Stratigraphic, sedimentologic, and dendrogeomorphic analyses of rapid floodplain formation along the Rio Grande in Big Bend National Park, Texas

D.J. Dean[1,†], M.L. Scott[2], P.B. Shafroth[2], and J.C. Schmidt[1]

[1]*Department of Watershed Sciences, Utah State University, 5210 Old Main Hill, Logan, Utah 84322-5210, USA*

[2]*U.S. Geological Survey, Fort Collins Science Center, 2150 Center Avenue, Building C, Fort Collins, Colorado 80526-8118, USA*

ABSTRACT

The channel of the lower Rio Grande in the Big Bend region rapidly narrows during years of low mean and peak flow. We conducted stratigraphic, sedimentologic, and dendrogeomorphic analyses within two long floodplain trenches to precisely reconstruct the timing and processes of recent floodplain formation. We show that the channel of the Rio Grande narrowed through the oblique and vertical accretion of inset floodplains following channel-widening floods in 1978 and 1990–1991. Vertical accretion occurred at high rates, ranging from 16 to 35 cm/yr.

Dendrogeomorphic analyses show that the onset of channel narrowing occurred during low-flow years when channel bars obliquely and vertically accreted fine sediment. This initial stage of accretion occurred by both bedload and suspended-load deposition within the active channel. Vegetation became established on top of these fine-grained deposits during years of low peak flow and stabilized these developing surfaces. Subsequent deposition by moderate floods (between 1.5 and 7 yr recurrence intervals) caused additional accretion at rapid rates. Suspended-sediment deposition was dominant in the upper deposits, resulting in the formation of natural levees at the channel margins and the deposition of horizontally bedded, fining-upward deposits in the floodplain trough. Overall, channel narrowing and floodplain formation occurred through an evolution from active-channel to floodplain depositional processes. High-resolution dendrogeomorphic analyses provide the ability to specifically correlate the flow record to the onset of narrowing, the establishment of riparian vegetation, the formation of natural levees, and ultimately, the conversion of portions of the active channel to floodplains.

†E-mail: david.dean@usu.edu

INTRODUCTION

Channel narrowing has occurred on many rivers with large suspended loads in arid and semiarid regions during the last century. Channel narrowing has been attributed to reductions in flood magnitude and/or total stream flow caused by dam construction (Everitt, 1993; Friedman et al., 1998; Allred and Schmidt, 1999; Grams and Schmidt, 2002; Shafroth et al., 2002; Zahar et al., 2008; Dean and Schmidt, 2011), irrigation diversions (Everitt, 1993), climate (Hereford, 1984, 1986; Graf et al., 1991; Allred and Schmidt, 1999), the concomitant expansion of non-native riparian vegetation (Graf, 1978; Friedman et al., 1996, 2005; Allred and Schmidt, 1999; Dean and Schmidt, 2011), and increases in the supply of fine sediment (Grams and Schmidt, 2005; Zahar et al., 2008). Studies of the processes by which rivers narrow provide fundamental insights about the linkages among stream flow, sediment supply, and channel and floodplain formation. Channel narrowing is also an important environmental process that affects the temporal and spatial dynamics of aquatic and riparian ecosystems, and thus, a clear understanding of the processes by which rivers narrow is imperative for planning successful river rehabilitation programs. Understanding modern examples of channel narrowing may also help us to interpret analogs in the rock record (Nanson and Croke, 1992; Brierley et al., 1997; Moody et al., 1999).

Demonstrating how channel narrowing and floodplain accretion occur is difficult. These processes can occur over many decades (Schumm and Lichty, 1963; Burkham, 1972; Hereford, 1984), and thus, long, temporally accurate data sets are required to resolve the underlying mechanisms. Several tools have been used to analyze the rate and magnitude of narrowing on many rivers; however, these tools are all limited in their ability to precisely describe the timing and style of deposition. For example, aerial photographs can provide insight into mean narrowing rates, but they only provide the temporal resolution of the interval between photos—a few years to a decade—and do not provide sufficient topographic information to investigate changes in bed or floodplain elevation. Measurement notes associated with streamgage records contain temporally precise cross-section data (Smelser and Schmidt, 1998), yet they are only useful for describing channel change at the location of gage sites. Dendrochronologic techniques (Hereford, 1984), which use the age and germination elevation of buried riparian plants to obtain the maximum age of an aggregated thickness of floodplain sediment, are useful but lack the precision needed to determine the frequency, timing, type, or process of overbank deposition. Radiocarbon dating is limited in its ability to accurately date young fluvial deposits because sufficient organic material may be lacking or may be reworked, and optically stimulated luminescence (OSL) techniques may be limited if recently deposited sediment was only partially bleached by light, causing large uncertainty around age determination (see partial bleaching discussions by Galbraith et al., 1999; Rittenour, 2008).

Channel narrowing and floodplain deposition have been well described on the Powder River, Montana (Pizzuto, 1994; Moody et al., 1999; Moody and Troutman, 2000; Pizzuto et al., 2008), and the Green River, Colorado and Utah (Allred and Schmidt, 1999; Grams and Schmidt, 2002, 2005). These studies combined analyses of hydrologic records, aerial photographs, discharge measurement notes at stream gages, and stratigraphic and sedimentologic analyses of floodplain deposits to comprehensively describe the timing and rates of channel change. Studies on the Powder River also utilized annual and biannual topographic surveys of the changing channel and floodplain surfaces, from which accretion rates could be determined and flow and sediment transport could be modeled.

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Without this long record of repeated surveys, the dominant processes of formation could not have been interpreted. However, repeat topographic surveys cannot be used to track and interpret geomorphic changes of landforms that have already formed.

Here, we used an improved dendrogeomorphic approach developed by Friedman et al. (2005) to accurately reconstruct the history of floodplain development observed in two large floodplain trenches along the Rio Grande in Big Bend National Park, Texas. This study complements the twentieth-century geomorphic history described by Dean and Schmidt (2011) and specifically describes the processes by which decadal-scale channel narrowing of the Rio Grande occurred. The dendrogeomorphic approach applied in this study combines stratigraphic and sedimentologic analyses of floodplain sediment with a new technique that is able to identify internal anatomical responses of tree rings to burial by alluviation. We used these techniques to specifically correlate the onset of narrowing, the establishment of riparian vegetation, and the rapid accretion of channel bars to the flows responsible for these processes. This study also describes the sedimentary characteristics and depositional relationships within these deposits and demonstrates that channel narrowing and floodplain formation on the Rio Grande occur through an evolution from active-channel to floodplain deposition processes. The results described here provide essential information for planning effective rehabilitation programs, including the management of non-native vegetation and the prescription of dam releases for environmental purposes.

Floodplain Formation on Suspended Load Rivers

Most cases of channel narrowing are attributable to reductions in mean and/or peak flow (Hereford, 1984; Everitt, 1993; Grams and Schmidt, 2002), increases in sediment supply relative to the transport capacity of the stream flow (Everitt, 1993; Grams and Schmidt, 2005; Schmidt and Wilcock, 2008; Zahar et al., 2008), or deposition within an overwidened channel after large floods (Schumm and Lichty, 1963; Pizzuto, 1994; Friedman et al., 1996; Dean and Schmidt, 2011). The establishment of riparian plants within the channel can further promote channel narrowing through bar and bank stabilization, increases in roughness, and sediment trapping (Tal et al., 2004; Tal and Paola, 2007; Braudrick et al., 2009). On rivers with large suspended-sediment loads, vertical accretion is the dominant mechanism by which channels narrow (Schumm and Lichty, 1963; Burkham, 1972; Pizzuto, 1994; Moody et al., 1999; Allred and Schmidt, 1999; Grams and Schmidt, 2002; Pizzuto et al., 2008; Dean and Schmidt, 2011).

Previous studies have shown that the initial stages of channel narrowing and floodplain formation occur through the construction of low-lying benches, often on top of channel-margin or mid-channel bars (Woodyer et al., 1979; Pizzuto, 1994; Moody et al., 1999; Allred and Schmidt, 1999). Woodyer et al. (1979, p. 111) and Pizzuto (1994, p. 1496) described these benches as "actively accreting flat-topped bodies of sediment occurring along the banks of a stream channel." These benches obliquely (Page et al., 2003) and vertically accrete through time as they are inundated by floods carrying loads of sand and mud. Although the developing surfaces are depositional features, their shape can also be affected by erosional processes that sculpt the channel banks during the rising stages of floods, or form shallow flood channels on the top of these benches (Ferguson and Brierley, 1999; Moody et al., 1999). As vertical accretion occurs, levees may be constructed through advective and/or diffusive transport of sediment from the channel to the developing floodplain (Filgueira-Rivera et al., 2007; Pizzuto et al., 2008). The shapes of levees are controlled by the stage of flood flow (Filgueira-Rivera et al., 2007), the stream power of the reach (Ferguson and Brierley, 1999), and the amount and size of supplied sediment (Cazanacli and Smith, 1998). In general, the steepest, highest levees form during the largest flows that transport and deposit the coarsest sediment on the proximal portions of the channel banks ("front-loading"; Filgueira-Rivera et al., 2007). The relief of levees may be reduced by smaller floods that inundate the distal portion of the developing floodplain through breaks in the levees that deposit fine-grained sediment and reduce distal levee slope ("back-loading"; Filgueira-Rivera et al., 2007). Vegetation establishment promotes further vertical accretion by trapping sediment and stabilizing these developing surfaces (Tal and Paola, 2007; Braudrick et al., 2009; Dean and Schmidt, 2011), and this process effectively converts these benches to floodplains.

Stratigraphically, floodplains are composed of obliquely and vertically accreted interbedded deposits of sand and mud (Allred and Schmidt, 1999; Ferguson and Brierley, 1999; Moody et al., 1999; Page et al., 2003). Obliquely accreted sediment has both lateral accretion and vertical accretion components. The lateral component is what causes the channel to narrow, and the vertical component causes these surfaces to grow upward in elevation relative to the channel bed. The crests of channel banks and levees are composed of coarser sediment than the floodplain trough. Sediment fines away from the channel: from sand and silty sand within the floodplain crests to sandy and silty clay in the floodplain trough (Moody et al., 1999; Allred and Schmidt, 1999; Pizzuto et al., 2008). On the channel side of the floodplain crest, bedding slopes toward the channel at steep angles, while in the floodplain trough, bedding planes are horizontal or slope gently away from the channel. Many studies have described the lateral trends in floodplain bedding and sedimentology, but with the exception of Nanson (1980), few studies have described vertical trends through the deposit.

Nanson (1980) showed that scroll bars and their related floodplains form through the initial migration of gravel and sand onto the upstream portions of point bars, which are then sorted downstream as velocities decline around the channel bend. A gradual transition from coarse bed load to fine suspended load occurs upward through the floodplain, and the sediments grade from large-scale cross-stratified gravel and sand at the base into small-scale cross-stratified and structureless silts at the top. In the upper portions, when suspended load deposition is dominant, a distinctive floodplain ridge (initial scroll) forms near the channel that thins onshore. Above this "initial scroll," vertical accretion through suspended-sediment deposition is the dominant mechanism. Sedimentologically, scroll bars evolve from coarse-grained channel features to fine-grained floodplain features that generally fine downstream, upward, and onshore. Nanson (1980) provided a complete sedimentologic analysis of scroll bars and their related floodplains but did not, however, investigate the timing and rate of formation for these features.

