ANATOMY AND DYNAMICS OF A FLOODPLAIN, POWDER RIVER, MONTANA, U.S.A.

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ABSTRACT: Centimeter-scale measurements on several Powder River floodplains provide insights into the nature of overbank depositional processes that created the floodplains during a 20-year period after a major flood in 1978. Rising stages initially entered across a sill at the downriver end of the floodplains. Later, as stages continued to rise, water entered the floodplains through distinct low saddles along natural levees. The annual maximum depth of water over the levee crest averaged 0.19 m from 1983 through 1996, and the estimated flow velocities were approximately 0.15 m s⁻¹. Water ponded in the floodplain trough, a topographic low between the natural levee and the pre-flood riverbank, and mud settled as thin layers of nearly constant thickness. Mud layers alternated with sand layers, which were relatively thick near the channel. Together, these beds created a distinctive natural levee. In some locations, individual flood deposits began as a thin mud layer that gradually coarsened upwards to medium-grained sand. Coarsening-upwards sequences form initially as mud because only the uppermost layers of water in the channel supply the first overbank flows, which are rich in mud but starved of sand. At successively higher stages, fine sands and then medium sands increase in concentration in the floodwater and are deposited as fine- and medium-sand layers overlying the initial mud layer. Theoretical predictions from mathematical models of sediment transport by advection and diffusion indicate that these processes acting alone are unlikely to create the observed sand layers of nearly uniform thickness that extend across much of the floodplain. We infer that other transport processes, notably bedload transport, must be important along Powder River. Even with the centimeter-scale measurements of floodplain deposits, daily hydraulic data, and precise annual surface topographic surveys, we were unable to determine any clear correspondence between the gauged flow record of overbank floods and the depositional layers mapped in the floodplain. These results provide a detailed example of floodplain deposits and depositional processes that should prove useful for interpreting natural levee deposits in a variety of geologic settings.

INTRODUCTION

Overbank sedimentation on floodplains may involve several different transport processes. These include turbulent diffusion and advection of suspended sediment, bedload, and eolian transport. Turbulent diffusion involves the transport of suspended sediment by eddies away from the main channel where the concentration of suspended sediment in the main channel is greater than the concentration over the floodplain. Turbulent diffusion has been quantified by Pizzuto (1987) and James (1987), and these theories are commonly used in theoretical models of overbank deposition (Gross and Small 1998; Howard 1996). The diffusion model appears to be successful in explaining the morphology of floodplains along the Brandywine Creek in southeastern Pennsylvania (Pizzuto 1987). Marriott (1992) found that James’ (1987) model (which uses a spatially variable diffusivity to account for changes in turbulence intensity across the floodplain) agreed qualitatively with field observations of sand deposits following a flood in the U.K. However, the diffusion model could not explain the distribution of grain sizes across the floodplain of the Brandywine Creek, and Pizzuto (1987) concluded that bedload transport and advection of suspended sediment were likely more important than diffusion, although no direct observations of these processes were available. A recent review by Bridge (2003) of many previous studies reached similar conclusions.

Diffusion is not the only process that transports sediment away from the channel during overbank flows. Advection is the transport of suspended sediment by currents flowing away from the channel onto the floodplain (James 1987; Parker et al. 1996; Narinesingh et al. 1999). Dense vegetation on floodplains often reduces the ability of floodwaters to transport suspended sediment, promoting deposition (Fujita et al. 1996; Kean and Smith 2004; Sweet et al. 2003; Smith 2004). Bedload transport (Bridge 2003; Florsheim and Mount 2002) and eolian transport after floods (Bagnold 1954) can also carry sediment across a floodplain.

Although many studies have documented different processes of sedimentation on floodplains, we are not aware of any previous study that has been able to clearly indicate the relative importance of each process. This lack of clarity hinders the development of useful theoretical models of overbank sedimentation and floodplain evolution.

In this paper, we present comprehensive, high-resolution (centimeter-scale) observations of the stratigraphy of overbank deposits on three floodplains formed within the channel of Powder River after a major flood widened the river in 1978 (Fig. 1). Previous studies have provided detailed information on the history of these floodplains, including (1) annual surveys of the topography and evolution of the floodplains (Moody and Meade 1990; Moody et al. 1999; Moody and Troutman 2000; Moody et al. 2002), (2) daily water levels and discharges for the
Fig. 1.—A) Locations and B, C, D) morphology of the floodplains described in this study. Topographic contours in Parts B, C, and D are in meters above local datum, which is approximately the stage of the bed-full discharge (12 m$^3$ s$^{-1}$, Moody et al. 1999). The line with an arrowhead and section number indicates the line of section measured annually from reference station 0 m on the left bank to reference stations on the right bank (100 m at PR120 and PR125 or 130 m at PR156A). Additional data describing the locations of these cross sections within the study reach are given by Moody et al. (2002).
entire period of floodplain development (USGS 1976–2002), (3) suspended-sediment gauging records (USGS 1976–2002), (4) analyses of the role of different discharges in floodplain erosional and depositional processes (Pizzuto 1994), and (5) studies of the planform development of the river (Martinson and Meade 1983; Gay et al. 1998). By combining new observations from trenches excavated across the floodplain with this previous information, we investigate the relative importance of different overbank sedimentation processes, in addition to providing a detailed description of the anatomy of a floodplain.

