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Late quaternary alluvial history of the Brazos River in central Texas

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ABSTRACT

The late Quaternary history of the bedrock-controlled Brazos River system in central Texas is poorly understood as to the complex interplay between bedrock and climate on episodes of channel incision and aggradation. Through geomorphic assessment, sediment core analysis, and luminescence dating (OSL) we map the alluvial terrace and floodplain deposits in the Steinbeck Bend study area in central Texas. Five stratigraphic (allostratigraphic) units were identified beneath four alluvial terrace-sediment complexes (T3-Unit I, T2a-Unit II, T2b-Unit III, T1a-Unit IV, T1b-Unit V) and the current floodplain (T0-Unit VI) of the Brazos River, with the accompanying OSL geochronology ranging from >60 to 0.3 ka. Channel incision appears to have occurred during the transition to cooler and wetter intervals at the beginning of MIS 4 and MIS 2. Alluvial deposition proceeded mainly during the latter stages of the warmer MIS 5 and during the first half of MIS 3, both characterized by a slight warming trend. The alluvial architecture of all units was formed by single story, mixed load meandering channels migrating laterally across Cretaceous marls. Upstream from the study area, the bedrock valley narrows because of the presence of more resistant limestones forming the bedrock channel floor and valley walls. In the Steinbeck Bend study area, the incised meanders develop into larger radius of curvatures as the Brazos River migrates across less resistant Cretaceous marls. Below the study area in the weakly consolidated Tertiary coastal plain deposits, the Brazos River becomes freely meandering, cutting laterally and vertically through previously deposited alluvium interceded by channel avulsions.

1. Introduction

The headwaters of the Brazos River begin in the southern High Plains of northwest Texas and continues as a perennial stream until it empties into the Gulf of Mexico in southeast Texas (Fig. 1; Bozarth, 1995). Yet our understanding of the late Quaternary alluvial history of this important river is poorly understood because so few formalized geological studies have been conducted. Separated by the Balcones Escarpment fault line in central Texas, the drainage basin can be subdivided into the upper reach dominated by Cretaceous limestones and marls, and the lower reach dominated by weakly consolidated Tertiary sandstones and shales (Barnes, 1970). Previous studies from the upper reach show that the Brazos River is a bedrock-controlled channel system eroding across and incising through Cretaceous bedrock, while storing thin alluvial deposits beneath laterally inset terraces and floodplains (Abbott, 2011; Blum et al., 1992; Mandel et al., 2018). In the Tertiary coastal plain of the lower reach, the river is freely flowing in a wide valley filled with vertically stacked alluvial deposits and buried soils (Waters and Nordt, 1995). The central Texas study area at Steinbeck Bend is located in the transition between these two reaches near where the Balcones Escarpment crosses the Brazos River valley. Here, sediment cores taken from an alluvial terrace at the Waco Mammoth National Monument, revealed relatively thin alluvial deposits resting on Cretaceous bedrock (Nordt et al., 2015) similar to that observed in stratigraphic sequences further upstream. Water well logs indicate that floodplain deposits in the Steinbeck Bend study are resting on bedrock (Cronin and Wilson, 1967), yet the channel pattern in this region, while apparently bedrock controlled, has a much larger meander of radius compared to the bedrock-controlled river pattern further to the north. Further limiting our understanding of channel activity along the Brazos River during the late Quaternary are sparse climate proxy leading to varying interpretations of the role that climate played on cut and fill episodes as an external forcer versus internal controls imposed by bedrock and alluvial channels (Nordt, 1995; Ferring, 1994; Blum et al., 1994; Blum and Aslan, 2006; Waters and Nordt, 1995; Sylvia and Galloway, 2006).

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Here we investigate the critical transition between bedrock channel control and alluvial channel control of the Brazos River in central Texas to better understand the complex interplay with climate during the late Quaternary. Two late Pleistocene alluvial terraces (T3 and T2), a lower alluvial terrace within the Steinbeck Bend meander belt (T1), and the modern floodplain (T0) were previously mapped by Nordt et al. (2015; Fig. 2), and are the focus of this investigation. The objectives of this study were to 1) identify and describe the sequence of stratigraphic units (unconformable boundaries), 2) reconstruct the environments of deposition, 3) geochronologically constrain these units using stratigraphic relationships and OSL dating, 4) infer the factors leading to episodes of deposition and erosion, and 5) compare the record to regional alluvial and climate studies.

2. Geologic setting

The Brazos River flows southeastward from the southern High Plains of Texas (Llano Estacado) to the Gulf of Mexico with its drainage basin covering some 160,000 km^2 (Fig. 1A and B Bozarth, 1995). Above the central Texas study area, the alluvial sediments consist of gravels, sands, silts and clays derived from Paleozoic to Mesozoic marine and terrestrial deposits. The limestone gravels, including chert, are derived mainly from Cretaceous bedrock with other siliceous components (quartz and quartzite) derived from early Quaternary alluvial deposits sourced from the southern Rocky Mountains (Abbott, 2011).

Climate today in central Texas is humid subtropical, with hot summers. Tropical air masses from the Gulf of Mexico predominate through the late spring to early fall and sub-Polar air masses dominate the winter months. The mean annual temperature from the city of Waco is 19.1 °C and mean annual precipitation is 881 cm (Worldclimate, 2016; http://www.worldclimate.com/).

The area of interest is the Steinbeck Bend area near the confluence of the Brazos and Bosque Rivers north of Waco, Texas (31°36′32″ N, 97°8′50″ W; Figs. 1 and 2). The modern Brazos River in the study area can be divided into three sectors (Fig. 1C). Sector 1 begins upstream north of the confluence with Hackberry Creek where the river is entrenched to limestone of the Fredericksburg Group and flows within a narrow, valley accompanied by scattered alluvial deposits resting on bedrock straths. Sector 2 includes the present study area where the river remains entrenched but where the bedrock valley widens apparently because of the abundance of more easily erodible Cretaceous clays and marls (Grayson Marl). The floodplain narrows as it flows through the Austin Chalk that forms the Balcones Escarpment, and then widens again in Sector 3 downstream as the river becomes freely meandering through its own alluvium.