STUDY AREA

Big Bend National Park lies within the greater Big Bend region, which extends from the confluence of the Rio Grande and Rio Conchos 490 km downstream to Amistad Dam (Fig. 1). Today, the Rio Grande in the Big Bend region is single-threaded and flows through wide alluvial valleys in structural basins and narrow canyons that cross intervening ranges. Average channel slope ranges from ~0.0005 in the alluvial valleys to 0.002 in the canyons. The bed of the Rio Grande is predominately sand and mud, although gravel bars occur at the mouths and downstream from ephemeral tributaries, and in canyons. In the alluvial valleys, terraces exist at many elevations and bound the modern floodplain, providing evidence of the long-term cycles of degradation and aggradation that have occurred since the late Pliocene–early Pleistocene geologic history of the river

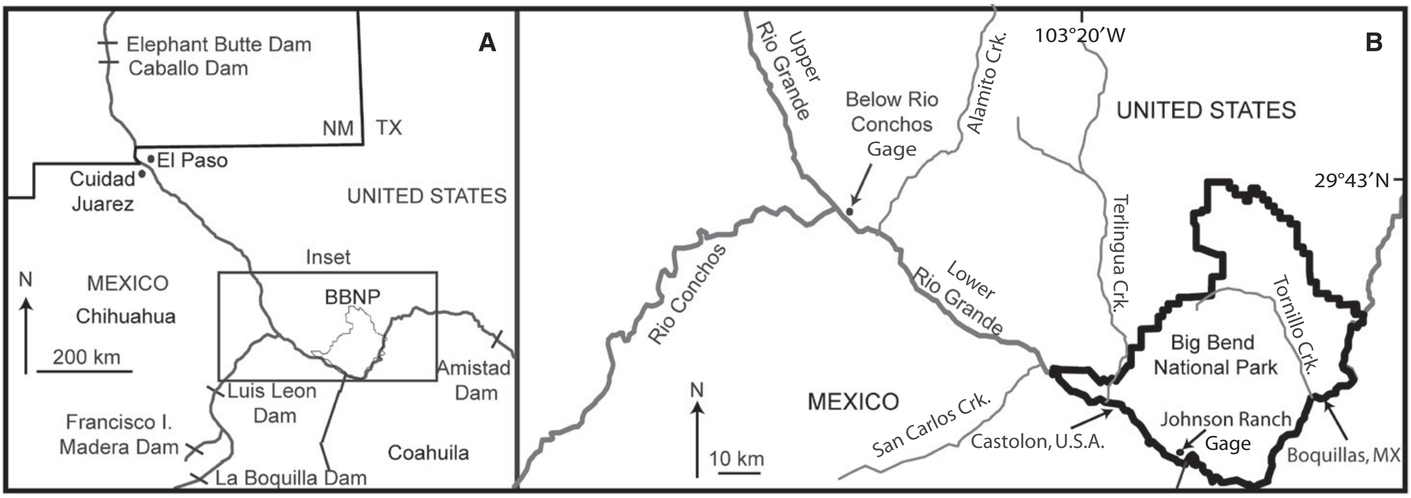

Figure 1. (A) Map of the Big Bend National Park (BBNP) region. (B) Study area.

(Berry, 2008). Modern floodplain topography consists of levees, benches, scroll bars, point bars, and flood basins.

Rio Grande floods have high suspended loads of sand and mud. Modern sources of sediment are the Rio Conchos downstream from Luis Leon Dam (Fig. 1) and regional ephemeral tributaries that drain the sparsely vegetated Chihuahuan Desert. The largest ephemeral tributaries in the region are Alamito, San Carlos, Terlingua, and Tornillo Creeks (Fig. 1B).

Dean and Schmidt (2011) described the geomorphic history of the Rio Grande in the Big Bend since the turn of the twentieth century. In the early 1900s, spring snowmelt in the Rocky Mountains and monsoon rains and tropical storms in the Sierra Madre Occidental caused frequent, large (>1000 m^3/s), long-duration floods (Schmidt et al., 2003; Dean and Schmidt, 2011). The Rio Grande was wide, multithreaded, and laterally unstable (Dean and Schmidt, 2011). Spring snowmelt is now entirely dammed and diverted in southern Colorado, New Mexico, and the El Paso–Juarez valley, and runoff in the Rio Conchos watershed is heavily impacted by dams and diversions for irrigated agriculture (Schmidt et al., 2003). Modern floods are typically low to moderate in magnitude (<1000 m^3/s) and of short duration, and they occur from dam releases on the Rio Conchos or from flash floods on ephemeral tributaries. Dean and Schmidt (2011) showed that between 1944 and summer 2008, the channel narrowed by 50% and was converted from multiple threads to a single thread.

Dean and Schmidt (2011) used aerial photographs and discharge measurement data from the International Boundary and Water Commission (IBWC) gage at Johnson Ranch to show that the channel of the Rio Grande was widened three times since the 1940s (1978, 1990–1991, and 2008; a fourth event was inferred in 1958; Fig. 2). Channel widening occurred when tropical storms in the Rio Conchos watershed overwhelmed reservoir capacity and caused large floods (>1000 m^3/s, ~10 yr recurrence). Dean and Schmidt (2011) termed these floods "channel reset events," because they temporarily reversed the trend of progressive channel narrowing. Channel narrowing resumed after the floods of 1978 and 1990–1991 and is currently in the nascent stages following the 2008 flood. Thus, the modern trend of geomorphic change on the Rio Grande in the Big Bend region consists of episodic disequilibrium (Nanson, 1986; Nanson and Erskine, 1988; Dean and Schmidt, 2011) characterized by channel narrowing on

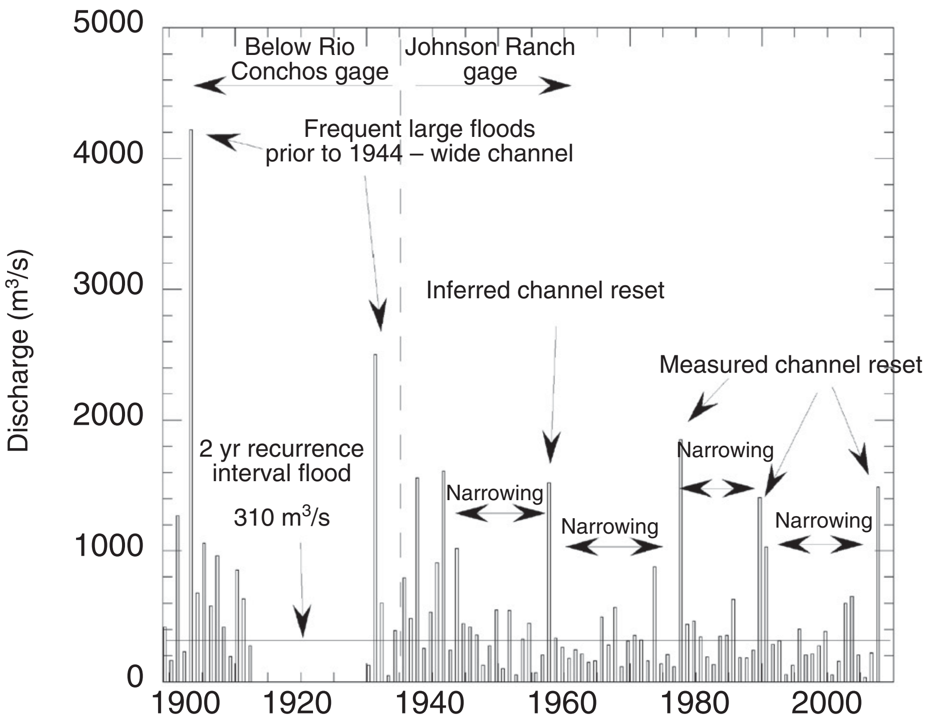

Figure 2. Annual peak floods at the International Boundary and Water Commission gages, Rio Grande below the Rio Conchos (#08-3742) and Rio Grande at Johnson Ranch (#08-3750). Geomorphic trends are described by Dean and Schmidt (2011).

decadal to multidecadal scales, punctuated by channel widening events caused by large, infrequent, long-duration floods. The timing of the disequilibrium channel changes is depicted in Figure 2. Annual peak data are from IBWC gages below Rio Conchos (#083742.00, record from 1900 to present) and Johnson Ranch (#083750.00, record from 1936 to present). Johnson Ranch data were used after 1935 because flash floods from ephemeral tributaries can significantly increase peak flows downstream from the Rio Conchos.

METHODS

Two trenches were excavated through the floodplain along relatively straight reaches of the Rio Grande, and the exposed bedding was mapped and interpreted. The Castolon trench was excavated in February 2008 near Castolon, Texas (Fig. 3). The Boquillas trench was excavated in January 2007 near the Rio Grande Village boat ramp, ~1.5 km upstream from Boquillas, Coahuila, Mexico (Fig. 3). The distance between the two trench sites is ~111 river km (Fig. 1). The Castolon trench was ~65 m long, and its maximum depth was 3.5 m. The Boquillas trench was ~45 m long and 3.35 m deep at its maximum.

Buried stems and roots of tamarisk (*Tamarix* spp.) and willow (*Salix exigua*) trees were excavated along the margins of the trenches. Each tree location was surveyed with a total station or a survey-grade global positioning system (GPS), and the excavated tree was photographed in situ. The buried portion of each tree was marked with nails at locations where an identified stratigraphic contact intersected the tree axis. We also noted the apparent elevation at which the tree germinated (Hereford, 1984). The germination point can be difficult to identify in the field based on gross morphology alone, so we used a hand lens to examine cross sections of the main plant axis to identify the point at which only root-wood anatomy existed (e.g., lack of pith; Schweingruber et al., 2006, chaps 1–2; Fig. 4). We then removed the buried axial stems and roots of the trees from each trench.

We analyzed changes in tree-ring anatomy due to burial, following methods described by Friedman et al. (2005). The removed stems were cut into cross-sectional slabs ~1 cm above the marked stratigraphic contacts. The slabs were then dried and sanded with progressively finer sandpaper to 600 grit. Rings were analyzed using a dissecting microscope, and ring widths were measured electronically using a Velmex measuring system with Measure J2X software. Burial signals were primarily identified by changes in wood anatomy and, in some cases, by abrupt declines in ring width. Burial signals consisted of reduced clarity of annual rings and changes in wood density related to an increase in the number and size of vessels typical of root-wood anatomy (Fig. 4). If burial occurred late in the year and an annual ring was mostly developed, burial signals may not have been apparent until the following year. Thus, there is generally 1 year of potential error for any given burial date.

Tree establishment date, elevation, and the location of burial signals along the tree axis were compared to the location of stratigraphic contacts in order to identify years in which individual beds were deposited. Seven tamarisk trees were removed from the Boquillas trench along with five tamarisk trees and one willow tree from the Castolon trench. Tree T23A in the Castolon trench had 3 stems, and we analyzed two of them. A Budweiser beer can was also found in the Castolon trench that helped constrain the dates of deposits that were older than deposits dated by the trees. Anheuser-Busch (Sahaida, 2008, personal commun.) provided the earliest and latest possible bottling dates based on can artwork. These dates were used to constrain the time of deposition, even though the consumption of the beverage and subsequent burial of the can may have occurred after the latest possible date of bottling.

For the oldest deposits within the Castolon trench, sediment samples were collected and analyzed using OSL to obtain dates of deposition. Samples were collected according to Utah State University (USU) Luminescence Laboratory protocols. Samples were analyzed by the USU laboratory using the single-aliquot regenerative-dose method (Murray and Wintle, 2000). OSL dating determines the last time sediment was exposed to light and, thus, was in transport before deposition (Aitken, 1998; Olley et al., 1999). During transport, sunlight bleaches accumulated latent radiation from grains of quartz and feldspar. After deposition, the bleached grains begin re-accumulating radiation from surrounding sediment. The amount of accumulated radiation can be determined by stimulating these grains with light in a laboratory and measuring the emitted luminescence using a photomultiplier. The measured luminescence is then used to calculate a deposition date. OSL is capable of dating sediment that was in transport as recently as a few years to a decade (Ballarini et al., 2003); however, the ability to obtain accurate deposition dates is dependent upon the strength of the bleaching event. In fluvial environments with large suspended loads, partial bleaching may occur, which may produce large uncertainty in the age determination (Galbraith et al., 1999; Murray and Olley, 2002; Rittenour, 2008).

Sediment samples were also collected for grain-size analysis at equally spaced intervals along the length of the trenches. At each

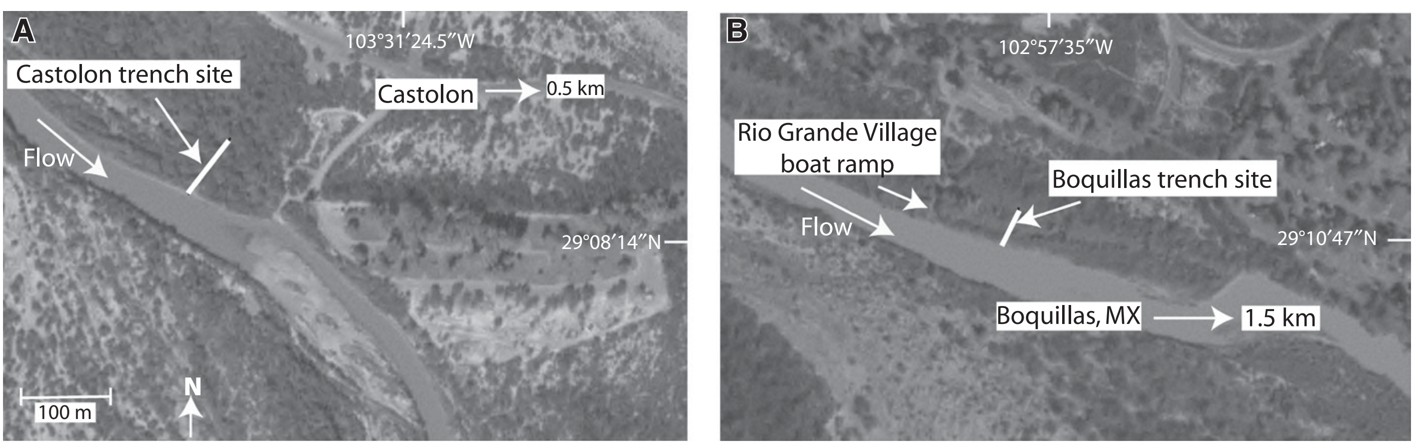

Figure 3. Vertical aerial photographs showing the locations of the Castolon (A) and Boquillas (B) trench sites. Aerial photo was taken in 2004. Trench locations are also shown in Figure 1B.