SETTING

Powder River is one of the largest rivers in the western United States that has not been influenced by significant engineering works. For this reason, Powder River is an ideal location to study natural processes of floodplain sedimentation. Since 1975, we have studied a 93-km reach of Powder River (Fig. 1) from the gauging station at Moorhead, Montana, near the Montana–Wyoming border to the gauging station at Broadus, Montana.

Powder River drains 34,706 km² of northeastern Wyoming and southeastern Montana. At the Moorhead gage, the mean annual water discharge is 12.7 m³ s⁻¹ (Moody et al. 1999), and the annual hydrograph is bimodal (Hodson et al. 1973), with an early peak usually between late February and early April caused by ice-breakup floods and a second, later peak (usually between mid-May and late June) caused by snowmelt from the Big Horn Mountains in Wyoming. Unpredictable flash floods from localized convective rainstorms also influence water levels in Powder River.

The average annual suspended-sediment discharge of Powder River into the Yellowstone River is 2–3 million metric tons (Moody and Meade 1990). Looped rating curves for suspended sediment in Powder River indicate that the fine fraction (silt and clay, < 0.063 mm) of the suspended sediment is supply limited but the sand fraction (0.063–0.125 mm), 40% fine sand (0.125–0.250 mm), 30% medium sand (0.250–0.500 mm), and 15% coarse sand and gravel (0.500–4.00 mm) (Hembree et al. 1952). Thus, very fine and fine sand compose about 52% of the bedload.

METHODS

Floodplain Topography

Floodplain topography was measured annually or biannually at 23 cross sections of Powder River since the 1978 flood. The cross sections are designated by a prefix “PR” and then the river distance (as of 1944) in kilometers downstream from the mouth of Crazy Woman Creek in Wyoming. Cross-channel stationing was measured in meters from a reference pin on the left bank, and stations are given in this paper without the suffix “m.” Cross-section elevations were not always measured at the same horizontal locations each time, nor at regularly spaced intervals, but rather at high, low, and inflection points with typical spacing of 1.0 to 2.0 m and maximum spacing of 3.0 to 5.0 m. An average elevation error between surveys was estimated to be about 0.015 m, and extreme elevation errors ranged from 0.06 to 0.12 m (Moody and Meade 1990). At three cross sections where stratigraphic data were collected (PR120, PR125, and PR156A), topographic maps (Fig. 1) were constructed of the floodplain using either a leveling rod and an automatic level (Wild NA2), or an electronic total station.

Stratigraphy

Sediment pits, cores, and trenches were used to determine the stratigraphy of the floodplain. Stratigraphic columns were drawn in 1992, 1994, 1995, and 1998 for sediment pits, which were dug along transects both perpendicular and parallel to the river channel. The pits extended through the annual flood deposits down to the 1978 gravel bar surface below the floodplains at PR120, PR125, and PR156A (Fig. 1). Sediment samples were collected from various layers, dried at 105°C, and then sieved by whole phi (ϕ) intervals (ϕ = −log₂ of the particle size diameter in mm; Krumbein 1934) to determine the grain-size distribution (Moody et al. 2002).

Two trenches were dug across the floodplain perpendicular to the river channel. A 23-meter-long trench was dug in 1998 (using a backhoe) at PR 120 down to the 1978 post-flood surface. This trench started at station 57, at the right edge of water, and traversed the floodplain to the contact with the Lightning Terrace at station 80. The stratigraphy was mapped on a 0.02 m × 0.02 m grid where the individual layers were resolved to 0.005 m. A second 7-meter-long trench was dug by hand across a portion of the floodplain trough at PR156A, normal to the dominant flow direction in the channel, and down to the 1978 post-flood surface.

Grain-size distributions of all the samples collected from the layers in the trenches were determined by either the visual-accumulation-tube method (time to settle 1.20 m) for sands or the pipette method for muds (Guy 1969). The median particle diameter, D₅₀, was determined from three equations that relate diameter to settling velocity (Rubey 1933; Inman 1963; Dietrich 1982). The differences in the predicted values of D₅₀ from these three equations were less than about 10%. The empirical fourth-order equation presented by Dietrich (1982) has been fitted to more recent data and was therefore used to calculate D₅₀ for the sand fractions of the sediment samples collected from the trenches.

Flow Direction

Directions of overbank flows were determined in several ways. Preserved ripples on the floodplain surface were used to infer the direction of flow when the ripples stopped moving. Similarly, the orientations of grasses and small trees bent by the flow also indicated flow directions during overbank flow. Finally, ripple cross-bedding preserved in overbank-flow deposits provided some data on the directions of flow. All flow directions were measured using a Brunton compass.