Terrace and floodplains were assigned surface elevations from LiDAR

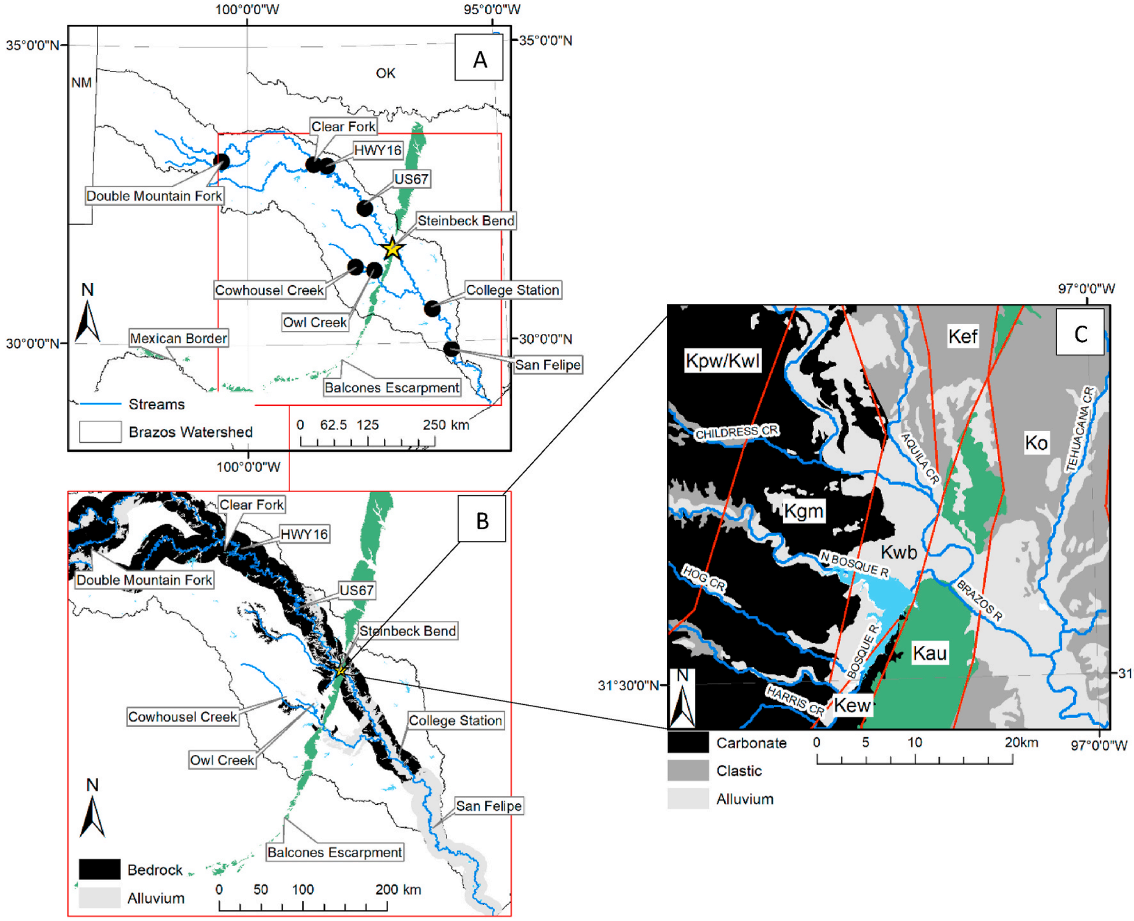

Fig. 1. A) Outline of the Brazos River Drainage Basin in the state of Texas. The star is the location of the Steinbeck Bend study area in central Texas and filled circles the location of other studies referenced herein. Double Mountain Fork (Blum et al., 1992), Clear Fork (Mandel, 1992), US67 (Abbott, 2011), Owl Creek (Meier et al., 2013), Cowhouse Creek (Nordt, 1995), College Station (Waters and Nordt, 1995), and San Felipe (Sylvia and Galloway, 2006). B) Enlargement of the Brazos River and select tributaries showing a bedrock confined channel upstream and an alluvial channel downstream, separated by the Balcones Escarpment. C) The Steinbeck Bend study area enlarged to show the three river sectors represented by narrow limestone-confined river canyons upstream, the transition into the shale-confined channel in the study area, and the freely meandering river downstream, below the Balcones Escarpment (below the Austin Chalk). The geologic formation symbols are Kau – Austin Chalk, Kef – Eagle Ford, Kew – Eagle Ford and Woodbine, Kgm – Grayson Marl, Ko – Ozan, Kwb – Woodbine, and Kpw/Kwl – Pawpaw and Upper Weno/Lower Washita.

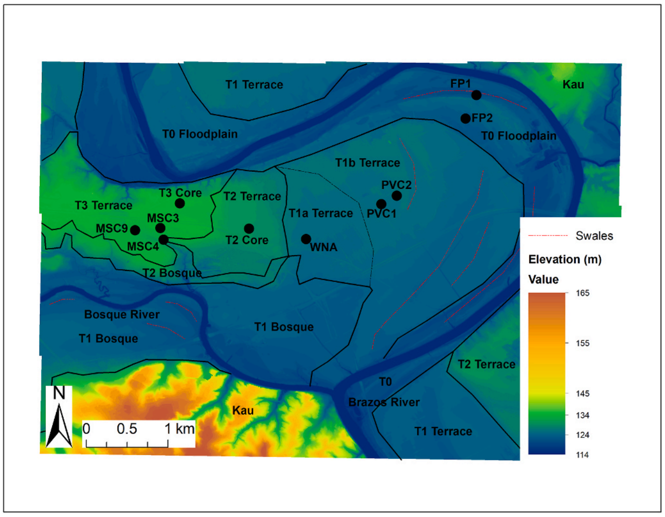

Fig. 2. Map of the study area showing the location of sediment cores extracted from the terrace and floodplain deposits in the Steinbeck Bend area. Black lines indicate terrace and floodplain boundaries where labels T3, T2, T1a, and T1b designate the terraces and T0 the modern floodplain. A dotted black line marks the boundary between T1a and T1b.

data with 30-cm accuracy.

3. Materials and methods

3.1. Sediment coring

Ten continuous sediment cores were extracted from T3, T2, T1 and T0 alluvial deposits along a transect at Steinbeck Bend using a hydraulic rig (Geoprobe 6620DT) (Fig. 2). Push tubes 7.6 cm in diameter were used to collect samples to the deepest depths possible before switching to 3.8 cm diameter tubes when sediments became more compacted. In a few instances flight augers were used at depth when it was no longer possible to extract with push tubes. Duplicate cores were extracted using opaque core liners for OSL dating.

3.2. Stratigraphic and soil descriptions

The ten sediment cores were described in the Baylor Sedimentary Geology Research Laboratory. Descriptions were written to identify unconformable boundaries (i.e. erosional contacts) and to identify and interpret depositional facies from texture, color, and sedimentary structures. Using methods of Miall (2014) and Galloway and Hobday (1996), we interpret channel, point bar (channel margin), flood basin (overbank) and levee (overbank) facies. Mixed load meandering streams were interpreted from facies where the proportion of channel versus flood basin/levee facies was approximately equal, suspended load meandering streams when the overbank facies dominated, and bedload streams when channel deposits dominated (Galloway and Hobday, 1996).

Soil descriptions were written from all sediment cores that included Munsell color, iron redoximorphic features, reaction to dilute HCl, ped structure, and other accessory features (i.e. slickensides, clay films, calcium carbonate nodules), following standards and procedures of Schoeneberger et al. (2012).

3.3. Optically stimulated luminescence

From the eleven samples dated by OSL, at least one was determined from each of the five identified stratigraphic units. Samples were collected in black sample tubes and transported in aluminum foil to avoid light contamination.

OSL measurements were carried out at the Sheffield Luminescence Laboratory, UK. Age was calculated from measurements of paleodose (D_e in Grays) and annual dose rate (Grays/yr). The latter was based on elemental concentrations of K, Th, U, and Rb as determined by inductively coupled plasma mass-spectrometry (ICPMS) and taking into account attenuation factors related to sediment grain size and density to annual dose rates (see Guérin et al., 2015 and see supplement for dosimetry; Table A1). Present-day moistures were applied as average paleomoisture with <5% accuracy. The contribution of cosmic sources was calculated using methods of Prescott and Hutton (1994).

For D_e determination, samples were prepared under subdued red lighting to extract and clean quartz grains per Bateman and Catt (1996). Samples were measured at the single grain (SG) level to ensure the burial age OSL signal was not masked by quartz grains that had received insufficient sunlight exposure (bleached) before burial, thereby containing an antecedent signal unrelated to burial age. Single grain measurements also help to distinguish grains recently bleached due to pedoturbation (Bateman et al., 2007). For single grain measurements, isolated quartz grains, sized between 180 and 250 μm, were mounted on 300 μm pits with 100 pits per 9.6 mm stainless steel aliquot. Grains were measured using a Risø DA-15® luminescence reader with radiation doses administered using a 90Sr beta source. A focused 532 nm Nd: YVO4 laser provided stimulation and luminescence detection was through a Hoya U-340 filter. Samples were analyzed to determine the D_e using the single aliquot regenerative (SAR) approach (Murray and Wintle, 2000, 2003). A dose recovery preheat experiment showed a preheated 220° for 10 s was optimal returning a value of 1.04 ± 0.04 of the given measured dose. Measurements were only used if the OSL signal measured above background, the SAR growth cure fitted the regeneration points well, value recycling was within ±20% of unity, and the error on the test dose used within the SAR was less than 20%. Only about 2% of the grains measured passed these criteria.

Saturated grains and zero-dose grains were measured in samples where D_e is within error or 0 Gy. Saturated grains are indicative of sample antiquity beyond the limit of the OSL technique employed or very poor sample bleaching before burial. Zero-dose grains are indicative of recent pedoturbation or sunlight exposure during sampling and/or grain mixing during transportation to the laboratory. Such grains were excluded from subsequent age analysis but were used to help interpret resultant OSL ages. Pedoturbation can manifest itself as D_e components smaller than the true burial age D_e (see Fig. 3 in Bateman et al., 2003). Incomplete bleaching of all grains in a sample can give rises to D_e components larger than the true burial age D_e.

When the replicate D_e values for each sample were evaluated, all but the youngest sample had high over-dispersion (OD) values and broad, non-normal D_e distributions indicative of partially bleached and/or disturbed samples. As a result, D_e values for age calculation were extracted using a Finite Mixture Model (FMM; Table 1; Galbraith and Green, 1990). As the dataset was complex, final age estimates required careful evaluation based on OSL data (D_e distribution, OD, number and dominance of FMM components and number of zero-grains/saturated grains) as well as *a priori* stratigraphic and sedimentological information.

3.4. Late quaternary landforms

The three terraces from oldest to youngest (T3, T2, T1), and the floodplain (T0), as mapped in the study area (Nordt et al., 2015), are traceable in both up and downstream directions (Fig. 2). The terraces appear to be unpaired, following the unidirectional migration of the bedrock incised meander belts from west to east. Remnants of older alluvial deposits to the west of the study area not investigated here (Barnes, 1970) may occur beneath a shallow pediment slope that rises up to the interfluve 10–12 m above the T3 terrace to the west of the study area. The underlying Cretaceous bedrock beneath terrace deposits in the study area is mainly the Grayson Marl (Barnes, 1970).