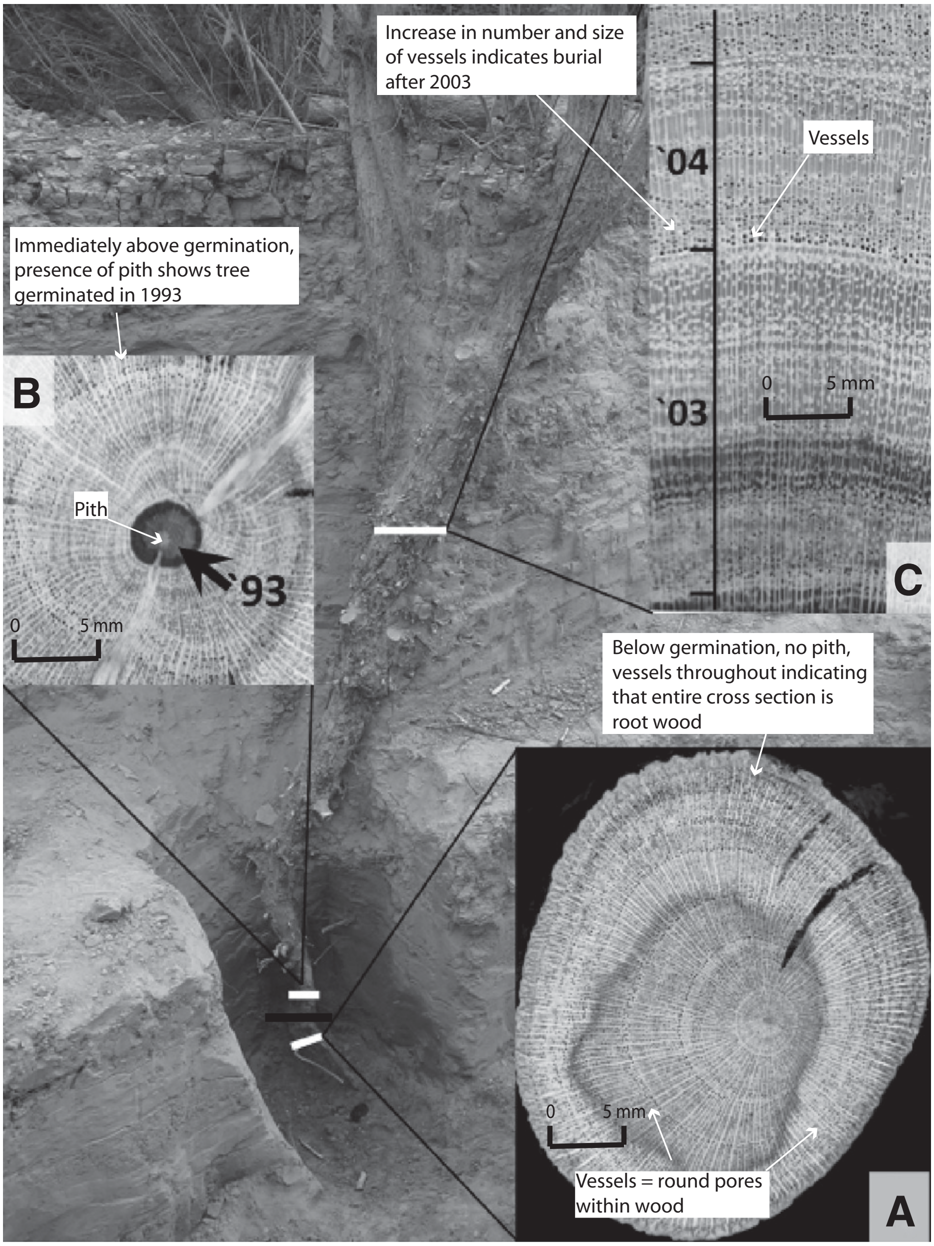

Figure 4. Excavated tamarisk T15 in Castolon trench (see Fig. 5D for locations). (A) The stem cross section immediately below the establishment surface (solid black line). Absence of pith indicates all root wood. (B) The stem cross section immediately above the establishment surface. Presence of pith indicates stem wood. Ring count indicates tree was established in 1993. (C) Burial signal as indicated by the increase in the number and size of xylem vessels. Ring count indicates burial occurred after 2003.

sampling location, samples were collected along vertical profiles to characterize grain-size trends vertically through the floodplain. Samples were analyzed at ½ phi intervals for sand, and hydrometer analyses were used to determine proportions of silt and clay. The presence of primary, secondary, and vegetation-induced sedimentary structures was also noted to determine depositional processes.

We describe floodplain formation by referring to the following geomorphic features: active channel, active channel bar, bench, and floodplain. These features are defined based on three criteria: (1) the relative elevation above the low-flow channel bed, (2) the cross-section surface topography of these features, and (3) the internal stratigraphic relationships and sedimentologic characteristics. The active channel is the portion of the river where bed-load transport regularly occurs and includes the main channel, side channels, and channel bars. Active channel bars are deposits within the active channel that generally have a convex surface or slope obliquely upward to the channel bank, are exposed at low flow, and are generally composed of gravel, but they may also be composed of sand and mud when located along channel margins or other low-velocity portions of the channel. A bench is an actively accreting, flat-topped body of sediment (Woodyer et al., 1979; Pizzuto, 1994) primarily composed of sand and mud; its elevation is higher than a bar, and its surface lacks distinctive topography such as a convex shape, a levee, and/or a trough (see following description). A floodplain is a body of deposits having the following characteristics: its surface is higher in elevation than a bench, and its surface topography is composed of a levee located near the channel margin and a trough further from the channel. The crest of the levee is the highest point on the floodplain, and the trough is the lowest. Inset deposits are those wherein bedding completely resides within the margins of an older floodplain or terrace. If these develop following a channel-widening flood, then they are the same as channel-expansion floodplains as described by Moody et al. (1999). Lastly, locations within the trenches are referred to by distance from the river channel at the time of trench excavation.

RESULTS

Timing of Channel Narrowing and Sediment Accretion

Dendrogeomorphic and stratigraphic analyses of floodplain deposits showed two periods of channel narrowing: from mid–1982 ± 2.5 yr to 1991, and from 1993 to 2008. Deposits from previous periods of narrowing described in Figure 2 were subsequently eroded or were not exposed in the trenches. The first period of narrowing occurred following the recession of a large flood in 1978 and was measured in the Castolon trench. These deposits accreted onto a buried cut bank, shown by a vertical erosional contact of horizontally bedded sediment at station 0 (Fig. 5B). The sediment within this cut bank was dated to 380 ± 110 yr and 360 ± 170 yr old using OSL (Table 1), and it is the oldest dated sediment within either of the trenches. Based on the dates of deposition and the slightly higher landform within which this sediment resides, we consider this surface to be a historic terrace (Osterkamp, 2008). The large error of these dates reflects the incomplete bleaching of the sediment prior to deposition. Considering error, the most recent deposition

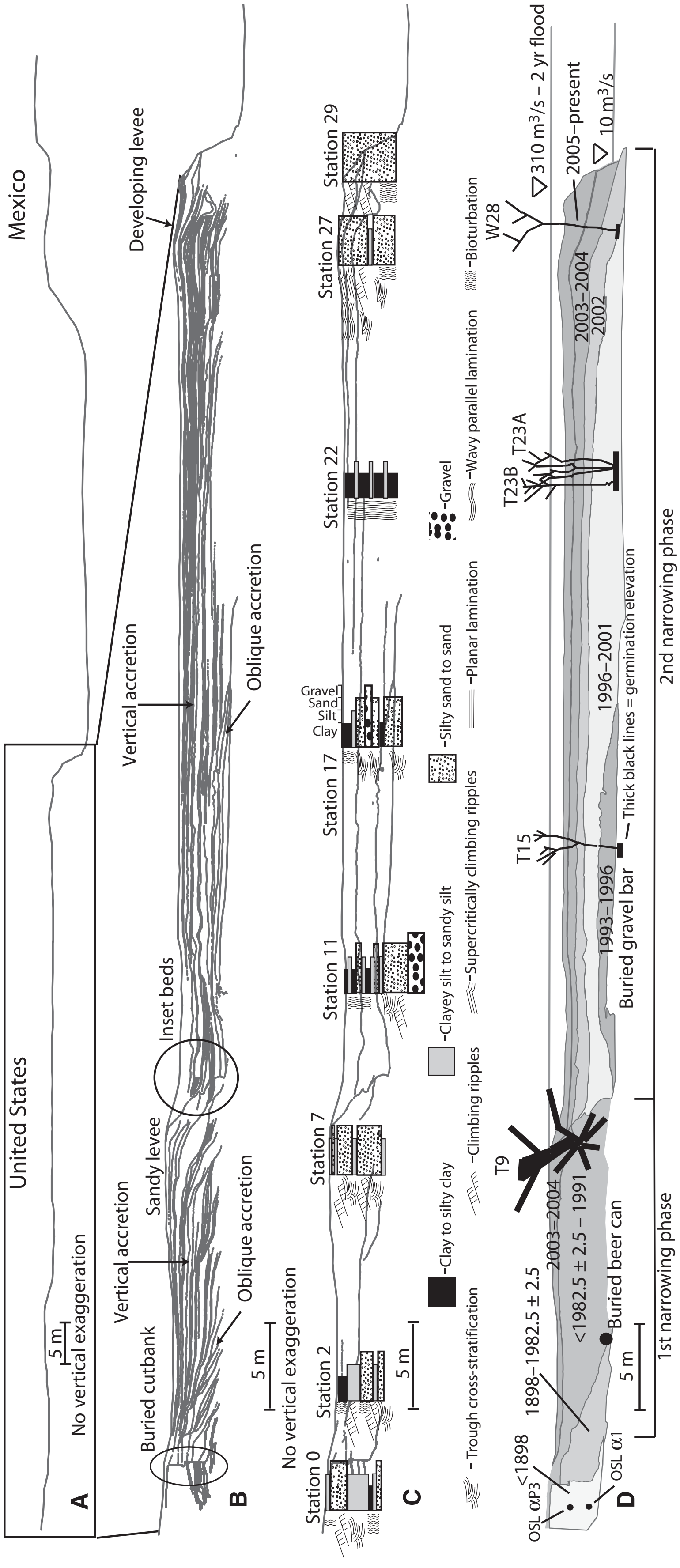

Figure 5. Stratigraphic, sedimentologic, and dendrogeomorphic analyses of the Castolon trench. (A) Surveyed channel cross section. (B) Mapped bedding, contacts defined by unconformities. (C) Stratigraphic columns, grain-size distributions, and dominant sedimentary structures. Grain size depicted is the dominant grain size of the bed. Internal gradational changes are not depicted. (D) Dated floodplain deposits and location of dated tamarisk (tamarisk codes listed). Germination horizons are indicated with dark black horizontal lines. Dates indicate periods of sediment accretion as observed from the wood anatomy of tamarisk trees. Stages of the base flow (~10 m^3/s) and the approximate 2 yr flood stage (310 m^3/s) are also displayed. Stages shown are based on measurements from January 2008.

date of sediment within this terrace was in the early 1800s. The cut bank is the erosional contact within which all twentieth- and twenty-first–century sediment is inset.

In the Castolon trench, stratigraphic analyses and an approximate bottling date from the beer can showed that during the first period of narrowing, at least 20 m of narrowing and 3 m of vertical accretion occurred. Vertical accretion occurred at a rate of 35 ± 8 cm/yr (Fig. 5, first narrowing phase, stations 2–7). The basal portion of these deposits consists of sediment obliquely accreted onto a buried cut bank near station 0 (Figs. 5B and 5D). Upward through the deposit, vertical accretion became dominant. The upper portion of the floodplain contained thick beds of cross-stratified sand that formed a natural levee near station 7. This levee, along with a levee in the Boquillas trench (Fig. 6, station 24), contained the thickest measured deposits. We infer that the channel-widening floods of 1990 and 1991 created these levees, because all bedding below was truncated and contacts were erosional, and trees growing on top of these deposits were established after 1991 (Figs. 7A and 7B). The thickest levee deposit in the Castolon trench was 1 m thick; the thickest levee deposit in the Boquillas trench was nearly 0.8 m thick.

