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Regional and local controls on the spatial distribution of bedrock reaches in the Upper Guadalupe River, Texas

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ABSTRACT

While studies on gravel mantled and mixed alluvial bedrock rivers have increased in recent decades, few field studies have focused on spatial distributions of bedrock and alluvial reaches and differences between reach types. The objective of this work is to identify the spatial distribution of alluvial and bedrock reaches in the Upper Guadalupe River. We compare reach length, channel and floodplain width, sinuosity, bar length and spacing, bar surface grain size, and slope in alluvial and bedrock reaches to identify whether major differences exist between channel reach types. We find that local disturbances, interaction of the channel and valley sides, variation in lithology, and regional structural control contribute to the distribution of bedrock reaches in the largely alluvial channel. Alluvial and bedrock channel reaches in the Upper Guadalupe River are similar, particularly with respect to the distribution of gravel bars, surface grain size distributions of bars, and channel slope and width. Our observations suggest that the fluvial system has adjusted to changes in base level associated with the Balcones Escarpment Fault Zone by phased incision into alluvial sediment and the underlying bedrock, essentially shifting from a fully alluvial river to a mixed alluvial bedrock river.

1. Introduction

Because of the recognition of the importance of fluvial bedrock incision on continental landscape evolution, many studies of bedrock incision have been undertaken in recent decades (e.g. Howard, 1980, 1998; Seidl and Dietrich, 1992; Howard et al., 1994; Sklar and Dietrich, 1998, 2001; Whipple and Tucker, 2002; Sklar and Dietrich, 2004; Bishop et al., 2005; Jansen, 2006; Montgomery and Stolar, 2006; Sklar and Dietrich, 2006; Turowski et al., 2007; Chatanantavet and Parker, 2008). Understanding the role of coarse bed material in bedrock incision processes is essential to understanding bedrock incision mechanics (Sklar and Dietrich, 1998, 2004, 2006) and has led to an increased interest in gravel mantled and mixed alluvial bedrock streams. Studies of mixed alluvial bedrock channels are generally focused on long profile development and are based on a model that attributes the occurrence of bedrock or alluvial channel type to spatial variations in the balance of sediment transport capacity and sediment supply that dates back to Gilbert's (1877) work on the Henry Mountains. While some field studies approach mixed alluvial bedrock streams as unusual fluvial forms and focus on geomorphologic descriptions (Kale et al., 1996; Gupta et al., 1999; Heritage et al., 1999; Tooth and McCarthy, 2004), few field studies have focused on spatial distributions of bedrock and alluvial reaches and differences between reach types (Brakenridge, 1985; Ashley et al., 1988; Montgomery et al., 1996; Montgomery and Buffington, 1997; Heritage et al., 2001; Massong and Montgomery, 2000).

In North America, field studies of mixed alluvial bedrock streams and reference reaches used for testing bedrock incision models have been conducted in humid regions in active tectonic settings (Brakenridge, 1985; Ashley et al., 1988; Seidl and Dietrich, 1992; Montgomery et al., 1996; Montgomery and Buffington, 1997; Howard, 1998; Sklar and Dietrich, 2004; Lancaster and Grant, 2006; Sklar and Dietrich, 2006) and focus on local and reach scale controls on the distribution of bedrock reaches (Seidl and Dietrich, 1992; Montgomery et al., 1996; Montgomery and Buffington, 1997; Howard, 1998; Sklar and Dietrich, 2004; Lancaster and Grant, 2006; Sklar and Dietrich, 2006). In order to improve the understanding of mixed bedrock–alluvial rivers, field investigations across a range of climates and tectonic settings are necessary. The Upper Guadalupe River in central Texas is a mixed alluvial bedrock river in a sub-humid, post-orgenic setting that provides an opportunity to investigate controls on the spatial distribution of alluvial and bedrock reaches in a setting that is often neglected in scientific research in fluvial geomorphology.