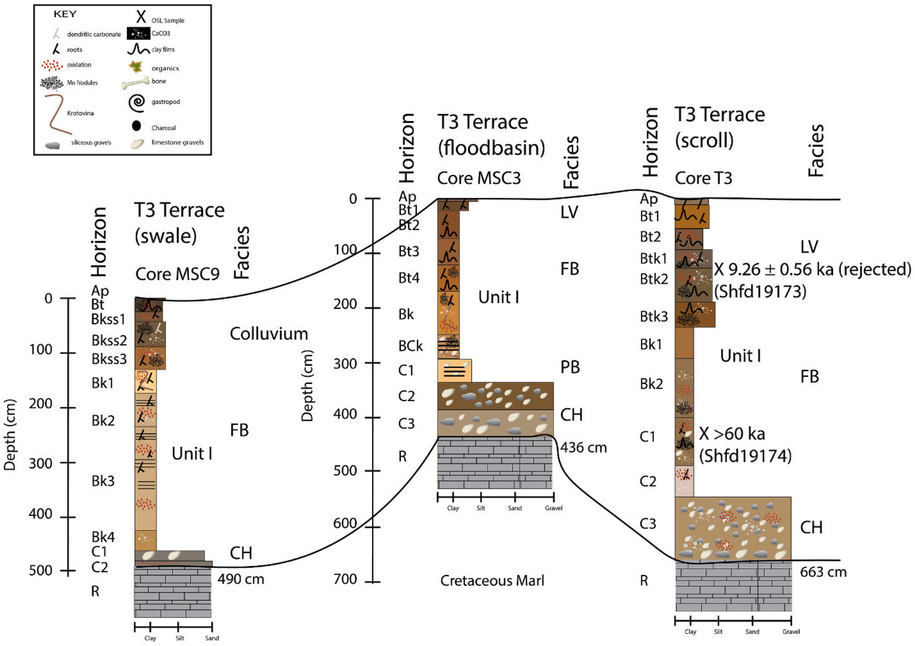

Fig. 3. Alluvial stratigraphy of three cores extracted from the T3 Terrace-Unit I complex in the Steinbeck Bend study area (see Fig. 2 for location). Soil symbols and associated features are indicators of soil maturity. Sediment layers are colored with corresponding Munsell Chart values. Facies symbols for Figs. 3–6 are CH-channel, PB-point bar, FB-flood basin, LV-levee. For Figs. 3–6, OSL ages given with laboratory sample numbers. Horizontal distances are not to scale.

The T3 terrace is mapped 21–23 m above the modern Brazos River channel, and assuming that it is unpaired, the floodplain valley of the river at that time may have been up 2 km wide. Soils mapped on this surface are mainly Alfisols (Bastsil and Wilson series) and Vertisols (Burleson series) giving the appearance of a relict meander scroll and swale topography (Greenwade and Wilson, 2001).

The T2 terrace is mapped along the outer margins of the current meander belt 13–19 m above the modern river channel. This terrace, where preserved at Steinbeck Bend, could have been only up to 1 km wide if unpaired. In the study area, this terrace is mapped mainly as the Branyon series (Vertisol), although in other T2 terrace localities in the area the Bastsil is mapped in association with the Branyon, again signifying what appears to be relict ridge and swale topography.

The T1 terrace is mapped within the incised meander belt of the modern Brazos River to the east of the T2 terrace at an elevation 9–11 m above the river channel. It's surface width ranges up to 2 km, or the width of the meander belt itself. Faint meander ridge and swale depositional features are observable on this terrace with the ridges mapped as Weswood silt loam and the swales as Weswood silty clay loam (Greenwade and Wilson, 2001). This topographic configuration tracks the unilateral migration of the river from west to east.

In the study area, the Brazos River is confined to a narrow floodplain (T0) valley with a width of 0.1–0.4 km situated 2–6 m above the river channel. The river is flowing on and laterally impinging into the resistant Austin Chalk Formation on the east side of the valley. The sandy Yahola series (Entisol) is mapped on T0, and includes rare to commonly flooded phases (Greenwade and Wilson, 2001). Sandy ridges are present, oriented parallel to the channel, that likely document former levees.

4. Late quaternary alluvial stratigraphy

4.1. T3 Terrace-Unit I complex

The three sediment cores extracted from this terrace alluvium are designated as MSC3, MSC9, and T3 (Fig. 2). OSL dating was performed on two samples from the T3 core as described below (see Table 1 and Table A1). The stratigraphic unit beneath the T3 terrace is designated as Unit I.

4.1.1. MSC3 sediment core

The MSC3 sediment core reveals an alluvial column exposing 4.36 m thick of Unit I that rests unconformably on the Cretaceous Grayson Marl (Fig. 3; Table A2). The alluvial succession consists of a basal channel gravel facies grading up into a loamy point bar facies and then up into a thick silty to clayey flood basin facies that form the constructional surface of the T3 terrace. The basal channel deposit contains 50% fine and medium, angular to subrounded, and grain and matrix-supported limestone and siliceous gravels. The point bar facies retains horizonal laminations and the flood basin facies has been weathered into the surface soil. The relative proportion of channel and overbank facies indicate the presence of a mixed-load, meandering stream in the study area at this time.

The surface soil of T3 at this locality is weathered into an Ap-Bt-Bk horizon sequence, typical of the Bastsil soil mapped in the area (well-drained Alfisol). Common distinct clay films appear on both vertical and horizontal ped faces between a depth of 20 and 170 cm. The Bt horizons in upper 165 cm of the soil profile have been decalcified, and immediately below in the Bk horizons, hard irregular carbonate nodules have accumulated that continue down to a depth of 300 cm. This degree of soil development is the most advanced of the soils identified in the present study area, consistent with formation on the oldest and highest T3 terrace.

4.1.2. T3 sediment core

The T3 sediment core was extracted from an elevation similar to core MSC3. The alluvial succession is thicker, however, extending to a depth of 6.33 m before encountering Cretaceous marl (Fig. 3; Table A2).

The lower 1.2 m of the Unit I alluvial succession beneath the T3 terrace at this locality consists of a channel facies with 50% grain and matrix-supported limestone and siliceous gravels, angular to subangular and 1–2 cm in diameter. This facies grades up into a flood basin silty clay facies that is about 2.6 m thick with pedogenic alteration. The upper 2.15 m of this alluvial succession forms the constructional surface of the T3 terrace, and is characterized by reverse grading from the lower clayey facies to textures dominated by silts and loams. The proportion of channel and flood basin facies in the lower part of the T3 sediment core points to the presence of a mixed load meandering stream similar to that identified in the previous core. Reverse grading observed in the upper part is interpreted as a conformable contact to a levee or meander scroll facies.

The surface soil at this location has weathered through the upper levee facies and into the flood basin facies below. Here the soil is mapped as Gholson very fine sandy loam (Alfisol) and is described here as an A-Bt-Btk-BCtk horizon sequence. The upper 127 cm of this profile is decalcified, below which occurs an accumulation of few irregular to spherical, medium carbonate nodules to a depth of 390 cm. Clay films are continuous and distinct on ped faces to a depth of 290 cm. The degree of soil development is similar to that described in the previous sediment core, both reflecting the greatest amount of soil weathering in the study area.

4.1.3. MSC9 sediment core

The MSC9 sediment core was extracted from a meander swale on the T3 terrace at an elevation approximately 2 m lower than the other two sediment cores (Figs. 2 and 3). At this locality the soil is mapped as the poorly drained Wilson Series (Alfisol). The alluvial deposit of Unit I at this location rests unconformably on Cretaceous marl at a depth of 4.9 m.

The lower part of MSC9 consists of a fine sand channel facies with few medium to coarse limestone and siliceous gravels grading up into a floodbasin facies of sandy clays totaling 3.6 m thick (Fig. 3; Table A2). Faint horizontal laminae are present from a depth of 1.74–4.24 m in the flood basin facies. Similar to sediments exposed in core MSC3, core MSC9 exhibits reverse grading in the upper 1.2 m as textures shift from sandy clays to silt loams and silts. This shift might represent the presence of a levee deposit, however, because the MSC9 core is in a lower topographic position it may have subjected to post depositional colluviation. Core MSC9 appears to expose remnants of a mixed load to suspended load, meandering stream based on the presence both channel and overbank facies, and the relict geomorphic configuration of meander ridges and swales.

The surface soil at this locality weathers through the levee facies and into the underlying flood basin facies, and is described as an Ap-Bt-Btkss horizon sequence. The profile is only decalcified to a depth of 25 cm possibly reflecting the introduction of more recent sediment to the stratigraphic column. Common, fine distinct carbonate nodules and slickensides appear beginning at a depth of 30 cm. Translocation of clay particles into the underlying Bt horizons. Redox concentrations are prominent in the matrix and along root traces of the soil indicating some periodic wetting and drying.

4.1.4. T3 Terrace-Unit I geochronology

Deposits containing bones from the Waco Mammoth National Monument (WMNM) are buried in an alluvial deposit inset to the T3 terrace on its south side (Fig. 2). Based on an OSL age of 66.0 +-5 ka, our interpretation is that the T3 terrace and Unit I are somewhat older than this. With this is mind, two OSL samples were collected from Unit I of the T3 sediment core. The lower sample (Shfd19174) is from the lower flood basin facies at a depth of 4.34 m. Based on the De values, it appears that this sample contains a dominance of quartz grains that have never been reset by light exposure during particle transport prior to deposition. The OSL signal for many grains was in saturation ($n = 126$), indicating that based on the dominant fraction of this sample ($FMM = 78\%$) is likely older than 60 ka (Table 1). The upper sample (Shfd19173) comes from a Btk horizon at a depth of 1.3 m. The lowest De value, assumed to be most likely reset during particle entrainment, matches the highest FMM (72%), which yields an age of 9.28 ± 0.56 ka. This estimated age is much younger than most of the OSL ages determined from younger deposits, and there is no unconformity between the two OSL ages in Unit I of sediment Core T3. Consequently, we reject this sample age because of an abundance of krotovina at this depth that likely translocated partially bleached (recent resetting of the luminescence signal) sediment from layers near the soil surface down to deeper depths.

