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The lowermost Mississippi River: a mixed bedrock-alluvial channel

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ABSTRACT

In this study, the distribution of channel-bed sediment facies in the lowermost Mississippi River is analysed using multibeam data, complemented by sidescan sonar and compressed high-intensity radar pulse seismic data, as well as grab and core samples of bed material. The channel bed is composed of a discontinuous layer of alluvial sediment and a relict substratum that is exposed on the channel bed and sidewalls. The consolidated substratum is made up of latest Pleistocene and Early Holocene fluvio-deltaic deposits and is preferentially exposed in the deepest thalweg segments and on channel sidewalls in river bends. The exposed substratum commonly displays a suite of erosional features, including flutes that are quantitatively similar in form to those produced under known laboratory conditions. A total of five bed facies are mapped, three of which include modern alluvial deposits and two facies that are associated with the relict substratum. A radius of curvature analysis applied to the Mississippi River centreline demonstrates that the reach-scale distribution of channel-bed facies is related to river planform. From a broader perspective, the distribution of channel-bed facies is related to channel sinuosity — higher sinuosity promotes greater substratum exposure at the expense of alluvial sediment. For example, the ratio of alluvial cover to substratum is *ca* 1·5:1 for a 45 km segment of the river that has a sinuosity of 1·76 and this ratio increases to *ca* 3:1 for a 120 km segment of the river that has a sinuosity of 1·21. The exposed substratum is interpreted as bedrock and, given the relative coverage of alluvial sediment in the channel, the lowermost Mississippi River can be classified as a mixed bedrock-alluvial channel. The analyses demonstrate that a mixed bedrock-alluvial channel boundary can be associated with low-gradient and sand-bed rivers near their marine outlet.

Keywords Bedrock-alluvial river, channel-bed facies, Mississippi River, river morphology, sediment transport.

INTRODUCTION

The beds of large lowland rivers have been characterized incompletely because of challenges in collecting the physical data necessary to quantify the bed sediments, channel bottom and sidewall morphology and the sediment-transport and fluid-flow fields. Fortunately, through advancements in technologies, the high-resolution measurements needed to capture the behaviours and characters of large rivers are beginning to emerge (e.g. Wilbers & Ten Brinke, 2003; Kostaschuk *et al.*, 2005; Galler & Allison, 2008). In one such study, Nittrouer *et al.* (2008) demonstrate that the bed of the lowermost Mississippi River is incompletely covered by modern

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alluvium — fields of active bedforms are spatially discontinuous, separated by deep channel pools devoid of dunes, where the bed comprised the Early Holocene and Late Pleistocene strata that underlie the river channel. These observations were made at two particular locations in the river: 165 and 135 km above the outlet of the river (New Orleans and the English Turn bend, respectively). The present study is an outgrowth of these observations and is intended to investigate whether this style of channel-bed cover is prevalent throughout the lower river. Presented here is an analysis that defines sediment facies for the lower 165 km of the Mississippi River channel and relates their distribution to channel planform. The observational data used here consist of spatially continuous maps for the river bed generated with multibeam, compressed high-intensity radar pulse (CHIRP) and side-scan sonar equipment, supplemented by grab samples of bed material and shallow cores.

The channel bed of low-sloping rivers near their outlet will respond to dynamic conditions such as delta subsidence and sea-level fluctuations. The conventional understanding is that sustained relative sea-level rise is complemented by aggradation of the channel bed and neighbouring floodplain through sediment transport continuity, so that the river maintains depth and slope consistency over its long profile (e.g. Whipple *et al.*, 1998). The Mississippi River has been subject to sustained base-level rise over the past few millennia and, therefore, it is expected that the channel bed will be a site of enhanced sedimentation. For example, researchers have shown that, over the past few thousand years, base level has been rising *ca* 0·002 to 0·01 m year^{-1} (Tornqvist *et al.*, 2008). The present day Mississippi River channel and its associated delta complex, the Balize lobe, have been a conduit for sediment transport and a site for sediment deposition over the past *ca* 1300 years (Frazier, 1967; Roberts, 1997). If channel bed elevation adjusts to the pace of base-level change, then over the past millennium alluvial aggradation on the Mississippi River channel should be roughly 2 to 10 m. The present study tests this hypothesis by describing channel-bed sediment facies and measuring the distribution and thickness of alluvial deposits.

Proposals to rebuild the deteriorating Louisiana coastal wetlands and barrier islands require sediment from the Mississippi River (e.g. Finkl *et al.*, 2006). The present study provides data for the thickness and coverage of sandy accumulations on the river bottom. Relationships are sought between the sandy resources, to the river planform and the reach-averaged fluid flow field. This knowledge will aid in optimizing placement of sediment dredges and timing for their use. Controlled diversions that distribute sediment-laden water from the Mississippi River directly to neighbouring wetlands require knowledge of the channel-bed sediment composition and successful development of diversions requires understanding of whether focused bed erosion could threaten infrastructure on or adjacent to the Mississippi River bed. Herein, the composition of the Mississippi River bottom is defined and its susceptibility to erosion is addressed.

SETTING

The Mississippi River has the third largest drainage area of all world rivers, extending over 12% of North America and 45% of the contiguous United States (Fig. 1). The river system ranks seventh worldwide in both annual sediment and water discharge (estimated sediment flux: 87 to 210 Mt year^{-1}; Meade, 1996; Horowitz, 2006). The area of interest for this study is the lowermost 165 river kilometres of the Mississippi River, from the city of New Orleans, Louisiana, to the outlet at Head of Passes (HOP), river kilometre 0 (location is reported as river kilometres above HOP and is denoted 'RK'; Fig. 2). The furthest downstream continuously operating river monitoring station is at Tarbert Landing (RK 492; Fig. 2A) and the daily water-discharge data collected at this site by the United States Army Corps of Engineers (USACE) are used in this study. Fortunately, there are no significant additions of water to the river below this station and there is relatively little loss of water discharge until very near the outlet (Tarbert Landing is downstream of the Old River control structure, RK 505, where water and sediment are diverted to the Atchafalaya River). Mississippi River water discharge is typically low during late summer and autumn (July to November) and high during mid-winter to late spring (January to May; Bratkovich *et al.*, 1994). For the period from 1961 to 2004, mean water discharge was 14 000 m^3 sec^{-1} and median discharge was 15 000 m^3 sec^{-1}. Average lowest and highest annual-water discharge is determined by averaging yearly low-water and high-water discharge extremes, based on daily measurements collected at Tarbert Landing, over the time period from 1961 to 2008. These water-discharge values are

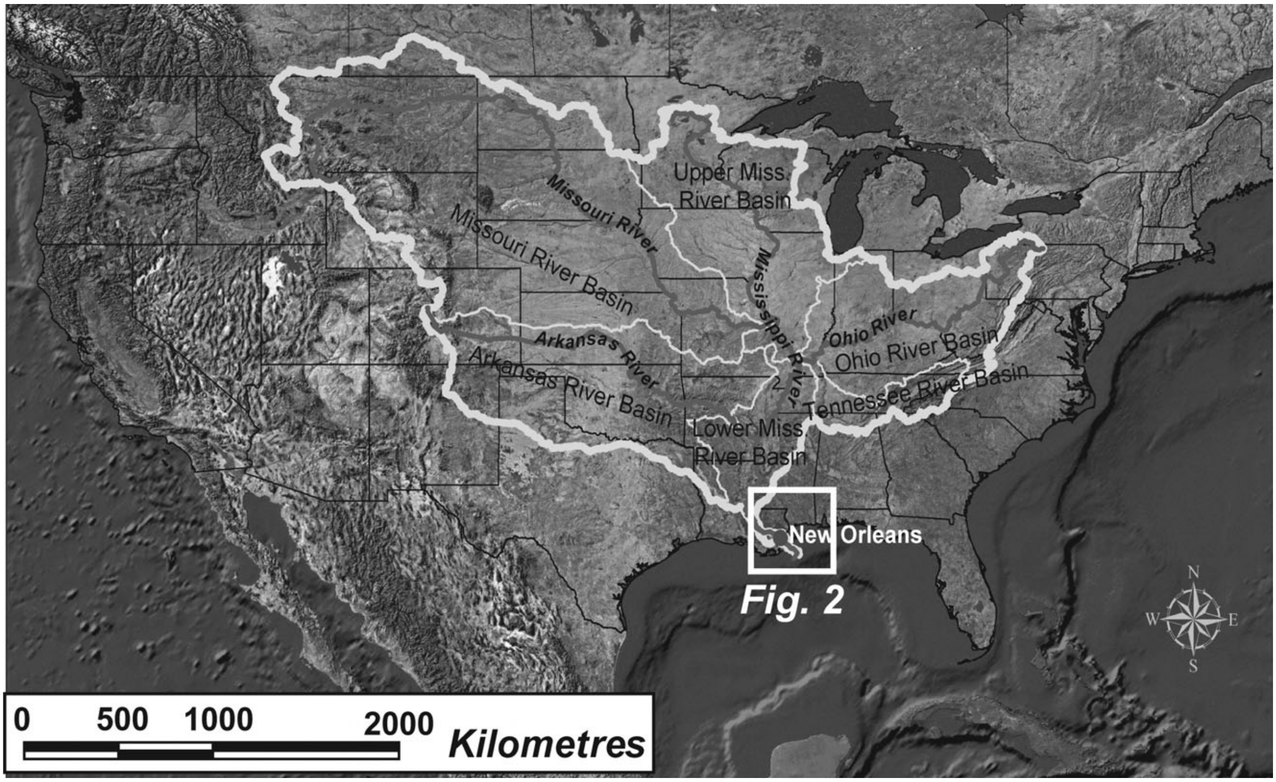

Fig. 1. Mississippi River drainage basin, outlined in white, with major tributaries labelled. The basin size is 3×10^6 km^2, covering roughly 12% of North America. Outlined near the river outlet is the field of view depicted in Fig. 2.

ca 5000 m^3 sec^{-1} and *ca* 30 000 m^3 sec^{-1}, respectively. Associated with this range of river discharge are flow velocities (cross-sectional averages) that vary between 0·59 and 1·46 m sec^{-1} (as measured at both New Orleans, RK 164 and Belle Chasse RK 122; http://www.mvn.usace.army.mil/eng/edhd/velo_no.htm). Water-surface slopes for the lower river vary in time and space; at RK 170, representative water-surface slopes for high and low discharge are $3{\cdot}2 \times 10^{-5}$ and 2×10^{-6}, respectively, and water-surface slopes at RK 8 for the same water discharges are $2{\cdot}3 \times 10^{-5}$ and $1{\cdot}4 \times 10^{-6}$ (Fig. 3). These values were calculated applying a box-car averaging technique to stage data measured by the USACE (data available at: http://www.mvn.usace.army.mil/eng/edhd/Wcontrol/miss.htm).

A tidal signal is recorded in stage records as far upstream as the Donaldsonville gauge at RK 280. The tidal perturbation of flow velocity is minimal because the diurnal tidal range, *ca* 0·30 m, is very small relative to channel depth. For the reaches measured between RK 165 and RK 30, bankful river width is relatively uniform, with a range of 650 to 1000 m (mean: 858 m) and thalweg depth varies between 20 and 65 m (Fig. 4). Downstream of RK 30 and RK 10, breaks in the east-bank and west-bank levées, respectively, allow water to leave the main channel. Coincident with this location, the channel bed shallows to 15 m and channel width widens to *ca* 1300 m. Channel sinuosity for the Mississippi River decreases at RK 120, where the channel straightens ahead of its outlet. Planform sinuosity between RK 165 and RK 130 is 1·76 and from RK 120 to RK 0 sinuosity is 1·21.

