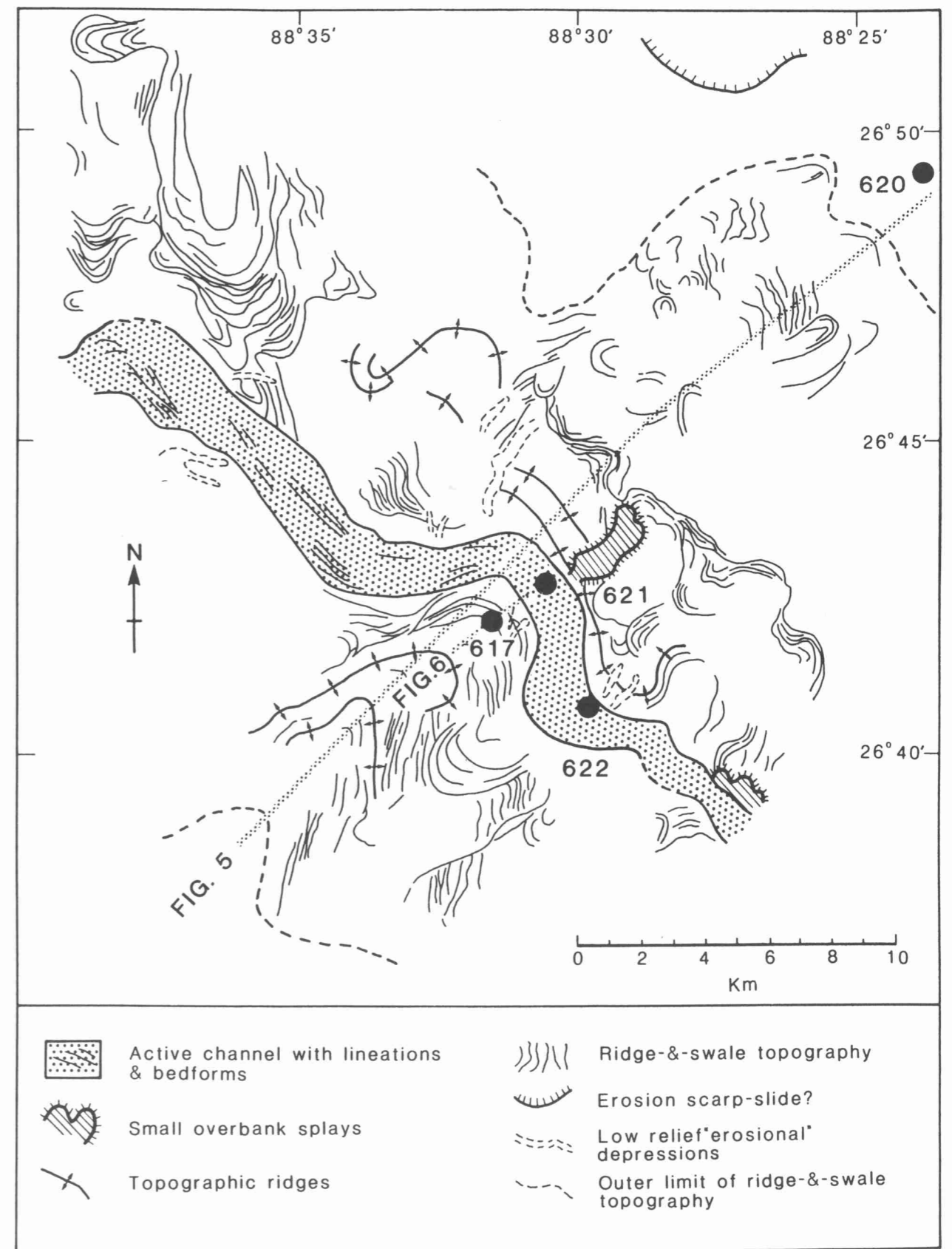


Figure 2 Morphologic features of segment of the meander-belt of the channel-levee-overbank system as mapped from side-scan sonar (from Kastens and Shor, 1985). Location of the DSDP drill sites and seismic reflection profiles shown in Figures 5 and 6

Site 617 is located on the western levee of the youngest fan channel 2.5 km from the levee crest on the inside of a channel bend (Figure 2). 191.2 m of sediments were drilled at this site with the Advanced Piston Corer (APC). The thalweg of the main channel

is 4.8 km to the NE. Local truncated seismic reflectors are associated with a ridge-and-swale topography with local sea-floor erosion (see Figure 6). The swales appear to have 15-50 m of sediment fill, and in some instances the uppermost seismic reflectors may be traced

between swales. Site 620 is located approximately 18.3 km NE of the fan channel immediately inside the southern boundary of the 'slump' described by Walker and Massingill (1970). 422.7 m of overbank sediments were drilled with the standard rotary piston coring bit. An E-log was run from the sea floor to 292 m sub-bottom. Site 621 is located in the axial part of the fan channel (Figure 2), where 214.8 m of sediments were recovered with the Hydraulic Piston Corer (HPC), and an E-log was run at this site. The fan channel in this region is approximately 3 km wide and 40 m deep from the top of the adjacent levee to the channel floor, and is flanked by well developed levees. Site 622, located on the inner bank of a channel meander (Figure 2) was hydraulically piston cored through 199.5 m of sediments, and an E-log was run from the sea floor to 208 m sub-bottom.

Analyses of side-scan sonar images (GLORIA, Sea MARC 1, and EDO) show a wide variety of morphologic features (Figure 2, see also Garrison, Kenyon and Bouma, 1982; Kastens and Shor, 1985). Lineations and bedforms suggesting sandy deposits on the present channel floor are shown to be foraminiferal ooze by drilling (see below). Features that superficially resemble fluvial ridge and swale topography are recognized on side-scan sonar and high-resolution seismic reflection profiles (Figures 2, 3 and 6). The relief of these features gives way to relatively smoother topography away from the fan channel.

Sediment facies

Eight different facies are defined for the sediments that were cored on Leg 96 and all facies are represented among Sites 617, 620, 621 and 622. The facies are based on lithology, sedimentary structures, composition and texture (Table 1). Representative photographs of these facies are shown in Figure 4. Pelagic biogenic sediments are volumetrically small compared to the predominant terrigenous facies interpreted as deposits of various sediment gravity flows. Clays, muds and silts are most abundant at all sites, with some sands and gravels occurring within the channel fill.

Biogenic oozes and muddy oozes

The oozes and muddy oozes occur in the uppermost 5–50 cm of sediments at most sites. Rodamin B staining indicates that none of the recovered organisms were living, implying that the uppermost sediment was not recovered; therefore the actual thickness of this facies is probably slightly greater than the retrieved core

Table 1

Facies	Sites	Middle Fan			
		Overbank		Channel	
	%	%	%	%	
1 Oozes and muddy oozes	0.1	0.1	0.2	0.1	
2 Calcareous muds	0.1	0	0	0	
3 Clays and muds	16	72	68	50	
4 Silty muds and muddy silts	2	8	10	4	
5 Silt-laminated muds	82	20	14	33	
6 Silts and sands	0	0	4	12	
7 Muddy gravels and pebbly muds	0	0	3	0.5	
8 Gravels	0	0	0.4	0	

interval. The facies appears structureless, possibly due to intense bioturbation. This facies is a yellow calcareous ooze containing mainly planktonic foraminifera, with less than 10% nannofossils and siliceous organisms, and up to 25% of terrigenous sediment. Typically, the oozes and muddy oozes are poorly sorted with fine-grained sand to fine-silt grade sediment. Rare, black, authigenic iron-sulphide-rich mottles occur.

Calcareous muds

The calcareous muds are distinguished from the biogenic oozes by containing less than 50% calcium carbonate, but clearly there is a complete gradation between both facies. This facies appears to be structureless, fine-grained, and contains a poorly-sorted assemblage of planktonic foraminifera, calcareous nannofossils, rare siliceous biogenics and terrigenous silt and mud.