The second period of channel narrowing occurred following the recession of channel resetting floods in 1990 and 1991, and it was measured in both the Castolon and Boquillas trenches. Dean and Schmidt (2011) described the rate and magnitude of narrowing during this period. They showed that narrowing occurred through the development of an inset floodplain within the flood-widened channel banks (Fig. 5, stations 7–29; Fig. 6, stations 32–39). Over 3.5 and 2.75 m of vertical accretion occurred after the 1991 flood at the Castolon and Boquillas trench sites (Dean and Schmidt, 2011; Figs. 5D and 6D, second narrowing phase), respectively, and the rate of vertical accretion was 20 and 16 cm/yr at these respective locations (Dean and Schmidt, 2011). Floodplain accretion occurred by the deposition of fine sediment on top of gravel bars exposed at the base of the trenches (Dean and Schmidt, 2011), which served as platforms for deposition. Oblique and vertical accretion occurred at the base of these deposits, and vertical accretion dominated the top of these deposits. A small levee formed near the channel margin in both trenches.

Dendrogeomorphic analyses indicate that tamarisk germinated in or after 1991 in two areas: on top of the 1990 and 1991 flood deposits high in the trenches, or within the widened active channel on low-lying channel bars. We determined these surfaces were bars based on their low elevation above the channel, their

TABLE 1. OPTICALLY STIMULATED LUMINESCENCE (OSL) AGE INFORMATION

Sample no.	Depth below ground surface (m)	Grain size (μm)	No. aliquots*	Equivalent dose (De) (Gy)	Dose rate (Gy/k.y.)	OSL age (ka)
Castolon α1	1.7	90–150	31(63)	1.09 ± 0.80	3.13 ± 0.15	0.38 ± 0.110
Castolon αP3	0.7	75–150	31(81)	1.09 ± 0.50	3.00 ± 0.14	0.36 ± 0.17

*Number of aliquots used for age determination; number of aliquots measured is in parentheses; error on equivalent dose and age is 1 standard deviation.

gravel composition, and the convex shape of their surface. Four of the trees were established in 1991 on the 1990 and 1991 flood deposits (T9 in Castolon trench and T19A, T19B, and T21 in the Boquillas trench; Table 2; Figs. 5, 6, and 7), and eight of the excavated trees were established within the active channel in or after 1993 (T15, T23A, T23B, and W28 in Castolon trench and T33.5, T34A, T34B, and T35 in Boquillas trench; Table 2; Figs. 5, 6, and 7). Seven of the eight trees within the active channel established themselves between 1993 and 1996 during a period of extremely low flows. Flows in 1994 and 1995 never exceeded 127 m^3/s (Fig. 7) (approximately a 1 yr recurrence flood at the Johnson Ranch gage). A second stem of tree T23A sprouted in 1997, and the willow tree in the Castolon trench (tree W28) established itself in 1998.

After the establishment of the trees within the active channel, sediment accretion on the channel bars progressively narrowed the channel and raised the elevation of these surfaces. Most sediment accretion occurred during years of moderate flooding between 1996 and 2001, and between 2003 and 2007 (Fig. 7). Floods between 1996 and 2001 ranged between 206 and 404 m^3/s (recurrence intervals between ~1.5 and 3 yr), and floods between 2003 and 2007 were between 186 and 651 m^3/s (recurrence intervals between ~1.4 and 7 yr). Burial signals within the trees indicate that between 1996 and 2001, ~0.6 and 1.5 m of vertical accretion occurred in the Castolon trench and ~0.8 and 1.4 m of vertical accretion occurred in the Boquillas trench (Figs. 5D, 6D, 7A, and 7B). Between 2003 and 2007, between 1 and 1.5 m of vertical accretion occurred in the Castolon trench (Fig. 7A) and 0.8–1.05 m of vertical accretion occurred in the Boquillas trench (Fig. 7B). Most of this accretion occurred in 2003 and 2004 in response to two floods of 599 and 651 m^3/s (recurrence interval of ~5–7 yr; Fig. 7C), which were the only floods capable of burying the trees on top of the sandy levees (Figs. 5, 6, and 7).

Sedimentologic Characteristics and Depositional Relationships

Sediment at the base of the trenches consists of sand and mud overlying gravel. The surfaces of the deposits are convex on top of underlying gravel bars or are inset obliquely onto these bars or against the flood-widened channel margins of 1978 and/or 1990–1991 (Figs. 5 and 6). Bedding ranges in thickness between 10 and 40 cm and is composed of clay, silt, and fine sand. Lenses of gravel are present but in small proportions. There are both erosional and conformable contacts. Beds of mud are often massive and appear to have settled out of suspension during low flow. Muddy beds often show signs of chemical reduction such as patches of secondary green or gray coloration that are generally spatially independent of any discernible bedding. Sandier beds are stratified and display bed forms indicative of both bed-load and suspended-sediment transport. Bed forms include extensive small-scale ripple drift cross-stratification, wavy parallel lamination, planar lamination, and to a lesser extent, climbing ripples, and a few supercritically climbing ripples (Fig. 8). Thin (0.5–10 cm), discontinuous bands of silt and clay are present. Bioturbation exists, but in small occurrences. Vegetation-induced sedimentary structures (Rygel et al., 2004) are occasionally present and usually consist of root casts and mud-filled hollows formed by roots penetrating sandy substrates below the ground surface or by decayed vegetation that has been replaced by mud. Downturned beds, formed by decayed vegetation and soft-sediment deformation, also occasionally exist.

Above these convex or obliquely accreted deposits at the base of the trenches, beds are vertically accreted on top of, or inset obliquely within, the convex beds of sand and mud. The surfaces of these deposits are flat-topped and resemble benches. Contacts are dominantly conformable, but some thicker deposits near the channel margins have erosional basal contacts (Fig. 9A). There is the occasional presence of coarse sand and fine gravel, indicating that at some discharges, coarse-grained bed-load transport occurs. Bedding generally consists of sand that gradationally fines upward into caps of silt and clay. The basal contacts of individual beds were identified based on abrupt changes in grain size between the mud below and the sand above, and occasionally by erosional contacts. Bedding ranges in thickness between 5 cm and 1 m; however, most beds are less than 20 cm. Near the channel margin, bedding is inclined upward away from the channel (Fig. 9A) and is sandy with thin caps of silt and clay. In these locations, beds are dominated by ripple drift cross-stratification and parallel lamination that is planar or wavy. Ripple migration direction is downstream or obliquely downstream away from the channel. Climbing ripples and supercritically climbing ripples are present but comprise a small proportion of these deposits. Further from the channel, bedding becomes horizontal, with alternating couplets of thin, rippled, very fine to medium sand that fines upward into thicker caps of silt and clay (Fig. 9B). Stratified sand is often only 2–5 cm thick in the horizontally bedded deposits, and mud caps are thicker and sometimes contain mud cracks. Rippled sands often contain stratified vegetation fragments. At the points most distal from the channel, some beds are entirely mud.

Extensive bioturbation exists within these bench deposits, especially in the muddy portions distal from the channel. Buried decomposing plants and extensive vegetation-induced sedimentary structures are present, including mud-filled hollows, root casts, upturned beds, downturned beds, and scour-and-mound beds. The quantities of bioturbation and vegetation-induced sedimentary structures indicate that these deposits are emergent for longer periods than the underlying beds. Most of the tamarisk and willow trees removed from the trenches germinated at the base of the bench deposits, indicating suitable moisture levels and an intermittent disturbance regime. Tamarisk stems removed from these deposits recorded progressive, up-stem burial events with anatomical shifts from stem wood to root wood.

Natural levees are vertically accreted on top of the bench deposits near the channel margin, and bedding is nearly entirely horizontally bedded. Beds range in thickness between 50 cm and 1 m within the levees. Levees are often erosional at the base, but they sometimes conformably drape onto underlying beds (Fig. 10A). Levees are composed of very fine and fine sand, and they are capped by thin bands of silt and clay ranging in thickness between 0.5 and 5 cm. Occasionally, complete flood cyclothems, or rhythmites exist, which consist of planar laminated mud that coarsens upward into ripple drift cross-stratified sand that fines upward into caps of mud. This sequence represents deposition throughout the complete rise and fall of a flood

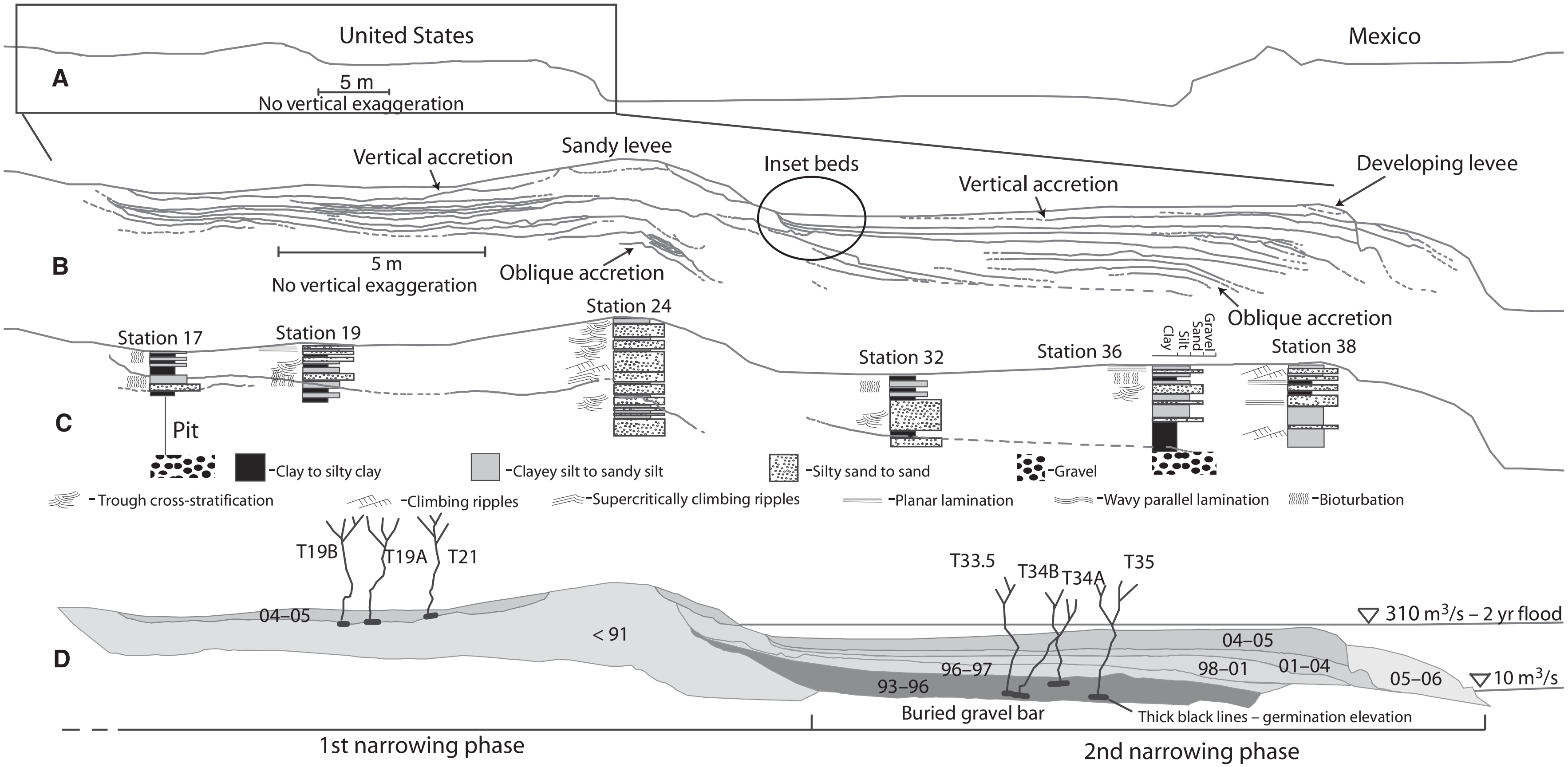

Figure 6. Stratigraphic, sedimentologic, and dendrogeomorphic analyses of the Boquillas trench. (A) Surveyed channel cross section. (B) Mapped bedding, contacts defined by unconformities. (C) Stratigraphic columns, grain-size distributions, and dominant sedimentary structures. Grain size depicted is the dominant grain size of the bed. Internal gradational changes are not depicted. (D) Dated floodplain deposits and locations of dated tamarisk (tamarisk codes listed). Germination horizons are indicated with dark black horizontal lines. Dates indicate periods of sediment accretion as observed from the wood anatomy of tamarisk trees. Stages of the base flow (~10 m^3/s) and the approximate 2 yr flood stage (310 m^3/s) are also displayed. Stages shown are based on measurements from January 2007.