Vegetation

Vegetation was surveyed on overbank deposits several times, although most of the data were collected during September 1995. Grasses, sedges,
and trees were identified along surveyed sections to document the vegetation species growing on the floodplain (Moody et al. 1999). The density of vegetation was determined in six squares (1 m²) at PR120, more or less evenly spaced across the floodplain. All plants within these squares were identified, and the stem diameter and height of each plant were measured.

**THEORY OF DEPOSITION AND TRANSPORT**

Simplified theories of depositional and transport processes on floodplains can provide a frame of reference for interpreting floodplain deposits. Here we briefly review several mechanistic theories; the discussion is kept very general, and the reader is referred to the literature for details. The geometry of observed beds is compared with theoretical predictions later in this paper to better understand the processes responsible for transport and deposition.

Suspended sediment from a channel can be transported across the adjacent floodplain by horizontal turbulent diffusion, advection by currents, or by some combination of these processes. As sediment is carried in suspension, it may be deposited with a characteristic settling velocity. If deposited sediment is not re-entrained, it may continue to be transported as bedload. After floodwaters recede and the newly deposited sediment dries, wind can cause further transport.

Under the simplest conditions, diffusion and advection both create deposits that are thickest near the channel and decrease in thickness exponentially with increasing distance from the channel. The rate of exponential decline in thickness is governed by the dimensionless parameters $h_d$ (advection) and $b_d$ (diffusion) of Table 1.

The relative effectiveness of advection and diffusion is important to assess because both processes create deposits with similar exponential form. The ratio of $h_d$ to $b_d$, is $uL/e$, (symbols are defined in Tables 1 and 2). Typical values of $u$ might be on the order of 0.1 m s$^{-1}$, $L$ is approximately 10 m (Fig. 1), and the horizontal diffusion coefficient is of the order $10^{-2}$ m$^2$ s$^{-1}$ (Pizzuto 1987), so $b_d/h_d$ is about 100. Thus, advection should be about two orders of magnitude more effective than diffusion in transporting sediment across the floodplain, and diffusion is unlikely to be a dominant process of overbank deposition.

The shear stress and shear velocity are the parameters that control entrainment and deposition of sediment on the floodplain. Vegetation modifies the shear velocity and the depth-averaged mean flow velocity (Tables 1 and 2) and consequently the transport processes (Smith 2004). This modified shear velocity is particularly appropriate for interpreting overbank depositional processes at our vegetated study site. We use the equations of Table 1 to estimate overbank flow velocities and to assess the ability of overbank flows to transport sand-size sediment as bedload (see Meyer-Peter and Müller 1948; Wiberg and Smith 1987; and Yalin and Karahan 1979).

**RESULTS**

**Floodplain Topography**

Floodplains of Powder River have topographic features that are typical of narrow floodplains (Figs. 1, 2A, B). A floodplain trough is commonly adjacent to the pre-flood bank, and a levee crest typically is adjacent to the channel. Both features undulate in the upriver-downriver direction. The floodplain trough has a sill across the mouth at the downriver end where the trough connects to the main river channel. The levee crest has slopes ranging from 0.02 to 0.006 (measured perpendicular to the channel), and the levee crest has high points and saddles (Fig. 2B).

**Flow Depths and Velocities**

Flow depths over the levee crest varied as the floodplain grew. Depths decreased after 1982 as the elevation of the floodplain increased by vertical accretion. Flows over the levee crest at PR120 were shallow (Fig. 3), averaging about 0.5 m before 1982. After 1982, the depths of overbank flow remained approximately constant, with an average value of 0.19 m and a standard deviation of 0.19 m.

We measured the vector velocities of the shallow overbank flows using floats in three different areas of the floodplain at PR125 on 9 June 1993. Flow speed over sand ripples at the levee crest was 0.08 m s$^{-1}$ in 0.2 m of water, and the direction was away from but perpendicular to the channel. Flow speed on the floodplain was 0.10 m s$^{-1}$ in 0.3 m of water where the direction was about 45° relative to the channel. Flow speed in the floodplain trough was 0.16 m s$^{-1}$ in 0.5 m of water, and the flow direction was downriver.

Bedforms, sedimentary structures, and vegetation also provided data on directions of overbank flows. At the levee crest, flow vectors were both perpendicular and parallel to the channel (Fig. 2A). In the floodplain trough, the flow direction was primarily downriver, although the direction turned towards the channel as water exited the trough over the sill (Fig. 2) and rejoined the flow in the main channel.

