Lateral bedrock erosion and valley formation in a heterogeneously layered landscape, Northeast Kansas

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Abstract
In this study, we present direct field measurements of modern lateral and vertical bedrock erosion during a 2-year study period, and optically stimulated luminescence (OSL) ages of fluvial material capping a flat bedrock surface at Kings Creek located in northeast Kansas, USA. These data provide insight into rates and mechanisms of bedrock erosion and valley-widening in a heterogeneously layered limestone-shale landscape. Lateral bedrock erosion outpaced vertical incision during our 2-year study period. Modern erosion rates, measured at erosion pins in limestone and shale bedrock reveal that shale erosion rate is a function of wetting and drying cycles, while limestone erosion rate is controlled by discharge and fracture spacing. Variability in fracture spacing amongst field sites controls the size of limestone block collapse into the stream, which either allowed continued lateral erosion following rapid detachment and transport of limestone blocks, or inhibited lateral erosion due to limestone blocks that protected the valley wall from further erosion. The OSL ages of fluvial material sourced from the strath terrace were older than any material previously dated at our study site and indicate that Kings Creek was actively aggrading and incising throughout the late Pleistocene. Coupling field measurements and observations with ages of fluvial terraces can be useful to investigate the timing and processes linked to how bedrock rivers erode laterally over time to form wide bedrock valleys.

KEYWORDS
bedrock erosion mechanisms, bedrock rivers, lateral bedrock erosion, luminescence dating, valley widening

1 | INTRODUCTION

Bedrock rivers play a central role in landscape evolution by communicating signals of climate shifts, base level changes, and tectonics through landscapes (e.g., Hancock et al., 1998; Lavé & Avouac, 2000; Whipple, 2004; Whipple & Tucker, 1999). Vertical erosion and subsequent channel adjustment in bedrock systems has been a highly researched area for the past 30 years through landscape evolution models (e.g., Snyder et al., 2003; Tucker & Whipple, 2002; Whipple & Tucker, 1999), flume experiments (e.g., Attal et al., 2006; Sklar & Dietrich, 2001), and field studies (e.g., Brocard & Van Der Beek, 2006; Whipple et al., 2000). Despite the substantial advances on processes of vertical incision, comparatively few studies have attempted to resolve controls on the processes and rates of lateral bedrock erosion (Beer et al., 2017; Bufe et al., 2017; Collins et al., 2016; Fuller et al., 2016; Langston & Tucker, 2018; Li et al., 2020; Turowski, 2018). This presents a fundamental knowledge gap in understanding how bedrock rivers respond to climatic and tectonic changes by widening their valleys, and how channel geometry is maintained and changed over time.

Wide bedrock valleys indicate a period when lateral erosion outpaces vertical incision. Evidence of prolonged periods of lateral bedrock erosion in the past are left in the form of strath terraces, flat beveled bedrock surfaces that are capped by fluvial sediments. In
order to better use strath terraces to interpret past periods of climate change (e.g., Hancock et al., 1999), the controls on valley widening, and the mechanisms of both vertical and lateral erosion, must be considered together to describe the formation of strath terraces. However, due to an incomplete understanding of the drivers of lateral erosion and controls on rates of bedrock valley widening, it is difficult to interpret how climate, and fluvial processes influenced by climate, drove vertical and lateral erosion in the past and will continue to shape landscapes in the future.

While some studies suggest specific mechanisms or drivers of lateral bedrock erosion (e.g., Fuller et al., 2016; Johnson & Finnegan, 2015; Langston & Tucker, 2018; Li et al., 2020), few have measured the rate at which lateral bedrock erosion occurs in natural channels (Beer et al., 2017; Collins et al., 2016) nor explored how lateral bedrock erosion rates and other processes influence valley widening rates. Due to the insufficient understanding of these interacting processes, lateral migration and valley widening in bedrock channels is neglected in nearly all existing landscape evolution models (Langston & Tucker, 2018). Furthermore, landscapes with bedrock units of variable erodibility are ubiquitous around the world, yet are seldom systematically studied in landscape evolution models (Barnhart et al., 2020; Forte et al., 2016; Perne et al., 2017). Thus, considerable research is needed to achieve the same level of understanding of processes and mechanisms of lateral bedrock erosion compared to vertical incision.

2 LITERATURE REVIEW

Fluvial incision into bedrock is achieved largely through abrasion and plucking (e.g., Whipple et al., 2000), and the dominant mechanism of erosion is often a function of lithological properties of the bedrock (Chatanantavet & Parker, 2009; Hartshorn et al., 2002; Langston & Temme, 2019b; Spotila et al., 2015; Whipple et al., 2000). Erosion via abrasion increases with increasing sediment due to greater number of sediment impacts (the “tools effect”; Attal & Lavé, 2009; Lamb et al., 2008; Sklar & Dietrich, 2004). Continuous sediment addition to the channel can lead to decreased erosion rates, as sediment covers the bed protecting it from sediment impacts (the “cover effect”; Johnson & Whipple, 2010; Sklar & Dietrich, 2001, 2004), which in turn may increase lateral erosion (e.g., Turowski et al., 2008). Plucking is the removal of bedrock blocks from the channel bed and occurs when hydraulic lift forces are sufficient to extract blocks from the channel bed (Whipple et al., 2000; Wilkinson et al., 2018). Flows capable of plucking occur to occur less frequently than flows capable of abrasion (Snyder et al., 2003). However, when plucking occurs, erosion tends to be more efficient than via abrasion and can lead to large amounts of erosion in a small amount of time, such as during flood events capable of entraining and transporting large blocks (Baynes et al., 2015; Lamb et al., 2015; Lamb & Fonstad, 2010).

Sediment plays a fundamental role in both vertical and lateral bedrock erosion (e.g., Sklar & Dietrich, 2001; Whipple et al., 2000). Lateral erosion that outpaces vertical incision can be achieved when sediment covering the bed inhibits vertical incision (Hancock & Anderson, 2002; Johnson & Whipple, 2010; Langston et al., 2015; Turowski et al., 2008). Studies suggest that lateral erosion rates increase in high sediment supply settings, for example, when the channel bed is protected from vertical incision (the “cover effect”), and sediment impacts on the channel banks laterally erodes bedrock (Beer et al., 2017; Li et al., 2020). Lateral erosion through sediment impacts on bedrock walls can occur when sediment trajectories deviate from flow lines and impact the channel wall, from interaction with roughness elements in the channel bed (Fuller et al., 2016) or in channel bends (Beer et al., 2017; Cook et al., 2014; Wohl & Ikeda, 1998). This can happen independently of the sediment “cover effect”. A high sediment supply environment also encourages channel mobility, thus driving lateral erosion and the development of wide bedrock valleys (Baynes et al., 2020; Bufe et al., 2016; Langston & Tucker, 2018; Tomkin et al., 2003; Wickert et al., 2013). Greater channel mobility as a result of high sediment load contributes to lateral erosion due to a higher frequency of contact between the river and channel banks (Brocard & Van Der Beek, 2006; Hancock & Anderson, 2002).

Wide bedrock valleys and strath terraces are often found in weak lithologies, such as mudstones or sandstone (Collins et al., 2016; Johnson & Finnegan, 2015; Montgomery, 2004; Schanz & Montgomery, 2016), suggesting higher lateral erosion rates in weak lithology. Mudstones may erode more rapidly even when not submerged due to cyclical wetting and drying cycles that decrease the tensile strength and cause crumbling upon drying (Montgomery, 2004), and can be easily swept away by the flow (Johnson & Finnegan, 2015). Rapid lateral erosion of weak lithologies often happens via plucking (Langston & Temme, 2019a), yet plucking has been noted as the dominant erosion mechanism even in massive or resistant lithologies, such as quartzite when the resistant lithology is highly fractured (Spotila et al., 2015).