There are no river studies from the central Texas documenting an age chronology of alluvial sediments >60 ka. However, Owl Creek, a bedrock-confined channel system to the west, shows that fluvial and alluvial fan deposition was ongoing between about 83 and 75 ka (Meier et al., 2013). Soil here formed in carbonate rich parent materials, forming a thin Bkm (calcite hardened) horizon during the interval of weathering. The degree of soil development on the Terrace T3-Unit I complex, however, in terms of thickness of the decalcified zone and thickness of the Bt and Bk horizons, is similar to those mapped on Pleistocene deposits similar in age to the upper part of the Beaumont Formation in the coastal plain of Texas (Blum and Price, 1998). Given this observation and that the T3 terrace is older than 66 ka indicates that it may have been deposited during the last interglacial of MIS 5 stage (>72 ka), similar to the upper part of the Beaumont Formation.

4.2. T2 Terrace-Unit II and unit III complex

We analyzed a core for correlation purposes taken from a previous study at the WMNM and designated it as Unit II (Nordt et al., 2015) (Fig. 2). One core (T2 core) was extracted from sediments beneath the T2 Terrace, designated as Unit III. OSL dating was performed on two samples from the T2 sediment core. Another OSL age is extrapolated from the MSC4 core at the WMNM.

4.2.1. MSC4 sediment core – unit II

The MSC4 core was extracted from the same deposit containing *Mammuthus columbi* from the WMNM, 19 m above the current Bosque and Brazos River channels and inset below the T3 surface by 2 m of vertical relief. The sediments exposed in this core consist of 5.23 m of silts and loams resting unconformably over Cretaceous marls, which is adjacent to a thick, incised gravelly channel facies (not shown here) (Fig. 4; Table A2). This area is typically mapped as the Sunev clay, a Mollisol, and is weathered to an Ap-A-Bk-BC horizon sequence. Few medium to coarse and irregular pedogenic carbonate nodules begin at a depth of 90 cm. The depositional environment exposed in the MSC4 core is thought to interpreted as a mixed load meandering stream. These deposits contain higher carbonate contents having been sourced entirely from Cretaceous limestones and marls of the Bosque River drainage basin. The degree of soil formation is similar to that described on the T2 terrace along the Brazos River, except that because of the high carbonate content, Bk horizon formation dominates over Bt horizon formation.

4.2.2. T2 sediment core – unit III

The lower channel facies of Unit III beneath the T2 terrace consists of 1.4 m of fine and medium sands interpreted as a channel-point bar facies complex. The overlying flood basin facies forms the constructional surface of the T2 terrace and consists of silty clays except for a surface veneer with a texture of SiCL (Fig. 4; Table A2). The lack of a channel gravel facies, along with a much thicker a flood basin facies, suggests that the Brazos River at this time was a suspended load, meander stream. It is possible, however, that based on an intermingling of fine-grained (Vertisols) and coarse-grained (Alfisols) deposits forming the surface of the T2 terrace up and downstream from the study area (Miller and Greenwade, 2001), that the Brazos River at this time was still forming a relict ridge and swale topography.

The surface soil at this locality is weathered to a depth of 456 cm and consists of an Ap-Bk-Bkss horizon sequence typical of the mapped Branyon series (Vertisol). The upper 92 cm of the soil profile has been decalcified with common coarse spherical carbonate nodules occurring between depths of 80 cm and 456 cm. Redox concentrations are prominent in the matrix and along root traces of the soil indicating some periodic wetting and drying.

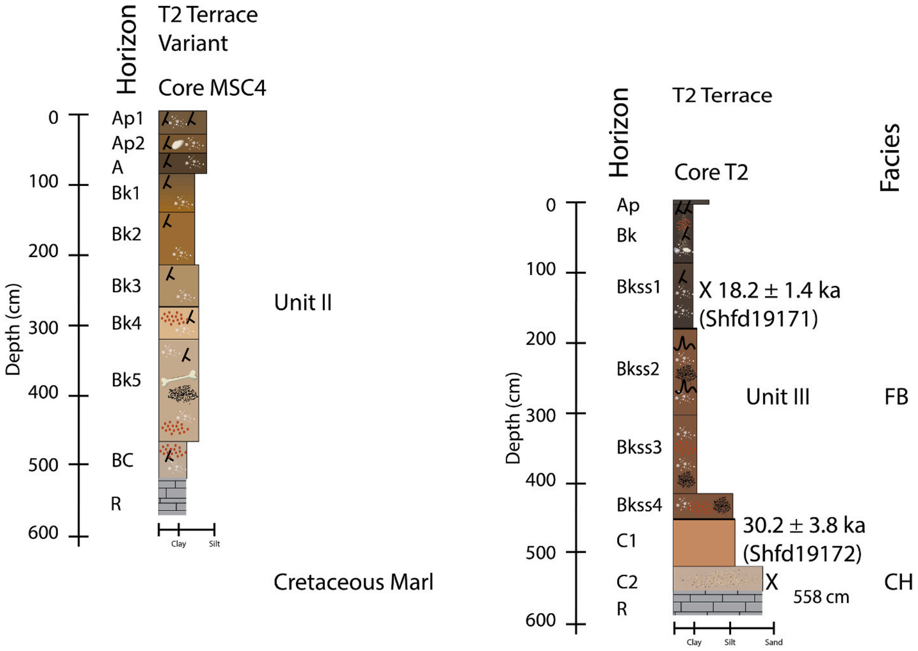

Fig. 4. Alluvial stratigraphy of the one core extracted from the T2 Terrace-Unit II complex and another from a T2 terrace-Unit III along the Bosque River (see Fig. 2 for location). *OSL age from core MSC4 is from Nordt et al. (2015).

4.2.3. *Terrace T2-Unit II and unit III geochronology*

Two samples were collected from Unit III sediments from the T2 terrace core (Table 1). The lower OSL sample (Shfd19172) was extracted from the well-sorted sand facies at a depth of 5.43 m depth. This sample yielded two ages, both of which fit within the overall stratigraphic framework. However, we accept the younger age of the two (30.2 ± 3.8 ka) because these particles contain the lowest De. The lower De and youngest age is preferred in fluvial sediments as the particles most likely to have been reset from sunlight during sediment transport.

The upper sample (Shfd19171) in Unit II beneath the T2 terrace comes from the Bkss horizon at a depth of 1.34 m. Here, the age from the youngest D_e component represents only 14% of the data yielding an age of 2.30 ± 0.26 (Table 1). The second component yields an age of 6.95 ± 0.54 ka, representing a greater percentage of the FMM. However, the first and second components are assumed to be a result of post-depositional mixing from shrink-swell processes. The estimated ages are too young when compared to reliable OSL dates reported in younger sediments beneath the lower T1 terrace (see next section). We accept the third age reported from this sample (18.0 ± 2.2 ka) because it has the next lowest De, which also fits the overall alluvial chronology. The T2 Terrace-Unit II complex is interpreted as forming mainly during MIS 3 and terminating during MIS 2.

The degree of soil development showing a decalcified zone of up to a meter thick with common carbonate nodules below is consistent with soils that have been forming for 15 to 20 ka as noted in the upper (Blum et al., 1992) and middle (Blum et al., 1994) Colorado River of central Texas.

4.3. *T1 Terrace-sedimentological complex*

We subdivide the T1 terrace into T1a on the outer part of T1 terrace adjacent to the riser leading up to the T2 terrace, and into T1b on the channel side of the terrace exhibiting ridge and swale topography. Sediment core WNA was extracted from Terrace T1a and sediment cores PVC1 and PVA2 from Terrace T1b. OSL dating was performed on two samples each from the WNA and PVC1 cores and on one sample from the PVC2 core.

4.3.1. *Terrace T1a-Unit IV complex*

Unit IV sediments beneath Terrace T1a consist of 4.14 m of alluvium resting unconformably on Cretaceous marls. In the lower part of the WNA core is 1.15 m of medium and fine sand of basal channel facies (Fig. 5; Table A2). This facies grades up into a thin loamy deposit that appears to represent a transitional point bar facies, before grading up into a thick and clayey floodbasin facies. The uppermost 15 cm (Ap horizon) may be a flood veneer from the adjacent T1b terrace. Unit IV forms the constructional surface of Terrace T1a and is weathered into an Ap-A-Bt-Btkss-Bt-BCk horizon sequence. This soil is mapped as the Wilson series (Alfisol), but is probably a Mollisol similar to the Lewisville series in this locality because of the thick, dark surface horizon. The upper 63 of Unit IV cm has been decalcified with very few soft, fine to medium carbonate masses appearing below at a depth of 110 cm. Prominent iron depletions and hard, spherical Mn nodules were present throughout much of this soil profile. Few hard, medium and pinkish/white carbonate nodules occur throughout the matrix beginning at a depth of 183 cm. Thin gravel-free channel and point bar facies grading up into thick, fine-grained flood basin facies, indicates that the Brazos River was a low competency suspended to mixed load meandering stream at this time.

