Scroll bars are inner bank levees along meandering river bends

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ABSTRACT: Scroll bars across a 65-km stretch of the Trinity River in Texas, USA were studied using LiDAR data as well as with a series of 11 trenches spread out across the survey area. We conclude that scroll bars are levees that are deposited along the inner banks of these meandering river bends. Scroll bar crests were found to have similar elevations to those of outer bank levee crests, implying that they are constructional features that create positive topographic relief above the elevation of the floodplain. Trenches reveal that scroll bars are built from reworked suspended sediment, with common ripple-scale cross stratification, planar laminations and muddy bioturbated layers – characteristics often associated with levee sedimentation in other systems. LiDAR observation of the erosion of scroll bars by bed material transport during flood implies that scroll bar spacing is an imperfect proxy for estimating overall channel migration rates. In addition, interspersed lenses of coarser sediment with dune-scale cross stratification represent the stratigraphic record of these erosional events and suggest that erosion of the channel-ward edge of the scroll bar is not uncommon. Preservation of scroll bars is unlikely, given that they are responsible for an average of only the uppermost 12% of the total inner bank relief. We suggest that misidentification of point bar lateral accretion surfaces as scroll bars is common and can lead to issues with reconstructing channel properties due to systematic differences between point bar and scroll bar planform geometries. © 2019 John Wiley & Sons, Ltd.

KEYWORDS: scroll bars; levees; fluvial geomorphology; stratigraphy; river meanders

Introduction and Background

Scroll bars are responsible for some of the most striking patterns on Earth’s surface. These arcuate topographic features, present on the inner banks of migrating river bends, are widely recognized as a distinct component of fluvial systems despite being incompletely understood. Published explanations for scroll bar formation are varied, with even their production by constructional or erosional processes not universally agreed upon. Scroll bars are alternately described as simply the top of a point bar behind which deposition is dammed (Hickin, 1974; Nanson, 1980; van de Lageweg et al., 2014), the result of enhanced sedimentation at the leading edge of inner bank vegetation or in the shadow of woody debris (Jackson, 1976; Nanson, 1981; Zen et al., 2017), topography built from longitudinal bars migrating up and out of the channel during flood (Ielpi and Ghinassi, 2014; Jackson, 1976; Nilsson and Martvall, 1972; Sundborg, 1956), the result of depositional patterns produced by a bimodal distribution of grain sizes (Nanson, 1980), the result of suspended sediment deposition due to flow separation over a point bar (Nanson, 1980), or the product of chute channel erosion between the point bar and inner bank (McGowen and Garner, 1970; Nanson and Croke, 1992). Even with an ambiguous formative process, for decades scientists have understood scroll bars to be intimately related to river channel migration, even using scroll bar age and spacing to estimate lateral migration rates (Hickin, 1974; Hickin and Nanson, 1975; Nanson and Hickin, 1983; Rodnight et al., 2005). Their occurrence is reported in ancient riverine deposits exposed at Earth’s surface (Ielpi and Ghinassi, 2014; Durkin et al., 2015; Wang and Bhattacharya, 2017), in seismically imaged subsurface deposits (Durkin et al., 2017), and even in remote sensing studies of strata on other planets (Burr et al., 2009; Moore et al., 2003; Moore and Howard, 2005; Schon et al., 2012), where they have been used to estimate paleochannel position, wavelength and curvature.

This paper presents a comprehensive survey of modern scroll bars along the lower Trinity River in east Texas, USA, describing their form and stratigraphy and inferring processes required for their formation. We use an airborne LiDAR survey that was flown in 2015 in conjunction with focused trenching of five scroll bars to determine the nature of scroll bar deposition, stratigraphy and evolution along the Trinity River. Our results have implications for using scroll bars as a measure for migration rate on modern rivers and highlight the systematic differences between scroll bars and their adjacent point bars. In addition, results suggest that lateral accretion surfaces associated with point bar growth are commonly misidentified as scroll bars along modern rivers, in outcrop, in subsurface data and on other planets.
Study Area