The width of a bedrock valley is additionally influenced by valley-widening mechanisms (Langston & Temme, 2019b), as valleys with differing bedrock strengths or bedrock properties widen through different mechanisms (Spotila et al., 2015; Wohl & David, 2008). Valley widening is achieved when the base of the valley wall is undercut by the river and the overlying material collapses onto the valley floor (Shobe et al., 2016). In soft lithologies, collapsed valley wall material that collects at the base of the wall often consists of small grain sizes or easily weathered blocks that are readily transported away (“erodible mechanism”; Langston & Temme, 2019b). In more resistant lithologies, massive material made of large blocks often collapses into the valley bottom, covering the base of valley wall and halting further valley widening until the collapsed blocks are transported away (“resistant mechanism”; Langston & Temme, 2019b). The valley widening mechanism is also determined by the size of the material released from the valley wall and the transport competence of the river. In natural systems, valley widening may be limited by one of these factors or may occur through a combination of both mechanisms.

Many studies suggest that rivers spend long periods laterally carving wide bedrock valleys that are abandoned by punctuated intervals of rapid vertical bedrock incision (Dühhoforth et al., 2012; Foster et al., 2017; Hancock & Anderson, 2002). However, recent studies show that lateral erosion rates can reach tens of meters per year (Collins et al., 2016; Cook et al., 2014) and that dramatic changes in the ratio of lateral to vertical erosion rate are needed to explain some instances of strath terrace formation (Bufo et al., 2017).
Here, we report direct field measurements of lateral and vertical bedrock erosion over a 2-year period in a landscape with heterogeneously layered lithology. We used optically stimulated luminescence (OSL) dating to determine the ages of fluvial material capping a beveled bedrock surface. We found that modern lateral erosion rates in both limestone and shale lithologies at our study site were much higher than originally anticipated owing to several high magnitude flow events during an exceptionally wet year. We also found that limestone and shale erosion rates are a strong function of discharge and wetting–drying cycles. We use these observations to explore the relationship between the modern lateral erosion rates and the OSL dated terrace material to better understand valley-widening mechanisms in this layered landscape.

3 | STUDY AREA

This study was conducted at Konza Prairie Biological Station and Long Term Ecological Research (LTER) site, hereafter referred to as Konza. Konza is a tallgrass prairie ecosystem located in the Flint Hills region of northeast Kansas (Figure 1b). Konza has a mean annual precipitation of 835 mm/yr that primarily occurs between April and September in relatively brief and intense events (Costigan et al., 2015). The elevation of Konza ranges from 317 to 455 m above sea level in an incised landscape, with native tallgrass throughout and gallery forests along the stream channels. The underlying bedrock consists of alternating layers of fractured and jointed limestone and tightly bedded shale of Permian age (Oviatt, 1998). The limestone layers are 1–2 m thick and the shale layers are 2–4 m thick (Macpherson, 1996). The landscape is largely a product of weathering and fluvial erosion of streams that are tributaries of the Kansas River over significant geologic time, and streams dissecting the landscape reveal the limestone and shale layers (Macpherson, 1996).

Kings Creek is the main stream draining Konza (Figure 1a) and has a drainage area of ~17 km². Kings Creek is an intermittent stream, with perennial portions on the main trunk. Kings Creek is a mixed-alluvial bedrock river in most locations of the main trunk, with primarily bedrock channels in the upstream tributaries. It typically exhibits high variability in streamflow, with greatest amount of discharge often occurring in April, May, and July and lowest average flows in the late summer and winter resulting in a near-completely dry channel (Gray et al., 1998).

3.1 | Fluvial terraces

Several prominent fluvial terrace levels exist surrounding Kings Creek (Figure 1a) that mark higher elevations formerly occupied by the stream and indicate numerous periods of aggradation and incision. Smith (1991) found that two fill terraces in the downstream most reach of Kings Creek (Figure 1a) were Holocene in age (8920 ± 120 cal yr BP, upper terrace; 1770 ± 80 cal yr BP lower terrace) from radiocarbon dating. These radiocarbon ages correlate well with previous work establishing fluvial chronologies and stream behavior in the central Great Plains during the Holocene (e.g., Johnson & Martin, 1987; Mandel, 2008). Smith (1991) also made a comprehensive map and correlated different terrace elevations to each other based on sedimentary structures, lithologies, textures, and terraces heights above the channel (Figure 1a). We identified other high-elevation terraces overlying bedrock in Konza with red, oxidized fluvial material (Supporting Information Figure SB2) similar to our Main Trunk site, as opposed to tan-colored fluvial material in the Holocene terraces described by Smith (1991). While previous work on Kings Creek terraces focused on aggregational terraces in the downstream-most reaches of the stream, strath-like terraces with fluvial deposits capping a bedrock surface also exist within Konza Prairie and the region.
3.2 | Field sites

Three reaches at Kings Creek were selected as study areas for this project (Figure 1a): The North Fork site, the Nature Trail site, and the Main Trunk site. All sites are located at meander bends where the stream is actively eroding bedrock along both the banks and bed (Figure SB1), rather than straight segments of the stream because no straight segments with both exposed bedrock bed and banks were found.

3.2.1 | North Fork site

The upstream most study site is located along the North Fork of Kings Creek (Figure 1). Two cross-channel erosion pin transects approximately 25 m apart from each other serve as study sites to monitor bedrock erosion on channel banks and bed. The channel banks are 3–4 m high and consist of bedrock with interbedded limestone layers ~0.5 m thick and thinner layers of shale ~0.30 m thick and a layer of colluvium (~40–50 cm) resting on top (Figure 2a). Limestone boulders ~0.5–1 m in diameter have collapsed from the banks and cover the base of bedrock walls in places. The channel bed is limestone bedrock that is periodically partially or fully covered with a thin layer of gravel-sized alluvium.

3.2.2 | Nature Trail site

The Nature Trail site is located approximately 770 m downstream of the North Fork site on the main trunk of Kings Creek (Figure 1). Here, there are also two cross-channel erosion pin transects approximately 25 m apart from each other that serve as study locations at this reach. The ~6.5 m tall channel bank at this reach is composed of alternating layers of shale and limestone bedrock that are ~30–50 cm thick (Figure 2b) and capped by a ~3 m thick layer of colluvial/alluvial material. The sediment material that overlies the bedrock in this location is made up of interbedded cobbles and gravels at the bottom of the profile, grading into fine-grained colluvial material, including some loess, towards the top of the profile. The channel bed is made up of limestone bedrock with intermittent alluvial cover.

3.2.3 | Main Trunk site

The Main Trunk site is located ~660 m downstream of the Nature Trail site on the main trunk of Kings Creek (Figure 1). The channel bank is made up of 2 m of alternating layers of imbricated cobbles and fine-grained floodplain deposits that rest directly on a flat bedrock surface in the lower part of the channel bank (Figure 3). This suggests that this site was formerly occupied by the stream and can be considered a strath-like terrace.

4 | MATERIALS AND METHODS

4.1 | Fieldwork

We installed erosion pins in the bedrock banks at North Fork and Nature Trail sites to determine modern erosion rates. At the Main Trunk site, we collected samples from exposed terrace material for OSL dating.

Moultrie Trail cameras were installed facing the stream bank at the Nature Trail and North Fork sites to monitor the water stage at each site, help determine mechanisms of bedrock bank erosion, and identify when limestone blocks collapsed and were transported. The trail cameras took photographs at 30-minute intervals for the duration of the study period. The trail camera photographs were paired with discharge data to determine the water stage during high flow events to help determine how long the study sites were submerged.

Fracture spacing is a key parameter in predicting bedrock erosion rates and block sizes in channels (Moore et al., 2009; Sklar et al., 2017). We measured fracture spacing in both horizontal and vertical directions in limestone layers at sites with erosion pin transects (two transects at the North Fork site and two transects at the Nature Trail site). We selected the measurement sites to coincide with the location of our erosion pins; the lithological sequences were similar along the channel bank between the erosion pin locations such that we considered the sampling area representative. Horizontal fracture spacing was measured by counting all fractures greater than 10 cm long in representative sections of 1–2.5 m in length. Vertical fracture spacing was measured by counting fractures greater than 10 cm long in vertical sections 0.35–0.7 m high, equal to the thickness of the limestone units.
4.2 | Erosion pins

Twenty-five erosion pins were installed horizontally in the bedrock channel banks and 11 were installed vertically in the bedrock beds in Spring 2018. At each transect, one or more erosion pins were placed in each of the limestone and shale layers in order to capture variability in erosion rate within lithology sequences and distance from the channel bed (Figure 4). The erosion pins in the limestone layers were 80 mm-long anchored masonry nails, and in the shale layers erosion pins are 160 mm-long lag screws. Both limestone and shale pins are 6.5 mm in diameter.

