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Dating floodplain sediments using tree-ring response to burial†

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Abstract

Floodplain sediments can be dated precisely based on the change in anatomy of tree rings upon burial. When a stem of tamarisk (*Tamarix ramosissima*) or sandbar willow (*Salix exigua*) is buried, subsequent annual rings in the buried section resemble the rings of roots: rings become narrower, vessels within the rings become larger, and transitions between rings become less distinct. We combined observations of these changes with tree-ring counts to determine the year of deposition of sedimentary beds exposed in a 150-m-long trench across the floodplain of the Rio Puerco, a rapidly filling arroyo in New Mexico. This method reliably dated most beds thicker than about 30 cm to within a year of deposition. Floodplain aggradation rates varied dramatically through time and space. Sediment deposition was mostly limited to brief overbank flows occurring every few years. The most rapid deposition occurred on channel-margin levees, which migrated laterally during channel narrowing. At the decadal timescale, the cross-section-average sediment deposition rate was steady, but there was a shift in the spatial pattern of deposition in the 1980s. From 1936 to 1986, sediment deposition occurred by channel narrowing, with little change in elevation of the thalweg. After 1986 sediment deposition occurred by vertical aggradation. From 1936 to 2000 about 27 per cent of the arroyo cross-section filled with sediment. The rate of filling from 1962 to 2000 was 0·8 vertical m/decade or 85 m²/decade. Published in 2005 by John Wiley & Sons, Ltd.

Keywords: burial; dendrochronology; *Salix*; stratigraphy; *Tamarix*

Introduction

There are few methods capable of providing precise deposition dates for floodplain sediments deposited in the last century. For example, ^{14}C dating of recent sediment is limited by the oscillations of the curve relating ^{14}C to calendar years (Trumbore, 2000). The ^{137}Ce method can only determine whether a deposit is more recent than about 1950 (Ely *et al.*, 1992). Optically stimulated luminescence (OSL) can be hampered by the problem of incomplete bleaching of sediments carried for a short time at night or in turbid water (Lepper *et al.*, 2002, 2003). Analysis of flow records can identify specific events that could have deposited sediment on a particular alluvial surface, but does not resolve which sediment was deposited by each event. Historical artifacts are typically scarce, and can give only an approximate age. Stereo pairs of aerial photographs have limited vertical precision, and historical measurements and photographs are available only where previous researchers have had the foresight to collect them (Malde, 1973; Elliott, 1979; Elliott *et al.*, 1999; Moody *et al.*, 1999). Analysis of ^{210}Pb is capable of detailed stratigraphic dating of recent sediments (Noller, 2000), but can be frustrated in the alluvial setting where variation in the concentration of lead in the sediment supply obscures atmospheric deposition (Popp *et al.*, 1988). Because of all these methodological problems, stratigraphic cross-sections of recent alluvial deposits typically include far more sedimentary units than precise dates. Tree rings, because of their chronological precision, present an opportunity for improved dating of these deposits.

Tree-ring dating of sediment ties deposition to a datable event during the life of a tree, such as germination or flood injury (Sigafoos, 1964; Everitt, 1968; Hupp and Simon, 1991; Friedman *et al.*, 1996; Strunk, 1997; Allred and Schmidt, 1999). For example, the most common use of tree rings for stratigraphic dating is to locate the establishment level of a buried tree and to count the number of annual rings at that level (Alestalo, 1971; Hupp, 1988). If the tree is

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alive, the establishment year can be determined by counting back from the present (Hereford, 1984; Scott *et al.*, 1997). If the tree is dead, the establishment year can be determined by cross-dating with living trees (Karlstrom, 1988). The establishment date provides a maximum age of the overlying sediment deposit and a minimum age of the underlying deposit. Shortcomings of this method include the difficulty of precisely locating the establishment level, the provision of only one date per tree, and reduced precision if there was a long time between deposition of the overlying and underlying sediments. Finally, changes in ring anatomy following deep burial obscure the annual transitions, making ring counts difficult. These burial-induced changes in anatomy provide, however, an opportunity for a more powerful method. If such direct effects of burial could be reliably identified, it would be possible to date precisely all of the sedimentary units deposited around a stem. That idea is the kernel of the method presented here.

Sigafoos (1964) observed a burial-induced change in ring anatomy of green ash (*Fraxinus pennsylvanica*) and demonstrated how this could be used to date sediment deposition events. Nanson and Beach (1977) observed a sudden increase in vessel size within annual rings of buried balsam poplar trees on point bars along a British Columbia river. They attributed this change to burial, and dated stratigraphic units exposed in pits by dating the anatomical change within several slabs from a single stem. Rubtsov and Salmina (1983) dated sediment deposits along a river in northern Russia on the basis of a decrease in annual ring width in buried willow stems. Shafroth and Friedman (unpublished work) observed both an increase in vessel size and a decrease in annual ring width in buried stems of tamarisk (*Tamarix ramosissima*). They used a manipulative experiment to demonstrate that this anatomical change is, in fact, produced by burial (Figures 1 and 2).

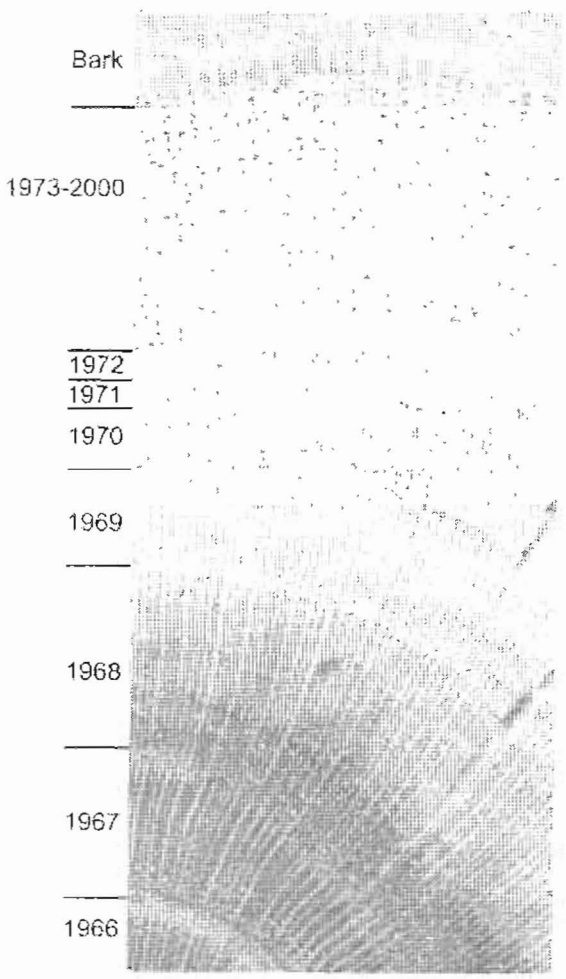

Figure 1. Tamarisk stem cross-section cut 2·8 m below the ground surface. Following initial burial of 68 cm in 1969, ring-width decreased, vessel size increased, and annual transitions became less distinct. After a second burial by 41 cm in 1972, annual transitions became indistinguishable. The colour change from dark to light within the 1968 ring is unrelated to burial.