Predicted flow speed at the levee crest ranged from 0.11 to 0.36 m s$^{-1}$. We used equations 5–8 in Table 1, estimates of the vegetation density (424 stems m$^{-2}$ or = 0.049 m, measured in September 1995), and measured vegetation height (0.58 m). The flow speed depended on the choice of $z_0$.
(Nikuradse $z_0 = k/30$, where $k_s = 0.125$ mm; grain diameter roughness, $= 0.0001$ m; and small-bed-form roughness, $= 0.01$ m). These predicted velocities were similar to those observed in the field and are used below in some exploratory computations of floodplain depositional processes.

**Table 2.** Definitions of variables used in the equations of Table 1.

<table>
<thead>
<tr>
<th>Variable Symbol</th>
<th>Definition (with mks units)</th>
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<tbody>
<tr>
<td>$C_D$</td>
<td>Vegetation drag coefficient (dimensionless)</td>
</tr>
<tr>
<td>$D_s$</td>
<td>Vegetation stem diameter (m)</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration of gravity (m/s$^2$)</td>
</tr>
<tr>
<td>$H$</td>
<td>Water depth (m)</td>
</tr>
<tr>
<td>$L$</td>
<td>Characteristic floodplain width (L)</td>
</tr>
<tr>
<td>$S$</td>
<td>Water surface slope (dimensionless)</td>
</tr>
<tr>
<td>$V_s$</td>
<td>Sediment settling velocity (m/s)</td>
</tr>
<tr>
<td>$z_o$</td>
<td>Roughness length (m)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Vegetation stem spacing (m)</td>
</tr>
<tr>
<td>$k$</td>
<td>Von Ka’rma’an constant (dimensionless)</td>
</tr>
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**Patterns of Floodplain Inundation**

The elevations of the sill at the downriver entrance to the floodplain trough and the elevations of the saddles at the levee crest control the flow of water and sediment during a flood. To illustrate these ideas, we describe three floods between annual surveys in September 1994 and September 1995. During the floods of October 1994 and May 1995, the water was above the levee crest for about 3 days, but in June 1995 the water was above the levee crest for about 15 days with three peaks on 5 June, 12 June, and 18 June (Fig. 4A).

Water and sediment initially left the channel and entered the downstream end of the floodplain across a sill of the floodplain trough and was observed to flow in the upriver direction. This created a “pond” at the downstream end of the floodplain with estimated velocities on the order of 0.05 m s$^{-1}$, which allowed mud to settle. Later, as the stage continued to rise, additional water and sediment flowed onto the floodplain through the saddles in the levee crest. On 5 June 1995, the estimated peak water elevation was only higher than two saddles in the...
levee crest (Fig. 2B) whereas on 12 June 1995, the water flowed through three saddles. For the 5 June flood, the water depth in the channel was about 2.0 m (thalweg elevation = 1010.6 m on 24 September 2004), so that the shear velocity, $u^*_{\text{channel}}$, was about 0.17 m s$^{-1}$ ($S = 0.0015$). The water was about 0.10 m deep as it flowed through the saddle (Fig. 2B), and the shear velocity, $u^*_{\text{floodplain}}$, decreased from 0.22 m s$^{-1}$ near the levee crest ($S = 0.05$) to 0.14 m s$^{-1}$ farther ($S = 0.02$) away from the levee crest. Thus, some sand should have settled out from suspension from the 5 June flood. For the other June floods the water was deeper (~ 0.35–0.50 m) and the shear velocities (0.26–0.49 m s$^{-1}$) were greater than the critical shear velocities for all particle sizes, and therefore some sediment was probably transported as bedload.

The flood water probably did not inundate the entire floodplain but flowed along multiple shallow depressions and collected in the floodplain trough. Initially, on the rising limb of the flood, the water surface in the floodplain trough was not high enough to exit from the downriver end of the trough, and a “pond” of water would have formed in the trough (Fig. 2B), allowing mud to settle. The peak water level in the river channel was estimated to be substantially greater than the elevation of the sill of the trough for the floods in October 1994, May 1995, and the peaks on 12 and 18 June 1995. Therefore, a downstream water-surface slope was maintained across the trough and some overbank flow likely exited the trough and re-entered the river. For the 5 June 1995 flood, the water level never exceeded the elevation of the sill. Thus, no water could flow out of the trough ($S = 0$), and it is likely that all the mud in suspension would have been deposited in the floodplain trough. This also would have been true for each flood when the falling stage fell below the elevation of the sill of the floodplain trough, trapping water in the trough.

**Stratigraphic Cross Section**

The floodplain at PR120 consists of decimeter- and centimeter-thick layers of alternating sand and mud. Layers that dip towards the river close to the channel were deposited on the bank (Fig. 5). Layers that dip away from the river were deposited on the growing floodplain, landward from the levee crest and close to the Lightning Terrace (Fig. 5). Sand layers are thicker closer to the channel, and thin away from the channel. Mud layers are much thicker in the floodplain trough than closer to the river. They are discontinuous riverward of the levee crest but continuous landward of the levee crest. The lack of continuity of the mud deposits near the river is likely related to the high probability of erosion. Our annual surveyed cross sections at PR120 demonstrate clearly that preserved deposits close to the channel only represent about 50% of the total sediment deposited there between 1978 and 1996, in contrast to those on the landward side of the levee crest, which represent 96% of the total (Moody et al. 1999).