The Mississippi River in the present survey reach is incised into consolidated, seaward-dipping fluvio-deltaic strata (Galler *et al.*, 2003); based on collection of cores from within 1 km of the modern Mississippi River channel, the age range of these sediments is from Late Pleistocene to Holocene (Stanley *et al.*, 1996). Holocene sediments thicken toward the Gulf of Mexico, from a few metres near New Orleans, to many tens of metres at HOP (Fig. 5). The channel bed is mantled by actively transported alluvial sediments that are composed of sand (very fine to medium) and mud deposits (Galler & Allison, 2008). Sand deposits are worked into fields of bedforms with average wavelength and height dimensions that vary 10 to 40 m and 0·1 to 1·5 m, respectively, during low-water discharge and up to 100 to 200 m and 3 to 10 m during high-water discharge (Nittrouer *et al.*, 2008).

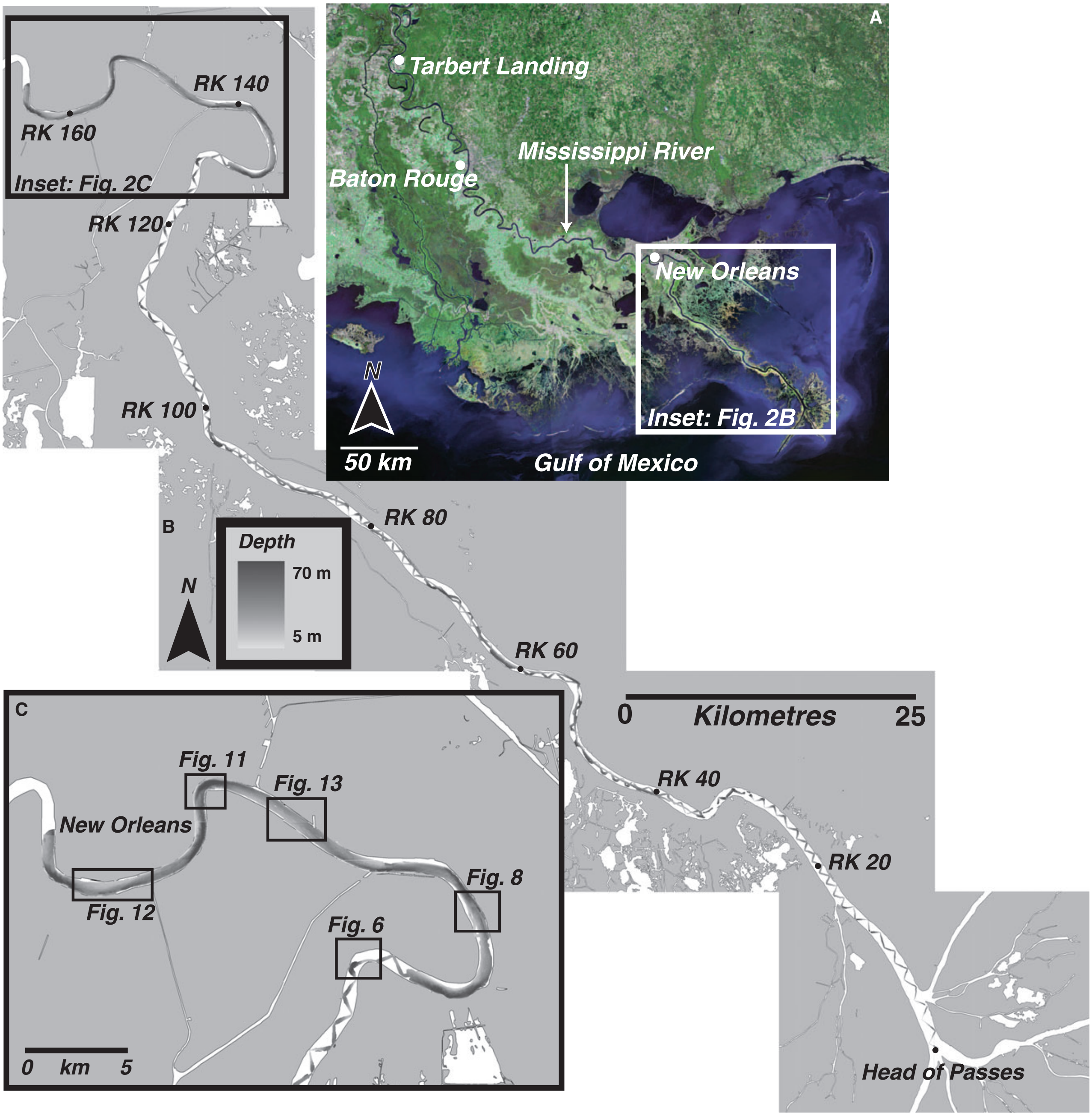

Fig. 2. (A) Louisiana and the lower *ca* 600 km of the Mississippi River. Daily discharge measurements are recorded by the USACE at Tarbert Landing. At Baton Rouge, the river turns eastward and below New Orleans the river straightens south-eastward as it approaches the outlet to the Gulf of Mexico. (B) Surveyed reaches for this study, from river kilometre 165 (i.e. RK 165; distance above Head of Passes) to RK 0 (the outlet at Head of Passes). Multibeam bathymetry data were collected for the entire channel, bank to bank, from RK 165 to RK 130 and along a single-line zigzag swath from RK 130 to RK 0. (C) RK 165 to RK 130, showing where full-channel multibeam data were collected. Boxed areas correspond to the field of view for Figs 6, 8, 11, 12 and 13.

METHODS

Data collection tools and processing

Two primary field campaigns onboard the 18 m long *R/V Eugenie* measured channel-bed topography and defined the composition of the Mississippi River bed from RK 165 to RK 0. Both surveys occurred during the month of November, when relatively low-flow conditions persist toward the end of the dry season. The initial survey took place during 2002 (water discharge: 9900 m^3 sec^{-1}) and

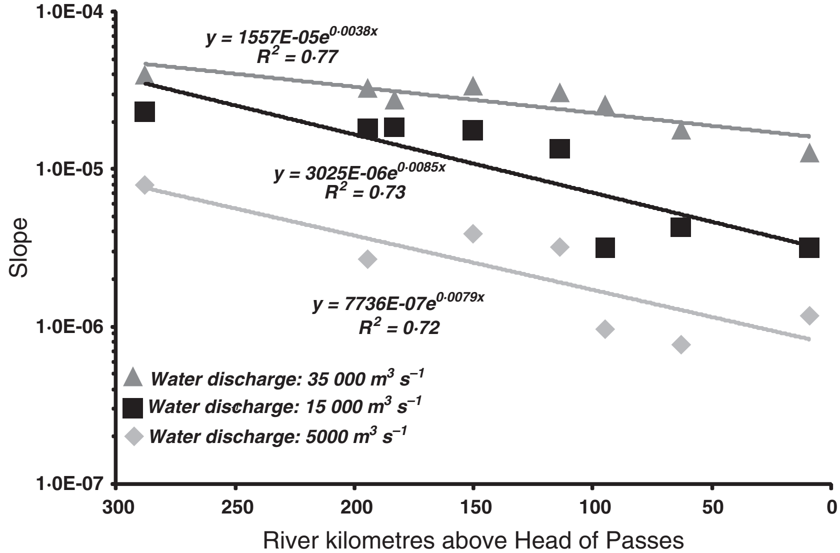

Fig. 3. Water-surface slopes for the lower 300 kilometres of the Mississippi River. Data are shown for three water-discharge conditions: (i) high water (35 000 m^3 sec^{-1}); (ii) moderate water (15 000 m^3 sec^{-1}); and (iii) low water (5000 m^3 sec^{-1}). Slopes are calculated by applying a box-car averaging technique to water-elevation data collected at gauging stations within the lower 300 km of the Mississippi River (data are provided by the USACE; see text for details).

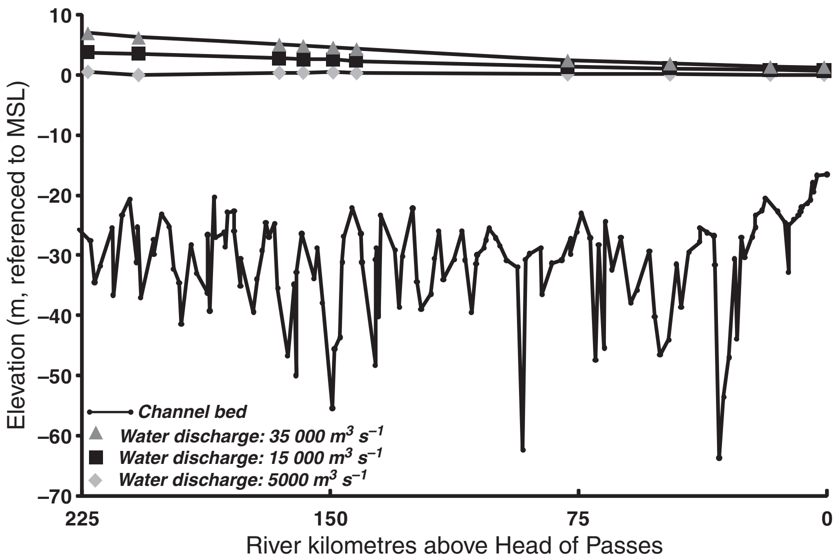

Fig. 4. Water-surface elevations in the lowermost Mississippi River for three water-discharge conditions: (i) high water (35 000 m^3 sec^{-1}); (ii) moderate water (15 000 m^3 sec^{-1}); and (iii) low water (5000 m^3 sec^{-1}). Each point represents a gauge location (data from the USACE; see text for details); data are plotted to river kilometres above Head of Passes. Also shown are channel-thalweg elevation data (Harmar & Clifford, 2007). Thalweg depths are determined by calculating the difference between channel-thalweg elevation and water-surface elevation; these values range between 20 and 65 m depth, shallowing near the approach to Head of Passes.

covered the portion of the river from RK 165 to RK 130 (Fig. 2B). A second, longer survey occurred during 2003 and measured from RK 130 to RK 0 (water discharge: 8300 to 9000 m^3 sec^{-1}; Fig. 2C).

The primary data set used to determine the composition of the channel bed was collected using a pole-mounted Reson Seabat™ 8101 swath-bathymetry profiler (101 transducers, vertical resolution of 0·015 m; Reson, Slangerup, Denmark) and a side-scan projector. Simultaneous to the collection of the multibeam data, high-resolution sub-bottom seismic data were acquired using an Edgetech CHIRP (Edgetech, West Wareham, MA, USA) 216 towfish (2 to 16 kHz). Core and grab samples were recovered periodically from the channel bed during the surveys and corroborated interpretations of the bathymetry and seismic data (>200 sediment samples; Allison & Meselhe, 2010). These physical data were used to construct an accurate

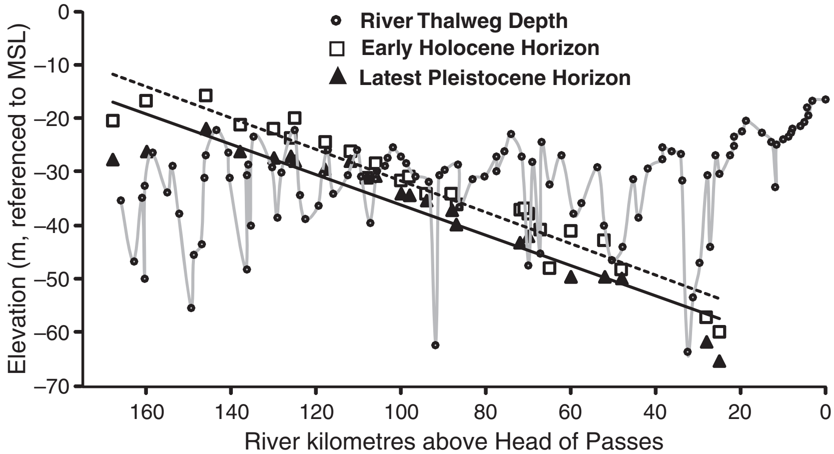

Fig. 5. Downstream distance above Head of Passes and elevation of the Pleistocene (hollow squares) and Holocene (filled triangles) sedimentary horizons (data from Stanley *et al.*, 1996). The Mississippi River thalweg entrenches into Holocene and Pleistocene sediments between RK 165 and Head of Passes (open circles; data from Harmar & Clifford, 2007). Although Holocene sediments thicken progressively toward the Gulf of Mexico, the river channel occasionally scours into Pleistocene sediments as far downstream as RK 35.

assessment of channel-bed sediment composition, particularly as evaluated from the multibeam bathymetry.