Erosion pins were measured six times during the study period, and only five times at the upstream Nature Trail site. Erosion pins were measured after flow events whenever possible to capture the effects. Bed pins often could not be located due to sediment or moss cover; thus, two pins were measured only once each during the study period. Erosion pins were measured using Vernier calipers (accurate within 0.05 mm). The measured length of the exposed pin relative to the channel bank was the total erosion between each visit. One person measured the erosion pins during this study. Each pin was measured at the same location around the perimeter of the pin head to reduce measurement error.

4.3 | Luminescence dating

To determine the depositional age of fluvial deposits sourced from a strath terrace we used single grain OSL dating of quartz grains from sediment samples collected at the Main Trunk site. The fluvial deposits that cap bedrock at this site were well-suited for OSL dating, compared to the sediments that cap the bedrock at the North Fork and Nature Trail sites. OSL dating is a technique that estimates the time of burial, or time since quartz or feldspar grains were last exposed to sunlight, therefore yielding a depositional age.

Four samples for OSL dating were collected from the fluvial material exposed on the channel bank: three samples at an upstream location (Site 2; Figure 3) and one sample ~20 m downstream (Site 1; Figure 3). The fluvial deposits consist of medium to large gravel and a few large cobbles. The sampled material itself is former floodplain material comprised of silt sized material and some lenses of fine sand.
Roughly 2.5 m of unconsolidated colluvial material overlie the fluvial sediments.

At Site 1 (Figure 3a), one sample (KNZ001) was taken 1.7 m above the bedrock exposed in the channel bank. At Site 2 (Figure 3b; 20 m upstream of Site 1), three samples were collected in a vertical profile from the fluvial material overlying exposed bedrock on the channel bank (Figure 3b). KNZ003 is the stratigraphically lowest sample, obtained ~0.20 m above the bedrock from a massively bedded, fine-grained layer that was sandwiched between layers of imbricated gravel-sized sediments. KNZ004 was collected 1.05 m above the bedrock and was separated from KNZ003 by a thick layer of gravel and cobble-sized material. KNZ005 was taken 1.55 m above the bedrock and was also separated from KNZ004 by a former channel deposit consisting of gravel-sized sediment. A final cobble layer sits above the KNZ005 sampling layer, indicating that the stream was active at a higher elevation after the deposition of KNZ005.

Samples were processed at the Desert Research Institute Luminescence Laboratory (DRILL) in Reno, Nevada, USA. We used the 90–125 μm fraction size of quartz grains for luminescence dating. “Pseudo” single grain or “micro-hole” quartz dating (Berger, 2011) was used due to the small size of the quartz grains. Pseudo single grain differs from single grain dating such that in single grain dating, each grain is an aliquot, whereas with pseudo single grain dating, one hole on the measurement disc is considered an aliquot, which were counted to contain ~3–10 grains. Measurement procedures are detailed in Supporting Information Tables SA1 and SA2; Figure SA1.

5 | RESULTS

5.1 | OSL chronology

OSL samples KNZ003, KNZ004, and KNZ005 from Site 2 yield ages of 30.79 ± 4.89 ka, 36.64 ± 4.36 ka, and 19.91 ± 3.67 ka, respectively (Table 1). The ages of samples KNZ003 and KNZ004 do not fall in the expected chronological order given the law of superposition, but they are consistent within error. OSL sample KNZ001 from Site 1 (1.7 m above bedrock) yielded an age of 19.84 ± 2.79 ka, which correlates well with KNZ005 (1.55 m above bedrock) dated to 19.91 ± 3.67 ka. The aggradation rate between samples KNZ003 and KNZ004 was likely relatively high given that these samples are the same age within error and are separated by ~0.8 m of sediment. Samples KNZ004 and KNZ005 in contrast, are separated by ~0.5 m of sediment and differ in age by up to 16.7 ka, suggestive of a lower sedimentation rate of ~40.04 mm/yr.

5.2 | Erosion rate measurements

Field observations indicate that plucking was the primary erosion mechanism in both limestone and shale lithologies. Plucking was likely the mechanism in the shale lithologies because of the slakey nature of shale (Figure SB3), and in limestones based on observations of large flakes of rock that were removed from rock surfaces (Figure Sb4).
The highest lateral erosion rates occurred in the shale layers and range from 28 to 159 mm/yr (Table 2). Most measured lateral erosion pin values were positive and correlate to bank retreat; however, a few negative readings occurred (a total decrease in the length of exposed pin) when small amounts of overlying bank material accumulated around the pin. Seven out of 13 shale erosion pins were removed from the bank by stream flow over the study period. Erosion rates from lost pins were calculated using the entire length of the pin under the assumption that a pin’s length of erosion had occurred. Limestone lateral erosion rates over the measurement period ranged from 0 to 65 mm/yr (Figure 5; Table 2). Most limestone erosion pins tended to erode very little or eroded in large blocks that completely removed the pin. Six out of the 13 limestone pins on the upper parts of the banks had no measurable erosion and three out of 13 limestone pins were removed from the bank by stream flow during the study period. The greatest magnitude of lateral erosion in both lithologies occurred near the bottom of the banks due to more flow events capable of eroding bedrock, and generally decreased with distance away from the channel bed (Figure 5; Table 2).

5.3 | Bedrock erosion rates versus discharge

Kings Creek exhibits variable stream flow, and there are often long periods in which the stream has zero measured flow (up to 356 days; Costigan et al., 2015). The summer 2019 season was exceptionally wet and was the third wettest summer on record in a 41 years of discharge data (US Geological Survey, 2020a). There were four high flow events in excess of 35 m$^3$/s, which is the estimated size of the 5-year flood (US Geological Survey, 2020b) at Kings Creek during the study period (Figure 6).

We observed that shale erodes more efficiently when it is dry rather than when it is submerged and wet. “Wet” versus “dry” determinations were made using the trail camera photographs and discharge data. Therefore, shale erosion is not only a function of discharge, but also a strong function of wetting and drying cycles. Conversely, limestone erosion is a function of discharge such that a higher discharge generally results in a higher erosion rate. We summarize the connection between stream discharge and measured erosion during the study period in five time intervals between measurement dates. We report erosion rates in limestone and shale that were calculated over the individual time intervals and averaged over all pins transects. We report “interval-averaged erosion rates” in units of millimeters per year in the sections later to facilitate comparison of erosion rates among the various time intervals. Interval-averaged erosion rate is found by dividing the amount of erosion during the time interval by the length of the time interval. Interval-averaged erosion rates should be considered maximum erosion rates, and are not necessarily reflective of average annual erosion rates.

5.3.1 | T1 (Installation–November 2018)

From the time of installation to the first measurement in November 2018, the channel was completely dry until a small discharge event (2 m$^3$/s) on October 9 (Figure 6). During T1, there was measurable erosion at 12 out of 13 shale pins. The interval-averaged shale lateral erosion rate averaged across both sites for this interval was 34 mm/yr (Figure 7a). There was no measurable limestone erosion at any pins during this interval (Figure 7a).

5.3.2 | T2 (November 2018–May 2019)

Kings Creek entered a wet interval at the beginning of T2 with a peak discharge of 42.5 m$^3$/s. The highest amount of shale erosion occurred during this interval and erosion was so efficient that three erosion pins were completely removed from the bank and lost (Figure 5; Table 2) as a result of the high flow event on May 8, 2019 (Figure 6). The interval-averaged shale lateral erosion rate, averaged over both sites, was 204 mm/yr for the T2 interval. This interval was also the first when there was measurable erosion of limestone at three out of eight measured limestone erosion pins (Table 2). Interval-averaged lateral limestone erosion rate during this interval was 24 mm/yr (Figure 7a).