Some sedimentary structures are evident in the sand layers. Sand layers are commonly laminated and occasionally cross-bedded, and several layers contain climbing ripples (see enlarged 1-m sections in Fig. 5). Climbing ripples indicate sand transport with a directional component away from the river channel and rapid deposition of sand from suspension over migrating ripples, which suggests both suspended-load and bed-load transport. Distinctive coarsening-upward layers (indicated by vertical arrows in Fig. 5) typically begin at the base of a mud layer. The basal contact of the mud layer is abrupt, while the upper contact of the mud is gradational, as the mud was replaced by very fine sand. The sand within the bed gradually coarsens upwards from very fine sand to medium sand near the top of the layer. Coarsening-upwards sequences range in thickness from several centimeters to several decimeters.

We also assessed the continuity of individual layers in the floodplain upriver and downriver from the trench at PR120. We were able to correlate layers for a distance of at least 64 m upriver from station 70.5 in the floodplain trough. For example, five sand layers (c, e, h, m, and o) alternating with five mud layers (d, f, jkl, n, and p) in the trench were identified in the six sediment pits, which were dug at 2, 4, 8, 16, 52, and 64 m upriver. All these layers dip downriver with a slope equal to 0.002. Thus, the section illustrated in Figure 5 is broadly representative of the floodplain at PR120. Correlation of individual layers upriver and downriver from under the levee crest at PR120 was not successful, further suggesting that layers at the crest are less continuous than those layers deposited farther away from the stream channel.

**Overbank Flows and Floodplain Stratigraphy**

At PR120 and PR125, we were unable to make a one-to-one correspondence between the layers and the floods between October 1994 and June 1995, even though the floodplain had been surveyed an extra time in March 1995 between the regular annual surveys conducted in September of 1994 and 1995. Two mud layers and two sand layers were found between the surfaces measured in September 1994 and March 1995 (Fig. 4B), whereas only one flood (October 1994) recorded at the Moorhead gauging station exceeded bankfull discharge (98 m$^3$s$^{-1}$) during this time period. A probable explanation for this conundrum is the occurrence of an ice-jam flood that created enough backwater in February–March 1995 (Fig. 4A) to cause the water surface to locally exceed bankfull at PR125 (and also at PR120). This backwater deposited ice floes and associated sediment on the floodplain (stacks of ice floes on the floodplain complicated the resurveying of the March 1995 surface). Local ice-jam floods, such as this one, are not recorded in the discharge hydrograph upriver, illustrating the general difficulty of correlating stratigraphic records to detailed flood records, even over the short time scale of one year. The continuity and excellent preservation of the deposits landward from the levee crest still invites comparisons between the number of floods and the layers preserved in the depositional record. Approximately 20 individual layers of sand, mud, or interlaminated sand and mud were exposed in the trench at PR120, but Powder River flooded overbank here 50 times between 1979 and 1996 (Moody et al.1999). Similarly at PR156A, also on the right bank and 36 km downstream from PR120, 10 individual layers were found, but 46 overbank floods were recorded between 1979 and 1996. At PR125 there were only five layers, but PR125 was flooded 46 times during the same time period. As noted above, these data also illustrate the general difficulty of correlating individual sedimentary layers with individual floods.
Sand-Layer Thickness

The measured thickness of sand layers varies considerably across the floodplain (Fig. 6A) (dimensionless axes are used in Figure 6A and B because the equations of Table 1 are best suited to explain relative, rather than absolute, changes in sand-layer thickness across the floodplain). Theoretical predictions of the thickness of deposition from advection and from diffusion only were calculated for fine to medium sand with a settling velocity of 0.012 m s\(^{-1}\) (Dietrich 1982), a flow depth of 0.2 m, a downvalley slope of 0.001, a levee slope of 0.02, and an average advective speed of 0.15 m s\(^{-1}\). In computing vertical diffusion coefficients, the downvalley slope was used for computing diffusive transport, and the levee slope was used for computing advective transport. The vertical and horizontal turbulent diffusion coefficients for diffusive transport were 6.8 \(\times\) 10\(^{-4}\) and 1.2 \(\times\) 10\(^{-3}\) m\(^2\) s\(^{-1}\), respectively, and for advective transport the vertical turbulent diffusion coefficient was 3.0 \(\times\) 10\(^{-3}\) m\(^2\) s\(^{-1}\). The relative thickness of sand layers predicted using these theoretical models of diffusion and advection is distinctly different from the average relative thickness of seven sand layers measured in the field (Fig. 6B). The decrease in thickness with distance is much less than the decrease predicted by either diffusion or advection (0.15 m s\(^{-1}\)) alone, suggesting that these transport processes are not robust enough to produce the observed distribution of sand across the floodplain. Advection can produce results that are consistent with field observations (Fig. 6B), using an advective velocity of 0.4 m s\(^{-1}\). This is higher than velocities measured during floods (0.08–0.16 m s\(^{-1}\)) or those computed using hydraulic relations (0.11–0.36 m s\(^{-1}\)). Thus, other processes in addition to pure advection and diffusion are probably required to completely explain the formation of these sand layers.