The Trinity River is a perennial, sand-bedded river within a humid, subtropical climate. The average annual discharge is around 200 m$^3$ s$^{-1}$ at Romayor, TX (Figure 1). The river delivers approximately 70 000 t of sediment into its delta per year (Phillips et al., 2004). The sediment typically moving through the study reach is sourced from erosion of the underlying floodplain substrate with a very minor contribution from tributaries (Smith and Mohrig, 2017). The substrate material is composed of weakly consolidated fluvial deposits that are estimated to be 50% mud, 45% sand and 5% gravel in grain size (Smith and Mohrig, 2017). Flooding sufficient to cause overbank flow has approximately a 40% exceedance probability at Liberty, TX (Figure 1), based on public data from the National Weather Service. The area covered by this survey is 65 river km long and includes data from 45 river bends. Our survey is focused along the coastal Trinity and includes a portion of the backwater zone, the region where flow within the river is affected by the presence of the receiving basin. As a result, change in river discharge in this backwater zone is primarily connected to change in mean velocity with minor variation in water-surface elevation (Nittrouer et al., 2012). Upstream of the backwater zone, the river experiences uniform flow conditions at the reach scale and discharge change is connected to change in both mean velocity and water-surface elevation (Lamb et al., 2012). The hydraulic transition between uniform flow and backwater flow occurs approximately halfway through the survey reach, near Liberty, TX. Several large-scale geomorphic readjustments are associated with this hydraulic transition, including a downstream increase in water depth within the channel during low discharge conditions, a downstream decrease in the volume and grain size associated with point bars, and a downstream decrease in the lateral migration rate of the channel (Mason and Mohrig, 2018; Smith, 2012). Despite these hydraulic and geomorphic changes, scroll bars are consistently present along the inner banks of the majority of river bends within the study area.

Methods

A bare-earth LiDAR data set collected in August 2015 by the National Center for Airborne Laser Mapping was used to measure elevations and planform curvatures of scroll bars (Figure 2). The LiDAR data set was collected at low discharge conditions using an Optech Titan with a reported vertical accuracy within 5–15 cm of the known elevation and rasterized to 1-m horizontal resolution. In addition, we will discuss scroll bar change based on previously published results by Mason and Mohrig (2018) that utilized time-lapse LiDAR covering the same survey area. Every topographic ridge along the inner bank of a river bend that had a planform geometry which mimicked that of the channel bend was considered a scroll bar. Bends were selected for measurement if there was an obvious associated point bar and at least one well-defined scroll bar. Ten bends that did not have obvious scroll or point bars associated with them were left out of the study, as well as two bends whose geometry was altered by the presence of human infrastructure. The bends that did not have multiple well-defined scroll bars were either associated with a recent bend cutoff (making the bend young enough to lack significant scroll bar deposition) or minimal migration (more common in the backwater zone, where lateral migration is dampened).

A channel centreline was created in Esri’s ArcMap 10.3 geographic information system by collapsing the manually mapped positions of the inner and outer river banks (demarcated by the landward edge of the point bar and the vertical cut bank, respectively). Transects perpendicular to the centreline were created every 100 m along channel bends with scroll bars. The elevation of the edge of the outer bank (i.e. the outer bank levee crest), the highest elevations associated with each consecutive scroll bar ridge and the elevation of the swale behind the youngest scroll bar (defined as the one closest to the point bar) were measured along each of these perpendicular transects (Figures 2A and B).

The planform shape of the youngest scroll bar was mapped (Figure 2A) and its radius of curvature was estimated by fitting...
a circle to the data points using the Pratt (1987) method. To determine any systematic difference in planform geometry between scrolls and their adjacent point bars, the shorelines on point bars were mapped and these close-to-horizontal surfaces were used to generate an estimate for the radius of curvature for each bar using the same method (Figure 2A). Any difference in planform curvature between a point bar and its youngest scroll bar has important implications for using the preserved depositional record of either of these to reconstruct channel bend sinuosity, curvature, length and amplitude. While there is undoubtedly a trend in point bar radius of curvature with the river stage at which the measurement is taken, our analysis is meant only to ascertain any systematic difference between scroll and point bar planform geometries, and is not intended to produce an exact quantitative value for this difference.