Clays and muds

The clays and muds are the finest grained terrigenous facies with 60–90% clay fraction and generally less than 0.5% sand-grade material. Contemporary Pleistocene and reworked Pliocene calcareous nannofossils typically constitute less than 5% of the sediments. Layer thickness is extremely variable; bedding and other primary sedimentary structures are rare although very thin silt laminae and a distinct colour banding occur locally. This colour banding is accentuated by dark, iron-sulphide-rich, bioturbated layers that are best seen on X-ray radiographs. Locally, gas disruption apparently has destroyed any structures/layering in the clays and muds, imparting a dark colouration to the facies, as for example in the upper parts of the cores from the channel system.

Silty muds and muddy silts

The silty muds and muddy silts show features transitional with the clays and muds. The facies contains 10–60% clay fraction and up to 5% sand. The facies occurs in beds from about 5 cm to over 1 m thick; in some cases, there are considerably thicker, apparently structureless, intervals. Silt-size quartz and clay minerals are the main components, with relatively minor feldspar, carbonate grains, mica, lignite and accessory minerals. Many grains appear partially altered and, or, coated with iron oxides. Included within this facies, there are distinct, dark-coloured, lignitic silty muds, varying from 5–50 cm thick, occurring as: (1) apparently structureless intervals, with gradational upper and lower boundaries; (2) discrete beds, with normal grading and mud clasts, and (3) as laminated, graded intervals, possibly within thicker sand or silt-laminated beds that contain a finer grained homogeneous mud or clay top.

Silt-laminated muds

The silt-laminated muds are the most common facies, occurring in intervals from a few centimetres to tens of metres in thickness. The facies range from uniform muds with 5–10% thin silt laminae, to muds with more than 50% silt laminae and thin silt beds (Figure 4a and b). The frequency of silt laminae may reach 400–500 per

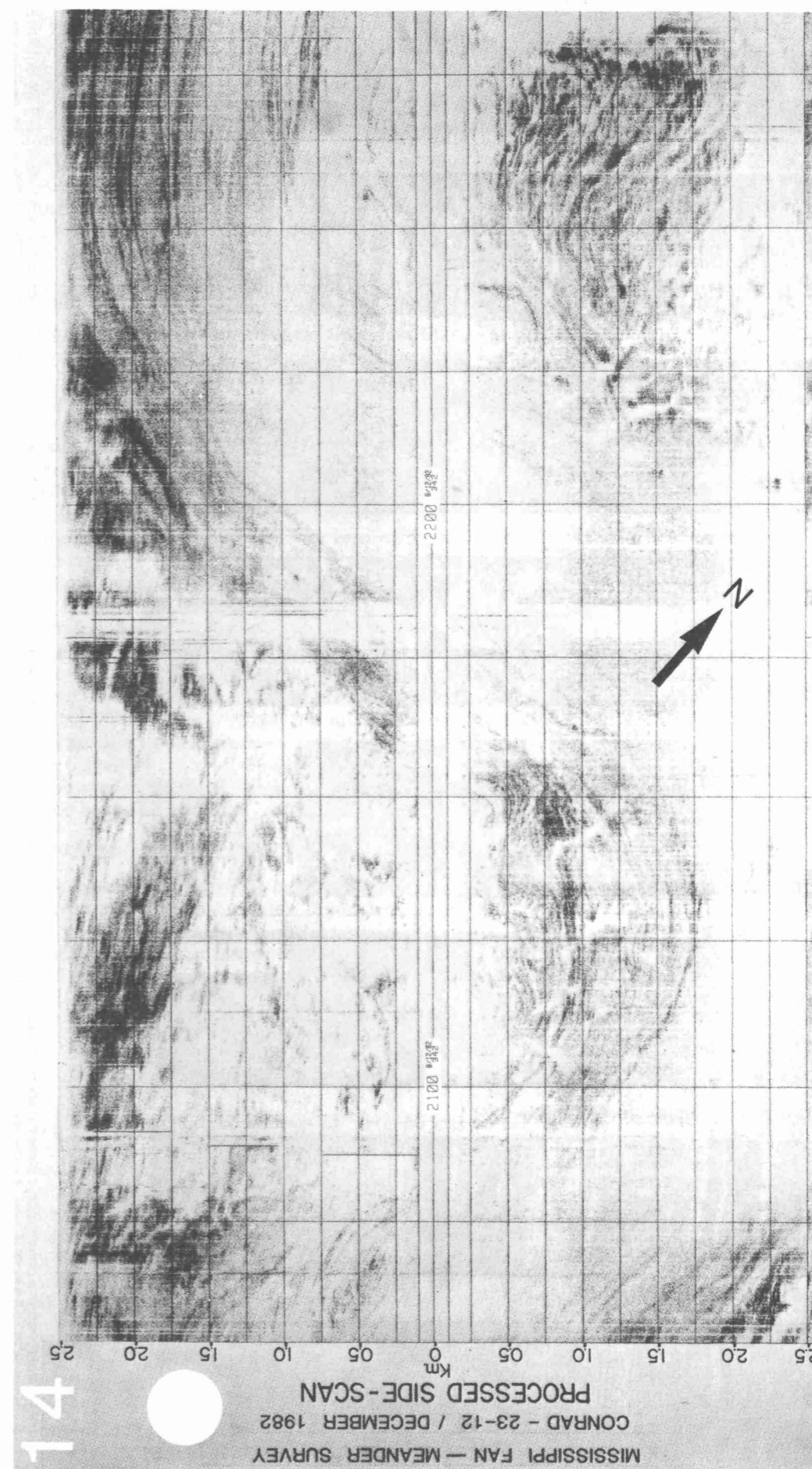


Figure 3 Processed side-scan 'SeaMARC' images of channel meander-parallel lineations with a 5 km (2.7 nmi) swath, from Kastens and Shor (1985). See text for explanation