The objective of this work is to identify the spatial distribution of alluvial and bedrock reaches in the Upper Guadalupe River. We compare reach length, channel and floodplain width, sinuosity, bar length and spacing, bar surface grain size, and slope in alluvial and bedrock reaches to identify whether major differences exist between channel reach types. To determine whether local or regional processes dominate the

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distribution of channel reach type in the Upper Guadalupe River, we examine local conditions at channel transitions from alluvial to bedrock (or vice versa) as well as regional scale patterns of structure and lithology that may influence the spatial pattern of channel type.

2. Regional setting

In central Texas, the Upper Guadalupe River flows from headwaters in the Edwards Plateau region of the Great Plains province at ~600 m above mean sea level. The study reach begins at Flat Rock Dam near the city of Kerrville and extends downstream for 140 km, ending just upstream of Canyon Lake Reservoir (Fig. 1). The drainage area of the study reach is 3405 km^2. The catchment geology is predominately Cretaceous limestone with some thinly bedded layers of shale and sandstone cropping out in the channel banks and valley sides (Brown et al., 1974; Ashworth, 1983). Average rainfall on the Edwards Plateau is 66 cm/year (Carr, 1967) and potential evapotranspiration is 114 cm/year (Clark, 1983). Precipitation is very seasonal and the region is prone to periods of drought and flood. The combination of low infiltration capacity of upland soils, a steep highly-dissected watershed, and dryland vegetation result in conditions for rapid runoff. Flooding and its effects on geomorphology in central Texas are well documented (Baker, 1975, 1977; Patton and Baker, 1977).

The Upper Guadalupe River channel type alternates from fully alluvial to fully bedrock reaches. Alluvial reaches have fully alluvial beds and banks. Bedrock reaches vary from bedrock floored reaches with alluvial banks to reaches with the cross-section composed entirely of bedrock. Many incised reaches appear incised into bedrock and overlying alluvium such that the bed and lower channel walls are composed of bedrock and the upper channel walls and banks are composed of alluvium (Fig. 2). Ground water sapping is evident in bedrock channel walls and on contacts between bedrock and overlying alluvium. Erosional features such as longitudinal grooves, knickpoints, and abrasion or quarrying scars are present in planar bedrock floored reaches (Fig. 3).

In a small nearby Texas watershed, Tinkler (1971) noted a channel morphology with two channels in cross-section, a small channel on the outside of the bend at a lower elevation and a larger one on the inside of the bend at a higher elevation. In cross-section, both of these channels are inset within a larger flood channel. Although the pattern is discontinuous, this morphology is common on the Upper Guadalupe River. This channel-within-channel morphology has been observed in rivers that have two dominant channel-forming flow regimes or are subject to high-magnitude floods (Tinkler, 1971; Rhodes, 1990; Gupta, 1995; Gupta et al., 1999) and has been observed in bedrock channels (Shepherd and Schumm, 1974; Baker, 1988; Wohl, 1992; Tinkler and Wohl, 1998; Richardson and Carling, 2005). In many cases on the Upper Guadalupe River, the small narrow channel on the outer bend is incised into bedrock and the wider, elevated inner channel is cut through coarse alluvial sediments. Between these channels, on the inside bends of the outer channels, are large gravel deposits stabilized by vegetation which contribute to the persistence of the form through high flows (e.g. Baker, 1977; Abernethy and Rutherfurd, 1998; Tooth and Nanson, 2000; Gurnell et al., 2001; Brooks and Brierley, 2002; Brooks et al., 2003; Pollen et al., 2004).

Coarse grained fluvial deposits are exposed in channel cut banks, suggesting a complex history of aggradation and incision (Fig. 4). Baker (1977), in an tributary catchment of the Guadalupe River downstream of our study reach, observed a similar sedimentary stratigraphy which he identifies as a series of ancient flood deposits and buried torrifluvents. Mid-channel, lateral, and point bars up to 2 km long are present in both alluvial and bedrock reaches. Bars are predominantly composed of rounded pebbles to cobbles although some point bars also have thin sand lenses along the inside of the bend