Relief of the youngest scroll bar, $H_s$, was measured by subtracting the average elevation of the flattened top of the adjacent point bar from the average elevation of the scroll crest for each bend. Bathymetry data collected by the Texas Parks and Wildlife Department (TPWD) in 2009–2010 was used to measure the average thalweg elevation for each river bend. The total height of the inner bank, $H_{tot}$, was measured by subtracting the average thalweg elevation from the average elevation of the scroll bar crest for each bend. $H_s$ and $H_{tot}$ were then used to calculate the fraction of total relief of the inner bank that was due to scroll bar topography, $R_s = \frac{H_s}{H_{tot}}$ (Figure 2C).

To complement the measurements taken from the LiDAR data, five separate point/scroll bar complexes were chosen for trenching (Figure 1, starred river bends). A total of 11 trenches were dug. These trenches were generally ~1 m deep and 10+ m long, and several captured the point bar to scroll bar transition. Trenches were inspected, photosurveyed and mapped in order to determine the depositional character of the scroll bars as well as the stratigraphic character of the transition from point bar to scroll bar. The bends associated with the trench sections are spread out across the entire length of the survey.

Trenches were oriented both parallel and perpendicular to the transport direction for each bend. Sediment samples were collected from each trench to define the change in grain size associated with the transition from point bar to scroll bar. If sediment samples contained no visible mud, they were run on a Retsch Camsizer P4 particle analyser, which uses dynamic image analysis to determine grain size. Samples containing a substantial mud fraction were run on a Malvern Panalytical Mastersizer 3000, which estimates grain size from the laser-diffraction pattern produced by a dispersed suspended sample. Grain size results were reported using the Wentworth grain size classes.

**Results**

**LiDAR data**

Results from time-lapse LiDAR data published by Mason and Mohrig (2018) show that the edges of the youngest scroll bars along the same portion of the Trinity River are actively experiencing aggradation and/or erosion. Figure 3 shows an example of a river channel bend where the position of the scroll bar moved landward away from the channel as a result of erosion due to a historically large flood on the river in 2015. All of the river bends studied in Mason and Mohrig’s previous survey show a change in the position of the edge of the youngest scroll bar (either moving away from the channel, as in Figure 3, or moving in the same direction as the erosion of the outer bank).

Measurements from scroll bars and adjacent point bars highlight consistent differences in their planform size and shape. First, the arc-length for a scroll bar is less than that of the adjacent point bar. Second, the radius of curvature for scroll bars is consistently greater than the radius of curvature of the associated point bar shoreline (Figures 2A and 4). No significant trend in the relationship between the radius of curvature of the point and scroll bars is found moving from the upstream to...
downstream ends of the survey area, despite increased point bar submergence with distance downstream due to the backwater effect. In the zone of uniform flow on average 57% of point bar relief was submerged, while in the downstream backwater zone the average submerged fraction increased to 71% of point bar relief. A Wilcoxon rank-sum test shows that the distributions of ratios of scroll bar to point bar radii of curvature for the uniform and backwater zones are indistinguishable at the 99% confidence level.

Figure 2B shows a representative channel cross-section from the outer bank levee crest to the oldest scroll bar. On the inner bank, the top of the point bar, defined by a relatively flat but still convex-upward surface, is positioned well below the elevation of the outer bank. The scroll bars rise several metres above the top of the point bar and are positioned only slightly below the elevation of the outer bank levee crest on average. This relationship holds true for the majority of transects measured across the survey reach. Figure 5A shows a histogram of the difference in elevation between all measured scroll bars and the corresponding outer bank levee crests along the same transects. The majority of scroll bar elevations are on the order of decimetres below the elevations of the outer banks (mean difference is $-0.4\, \text{m}$, with a standard deviation of $0.7\, \text{m}$). 82% of measured scroll crests were within 1 m of the outer bank in elevation. A quarter of the measured scroll bar crests are higher than their associated outer banks.