4.3.2. *T1a Terrace-Unit IV geochronology*

One OSL sample (Shfd19170) was taken from a depth of 3.22 m in the WNA core that yielded ages of 34.2 ± 2.6 ka, 18.0 ± 2.2 ka and 6.28 ± 2.2 ka, while another sample from a depth of 2.21 m yielded ages of 24.4 ± 1.9 and 11.1 ± 1.5 ka (Table 1). For the lower sample, we prefer the age of 18.0 ± 2.2 ka, rejecting the youngest sample as the time of burial at this depth because this youngest age and lowest De come from only 11% of the sample. We have chosen to accept the age of 24.4 ± 1.9 from the upper sample at 2.21 m depth as the time of burial as it represents a greater portion of the FMM, is likely representing an age from rapid burial in a point bar setting, and is still within a 2-sigma uncertainty of the 18.0 ka of the lower sample. Thus, deposition of Unit IV is inferred to have been ongoing around 24.4 to 18.0 ka.

Chronological studies of soils dating to around this age have not been reported in the study area, but the upper decalcified zone from this soil is intermediate to that observed on the older T2 terrace and the younger

Table 1
Summary of single grain OSL data and ages for samples from Brazos River alluvium in the Steinbeck Bend study area.

Lab Code	Terrace	Allo-Unit	Sampling Depth (cm)	Saturated Grains	Zero-Dose Grains	Total Grains	FMM (%)[a]	D_e (Gy)	Dose rate (μGy/a^{-1})	Age (ka)	Accepted Age (ka)
Shfd19164	0	VI	67	0	5	38	–	1.03 ± 0.07	3277 ± 160	0.31 ± 0.03[b]	0.31 ± 0.03
Shfd19165	0	VI	340	0	13	35	54	0.67 ± 0.11	1187 ± 61	0.56 ± 0.1	0.56 ± 0.1
							46	1.73 ± 0.18		1.46 ± 0.2	
Shfd19166	1b	V	70	6	1	45	55	6.3 ± 0.44	2636 ± 128	2.39 ± 0.20	2.39 ± 0.20
							45	12.62 ± 0.86		4.79 ± 0.40	
Shfd19167	1b	V	294	13	1	47	28	20.14 ± 2.22	1605 ± 77	12.6 ± 1.5	12.6 ± 1.5
							70	40.78 ± 2.17		25.4 ± 1.80	
Shfd19168	1b	V	440	6	0	41	70	18.87 ± 1.50	556 ± 30	33.9 ± 33	33.9 ± 33
							22	39.89 ± 5.95		71.7 ± 11	
Shfd19169	1a	IV	221	12	1	42	24	26.49 ± 3.22	2379 ± 115	11.1 ± 1.5	24.4 ± 1.9
							76	58.09 ± 3.38		24.4 ± 1.9	
Shfd19170	1a	IV	322	5	1	48	11	10.55 ± 1.27	1679 ± 79	6.28 ± 0.81	18.0 ± 2.2
							28	30.26 ± 3.38		18.0 ± 2.2	
							61	57.36 ± 3.35		34.2 ± 2.6	
Shfd19171	2	III	134	11	0	45	14	6.48 ± 0.66	2814 ± 132	2.30 ± 0.26	18.2 ± 1.4
							49	19.26 ± 2.23		6.95 ± 0.54	
							37	51.31 ± 3.22		18.2 ± 1.4	
Shfd19172	2	III	543	3	1	44	28	19.26 ± 2.23	637 ± 33	30.2 ± 3.8	30.2 ± 3.8
							64	34.96 ± 2.18		54.9 ± 4.5	
Shfd19173	3	I	130	23	0	59	72	21.32 ± 0.81	2302 ± 108	9.26 ± 0.56	9.26 ± 0.56
							28	84.29 ± 5.27		36.6 ± 2.9	
Shfd19174	3	I	434	126	0	57	20	45.19 ± 4.38	2509 ± 118	18.0 ± 1.9	>60.0 ± 3.9
							78	150.0 ± 6.6		>60.0 ± 3.9	

[a] Totals do not always add up to 100% as components of <10% were excluded.
[b] D_e extracted using Central Age model as these grains had very high D_e replicate coincidence.

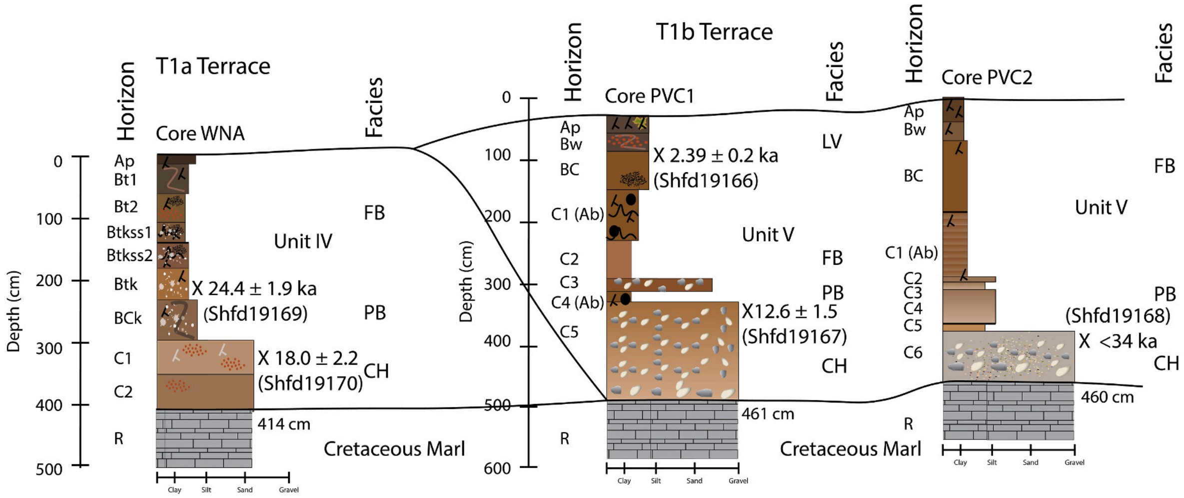

Fig. 5. Alluvial stratigraphy of one core extracted from the T1a Terrace and two cores extracted from the T1b Terrace (see Fig. 2 for location).

T1b terrace. The accepted age range of Unit III places it with MIS I.

4.3.3. Terrace T1b-Unit V complex

Cores PVCI and PVC2 were both extracted from Unit IV alluvium beneath the T1b terrace. The area around core PVC1 is mapped as the Weswood SiL of a meander ridge, while the PVC2 core is mapped as the Weswood SiCL in a meander swale. Unit V is laterally inset to the T1a-Unit IV complex by an erosional unconformity where the surface elevations and depth to marly Cretaceous bedrock are similar between the two terraces.

The basal channel facies of Unit V consists of 25% gravels and cobbles up to 3 cm diameter that are angular to subangular, matrix to grain supported, and mainly of limestones (Fig. 5; Table A2). The channel facies is thicker beneath the meander ridge in PVC1, possibly because it was more proximal to the river channel during deposition than in PVC2. The overlying and transitional channel to point bar facies is dominated by silts and loams about 75 cm thick. This facies grades upward into a clayey flood basin facies with horizontal bedding. At a depth of 2.15 cm, reverse grading into silts and loams indicates a transition into an evolving meander scroll/levee facies exposed in core PVC1. In the meanders swale of core PVC2, the thick flood basin facies forms the of the T1b terrace surface.

This combination of facies suggests deposition by a mixed load meandering stream of the Brazos River at this time, migrating eastward across the Cretaceous bedrock floor. Channel competency was higher though than that suggested by any of the previous channel facies associated with T3, T2 and T1a because of the abundance of coarser gravels. The surface soil is weakly developed with an A-Bw horizon sequence.

4.3.4. T1b terrace -unit V geochronology

An OSL sample (Shfd19167) extracted from Unit V in the PVC1 core returned an age of 12.6 ± 1.5 ka as the time of burial at a depth of 294 cm (Table 1). The age of 12.6 ± 1.5 ka is preferred as the burial age of these sediments as the presence of saturated grains (n = 13) would lead to skewness of the D_e. The OSL age obtained from 70 cm depth from Unit V sediments in core PVC1 (Shfd19166) is 2.39 ± 0.2 ka, representing 55% of the data and with the lowest De, which we accept as the burial age.