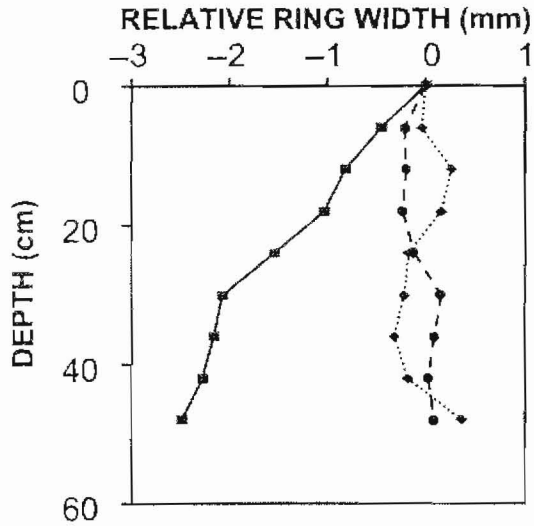

Figure 2. Effect of one year of controlled burial on tamarisk growth. Each line shows the vertical variation in thickness of a single ring along one stem. Ring-width is expressed relative to the value for the same ring at the post-burial ground surface (depth = 0). The solid line shows the decrease in growth with increasing burial depth; the dashed line is the ring laid down in the same stem in the year before burial. The dotted line is from a stem of similar size on a nearby tree that was not buried.

Tamarisk, a tree native to Eurasia, was introduced to North America in the 1800s and has since become a dominant riparian species in the southwestern USA (Friedman *et al.*, 2005). Therefore, development of a method to date stratigraphy using tamarisk stems would have broad applicability in the region. In this paper we demonstrate that stems of the abundant shrub sandbar willow (*Salix exigua*) show a similar burial signature, and we combine excavation of buried tamarisks and willows with stratigraphic mapping to develop a highly detailed and precisely dated stratigraphic cross-section of a New Mexico floodplain. To demonstrate the utility of this approach, we use the dated cross-section to assess the variability of sediment deposition rates across the floodplain and to calculate a cross-section-average sediment deposition rate.

Study Site

The Rio Puerco (of the east) flows about 250 km from the Nacimiento Mountains south to the Rio Grande near Albuquerque, New Mexico (Figure 3). The catchment area of 19 040 km^2 (Heath, 1983) is dominated by Mesozoic and Cenozoic sedimentary rocks that supply abundant sand, silt and clay (Wells *et al.*, 1983). In the lower 100 km of the Rio Puerco valley the late Quaternary sediments deposited by the Rio Puerco and its tributaries are underlain by sediments of the Santa Fe group, a thick accumulation of terrestrial sediments deposited in intermontane basins during the late Oligocene to middle Pleistocene (Heath, 1983). Except in the mountains the climate is semi-arid, with annual precipitation around 180 mm. Peak flows usually are flash floods generated by late-summer thunderstorms (Heath, 1983; Molnar and Ramirez, 2001). The Rio Puerco carries a heavy load of clay, silt and sand (Nordin, 1963; Love, 1986). Larger particles are less abundant but occur locally on the channel bed.

Erosion from the mid-1800s to early 1900s incised a continuous arroyo along the lower 200 km of the Rio Puerco (Bryan, 1928; Elliott *et al.*, 1999). Downstream from the confluence with the Rio San Jose (Figure 3), the period of erosion ended shortly after the highest known instantaneous discharge of 1070 m^3 s^{-1} on 23 September 1929 (Figure 4; New Mexico Office of State Engineer, 1930). In 1935, a braided channel occupied most of the arroyo bottom and woody vegetation was scarce within the arroyo (Figure 5). Since the 1930s, peak flows have decreased, the channel has narrowed, a densely forested floodplain has developed, and the arroyo has partly filled (Figures 4 and 5; Griffin *et al.*, in press). By 2002 the channel top width had narrowed to an average of 12·8 m, and the arroyo was about 250 m wide and 7 m deep (Griffin *et al.*, in press). The floodplain forest is dominated by tamarisk (locally introduced in 1926; Bryan and Post, 1927) with a fringe of sandbar willow along the channel.

The study site is a cross-section traversing the arroyo bottom 1·8 km downstream of the crossing of Highway 6 (Figure 3). Precise coordinates of the cross-section were determined using a differential global positioning system and

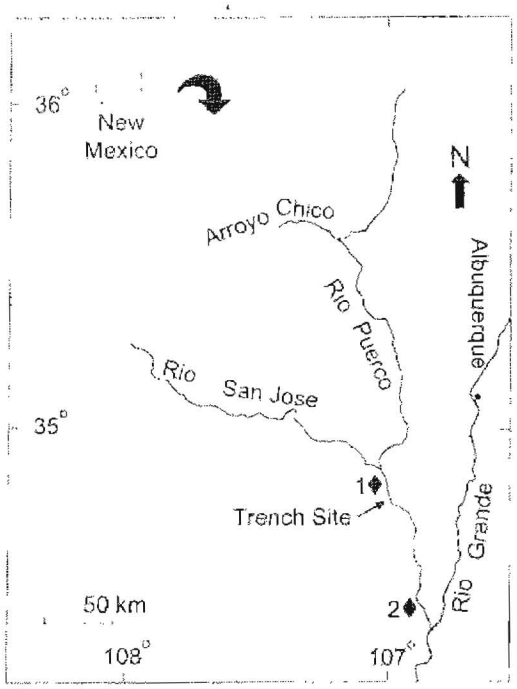

Figure 3. Trench site in the catchment of the Rio Puerco in north central New Mexico. Diamonds indicate US Geological Survey streamflow gauging stations: 1 = gauge 8352500, Rio Puerco at Rio Puerco; 2 = gauge 8353000, Rio Puerco at Bernardo. Data from the Rio Puerco at Rio Puerco gauge are intermittent after 1976.

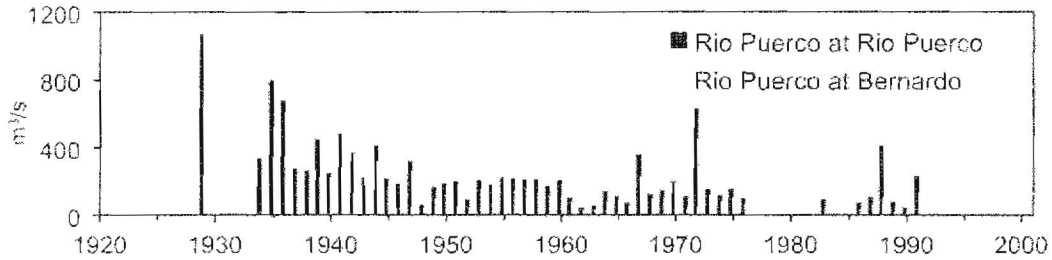

Figure 4. Peak instantaneous annual discharge, by water-year (1 October–31 September) at two gauging stations along the Rio Puerco, New Mexico.

are available upon request. The study site is 1523·97 m above mean sea level (NAVD88), and the streambed gradient is approximately 0·001 (Griffin *et al.*, in press). The study site is 1·5 km downstream of US Geological Survey Streamflow Gaging Station 8352500, Rio Puerco at Rio Puerco, and 79 km upstream of Station 8353000, Rio Puerco at Bernardo.