In general, the crest of a given scroll bar is highest at its upstream end and gradually decreases in elevation downstream (Figure 5B). Only 16% of the measured scroll bar crests are more than 1 m below the outer bank in elevation. Of these 169 measured points, 115 (68%) were located along the downstream half of the scroll bar. Of the 30 measured scroll bar crests that were more than 2 m below the outer bank (3% of all measurements), 27 were located along the downstream half of the scroll. The youngest scroll bar crest is on average 0.6 m lower than more landward scrolls, while the second scroll bar is just 0.1 m lower than all older scrolls on average (Figure 5D). Beyond the second scroll bar, there is no significant trend in crestal elevation with distance away from the channel. Figure 6 shows the topography of the swales associated with the active scroll bars. In general, the difference in elevation between the scroll crest and the adjacent swale increases down the length of the bar (Figure 6).

The crest elevations for scroll bars change character from the zone of uniform flow into the backwater zone (Figure 5C). In the backwater zone there are fewer scroll bars present ($n = 299$ for the backwater zone vs $n = 745$ upstream). The bends that were sampled in the backwater zone reveal a tighter distribution of elevation differences between scrolls and outer banks due to a decrease in the number of positive differences (fewer scroll bars were higher than their associated outer bank levee crests).

**Stratigraphy**

Eleven trenches dug along five separate scroll bars show similarities in stratigraphic architecture across the entire survey reach. Three characteristic trenches are shown in Figures 7, 8 and 9. The majority of trench walls were composed of ripple-scale cross strata that show a variety of transport directions (away from the channel, downstream and towards the channel; Figure 9 shows an example of multiple ripple migration directions within a single package of sediment). Boundaries between sets of rippled cross strata generally dip towards the channel but can dip away from the channel as well (Figure 7). These deposits were composed of very fine and fine sand. Often, dune-scale cross strata were dominant at the base of the trench (Figure 8) and lenses of coarser dune-scale strata were seen.
Figure 5. (A) Histogram of measured elevation differences between the outer bank levee crest and the scroll bar crest for all transects within the study area ($n = 1044$, bin width = 35 cm). Negative values indicate the scroll crest is lower than the outer bank. Elevation differences are centred just below zero and are negatively skewed. The mean elevation difference is $-0.4$ m, with a standard deviation of $0.7$ m. (B) Box plots showing the relative downstream elevation change for all measured scroll bar crests as a function of fractional distance down the bar. On each plot, the central line indicates the median, the bottom and top edges of the box represent the 25th and 75th percentiles, the whiskers indicate the range of the data and the points are considered outliers. On average, scroll crests tend to decrease in elevation with distance down the bar. (C) Cumulative distributions of elevation differences between measured scroll bar crests and the outer bank levee crests. Dashed grey vertical line represents equal elevation for measured scroll crests and outer bank levee crests. The scroll bars forming in the zone of uniform flow are shown by the solid line, and backwater-zone scrolls by the dotted line. There are fewer measured scroll bars present in the backwater zone, and they are less likely to be higher than the associated outer bank levee crest. (D) Cumulative distributions for elevation differences between measured scroll bar crests and their outer bank organized by distance away from the channel. Dashed grey vertical line represents equal elevation for measured scroll crests and outer bank levee crests. The youngest scroll bar (the one closest to the channel centreline) is on average $0.6$ m lower than the subsequent scrolls. The second scroll bar is higher. All remaining older scroll bars are still slightly higher in elevation.

Figure 6. (A) Elevation profiles along the crest of the youngest scroll bar (black line) and its adjacent swale (dotted line) for the river bend shown in Figure 2. The difference in elevation between the two increases downstream. (B) Box plots showing the distribution of elevation differences between the active scroll bar crest and its adjacent swale with fractional distance down the scroll bar for the youngest scrolls along each bend within the survey area. On each plot, the central line indicates the median, the bottom and top edges of the box represent the 25th and 75th percentiles, the whiskers indicate the range of the data and the points are considered outliers. The swale becomes progressively lower relative to the scroll crest farther along the scroll.
interspersed within rippled strata (white-coloured deposits in Figures 8 and 9). These deposits were most often composed of medium and coarse sand. Mud-rich intervals were common and these contained the highest densities of roots and bioturbation. Even so, organic-rich deposits were relatively sparse; if present, they were in the form of isolated root zones, buried branches or detrital leaf material.