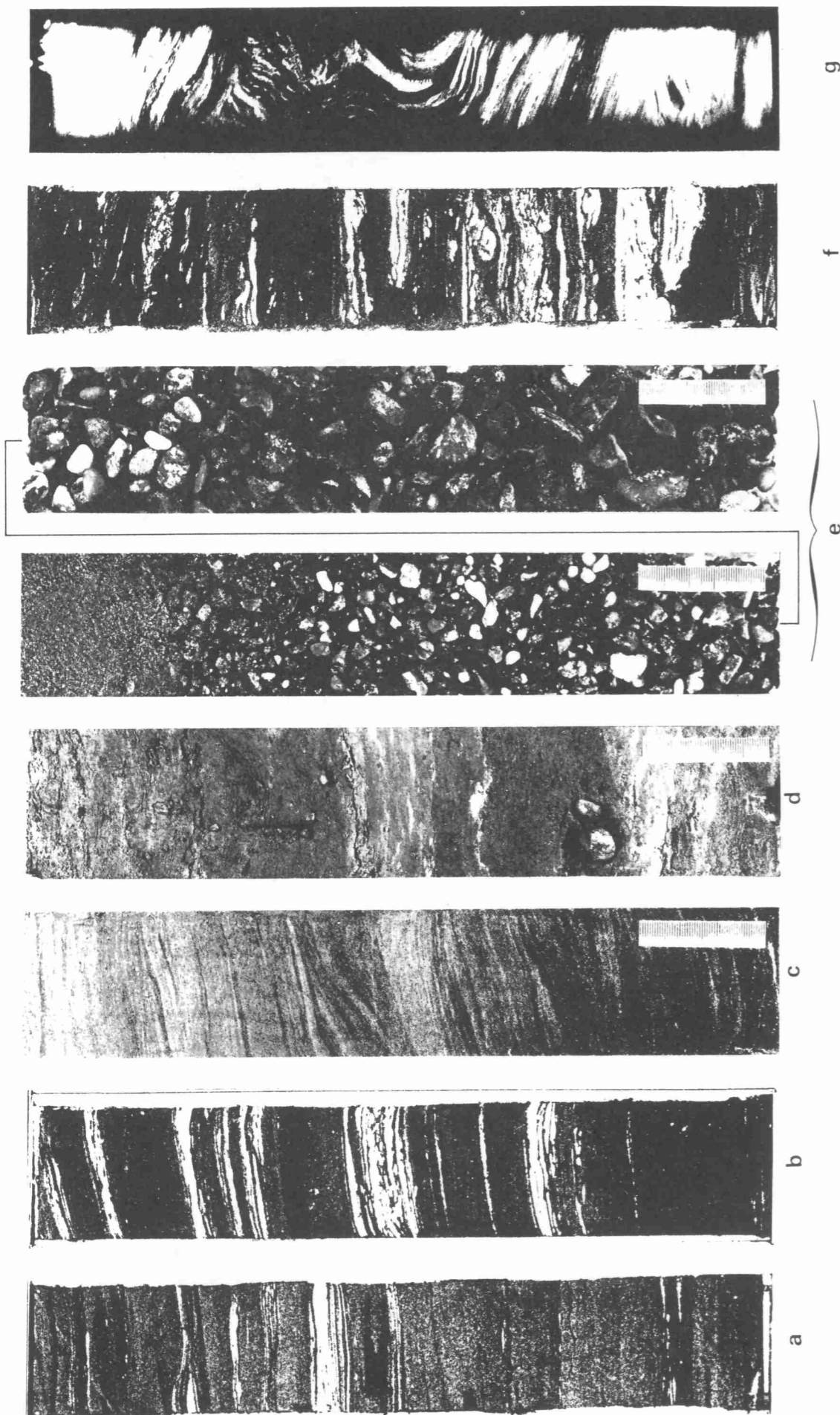


Figure 4 Representative photographic plates to show characteristics of sedimentary facies. Sub-bottom depths correspond to the top of each plate. 4a, Silt-laminated mud (Site 622, 93.4 m); 4b, Silt-laminated mud (Site 621, 158.7 m); 4c, Sandy silt (Site 622, 156.2 m); 4d, Pebbles in silt-laminated mud (Site 622, 197.7 m); 4e, Gravel overlain by sand (Site 621, 213.9 m); 4f, Muddy silts, silty muds and silts (Site 617, approx. 85 m); 4g, X-ray radiograph of sediment deformation (slide) in Site 617 (approx. 47 m). 5 cm bar scales shown; plates without scale have a core width of approx. 5 cm.

metre of section. X-ray radiography shows that the silt laminae frequency is considerably greater than can be resolved with the unaided eye. Parallel lamination and small-scale cross-stratification within graded layers are common sedimentary structures. The base of beds typically are clearly defined, probably scoured and loaded, whereas top surfaces vary from distinct to gradational. Compositionally and texturally, the silt-laminated muds appear similar to the silty mud and muddy silt facies (being finer grained and mainly terrigenous); this facies, however, shows much better sorting. The silts locally contain angular detrital carbonate grains and rarely volcanic ash.

Silts and sands

The silts and sands occur in intervals from less than 10 cm to 3 m in thickness, with E-log results suggesting dominantly sandy intervals that may exceed 10 m thickness. Coring-induced sand loss by wash-out, or conversely flow-in, probably gives a false impression of original silt and sand bed thicknesses. The thicker layers generally appear structureless, whereas the thinner silts and sands typically show Bouma Ta-Tc divisions. In many cases, the silty sands appear to be thoroughly laminated (Figure 4c). The base of beds/layers generally are distinct, erosional or loaded, and upper surfaces range from distinct to gradational. At the base of some beds, there are clasts up to 0.5 cm long. Mean grain size is typically from fine to medium-grade sand with a large amount of silt. The larger grains tend to be well-rounded, spherical to elongate, and polished. The thinner beds appear better sorted, medium to coarse silts, with angular and irregularly-shaped grains. Some thin, medium- to coarse-grained sand beds occur within the channel sites. The silts and sands mainly contain terrigenous, quartzose grains with subordinate biogenic material.

Muddy gravels and pebbly muds

Muddy gravels and pebbly muds occur in the channel sites in rare intervals up to 4 m thick. Pebbles range up to several centimetres diameter and comprise chert, macrocrystalline quartz, jasper, rare igneous and metamorphic fragments, mudstone and shell fragments. The facies lacks sedimentary structures, is very poorly sorted, and the pebbles occur in a clay-silt-sand matrix (Figure 4d).

Gravels

Clast-supported gravels were recovered in a 60 cm interval near the base of Site 621 in the channel thalweg (Figure 4e). Clasts are up to 3 cm long, poorly sorted, and have a similar composition to the muddy gravels and pebbly muds. Generally, clasts are rounded to sub-rounded and grade abruptly over a few centimetres into overlying medium-grained sands. The coring process may have washed out any fine-grained matrix and destroyed primary sedimentary structures.

Depositional processes

In general, the eight facies are believed to be the result of deposition from turbidity currents. Other sediment gravity flows, such as debris flow processes for the muddy gravels and pebbly muds, may have been active

within the channel sites. High velocity, dilute turbidity currents could have transported the gravels although, as with the muddy gravels and gravelly muds, debris flow may have been the long-distance sediment-transport process. Some of the oozes and clays probably were deposited by grain-by-grain settling from suspension over relatively long time periods to produce pelagic/hemipelagic deposits. Clearly, the nature of the recovered cores precludes any refined interpretations of the sediment transport/deposition processes. Furthermore, post-depositional and coring-induced liquefaction and fluidization almost certainly has destroyed many primary sedimentary structures, especially in the coarser grained facies.

Seismic facies

High-resolution and multi-channel seismic reflection profiling has revealed four seismic facies (Stelling *et al.*, 1985): (Type 1) high-amplitude, low continuity reflectors; (Type 2) medium-amplitude, short, semi-transparent, hummocky reflectors; (Type 3) low-amplitude, relatively continuous, curvilinear, semi-transparent to transparent reflectors, and (Type 4) medium-amplitude, subparallel, hummocky, discontinuous reflectors. All four seismic facies were drilled, and an interactive core and seismic data evaluation formed the basis for a lithological correlation for each of the seismic facies. Type 1 reflectors appear to be associated with the base of channel gravels and sands; Type 2, with channel margin sands and silts; Type 3, with the upper channel fill muds and clays, and Type 4, with the overbank silts, muds and clays.

Seismic stratigraphy

Multi-channel seismic reflection profiles over the channel sites show major reflectors '20' and '30' (Figure 5) used to define the boundaries of the fan-lobes. High resolution, 4.5 kHz EDO deep-towed seismic reflection profiling over the irregular topography near Site 617 (Figure 2) shows an upper onlapping channel fill overlying a more conformable channel fill. The upper reflectors show truncation above ridge crests (Figure 6).

Detailed study of the seismic reflection profiles suggests that the base of the high-amplitude reflectors is offset to the side of the channel and has shifted vertically and laterally to directly below the modern channel (Kastens and Shor, 1985; Stelling *et al.*, 1985). The zone of high-amplitude reflectors is divided into three distinct channel lag units, designated A, B and C in Figure 7A. Internal truncation of individual high-amplitude reflectors suggests that these units are composite: this geometry may be explained by erosion during deposition, possibly accentuated by very irregular depositional units. Figure 7C is a composite interpretation of the seismic facies associated with the channel, and based on many seismic reflection profiles. Reflectors A to F show the changing channel shape, and character, during the growth of the most recent fan-lobe. The three lower units thin away from the channel and downlap onto older surfaces (Stelling *et al.*, 1985).