Methods

In May 2000 we used a backhoe to dig a 1·8-m-deep trench across the floodplain, and cleaned the trench face with trowels and brushes. We used a self-levelling engineer's level and surveyor's rod to install horizontal strings on the trench face as vertical control, and we used surveyor's tapes to obtain horizontal distances, allowing us to determine the precise (±0·5 cm) locations of contacts on a stratigraphic log. The sedimentary textures, structures and facies were noted on the log. Using the backhoe and hand tools we excavated five tamarisks and one sandbar willow adjacent to

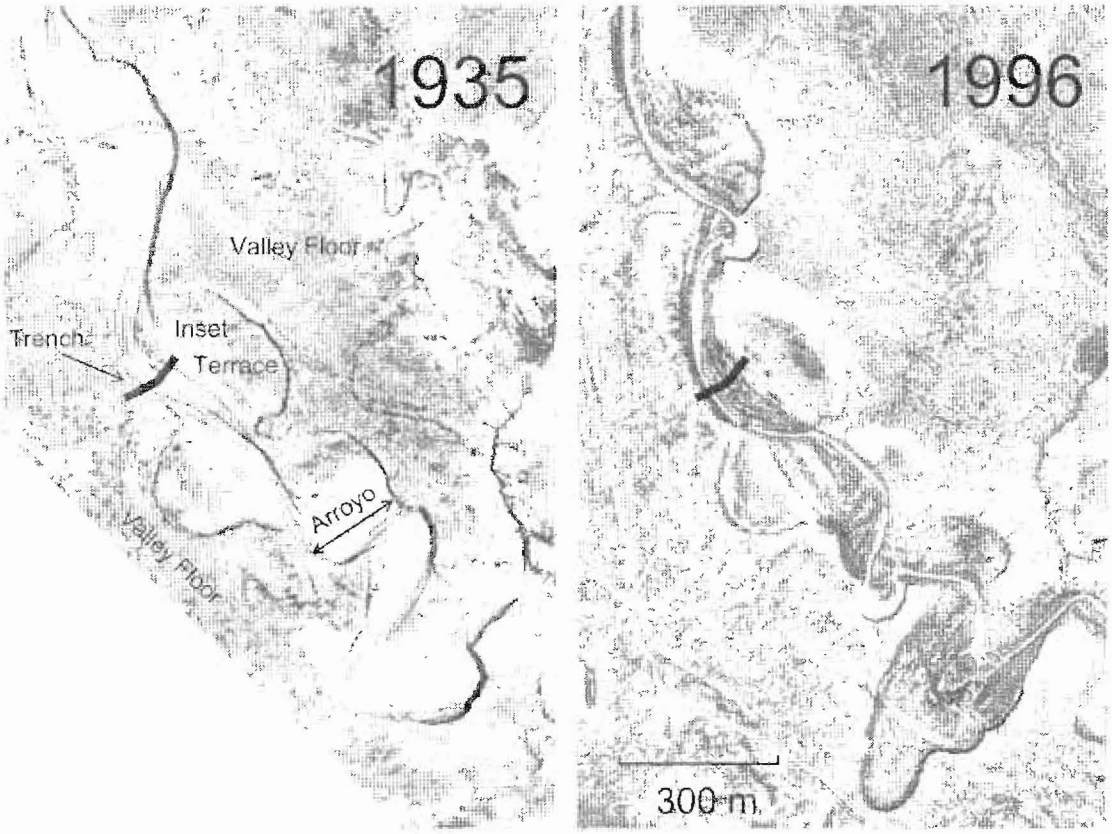

Figure 5. Aerial photographs of the trench site in 1935 and 1996. Downstream is to the lower right. Since 1935 arrroyo erosion has slowed, the channel has narrowed and aggraded, and a floodplain dominated by tamarisk has developed within the arroyo.

the trench. Tree excavations extended down to the apparent establishment surface or to the maximum depth of safe excavation (3–5 m). Each tree consisted of several buried stems, which joined at one to several metres below the ground surface. We harvested two to four stems from each excavated tree. Before harvesting, we mapped each tree and the adjacent stratigraphy, and used nails driven into stems to mark the major stratigraphic contacts. Those contacts were traced from the plant to the main trench, along the face of spur trenches connecting the two. After harvesting, we used a bandsaw to cut a slab 2–10 cm thick at each stratigraphic contact. The upper surface of each slab was about 1 cm above the contact. Additional slabs were cut between contacts to aid in cross-dating (the matching of annual rings between slabs). We cut 17 to 125 slabs per tree (266 total). To prepare slabs for tree-ring analysis we sanded them with progressively finer sandpapers to a median particle size of 15 μm (600 grit), applying frequent blasts of compressed air to prevent clogging of vessels by sawdust. Rings were inspected using a dissecting microscope. Ring-width and year were digitized on a Velmex TA Unislide measuring system with ACU-Rite linear encoder and QC1100 digital readout device acquired from Velmex, Inc., Bloomfield, New York. Our ring-reading software was Measure J2X, Version 3.1 (rel.25) from Project J2X, Voortech Consulting, Holderness, New Hampshire.

When stems of tamarisk or willow are buried, subsequent annual rings in the buried portions resemble the annual rings of roots. More specifically, compared to rings in unburied stems, rings produced after burial are narrower and vessels within these rings are larger, especially those produced in the latter part of the growing season (Figures 1 and 2). In addition, rays are more prominent and annual ring boundaries are less distinct (Figure 1). Because the changes become more pronounced with increasing depth of burial, it is often possible to identify multiple discrete burial events by examination of a single slab. However, once a stem is buried more than 1–2 m, subsequent annual rings are so narrow and indistinct that they can no longer be counted (Figure 1). In these deeply buried slabs the ring corresponding to the first burial event can be identified, but dating that burial event requires cross-dating with slabs from higher up the stem where rings can be counted all the way out to the year of harvest. We cross-dated within, and to a

Table I. Depth of stratigraphic contacts and year (calendar year minus 1900) of burial of slabs cut from a buried tamarisk tree (tree C) harvested in May 2001, along the Rio Puerco, New Mexico

Depth (cm)	Stem 1		Stem 2		
	Anatomy	Ring width	Anatomy	Ring width	Determination
	no burial		(94)	no burial	no burial
5	(99)				99
5			(93 or 97)		93 or 97
25	97	(97)			
	91 or 93	(94)	91	91	91
75	91	(90)	91	91	9
79	≤86	(90)	87	(86)	87 or 88
130	87 or 88	(90)			
	(72) or 73		87		
	(72) or 73		(72) or 73		73
166	≤69 or 72		72 or 73	(72)	72
192	69, 72 or 73		69, 72 or 73	(≤72)	69 or 72
225	68, 70				68, 70
254	(≤7)				
	67				67

Depths are centimetres below the ground surface. Dashed horizontal lines indicate truncated stratigraphic contacts. The dated surface of the lowest slab in a stratigraphic unit was 1 cm above the contact delineating the bottom of the unit. Values in parentheses are less reliable. 'Determination' is the date of deposition for the bottom of a stratigraphic unit based on tree ring evidence without reference to flow history. To conserve space, we present data for only one of six trees.

lesser extent between trees to ensure that rings were correctly dated. Characteristics most useful in cross-dating were year-to-year patterns in ring-width and the occurrence and seasonal timing of false rings. To determine the year in which a branch diverged from the main stem, we cut a slab just above the branch point and determined the difference in age between the two centres on the slab.