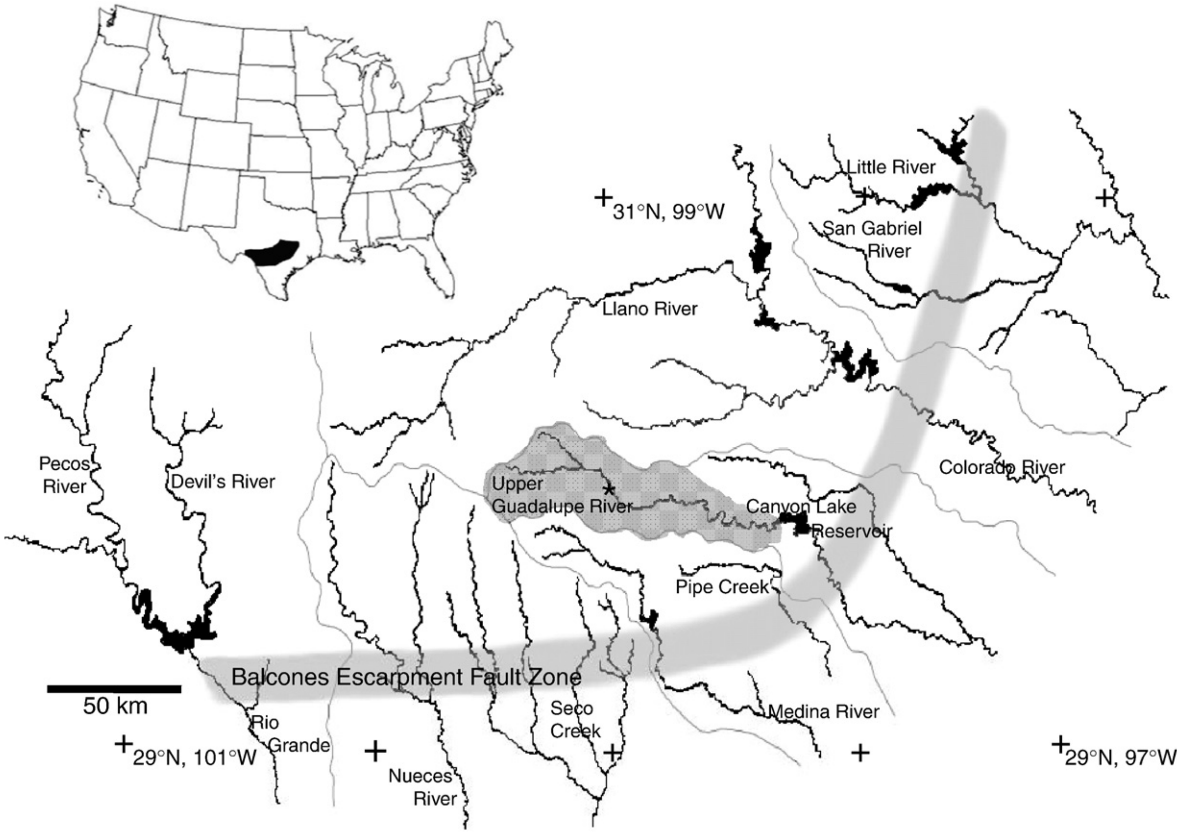

Fig. 1. The location of the Balcones Escarpment Fault Zone and major streams and watersheds in central Texas. The upstream end of the study reach is indicated by * within the Upper Guadalupe River watershed. The study reach extends 140 km downstream to the Canyon Lake Reservoir. Adapted from Caran and Baker (1986, Fig. 1 pg. 3).

Fig. 2. Examples of incision through bedrock and overlying alluvium and ground water sapping in the Upper Guadalupe River. Dashed lines indicate the contact between bedrock and alluvium. In these locations, the channel bed is bedrock.

and a few small tributary mouth bars are composed entirely of sand. The coarse alluvial bars may be depositional in the current environment, but may also be the remaining eroded surfaces of older deposits of which the soil surface horizons have been washed away by floods (Dittemore and Hensell, 1981; Dittemore and Coburn, 1986).

Regional structural control is dominated by the Balcones Escarpment Fault Zone (Fig. 1), a NE–SW trending surface expression of a crustal discontinuity resulting from the Ouachita orogen that divides the Great Plains province from the Coastal Plain (Woodruff and Abbott, 1986). The Balcones Escarpment is a series of “en echelon” normal faults with downthrown sides to the east that create a series of ramps and steps across the fault belt (Jordan, 1977; Grimshaw and Woodruff, 1986). The fault was highly active during the Miocene with subsequent adjustments during the Cretaceous but is considered inactive today (Woodruff and Abbott, 1986).