5.3.3 | T3 (May 2019–August 2019)

There were two large discharge events during this time interval (100 m$^3$/s and 49.5 m$^3$/s). Due to pin loss and some missed pin measurements in May 2019, the shale lateral erosion rate could only be calculated from three shale pins. There was very little erosion at the three shale pins that were measured at this interval, and interval-

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**Table 1** Luminescence ages for samples in this study

| Sample site | Sample | Depth (m) | Latitude (° N) | Longitude (° W) | Elevation (m a.s.l.) | N accepted (N analyzed)$^a$ | OD$^2$ (%) | Dose rate$^b$ (Gy/ka) | Equivalent dose$^c$ (Gy/ka) | Age$^d$ (ka) |
|------------|-------|----------|---------------|----------------|---------------------|---------------------------|-----------|----------------|-----------------|------------|
| 1          | KNZ001| 2.57     | 39.10497     | –96.6001       | 327                 | 57 (900)                | 51.9      | 4.08 ± 0.23   | 81.00 ± 10.68  | 19.84 ± 2.79 |
| 2          | KNZ003| 3.75     | 39.10445     | –96.5997       | 325                 | 44 (1200)               | 57.6      | 2.99 ± 0.17   | 91.96 ± 13.67  | 30.79 ± 4.89 |
|            | KNZ004| 2.95     | 39.10445     | –96.5997       | 325.5               | 77 (1300)               | 46.2      | 3.68 ± 0.20   | 135.09 ± 14.71 | 36.64 ± 4.36 |
|            | KNZ005| 2.45     | 39.10445     | –96.5997       | 326.5               | 47 (800)                | 67.5      | 3.25 ± 0.18   | 64.69 ± 11.55  | 19.91 ± 3.67 |

$^a$N accepted refers to the number of multi-grain aliquots measured in the sample that pass rejection criteria. See Supporting Information for details.

$^b$Dose rates (Gy/ka) were calculated using the conversion factors of Liritzis et al. (2013) and are shown to two decimal places; ages were calculated prior to rounding. Measured water content of 7% (expressed as the percentage of the mass of dry sediment) were used in age calculations. See Supporting Information for details.

$^c$The D$_0$ value of all samples were calculated using the Minimum Age Model (Galbraith et al., 1999).

$^d$Ages are rounded to the nearest 10 years and are reported in thousands of years before 2018. Age errors are 1σ.
averaged shale lateral erosion rate was 31 mm/yr during this interval (Figure 7). In contrast, this interval showed the highest rate of limestone erosion, and three erosion pins were completely removed at the North Fork site (Table 2). The interval-averaged limestone lateral erosion rate averaged over all pins during this interval was 106 mm/yr (Figure 7).

### 5.3.4 T4 (August 2019–October 2019)

From August 2019 to October 2019, the channel remained wet early in this interval, following the largest discharge event during the study period (Figure SB5; August 30, 2019, 121 m$^3$/s). Of the remaining eight shale pins, two pins had substantial measured erosion during this time period, yielding an interval-averaged erosion rate at this pin of 177 mm/yr. However, this pin was ~1.5 m above the channel bed (Figure 5b) and was not submerged for any substantial period of time, allowing the shale to remain dry and flaky. The remaining six shale erosion pins had little or no erosion during this time period, despite the exceptional discharge event. The interval-averaged shale lateral erosion rate during this interval was 49 mm/yr, averaged across all pins at both sites. At this point in the study, many of the remaining limestone pins that had not been plucked were situated in locations high on the channel banks. There was little measured erosion in five out of seven limestone erosion pins, with the notable exception of one pin installed in in-stream boulders at the North Fork site (pin #8, Figure 5a). The interval-averaged lateral limestone erosion rate for this single pin during this interval was 91 mm/yr, while the interval-averaged limestone lateral erosion rate for this time interval averaged across all pins was 16 mm/yr.

### 5.3.5 T5 (October 2019–January 2020)

During the final time interval, there was one small flow event (3 m$^3$/s), but generally discharge decreased to 0 m$^3$/s for the first

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**Table 2** Erosion pin measurements (mm) for all pins in this study

| Field site        | Pin # | Height above channel (m) | Lithology | November 2018 | May 2019 | August 2019 | October 2019 | November 2019 | January 2020 | Erosion ratea (mm/yr) |
|-------------------|-------|--------------------------|-----------|---------------|----------|-------------|---------------|----------------|----------------|---------------------|
| Nature Trail      | 1–3   | 1.52                     | LS        | 0             | 0        | 0           | 0             | 0              | 0              | 0                   |
| downstream        | 4     | 1.2                      | S         | 17.65         |          |             | 0             | 0              | 0              | 0                   |
| Nature Trail      | 5     | 0.79                     | S         | 38.95         |          |             | 0             | 0              | 0              | 0                   |
| Upstream          | 6     | 0.59                     | S         | 49.35         | 94.25    | 80.6        | 73.3          | 86.9           | 85.6           | 49                  |
|                   | 7     | 0.55                     | S         | 19.3          |          | 114.1       |               | 131.85         | 70.7           | 76                  |
|                   | 8     | 0.44                     | S         | 32.45         | 93.9     | 100.1       | 91.4          | 101.45         | 87.9           | 58                  |
| Nature Trail      | 1     | 1.8                      | LS        | 0             |          |             | 0             | 0              | 0              | 0                   |
| Upstream          | 2     | 1.49                     | S         | 24.1          | 60.05    | 62.1        |               | 59.25          | 34              |
|                   | 3     | 1.15                     | S/LS      | 0             |          |             | 0             | 0              | 0              | 0                   |
|                   | 4     | 1.05                     | S         | 16.75         |          | 44.9        | 45.95         | 47.7           | 49.3           | 28                  |
|                   | 5     | 0.68                     | S         | 14.6          |          | 108.65      |               | 110.1          | 113.6          | 65                  |
|                   | 6     | 0.38                     | S         | 48.8          |          |             | 0             | 0              | 0              | 0                   |
|                   | 7     | 0.21                     | S         | 44.9          |          | 114.1       |               | 131.85         | 70.7           | 76                  |
| North Fork        | 1     | 0.66                     | LS        | 0             | 0        | 0           | 0             | 0              | 0              | 0                   |
| upstream          | 2     | 0.54                     | LS        | 0             | 0        | 0           | 0             | 0              | 0              | 0                   |
|                   | 3     | 0.5                      | LS        | 1.70          |          |             | 0             | 0              | 0              | 0                   |
|                   | 4     | 0.4                      | LSB       | 0             |          | 45.5        |               | 46.6           | 44.8           | 26                  |
|                   | 5     | 0.29                     | S         | 6.4           | 106.3    | 104.9       | 108.15        | 100.05         | 99.5           | 65                  |
|                   | 6     | 0.18                     | S         | 0             |          | 90.55       | 120.05        | 99.5           | 94             | 94                  |
|                   | 7     | 0.01                     | S         | 25.0          |          |             | 0             | 0              | 0              | 0                   |
|                   | 8     | 0.01                     | LSB       | 0             | 20.85    | 30.05       | 44.45         | 44.6           | 46.5           | 27                  |
|                   | 9     | 0.01                     | LSB       | 0             | 29.4     |             | 0             | 0              | 0              | 0                   |
|                   | 10    | 0.01                     | LSB       | 0             | 33.1     |             | 0             | 0              | 0              | 0                   |
| North Fork        | 1     | LS                       |           |               |          |             | 0             | 0              | 0              | 0                   |
| upstream bed pins | 2     | LS                       |           |               | 12.40    |             | 0             | 0              | 0              | 0                   |
|                   | 3     | LS                       |           |               |          |             | 44.8          | 45.3           | 46.5           | 27                  |

Note: S lithology indicates that the pin is in shale, LS indicates a pin installed in limestone, and LSB indicates a pin that is installed in an instream limestone boulder. ●, pin spotted visually, but could not be measured because water was too deep and/or cold; ♦, pin not found visually due to sediment cover, turbid water or moss cover; ⊠, pin missing.