Survey methods varied between the two field campaigns: during the initial survey, multibeam data were collected by running a series of overlapping, bank-parallel lines up and down the river that completely covered the channel bed (bank to bank; Fig. 2). During the second survey, acoustic data were collected along a 190 km long single-line swath that zig-zagged upriver (Fig. 2B). The data collection line was oriented 45° to either bankline; when a bankline was intercepted, the boat turned 90° and proceeded to the opposing bankline. The purpose of this pattern was to optimize coverage for all sediment states of the channel bed while reducing the time required for data collection. The full-channel multibeam survey preceded the zigzag survey, so it was possible to confirm that there was no coverage bias by using the zigzag pattern versus complete channel coverage.

Multibeam measurements were collected with a gyroscope inertial guidance system (Applanix Inc., Ontario, Canada) mounted inside the vessel hull. Position, heading and velocity data were acquired using dual antenna differential GPS and these data were integrated with measurements for ship attitude and heave, pitch and roll using Reson 6042 software; both position and attitude data were collected at 1 msec intervals and tagged to the bathymetry measurements (spatial error <1 m; Nittrouer *et al.*, 2008; Galler & Allison, 2008). Raw files were converted to XTF format and imported into CARIS HIPS 6·0 software for post-survey processing, which included: (i) removal of multiples; (ii) correction for sound velocity in water; (iii) correction for water-surface elevation by accounting for both river stage and tidal phase (hourly gauge data from the Carrollton and Venice USACE stage monitoring stations); and (iv) integration with motion sensor and navigation information. Channel bathymetry data were then gridded using a 1 m^2 cell size and exported to ArcView 9·2, where a raster grid was constructed using an inverse-distance-weighting-interpolation function.

RESULTS

River-bed facies

River-bed sediment composition for the lowermost Mississippi River initially was determined from the combination of high-resolution surface-topography data (provided by the multibeam, sidescan and CHIRP systems) and sediment core and grab samples. After assimilation and cross-comparison of the data sets, the multibeam data imagery proved to be the primary tool for interpreting river-bed sediment composition. Five unique river-bed sediment facies were identified (Fig. 6), based on river floor morphology, for the section of river from RK 165 to where the system begins to shallow at RK 35 (Figs 4 and 5). Three of the facies are modern alluvial deposits: (i) actively migrating sandy dune field ('alluvial sand');

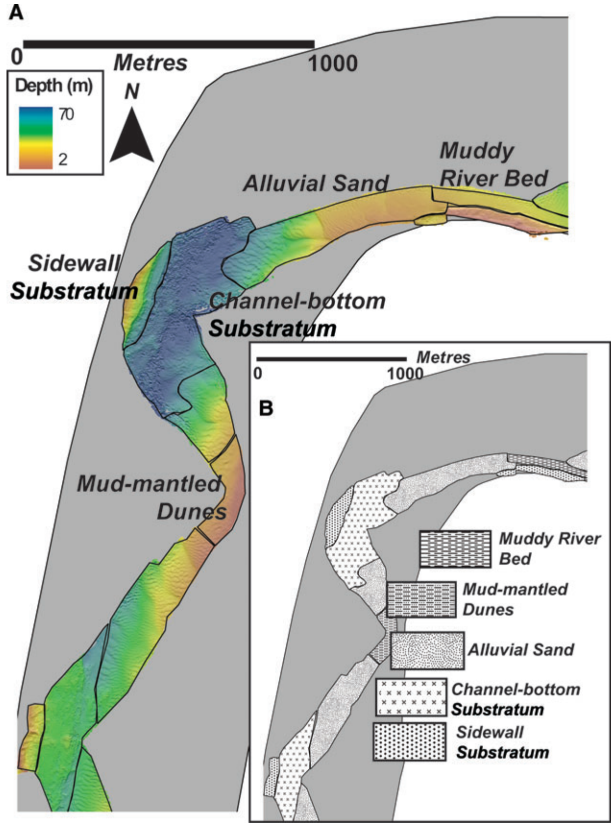

Fig. 6. (A) Sample of Mississippi River channel-bed sediment facies from a swath zigzag line, near RK 120; the channel is delineated by the grey backdrop. Alluvial sediments include alluvial sand (active mobile dune fields, 15 to 35 m water depth), mud-mantled dunes (stagnated dunes, <20 m water depth) and muddy river bed (<15 m water depth). 'Channel-bottom substratum' (>35 m water depth) and 'sidewall substratum' comprise Pleistocene and Holocene fluvio-deltaic sediments. (B) Sample of Mississippi River channel-bed-facies polygons, constructed using ArcGIS software. This processing method provides the area for each polygon and associated sediment facies.

(ii) 'mud-mantled dunes' that is a site of mud deposition during low-water and moderate-water discharge; and (iii) shallow-water 'muddy river bed'. Two sediment facies underlay alluvial sediments and are immobile unless eroded: 'sidewall substratum' and 'channel-bottom substratum'. The five sediment facies are described below.

Alluvial sand

'Alluvial sand' is defined as the portion of river channel bed comprising bedform trains (Nittrouer *et al.*, 2008). These dune fields are easily distinguished using multibeam bathymetry data and interpretation is confirmed by the high-intensity sidescan and CHIRP returns, plus grab and core samples. Dunes cover bar forms and commonly extend across the entire river bed, where the thalweg crosses from one side of the channel to the other. 'Alluvial sand' is typically found in water depths of 15 to 35 m. During low-water and moderate-water discharge, the sand dunes migrate downstream at rates of 1 to 10 m day^{-1}, whereas during high discharge, migration rates are 1 to 10 m h^{-1} (Nittrouer *et al.*, 2008). The CHIRP seismic system was not able to penetrate past the top few decimetres of the 'alluvial sand' fields and so internal bedding structure and sand-sheet thickness are not resolvable. Mean grain size for the active dune fields varies downstream from 250 μm at RK 160 to 175 μm at RK 0 (see fig. 7 from Allison & Meselhe, 2010).

Mud-mantled dunes

'Alluvial sand' fields transition to 'mud-mantled dunes' near the channel bank lines. Repeated multibeam surveys show no movement of 'mud-mantled dunes' over 24 to 72 h and it is inferred that the bed features are immobile during low-water discharge conditions. Relative to the active 'alluvial sand' fields, the topography of 'mud-mantled dunes' is subdued due to the deposition of acoustically transparent mud in the bedform troughs. CHIRP seismics resolve the preferential filling of sandy dune troughs by mud (Galler & Allison, 2008). 'Mud-mantled dunes' are common in water depths less than 20 m and frequently are positioned near the inner bank of river bends. Observations show that this portion of the channel bed becomes part of the active 'alluvial sand' field during high-water discharge.

Muddy river bed

'Mud-mantled dunes' transition to shallow-water 'muddy river bed' near the river banklines along the interior of bend segments, where water depths are <15 m. These deposits have been studied by Galler (2004), who used radioisotopes to demonstrate ephemeral deposition during low-water and moderate-water discharge and subsequent remobilization during high-water discharge. 'Muddy river bed' deposits are usually topographically featureless but occasionally scours develop during high-water discharge, when muds are eroded from shallow-water near-bank settings. Low-intensity CHIRP seismic returns indicate no underlying sand waves and grab and core samples lack significant sand interbeds. This sediment facies maintains its fine-grained composition during high-water discharge, distinguishing it from 'mud-mantled dunes' that transition to active dune fields during such discharge conditions.

Sidewall substratum

Steep-sloping sidewall substratum develops where the river thalweg is positioned along the outer bank of bend reaches and a well-consolidated substratum is exposed (Stanley *et al.*, 1996). The channel 'sidewall substratum' ranges in water depth from just below the water surface (*ca* 5 m depth) to the channel bed (30 to 60 m water depth; Fig. 6). 'Sidewall substratum' often is terraced due to erosion, probably as a result of spatially heterogeneous fluvio-deltaic sedimentary deposits that have variable resistance to erosion (Fig. 7). 'Sidewall substratum' terraces are not traceable reach to reach (>10 km) and it is not possible to demonstrate exposure of a continuous resistive sedimentary body. 'Sidewall substratum' morphology also suggests active mass wasting; gullies scour the sidewall from near the water surface to the channel bed in a manner similar to eroding hill slopes. Sidewall slopes range between 0·15 and 0·45 m m^{-1} from the water line to the channel bed (Fig. 7). The age of 'sidewall substratum' sediments are assessed based on data from Stanley *et al.* (1996); the Pleistocene–Holocene sediment transition intersects the Mississippi River channel bed near RK 85, indicating that 'sidewall substratum' sediments consist of a mixture of Pleistocene and Holocene sediments upstream of this location and are predominantly Holocene in age between RK 85 and RK 0, the exception being in segments where the river scours to Pleistocene sediments (Fig. 5).

Channel-bottom substratum

Exposed 'channel-bottom substratum' occurs where the river thalweg is positioned along the outer bankline of bend segments. There was difficulty in sampling the 'channel-bottom sub-