We identified the year of burial of a slab using two criteria. First, we searched the ring-width series for the earliest year in which radial growth decreased relative to that of higher slabs along the same stem. Second, we examined ring anatomy under a dissecting microscope to identify the earliest annual ring with enlarged vessels, a decreasing contrast between early and late wood, and more prominent rays. Because there were two criteria for determining burial date for each slab and at least two harvested stems per tree, there were at least four determinations of the year of burial for each sedimentary unit at a tree. Each slab was examined by two people, and final determinations of burial date were made according to the preponderance of evidence (Table I). Burial dates for sedimentary units near the excavated trees were transferred to the stratigraphic cross-section (Figure 6). Most units on the cross-section were dated by two or more trees, allowing a final consistency check for the determinations of sediment deposition date (Figure 6). Finally, we combined our knowledge of the stratigraphy, stem burial dates and flow history to construct a dated stratigraphic cross-section (Figures 6 and 7).

The data from individual trees provided records of the sediment deposition rate over time at various locations on the floodplain (Figure 8). We digitized the stratigraphic cross-section using a geographic information system (ARC/INFO) and calculated the area of each time-stratigraphic unit. This enabled us to determine the historic record of sediment deposition rate for the cross-section as a whole (Figure 9).

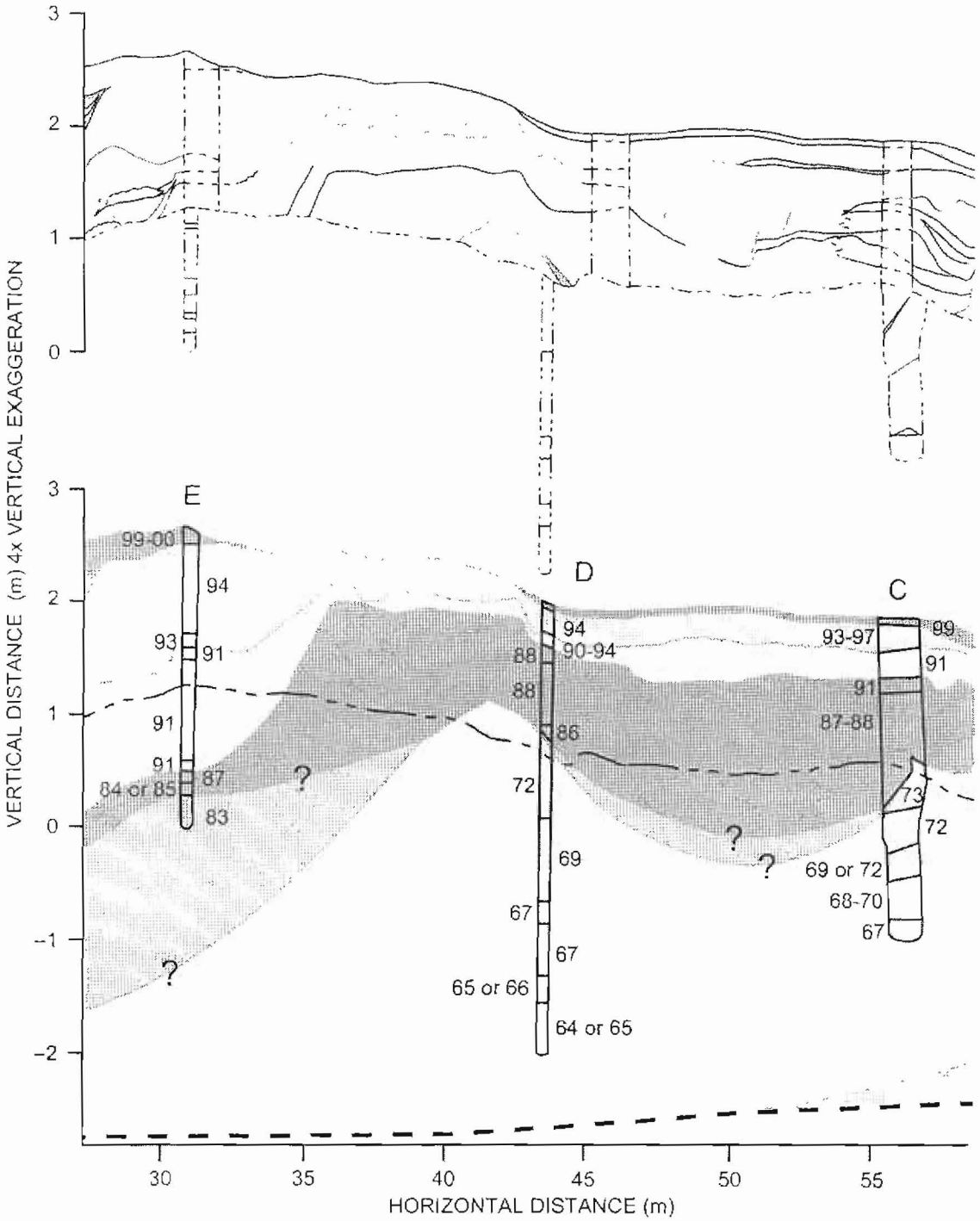

Figure 6. Partial cross-section of the Rio Puerco floodplain near Highway 6, New Mexico. View is looking upstream. Horizontal scale is relative to the left arroyo wall, and vertical scale is relative to the thalweg in 2000. The upper panel is a detail of the stratigraphic cross-section showing stratigraphic contacts and sediment textures. Yellow and white are sand, light green is silt, and red lines indicate erosional contacts. The lower panel is a detail of the chronostratigraphic cross-section. Dates are sediment deposition years indicated by tree rings. Colours represent deposits from specific time intervals as inferred from tree rings, stratigraphy, and flow history (see colour explanation on Figure 7). Inferred contacts below the trench bottom are indicated by question marks.