Mud-Layer Thickness

The thickness of the mud layers at PR120 depends on their location on the floodplain. Two types of mud layers are apparent: one that includes mud deposited landward from the floodplain trough, and another that includes mud deposited on both sides of the levee crest. Layers d, k, and...
n, which were deposited landward from the levee crest (between station 64 and 70 in Fig. 7), are 0.02 to 0.06 m thick and do not vary systematically in thickness. These layers are more precisely described as drapes of constant thickness. Mud layers p and r at lower levels of the floodplain are much thicker (Fig. 7), with a maximum thickness of 0.11–0.17 m near station 63 and a thickness of 0.06 m near station 74. The lowest layer, v, is the thickest; this layer actually represents the combined thickness of multiple mud layers that joined at about stations 64, 66, and 75 (Fig. 7).

The layers bb, cc, dd, and dd' on the riverward side of the levee crest have variable thicknesses ranging from 0.10 to 0.01 m, and some are discontinuous, indicating possible truncation by erosion. These discontinuous layers were not necessarily deposited by overbank flows, because mud can be deposited on the riverbanks by in-channel flows.

**Particle-Size Distribution of Layers**

Variation with Distance.—Particles of the sand layers are relatively uniform in size, ranging from fine to very fine sand. Within individual layers, the median particle settling diameters of some sand layers did not correlate with distance from the levee crest (Fig. 8). However, the \( D_{50} \) of the mid-depth layers e, h, m, o, and q (Figs. 5, 8) decrease linearly with distance from the levee crest (\( r^2 = 0.42 \) to 0.95; Fig. 8), which suggests hydrodynamic sorting of particle sizes. At the levee crest, the particle diameters averaged about 0.150 mm and the diameter decreased over a distance of about 10 m towards the floodplain trough, where sizes ranged from 0.063 to 0.110 mm. Broadly similar results have been obtained in other studies of overbank sedimentation (Cazanacli and Smith 1998; Marriott 1992; and many references summarized by Bridge 2003). Diffusion, advection, and bedload transport could all produce hydrodynamic sorting, but models of diffusion and advective transport are unable to produce the measured thickness of the layers (as noted above).

Coarsening-Upwards Sequences.—Deposits that coarsen upwards are common in Powder River’s floodplains. The base of each deposit consists of a layer of mud that gradually grades upwards to very fine-, fine-, and ultimately to medium-grained sand as illustrated in stratigraphic sections at PR141 and PR120 (Fig. 9A, B). Coarsening-upwards deposits are created not only by moderate floods (whose deposits are described in detail in this paper), but also by the larger flood in 1978 on Powder River (Moody and Meade, unpublished manuscript).

Multiple samples were collected from three coarsening-upward sequences in the stratigraphic section at PR120 to determine particle-
size distributions. The median size of the bottom sequence, in layer c (landward of the levee crest), layer x (sampled directly under the levee crest near station 63; layer x extends for more than 5 m), and layer x’ (riverward of the levee crest) ranged from 0.020 to 0.112 mm, respectively, so that the sizes within the sequence were normalized by to give the relative particle size. The relative particle size increased from the bottom to the top of the sequence in all three layers (Fig. 10). In layers x and x’ the relative particle size increased from 1 to about 5–6, but it was not as large for four out of five samples from layer c (Fig. 10). Thus, the particle size distribution within a coarsening-upwards sequence depends on the proximity to the channel and consequently on the immediate source of suspended sediment.

DISCUSSION

Hydraulics and Depositional Processes

Our data reinforce previous observations of the complex three-dimensional patterns of floodplain inundation by rising stages (Lewin and Hughes 1980; Mertes 1994; Sweet et al. 2003). In fact, our results are very similar to those presented by Schmude (1963), who described floodplain inundation along the lower Missouri River. To summarize, water and sediment initially leaves the channel and enters the downstream end of the floodplain and creates a pond with sluggish velocities. As the flood waters continue to rise, additional shallow water containing sediment enters through the saddles along the levee crest oblique to the channel. Thus, the overbank flows responsible for the deposits described in this paper are shallow and sluggish, with depths of around 0.20 m and flow velocities on the order of 0.1 m s\(^{-1}\).

Comparing theoretical predictions of sand-layer thickness with those observed provides useful clues regarding sand transport processes during overbank flows. Diffusion and advection (with characteristically low advective velocities) are apparently too weak to transport sufficient sediment to account for the extent and relatively uniform thickness of sand across the floodplain, so other processes must be invoked. If sand of varying sizes was deposited from suspension and preserved in place without further transport, then coarser sediments would be deposited close to the levee crest, and finer sediments would be deposited farther from the levee. This hydrodynamic sorting is not present in all layers, suggesting that other processes such as bedload or eolian transport may have contributed to the transport of particles in individual layers.