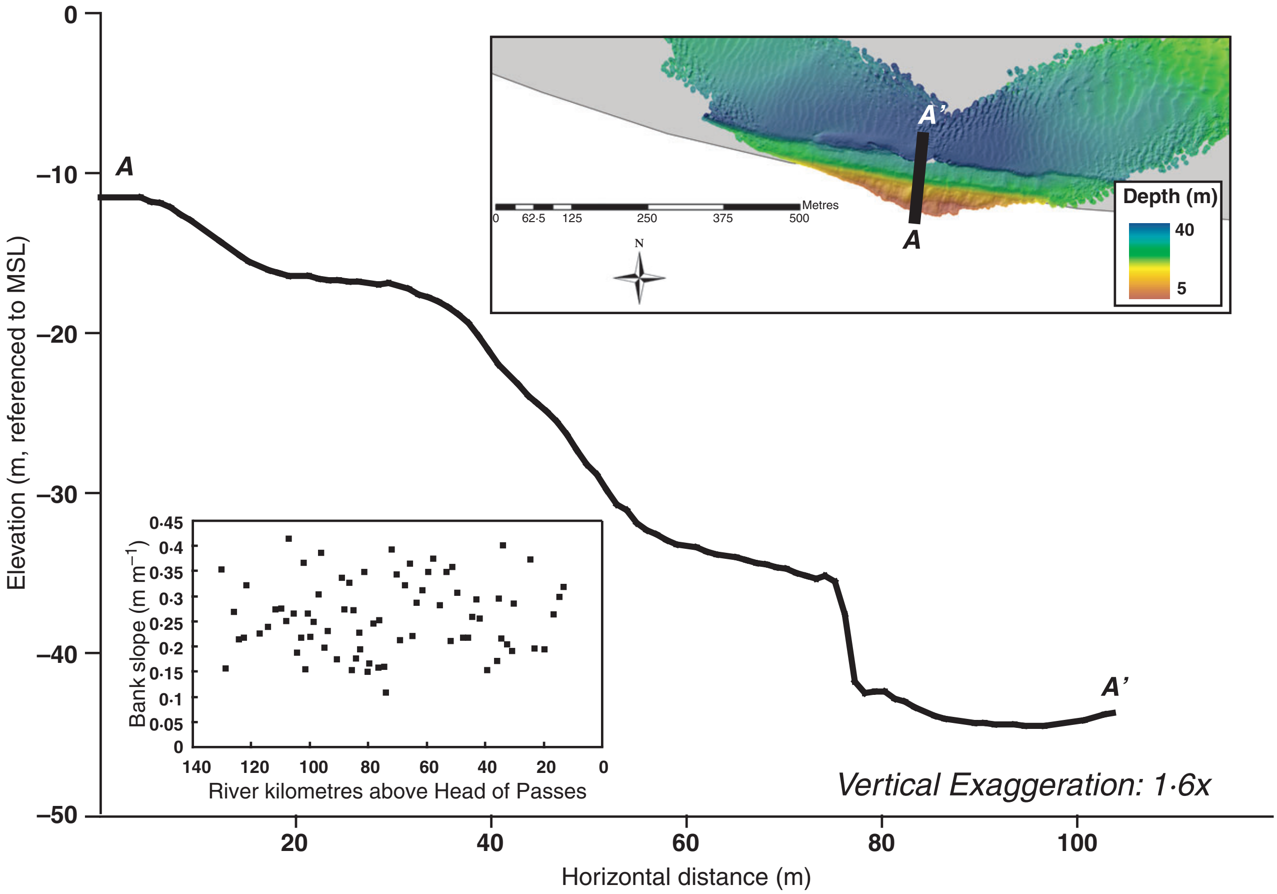

Fig. 7. Multibeam map and a profile of 'channel sidewall substratum' (A–A'); profile demonstrates terracing of 'sidewall substratum'. 'Sidewall substratum' is common along the exterior banks of bend reaches and along the interior of tight-bend reaches in the lowermost Mississippi River. Inset plot shows measured slope of channel sidewall substratum slopes, progressing downstream from RK 140 to RK 20 (kilometres above Head of Passes).

stratum' exposed in the Mississippi River. Gravity cores only penetrate *ca* 50 cm, owing to the consolidated nature of the palaeo-sediments. The recovered sediment is a mixture of consolidated and stratified muds with some organics (for example, peats) and trace amounts of sand (e.g. Galler *et al.*, 2003). Grab samples recovered small amounts of consolidated bed material composed of mud and peat, and a mixture of loose detritus that includes shell hash, wood fragments and some coarse sand. CHIRP records detect no stratification within the 'channel-bottom substratum'. Dating of organics present in the bottom substratum yields ^{14}C ages from Late Pleistocene to Early Holocene (Galler, 2004), as is expected based on data from deep, near-channel sediment cores reported by Stanley *et al.* (1996). Occasionally 'channel-bottom substratum' is exposed at relatively shallow water depths. A good example of this feature is at the English Turn bend (Fig. 8), where a platform at *ca* 22 m water depth is found >7 m above the active dune field for a distance of 1·5 km in the downstream direction.

The surface morphology of the 'channel-bottom substratum' is sometimes smooth, due to the absence of sand waves. However, there are a number of areas that contain a mixture of flute and scour erosional marks (Fig. 9). Measured flute size in the Mississippi River 'channel-bottom substratum' range from 8 to 55 m in length, 5 to 30 m in width and up to several metres in amplitude (Figs 9 and 10). The geometry of the flutes compare favourably with other bedrock flutes observed in the field and with flutes generated in laboratory flume experiments (Allen, 1971; Richardson & Carling, 2005). Allen (1971) subjected a plaster of Paris compound to water flow to mimic bedrock erosion. The experiments by Allen (1971) generated flutes with length to width and amplitude to width ratios that are quite similar to measurements made of flutes on the 'channel-bottom substratum' of the Mississippi

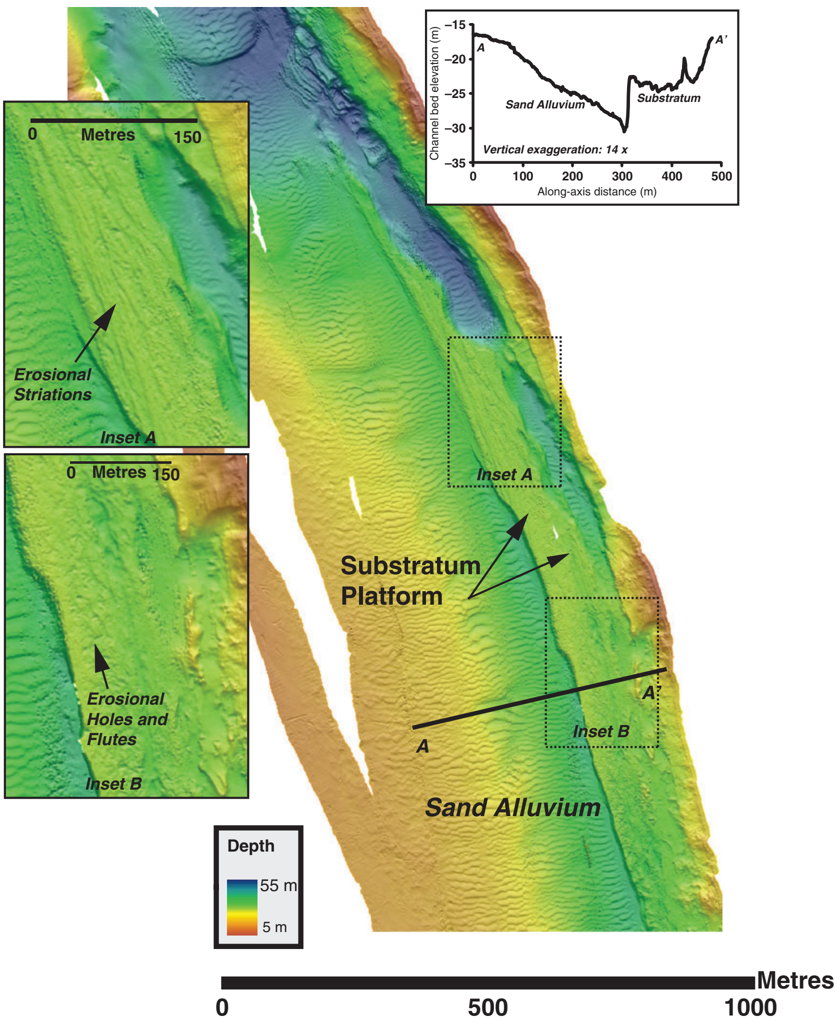

Fig. 8. Lower English Turn 'channel-bottom substratum' (RK 135). Exposed 'channel-bottom substratum' is often found in deep pools, but here the exposed bench is perched *ca* 7 m above the alluviated channel bed. This portion of substratum is exposed downstream for 1.5 km. Note the two inset images, highlighting erosional forms found in the substratum such as striations, holes and flutes.

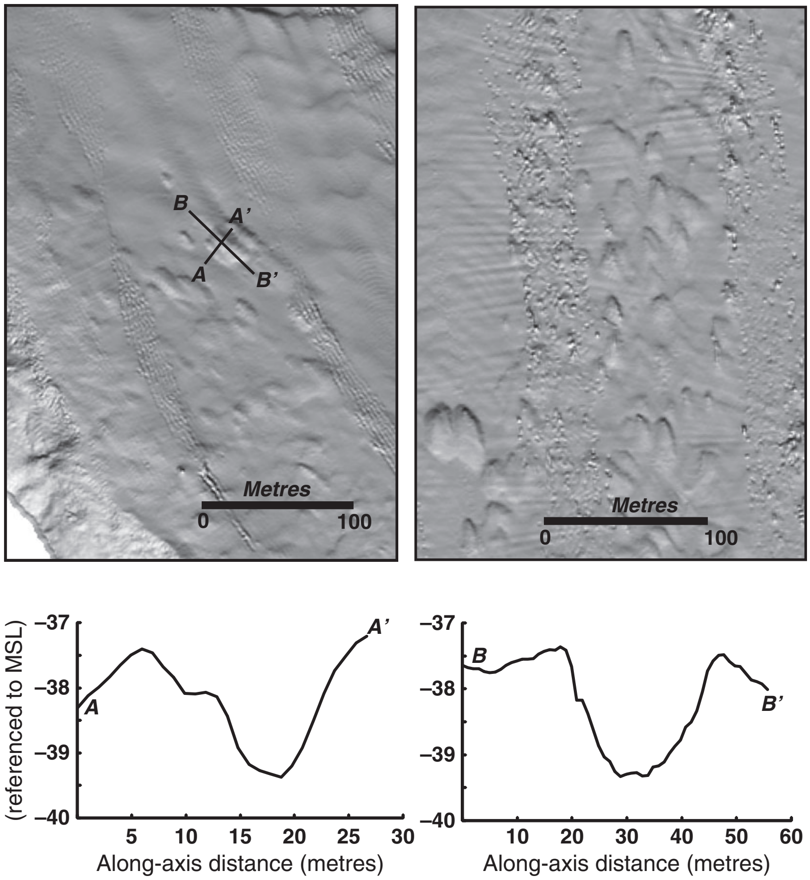

Fig. 9. Multibeam images of erosional flutes developed in the 'channel-bottom substratum'. Left-side image is from Audubon Park bend (RK 160); water depth for this image ranges from 35 to 55 m. Right-side image is from near RK 50; water depth for this image ranges from 35 to 40 m (the stippled pattern in the image arises as a result of errors in data stitching). These flutes mimic bedrock flutes described by Richardson & Carling (2005) and have a very similar aspect to flutes measured from bedrock flume experiments by Allen (1971).

River (Fig. 10). In addition to flutes, striations (Fig. 8, inset A) and much larger erosional scours are found in the 'channel-bottom substratum' (Figs 11 and 12). Unlike the measured flutes, scours do not have a characteristic geometric form; however, scours tend to be oriented with the direction of river flow (typical size: hundreds of metres in length, tens of metres in width and 1 to 10 m in depth). The presence of flutes and deep erosional scours implies active incision of the 'channel-bottom substratum'. In light of a study by Galler *et al.* (2003) that described channel deepening of the lower 250 km of the Mississippi River over the past century, it should not be surprising that portions of the channel bed display erosional marks.

The 'channel-bottom' and 'sidewall substratum' contain much of the area of the Mississippi River surveyed in this study; the thickness of the unconsolidated surface sediments associated with modern Balize lobe deposition is relatively small compared with the overall depth of incision for the river channel (*ca* 1300 years deposition; Frazier, 1967). For example, the Balize delta lobe complex is generally 1 to 10 m (Roberts, 1997); therefore, the consolidated Holocene and Pleistocene sediments that comprise the substratum facies present in the channel are considerably older and not related to deposition associated with the modern lobe.

Distribution of river-bed sediment facies and channel planform

The spatial extent and distributions of the river-bed sediment facies were analysed using GIS software. Polygon shape files were used to segregate the multibeam bathymetric data into a series of sub-raster grids that outlined sediment facies. Classification began upstream and moved downstream and every facies transition was identified and used to set the polygon boundaries (Fig. 6B). The footprint of local facies is often several hundreds of metres in the downstream length and many tens of metres in cross-stream width. Each polygon file was assigned a characteristic river position, based on the distance of the polygon centre above HOP.