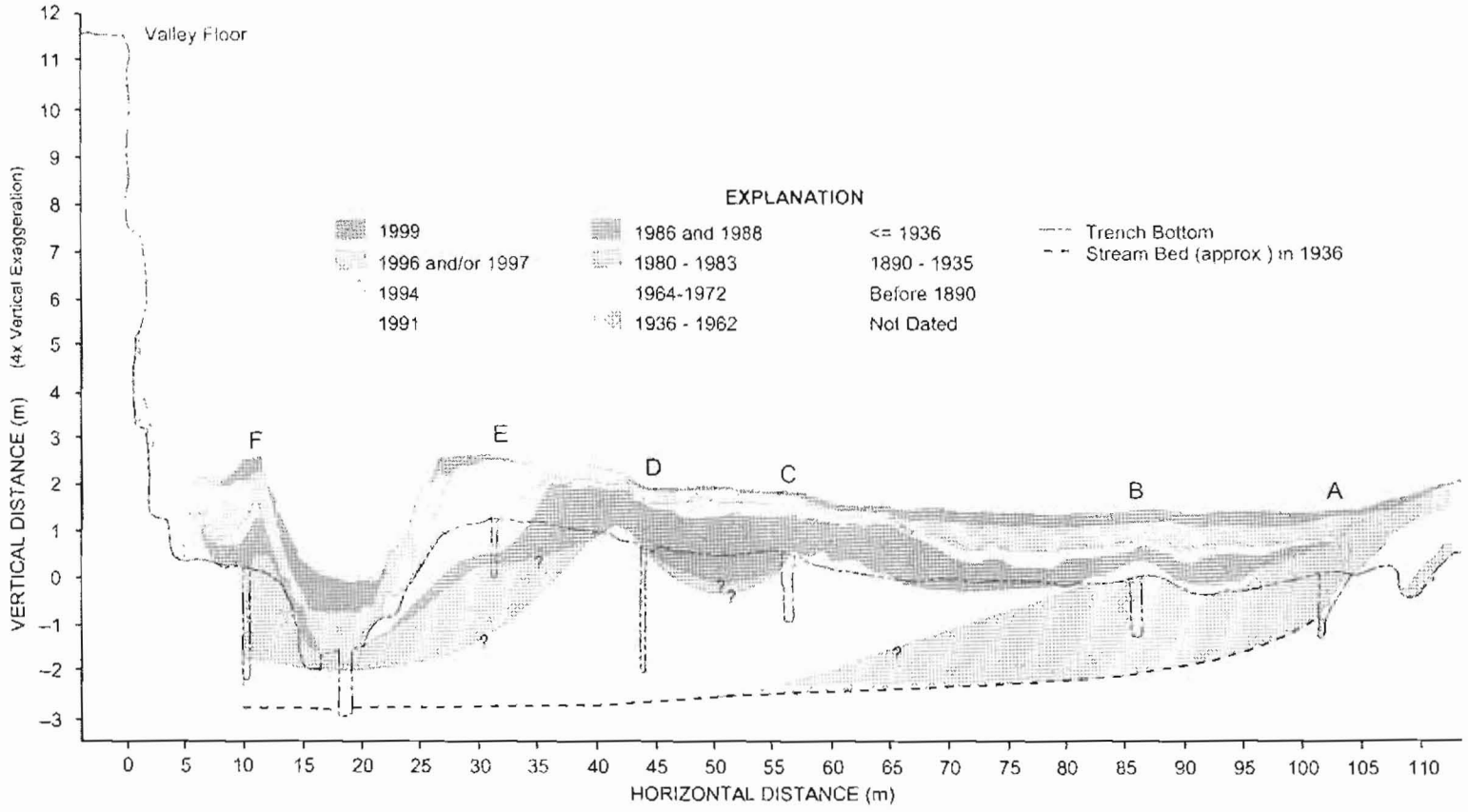

Figure 7. Full chronostratigraphic cross-section with locations of sampled trees (A–F). Horizontal scale is relative to the left arroyo wall, and vertical scale is relative to the thalweg in 2000. Colours represent deposits from specific time intervals as inferred from tree rings, stratigraphy and flow history

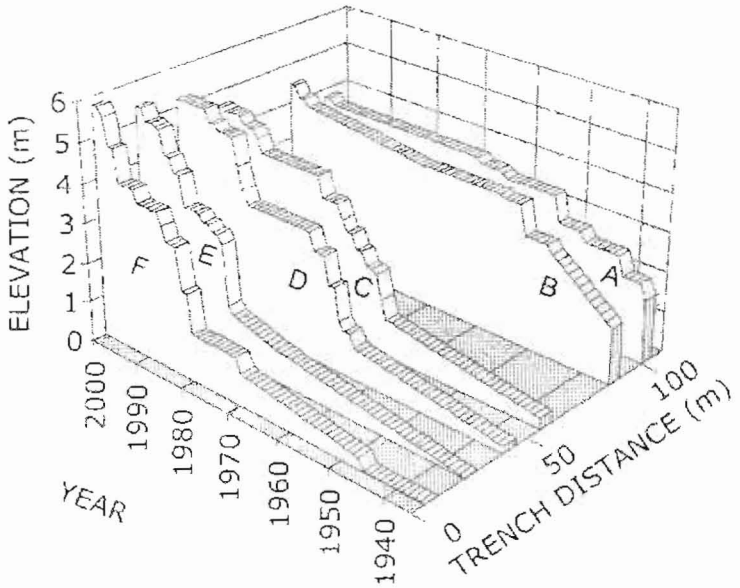

Figure 8. Diagram showing spatial and temporal variation in aggradation of the Rio Puerco floodplain, 1936–2000. Elevation is relative to the inferred 1936 thalweg. The letters A to F identify sampled trees whose locations along the trench are shown in Figure 7.

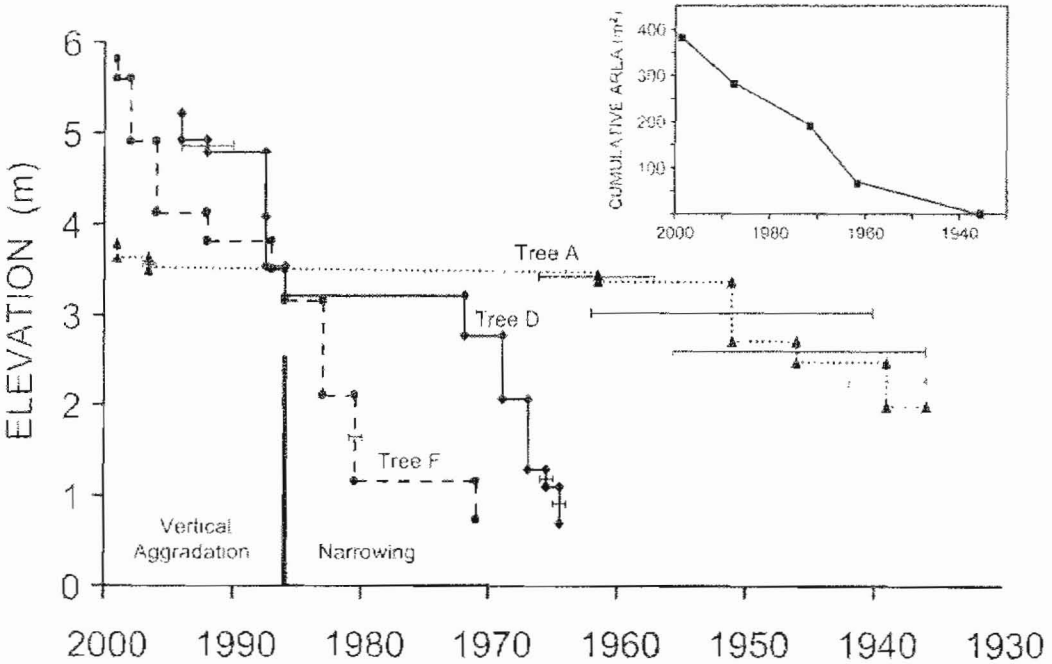

Figure 9. Sediment deposition history for trees A, D and F (see Figure 7 for tree locations). Uncertainty in burial date is indicated by horizontal error bars. The thick vertical line separates the period of channel narrowing from the period of vertical aggradation. Elevation is relative to the inferred 1936 thalweg. Inset is cumulative sediment deposit area for the entire cross-section over the decadal timescale.