One OSL age (Shfd19168) was determined from Unit V in core PVC2 at a depth of 440 cm. This sample is poorly sorted, with grain sizes ranging from coarse sand to cobbles. The youngest FMM D_e component from this sample, which represents 70% of the data, is 33.9 ± 3.3 ka. However, there is evidence for saturated grains (n = 6) that has skewed the distribution and indicates that the older component of >71 ka is

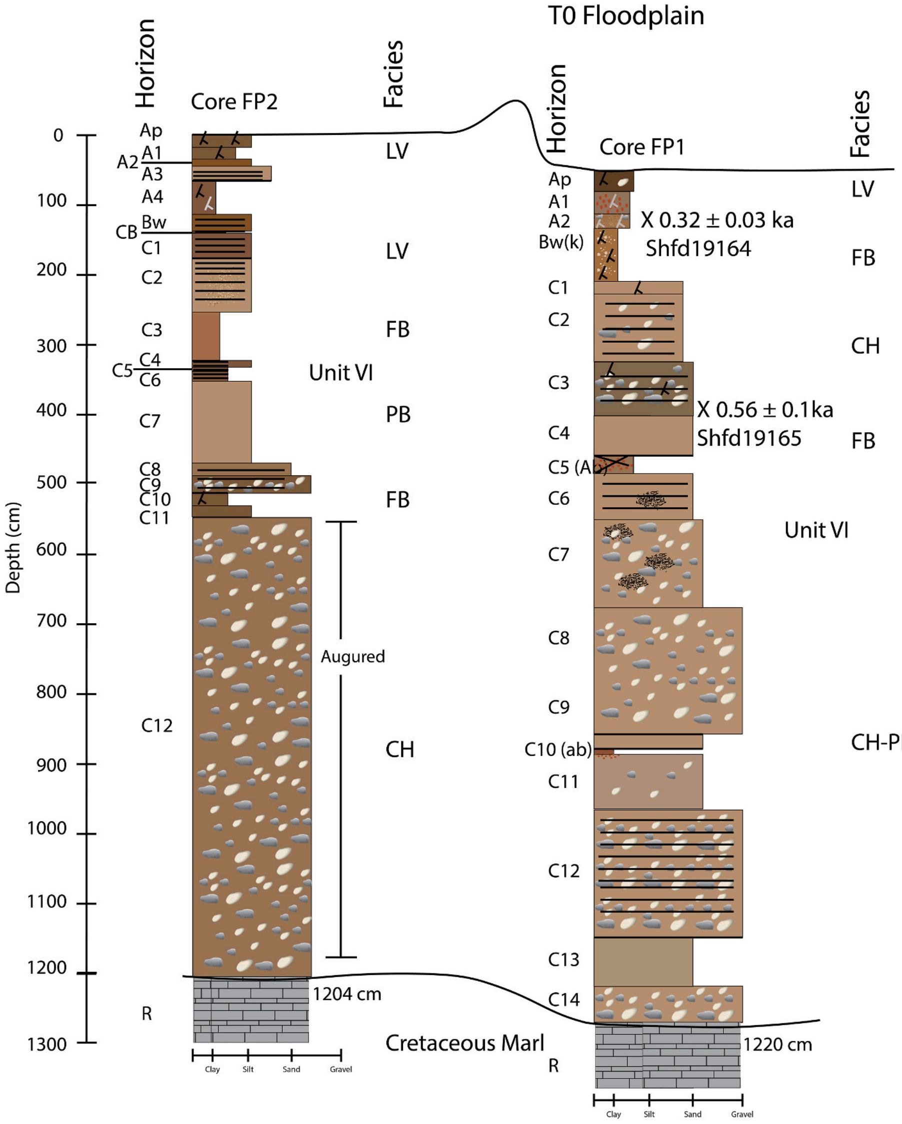

Fig. 6. Alluvial stratigraphy of two cores extracted from the T0 Floodplain (Fig. 2 for location).

likely a result of poor bleaching. We interpret this age to be < 33.9 ka.

Deposition of sediments beneath T1b by our interpretation of the OSL chronology is began sometime around 12.6 ka and continued until sometime between 2.39 ka and 0.56 ka (T0). Soils formed in alluvial deposits of similar age along the Colorado River show a similar degree of development that lacks appreciable carbonate leaching from the upper profile (Blum and Valastro, 1992; Blum et al., 1994) The sum of these data indicate that the T1 alluvium was deposited during MIS 1.

4.4. T0 floodplain-unit VI complex

Two sediment cores were extracted from the T0 floodplain, labeled FP1 and FP2 (Fig. 6, Table A2). A scroll bar divides the location of the two cores (Fig. 2).

The FP1 core is closest to the modern river channel and reveals 12.5 m of Unit VI alluvium resting unconformably on Cretaceous marls. The basal channel facies is 3.7 m thick and is comprised of alternating and thick to very thick gravel and sand beds representing three fining upward sequences. The presence of 50% coarse fragment includes a mix of limestone and siliceous poorly sorted, rounded to subangular gravels.

The upper channel facies occurs from a depth of 8.9 to 4.3 m and consists of a thick fining upward sedimentological package. The gravels in this upper facies are not as large as those in the lower facies, but still represent deposition from high magnitude flood events. The alluvial stratigraphy from FP2 core is similar, even though the samples were observed from auger tailings.

The surface soil on the T0 floodplain in this area is mapped as Yahola, which is a sandy Entisol. There is a layer about 1 m below the surface containing few, very fine carbonate nodules. These nodules may be pedogenic and formed very quickly because of the sandier substrate or they may be detrital having been washed in by erosion of older terrace deposits. There is no loss of carbonate from leaching in the upper profiles indicating that the nodules may be detrital.

The deposits exposed in cores FP1 and FP2 represent a bedload meandering stream dominated by fining upward packages of sand to loams with an abundance of coarse fragments.

4.4.1. T0 floodplain-unit VI geochronology

From core FP1 beneath T0, an age of 0.56 ± 0.10 ka (Shfd19165) representing 54% of the data with the lowest De, was determined on a sample extracted from between a depth of 330 and 350 cm (Table 1; Fig. 6). The second component, which represents 46% of the data, returned an age of 1.46 ± 0.20 ka. This sample contained a large number of zero-dosed grains (n = 13) indicative of recent pedoturbation. As this sample is primarily comprised of bedforms representing lateral accretion deposits, incomplete bleaching at the time of burial is possible. On this basis the age of 0.56 ± 0.10 ka was accepted as the time of burial.

The second OSL from the FP1 core is from between a depth of 62 and 72 cm, which returned an age of 0.31 ± 0.30 ka (Shfd19164). The overdispersion for this sample was low and the unimodal D_e distribution suggests advanced bleaching prior to burial and no (or limited) disturbance from pedoturbation. The grain-size in this sample is uniform, with less than 5% fine gravel fragments of limestone and quartzite that indicates less mixing. Thus, we accept this age as the approximate time of burial of the upper part of Unit VI.

4.5. Late quaternary alluvial landscape evolution

4.5.1. T3 terrace/unit 1 complex

The T3 terrace/Unit I complex was most likely deposited during the latter stages of MIS 5 (>60 ka, Railsback et al., 2015) and accordingly is interpreted as a warm and wet/dry interglacial climate similar to the current Holocene interglacial (Blum and Aslan, 2006; Figs. 7 and 8). During MIS 5, elevated temperatures in the Gulf of Mexico according to lower $\delta^{18}O$ values on planktonic foraminifera may have promoted the influx of warm and moist subtropical air to the central Texas region (Joyce et al., 1993). With this assumption, deposition from the Brazos River during this time, while reflecting a meander mixed load stream, indicates episodes of flashy discharge based on the presence of poorly sorted and angular channel gravels, perhaps promoted by monsoonal summer rainfall. The sediment supply and channel discharge, however, were at equilibrium such that the river was laterally migrating across limestone leaving behind a single-story package sediment. The valley walls at this time would have been a complex of older alluvial deposits towards the interfluve to the west and the Grayson Marl to the east towards the modern river (Fig. 1). Deposition along the Gulf Coastal Plain during MIS 5c to 5a has been correlated to rising sea level (Fig. 8; Blum and Aslan, 2006; Waelbroeck et al., 2002; Anderson et al., 1992; Thomas and Anderson, 1994). Thermoluminescence dates from the Beaumont Formation of Texas are 71.9 to >100 ka, which roughly correlates to the timing of the T3 terrace in Steinbeck Bend (Figs. 7 and 8; Durbin et al., 1997; Sylvia and Galloway, 2006). However, for the Texas Gulf Coastal Plain the portion of the rivers affected by eustatic sea level is about 40 km inland during high stands and 100–200 km during low stands (Blum and Törnqvist, 2000). So, any correlation would be a climatic response to changes in temperature or precipitation and sediment supply.