There are noticeable relationships between the distributions of sediment facies and the planform

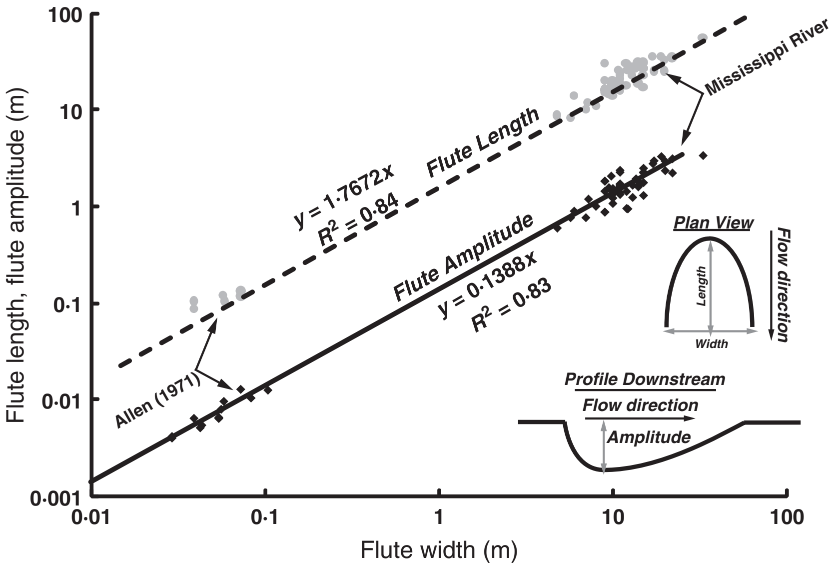

Fig. 10. (A) Comparison of length and amplitude versus width of erosional flutes created experimentally (Allen, 1971; lower data clusters) and measured erosional flutes on 'channel-bottom substratum' of the lowermost Mississippi River (upper data clusters). Regression lines represent uniform length to width and amplitude to width ratios for data collected by Allen and the data collected from the Mississippi River; equations of the regression lines demonstrate that flutes have lengths that are generally 1.77 × width and amplitudes that are 0.14 × width. Cartoons show the measured geometries of the flutes (after Allen, 1971).

of the Mississippi River channel. For example, 'sidewall substratum' occurs where the channel thalweg is positioned along the outer bankline in river bends. Steeply sloping and erosionally terraced 'sidewall substratum' extends from the water surface to the channel bed, transitioning to 'channel-bottom substratum'. Some bends contain 'channel-bottom substratum' that extends across the width of the channel before intersecting an inner-bank sidewall (Fig. 11). Alternatively, some bends have 'channel-bottom substratum' that transitions to subaqueous 'alluvial sand' fields and water depths decrease, progressing across the channel toward the inner bend (Fig. 12). In this case, 'channel-bottom substratum' gives way to 'alluvial sand' as indicated by the presence of active dune forms. With progression toward the inner bank and decreasing water depth, 'alluvial sand' transitions to 'mud-mantled dunes' and/or 'muddy river bed'. Where the thalweg crosses the channel, frequently between opposing bends, 'alluvial sand' covers the channel bank to bank (Fig. 13).

To further evaluate a relationship between river planform and bed sediment composition, the radius of curvature, RC, was measured for the river-channel centreline between RK 165 and RK 0. The channel centreline is evaluated for the Mississippi River from RK 165 to RK 0 by digitally mapping points along the centreline; each point is spaced *ca* 240 m apart and so a total of 710 points trace the centreline. Minor deviations between neighbouring points that arise during the digitization process were removed using a moving-average Dolph-Chebyshev function with a window length of 41 points, downsizing the window at the upstream and downstream boundaries (i.e. approaching RK 165 and RK 0). The filtering window of 41 points is sufficient to match the centreline of the river in all portions of the river except in tight bends, where the filtered points deviate from the actual channel centreline by short-cutting the river bend. In these bends, the filtering window is reduced to 21 points to sufficiently approximate the channel centreline. The X and Y coordinates for filtered points are used to determine the radius of curvature (RC) for each pair of neighbouring points. Writing y as a function of x $(x, y(x))$:

$$\mathrm{RC}(x, y(x)) = \frac{\left[1 + \left(\frac{\partial y}{\partial \mathrm{x}}\right)^2\right]^{\frac{3}{2}}}{\frac{\partial^2 y}{\partial x^2}} \qquad (1)$$

Inflections in the channel planform occur where RC values interchange between positive and negative values. Associated with inflections

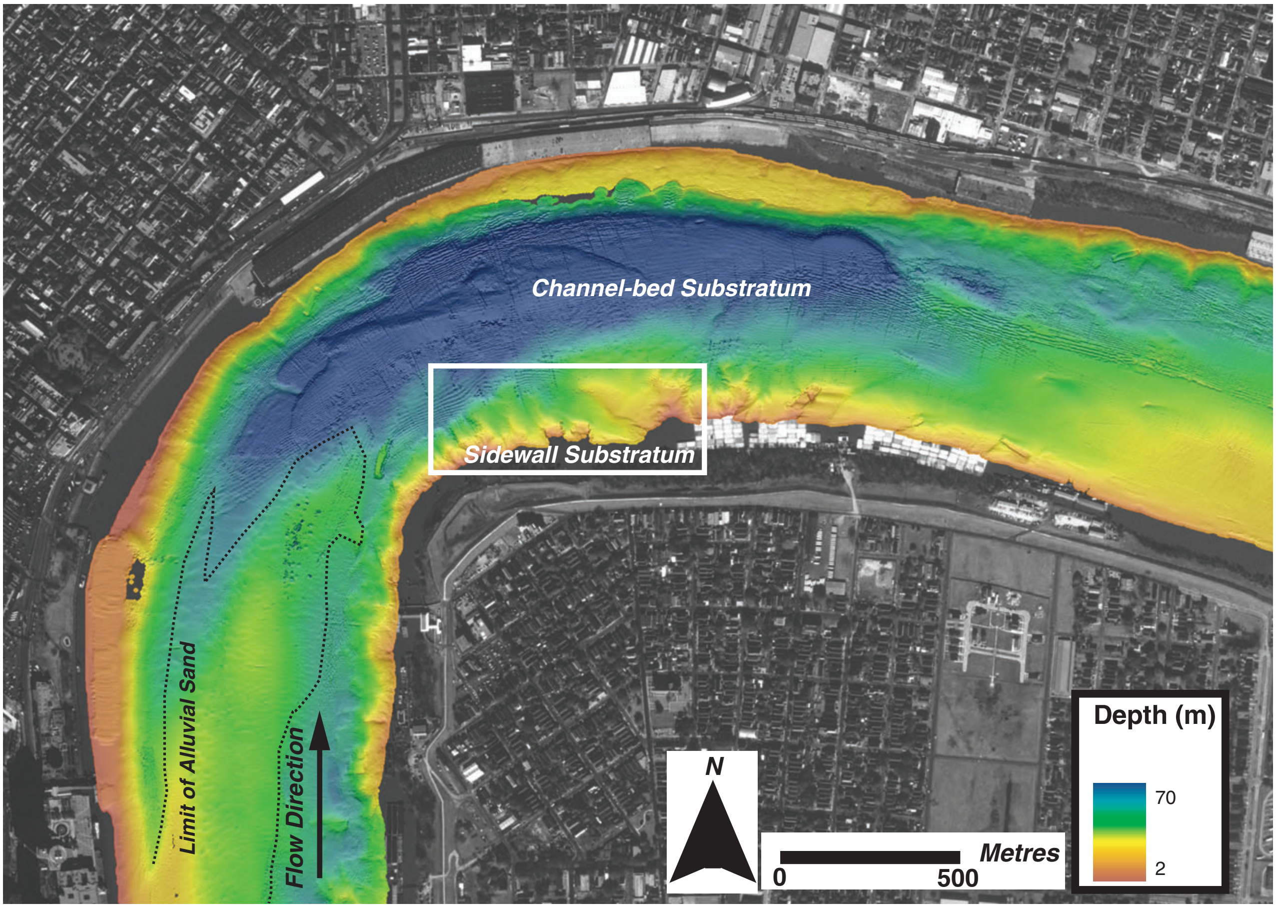

Fig. 11. Multibeam bathymetry data showing the character for a tight bend (French Quarter bend, RK 150, see Fig. 2C for location). 'Channel-bottom substratum' is contained between eroding 'sidewall substratum', composed entirely of Pleistocene and Holocene sediments. Alluvial sediment disappears from the channel bed preceding the bend (the limit of alluvial sand is shown by a dashed line). The erosional features on the 'sidewall substratum' mimic the morphology of eroding hill slopes in terrestrial environments.

is a straightening of the channel planform and an increase in the RC. To interpret the data continuously downstream, the absolute RC value is calculated for each pair of neighbouring points (RC $n = 709$). The data are divided by the median channel width of the lowermost 165 river kilometres of the Mississippi River (859 m) and are plotted to respective distance above HOP (Fig. 14). The range of width-normalized RC_b values ranges four-orders of magnitude, from <1 to >1000.

DISCUSSION

River bed composition and channel radius of curvature

Here, it is established that the changing planform in the lowermost Mississippi River, depicted by variable RC_b values, coincides with local distribution of channel sediment facies. 'Channel-bottom substratum' is consistently observed in bend segments and, to further elucidate this trend, bends with 'channel-bottom substratum' exposed bank to bank (Fig. 11) are separated from bends that display a mixture of 'channel-bottom substratum' and 'alluvial sand' (i.e. partial-substratum bends; Fig. 12). Bends composed entirely of 'channel-bottom substratum' have RC_b values <2·57 (Fig. 14, square label), and partial-substratum bends have RC_b values of 2·57 to 17·38 (Fig. 14; triangle label). The former are defined as 'tight-bend segments', and the latter as 'subtle-bend segments'. Where the river straightens, typically between opposing bend segments, RC_b values are >100, and alluvial sediment facies cover nearly the entire channel bed bank to bank (Figs 13 and 14, circle label). Local water depth also varies as a function of RC_b and, therefore, bed

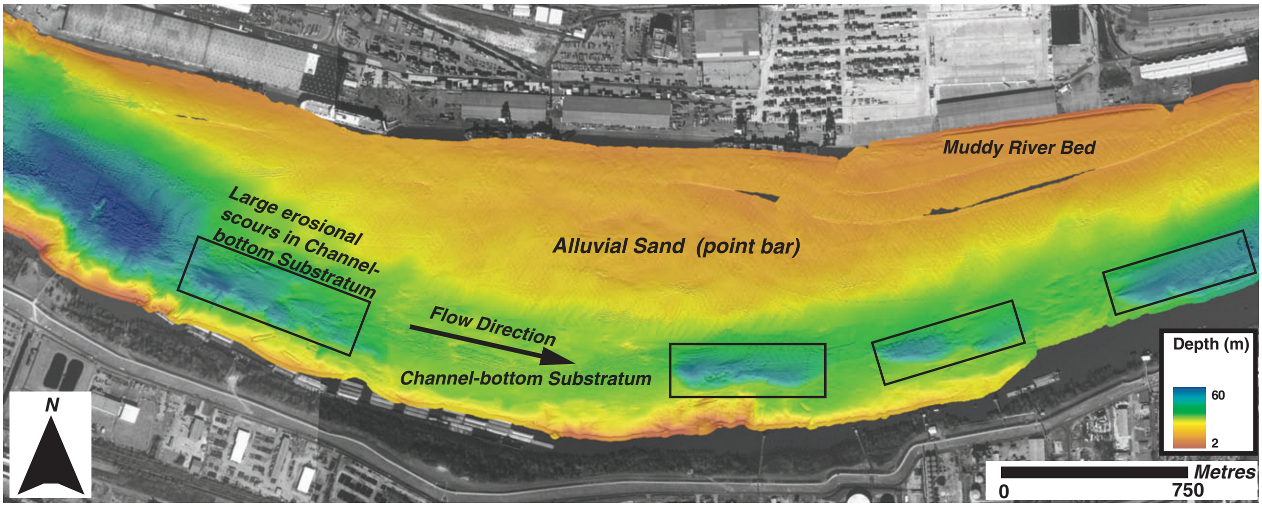

Fig. 12. Multibeam bathymetry data showing river-bed character of a subtle bend (RK 155; see Fig. 2C for location). The thalweg is positioned along the outer bank due to the river bend. Substratum is exposed along the outer sidewall and on the channel bed under the thalweg. The boxed areas in the thalweg depict large erosional features on the 'channel-bottom substratum' that are larger than measured flutes. Bathymetry shallows across-channel toward the inner bank; alluvial bedforms grow on the flanks of the subaqueous bar in water depths <35 m. Eventually, dunes transition to muddy sediments nearest the inner bank (<15 m water depth).