Results and Discussion

Evaluation of methodology

Our method reliably dated deposition of most beds thicker than 30 cm to within one year. In dating these thicker beds, there was typically agreement between the two criteria applied to any stem (Table I, Figure 9), between stems from the same tree (Table I, Figure 9), and between trees (Figure 6). In sandbar willow, but not tamarisk, anatomical changes were often sudden enough to distinguish burial events that occurred within a growing season from those that occurred during the dormant period. Because most large flows along the Rio Puerco occur in late summer near the end of the growth season, we assumed that tamarisk burial occurred in the year before the first annual ring showing evidence of sediment deposition. For example, a burial date of 1994 (Table I, Figure 6) signifies that evidence of burial first appeared in the 1995 growth ring. The burial signature for beds thinner than 30 cm was not always detectable. It was often possible to date such beds by tracing them to another tree where they were thicker and produced an unequivocal burial signature (Figure 6).

Slabs and stems varied in their utility for dating of stratigraphy. Healthy, young, cylindrical stems typically produced the clearest burial signatures. Rot or consumption of wood by insect larvae sometimes destroyed a burial signature or made cross-dating impossible. Drought or disease sometimes slowed growth so much that accurate ring counts were impossible or elicited a response that could be confused with a burial signature. Where a stem was bent or flared, rings were indistinct on parts of slabs because no planar cut could be perpendicular to all of the xylem vessels. Anatomical burial signatures were stronger for thin stems than for thick stems. On the other hand, determination of burial date from the ring-width series was less accurate when the number of rings was small. Therefore, for stems that were young and thin at the time of burial, the anatomical criterion was more useful than the ring-width criterion. For the sandbar willow (tree E, Figure 7), all stems were thin and young and anatomical burial signatures were sharp, which was fortunate because the ring-width series was too short to provide reliable evidence of burial. Our approach of selecting the largest stems of a tree for harvest was not ideal. Smaller stems were generally more sensitive to burial than larger stems. For example, the largest stem (tree A) had the least distinct burial signatures and the greatest error in burial dates (Figure 9). In summary, the most reliable approach would be to select multiple healthy stems of various sizes from each buried tree.

Burial decreases radial growth and the clarity of the transition from one annual ring to the next. We took advantage of these anatomical changes in developing the stratigraphic dating method presented here. Other studies have ignored these changes, simply counting rings at the germination level to determine the depth of sediment deposition since establishment (e.g. Hereford, 1984; Friedman *et al.*, 1996). That approach may, however, underestimate the age of the tree. At the Rio Puerco, slabs from stems buried more than 1 m typically had readable rings in the centre formed before burial and a narrow unreadable zone at the periphery formed after deep burial. The narrow unreadable zone sometimes spanned more than 30 years (Figure 1). The only way to account for these years is to cross-date the slab with others higher along the stem. Failure to do so could lead to underestimation of the age of the tree by decades.

From the standpoint of understanding the history and processes of channel and floodplain development, the method discussed here is important in several ways. The obvious advantage is the precision of dating where sediment accumulation rates are rapid. Precisely dated beds at individual exposures can be correlated even where the stratigraphy is obscured between the exposures. Sedimentary deposits can be dated without a known flood series, although knowledge of the flood series will improve the results. When the method is combined with stratigraphy there are other advantages. The duration of periods of non-deposition can be determined, and the recurrence interval for floods that act to construct and maintain the channel and floodplain can be calculated. Process rates, such as aggradation rates or levee migration rates, can be calculated. Determination of the aggradation rate for an entire cross-section, as opposed to a local stratigraphic column, improves the precision of sediment budget calculations.

Application of method: aggradation at the Rio Puerco

Sediment deposition was mostly limited to overbank flows occurring every few years, and these typically persisted no longer than a few days (E. Griffin, unpublished results). The years of sediment deposition on the floodplain determined using tree rings (e.g. Table I, Figure 6) matched years of high flow recorded for the Rio Puerco at Rio Puerco (Figure 4) usually to within one year. Important flows for sediment deposition occurred in 1967, 1969, 1972, 1988 and 1991. Note that the high flow for water-year 1970 in Figure 4 occurred on 23 October 1969, which is consistent with evidence from multiple trees indicating that sediment deposition occurred prior to the 1970 growing season (Figure 6). No data are available for this gauge after 1991, but the dated sediment record indicates there were minor overbank flows in 1994, 1996, 1997 and 1999 (Figures 6 and 7).

The timing and amount of deposition varied dramatically across the floodplain. The depth of sediment accumulated at tree F since 1980 was about ten times greater than that accumulated at tree A since 1962 (Figure 9). The period 1964–1972 dominated sediment deposition at tree D, but made little contribution at tree B (Figure 7). Locally, the most rapid vertical aggradation around any tree occurred when that tree coincided with a primary levee (Figure 7).

Overall, sediment deposition since 1936 at the study site has occurred in two phases. In the first phase (1936–1972) deposition resulted in channel narrowing with little change in thalweg elevation (Figures 8 and 9). In the second phase (1986–1999) sediment deposition resulted in a rise in the level of the streambed and floodplain, with reduced channel narrowing (Figures 8 and 9).

In the 1930s the channel occupied most of the cross-section, was dominated by sand and had gradually sloping banks (Figures 5 and 7). Between 1936 and 1972 the channel narrowed by construction of a series of sand levees, which over time encroached on the thalweg (Figures 7 and 8). Much of this deposition occurred in 1967, 1969 and 1972. Each levee grew to an elevation of about 3·2 m on Figures 8 and 9 (0·6 m on Figure 7) and then received little additional sediment deposition until after 1986. Tree A was established in about 1936 at the edge of the channel. Tree B was established in 1946 ± 3 years and its growth occurred in association with development of a levee of very fine sand. This levee reached the 3·2 m level by about 1968 (Figure 8). Trees C and D were established below our excavation depth and grew in association with levees that reached the 3·2 m level in the 1972 flow (Figures 8 and 9).

Beginning in 1986 or 1988, the levee at tree D grew toward the channel and upward (Figures 7–9). The continued growth of this levee in the 1990s is recorded by tree E. Vertical aggradation of the levee coincided with aggradation of the thalweg. The deepest sampled section of tree F was not buried until 1972, but by 2000 was more than 2 m below the thalweg. We observed the branches of many similarly buried trees protruding from the bed or banks elsewhere along the lower Rio Puerco. Beginning in 1986, aggradation of the channel and levees led to overbank deposition of silt and clay facies on the floodplain, thereby reducing floodplain topographic relief. Thus at present, the only surficial evidence of former levees is the conspicuous rows of tamarisk marking their location. The sequence of channel narrowing with steady streambed elevation followed by vertical aggradation of streambed and floodplain is confirmed by a monumented historic cross-section 640 m upstream that was surveyed in 1936, 1972 and 1995 (Elliott *et al.*, 1999).