Both climbing ripples and planar lamination in sand layers indicate that sand was transported as bedload over the floodplain, at least near the levee crest. Once sand is deposited from suspension, the maximum boundary shear velocity in 0.2 m of water along (0.06–0.11 m s\(^{-1}\)) and across (0.20–0.24 m s\(^{-1}\)) an unvegetated floodplain would be sufficient to move very fine to medium sand farther away from the channel. These

**Fig. 6.**—Relative thickness of sand deposited as a function of the perpendicular distance from the levee crest. A) Sand layers c, e, h, m, x, o, and q are shown along with the average thickness of all these layers (field observations averaged in bins of 0.1 units of the ratio of the distance from the levee crest to the total width of the floodplain). B) Theoretical curves are illustrated for turbulent diffusion and for advection.
shear velocities would be reduced by vegetation (Smith 2004) by a factor of about 10 on the floodplains, but still would be sufficient to move very fine to fine sand. Unfortunately, clear evidence of bedload transport is not preserved in the sand layers in the floodplain trough.

It is also possible that sand was transported by wind after deposition from suspension on the levee crest. Frequently, the levee crest after the floods was essentially a bare surface with sparse vegetation, leaving newly deposited sand exposed to the wind. We have analyzed data on the direction and strength of winds along Powder River, and this analysis suggests that eolian transport is capable of moving sandy sediment across the floodplain. However, because we lack quantitative observational evidence, we cannot evaluate this hypothesis rigorously.

Coarsening-Upwards Layers

Individual floods initially deposit a thin layer of mud that is followed by gradually coarsening deposits that grade upwards to medium-grained sand. Coarsening-upwards sequences form because initially only the uppermost layers of the floodwaters inundate the floodplain. These are rich in mud but starved of sand because sand concentration is lowest near the water surface. At peak stages, however, the silt and sand concentration at the surface is high enough in the channel to be available for overbank deposition, so silt and then sand is deposited on top of the initial mud deposits. During the falling stages, decanted water flows across the floodplain back into the channel and no overbank deposits are created. This conceptual model suggests that the origin of coarsening-upwards layers is controlled, in time, by both the limit of supply of the fine fraction as suggested by Iseya (1989) and, in space, by the differential vertical concentration distributions of the fine and the coarse fractions in the top of the water column (Parker et al. 1996).

Sedimentary Architecture and Stratigraphy

Figures 2, 4, and 5 present very detailed examples of the morphology, lithology, and architecture of natural levees that is consistent with previous observations. For example, Brierly et al. (1997) suggest that typical natural levees are “prismatic bodies of triangular cross-section.” Beds “dip away from the channel” and are composed of “interbedded ripple-laminated very fine sand and mud.” They represent “thinnly interbedded flood cycle deposits (rhythmites) reflecting rising and waning stage…..coarsening-upwards sequences are common.” The detailed nature of our stratigraphic data also provide additional information not emphasized in previous studies. For example, Figure 5 indicates that the levee crest represents an important boundary in natural-levee deposits. Towards the river from the levee crest, beds dip towards the river, and they are composed of relatively discontinuous, thick sand layers with interbedded, discontinuous mud layers. Landward from the levee crest, beds dip away from the river, and they are composed of relatively continuous, thin sand and mud layers. Although not emphasized in this paper, the location of deposits relative to the levee...
The levee crest also influences their preservation: deposits are much less likely to be preserved on the riverward side of the levee crest. These characteristics could help to identify and interpret natural-levee deposits preserved in the geologic record.

**Correlating Flood Records with the Stratigraphic Record**

Even though very detailed stratigraphic and hydrologic data are available, we have been unable to correlate individual layers with individual floods. This is likely caused by factors arising from both the sedimentary processes themselves and from limitations of our data.

The nature of sedimentation on natural levees can lead to incomplete preservation and to complex patterns of deposition, leading to difficulties in correlating hydrologic and geologic records. For example, erosion may remove deposits of some floods from the preserved record. Or, some floods may create deposits only in localized areas outside of a particular cross section, such as in the ponded section at the downstream end of the trough in Figure 2B. Two floods may also create deposits of similar texture, without preserving a contact between them. An example is provided by the sand deposits between the topographic surveys of 9/94 and 3/95 (Fig. 4B)—these appear as a single layer, but they were deposited by more than one overbank flow. Other floods may deposit small, discontinuous layers that might not appear to record a single overbank flow (mud lenses at the base of Figure 4B from the 10/04 flood provide an example).

We are also hampered by limitations of our data. Local ice-jam floods that do not appear in gaged discharge records (Fig. 4A) provide an instructive example. Our surveying methods, though very detailed, suggest additional limitations, for they lack the temporal and spatial precision to date many layers unambiguously.