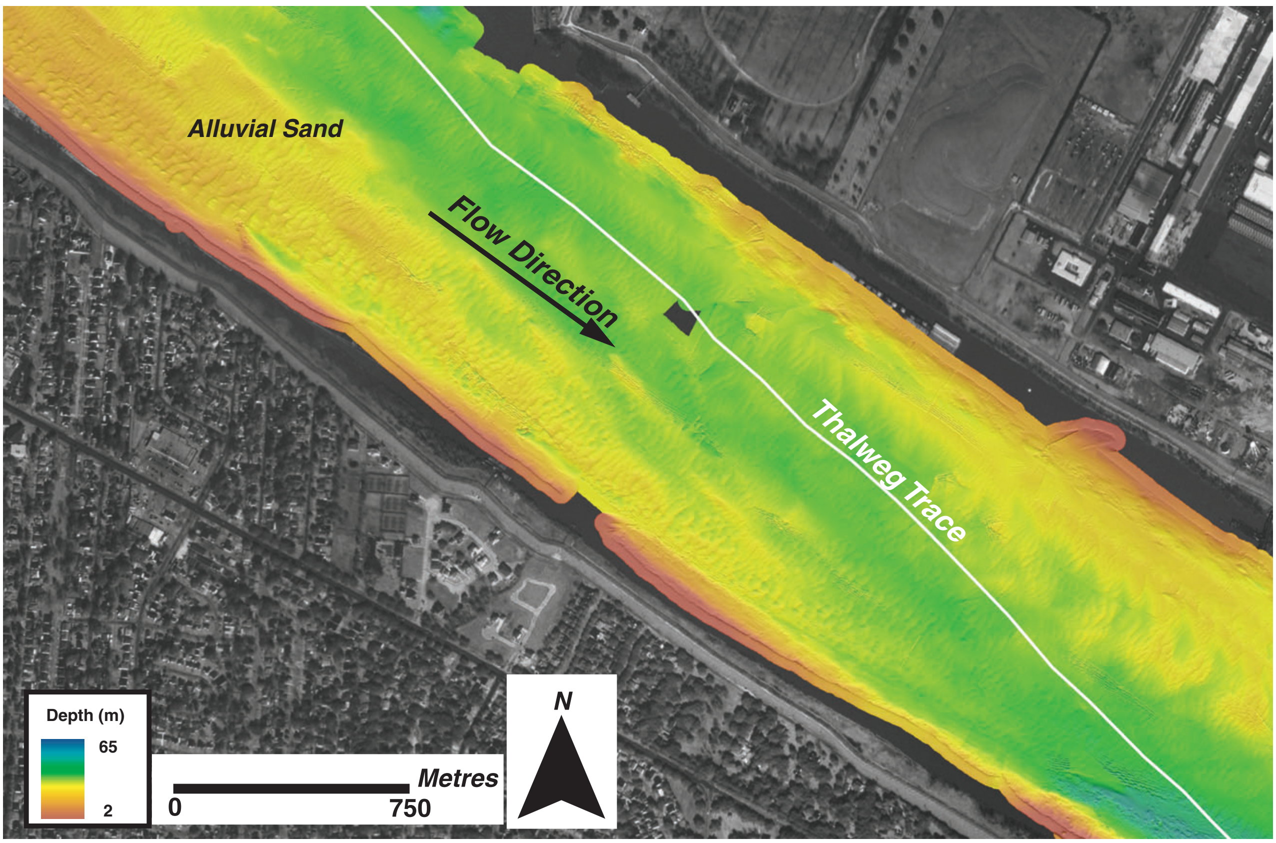

Fig. 13. Multibeam bathymetry data showing river-bed character for a thalweg crossing (RK 150 see Fig. 2C for location). The thalweg (traced by the white line) crosses the channel from bank to bank between two opposing bends. Alluvial sand cover and dunes are distributed across the channel bed and there is little exposure of 'channel-bottom substratum' or 'sidewall substratum'.

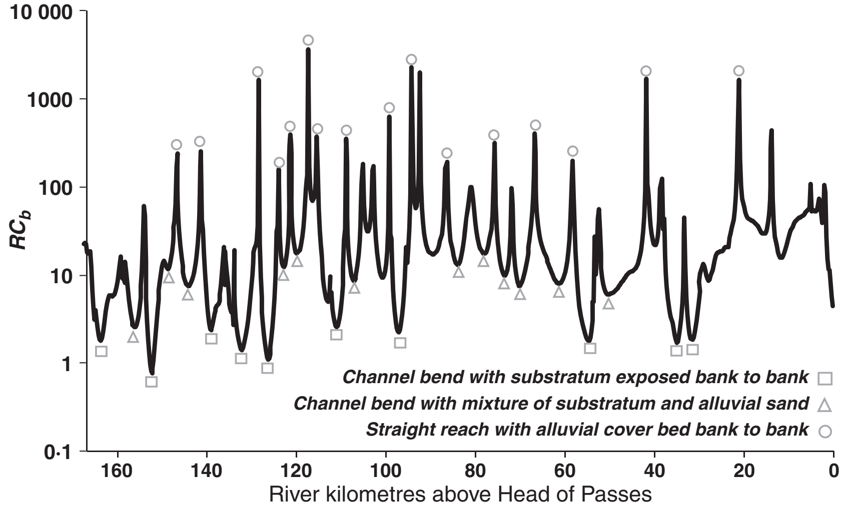

Fig. 14. Radius of curvature divided by median channel width (RC_b) for the lower 165 km of the Mississippi River (referenced to distance above the outlet at Head of Passes). Tight bends containing 'channel-bottom substratum' and lacking alluvial cover are labelled with squares; subtle bends with a mixture of 'channel-bottom substratum' and alluvial-sediment facies are labelled with triangles; straight-reach segments with sandy alluvium bank to bank are labelled with circles. Based on these data, it is surmised that bends with a RC_b <2.57 comprise only 'channel-bottom substratum' and bends with a RC_b value between 2.57 and 17.38 contain a mixture of 'channel-bottom substratum' and alluvial-sediment facies. These data demonstrate that sediment composition of the channel bed is related to local planform.

sediment composition circumstantially is related to water depth (Fig. 15). Straight segments of the river are relatively shallow and, in bend segments, depth deepens with reducing RC_b. The presence of erosional marks in the 'channel-bottom substratum' implies active deepening of channel bends.

The relationships depicted in Figs 14 and 15 demonstrate that RC_b is a useful predictor for both channel sediment facies and water depth for a given reach in the lowermost Mississippi River. However, these relationships are confined to local reaches (<10 km) and to demonstrate how the proportions of facies change over broader scale in the survey, the river sinuosity and the relative distribution of channel sediments are considered. In the relatively sinuous portion of the survey (RK 165 to RK 120; sinuosity: 1·76), the percentage of non-alluviated channel bed (combining 'sidewall substratum' and 'channel-bottom substratum') equals 40% of the total area and 'alluvial sand' cover is 53% of the total area (Fig. 16). In the straighter segment of the survey (RK 120 to RK 0; sinuosity: 1·21), the non-alluviated channel bed

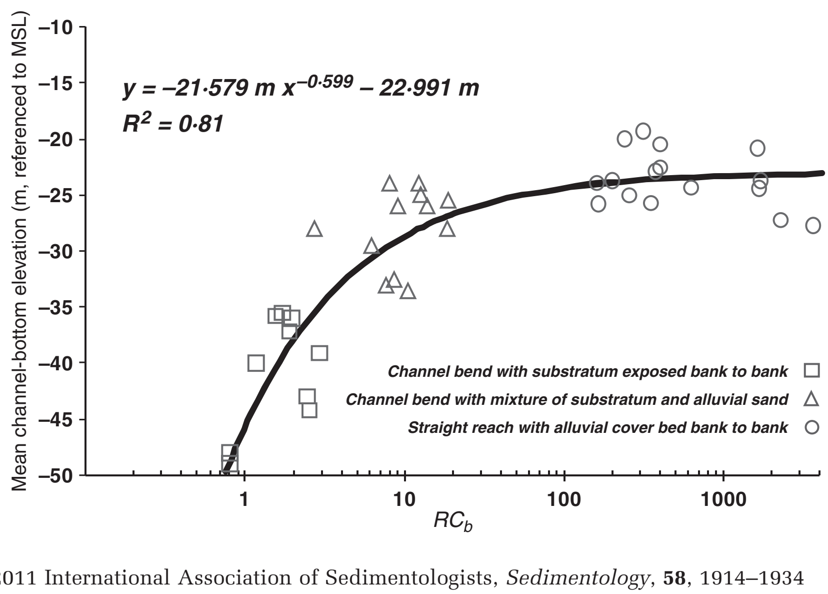

Fig. 15. Mean channel-bed elevation and radius of curvature divided by median channel width (RC_b) for the reaches labelled in Fig. 14. These data show that local water depth also varies as a function of RC_b and therefore bed sediment composition is circumstantially related to water depth. Straight segments of the river are relatively shallow. Within bend segments, depth deepens with reducing RC_b. The presence of erosional marks in the 'channel-bottom substratum' implies active deepening of channel bends.