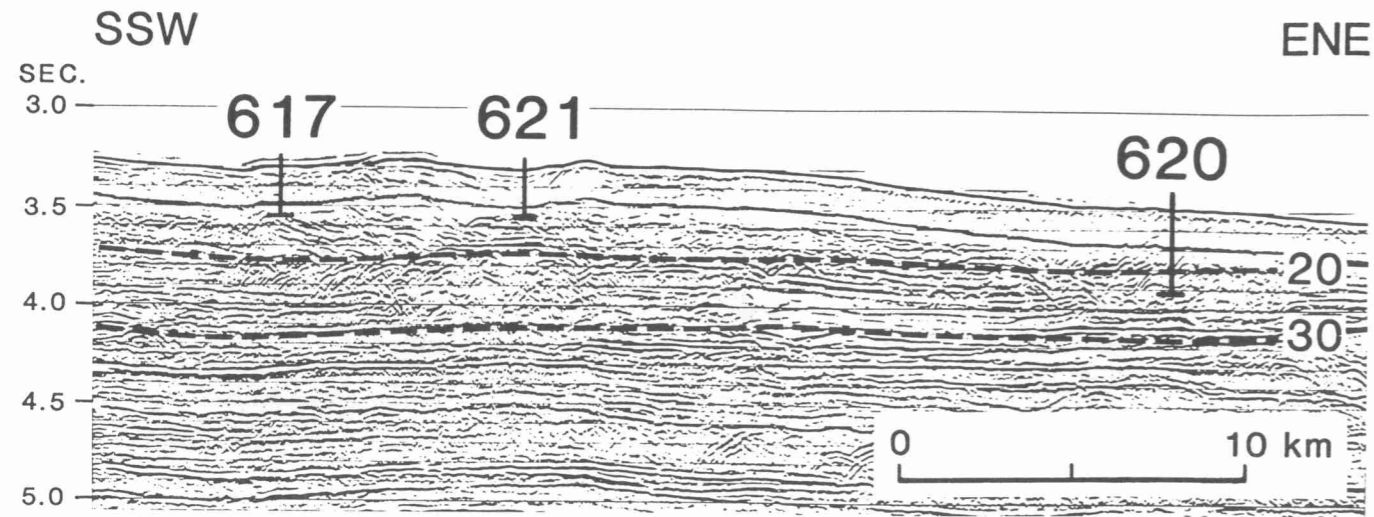


Figure 5 Multi-channel seismic reflection profile (Line MC 11-A) over the channel region. Major seismic reflectors '20' and '30', seismic facies (including high amplitude reflectors beneath modern channel), and location of Sites 617, 621 and 620 are shown. See Figure 2 for location. Printed by permission of Univ. Texas, Institute for Geophysics

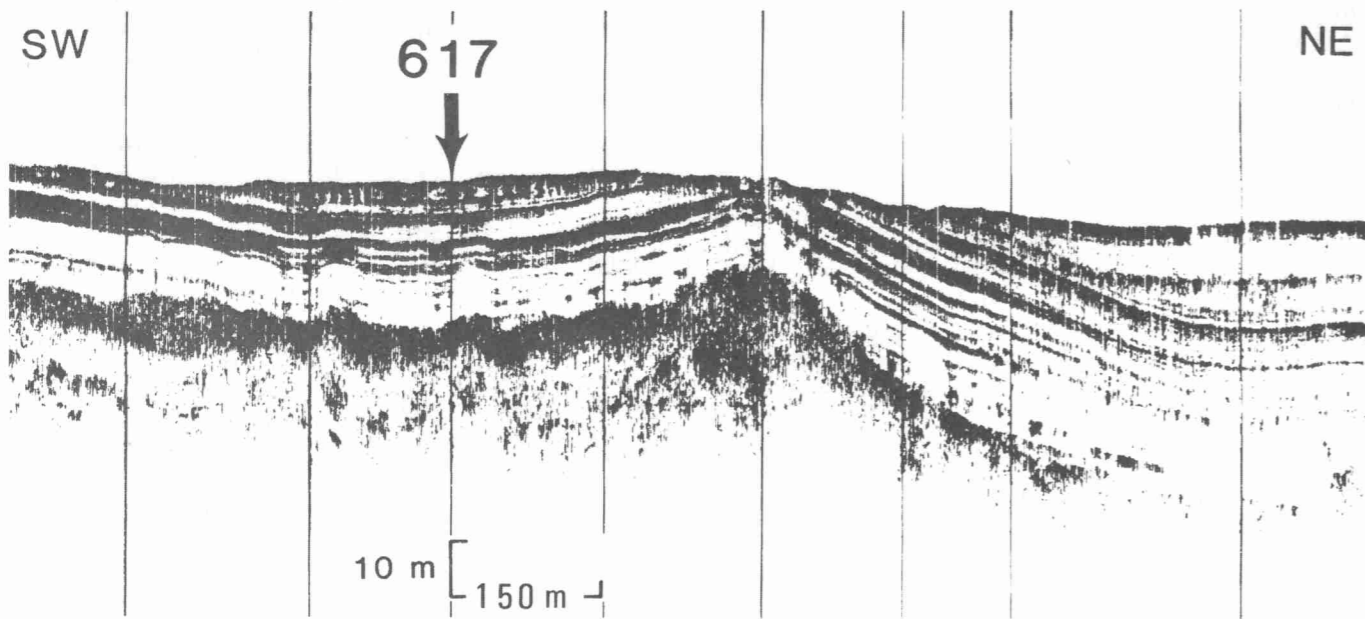


Figure 6 4.5 kHz high resolution EDO deep-towed seismic reflection profile over irregular topography near Site 617. Transparent fill of channel (NE side) overlaps the draped, regularly bedded reflectors that are truncated over the top of the levee and that overlie a deeper seismically opaque zone are shown. See Figure 2 for location. Printed by permission of Louisiana State Univ., Coastal Studies Inst.

Vertical sequence analysis

At the four middle fan sites, core recovery generally was good in the uppermost 80–90 m, but considerably worse below this depth. Therefore, the wire-line logs, mainly gamma-ray logs, were used to supplement and interpolate between missing core sections.

At all four sites, the uppermost 10–25 cm comprises a thin cover of Holocene, marly foraminifer oozes, or calcareous mud, overlying the Late Pleistocene terrigenous clays, muds, silts, sands and gravels. Only the Upper Wisconsin glacial stage sediments were penetrated at all four sites (Kohl *et al.*, 1985).

Channel sites (Sites 621 and 622)

Two sites, approximately 4 km apart were drilled (Figure 2) using the Hydraulic Piston Corer (HPC): Site

621 to 214.8 m sub-bottom in the axial part of the channel, and Site 622 to 208 m sub-bottom (with core recovery to 199.5 m sub-bottom) on the channel margin. Wire-line logs were run from the seafloor at both sites.