Mean floodplain aggradation rates can be determined by linking individual tree sites together stratigraphically (Figure 7), thus providing the information needed for sediment budget calculations (Figure 9). Since 1936, about 27 per cent of the arroyo cross-section has filled with sediment. In spite of the great variation in local sediment deposition rates, cross-section-averaged sediment deposition has been steady (Figure 9). Thus there is no evidence suggesting that the beginning of vertical aggradation of the streambed in the late 1980s was a consequence of increased sediment supply to the study reach. Instead, the beginning of vertical aggradation may have been a consequence of a local constraint of channel geometry, namely reduced space available for channel narrowing. Since 1962, the cross-section-averaged rate of filling has been steady at 0·8 vertical m/decade or 85 m^2/decade. If the rate of vertical aggradation continued unchanged the arroyo would be filled in 100 years. If the area rate of aggradation continued unchanged the arroyo would be filled in around 200 years.

Accumulation of sediment within the arroyo of the lower Rio Puerco has contributed to a decline in suspended sediment concentrations by more than 50 per cent from 1948 to 1994 at Bernardo (Gellis and Elliott, 1998). The Rio Puerco is a major source of sediment to the Middle Rio Grande and Elephant Butte Reservoir (Love, 1986). The rate of filling of Elephant Butte Reservoir by sediment has declined from $30{\cdot}3 \times 10^6$ m^3 a^{-1} (or 0·93 per cent of full capacity per year) for 1915–1925 to $4{\cdot}7 \times 10^6$ m^3 a^{-1} for 1988 to 1999 (Collins and Ferrari, 2000). Therefore, storage of sediment in the lower Rio Puerco arroyo appears to be increasing the longevity of this regionally important reservoir.

Sediment accumulating along the lower Rio Puerco is derived from two sources, upland erosion and widening and deepening of the arroyo upstream. Analysis of cosmogenic isotopes indicates that the long-term upland erosion rate in the Rio Puerco Basin is 102 ± 24 m per million years (Clapp *et al.*, 2001). If the arroyo trapped 25–50 per cent of this sediment, it would fill in roughly 1000 years (Clapp *et al.*, 2001). Locally, in the lower Rio Puerco, our results show that the current rate of aggradation would fill the arroyo more rapidly (in 180–280 years). At a broader scale, however, our results are consistent with those of Clapp *et al.* (2001) because much of the sediment currently being deposited in the lower Rio Puerco is derived from upstream arroyo incision and lateral erosion (Elliott *et al.*, 1999).

Along the lower Rio Puerco, sediment deposition and tamarisk forest development have promoted each other: sediment deposition provides an ideal seed bed for tamarisk, which in turn reduces flow velocity and increases bank stability. Tamarisk was introduced to the lower Rio Puerco in 1926 to control erosion (Bryan and Post, 1927). At that time the broad channel occupied most of the arroyo floor, levees were absent, and woody vegetation was scarce (Figures 5 and 7). At present the channel is narrow, and pronounced levees are elevated above a broad floodplain (Figure 7) dominated by a dense tamarisk forest (Figure 5). Although tamarisk forest is not limited to levee tops, most current and past levee tops are marked by a row of tamarisk. Fluid drag on tamarisk stems reduces local velocity

promoting sediment deposition and growth of levees (Kean and Smith, 2004). Bank stabilization by tamarisk may be partly responsible for the lack of recent channel migration. Formation of pronounced levees and development of dense tamarisk stands have resulted in low velocities in back-channel areas of the floodplain. Back-channel deposits beginning in 1986 include the only abundant silt and clay in the post-1936 sediment record. At the reach scale, the fluid drag on the increasingly dense tamarisk forest (Kean and Smith, 2004) has apparently increased the attenuation of short-duration flood peaks between the two gauges on the lower Río Puerco (Figure 4; Molnar and Ramirez, 2001). Although the invasive tamarisk is often considered a nuisance, it can promote floodplain stability, sediment deposition, and flood attenuation. Research is needed to investigate the possibility that eradication of tamarisk from a river reach could increase downstream flood peaks and sediment loads.

Comparison to other methods

In this section we compare available methods for dating recent alluvial sedimentary deposits. We restrict our discussion to methods that have been demonstrated to produce useful results for stream deposits less than 500 years in age, and those that produce a numerical age. These methods include: analysis of the isotopes ^{14}C, ^{210}Pb, ^{137}Cs; optically stimulated luminescence (OSL); discovery of historical artifacts; eyewitness observations; repeat photographs and cross-sections; and use of tree rings to date wood fragments, tree establishment, tree damage or stem burial. The comparison is made in terms of the most important factors limiting utility or accuracy.

Lack of opportunity to apply method. One measure of the utility of a method is how frequently the opportunity arises to employ it. The ^{210}Pb, ^{137}Cs and luminescence methods all involve measuring a property of the sediment, which means that any fine-grained sediment could ostensibly be dated using those methods. The same might be said for using the pollen of a widespread introduced plant species. Other methods involve some degree of serendipity, such as the discovery of a charcoal fragment or potsherd. Examination of tree rings for a burial signature is possible wherever appropriate woody species are present. Fortunately, the method works with tamarisk and sandbar willow, two of the most abundant riparian plants in the southwestern United States. We do not yet know whether this method could be successfully applied to other abundant species with clear annual rings, such as cottonwood or Russian olive. The method is unlikely to work with species lacking clear annual rings, such as mesquite and most tropical species. Our method requires trees that were present at the time of sediment deposition and are still present today. Along the lower Río Puerco, this means that we cannot date sediment deposited before 1926, the year of tamarisk introduction (Bryan and Post, 1927). Because buried sandbar willow stems at this site are consumed by insect larvae, we were not able to use willow to age sediment deposits older than 20 years. In contrast, Vincent and Elliott (2005), working along the Animas River at a subalpine site (altitude 2970 m), dated flood damage in 100-year-old buried willow stems, and Karlstrom (1988) used establishment years of buried junipers to date sediments deposited several hundred years ago.

Limiting assumptions. Some methods for dating alluvial deposits require assumptions that may be valid only in certain circumstances. For example, lead-210 is created by the radioactive decay of radon gas and is itself transformed by radioactive decay (Noller, 2000). The ^{210}Pb method requires an understanding of the accumulation and radioactive decay of ^{210}Pb from atmospheric and terrestrial sources. Some applications of the method rely on a steady sedimentation rate, which rarely occurs in many alluvial settings. The method has successfully dated sediments less than 200 years old, particularly marine and lacustrine sediments, and has successfully dated stream sediments (Noller, 2000; Aalto *et al.*, 2003). Popp *et al.* (1988), however, did not succeed in using ^{210}Pb to date sediments deposited by the Río Puerco, stating that the terrestrial source was too large and variable in comparison to the atmospheric source. Other methods that must be correlated with a previously dated chronology (e.g. palaeomagnetic secular variation), or require a calibration to account for local conditions (e.g. obsidian hydration), involve uncertainties that are beyond the scope of this discussion. No such limiting assumptions or correlation or calibration are necessary in the use of burial signatures to date alluvial deposits.