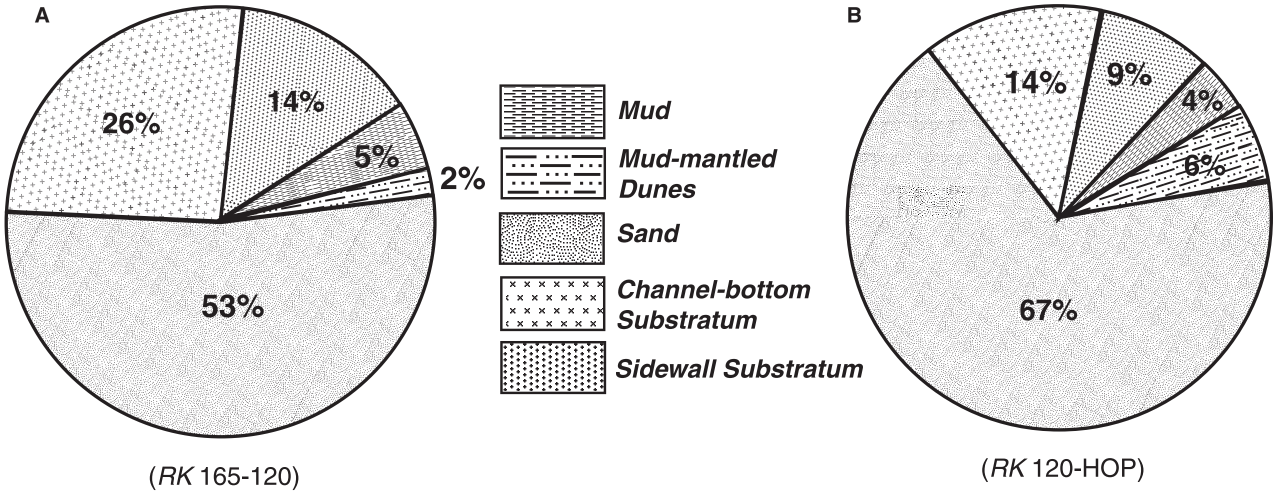

Fig. 16. (A) Percentage of sediment facies covering the channel bed between RK 165 and RK 120; and (B) percentage of sediment facies covering the channel bed between RK 120 and RK 0. Sinuosity for these two channel segments decreases from 1.76 to 1.21, demonstrating that straightening of the of river planform results in greater alluviation of the channel bed. Nevertheless, the ratio of combined 'channel-bottom' and 'sidewall substratum' to alluvial sediment qualifies the lowermost Mississippi River as a mixed bedrock-alluvial river (Howard, 1998; Turowski *et al.*, 2008).

drops to 23% and 'alluvial sand' cover increases to 67% of the total area (Fig. 16). Additionally, Fig. 17 illustrates the relative downstream distribution of sediment facies quantified over 10 km increments. The percentage of alluvial cover is relatively low between RK 165 and RK 90, where seven tight-bend segments are observed. 'Alluvial sand' dominates from RK 90 to RK 15, where the Mississippi River straightens before HOP, and where there are only three tight-bend segments. Below RK 15, 'alluvial sand' is replaced by 'mud-mantled dune' facies, probably because of estuarine circulation that results in flocculation and settling of fine-grained sediments to the channel bed during low-water and moderate-water discharge (Galler & Allison, 2008). These data demonstrate a relationship between channel-bed-sediment composition and river sinuosity at the multiple-reach scale.

Mixed bedrock-alluvial river

The lowermost Mississippi River is 20 to 35 m deep in thalweg crossings and up to 65 m deep in tight bends. In bend reaches, much of the channel is contained by 'sidewall substratum' with

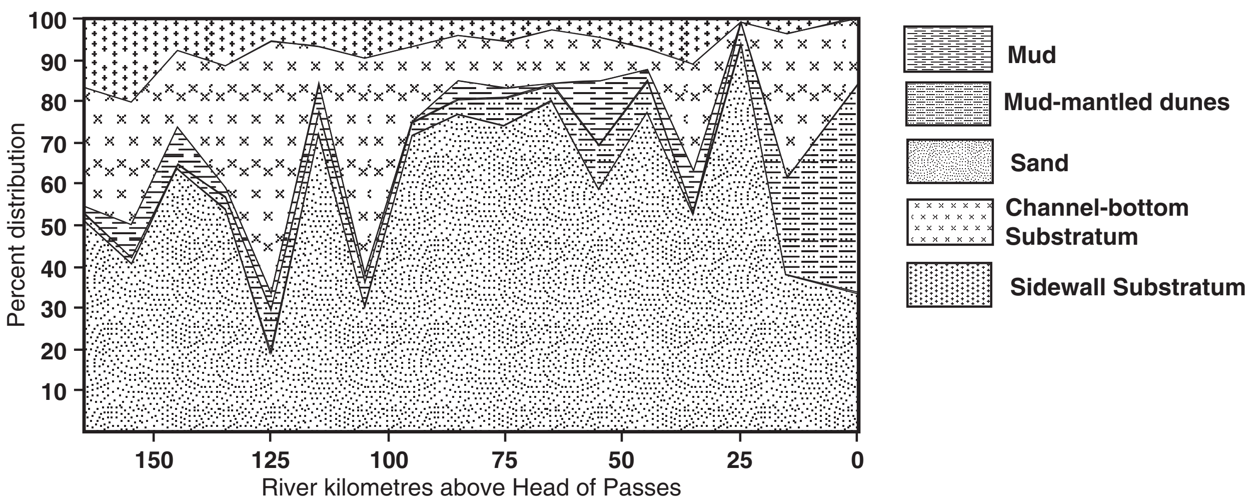

Fig. 17. Proportion of channel sediment facies for the lower 165 kilometres of the Mississippi River. The data are quantified over 10 km increments and show that the percentage of alluvial cover dwindles to as little as 30% between RK 165 and RK 90, where there are seven tight-bend segments. Sandy cover dominates from RK 90 to RK 15, where the Mississippi River straightens as it approaches HOP and there are only three tight-bend segments.

morphology indicating active mass wasting from near the water surface to the 'channel-bottom substratum'. With the exception of modern levées (the height of which are less than 6 m and represents 5 to 15% of the total flow depth) nearly the entirety of the wetted perimeter in sharp bends is represented by palaeo substratum. 'Channel-bottom substratum' displays distinctive erosional features that indicate active incision. Although the substratum is eroding where exposed along the channel sidewalls and on the bed, repeated surveys do not resolve a change in the incisional topography and, therefore, the contribution of these palaeo sediments is probably insignificant when compared with total alluvial sediment flux of the Mississippi River.

The thickness of modern alluvial bed sediments is not well-constrained. It is difficult to directly measure the interface between alluvial sediment and the underlying substratum, because the sand-rich alluvial cover effectively absorbs the acoustic signal emitted from the 216 CHIRP seismic instrument used in this study. However, bathymetry data and the distribution of 'alluvial sand' and 'channel-bottom substratum' can be used to infer a range of thicknesses for the alluvial sediments, where present on the channel bed. 'Alluvial sand' bars generally have a depth range of *ca* 15 to 35 m and 'channel-bottom substratum' generally is exposed in the thalweg, where water depths are >35 m. The average depth and location above HOP have been plotted for each 'channel-bottom substratum' and 'alluvial sand'-field polygon identified from the survey data; regression lines then were fitted to the data of both sediment facies (Fig. 18). The difference between the means of the two regression lines provides a characteristic depth difference between alluvial sediments and substratum and can be used to approximate the thickness of alluvial cover over the substratum for a given location; this value is 0 to 15 m, increasing slightly downstream from RK 130 to RK 35. The scatter in the data about the regression lines, however, shows that locally the depth differences between 'alluvial sand' and 'channel-bottom substratum', and therefore the alluvial sediment thickness, can vary from no cover to up to 25 m. These observations confirm those by Finkl *et al.* (2006), who report sand thickness ranging from 3 to 20 m based on vibracores collected from channel bars between RK 30 and RK 45. Based on the difference in local elevations of the 'alluvial sand' and 'channel-bottom substratum', the thickness of alluvial cover measures 0 to 30% of the thalweg depth.

'Alluvial sands' thin considerably near the transition with the channel bed substratum. Nittrouer *et al.* (2008) show bathymetry data for a sandy bar and the substratum transition in the Audubon Park bend (RK 160). During high-water discharge, the 'alluvial sand' on the channel bed at the downstream end of the bar is swept clean of sandy dune forms that are present during low-water and moderate-water discharge (see fig. 6 in Nittrouer *et al.*, 2008). Based on the difference in bathymetry between low-water and high-water discharge, it is estimated that *ca* 2 to 4 m of alluvial sediment is removed to expose the underlying 'channel-bottom substratum'. As a result, the area of the 'channel-bottom substratum' in the river bend is expanded during high-water discharge.

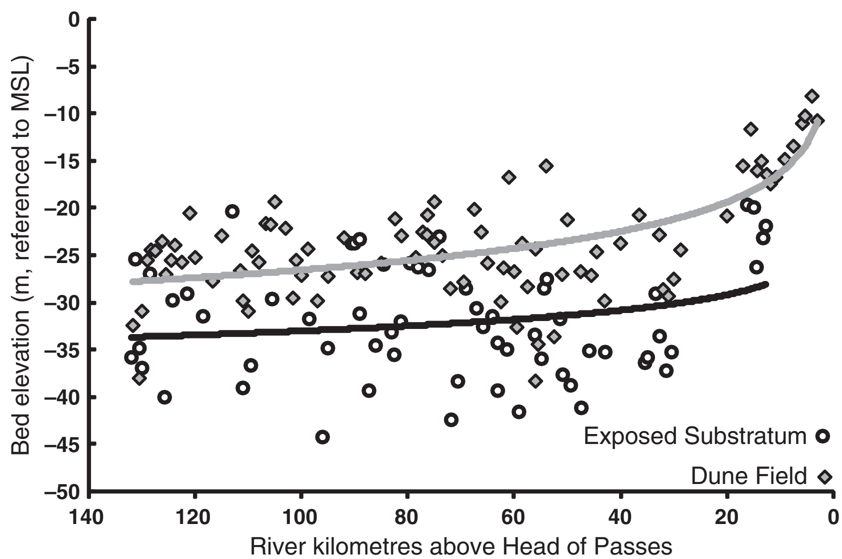

Fig. 18. Depth of local substratum and dune fields from RK 135 to RK 25. Regressions are fit to each of the data sets; the elevation difference between these two regressions, *ca* 7 to 12 m, represents the characteristic thickness for sand faces in the lowermost Mississippi River; however, this varies significantly reach to reach, from zero cover to as much as 25 m.

The observations depict a channel entrenched into and confined by a steep 'sidewall substratum'. The channel bed comprises a patchwork of discontinuous and relatively thin inner-bend alluvial bars intermixed with an exposed and eroding 'channel-bottom substratum'. Erosional features on the 'channel-bottom substratum' geometrically and qualitatively match erosional features produced in flume experiments and observed in bedrock channels (Allen, 1971; Richardson & Carling, 2005; Figs 9 and 10). Here it is proposed that the 'sidewall substratum' and 'channel-bottom substratum' behave as surrogate bedrock for the lowermost Mississippi River. Comparing the area of substratum to alluvium (Figs 16 and 17), between one-quarter and one-half of the channel comprises the bedrock substratum and, therefore, by standard definitions, the lowermost Mississippi River can be classified as a mixed bedrock-alluvial river (Howard, 1998; Turowski *et al.*, 2008).

The description of the lower Mississippi River is based on data collected for the lower 165 river kilometres, from New Orleans to HOP. However, it is probable that the mixed bedrock-alluvial character of the channel bed extends further upstream. A study conducted by Carey & Keller (1957) collected single beam bathymetry data from New Orleans to Baton Rouge (RK 160 to RK 365) during high-water and low-water discharge in April and July, 1956, respectively. The Carey and Keller data are spatially constrained by a navigation scheme that followed the approximate channel thalweg (the 'sailing line') as judged by an experienced river pilot. The findings are intriguing in light of the analyses presented in this study: within bend segments, Carey and Keller describe a channel bed devoid of dunes and 'anomalously smooth'. Fields of sandy bedforms were observed on the upstream and downstream ends of the bend segments, where the channel thalweg crosses the channel bank to bank. This behaviour is noted as far upstream as the extent of the survey, which ceased at Baton Rouge (RK 365). Based on these findings, which are similar to the present observations, it is hypothesized that the mixed bedrock-alluvial channel bed may persist at least as far upstream as Baton Rouge.