Sites 621 and 622 show an overall fining-upwards from gravel, through sand and silt, to mud and clay facies (Figure 8). In the channel axis site (621), the sequence from the bottom upwards is: (1) gravels and sands from 214.8 to 206 m sub-bottom; (2) silty muds and muddy silts, silt-laminated muds, and silts and sands, together with minor muddy gravels and pebbly muds, from 206 m to 156 m sub-bottom; (3) clays and muds, silty muds and muddy silts, and silt-laminated muds, from 156 m to 115 m sub-bottom. Above this fining-upward sequence, there is a thick interval of mainly silty muds and muddy silts, silt-laminated muds, and silts and sands, from 115 m to 98 m sub-

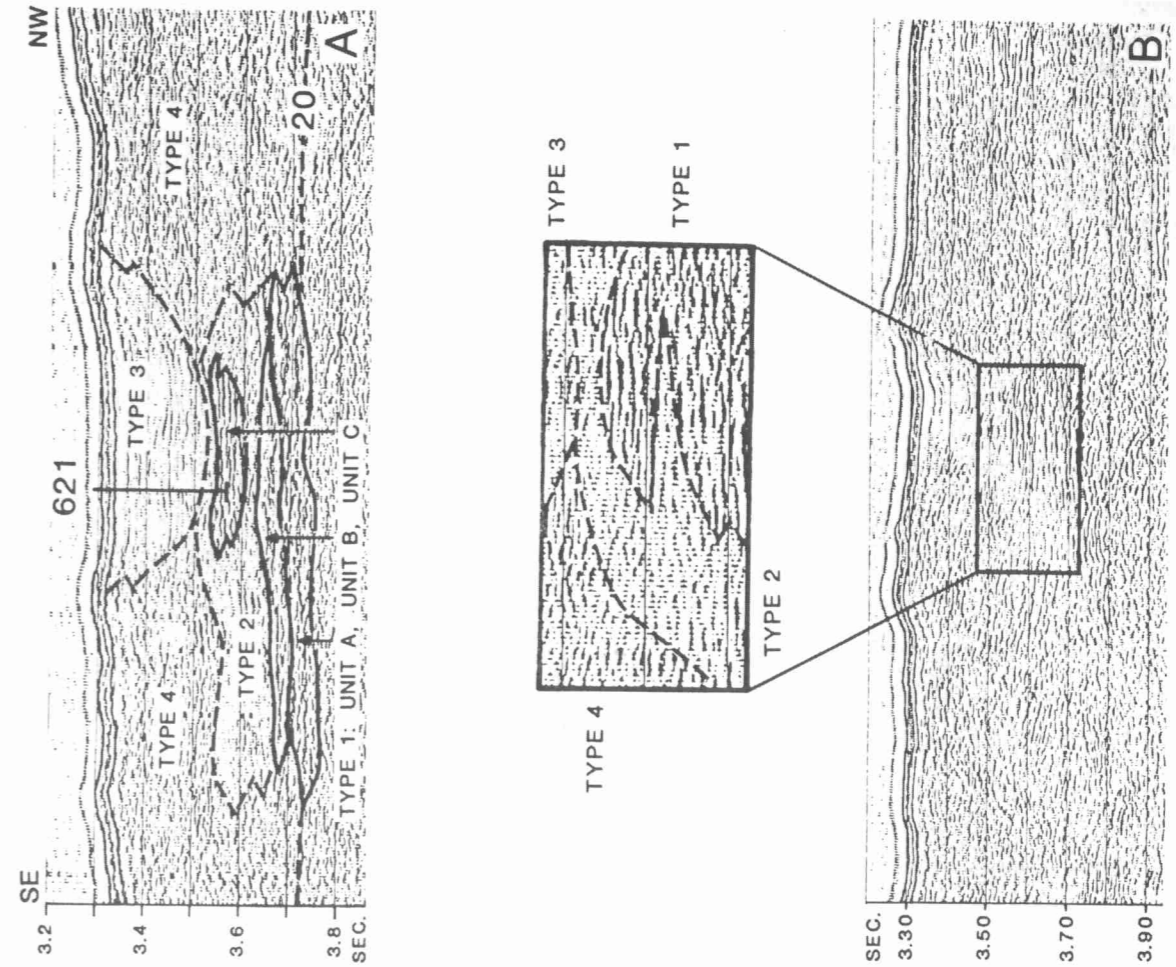
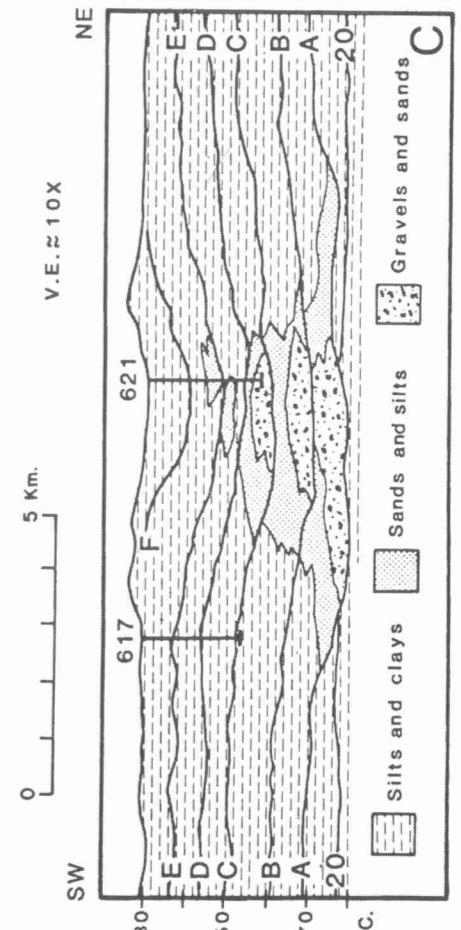
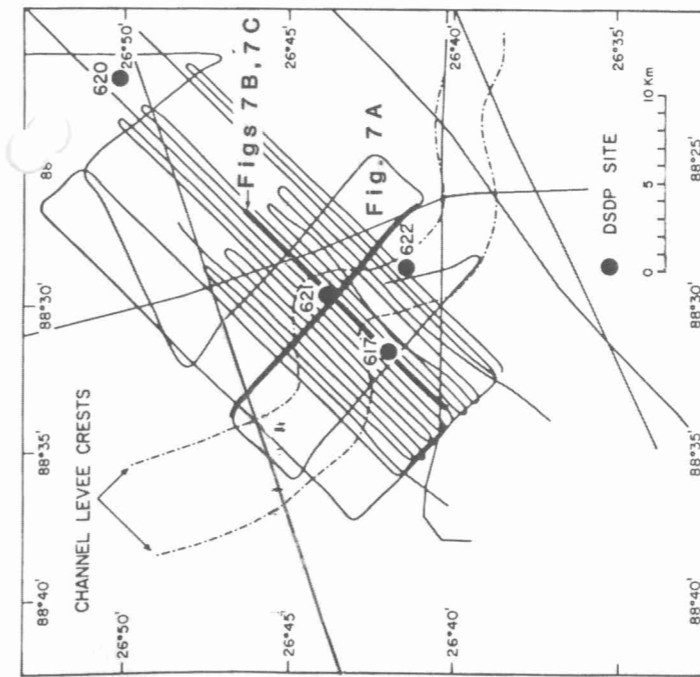


Figure 7A, Annotated, dip-orientated, water-gun record (R/V Conrad Line 2003) showing seismic facies, channel lag units, and position of Site 621. Vertical scale in seconds (two-way travel time). See inset map for location. 7B, Water-gun seismic reflection profile (R/V Conrad Line 1017). Top of Figure is enlargement to show detailed character of seismic reflector types. Vertical scale in seconds (two-way travel time). See inset map for location. 7C, Composite interpretation showing seismic unit boundaries, probable channel margins, inferred lithologies, and Sites 617 and 621. Inset location map for reference. From Stelling *et al.* (1985)