The modern scroll bar topography was overwhelmingly composed of rippled, very fine to fine sand deposits that were interspersed with lenses of coarser, dune-scale cross stratified sands and mud-rich intervals. If a base of coarser, dune-scale cross stratified sands was present in a trench, it was below the elevation associated with the modern scroll bar topography and was instead consistent with the elevation of the adjacent point bar.

A total of 85 sediment samples were taken from representative locations along each trench (35 from dune-scale cross strata, 50 from rippled and/or mud-rich locations) and analysed for grain size (Figure 10). The mean value for D50 from the 50 rippled/muddy samples was 0.17 mm (lower fine sand; all grain size classifications correspond to the Wentworth classes). 25 out of the 50 rippled samples contained more than 20%...
medium sand. The coarsest rippled sample was composed of 60% medium sand or coarser. This sample was taken from the trench in Figure 7, just above the transition from coarser, cross stratified sands to the rippled deposit (the bottom star near metre 4). The 35 samples with dune-scale cross strata were measurably coarser than the rippled samples, with a mean D10 of 0.19 mm (upper fine sand, coarser than the D50 for the rippled samples) and a mean D50 of 0.36 mm (upper

Figure 8. Photos and line drawing of an 8-m long trench (2× VE) oriented perpendicular to the channel centreline on the channel-ward side of the youngest scroll bar in the bend (see inset aerial image for relative location). The most upstream star in Figure 1 marks the position of this river bend. Surface context is provided by the small bottom-centre image looking at the trench and up to the scroll bar crest from the top of the point bar. The crest of the scroll bar is ~3 m beyond the left end of the line drawing, and the trench dips towards the channel. Flow within the main channel is moving out of the page. Darker-coloured deposits indicate finer grain sizes. The base of the trench is composed of pebbly sand with dune trough cross stratification indicating bed material transport out of the page and interpreted as deposition connected to a previous position of the point bar. The transition into deposits composed of reworked suspended material (indicated by the thick dashed line) is abrupt. Ripple cross stratification makes up the majority of the scroll bar deposit, with some plane bed stratification and lenses of coarser bed material interspersed within the rippled sediment.

Figure 9. Photos and line drawing of a 20-m long trench (2× VE) that was positioned perpendicular to the channel centreline on the channel-ward slope of a scroll bar (fourth starred bend near Liberty, Figure 1). The right-hand edge of the trench is at the position of the scroll bar crest (see aerial image for the relative location of trench). Flow within the main channel is moving out of the page. Trench is dipping towards the channel. Darker-coloured deposits indicate finer grain sizes. This trench is primarily composed of deposits with ripple cross strata, with some supercritically climbing ripples indicating transport out of the channel. Lenses of dune-scale cross stratification are interspersed within the finer-grained rippled beds associated with scroll bar deposition. Surfaces between packages of rippled sediment are subtle and often unable to be followed laterally (see right side of trench), and likely reflect local variability in deposition rate. (Colour figure can be viewed at wileyonlinelibrary.com)
medium sand). Eight out of the 35 dune-scale cross-stratified samples were composed of more than 20% coarse sand or above. The largest measured grain sizes are within the lower fine pebble range (5 mm) and are present only within the dune-scale cross-stratified basal portions of trenches (see top right inset photo in Figure 8). A Kruskal–Wallis test carried out on the two groups of grain size distributions confirmed that they are statistically different at the 1% significance level.

**Discussion**

The trend of increasing scroll bar crestal elevation with orthogonal distance away from the channel (Figure 5D) is only significant for the first two scroll bars. Beyond the second scroll bar, the crestal elevations appear to stabilize. This is likely due to the amount of time that each scroll has had to aggrade. The youngest scroll bar has experienced the fewest overbank flooding events and is likely lower as a result of the relatively limited sediment delivery. The maximum elevation that a scroll bar crest can reach is capped by the elevation of the free surface of the overbank flow, which cannot exceed a certain depth as the flow is no longer confined within the channel. An alternative interpretation to explain the lower elevation of the youngest scroll bar requires that the channel is actively incising into the floodplain. However, several depth profiles taken along a 27-km stretch of the river preceding, during and following a historically large flooding event on the Trinity show no net aggradation or erosion (Mason and Mohrig, 2018), implying that active vertical incision is not an important factor dictating scroll bar crestal elevations in this system.