Uniqueness of the lowermost Mississippi River as a mixed bedrock-alluvial channel

The classification of the lowermost Mississippi River as a mixed bedrock-alluvial channel is surprising because continental-scale meandering fluvial systems are expected to have an alluvial sediment supply that is adequate to cover the bed, particularly in depositional settings near the river outlet (Fisk, 1961; Walker & Cant, 1984; Bridge, 2003). For example, the annual Mississippi River sediment flux is estimated to range between 87 and 210 Mt year^{-1} and roughly 5% of this is sandy sediment associated with the bedload flux (Meade, 1996; Horowitz, 2006; Nittrouer *et al.*, 2008). If this bedload sand flux was deposited evenly on the channel bed, the load would be sufficient to cover the lower 165 km of the Mississippi River with *ca* 2 to 5 cm of sand per year. The sediment flux of the river is not deficient of sand, yet the channel seemingly is deprived of the alluvial sediment necessary for full channel-bed coverage.

An alluvial river positively adjusts its planform elevation to changes in relative sea-level; this dynamic process arises via sediment-transport continuity and works to maintain both depth and water-surface-slope consistency, so that transport stress remains relatively constant in time and space (Whipple *et al.*, 1998). Therefore, to first order an equal-value response of either sediment aggradation or degradation is anticipated given a rise or fall in relative sea-level, respectively. Consider that the modern Mississippi River channel and its associated delta, the Balize lobe, have been active for the past 1300 years (Roberts, 1997) and that base level has been rising over this time period. Assuming that channel bed aggradation and relative sea-level rise are time-equilibrated and space-equilibrated, one value can be used to predict the other. For the present calculation, the relative sea-level rise is constrained by accounting for subsidence and eustasy. Here subsidence is considered as comprising both deep-seeded geophysical subsidence (0·3 mm year^{-1}; Straub *et al.*, 2009) and sediment compaction (0·3 to 1·3 mm year^{-1}, depending on the thickness of Holocene sediments; Meckel *et al.*, 2006). Accelerated subsidence measured during the 20th Century as a result of ground-fluid withdrawal is considered a transient anthropogenic effect and is ignored in this calculation (Morton *et al.*, 2005). Eustatic sea-level rise for the past millennia has remained relatively consistent at 1·8 mm year^{-1} (Church & White, 2006). Coupling rates for eustasy and subsidence, a base-level rise is predicted during the development of the Balize lobe of 3·1 to 4·7 m and, therefore, this should drive sediment deposition of nearly equal magnitude. Instead the observations indicate that the channel bed continues to erode despite a condition of continued relative sea-level rise.

It is argued that the incision of the lower 165 km of the Mississippi River is a natural occurrence and not the result of anthropogenic modifications to the river system. Artificial levées were installed following the catastrophic 1927 flooding, restricting movement of water and sediments to surrounding wetlands by overbank and crevasse-splay flooding. Although flow is now confined, the river stage within the lower 165 river kilometres varies by 0·5 to 5 m between low-water and flood-water discharge (Fig. 4). This change in stage represents only a small proportion of the average thalweg depth and, therefore, bankfull depths in the survey reach probably have not been significantly affected since the addition of human-engineered levées to the lowermost Mississippi River. Revetments and levées impede the river from moving laterally; however, channel migration prior to human modification was essentially negligible (<1 m year^{-1}) for the lower 300 river kilometres (Hudson & Kesel, 2000), probably because of the fact that most of the channel is incised 30 to 70 m in well-consolidated Holocene and Pleistocene fluvio-deltaic deposits.

The quasi-bedrock state of the lowermost Mississippi River is reflective of the long-term equilibrium condition of the channel bed and, therefore, not a consequence of reduced suspended-sediment load documented in the Mississippi River since the construction of dams and reservoirs (Meade & Moody, 2010). As evidence, similar observations for sporadic dune coverage presented by Carey & Keller (1957) can be cited; these data were collected in 1952, before the closure of reservoirs during the 1960s. Furthermore, sediment transport data from the lowermost Mississippi River indicate that the river is at transport capacity for all water discharge conditions (Nittrouer, 2010) and, as described above, the annual bedload flux of the system is sufficient to cover the lower 165 km of the channel bed with a deposit *ca* 2 to 5 cm year^{-1}.

Sediment transport in a mixed bedrock-alluvial channel and implications for substratum erosion

Alluvial bars are not free to migrate in the lowermost Mississippi River and instead are fixed by river planform. Such bars have been discussed by Whiting & Dietrich (1993), who explain that bar immobility results from enhanced sediment transport leading to the removal of sediment delivered at the downstream end of bars approaching river bends; Whiting & Dietrich (1993) relate the divergence in the sediment-transport field to centrifugal and pressure-gradient forces in the river bend. Tight bends in the lowermost Mississippi River lack alluvial cover and, therefore, it can be argued that sediment translating as a part of migrating dune forms on the preceding bar must transition to suspended-load transport to pass through these bends. Some portion of the suspended sand must deposit downstream of the tight bend to develop the subsequent sandy dune field. In subtle bends, a mixture of 'alluvial sand' and 'channel-bottom substratum' suggests that sediment translates as a part of both bedload and suspended load. It is concluded that the mode of alluvial sediment transport, particularly sands, is conditioned by the configuration of the channel planform.

Transverse erosional features are observed on the 'channel-bottom substratum' that resemble erosional features in bedrock fluvial systems (Richardson & Carling, 2005) and match the aspect ratios of flutes generated in flume experiments (Fig. 10 in this study, compared with Allen, 1971). Mechanisms for bedrock erosion in fluvial streams include: sediment abrasion, plucking, cavitation, dissolution, propagating knickpoints and debris flows (Allen, 1971; Seidl *et al.*, 1994; Hsu *et al.*, 2008). For the lowermost Mississippi River, however, the primary mechanisms driving substratum erosion are almost certainly fluid shear and abrasion by suspended bed materials (sands). Additionally, Allen (1971) noted that small defects in the channel bed can quickly grow in size through positive feedbacks with the fluid flow (i.e. vortex and roller stressing) and so it is possible that accelerated flow around embedded detritus in the channel bed (large woody debris, shipwrecks, etc.) and water-logged organic detritus abrading the bed may also be important erosion mechanisms. Using the present data, it is not possible to distinguish between erosional marks sculpted predominantly by fluid forcing or abrasion.

The 'channel-bottom substratum' is probably subjected to the highest rates of erosion during high-water discharge, when the area of 'channel-bottom substratum' expands and is exposed to high sediment flux and amplified fluid stress (100-fold increase in bedform sediment flux from low-water to high-water discharge; Nittrouer *et al.*, 2008). However, 'channel-bottom substratum' is prevalent at all times and so erosion may also arise during low-water and moderate-water discharge.

Flutes (Fig. 9) and the large, extensive scour marks imprinted on the 'channel-bottom substratum' (Fig. 12) probably evolve over many high-flow events, but because there is no evidence for growth during the time of observation for this study, a time frame cannot be determined for the development of erosional features of any size or form.

Previous research on bedrock erosion has focused on small mountain rivers (Sklar & Dietrich, 2004). To first order, physical erosion rate is set by the interplay between impacting erosional agents (saltating bedload) and the fraction of exposed substratum with respect to alluvial cover; this presumes that saltating bedload is the primary mechanism responsible for bedrock denudation. However, the present analysis for bed material transport in the lowermost Mississippi River depicts two-phase transport for bed materials, neither of which are conducive to isolating saltating sediments over a substratum. Sand saltation is probably robust in 'alluvial sand' fields; however, dunes imply a collection of alluvial material that is available to cover and protect the substratum from physical wear, thereby lessening substratum susceptibility to erosion. Alternatively, where the 'channel-bottom substratum' is exposed, in bend segments, it is predicted that the predominant mode of transport is suspended load, thereby excluding bed-material saltation as an agent for eroding the exposed 'channel-bottom substratum'. Application of a bedrock-erosion model developed for small mountain rivers is complicated in large, lowland sand-bed rivers. Further research is required to give consideration to orders-of-magnitude difference in system scales; for example: sediment flux, grain size, water discharge, depth, slope, transport capacity versus sediment supply and strength of bedrock.

Implications for coastal restoration projects

Coastal restoration projects seek to mine sandy sediment from the lowermost Mississippi River channel bed for barrier island restoration (Finkl *et al.*, 2006) and this study provides information for assessing spatial distribution and volume of sandy deposits. Namely, sands are predominantly found in subaqueous bar deposits fixed along the interior of subtle river bends. Channel depth and RC_b can be used to identify distribution of sand resources. Full-channel sand coverage occurs between opposing bends, where the channel straightens and the thalweg crosses from bank to bank. Sand transport occurs as a mixture between suspended-load and bedload and the distribution between the two modes is spatially conditioned by river planform.

Restoration projects that seek to distribute water and sediment to neighbouring wetlands propose utilizing controlled diversions. Consideration has been given the fact that this engineering would enhance local water slopes and bed stress, leading to channel-bed degradation that could imperil pipes and other infrastructure residing on the channel bed. The current observations and analyses demonstrate that any significant bed erosion via removal of alluvial sediment would impact only as far as the limit of the local sand bars. The prevalence of a relatively consolidated 'channel-bottom substratum' should stabilize channel-bed degradation.

CONCLUSIONS

Despite proximity to its outlet and marine and deltaic depositional settings, the lowermost Mississippi River channel bed is incompletely covered with alluvial sediment. Alluvial sediments are intermixed amongst channel-bottom substratum and sidewall substratum. The distribution of substratum and alluvial sediment cover on the channel bed is related to width-normalized channel radius of curvature (RC_b). Channel-bottom and sidewall substratum dominate in tight bends, where RC_b values are <2·57, and a mixture of alluvial sediment and channel-bottom and sidewall substratum are located in subtle-bend segments (RC_b: 2·57 to 17·38). Where the channel planform straightens ($RC_b > 100$) and the thalweg moves to the opposite bank, alluvial sediment is distributed on the channel bed bank to bank.

The channel is confined by relict substratum and alluvial sediment cover is thin, consisting of a discontinuous patchwork of deposits on bars fixed by river planform. Based on the area of cover for alluvial sediments to substratum, the lowermost Mississippi River is classified as a mixed bedrock-alluvial channel.

Despite conditions of rising relative sea-level since the positioning of the modern Balize channel system (past *ca* 1300 years), the lower 165 km of the Mississippi River channel appears to be actively incising via erosion of its underlying substratum. In its present form, the lowermost Mississippi River therefore runs contrary to commonly held theory predicting that a rise in relative sea-level induces downstream sedimentation.

Bed-material movement in the river occurs as a part of two-phase transport (suspended load and bedload) and the partitioning between the two modes is spatially conditioned by river planform. Two-phase transport renders present theory for bedrock erosion unlikely to apply for the lowermost Mississippi River; current theory requires saltation abrasion to the underlying bedrock, however saltating bedload transport probably occurs only where there are dunes and, therefore, where a collection of alluvial material is available to cover and protect the substratum from physical wear. Additionally, where channel-bottom substratum is exposed and susceptible to erosion (bend segments), transport of bed materials occurs via suspended-load transport. Consideration for differences in system scale — grain size, sediment flux, depth, transport stress versus sediment capacity and strength of bedrock is necessary before applying mountain-stream bedrock erosion theory to large, lowland sand-bed rivers.

This research should help guide decisions regarding the distribution of water and sediment to surrounding wetlands. Proposals that seek to extract sandy sediment for barrier island restoration have a means to determine the location and relative volume of sand resources in the lowermost Mississippi River (i.e. RC_b and mean flow depth). It is predicted that the diversion of water and sediment from the mainstem Mississippi River will not lead to serious degradation of the alluvial channel bed, in light of the fact that modern alluvial deposits are thin and intermixed with channel-bottom substratum.

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