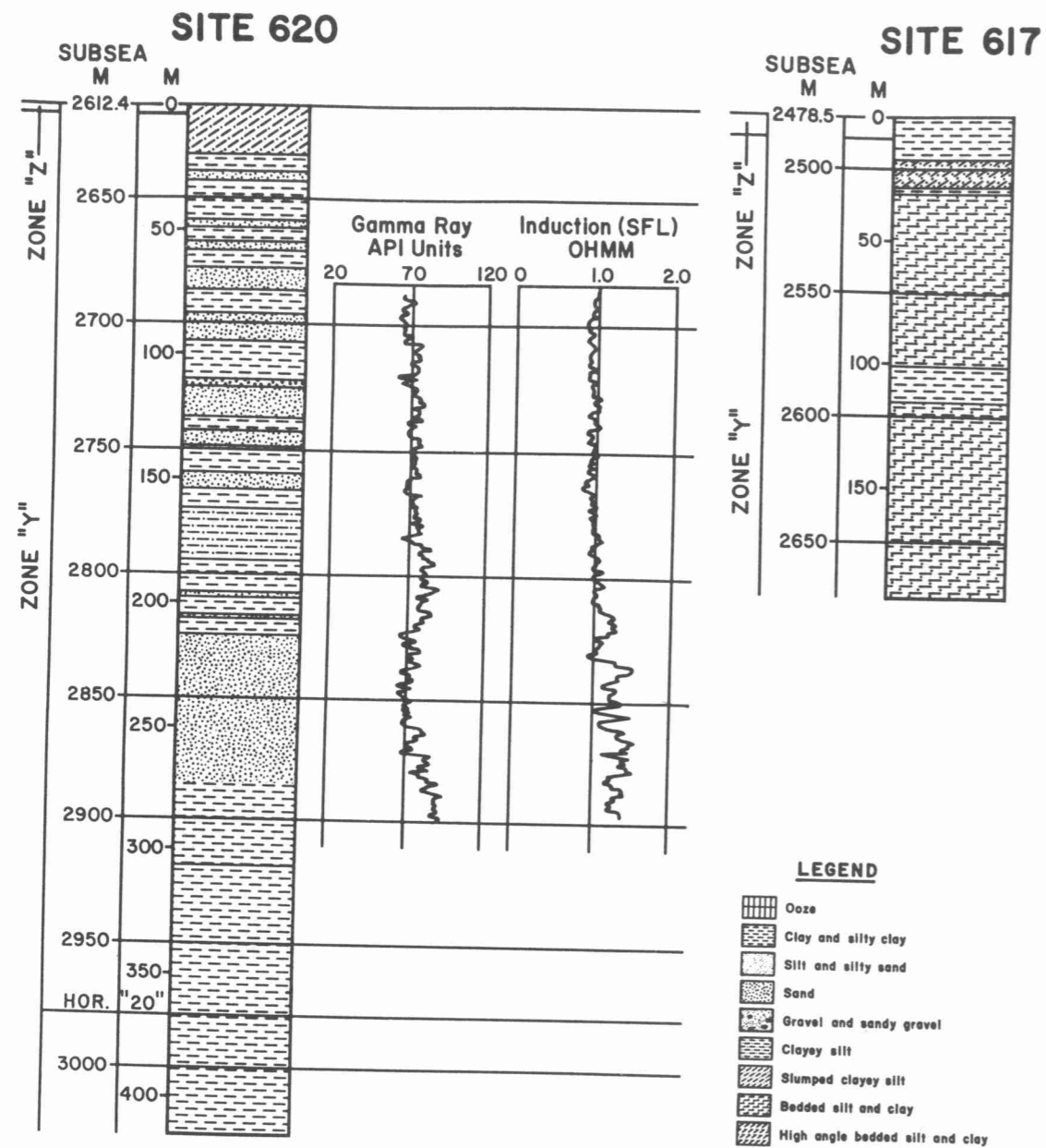


Figure 8 Interpretive lithostratigraphy of overbank (Site 620) and levee site (617) to show age, lithology, gamma-ray and induction log responses.

bottom, above which there are clays and muds, silty muds and muddy silts, and silt-laminated muds, from 98 m sub-bottom upwards. The uppermost 25 cm is a marly foraminiferal ooze.

The Pleistocene Ericson 'Y' Zone at Site 621 has a mixed displaced fauna with common shallow-neritic, and rare upper-bathyal benthic foraminifera (Kohl *et al.*, 1985). This zone includes predominantly Cretaceous calcareous nannofossils and a poorly developed planktonic foraminifera component, with rare Cretaceous species. The diverse neritic benthic fauna that is well developed between 114 m and 3.5 m sub-bottom decreases in abundance below 114 m to the base of the site. The scarcity of planktonic faunas suggests high rates of sediment accumulation and, or, low productivity in the water mass, and the occasional rare bathyal species implies transport of mixed upper bathyal and neritic sediments/faunas to the 'abyssal' environment.

The succession in the channel margin site (622), on the inner bank of the next meander down-channel, essentially is similar to that of Site 621, but generally finer grained (Figure 8). Wire-line logs indicate probable gravels below the recovered core interval that would correlate with the gravels at the base of the channel axis site (621). The occurrence of some pebbles in silt-laminated muds at approximately 198 m sub-bottom (Figure 4d), also may represent the feather-edge of the relatively thick gravel-rich section recovered in Site 621. The pebbly mud is overlain by finer grained sediments that, perhaps, show a coarsening-upward sequence through about 25 m of section to the silts and sands recovered at 180-170 m sub-bottom. The section then fines upwards over about 60 m from silts and sands, through silty muds and silt-laminated muds, to clays and muds at 115 m sub-bottom. Above this, there is a possible coarsening-upward sequence to silts and sands that are interpreted from the wire-line logs to