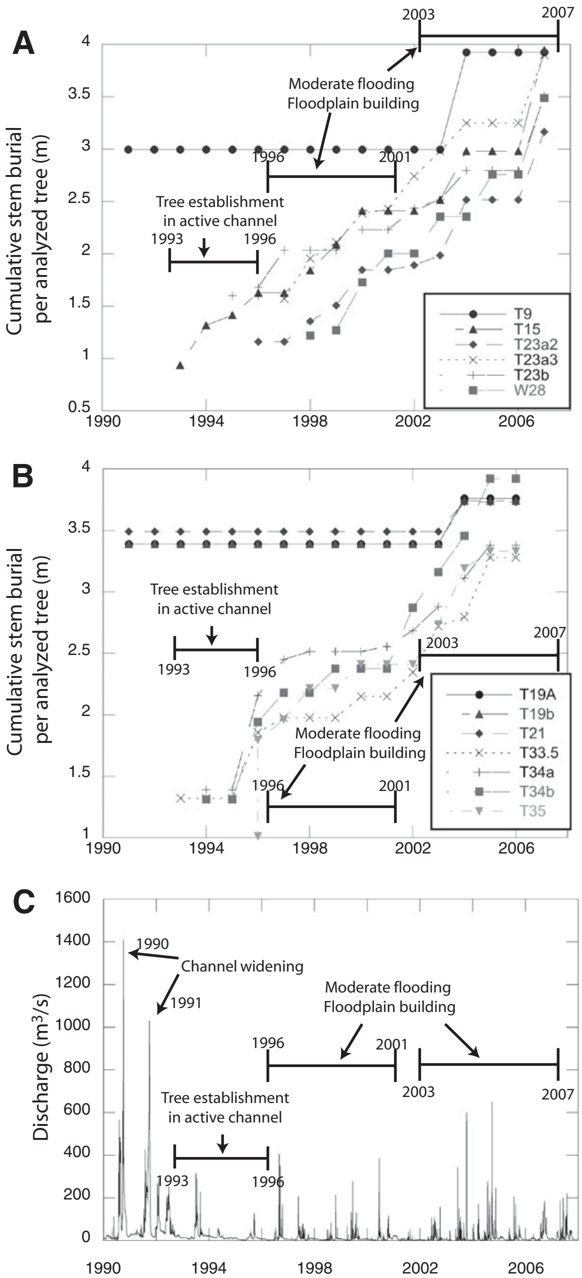

Figure 7. Depth of burial and associated hydrograph for analyzed trees. (A) Cumulative stem burial for trees analyzed from Castolon trench. (B) Cumulative stem burial for trees analyzed from Boquillas trench. (C) Stream flow recorded at the Johnson Ranch gage in Big Bend National Park between 1990 and 2008. Establishment elevations of the trees are relative to the elevation of the channel bed at the time of trench excavation. Note that most trees germinated during the period of low stream flow within the active channel between late 1993 and 1996 and were buried by moderate-magnitude floods between 1996 and 2001 and between 2003 and 2007.

(Nanson, 1980; Brierley et al., 1997). Sands within the levees are dominated by climbing ripples, supercritically climbing ripples, and sinusoidal ripple lamination, and a small portion of these deposits contains ripple drift cross-stratification and planar lamination (Fig. 10). Some beds are inset into the natural levees, which reflect deposition by small floods that did not inundate the levee crests. The mud caps on the levee deposits indicate that the supply of silt and clay is not limited.

Levee-building sands fine rapidly away from the channel into thin beds (2–10 cm) of faintly cross-stratified very fine sand capped by silt and clay. Mud caps are often cracked and filled with very fine sand from the overlying bed. There are also thin beds that onlap the distal portion of the levee. These beds were deposited by floods that did not inundate the levee crests, but filled the floodplain trough through breaks in the levees ("back-loading"; Filgueira-Rivera et al., 2007).

Within the deposits exposed near the top of the trenches, buried layers of duff exist between the underlying mud and the overlying deposit, reflecting a sufficient passage of time that duff could accumulate on the ground surface. Levees are generally colonized by non-native giant cane (*Arundo donax*), although some tamarisk trees occur, such as tree T9 in the Castolon trench. Vegetation-induced sedimentary structures and bioturbation are most prominent within these deposits. Within the levees, vegetation-induced sedimentary structures include mud-filled hollows, centroclinal cross strata, coalesced scour fills, and scour-and-mound beds (Fig. 11). Buried vegetation is common. Mud-filled hollows and root casts are most prominent in the deposits distal from the channel, and occasionally downturned beds exist.

Stages of Deposition

The sediments described here comprise the entirety of the deposits formed during the last two stages of channel narrowing. Within these deposits, we observed distinct stratigraphic and sedimentologic differences vertically through the deposits, reflecting an evolution in depositional processes that occurred during the creation of these landforms. Stratigraphic relationships evolved from oblique and vertical accretion of gravel, sand, and mud at the base of the deposits, to the vertical accretion of sand and mud at the top. The topography of the bedding surfaces transitions from convex-topped or inclined deposits at the base, to flat-topped bench deposits in the middle, and natural levees at the top. Sedimentologically, deposits at the base of the trenches contain bed forms indicative of mixed bed-load and suspended-load deposition, and deposits at the top are dominated by suspended-sediment deposition. Based on these observations, we identified three components of floodplain formation: (1) the channel-margin bar component, (2) the floodplain conversion component, and (3) the floodplain component (Fig. 12). The depositional styles within these components are dependent upon the relative elevation of the developing surfaces to the channel bed, the capacity of flow to transport the available sediment onto the developing surfaces, the grain size of that sediment, and the relative amount of vegetation growing on these surfaces. Next, we summarize the key defining features of these components.

The deposits within the channel-margin bar component appear to comprise former unit bars of sand or mud. These are either convex in shape or obliquely accreted at the base of the trenches. We distinguish these deposits in four ways. First, the deposition of these deposits is significantly oblique and is responsible for the initial stage of narrowing (Figs. 5B and 6B). Second, bed forms are diverse and range from bed-load deposition of rippled, planar, or parallel laminated sand and at times gravel, to suspended-sediment deposition of mud and sand, the deposits of which may be massive or contain

TABLE 2. EXCAVATED TREE LOCATIONS AND DEPTHS

Trench	Tree*	Distance from channel bank (m)	Excavation depth (m) to germination	Germination date
Castolon	T9	48.6	0.93	1991
	T15	34	3.01	1993
	T23a2	15	2.01	1996
	T23a3	15	2.33	1997
	T23b	15	2.36	1995
	W28	4	2.27	1998
Boquillas	T19a	33	0.37	1991
	T19b	33	0.35	1991
	T21	29	0.24	1991
	T33.5	13	1.96	1993
	T34a	12	1.99	1994
	T34b	12	2.61	1994
	T35	11	2.32	1996

*T—tamarisk, W—willow, #—trench station number, a—upstream tree if more than 1 tree at a station, b—downstream tree, number following letter denotes stem number, i.e., T23a2 = upstream tamarisk at station 23, stem 2.

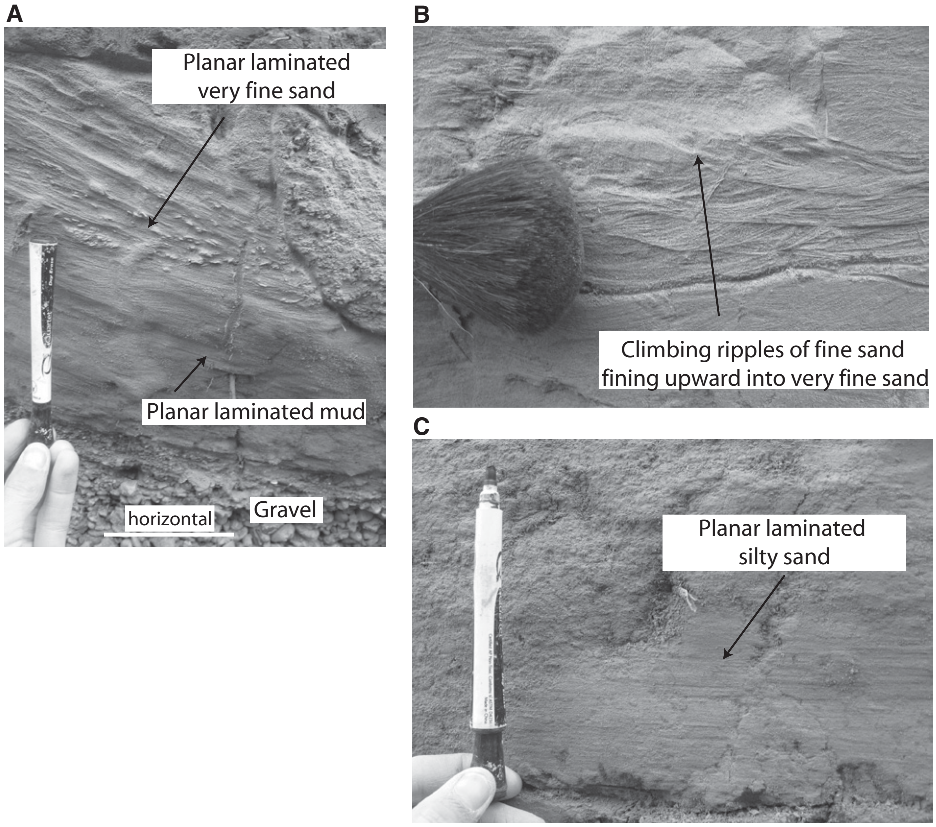

Figure 8. Sedimentologic characteristics observed within convex and inclined bedding at base of trenches. (A) Inclined parallel laminated silty sand overlying gravel deposit at the base of the Castolon trench. (B) Ripple drift cross-stratification fining upward into silty sand. (C) Planar bedded silty sand interrupted by overlying bioturbated mud. Marker is 13 cm long, and brush head is 5 cm in width.

supercritically climbing ripples (Table 3). Third, vegetation is rare and plays a minor role in deposition or subsequent reworking. Last, muds show signs of chemical reduction, indicating prolonged subaqueous submersion and a small elevation difference between these deposits and the former channel bed. These characteristics are all indicative of phenomena that occur within the boundaries of an active channel, and the massive, muddy deposits indicate that these deposits were formed in the low-velocity margins of the channel (Table 3).

The floodplain conversion component consists of deposits that vertically and obliquely build upon the channel-margin bars, and that have surface topography resembling flat-topped benches. The increase in elevation above the channel bed results in the increased prevalence of suspended-sediment deposition; however, coarse-grained bed load is occasionally present, indicating that at some discharges, active-channel deposition still occurs (Fig. 9C; Table 3). Bedding is dominated by the vertical accretion of fining-upward deposits of sand with mud caps formed during the rising and falling limbs of floods (Table 3).

There is little evidence of coarse bed-load deposition within the floodplain conversion component in the Boquillas trench; however, we distinguished the floodplain conversion component based on the presence of fining-upward couplets of sand and mud, which are not distinguishing characteristics of the channel-margin bar component (Table 3). Although many beds are dominated by mud, this component was differentiated from the channel-margin bar component because the muddy beds are not chemically reduced, beds are mud cracked, indicating subaerial drying, woody vegetation is present, and beds are extensively bioturbated. Beds also fine upward from silt and sand at the base to silt and clay at the top, which is not a distinctive feature of the channel-margin bar component (Table 3). These characteristics indicate that as a developing surface grows in elevation above the channel bed, floodplain processes, such as suspended-sediment deposition and woody vegetation establishment, begin to replace channel processes such as coarse-grained bed-load deposition. The floodplain conversion component consists of the sediment responsible for the upward growth of the channel-margin bar component and the transition from active-channel deposition to floodplain deposition.

The floodplain component is the body of sediment that forms the natural levees on top of the floodplain conversion component. The topography of the floodplain component is a distinguishing feature, with thick beds of sediment deposited from suspension near the channel, shown by the dominance of the supercritically climbing ripples and sinusoidal ripple lamination. Deposition within this component is nearly entirely vertical (Table 3). Vegetation is most dense within this component, and the accumulation of duff on top of deposits reflects the intermittent flooding and periodic deposition. The presence of a mesquite stem in the Boquillas trench also suggests that these surfaces may be stable for some time. This component is different than the floodplain conversion component because levees are built, sand and gravel are not present, and the density and cover of vegetation are the greatest (Table 3). The dense vegetation helps to stabilize these surfaces and inhibits possible erosional processes.