*aErosion rates were calculated over the duration of the study period or over the time period the pin was present in the bedrock bank. If a pin was missing at the time of measurement, we used the entire length of the erosion pin and assumed that was the amount of erosion that occurred for calculations.*
time in nearly a year, and the channel began to dry out. During this interval, peak shale lateral erosion rates again were high (Figure 7a), largely due to two remaining shale pins at North Fork eroding from the bank, with interval-averaged lateral erosion rates of 130 and 169 mm/yr. Shale lateral erosion rates at Nature Trail, where erosion pins were still submerged, were lower in comparison (0–19 mm/yr). There was little to no limestone erosion at either site during this interval.

**FIGURE 5** Measurement of cumulative erosion at each erosion pin at each site since installation in spring 2018. (a) North Fork upstream site. The bottom graph represents measurements of lateral erosion made on the in-stream boulder. (b) Measurements at the Nature Trail upstream site. (c) Measurements at the Nature Trail downstream site. In all figures, the tan background color represents limestone lithology and the gray background represents shale lithology. The hollow shape and color of the outline indicate the month that the pin went missing. The black triangles along the left side of each figure indicate the pin number.

**FIGURE 6** Discharge at Kings Creek (US Geological Survey stream gauge #06879650) for the duration of the study period. Red dotted lines and the colors beneath the graph indicate the time slices (i.e., T1, T2, ...), which are described in Section 5.3.
Interval-averaged lateral erosion rates calculated over five time intervals during the study period for all shale erosion pins (blue) and limestone erosion pins (orange), and box plots of lateral erosion rates within the time intervals. The square markers indicate interval-averaged erosion rates averaged over all shale or limestone erosion pins (markers) in Kings Creek during each time interval.

**Figure 7** (a) Interval-averaged lateral erosion rates calculated over five time intervals during the study period for all shale erosion pins (blue) and limestone erosion pins (orange), and box plots of lateral erosion rates within the time intervals. The square markers indicate interval-averaged erosion rates averaged over all shale or limestone erosion pins (markers) in Kings Creek during each time interval.

**5.4 | Vertical incision**

Erosion pins installed in the channel beds were often impossible to locate due to sediment cover or water in the channel and thus were measured less frequently compared to the bank pins. Bed pins were never measured at the Nature Trail site because of the high-water stage during the study interval; after the end of the study period, three bed pins at the Nature Trail were located that showed 0 mm of erosion.

When vertical incision of the channel bed occurred, it was highly spatially variable. At the North Fork site, bed pins were measured three times during the study interval, yielding interval-averaged vertical incision rate for the limestone bed of 55 mm/yr calculated over a high flow interval (T3). The study-averaged vertical incision rate for limestone (total erosion divided by the length of the study period) was 8 mm/yr. During the high flow intervals T3 and T4 (May 2019–October 2019), we observed substantial vertical incision at North Fork in excess of erosion measured at the single bed pin. Figure SB6 shows ~15 cm of vertical incision in the limestone bed in a location ~1 m away from the bed erosion pins. Our field observations suggest that all of this ~15 cm of vertical incision occurred in T3 and T4. At this location near the bed pins in the North Fork channel, the study-averaged vertical incision rate was estimated at ~88 mm/yr.

**5.5 | Lateral/vertical erosion ratio**

Using measured rates of vertical and lateral erosion, we calculated a ratio of erosion rates (El/Ev) that reflects the relative speed of lateral erosion versus vertical incision. Vertical incision on the bed over the study period ranged from 0 mm at most erosion pins to ~150 mm near the bed pins (Figure SB6), therefore a range of El/Ev values are possible. We use the vertical erosion rate from North Fork bed pin #1 (8 mm/yr), the only bed pin that had measurable erosion over the study period, as the characteristic limestone vertical incision rate. For the characteristic limestone lateral erosion rate, we use North Fork pin 8 (27 mm/yr), which is ~20 cm above the channel bed and could potentially be eroded in both low and high flow events. The El/Ev ratio for limestone was 3.4, indicating that lateral erosion of limestone occurred at more than three times the rate of vertical limestone incision during the study interval. Using the median shale erosion rate of 94 mm/yr (North Fork pins #5 and #6), El/Ev ratio was 11.6, indicating that lateral erosion of shale banks was substantially faster than vertical incision of the limestone bed.

We also calculated El/Ev using the substantially higher vertical erosion rate from the North Fork location (88 mm/yr) as the maximum limestone vertical incision rate and the same characteristic limestone lateral erosion rate as mentioned earlier, yielding an El/Ev ratio of 0.31. Using the maximum value for limestone vertical incision, El/Ev for shale banks was 1.1, indicating that at times lateral erosion of shale bedrock was only marginally faster than vertical incision of limestone.

**5.6 | Large block collapse**

Fracture spacing is a proxy for size of blocks that collapse into the stream and reflects the observed sizes of collapsed blocks at the Nature Trail and North Fork site. We found that the horizontal fracture spacing at the North Fork site was 364 mm, and the vertical fracture spacing ranged from 91 mm to 700 mm. At the Nature Trail site, the horizontal fracture spacing ranged from 166 to 62 mm, and the vertical fracture spacing ranged from 56 to 87 mm.

Mass wasting of limestone blocks from the channel wall into the stream was also an observed mechanism of lateral erosion, which may be influenced by fracture spacing. The first instance occurred on December 23, 2018 when a large limestone boulder ~1.5 m in diameter collapsed into the stream at the downstream North Fork site (Figure SB6). As a result, erosion pins at this site were buried underneath this boulder. At the North Fork upstream site, a limestone block collapsed into the stream in May 2019 but was transported away. The limestone blocks at the Nature Trail site also broke off and collapsed from the bank (Figure SB6); however, these blocks were smaller and were relatively rapidly transported away, thus not halting lateral erosion at the Nature Trail site.

**6 | DISCUSSION**

**6.1 | Rates of lateral and vertical erosion**

Our data show that the shale lateral erosion rate, unlike the limestone lateral erosion rate, is not a strong function of discharge. Rather, shale
lateral erosion rate is dependent on whether or not slaking has occurred between high flow events (Schanz & Montgomery, 2016). Shale erodes most rapidly when it undergoes cyclical wetting and drying cycles that decrease the tensile strength and cause crumbling upon drying (Montgomery, 2004). Once shale is slaked, it can be easily swept away by small flow events (Johnson & Finnegan, 2015; Schanz & Montgomery, 2016; Small et al., 2015).

The highest amount of shale erosion (200 mm/yr, interval averaged across all shale erosion pins), occurred during the T2 time interval, an interval with generally low flow culminating with a large discharge event. The high erosion rates are likely due to a combination of a long, dry period in which weak, slaked shale could develop followed by a large discharge event. During the T3 time interval, shale erosion rate was only 30 mm/yr, despite two large discharge events in this interval. We conclude that this low erosion rate is the result of the stream eroding unslanded shale bedrock, which is more resistant because the shale was submerged and cohesive, and thus had not been slaked. The conclusion that shale erodes most rapidly with frequent wetting and drying is additionally supported by shale erosion rates during the T5 time interval. During T5, the channel at the North Fork site completely dried out and the final two remaining shale erosion pins were completely eroded from the bank, whereas shale erosion rates at the Nature Trail site were low during T5 because the pins were still largely submerged.

Our results point to the importance of event sequencing in bedrock incision and landscape evolution, a phenomenon that has rarely been recognized or documented (Baartman et al., 2013). Our data show that in shale bedrock, and other lithologies prone to slaking, erodes most rapidly not under conditions of high discharge, but under conditions of cycles of shale drying and slaking followed by a moderate discharge event. Conversely, the limestone bedrock in our study area showed no evidence that event sequencing is important in erosion. These results demonstrate the complexities of bedrock erosion processes in different lithologies and suggest that an understanding of antecedent conditions (here, cycles of shale wetting and drying) is important for modeling and predicting bedrock incision.