On the average scroll bar, the crestal elevation tends to decrease with distance down the river bend (Figure 5B). In addition, the swales behind the active scroll bars become increasingly lower farther downstream (Figure 6). This is likely due to the direction of the sediment source responsible for the growth of the scroll bars and infilling of the swales. During prolonged overbank flood conditions, flow is supplied to the floodplain not only from the orthogonally adjacent channel but also from the upstream bends (which is also evidenced by the dominance of downstream-migrating ripple cross strata present in scroll bar trench walls; see Figures 7 and 9).
sediment within the flow is deposited quickly upon exiting the channel, leading to preferential deposition along the upstream portions of the scroll bars and swales. In other words, the rate of growth for a single scroll bar decreases downstream.

Scroll bars within the backwater zone exhibit slightly different characteristics than their uniform flow counterparts. Lateral migration of the channel is dampened within the backwater zone (Fernandes et al., 2016; Hudson and Kesel, 2000; Lamb et al., 2012; Nittrouer et al., 2012; Smith, 2012), leading to fewer total scroll bars (Figure 5C). The scroll bars that are present in the backwater zone are less likely to have crest elevations that are higher than the outer bank levee crests. The reason behind this remains unclear; future research aimed at understanding why scroll bars appear to behave slightly differently within the backwater zone would be beneficial.

The existing literature about scroll bars has been inconsistent on their identification as constructional or erosional features. Some authors suggest that focused erosion between bars is what creates the topography associated with scrolls, making them a negative relief feature (McGowen and Garner, 1970; Nanson and Croke, 1992; Lewin and Ashworth, 2014). In Figure 2B it is clear that the swales between successive scroll ridges are not lower than the top of the point bar. While the swales between scroll bars tend to focus overbank flow and drainage once a succession of scroll bars has been established (see the downstream portion of Figure 2A for an example of swales between older scrolls focusing drainage), our data suggest that at least on the Trinity River, the swales are not formed from wholesale erosion, but from minor to negligible deposition compared to the adjacent scroll crests. The ridge-and-swale topographic relief is therefore primarily formed through preferential and focused deposition of scroll bars along point bar banks.

The Trinity River has extensive, mature levees associated with overbank deposition along the outer banks of most bends. The mean levee height above the adjacent floodplain on the studied reach of the Trinity River is 1.3 m (Hasenruck-Gudipati et al., 2017). Levees are highest at the edge of the main channel, where the outer bank elevation measurements used in this study were taken. While the nature of levee deposition and growth is not perfectly understood, they are universally recognized as features that create positive relief above the elevation of the floodplain (Leopold et al., 1964). Because the crests of scroll bars are on average only 0.4 m below the outer bank levee crests (Figure 5A), scroll bars can also be considered constructional features of positive relief 0.9 m above the floodplain, on average.

The constructional nature of scroll bars has implications for their identification in the sedimentary record. We suggest that unless a feature can be definitively identified as having positive relief above the elevation of the associated point bar, it should not be interpreted as a scroll bar. There are several likely examples of misinterpretation of features as scroll bars. For example, planetary geomorphologists often interpret curved strata within preserved channel belts on Mars as scroll bars (Burr et al., 2009; Moore and Howard, 2005; Schon et al., 2012). These features are much more likely to represent the lateral accretion surfaces associated with point bar growth and bend migration, as the likelihood of preserving a scroll bar is low considering that they are confined to the upper portion of the deposit and the average scroll bar is responsible for only 12% of the total inner bank relief (Figure 2C). Without clues indicating that scroll-like features are topographically higher than the point bars or floodplain they are associated with, the definitive identification of these features as scroll bars would be difficult.

While we believe the misidentification of point bar lateral accretion surfaces as scroll bars is common, it does not greatly alter most interpretations because both scrolls and point bar surfaces are indicative of deposition associated with meandering river channels. However, the misidentification becomes problematic if the deposits are subsequently used to reconstruct paleochannel properties. Point bars consistently have a lower radius of curvature than their associated scroll bars (Figure 4). The few bends that have scroll bars and point bars with similar curvature are low-amplitude young bends affected by recent cutoffs or bends with narrow point bars. Reconstructions of river bend length and amplitude based on a set of point bar surfaces misinterpreted as scroll bars would therefore be overestimates. In addition, the reconstructed centreline would have a higher sinuosity than one reconstructed from a set of actual scroll bars.