The cumulative result of these factors is apparent when trying to interpret the very detailed stratigraphic observations presented in Figure 5. We cannot identify layers within this cross section that were clearly deposited by any individual overbank flow. Furthermore, in the absence of hydrologic data, we could not use these stratigraphic data to reconstruct the history of overbank flows at this site.

**Local and Geological Applicability**

Our results document the stratigraphy of narrow floodplains formed in a widened channel created by the 1978 flood. As we have discussed in previous papers (Moody et al. 1999, Pizzuto 1994), these deposits were formed by moderate discharges that did not inundate the valley outside of the margins of the 1978 flood-widened channel. What is the likely relation between the deposits described in this paper and the architecture of Powder River’s floodplain in general? Can our results be applied to other rivers in different geologic settings?

Extensive studies of Powder River’s floodplain have not been completed, but related studies allow some speculative judgments. Most of the valley of Powder River was flooded in 1923 and in 1978. These floods deposited extensive, horizontally bedded layers (Moody and Meade, unpublished manuscript). During these events, and also during more moderate discharges, Powder River moved significant distances laterally, largely through meander migration (Martinson and Meade 1983).

These observations suggest that much of the floodplain has been built through large-scale overbank flows and deposition associated with point-bar migration and associated floodplain development. Neither of these two processes will create deposits with the architecture mapped in Figure 5, even though the coarsening-upward beds and other specific sedimentologic features we have described may be quite widespread. Thus, it is probably reasonable to limit the application of the results we have presented in this paper to depositional environments along Powder River that can be characterized as “natural levees.”

The applicability of our results to other geologic settings is important to assess. Natural-levee deposits are quite diverse, leading Brierly et al. (1997) to conclude that there are “no sedimentologic attributes that allow for definitive identification of natural levees.” This would suggest that any study of deposits created by a single river will have limited generality.

![Fig. 8.— Variation of the median settling diameter of sand-size particles within the sand layers as a function of the distance from the PR120 benchmark. Dashed lines are drawn by hand to help illustrate visual trends in the data; the lines do not represent statistically valid relationships. The levee crest was located in the vicinity of station 64 in 1998. See Figure 5 for illustration of the geometry and stratigraphic position of the sand layers at the levee crest.](image-url)
However, it is also possible that the processes we have identified that have created natural levees along Powder River are similar in some broad sense to those that create many natural levees. Given a widespread similarity in formative processes, a speculative working hypothesis would posit that variability in the sedimentologic characteristics of natural-levee deposits of different streams might be caused by differences in the nature of the sediment in transport and to local characteristics of fluvial morphology and vegetation. This would imply that levees are generally created by deposition from sediment advected from a channel onto an adjacent floodplain, and, following deposition, sediment may then be transported farther as bedload or possibly eroded. Additional sedimentation could occur as a result of ponding, if sufficient silt and clay are available. As we have documented along Powder River, sedimentation on natural levees should also be generally influenced by complex three-dimensional patterns of topography and floodplain inundation and hydraulics. These ideas suggest that a more complete understanding of natural levees and an enhanced ability to interpret natural-levee deposits could be attained by coupling an improved understanding of a limited set of depositional processes operating with a broad spectrum of different sediment types and substrates. Exploring these ideas in detail is beyond the scope of this paper, but such an approach should provide fruitful opportunities for further research.

**CONCLUSIONS**

Topographic maps and hydraulic data support a detailed conceptual model for overbank deposition along Powder River. As the river stage rises above the elevation of the sill across the downriver end of the floodplain trough, water and sediment flow in the upvalley direction and create a pond in the trough where thin mud drapes of nearly constant thickness are deposited. As the river stage continues to rise, water and sediment flow onto the floodplain through localized low saddles in the levee crest. These overbank flows are shallow (≈ 0.2 m) and slow moving (≈ 0.1 m s⁻¹); they deposit sand layers that are thicker close to the channel, forming a prominent natural levee. As the flow though the saddles continues, it expands the pond in the trough, eventually reversing the direction of flow from upriver to downriver.

Theoretical analyses suggest that advection and turbulent diffusion processes acting alone are unlikely to have created the sand layers of nearly uniform thickness that extend across the entire floodplain. Estimated boundary shear velocities and sedimentary structures indicate that bedload transport could have moved sand across the floodplain once it had been deposited from suspension.

The deposits created by these processes consist of alternating layers of sand and mud that dip away from the channel landward from the levee.
crest and dip towards the channel riverward from the levee crest. Centimeter-scale layers are highly continuous and many span the entire width of the floodplain. Many layers coarsen upwards with thin mud deposits at the bottom. Even with the detailed sampling and hydraulic data available, however, we were not able to determine any clear relation between the gauged record of overbank flows and the characteristic layers in the floodplain.

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REFERENCES


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