Limestone is a relatively resistant lithology (Sklar & Dietrich, 2001), and limestone erosion rates during the study period were higher than anticipated, exceeding 100 mm/yr. Higher than anticipated erosion rates were due to exceptional high flow events during the study period (Figure 6) and bedrock erosion via plucking. It is possible that erosion rates may be higher on meandering sections of the creek, in comparison to straight sections lacking flow obstacles (Beer et al., 2017), given that bedrock erosion is often concentrated on curved channel sections, either due to bedload impacts (Cook et al., 2014) or increased shear stress (Johnson & Finnegan, 2015). Many limestone layers at Konza are highly fractured, which favors erosion via plucking. In some places, limestone layers grade into shaley limestone that is also prone to erosion via plucking. Additionally, the limestone bedrock may be weakened over time through weathering or abrasion by impacts from bedload particles (Chatanantavet & Parker, 2009). Dissolution of limestone was not observed during the study period; however, it may also contribute to the weakening of the rock and make plucking more efficient (Krautblatter et al., 2012). Given our field measurements and observations, limestone erosion at Konza occurs as a threshold function of peak discharge (e.g., Figure SB8), consistent with erosion via plucking.

The rapid limestone erosion measured during this study period is likely not typical, given the exceptionally high flow events during the study period that were necessary to erode the limestone bed and banks.

Because both vertical and lateral erosion rates were highly spatially variable, there is a wide range of values for the El/Ev ratio that describes the relative speed of lateral versus vertical erosion and the likelihood that a stream can carve an incised canyon versus a wide bedrock valley or strath terraces (Bufe et al., 2017; Merritts et al., 1994; Pazzaglia, 2013). Vertical incision was highly episodic in the study locations due to periodic sediment cover on the bed and the general infrequency of flood events that are capable of plucking limestone. Many studies suggest that vertical incision is much faster than lateral erosion (Dünhforth et al., 2012; Foster et al., 2017; Hancock & Anderson, 2002). However, calculated ratios of El/Ev from our data indicate that lateral erosion rates can equal or outpace vertical incision rates, even in the same lithology, particularly where vertical incision is inhibited by sediment cover on the bed. Previous numerical modeling studies found that substantial lateral channel migration and development of wide bedrock valleys can occur when El/Ev ratios exceed 1.0 (Langston & Tucker, 2018); this data supports potentially higher, if short lived, ratios of lateral to vertical incision.

Our data show that El/Ev in shale banks is consistently equal or much greater than 1, approaching 20. Such high El/Ev ratios are necessary to explain rapid lateral erosion and terrace beveling reported by Bufe et al. (2017). Very high El/Ev ratios can occur in scenarios with weak bedrock banks and a resistant bedrock bed, for example in heterogeneous layered lithology. A potentially common scenario in landscapes with strong contrasts in rock strength among flat-lying lithologic units, is that rivers may be unable to incise into a resistant bed, allowing sufficient time to erode weaker banks laterally. Our data suggest that even when streams incise into a typically erodible lithology, such as shale, vertical incision rates can be relatively low compared to lateral erosion rates if the lithology only becomes easily erodible via slaking following drying (Small et al., 2015). High El/Ev ratios can also potentially occur where resistant, coarse grained bed material protects a less resistant bedrock channel, for example at the transition from the crystalline core of the Front Range of the Rocky Mountains to the High Plains. In such cases, the resistant, coarse grained bedrock protects the shale channel bed from incision, while bedrock banks are exposed to potentially rapid lateral erosion (Langston & Temme, 2019a).

6.2 Valley widening in layered lithologies

The rapid lateral erosion rates measured during this study are likely not representative of long-term lateral erosion rates in these reaches. The bedrock channel banks and bed in our study area are likely intermittently covered and uncovered by colluvium and fluvial deposits over decadal timescales, which may halt both lateral erosion and vertical incision (e.g., Lague et al., 2005). Bedrock erosion rates are zero not only when bedrock is shielded, but also when there is no flowing water such as during a drought or channel avulsion away from the bedrock valley wall (Brocard & Van Der Beek, 2006; Bufe et al., 2016; Hancock & Anderson, 2002).

Long-term rates of bedrock valley widening also depend on lateral bedrock erosion rate and how effectively a stream can transport
collapsed valley wall material (Langston & Temme, 2019a, 2019b). In layered landscapes with a strong contrast in rock properties, the collapse of large or resistant overlying blocks into the stream can effectively shut down lateral erosion on the valley wall if the stream is unable to readily erode or transport the collapsed blocks, as observed at the North Fork downstream site (Figure SB7). It is likely that continued rapid erosion of shale bedrock at the undisturbed North Fork upstream site will undercut the bank and cause limestone blocks collapse into the stream, shielding the bank from continued rapid erosion at this location as well.

Our data suggest that fracture spacing in the overlying limestone units at each site predicts the potential transport and removal of collapsed blocks from the channel bank (e.g., Gabet, 2020). The limestone units at the North Fork site tend to have a larger fracture spacing and collapse as boulders up to ~1 m in diameter, whereas the limestone blocks that detached from the channel bank at the Nature Trail site during this study were estimated ~0.2 m maximum in diameter and readily transported away from the bank by the stream (Figure SB7). Additionally, the limestone layers at the Nature Trail site are thinner and cannot provide as extensive coverage of the bank compared to the limestone blocks at the North Fork site.

In locations with layered lithology, such as the Colorado Plateau or the French Alps, long term lateral erosion rates and valley widening depend not only on the rock properties at the base of the valley wall but also on rock properties of overlying material as well (Brocard & Van Der Beek, 2006; Forteet al., 2016). Our data also show that in Konza and northeast Kansas, varying lateral erosion rates can influence valley widening rates, even in channel banks comprised of a single lithology. Variation in lateral erosion and valley widening rates in the same lithology on annual and decadal timescales can occur due to variable rock properties that make different limestone units more or less susceptible to abrasion or plucking, and may be influenced in part by fracture spacing, which is a first-order control on block sizes of collapsed overlying material.

## 6.3 | OSL and terraces

### 6.3.1 | Fluvial terraces in Northeast Kansas

The OSL ages from this study are the oldest ages of fluvial material reported from Kings Creek at Konza and northeast Kansas. Most previous studies in northeast Kansas report fluvial material that is no older than Holocene in age (Johnson & Martin, 1987; Mandel, 2008), including fluvial terraces in Konza (Ross, 1995; Smith, 1991). The two other high-elevation terraces overlying bedrock in Konza with red, oxidized fluvial material similar to our Middle Trunk site suggest a longer time exposed to weathering and an older age than tan colored terraces in Konza (Birkeland et al., 1991; Foster et al., 2017). The similarity in color and elevation above stream level suggest that Pleistocene-aged surfaces and stratified terraces may be more common than previously indicated by prior studies in northeast Kansas (Johnson & Martin, 1987; Mandel, 2008; Ross, 1995; Smith, 1991).

Smith (1991) originally mapped terraces in Konza as one terrace level based on elevation above current stream level ranging from ~1.5 m to 6 m. Our OSL ages of the Main Trunk terrace site, laying at ~7–8 m above the modern channel, coupled with the varying terrace material demonstrate that terraces similar in elevation above the channel do not always share the same age (e.g., Foster et al., 2017), and in fact have the potential to be quite different in age (Merritts et al., 1994). The OSL ages of fluvial material from this study (~30 ka to 19 ka) and the carbon-14 (~9 ka, Smith, 1991; Ross, 1995) demonstrate the likelihood of multiple evolutionary timescales of Kings Creek terraces throughout the Pleistocene.

### 6.3.2 | Fluvial history of Kings Creek during the Pleistocene

Identifying a late Pleistocene depositional age for these fluvial deposits overlying a bedrock surface provides an opportunity to interpret river behavior and identify potential drivers of river aggradation and valley widening. Lateral beveling of the bedrock surface at the Main Trunk site that KNZ003 sits on must have been complete by the time the KNZ003 material was deposited ~30 ka. The OSL age of KNZ003 indicates the last time the stream was active on this beveled bedrock surface, but the depositional age of KNZ003 does not necessarily indicate the time when this bedrock surface was cut laterally. The OSL ages of KNZ003 (30.8 ± 4.8 ka) and KNZ004 (36.64 ± 4.36 ka) overlap, suggesting a period of rapid deposition ~30 ka. The ages of KNZ004 and KNZ005, 50 cm from each other, have a larger age range (33.71 ± 4.59 ka, mean age of KNZ003 and KNZ004, and 19.91 ± 3.67 ka respectively) and indicate that the sedimentation rate at this site slowed during this time, potentially due to the stream channel shifting southward and away from the sampling site during this interval.