Trench walls show that the volumetric majority of sediment associated with scroll bars was deposited by grains that settled out of suspension and were subsequently reworked as a low transport stage bedload (i.e. ripples; Figures 7, 8 and 9). Because of their association with the modern scroll bar topography, we interpret these deposits to represent the construction of the scrolls. Ripple cross stratification records a variety of transport directions that are consistent with flow out of the channel, down the channel and back into the channel. These ripples are interpreted to record multiple stages of the flood duration (i.e. flood stage as it begins to flow overbank, sustained overbank flow and drainage of the floodplain following recession of the flood, respectively). Planar laminations in the form of lower plane bed are also fairly common, as well as mud-rich layers. All of these observed depositional structures are commonly used as stratigraphic indicators of levee deposition in modern and ancient channel belts (Bridge, 2009; Brierley et al., 1997). The coarser, dune-scale cross strata often present along the bases of trenches are interpreted as deposition associated with earlier point bar growth. Scrolls are relatively enriched compared to point bars in all grain sizes smaller than fine sand, the largest grain size that is commonly moved in coastal fluvial systems as both bedload and in suspension (Nittrouer et al., 2008). Based on the stratigraphic evidence, scroll bar depositional style and grain size appear to be comparable to proximal overbank deposition.

Proposing that there exists a genetic distinction between scroll bars and outer bank levees is an increasingly difficult argument to support. The crestal elevations of scrolls and outer bank levees are quite similar, implying that they are both constructional features that create positive relief above the adjacent floodplain (Figures 2 and 5). They also have similar stratigraphic architectures and sedimentary structures (Figures 7, 8 and 9). Thus, we interpret scroll bars as levees that have been deposited along the inner banks of these meandering river bends. The form of scroll bars is more complex than that of the outer bank levees because of their interaction with the point bar along the inner bank. The elevation of the top of the point bar is consistently lower than the elevation of the floodplain (Figure 2B). As the channel laterally migrates, the outer bank erodes and the point bar aggrades, widening the flattened top of the point bar. After a large amount of widening, any subsequent flow that manages to submerge the bar will be forced to spread out along the top of the point bar. If enough point bar widening has happened, the spreading, relatively unconﬁned ﬂow on the bar top will sufﬁciently decelerate and deposit suspended material from the water column, promoting scroll bar formation. Of course, the locus of maximum suspended sediment deposition will depend on the river discharge, point bar shape and size, as well as channel morphology, making it difﬁcult to predict the timing and positioning of new scroll bars. The base of the scroll bar deposition (i.e. the top of the point bar) is lower than the base of the outer bank levee (deﬁned by the ﬂoodplain elevation). Because of this, scrolls must vertically aggrade much more than an outer bank levee to reach an
equivalent crestal elevation. As a result, they tend to be lower than their associated outer bank levees (Figure 5).

What determines the spacing between scroll bars is unknown. The formation of a new scroll bar at a more channelward position likely requires river bend migration to exceed some threshold distance dictated by the geometry of the bend and point bar. We hypothesize that when the bend migrates less than this threshold distance, the highest deposition rates for suspended sediment remain connected to the established scroll bar. When the river bend migrates more than the threshold distance, the widening of the point bar top causes the flow to decelerate sufficiently to focus deposition of suspended sediment in a new, more channel-ward position.

The relative scarcity of organic-rich deposits within the observed trench walls implies that the sedimentation associated with scroll bar growth is not necessarily linked to the presence of vegetation. While there certainly tends to be a correlation between the position of scroll bars and the presence of vegetation in many modern rivers, causation cannot be applied to one or the other, especially as many plant species likely preferentially colonize areas characterized by finer grain sizes and less frequent inundation. In addition, plants are more likely to establish surfaces that are prone only to next sedimentation versus both the sedimentation and bed remobilization/erosion occurring on active point bars that can uproot plants.