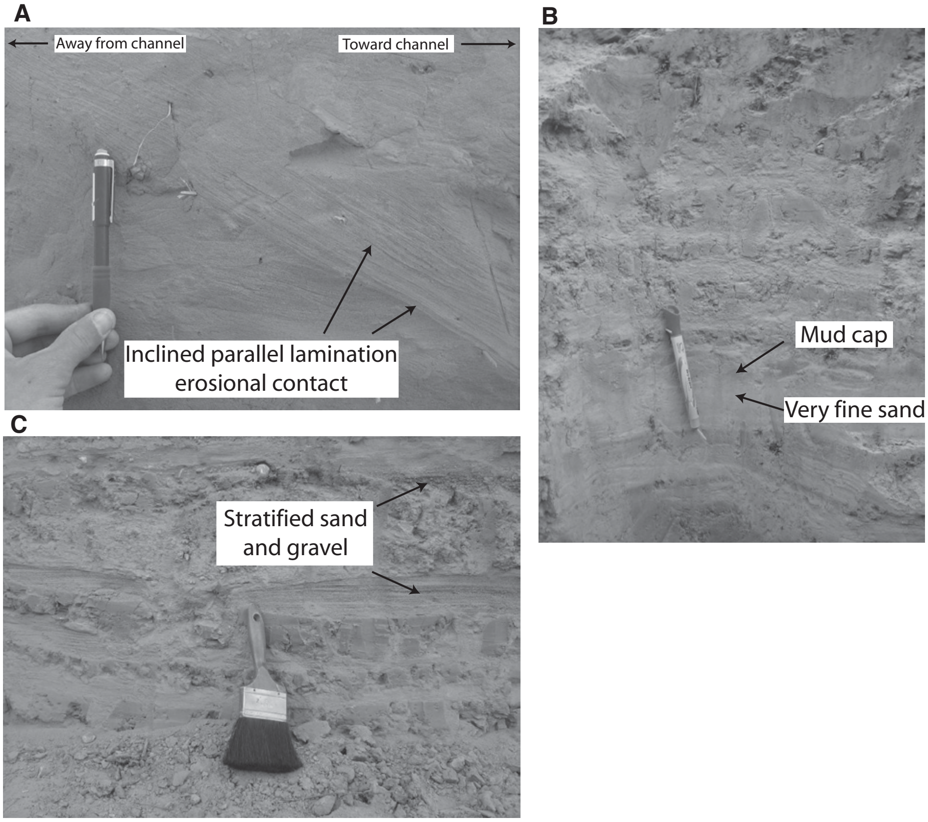

Figure 9. Sedimentologic characteristics observed within bench deposits. (A) Erosional contact showing inclined parallel lamination truncating ripple drift cross-stratification below. (B) Banded couplets of fine sand overlain by caps of dark mud. (C) Planar laminated bed load gravels inter-fingered with couplets of sand and dark mud. Pencil in A is 14 cm long, marker in B is 13 cm long, and brush in C is 25 cm long.

Grain Size

The deposits exposed in the trenches fine upward and onshore, and mean grain sizes decrease from very fine sand at the base of the trenches to coarse silt near the top of the trenches (Figs. 5C, 6C, and 13). The decrease in sorting from the channel-margin bar component to the floodplain component in the Castolon trench reflects the difference in grain size for the thick sand units within the levees and the mud in the floodplain trough (Fig. 13). Grain sizes within the Boquillas trench for the channel-margin bar and floodplain conversion components are similar, but we were able to distinguish them based on the style of deposition—the sediment within the channel-margin bar component was predominantly mud and lacked sedimentary structures, whereas the sediment in the floodplain conversion component consisted of relatively thin, fining-upward couplets of sand and mud with faint ripple drift cross-stratification. The coarser texture and less-sorted nature in the Castolon trench probably reflect the influence of Terlingua Creek, a large tributary and major sediment source, located ~9 km upstream.

DISCUSSION

The analyses presented here show that channel narrowing on the Rio Grande occurred through an evolution of depositional processes as portions of the active channel were converted to floodplains. This evolution is apparent in the stratigraphic relationships and sedimentologic characteristics of these deposits, and we illustrate these in a depositional model that describes the stages of floodplain development (Fig. 14).

In the nascent stages of sediment deposition, sand and mud vertically and obliquely accreted on top of gravel bars (Fig. 14). Oblique accretion occurred as sediment was deposited at an angle inclined upward and away from the channel against the channel bar or channel margin similar to epsilon cross-stratification (Allen, 1963) and inclined heterolithic cross-stratification (Thomas et al., 1987). The main difference between oblique accretion and epsilon cross-stratification and inclined heterolithic cross-stratification is that oblique accretion contains a significant vertical component as well as a lateral component. Many beds were also convex in cross-section shape because they were draped onto the underlying gravel bars. This initial stage of deposition occurred within the active channel, as indicated by the range of bed forms and grain sizes present, the absence of vegetation, and the relatively small elevation difference between these deposits and the low-flow water surface. Based on these characteristics and their surface morphology, these deposits resembled channel-margin bars. After the 1990 and 1991 floods, this initial stage of deposition occurred during a period of low peak flows (recurrence intervals of ~1 yr).

Moderate flooding (recurrence intervals between 1.5 and 3 yr) between 1996 and 2001 caused additional accretion of sediment upon the channel-margin bar deposits that were exposed at the base of the trenches. These deposits were no longer inclined upward away from the channel, but were flat-topped benches. Sediment deposited during this period was also vertically and obliquely accreted; however, the bed forms present, such as supercritically climbing ripples and sinusoidal ripple lamination, indicate that suspended-sediment deposition began to dominate. The transition from mixed bed-load and suspended-load deposition of mud, sand, and gravel in the channel-margin bar deposits to dominantly suspended load deposition of sand and mud in the overlying deposits indicates that depositional processes evolved as the developing surfaces continued to grow above the channel bed. The occasional presence of coarse sand and gravel bed load, however, indicates that during some discharges, these surfaces still resided within the active channel. Woody vegetation also began to proliferate, indicating suitable moisture levels and an intermittent disturbance regime that allowed plants to successfully establish themselves on these surfaces. After successful establishment, these plants were continually buried by additional vertical accretion of fine sediment. We classified these deposits as the floodplain conversion component because they were intermediate deposits that contained many features indicative of floodplains (supercritically climbing/sinusoidal ripple lamination, woody vegetation) but also included occasional evidence of features found within the active channel (gravel bed load). The oblique accretion of both the channel-margin bars component and floodplain conversion component was the mechanism responsible for narrowing the channel (Fig. 14).

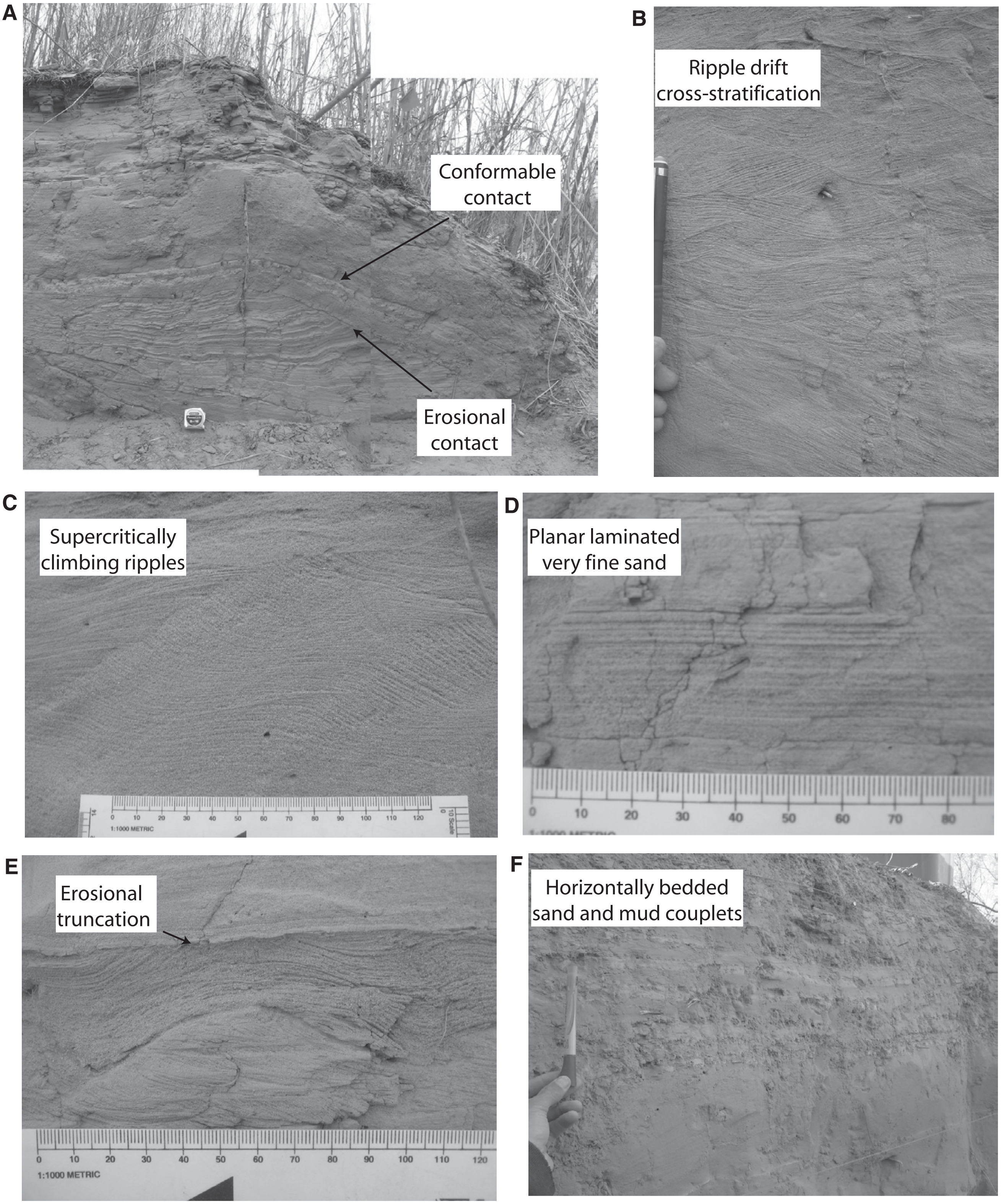

Figure 10. Sedimentologic characteristics of levee and trough deposits near top of trenches. (A) Sediment of levee in Castolon trench near station 27. Note the erosional truncation of parallel laminated sediment in center, and the conformable sediment drapes that form the levee crest. (B) Ripple drift cross-stratification within the levee. (C) Supercritically climbing ripples within levee. (D) Planar laminated very fine sand. (E) Erosional truncation of rippled sand by overlying planar-bedded sediment. (F) Horizontally bedded vertically accreting couplets of sand and mud within floodplain trough. Steel tape in A is 8 cm long, pencil in B is 14 cm long, scale card in C is 15 cm long, scale bar in D is 9 cm long, scale bar in E is 12.5 cm long, and marker in F is 13 cm long.