Uncertain age of creation. Many methods are hampered by the uncertainty in the creation age of the object used to date the sediment. This is the principal limit to the accuracy of dates derived from man-made artifacts, except those rare objects that are inscribed or are otherwise so unique that their manufacturing age is tightly constrained. For example, Vincent and Elliott (2005) discovered a cast iron stove leg in a floodplain deposit but had no way to know (without independent evidence) when in the last 250 years the cast leg was manufactured. The uncertainty in the age of the host deposit was thus on the order of 250 years. This is also a problem with recent radiocarbon ages: they do not correspond to a unique calendar age because of fluctuations in the atmospheric concentration of ^{14}C over the past 500 years. For example, a conventional radiocarbon age of 110 years BP intercepts the calibration curve at seven dates between AD 1700 and 1950, and when typical laboratory uncertainties are considered the dated plant tissue could have grown during almost any year after AD 1650 (Trumbore, 2000). However, carbon-14 activity (excess above 1950 ^{14}C level) for short-lived plant tissue (leaves and pine needles) can date 'post-bomb' flood deposits to within a few years,

when other age constraints are available (Ely *et al.*, 1992). Caesium-137 is a radioactive isotope, but since it is the product of man-made thermonuclear bombs it is used like a historical artifact for dating. Presence of ^{137}Cs in a sediment deposit indicates that deposition occurred some time after 1945–55 (Perkins and Thomas, 1980), but the absence of ^{137}Cs in individual beds is inconclusive (Bishop *et al.*, 1991; Ely *et al.*, 1992). In contrast, the creation age of a tree burial signature can be determined to within a year in tamarisk and to within several months in sandbar willow.

Delayed delivery. Several methods are hampered by the possibility that the delivery of the datable object to the host deposit was delayed until long after the object was created. This problem is inherent for all man-made objects (including ^{137}Cs), charcoal samples and wood fragments. Delayed delivery can be caused by reworking. A charcoal fragment exhumed from an older deposit may have a precise creation age, but the accuracy of the age of the deposit in which the fragment was discovered is not knowable in isolation. To illustrate the magnitude of the problem, we mention examples from Chaco Canyon, New Mexico (K. R. Vincent, unpublished data). A potsherd approximately 1000 years in age was discovered in a deposit that must be less than 50 years old. A charcoal fragment of a plant stem was discovered in a deposit along Chaco Wash that independent evidence demonstrated must be less than 500 years old. That charcoal fragment produced a radiocarbon age of about 3000 years BP even though it was pristine in appearance, not abraded, and thus not obviously reworked. Burial signatures in trees found in growth position are not subject to the problem of delayed delivery. On the other hand, wood fragments found out of growth position may have been deposited many years after they were formed.

Inheritance. Inheritance of a property from an older deposit has the same consequence as delayed delivery. Luminescence, a fundamental property of most silicate minerals, accumulates through time with exposure to environmental radiation and is reset or 'bleached' when the mineral is exposed to sunlight or heat (Forman *et al.*, 2000). The OSL method can be suitable for waterlain sediments that experience exposure for sunlight before deposition. If sediment transport occurs at night or if the water is turbid, however, the minerals may be only partially bleached, making the age determination too old. For example, Lepper *et al.* (2002, 2003) applied OSL to sediments deposited by the turbid Chaco Wash using a standard multiple-grain analysis and a 'leading edge' analysis of measurements of numerous single grains. Both methods accurately reproduced the age of a deposit known to be about 1000 years old. For sediment known to have been transported at night and deposited in April 2000, however, the standard method produced an age of 2070 years whereas the 'leading edge' approach produced an age of 55 years.

In our analysis of stem burial signatures we have assumed that the date of first burial of a slab is the same as the date of deposition of the sediment surrounding that part of the plant stem. This assumption is valid in rapidly aggrading systems like the lower Rio Puerco. Where both erosion and deposition are important, however, the sediment that originally buried a stem may since have been eroded. Ash trees that have been buried and then later unburied show reversal of the burial signature (Sigafoos, 1964). If the original sediment deposit is eroded and replaced in the same year, the record of burial revealed by the tree may disagree with the record as preserved in the stratigraphy. Thus tree rings may be subject to a form of inheritance, but this could be used to provide information about sediment deposits that are no longer present.

Ages of samples where there is an inherent uncertainty in the creation age, or a possibility of inheritance or delayed delivery, provide a 'younger than' constraint for the age of sediment overlying the samples. Such sample ages do not constrain the age of underlying deposits, however. Consider the 50-year-old deposit containing the 1000-year-old potsherd. It would be illogical to claim the underlying deposit was 'greater than 1000 years old' when it could in fact be 60 years old. A few methods have the enhanced utility of providing limiting ages for deposits beneath the 'sample'. Most of these methods define the age of a time-stratigraphic boundary (at a bedding contact) rather than the age of a host deposit. They include finding the establishment age and level of a tree (Hereford, 1984), repeatedly surveying cross-sections (Moody *et al.*, 1999; Gellis and Elliott, 1998), and matching sequences of photographs taken over time (Malde, 1973; Vincent and Elliott, 2005; Popp *et al.*, 1988). The opportunity to apply these methods is typically uncommon. Furthermore, their precision is limited where several years can transpire between sediment deposition events, as along the Rio Puerco.

Summary and Conclusions

When stems of tamarisk and sandbar willow are buried, annual rings take on root-like characteristics, including narrower width, larger vessels and less distinct annual transitions. Observations of these changes can be combined with stratigraphic mapping to determine the year of deposition of sedimentary beds. This method has abundant opportunities for application, little uncertainty in creation age, no delayed delivery, and only limited inheritance. Thus stem burial signatures can accurately constrain the ages of entire stratigraphic exposures.

Along the Rio Puerco this method reliably dated most beds thicker than 30 cm, and some thinner beds, to within a year of deposition. An equivocal deposition date for a bed at one tree could often be improved by using the stratigraphy to trace the bed to another tree. In sandbar willow, but not tamarisk, anatomical changes were often sudden enough to determine whether burial had occurred during the growing season or the dormant period. Sediment deposition at the Rio Puerco was mostly limited to brief overbank flows occurring every few years and was most rapid on channel-margin levees. Although the cross-section-average sediment deposition rate was steady at the decadal scale, there was a shift in the spatial pattern of deposition in the 1980s. From 1936 to 1986, sediment deposition occurred by channel narrowing, with little change in elevation of the thalweg. After 1986 sediment deposition occurred by vertical aggradation. From 1936 to 2000 about 27 per cent of the Rio Puerco arroyo cross-section filled with sediment. Storage of sediment in the lower Rio Puerco is decreasing the sediment load downstream in the Rio Grande and extending the useful life of Elephant Butte Reservoir.

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