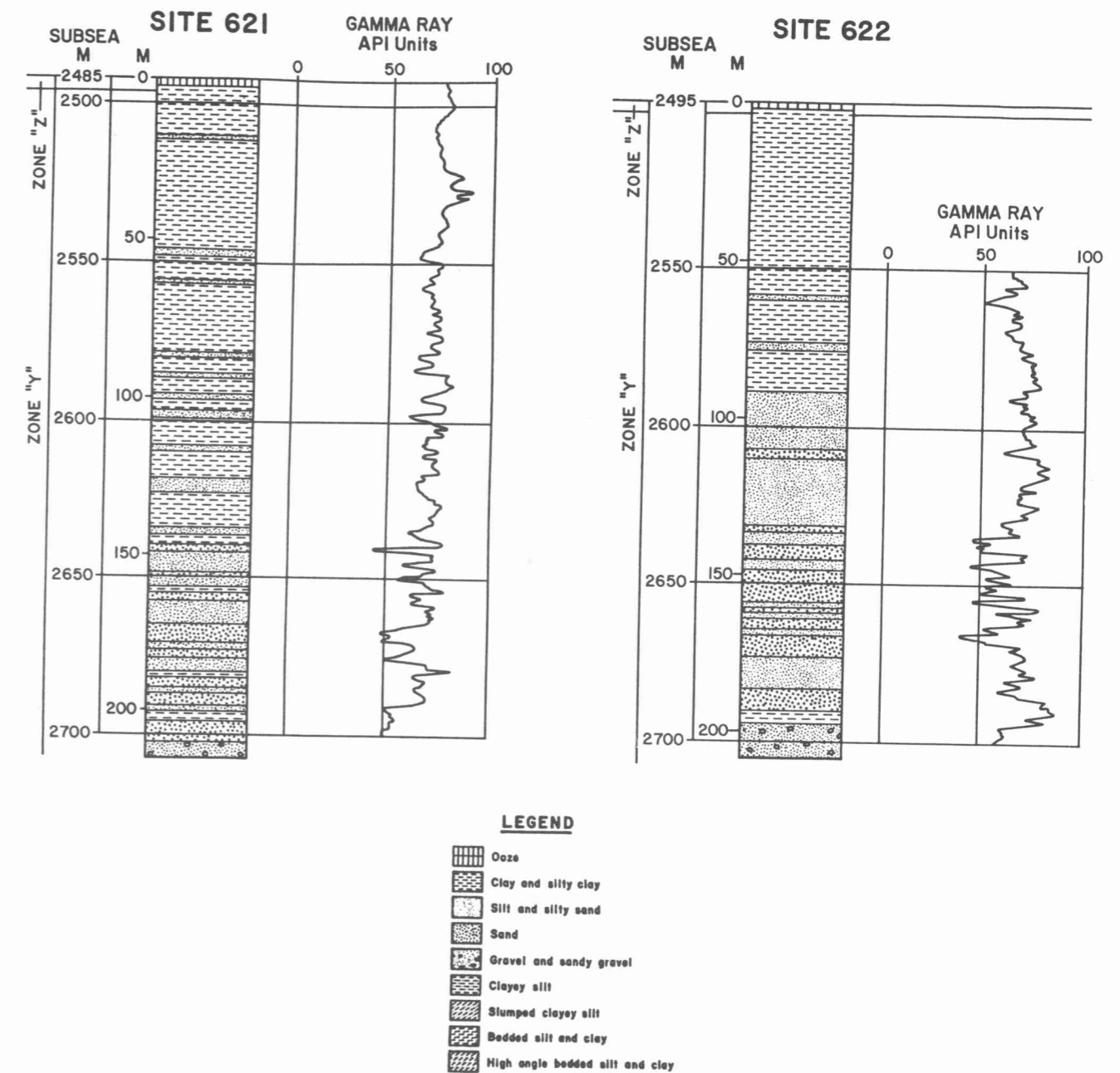


Figure 9 Interpretive lithostratigraphy of channel sites 621 and 622 to show age, lithology and gamma-ray log response. Summaries based on recovered sediment and well-log data. For actual core recovery and observed lithologies, see Leg 96 Scientific Party (1984) Challenger drills Mississippi Fan, *Geotimes* 29, 15-18

occur 60 m to 50 m sub-bottom. This fining-upward to coarsening-upward pattern is somewhat irregular and generally fine-grained. The uppermost 50 m of recovered section comprises mainly clays and muds, with some silty muds, muddy silts and silt-laminated muds.

Displaced foraminiferal faunas, with common neritic benthic species, are common in the upper parts of Site 622. Pleistocene foraminifera and calcareous nannofossils are very rare in the lower parts: those present are mainly Cretaceous reworked foraminifera. From about 89.4 m to 3.5 m sub-bottom, benthic foraminifera are dominant, and together with the absence of normal bathyal species, suggests rapid sedimentation of shallow water sediments and faunas. The high rates of sediment accumulation are supported by very rare planktonic foraminifera, and the increase in planktonic species between 142.5 m to 89.4 m sub-bottom suggests relatively decreased sediment

accumulation rates in this interval. There is a very poor Pleistocene foraminiferal fauna although reworked Cretaceous species are common.

Levee site (Site 617)

Site 617, located on the western levee of the most recent channel, is 2.5 km from the levee crest on a channel bend and 4.5 km southwest of the main channel axis (Figure 2). This site was drilled to 191.2 m sub-bottom with the Advanced Piston Corer (APC). Local truncated seismic reflectors indicate an irregular topography with some seafloor erosion (Figure 6). The 'swales' appear to have 15-50 m of sediment fill, and in some instances the uppermost seismic reflectors may be traced between swales.

Site 617 consists of clays and muds (16%), silty muds, muddy silts and silt-laminated muds (84%). The uppermost 25 cm comprise Holocene olive-brown

foraminiferal mud. Two sequences were defined at this site, separated by a packet of relatively uniform sediments (Figure 9).

The oldest sequence is a 91 m thick coarsening-upward sequence almost entirely consisting of silty muds, muddy silts and silt-laminated muds. The percentage of silt laminae increases from 6% at about 161 m to 164 m sub-bottom up to 18% at about 84.5 m to 88 m sub-bottom (Figure 4f), with the uppermost 19 m of this interval being mainly silty muds and silt-laminated muds. Inclined, contorted and folded laminae (frequently colour-enhanced), at about 113.2 m, 122.6 m to 125.6 m, 129 m to 129.6 m, and 162.5 m to 165.5 m sub-bottom, suggests possible wet-sediment slide deformation.

Above the basal coarsening-upward sequence, there is a 38 m thick relatively uniform section of muds, silty muds, muddy silts and silt-laminated muds. Only at about 46.3 m to 47.8 m sub-bottom are there inclined beds that may be the result of local sediment sliding (Figure 4g).

The uppermost 46 m of Site 617 is a fining-upward sequence defined by a change from muds, silty muds, muddy silts and silt-laminated muds to clays and muds. Silt laminae vary from approximately 26% of the total section between 46 m to 37 m sub-bottom, through about 13% at 24 m sub-bottom, to rare from the sediment surface to 17.6 m sub-bottom. In addition, there is a notable decrease in bed thickness upwards, suggesting that there is a thinning-and-fining-upward sequence. Local episodes of sediment instability (sliding) are recorded in the inclined, contorted and folded laminae from 23.8 m to 17.6 m sub-bottom and 39.6 m to 44.9 m sub-bottom.

The levee site (617) contains a very poorly preserved Pleistocene planktonic and benthic fauna with predominantly reworked Cretaceous calcareous nannofossils in the muds, silty muds and silt-laminated muds. Rare, well preserved radiolaria occur between about 8 m and 56 m sub-bottom. The absence of a bathyal benthic fauna and a very low abundance of planktonic foraminifera suggests high rates of sediment accumulation.

Overbank site (Site 620)

Site 620, located approximately 18.3 km northeast of the present channel (Figure 2) within the southern edge of the 'slump' described by Walker and Massingill (1971), penetrated 422.7 m of sediments (Figure 9) with the standard rotary coring bit. The rotary coring methods at this site, together with the very low core recovery (47%), meant that only poor facies definition proved possible. The gamma-ray log run from 72 m to 287 m sub-bottom, however, provided additional data for delineating sedimentary sequences. The uppermost 20 cm of section is Holocene, marly foraminiferal ooze.

In contrast to the levee site (617), the overbank site (620) generally is finer grained, with little evidence of sediment sliding and slumping. With the aid of the well logs, two possible sequences were delineated. The oldest sequence, from 289 m to 217 m sub-bottom, is a coarsening-upward sequence from clays and muds to silty muds, muddy silts and silt-laminated muds at 258 m sub-bottom. The wire-line log from 258 m to 237 m

sub-bottom has a saw-toothed pattern suggesting considerable variability in the silt, mud and clay content. The silt component becomes dominant at 237 m sub-bottom and remains so to the top of the sequence at 217 m sub-bottom. Since the interpreted succession of sediments is relatively consistent with the core lithologies, and as the sediments do not appear to change much to within the bottom of the cored interval, this poorly-defined sequence might extend from 421.3 m to 217 m sub-bottom.

Above the lower coarsening-upward sequence, there is another coarsening-upward sequence between 217 m and 70 m sub-bottom. The sequence begins with clays and muds to 172 m sub-bottom that are overlain by silty muds, muddy silts and silt-laminated muds to 110 m sub-bottom, above which there are silty muds, silts and sands to about 70 m sub-bottom. The occurrence of sand at the very top of the sequence is interpreted only from the gamma-ray log as the recovered core lithologies are all fine-grained.

Extensive disruption of the sediments occurred from 70 m sub-bottom to the seafloor as a result of the coring techniques. However, recovered core lithologies suggest that this section contains mainly clays and muds, with the frequency of silt laminae increasing towards the top. This interval (70-0 m sub-bottom), therefore, may represent another coarsening-upward sequence.

Site 620 has a poorly developed foraminiferal faunal assemblage in the Pleistocene Ericson Zone 'Y', with mainly reworked Cretaceous calcareous nannofossils in the silty muds, muddy silts and silt-laminated muds. Rare, well preserved radiolaria occur between about 220.5 m and 9.5 m sub-bottom. The low abundance of foraminifera (reworked Cretaceous forms between about 346 m and 289 m sub-bottom) suggests rapid sediment accumulation. Towards the bottom of this site, the slight increase in the abundance of Pleistocene nannofossils suggests a slightly lower sediment accumulation rate.