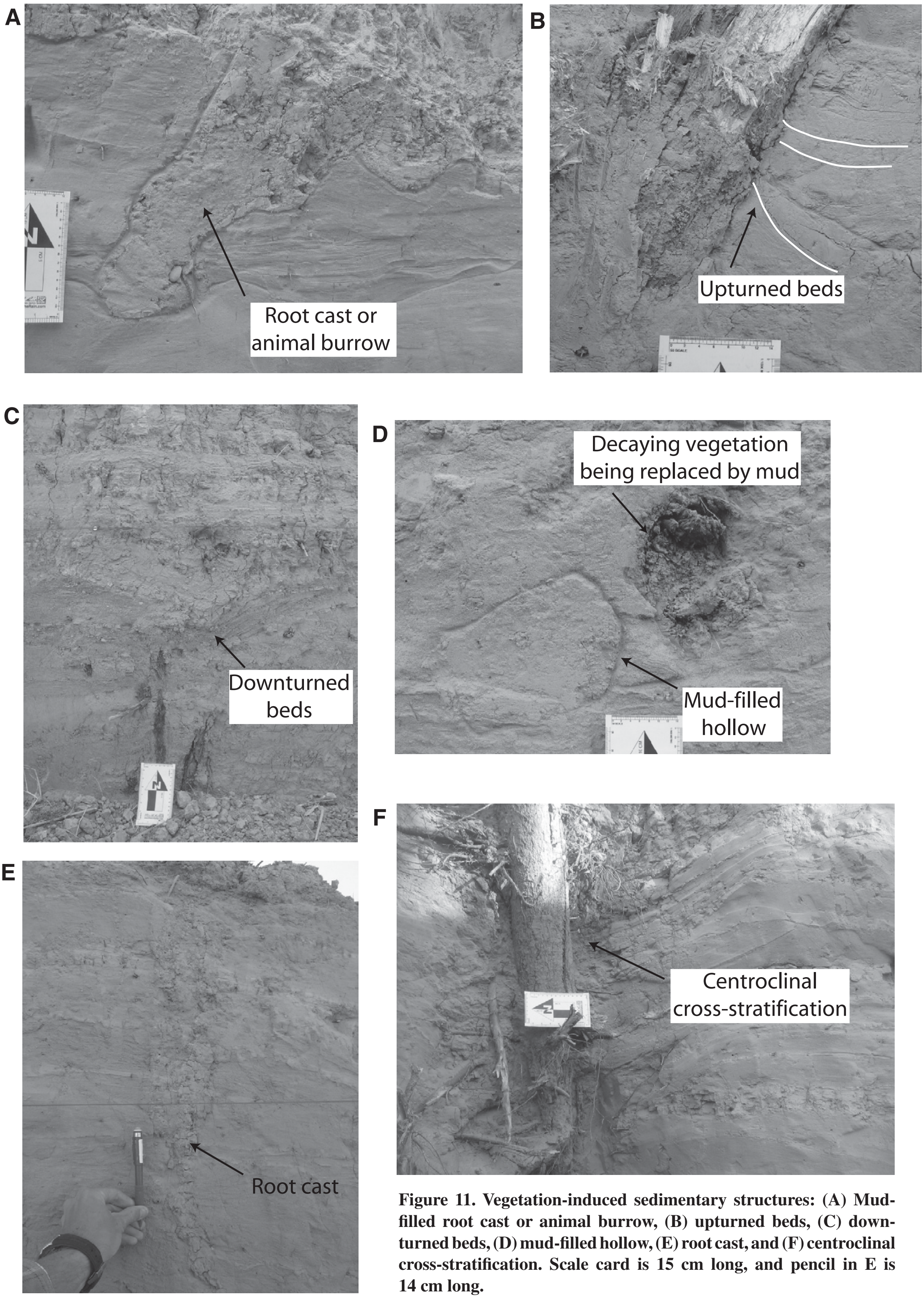

Figure 11. Vegetation-induced sedimentary structures: (A) Mud-filled root cast or animal burrow, (B) upturned beds, (C) downturned beds, (D) mud-filled hollow, (E) root cast, and (F) centroclinal cross-stratification. Scale card is 15 cm long, and pencil in E is 14 cm long.

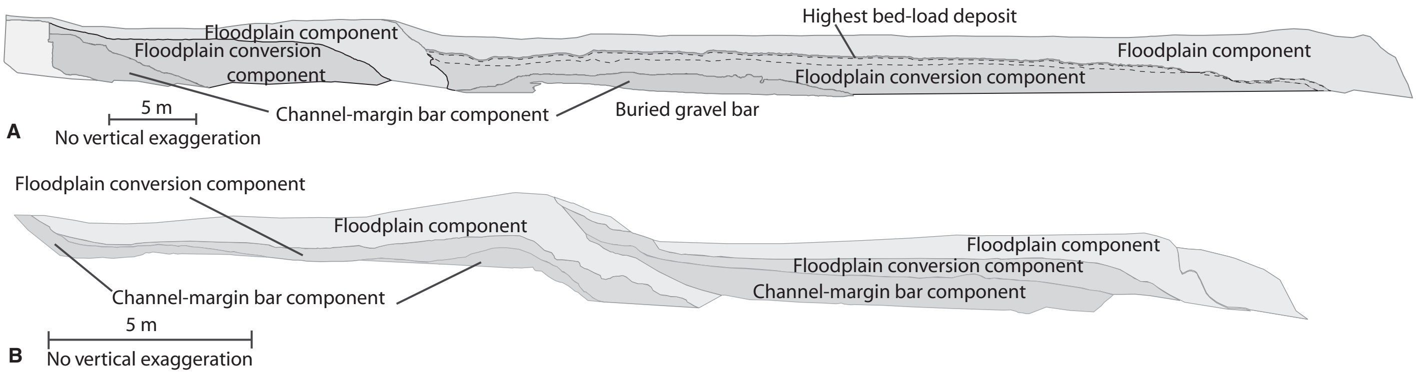

Figure 12. Depositional components of (A) Castolon trench and (B) Boquillas trench.

TABLE 3. DEFINING CHARACTERISTICS OF DEPOSITIONAL COMPONENTS

Component	Surface topography/ bedding orientation/ accretion style	Grain sizes present	Bed-load or suspended-load deposition	Sedimentary structures	Bioturbation and vegetation influence	Other characteristics
Channel-margin bar	Convex or inclined upward away from channel, oblique accretion	Gravel, sand, and/or mud	Mixed bed load and suspended load	Massive mud, ripple drift cross-strata, planar and parallel lamination, few occurrences of climbing and supercritically climbing ripples	Minor burrowing, few occurrences of root disturbance, woody vegetation generally absent but may establish within uppermost beds of component	Beds may fine upward, coarsen upward, or show little grain-size trends laterally or vertically
Floodplain conversion	Flat-topped, bedding dominantly horizontal but may be inclined near channel margin, oblique and vertical accretion	Dominated by sand and mud, occasional presence of coarse sand and fine gravel	Dominated by suspended load, but bed-load deposits of sand and gravel bed load may exist	Ripple drift cross-strata, climbing ripples, supercritically climbing ripples, and sinusoidal ripple lamination near channel margin, lesser occurrences of planar lamination; muddy beds may be cracked	Woody vegetation establishes near base of deposits and is rooted within uppermost channel-margin bar deposits, vegetation density is moderate, vegetation-induced sedimentary structures present	Beds generally fine upward from very fine sand and sandy silt into mud caps
Floodplain	Levee and trough topography, bedding horizontal, vertical accretion	Sand and mud	Suspended load	Climbing, supercritically climbing, and sinusoidal ripple lamination within levees near channel margin; climbing ripples and ripple drift cross-strata within trough; massive mud caps, which may be cracked	Dense woody vegetation, vegetation-induced sedimentary structures prevalent throughout	Duff present between beds

After the adjustments in channel width through the oblique accretion of the channel-margin bar and floodplain conversion components, vertical accretion of fine sand and silt resulted in the formation of natural levees. Levees were built upward as a ridge, similar to a scroll bar (Nanson, 1980), forming steep banks at the river margin and a gentle slope toward the floodplain trough (Brierley et al., 1997). The most prominent levees were constructed during the large flood events in 1990–1991. The smaller levees at the channel margins were constructed by floods having a recurrence interval of ~5–6.6 yr (599 and 651 m^3/s). Thus, the size of the levees appears to be related to the magnitude of the flows that created them and the relative amount of sediment delivered by those flows. The fact that most of these deposits fine upward indicates that the supply of fine sediment does not appear to be limited on this river. The development of levee and trough topography, the nearly entirely vertical nature of accretion, the presence of dense vegetation, and the absence of any coarse bed load indicate that the developing surfaces were converted to floodplains.

Floodplain construction on the lower Rio Grande is similar to that documented in studies of the Powder River (Pizzuto, 1994; Moody et al., 1999; Pizzuto et al., 2008) and the Rio Puerco (Friedman et al., 2005), but a few key differences exist. Channel narrowing on the Rio Grande occurred within a flood-widened channel similar to that of the Powder, with gravel bars serving as a platform for floodplain development. Inset deposits, similar to the channel-expansion floodplains of the Powder River (Moody et al., 1999), grew upward through time, resulting in the formation of well-formed levees (floodplain crests) and gentle sloping floodplain troughs. Unlike the Powder River (Moody et al., 1999; Moody and Troutman, 2000) and studies on the Green River (Allred and Schmidt, 1999), the Rio Grande did not undergo a decline in floodplain inundation frequency over time as the developing floodplains increased in height above the main channel bed. In fact, Dean and Schmidt (2011) showed that a positive feedback occurred as the channel lost conveyance capacity, resulting in frequent overbank flow, even though the floodplain surface continued to grow in height above the river bed, and peak flows were relatively small.

Similar to the Rio Puerco (Friedman et al., 2005), channel narrowing on the Rio Grande occurred within the earliest stages of deposition through the oblique accretion of sediment, which reduced the wetted width of the low-flow channel. This indicates that channel narrowing generally occurs during the early part of the floodplain-building process. The early stages of narrowing on the Rio Puerco, however, occurred through the construction of levees that encroached on the thalweg (Friedman et al., 2005). These levees later lost relief as vertical accretion filled in the low-lying areas on the floodplain. On the Rio Grande, narrowing occurred as bedding

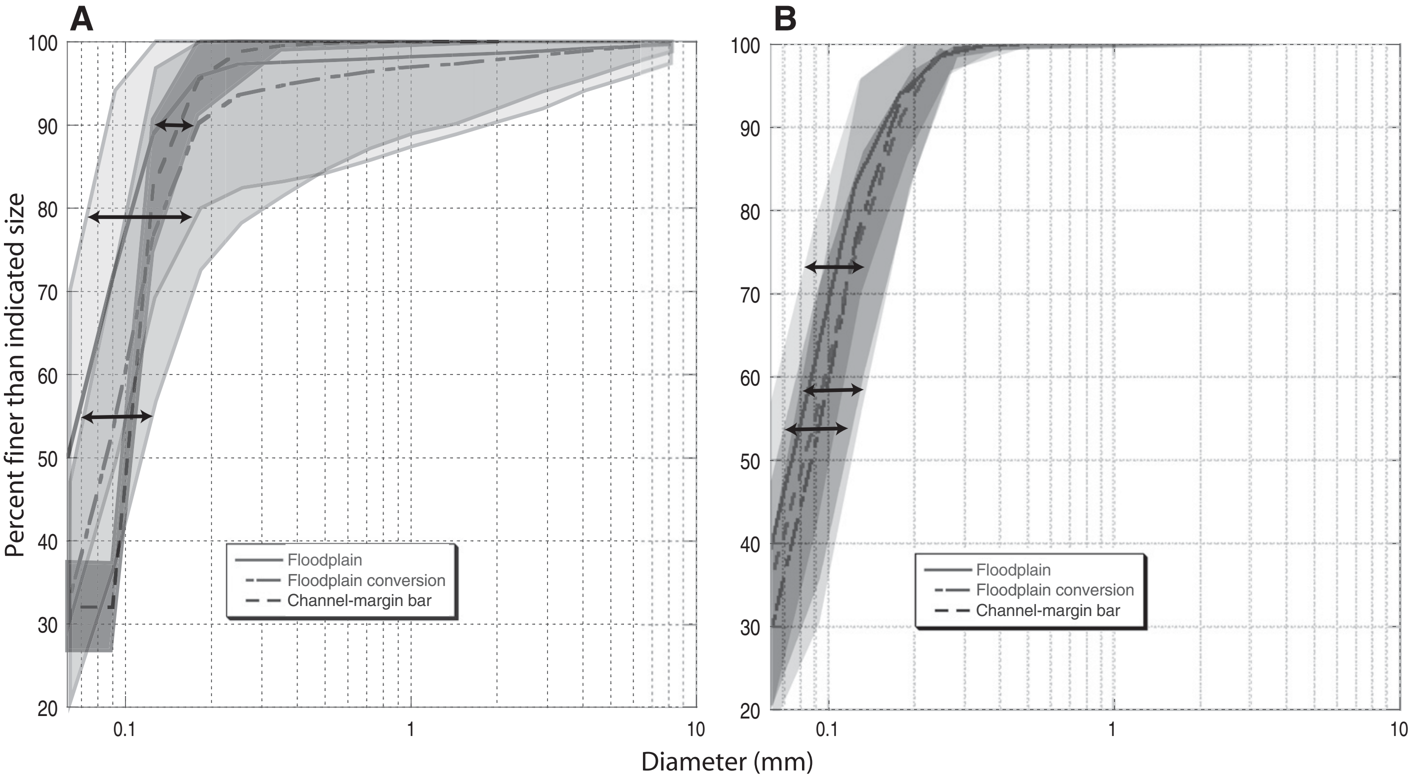

Figure 13. Average grain-size distribution of channel-margin bar component, floodplain conversion component, and floodplain component for the (A) Castolon and (B) Boquillas trenches. Shaded regions represent 1 standard deviation about the mean. Note that the floodplain component is finer than the other two components due to the increase in suspended-sediment deposition upward through the deposits. The coarser grain size and decreased sorting at the Castolon site are probably due to the proximity of the Castolon trench to Terlingua Creek, a large desert tributary and sediment source located ~9 km upstream.

progressively onlapped or was draped upon underlying deposits. The construction of levees came later, when vertical accretion dominated and floods were large enough to significantly inundate the developing floodplain. Thus, the Rio Grande levees were not constructed early in the floodplain-building process, because floods of sufficient stage and suspended-sediment concentration had not occurred. It was not until the 5–6.6 yr recurrence floods in 2003 and 2004 that the levees at the channel margin became prominent. There is also no evidence that the channel bed aggraded near the trench sites, in contrast to the Rio Puerco. We believe this is because moderate floods are still capable of scouring the muddy channel bed of the river, offsetting the effects of sediment accumulation on the channel bed during low-flow periods.