Sometime after the deposition of the sediments at KNZ003 (~19 ka), the stream incised into the alluvial fill sequence of KNZ003, KNZ004, KNZ005, and KNZ001. The timing of the incision and abandonment of the Main Trunk terrace is unknown but must have occurred no later than ~9 ka, the depositional age of the fill terrace ~1 km downstream of our OSL site (Smith, 1991). Incision of the Main Trunk terrace may have occurred due to changes in mid-continent climate or vegetation during early to mid-Holocene (Knox, 1984; Mandel, 2008). The Kings Creek valley then likely experienced cycles of repeated aggradation and incision to create the fill terrace sequences identified by Smith (1991).

The OSL ages reported in this study indicate that fluvial material was deposited during the Wisconsin glacial period and around the time of the onset of Northern Hemisphere deglaciation (~19 to 20 ka; Clark et al., 2009). Previous research suggests that stream aggradation and stratified terrace beveling often occurs during glacial intervals (Dühnforth et al., 2012; Hancock et al., 1999; Molnar, 1994). Northeast Kansas was generally cool and dry during glacial periods (Baker et al., 2009; Mandel et al., 2016), which could have induced stream aggradation by decreasing the transport capacity of the stream (Schildgen et al., 2016). Stream aggradation may also have been driven by increased sediment flux from hillslopes due frost-cracking and freeze–thaw processes, which were more active than present during the late Pleistocene (Anderson et al., 2013; Marshall et al., 2015).
Lateral bedrock erosion and valley formation through time

The notably old depositional age of sediments on our sampled terrace and the presence of similar fluvial sediments overlying bedrock on additional terraces, suggest that Kings Creek has undergone periods of both lateral and vertical bedrock erosion, in addition to cycles of alluvial aggradation and incision over the past ~36 ka. In the late Pleistocene, reaches of Kings Creek were depositing and aggrading on a bedrock surface, were likely laterally mobile, and thus eroding bedrock valley walls and widening the valley (Bufo et al., 2016; Fuller et al., 2009; Hancock & Anderson, 2002; Whitbread, 2012). The late Pleistocene age of fluvial sediment on top of the bedrock surface may suggest a period of beveling a flat bedrock surface throughout the valley. Bedrock valley widening in Kings Creek is actively ongoing in the present. Modern erosion rates from this study demonstrate that lateral bedrock erosion can proceed rapidly, suggesting that when the stream is in contact with bedrock walls, it can readily erode them. This result implies that the biggest limitation to bedrock valley widening in Kings Creek is contact between bedrock banks and the stream (Brocard & Van Der Beek, 2006; Bufo et al., 2019).

The modern lateral bedrock erosion rates can provide a minimum estimate of how long it took Kings Creek to carve to the current ~450 m wide bedrock valley. Assuming that lateral erosion occurred continuously at the lateral erosion rate for shale measured during this study, the minimum time spent laterally widening the Kings Creek valley would be ~48000 years. Assuming the bedrock banks are made entirely of limestone, the minimum time to widen the valley 450 m wide would be ~16,700 years. While the modern lateral erosion rates suggest the possibility of rapid bedrock valley development, the actual time spent widening is likely substantially longer than the earlier mentioned minimum estimates, given that erosion rates in layered landscapes are complex and vary greatly in space and time as shown by our data and previous studies in layered landscapes (Peme et al., 2017). Additionally, complexity in spatio-temporal erosion rates could be due to the fact that our erosion rates were measured at meander bends along the stream, potential erosion hotspots where erosion rates may be higher than straight portions of the channel where it is possible that little or no erosion has occurred. Furthermore, if long-term lateral bedrock erosion rates were the same as measured modern rates over the past 36 ka, Kings Creek valley would be at least 3000 m wide, rather than 450 m wide. This suggests that processes such as block collapse and stream migration away from bedrock valley walls that interrupt rapid lateral bedrock erosion and slow valley widening may be common in the history of Kings Creek's evolution. Our results suggest that Kings Creek has undergone cycles of both alluvial aggradation and incision and bedrock valley widening and incision for at least the past ~36 ka, likely longer. Our data suggest that the elevation of Kings Creek has been within ~6 m of its present elevation for the past ~36 ka, and we have no evidence stream elevation has been higher earlier than 36 ka. During this time, Kings Creek has not simply undergone repeated cycles of valley filling and incision, detached from the channel on the bedrock valley walls. Rather, we suggest that Kings Creek and many other streams in northeast Kansas erode and widen valleys through substantial lateral and vertical bedrock incision in addition to periods of fill terrace aggradation and incision.
REFERENCES

Anderson, R.S., Anderson, S.P. & Tucker, G.E. (2013) Rock damage and regolith transport by frost: An example of climate modulation of the geomorphology of the critical zone. Earth Surface Processes and Landforms, 38(3), 299–316. https://doi.org/10.1002/esp.3330

Attal, M. & Lavé, J. (2009) Pebble abrasion during fluvial transport: Experimental results and implications for the evolution of the sediment load along rivers. Journal of Geophysical Research - Earth Surface, 114(F4), 1–23. https://doi.org/10.1029/2009JF001328

Attal, M., Lavé, J. & Masson, J.-P. (2006) New facility to study river abrasion processes. Journal of Hydraulic Engineering, 132(6), 624–628. https://doi.org/10.1061/(asce)0733-9429(2006)132:6(624)

Baartman, J.E.M., Temme, A.J.A.M., Veldkamp, T., Jetten, V.G. & Schoorl, J. M. (2013) Exploring the role of rainfall variability and extreme events in long-term landscape development. Catena, 109, 25–38. https://doi.org/10.1016/j.catena.2013.05.003

Baker, R.G., Bettis, E.A., Illi, Mandel, R.D., Dorale, J.A. & Fredlund, G. (2009) Mid-Wisconsinian environments on the eastern Great Plains. Quaternary Science Reviews, 28(9–10), 873–889. https://doi.org/10.1016/j.quascirev.2008.12.021

Barnhart, K.R., Tucker, G.E., Doty, S.G., Glade, R.C., Shobe, C.M., Rossi, M. W. & Hill, M.C. (2020) Projections of landscape evolution on a 10,000 year timescale with assessment and partitioning of uncertainty sources. Journal of Geophysical Research - Earth Surface, 125(12), 1–15. https://doi.org/10.1029/2020JF005795

Baynes, E.R.C., Attal, M., Niedermann, S., Kirstein, L.A., Digmore, A.J. & Naylor, M. (2015) Erosion during extreme flood events dominates holocene canyon evolution in northeast Iceland. Proceedings of the National Academy of Sciences of the United States of America, 112(8), 2353–2360. https://doi.org/10.1073/pnas.1415443112

Baynes, E.R.C., Lague, D., Steer, P., Bonnet, S. & Illien, L. (2020) Sediment flux-driven channel geometry adjustment of bedrock and mixed gravel–bedrock rivers. Earth Surface Processes and Landforms, 45(14), 3714–3731. https://doi.org/10.1002/esp.4996

Beer, A.R., Turówski, J.M. & Kirchner, J.W. (2017) Spatial patterns of erosion in a bedrock gorge. Journal of Geophysical Research – Earth Surface, 122(1), 191–214. https://doi.org/10.1002/2016JF003850

Berger, G.W. (2011) Surfumting luminescence age overestimation in Alaska-margin Arctic Ocean sediments by use of “micro-hole” quartz dating. Quaternary Science Reviews, 30(13-14), 1750–1769. https://doi.org/10.1016/j.quascirev.2011.03.019

Birkeland, P.W., Machette, M.N. & Haller, K.M. (1991) Solis as a tool for applied quaternary geology. Salt Lake City, UT, USA: Utah Geological Survey Miscellaneous Publication.