4.5.2. Terrace 2/unit II and unit III complex

If the T3 terrace-Unit I complex is taken as late MIS 5, then the Bosque River in the study area incised shortly thereafter but prior to 67 ± 5 ka based on OSL ages from the WMNM (Figs. 7 and 8). We have no additional information on the alluvial history of the Bosque River other than mammoth remains being buried at this time during MIS 4, a time generally characterized as colder and wetter as supported by rapid

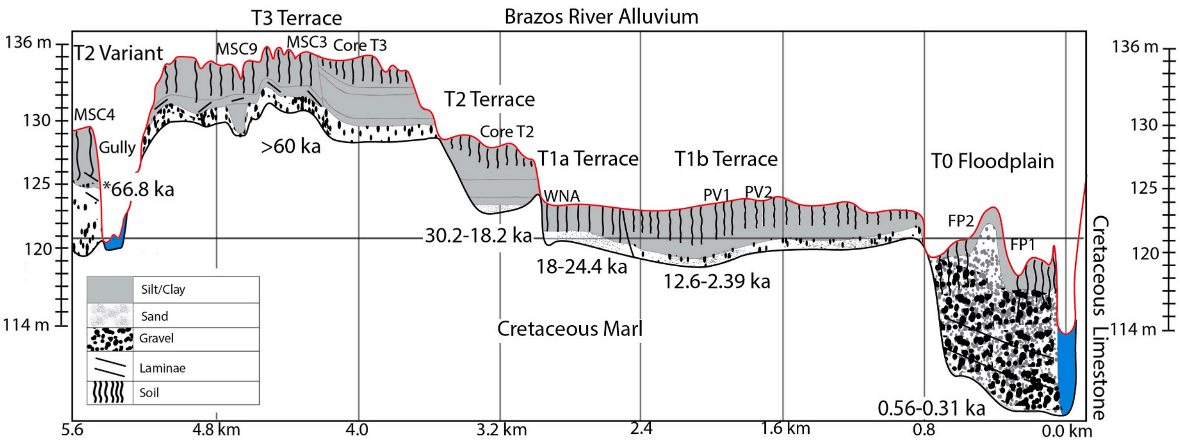

Fig. 7. Composite alluvial stratigraphic cross-section of the Brazos River in the Steinbeck Bend study area and location of sediment cores, terraces, and floodplain.

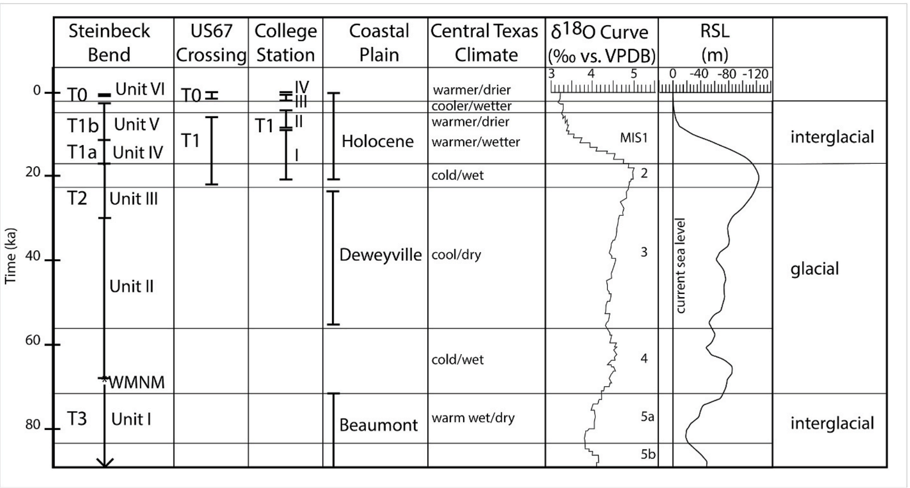

Fig. 8. Correlation of climate conditions and episodes of alluvial aggradation and channel incision of the Brazos River in the Steinbeck Bend study area, compared to the US67 location upstream and the College Station location downstream. Central Texas climate adapted from marine isotope stage interpretations (Railsback et al., 2015), speleothems from central Texas (Musgrove et al., 2001), and stable carbon isotopes of latest Pleistocene/Holocene sediments (Waters and Nordt, 1995). Relative Sea Level (RSL) adapted from Waelbroeck et al. (2002).

speleothem growth in central Texas caves (Musgrove et al., 2001).

Along the Brazos River sometime between 72 ka and 30.2 there was a period of channel incision that penetrated the underlying limestones by some 6 m. Other than evidence of incision along the Bosque River sometime just prior to 67 ka, we do not know if other episodes of incision occurred along the Brazos River within this interval or whether other alluvial units were deposited and subsequently eroded away. However, incision into several meters of bedrock did occur along Owl Creek to the west sometime shortly before 44 ka (Meier et al., 2013), which is within the time interval of incision proposed here. The Beaumont Formation beneath the Quaternary coastal plain was abandoned by incision sometime between 71.9 and 52.5 ka leading to renewed deposition of the highest and oldest Deweyville terrace (Durbin et al., 1997). One explanation for channel incision at this time is that the shift from a warm and wet/dry climate to a cool and wet climate occurred in response to increased precipitation as uplands became more vegetated leading to greater channel discharge but with less sediment load (see Bull, 1991).

Deposition of the T2/Unit III complex continued from 30.2 ka until no later than 18.1 ka from a suspended to mixed load meandering stream similar to the T3/Unit 1 complex (Figs. 7 and 8). Deposition of Unit Q6 along Owl Creek was ongoing during this interval near and shortly after 44 ka (Meier et al., 2013), as was deposition of a higher terrace along the Pedernales River of west Texas ~39 ka (Blum and Valastro, 1989) and deposition of the middle to lower Deweyville terraces inset to the Beaumont Formation from ~41 to 36 ka (Durbin et al., 1997).

The T2-Unit II&III complex spans mainly MIS 3 and appears to have terminated during MIS 2. MIS 3 is interpreted as a cool and dry interval within the past glacial, that in the Gulf of Mexico would have been accompanied by marine regression and cooling mitigating the influx of warm and moist masses into the central Texas study area (Maasch and Oglesby, 1990; Bromwich et al., 2004; Joyce et al., 1993 et al., 2012; Tripsanas et al., 2007; Dorale et al., 1998; Rittenour et al., 2007). However, data from central Texas speleothems (Musgrove et al., 2001) indicate that the second half of MIS 3, when the T2/Unit II&III complex formed, was colder and wetter than the first half of MIS 3, consistent with climate simulations (Sylvia and Galloway, 2006). Higher discharge during deposition of Unit II may be a response to greater effective precipitation (Sylvia and Galloway, 2006).

4.5.3. Terrace 1a-Unit IV complex

Near ~18 ka, the Brazos River in the Steinbeck Bend study area incised again and this time by approximately 4–5 m into underlying Cretaceous marls (Fig. 7.). The timing of incision approximates a wood radiocarbon age of 17,730 ± 130 BP (~21 ka) from near the base of the thick floodplain fill downstream in the College Station study area, a radiocarbon age of 19,770 ± 60 (~23 ka calendar yrs) upstream at US67, and within the time interval documented along the Colorado and Pedernales Rivers, and Cowhouse Creek between ~17 and 13 ka (Fig. 9.; Waters and Nordt, 1995; Blum and Valastro, 1992).

This episode of incision occurred during a return to cooler and wetter conditions leading up to the Last Glacial Maximum (LGM), according to increased speleothem accumulation rates in central Texas caves (Musgrove et al., 2001). However, this cooler and wetter interval extended to as late as 14 ka, even though the investigators cited in the above paragraph attribute channel incision at this time to a transition to a warmer and drier climate after the LGM. If incision occurred during a cooler and wetter interval, then rapid warming and drying shortly thereafter would have been responsible for deposition of the T1a-Unit IV complex in the Steinbeck Bend study area (Fig. 7.). Interpretations from the lower Brazos River basin indicate that the El Niño was at full strength during the latest Pleistocene, and may have brought with it greater than 50% more precipitation in the upper drainage basin on the Llano Estacado (Sylvia and Galloway, 2006; Corbet, 2000).

Following this period of latest Pleistocene channel incision, formation of the T1b-Unit IV complex proceeded up until no later than 12.1 ka, which spans the lower half of MIS 1. This episode of alluvial deposition correlates with deposition ongoing at ~15 ka documented from the base of the T1 equivalent upstream along US67 (Fig. 9.; Abbott, 2011), and at ~14 ka to deposits along Owl Creek (Meier et al., 2013). Even though we have a limited view of this terrace-sediment complex because so little is preserved, it does suggest a river system depositing well sorted and sandy sediment of a meandering stream without deposition of channel gravels. The fine-grained nature of this unit, suggests that upland soils were being evacuated at this time, possibly induced by reduction of hillslope vegetative cover in response to warming and drying interpreted from nearby soil stable carbon isotopic data (Nordt, 1995), faunal abundances (Blum et al., 1994), and transitioning of pollen from arboreal to grassland (Bousman, 1998; Koch et al., 2004).