Point bar deposition is consistent with bed material transport within the channel, and we have established that the scroll bar represents the inner bank levee, it can be inferred that the edge of the scroll bar marks the geomorphic edge or inner bank of the channel. Time-lapse LiDAR data covering the same area of the Trinity River as the LiDAR data discussed here show that landward movement of the inner bank occurred in 32 out of 55 measured bends as a result of a flood in early 2015 (Mason and Mohrig, 2018; that duration of overbank flood had not previously been measured on the Trinity since the installation of the Liberty flood gauge in 1938). Figure 3 (Figure 11 from Mason and Mohrig, 2018) shows a single bend where the scroll bar in its antecedent position has been eroded and subsequently covered with large bed forms after the sustained flooding event. The observation of bed material depositing over the position of an antecedent scroll can also account for the lenses of coarser-grained material with larger-scale cross stratification present in scroll bar trench walls (Figures 8 and 9). Lenses of point bar material encapsulated within scroll bar deposits were present within trenches in three of the five sampled scroll bars, implying that the process of scroll bar erosion by landward point bar widening is not uncommon.

Scroll bar growth and migration is not necessarily unidirectional, as our trenches and the data from Mason and Mohrig (2018) suggest (Figures 3, 7, 8 and 9). Packages of rippled sediment defining the growth of scroll bars mostly dip towards the channel, consistent with growth of the scroll bar to follow the overall outward migration of the river bend. However, some packages dip away from the channel along the landward slope of the scroll (see Figure 7). These packages imply that scroll bars can widen both channel-ward and in the landward direction as well, reducing the spacing between consecutive scroll bars. These observations should induce caution when attempting to use the spacing between scroll bars as a proxy for overall channel migration. However, it is clear that on average, scroll bars tend to track the outward migration of the river bend.

Conclusions

We posit that scroll bars on the Trinity River are analogous to outer bank levees that have instead been deposited along the inner banks of the river. We draw the analogy between scroll bars and levees based on their similar crestal elevations (Figures 2 and 5) and comparable stratigraphic architectures (Figures 7, 8 and 9). While it is undoubtedly true that the presence of a number of scroll bars in other systems is likely due to other factors (e.g. flood debris or vegetation inducing fall-out of suspended sediment), our hypothesis implies that the presence of scroll bars in rivers can occur without significant vegetation (on Mars, for example). Future modelling efforts to determine when and where flow decelerates enough along the tops of point bars to induce suspended sediment deposition will be immensely helpful for understanding why scroll bars form where they do.

Because the position of preferred scroll bar deposition continues to move as the channel itself migrates, scroll bars are likely representative of the initial stages of levee development. It is interesting then to consider the transition from a young levee (i.e. scroll bar) to a larger mature levee. Using scroll bars as a proxy for early levee growth would be hugely beneficial for learning more about levee sedimentation, a process that is still relatively understudied.

The results presented here should promote the use of caution when attempting to identify scroll bars preserved in the stratigraphic record. Positive topographic relief above the tops of the associated flood plain or point bar, as well as structures consistent with proximal overbank deposition, should be used as distinguishing characteristics before a feature can be recognized as a scroll bar. Point bar lateral accretion surfaces may at first appear qualitatively similar to scroll bars but represent a different process with markedly different geometries (Figure 4) and stratigraphic architectures (Figure 8). If one accepts the interpretation of scroll bars as inner bank levees, then they should be considered the geomorphic edge of the channel. The point bar, by definition, is fixed within the channel, meaning that its upstream and downstream limits must converge with the position of the inner bank. Therefore, if the point bar extrudes into the channel at all, its curvature will be exaggerated compared to that of the scroll bar. The consequence of this is that the radius of curvature of point bars never exceeds that of associated scroll bars (Figure 4). Misidentification of a point bar lateral accretion surface as a scroll bar can thereby lead to errors in bend length and amplitude estimates, as well as estimations of the channel centreline position. It should be noted as well that preservation of scroll bars in the rock record is unlikely given that their relief is small compared to the total relief of the channel (Figure 2C), and many features identified as scroll bars in the rock record may instead be point bar lateral accretion surfaces.

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