Brocad, G.Y. & Van Der Beek, P.A. (2006) Influence of incision rate, rock strength, and bedload supply on bedrock river gradients and valley-flat widths: Field-based evidence and calibrations from western Alpine rivers (southeast France). Special Paper of the Geological Society of America, 398, 101–126. https://doi.org/10.1130/2006.2398(07)

Bufo, A., Burbank, D.W., Liu, L., Bookhagen, B., Qin, J., Chen, J., et al. (2017) Variations of lateral bedrock erosion rates control pluviation of uplifted folds in the foreland of the Tian Shan, NW China. Journal of Geophysical Research - Earth Surface, 122(12), 2431–2467. https://doi.org/10.1002/2016JF004099

Bufo, A., Paola, C. & Burbank, D.W. (2016) Fluvisial bevelling of topography controlled by channel lateral mobility and uplift rate. Nature Geoscience, 9(9), 706–710. https://doi.org/10.1038/ngeo2773

Bufo, A., Turówski, J.M., Burbank, D.W., Paola, C., Wickert, A.D. & Tofelde, S. (2019) Controls on the lateral channel-migration rate of braided channel systems in coarse non-cohesive sediment. Earth Surface Processes and Landforms, 44(14), 2823–2836. https://doi.org/10.1002/esp.4710

Chatanantavet, P. & Parker, G. (2009) Physically based modeling of bedrock incision by abrasion, plucking, and macroabrasion. Journal of Geophysical Research – Earth Surface, 114(F4), 1–22. https://doi.org/10.1029/2008JE003144

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., et al. (2009) The Last Glacial Maximum. Science, 325(5941), 710–714. https://doi.org/10.1126/science.1172873

Collins, B.D., Montgomery, D.R., Schanz, S.A. & Larsen, I.J. (2016) Rates and mechanisms of bedrock incision and strain terrace formation in a forested catchment, Cascade Range, Washington. Bulletin of the Geological Society of America, 128(5–6), 926–943. https://doi.org/10.1130/B31340.1

Cook, K.L., Turówski, J.M. & Hovius, N. (2014) River gorge eradication by downstream sweep erosion. Nature Geoscience, 7(9), 682–686. https://doi.org/10.1038/geo2224

Costigan, K.H., Daniels, M.D. & Dodds, W.K. (2015) Fundamental spatial and temporal discrepancies in the hydrology of an intermittent prairie headwater network. Journal of Hydrology, 522, 305–316. https://doi.org/10.1016/j.jhydrol.2014.12.031

Düührnforth, M., Anderson, R.S., Ward, D.J. & Blum, A. (2012) Unsteady late Pleistocene incision of streams bounding the Colorado Front Range from measurements of metricoric and in situ 10Be. Journal of Geophysical Research - Earth Surface, 117(F1), 1–20. https://doi.org/10.1029/2011JF002232

Forte, A.M., Yanites, B.J. & Whipple, K.K. (2016) Complexities of landscape evolution during incision through layered stratigraphy with contrasts in rock strength. Earth Surface Processes and Landforms, 41(12), 1736–1757. https://doi.org/10.1002/esp.3947

Foster, M.A., Anderson, R.S., Gray, H.J. & Mahan, S.A. (2017) Dating of river terraces along Lefthand Creek, western High Plains, Colorado, reveals punctuated incision. Geomorphology, 295, 176–190. https://doi.org/10.1016/j.geomorph.2017.04.044

Fuller, T.K., Gran, K.B., Sklar, L.S. & Paola, C. (2016) Lateral erosion in an experimental bedrock channel: The influence of bed roughness on erosion by bed load impacts. Journal of Geophysical Research – Earth Surface, 121(5), 1084–1105. https://doi.org/10.1002/2015JF003728

Fuller, T.K., Perg, L.A., Willenbring, J.K. & Lepper, K. (2009) Field evidence for climate-driven changes in sediment supply leading to strathe terrace formation. Geology, 37(5), 467–470. https://doi.org/10.1130/G25487A.1

Gabet, E.J. (2020) River profile evolution by plucking in lithologically heterogeneous landscapes: Uniform uplift vs. tilting. Earth Surface Processes and Landforms, 45(7), 1579–1588. https://doi.org/10.1002/esp.4832

Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H. & Olley, J.M. (1999) Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia: Part I, experimental design and statistical models. Archaeometry, 41(2), 339–364. https://doi.org/10.1111/j.1475-4754.1999.tb00987.x

Gray, L.J., Macpherson, G.L., Koelliker, J.K. & Parker, G. (1999) Physically based modeling of bedrock incision by abrasion, plucking, and macroabrasion. Journal of Geophysical Research – Earth Surface, 114(F4), 1–22. https://doi.org/10.1029/2008JE003144
Spotila, J.A., Moskey, K.A. & Prince, P.S. (2015) Geologic controls on bedrock channel width in large, slowly-eroding catchments: Case study of the New River in eastern North America. Geomorphology, 230, 51–63. https://doi.org/10.1016/j.geomorph.2014.11.004

Tomkin, J.H., Brandon, M.T., Pazzaglia, F.J., Barbour, J.R. & Willett, S.D. (2003) Quantitative testing of bedrock incision models for the Clearwater River, NW Washington State. Journal of Geophysical Research: Solid Earth, 108(B6), 2308. https://doi.org/10.1029/2001jb000862

Tucker, G.E. & Whipple, K.X. (2002) Topographic outcomes predicted by stream erosion models: Sensitivity analysis and intermodel comparison. Journal of Geophysical Research: Solid Earth, 107, ETG 1–ETG 1–16. https://doi.org/10.1029/2001jb000162

Turowski, J.M. (2018) Alluvial cover controlling the width, slope and sinuosity of bedrock channels. Earth Surface Dynamics, 6(1), 29–48. https://doi.org/10.5194/esurf-6-29-2018

Turowski, J.M., Hovius, N., Meng-Long, H., Lague, D. & Men-Chiang, C. (2008) Distribution of erosion across bedrock channels. Earth Surface Processes and Landforms, 33(3), 353–363. https://doi.org/10.1002/esp.1559

US Geological Survey. (2020a) National Water Information System: Web Interface. US Geological Survey: Reston, VA, USA.

US Geological Survey. (2020b) The StreamStats program. US Geological Survey: Reston, VA, USA.

Whipple, K.K. (2004) Bedrock rivers and the geomorphology of active orogens. Annual Review of Earth and Planetary Sciences, 32(1), 151–185. https://doi.org/10.1146/annurev.earth.32.101802.120356

Whipple, K.K., Hancock, G.S. & Anderson, R.S. (2000) River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion, and cavitation. Bulletin of the Geological Society of America, 112(3), 490–503. https://doi.org/10.1130/0016-7606(2000)112<490:RIBMA>2.0.CO;2

Whipple, K.X. & Tucker, G.E. (1999) Dynamics of the stream-power river incision model: Implications for height limit of mountain ranges, landscape response timescales, and research needs. Journal of Geophysical Research, 104(B8), 17661–17674. https://doi.org/10.1029/1999JB900120

Whitbread, K. (2012) Postglacial evolution of bedrock rivers in post-orogenic terrains: the NW Scottish Highlands. PhD thesis, University of Glasgow.

Wilkinson, C., Harbor, D.J., Helgans, E. & Kuehner, J.P. (2018) Plucking phenomena in nonuniform flow. Geosphere, 14(5), 2157–2170. https://doi.org/10.1130/GES01623.1

Wohl, E. & David, G.C.L. (2008) Consistency of scaling relations among bedrock and alluvial channels. Journal of Geophysical Research - Earth Surface, 113(F4), 1–16. https://doi.org/10.1029/2008JF000989

Wohl, E.E. & Ikeda, H. (1998) Patterns of bedrock channel erosion on the boso peninsula, Japan1. Journal of Geology, 106(3), 331–345. https://doi.org/10.1086/516026

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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