4.5.4. Terrace 1b-Unit V complex

Lateral erosion into the T1a terrace occurred sometime around 12.6 ka and was followed by deposition of the T1b terrace-Unit V complex until sometime between 2.39 ka and 0.53 ka (Figs. 7 and 8). The depositional environment shifted to a mixed load stream containing channel facies dominated by thicker and coarse gravel and sand channel facies. Multiple, conformable fining upward sequences indicate differential discharge as the river continued to cut laterally across Cretaceous marls to the east. The cause of lateral channel erosion of the T1a-Unit IV might be related to the crossing of an internal geomorphic threshold as a response to renewed flashy discharge and progressive warming depleting soils on the surrounding hillslopes as vegetation cover

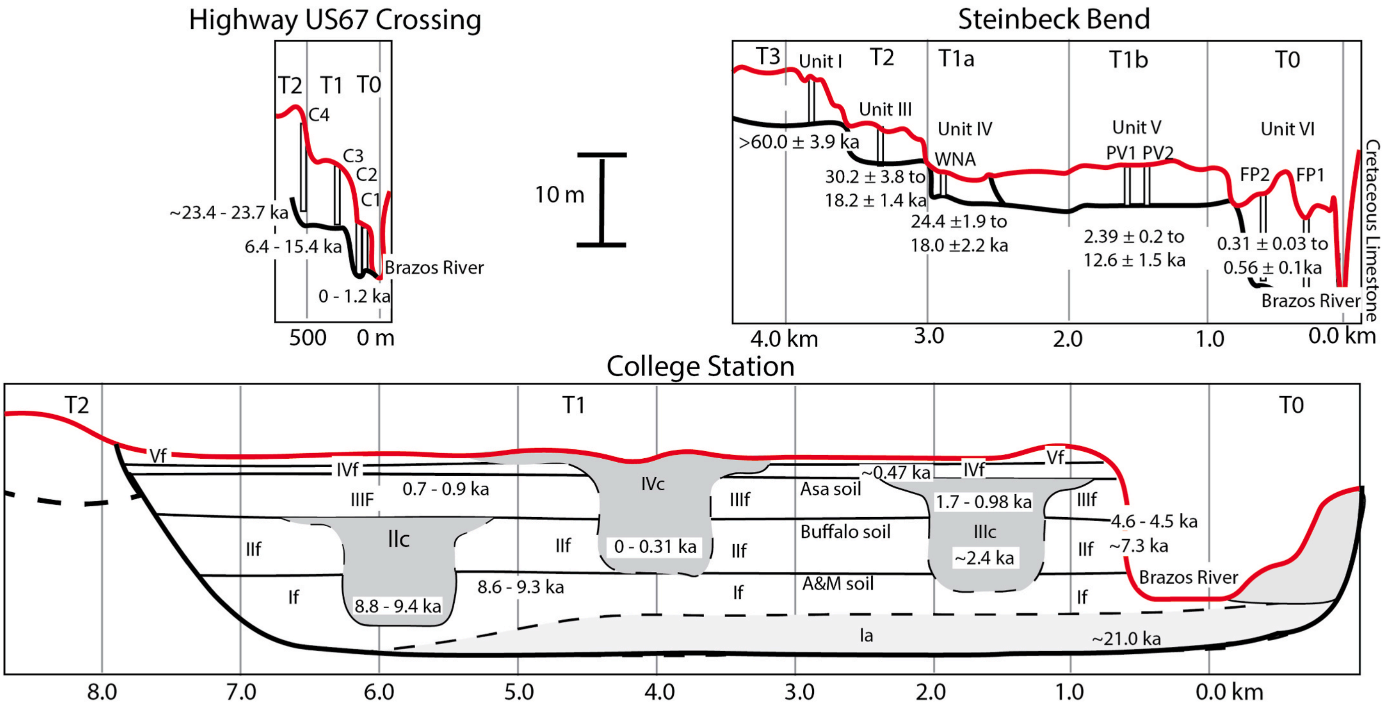

Fig. 9. a) Composite alluvial stratigraphic cross section of the Brazos River in the study area (middle panel) compared to the Highway US67 crossing upstream (top panel) (Abbott, 2011) and to the downstream College Station section (Waters and Nordt, 1995). For locations see Fig. 1.

diminished (Toomey et al., 1993; Blum et al., 1994; Nordt, 1995).

Evidence from the US67 crossing north of Steinbeck Bend (Fig. 1) indicates that the Brazos River in the bedrock-constrained valley was depositing an undifferentiated alluvial package from less than ~15 ka to sometime between ~6.5 and 1.4 ka (Fig. 9.; Abbott, 2011), which temporally spans both Units IV and V in the Steinbeck Bend study area.

Deposition of early and late Holocene alluvium, was interceded by an episode of lateral channel erosion observed in many studies in central Texas (Nordt, 1995; Blum et al., 1992, 1994; Mandel et al., 2018). Floodplain sedimentation in higher order streams in the Gulf Coastal Plain of Texas was rapid after 12.5 ka and slowed as temperatures cooled between 9.9 and 9.6 ka in conjunction with relative increase in sea level to current conditions along the Medina River (Fig. 8.; Mandel et al., 2018; Waelbroeck et al., 2002). Warmer conditions associated with the Altithermal climatic event peaked around 5.8 ka and may have led to a period of instability with bedrock-controlled streams downcutting, migrating laterally, and experiencing headward erosion and characterized by net transport of alluvium with little accumulation (Bettis and Mandel, 2002; Mandel, 1995, 2006). Large volumes of this sediment then accumulated downstream. Evidence of massive volume of sedimentation can be seen in the College Station alluvium and Tertiary Gulf Coastal Plain alluvium (Fig. 9.; Waters and Nordt, 1995; Mandel et al., 2018; Sylvia and Galloway, 2006). There is insufficient evidence for accumulation beneath the T1 terrace at Steinbeck Bend possibly because of the lack of sedimentological and geochronological resolution or the stream lateral is just experiencing lateral migration at this time with little accumulation.

In contrast to the bedrock-controlled channels of the Cretaceous sector of the Brazos River drainage basin in the Steinbeck Bend study area (equivalent to T1a-Unit IV and T1b-Unit V), including the upper Colorado and Pedernales Rivers, and Cowhouse and Owl Creeks, downstream along the Brazos River below the Balcones Escarpment three vertically stacked alluvial units were deposited between around 9 and 0.4 ka in the Holocene. Termination of deposition of the lowest unit ended in formation of the now buried A&M soil near 9 ka calendar yrs, and was followed by termination of deposition of the next unit by the Buffalo soil near 7 ka. There is a 2000-year gap before deposition of the next unit began near 2500 ka following by termination of deposition ending with formation of the Asa buried soil by 800 years ago (Fig. 9.; Waters and Nordt, 1995). In the Double Mountain Fork area of the upper Brazos River basin, deposition dominated during the past 2500 years (Blum et al., 1992). All of these deposition and erosional events occurred while Unit V undifferentiated was being deposited in the Steinbeck Bend study area on a bedrock strath by lateral channel migration.

These avulsion events coincide with a transition from cooler/wetter to warmer/drier conditions as sediment load increased causing channel filling, leading to the formation of extensive levees and crevasse splays and ultimately avulsion (Waters and Nordt, 1995). While avulsion events and buried soils mark the separation of these buried Holocene units downstream in the College Station area and the Gulf Coastal Plain (Sylvia and Galloway, 2006), the Brazos River at Steinbeck Bend continued to migrate laterally across bedrock.

4.5.5. *T0-unit VI complex*

Sometime between 2.34 and 0.53 ka the Brazos River in the Steinbeck Bend study area incised by a remarkable 12 m into the underling Cretaceous marls during the Holocene (Figs. 7 and 8). Deposition of Unit VI, and the formation of the T0 floodplain surface, proceeded from a bedload stream within a narrow-entrenched valley, and continued until at least 0.31 ka. Downcutting may have been promoted by continued climate warming according to pollen records in central Texas (Bousman, 1998) leading to further depletion of the upland soil base by erosion and subsequent and flashy channel discharge (Toomey et al., 1993; Nordt, 1995). At this time, the Brazos River began to laterally impinge into the resistant Austin Chalk on its east side, which may have diminished lateral channel migration in favor of incision (Fig. 2). Deposits within the last 1000 years are documented in most streams of central Texas after a period of incision shortly before (Nordt, 1995; Blum et al., 1992; Mandel et al., 2018). A final pulse of sediment is noted after 2.5 ka in the lower Brazos (Sylvia and Galloway, 2006) and the Medina River alluvium is interpreted to correlate with conditions that are slightly cooler and wetter than today (Mandel et al., 2018). A major surficially exposed, avulsion of the Brazos River occurred downstream at about 0.5 ka (Fig. 9.; Waters and Nordt, 1995).

5. Conclusions

In conclusion, the Brazos River in the Steinbeck Bend study area during the late Quaternary (MIS 5-MIS 1) has been a bedrock-controlled stream similar in character to other segments of the river upstream and to other rivers in the Edwards Plateau, above the Balcones Escarpment. Laterally juxtaposed terrace and floodplain deposits resting on Cretaceous marls are in contrast to the Brazos River downstream below the Balcones Escarpment where vertically stacked units of former floodplain surfaces are marked by basal erosional surfaces and upper buried soils. Below the study area, there are ever increasing meanders and widening alluvial floodplains, whereas above the Steinbeck Bend are narrower valleys carved into more resistant limestones.

Episodes of incision during the Pleistocene appear to have responded to a transition from warmer and wet/dry to cooler and wetter possibly conditioned by greater vegetative cover and reduced sediment load and increased precipitation. Progressive warming during the Holocene led a lateral channel erosion without incision until within the last 1000 years, possibly from increase flashy discharge as upland soils became depleted.

Author contributions

R.T. and L.N. developed this project as part of a doctoral dissertation project. R.T. carried out the field work and analysis and was overseen by L.N. M.B. performed the optically stimulated luminesce dating and contributed to writing the methods and part of the results and discussion. All authors discussed the findings and contributed to the final manuscript.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article. Additional information about the data that support the findings are available from the corresponding author, R.T., upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quaint.2022.05.008.

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