Summary of lithostratigraphy

A comparison of the sedimentology of the channel axis (Site 621), channel margin (Site 622), levee (Site 617), and overbank (Site 620) reveals that:

- (1) Sequences can be recognized on a scale from 147-46 m thick.
- (2) Fining-upward sequences characterize the intrachannel sites.
- (3) Coarsening-upward sequences (stacked in Site 620) may typify the extrachannel sites, although the levee (617) also shows a fining-upward sequence.
- (4) Wet-sediment deformation is pronounced only in the levee (617).
- (5) The coarsest grained facies are confined to the intrachannel sites, with very little overspill onto the levee (617) or more distal overbank (620). Similarly, the bulk clay content increases away from the channel.
- (6) The axial part of the channel contains the thickest sections of the coarsest grained facies.

Geometrical development of channel

This section, inserted for completeness and to provide an important insight into the channel processes, is based on the published data of Kastens and Shor

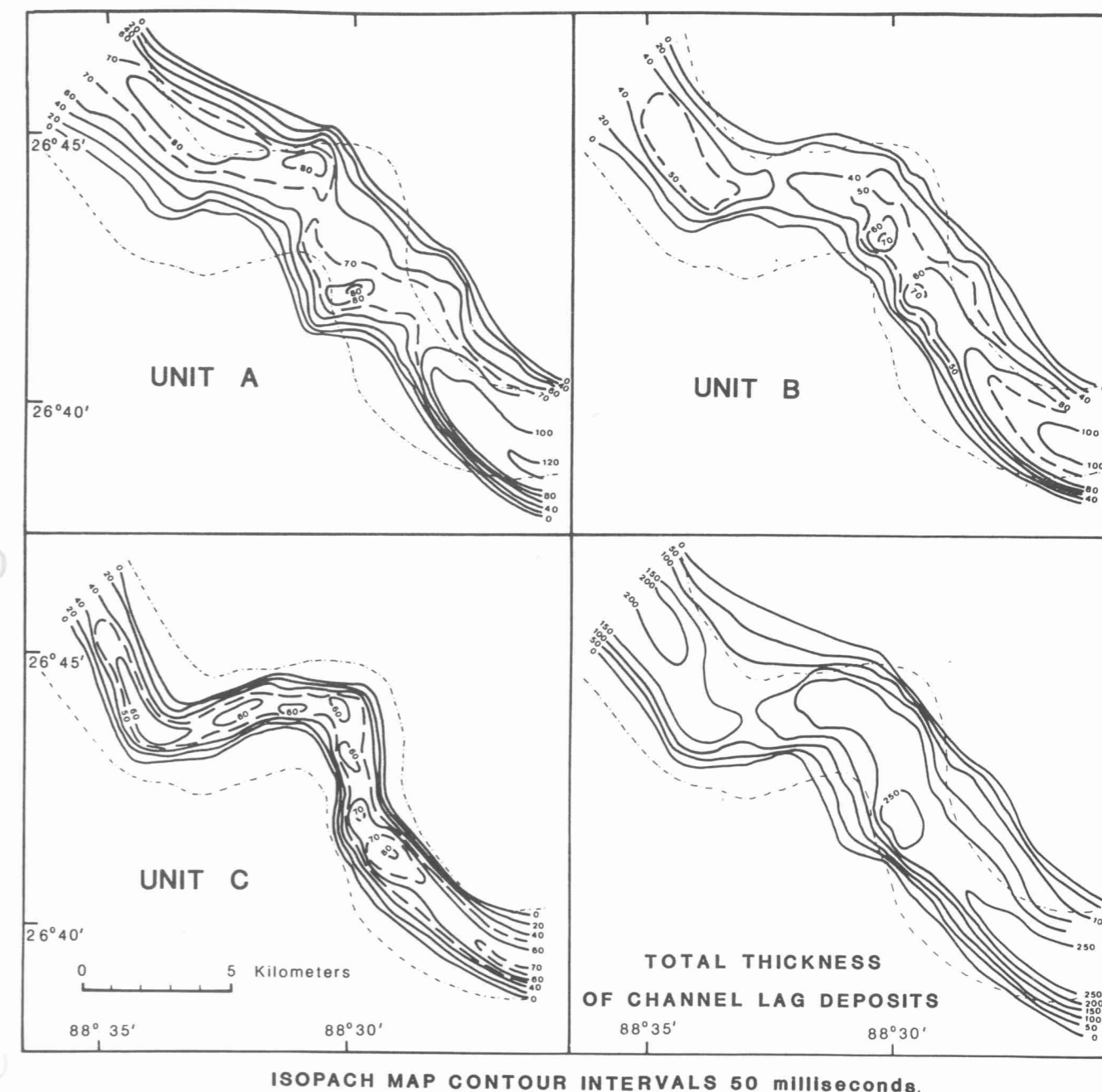


Figure 10 Isopach maps of the channel-lag deposits (high amplitude reflectors). A = channel lag unit A (oldest unit); B = channel lag unit B; C = channel lag unit C (youngest unit), and D = total thickness of the three channel lag units. Levee crests of the modern channel (dash-dot line) are shown for reference. For an approximate depth conversion, 20 msec = about 15 m and 50 msec = about 38 m. (Data from Stelling et al., 1985)

(1985). Isopach maps of the three channel lag units A, B and C, referred to above (seismic stratigraphy) are shown in Figure 10. The oldest unit, A, unconformably overlies seismic horizon '20'. In contrast to unit A, unit B is typified by a low sinuosity and approximates more closely the shape of the modern channel, whereas unit C is narrower than the present channel margins and lies directly beneath the present channel axis. While unit B is in contact with Unit A, unit C is separated from unit B by a thin zone of semitransparent to medium amplitude discontinuous reflectors approximately 30-40 msec. thick (Figures 7A and 7C).

Figure 10D shows the lateral extent and total thickness of units A, B and C. The interval between units B and C is interpreted as predominantly sands

and silts, and is included in the total thickness calculations. The lateral extent of the channel lag deposits varies from 6.5 km in the northwest, to a minimum 4.3 km downfan of the first meander loop (unit A). Cumulative channel lag deposit thickness is essentially uniform although slightly thicker in the northwest and southeast.

The isopach maps in Figure 10 suggest that the channel lag (axis) shifted southwestwards in the northern area, northeastwards in the central area, and southwestwards in the southern part of the study area. In total, the channel thalweg shifted laterally 1.5-2 km, migrated downfan 1.2 km, and vertically accreted 175 m (220 msec.) of sediments during the accumulation of the coarsest grain sizes found within the channel. The seismic reflection profiles and

paper is defined as the middle fan (Bouma *et al.*, 1984). It is likely that this part of the fan only contains a single large channel with well developed levees, so it would be defined as inner (upper) fan in other modern and ancient turbidite systems. However, on the Rhone Fan where there is good seismic coverage, Droz and Bellaiche (1985) define the upper fan as the region in which the single channel-levee has maintained an essentially constant location through time, in contrast to the middle fan where the channel-levee system has migrated laterally and shifted its position considerably.

Distinctions between upper and middle fan are impossible in ancient turbidite systems, and there are no accepted definitions even for modern fans. In comparing ancient submarine channel-levee-overbank systems with that of the Mississippi Fan, therefore, it may be appropriate in some cases to compare the ancient inner (upper) fan with the Mississippi middle fan as used here and in the Leg 96 reports. Also, the width and depth of the active Mississippi Fan channel, at about 3–4 km and 100 m, respectively, would compare favourably with many ancient channels interpreted as inner fan.

Finally, it is recognized that much of our current models for submarine fan sedimentation patterns comes from research on ancient turbidite systems. Such models have proved extremely useful, and while DSDP Leg 96 has been amongst the first major studies of a modern fan where the data has been publically available, it may be that the growth patterns and nature of sedimentation in this fan is atypical of most submarine fans. Perhaps, we are at a stage where many fans need to be intensively studied before further general models for fan sedimentation are developed.

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