Another key distinction between our study and others is that in addition to showing lateral changes in depositional relationships and sedimentology within a floodplain, we show that channel narrowing occurred as in-channel deposition gave way to floodplain deposition as the elevation of developing surfaces increased above the bed of the river, and vegetation became established. The transition from mixed suspended-load and bed-load deposition to nearly exclusive suspended-load deposition upward through the deposits is similar to observations of scroll bar formation described by Nanson (1980).

The results of this study may provide insight for interpretations of ancient deposits. Episodes of channel narrowing may produce deposits that contain sediment representative of both in-channel and floodplain depositional processes. These different deposits may be in close proximity to one another or may be intermixed as portions of the active channel are converted to floodplains. Thus, deciphering this transition may allow new interpretation of ancient deposits that show this combination of depositional styles. The deposits observed on the Rio Grande are also similar to deposits (inclined heterolithic cross-stratification and epsilon cross-stratification) that usually occur at concave outer bends and convex point bars of meandering streams with high suspended-sediment loads (Allen, 1965; Woodyer, 1975; Woodyer et al., 1979; Nanson, 1980). Thus, depositional relationships in the rock record previously correlated to processes of meander migration may instead be due to episodes of channel narrowing.

In these instances, differentiation between channel-narrowing deposits and channel-migration deposits may be difficult if entire sedimentary sequences are not visible. Thus, the key to identifying floodplain deposits formed during episodes of channel narrowing would be the shift in depositional orientation from oblique at the base to vertical at the top, and the increased presence of fining-upward couplets vertically through a deposit. The relative influence of vegetation would also increase vertically and could be identified by the increased presence of vegetation-induced sedimentary structures, or fossil plant material.

With the exception of the largest floods, we were unable to develop a precise correlation between individual floods and our mapped stratigraphic records. This is a similar finding to Pizzuto et al. (2008), who attributed the inability to develop a precise correlation to the complex patterns of deposition and incomplete preservation of the deposits. Those reasons also apply to

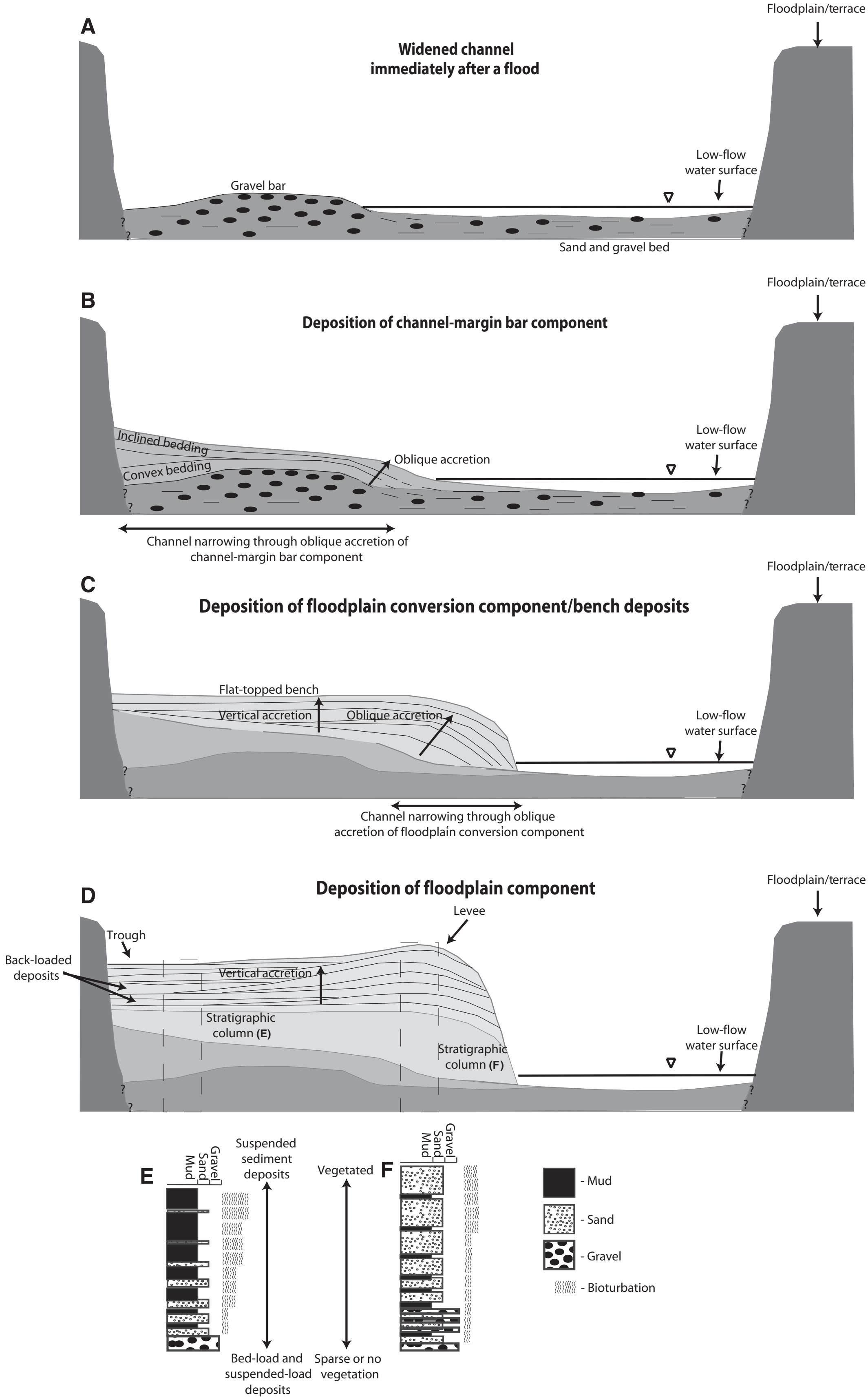

Figure 14. Depositional model depicting stages of inset floodplain formation on the Rio Grande. See text for definitions and descriptions of terms. (A) Extent of flood-widened channel and topography of the postflood channel bed. The postflood channel banks are composed of either a previous floodplain or terrace for which inundation frequency is greater than ~10 yr. The channel bed is composed of sand and gravel. (B) The initial stage of channel narrowing depicting the channel-margin bar component. Bedding is obliquely accreted, convex, or inclined upward away from the channel. (C) Characteristics of the floodplain conversion component depicting oblique and vertical accretion, and horizontal bedding resembling benches. (D) Characteristics of the floodplain component depicting vertical accretion, levee and trough topography, and back-loaded deposits. (E) Stratigraphic column depicting grain sizes of deposits distal from channel. Note the fining of grain sizes and increase in bioturbation upward through the deposits. (F) Stratigraphic column depicting grain sizes of deposits near the channel. Note the mixed grain sizes near the base, the interbedded sand and mud, and the increase in the amount of sand upward through the deposits which form the natural levee. Note that there is an increase in bioturbation upward through the deposits near the channel, but that there is less bioturbation than in deposits distal from the channel. Additional characteristics include the increase in suspended-sediment deposition, and vegetation upward through the deposits.

this study; however, on the Rio Grande, the inability to correlate individual deposits to specific floods is probably also attributable to the tremendously variable flood source, magnitude, and sediment supply on this river. Floods, whether small or large, may be derived either from the Rio Conchos or the many ephemeral tributaries that feed the Rio Conchos and Rio Grande. Many tributaries are capable of producing overbank floods on the Rio Grande, and the duration of these floods may be as short as 24 h and as long as a week or two. The sediment supplied by these floods is also tremendously variable and dependent upon the extent of precipitation in the Rio Grande–Rio Conchos basin or tributary basins, and the duration and intensity of that rainfall. Thus, a short intense rain event over a tributary basin may input more sediment to the Rio Grande than a longer, lower-magnitude rain event, which may produce greater total runoff for the same basin. Additionally, a dam release on the Rio Conchos may result in a long-duration, small to moderate flood, yet it may transport and deposit a smaller quantity of sediment than a short-duration tributary flood. Thus, there is no clear relationship among discharge, duration, sediment supply, erosion, and deposition, and it is difficult to tie individual deposits to specific events. The exceptions are the large floods in 1990–1991, which deposited the thickest deposits, and the floods of 651 and 599 m^3/s in 2003 and 2004, which buried the tamarisk that had become established high in the trenches.

Dean and Schmidt (2011) attributed the extremely high rates of vertical accretion measured on the Rio Grande to declines in flood magnitude and duration caused by water management infrastructure. However, we believe that the findings in this study may also be applied to other high-suspended-load semiarid rivers that are unregulated. Many studies have documented twentieth-century channel changes on other rivers driven by climate (Hereford and Webb, 1992; Allred and Schmidt, 1999). Thus, it is reasonable to expect that future climate changes, such as reductions in runoff or the alteration of precipitation intensity, may produce similar morphologic responses as described on the Rio Grande in the Big Bend region, or that ancient abrupt climate changes may have produced similar deposits in the rock record. However, on unregulated rivers experiencing climate change, the rate and magnitude of geomorphic change will ultimately be driven by the rate and magnitude of climatically driven changes. Thus, there will have to be rather extreme climatic changes in order to produce fast rates of change on an unregulated river.

The dendrogeomorphic and stratigraphic analyses in this study provided invaluable information for managers aiming to limit the rate and magnitude of channel narrowing and vertical floodplain accretion on the lower Rio Grande. Channel narrowing results in the loss of essential aquatic habitat, and loss of habitat complexity, for many native species, including the abandonment of side channels and the filling in of backwaters (Dudley and Platania, 1997; Porter and Massong, 2004). Dendrogeomorphic analyses indicate that consecutive years of low peak flow, such as between late 1993 and 1996, encourage non-native vegetation establishment within the active river channel. Moderate floods up to a 6.6 yr recurrence interval are inadequate to erode banks and strip established woody vegetation. Floods of this magnitude, interacting with vegetation-induced roughness and stability, instead contribute to vertical accretion and channel narrowing. Without the high-resolution dating provided by the dendrogeomorphic analyses (or a long-term record of channel surveys), it would have been impossible to determine the portions of the flood regime that allow vegetation to establish, the size of floods that result in significant vertical accretion, and the floods that promote levee construction. The data obtained by the dendrogeomorphic analyses show that in the absence of channel-resetting floods (i.e., >10 yr recurrence interval), control of vegetation during low-flow periods may prevent the stabilization of near-channel surfaces until floods of a sufficient magnitude and duration erode the accumulated channel sediments. Other studies (Pollen-Bankhead et al., 2009; Vincent et al., 2009) have shown that vegetation removal is a feasible mechanism to promote bank destabilization and channel widening. Although management efforts are focused on the promotion of bank destabilization, and limiting the rate and magnitude of channel narrowing, it must also be noted that other associated environmental effects of erosion, such as salt and contaminant transport, are currently unknown.

CONCLUSIONS

Recent channel narrowing of Rio Grande in the Big Bend region occurred through the development of floodplains inset within previous channel margins. Narrowing occurred by oblique and vertical accretion of sediment on top of coarse-grained channel-margin bars. Initial stages of floodplain formation consisted of the deposition of sediment within the active channel on top of channel bars, resulting in the formation of benches that were mostly devoid of vegetation. Sediment accretion continued due to moderate flooding and was dominated by oblique accretion at the channel margins and vertical accretion in the developing floodplain trough. Woody vegetation became established during years of low peak flow, which helped stabilize the developing surfaces. Continued vertical accretion of suspended sediment resulted in the conversion of the active channel deposits to floodplains. The final stage of floodplain development consisted of high suspended-sediment deposition at the channel margins, which created natural levees. This stage of floodplain development also occurred during a period characterized by moderate flooding.

The stratigraphic, sedimentologic, and dendrogeomorphic analyses in this study allowed us to reconstruct a precise depositional history of floodplain formation on the Rio Grande in the Big Bend region, to determine the date that channel narrowing began, the rate and magnitude of narrowing, the style of deposition, the timing of vegetation establishment, and the hydrology responsible for narrowing. The dendrogeomorphic analyses proved to be a useful method for reconstructing a precise depositional history in the absence of long records of channel and floodplain surveys. The results obtained from these methods also show how active portions of the channel can be rapidly converted to floodplains through sediment accretion and vegetation establishment.

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