3. Materials and methods

In order to identify the spatial distribution of channel type and differences between alluvial and bedrock reaches, we have used field techniques, historical aerial photography, and map interpretation to investigate the pattern and characteristics of alluvial and bedrock reaches. Field mapping of the 140 km study reach was undertaken because significant differences between bedrock and the flat surfaces of large gravel bars were not distinguishable using remote sensing or aerial photography techniques. The channel was classified as alluvial or bedrock based on the 50% wetted perimeter criteria (Howard, 1987; Tinkler and Wohl, 1998; Carling, 2006). Herein, “reach(es)” refers to the classified alluvial and/or bedrock reaches. In the few instances where the water in the channel was not clear enough to observe the bed visually, the bed was felt by hand or with a stake at regular intervals to determine if it was bedrock or covered with gravel. In addition to channel type, gravel bar perimeters, boulder berms, knickpoints, tributaries, individual boulders >1 m or groups of boulders, and built structures such as dams, road crossings, and bridges were mapped in the field using differentially corrected GPS and verified on aerial photographs. The surface grain size distribution of bars was determined using the Wolman pebble count method (Wolman, 1954). The same person performed all the pebble counts in order to reduce error attributable to the user.

Digital historical aerial imagery was obtained from Texas Natural Resources Inventory Services (TNRIS) for years 1996 and 2004 and the

Fig. 3. Examples of bedrock channel features. Longitudinal grooves and fluting are common in bedrock reaches in the study area. Both photos show downstream view.

channel was digitized using ArcMap GIS software for both years. The locations of bars mapped in the field in 2005–06 were used to aid identification of bars in current and historical aerial photography. Digitized floodplain zones for 1 year and 500 year floodplains designated by the US Federal Emergency Management Agency (FEMA) were also obtained from TNRIS. Valley sides were digitized using the historical aerial imagery with reference to 1:24,000 topographic maps available from US Geologic Survey (USGS). Widths of the wetted channel, 1 year floodplain, 500 year floodplain, and river valley were measured perpendicular to the downstream flow direction at intervals of 160 m (the largest unit that captured all reach transitions between types). Reach sinuosity was calculated by dividing the channel reach length by the valley length for each alluvial or bedrock reach. The surficial geologic unit for each reach was determined from geologic maps at 1:62,500 published by the Texas Bureau of Economic Geology (Barnes, 1977). Channel slope was determined from 1:24,000 USGS topographic maps. The text of this paper makes frequent reference to "river kilometers," abbreviated: Rkm. This is analogous to river miles and refers to longitudinal distance from the upstream end of the study reach.

4. Results

Bedrock and alluvial reach type varies longitudinally downstream and most of the study reach is alluvial in character with short reaches of bedrock interspersed throughout (Fig. 5). In the Upper Guadalupe River, bedrock and alluvial channel reaches have similar physical characteristics (Table 1). While there are statistically significant differences between alluvial and bedrock reaches with respect to reach length; sinuosity; and channel, floodplain, and valley widths, actual differences are small. For example, channel widths were found to be statistically different but the average channel width of alluvial reaches is 26 m and the average of bedrock reaches is 28 m. Surface grain size distributions and bar size vary little between alluvial and bedrock reaches (Table 2). We observed negligible change in the location and size of gravel bars between 1996 and 2004–05, suggesting overall stability despite a 250 year flow event in 2002.

All variables were analyzed for apparent spatial trends. No downstream trends in the surface grain size of bars are evident when examined over the entirety of the study reach. When separated into reaches between tributary inputs, only 11 between tributary

Fig. 4. Gravel deposits are exposed in many cut banks in the study area. The Orif Soil/Fluviatile Terrace deposits are extensive and consist of mostly water worn pebbles to cobbles.

reaches contained more than three bars. These 11 reaches were used to examine trends in surface grain size between tributaries. Of these, six have downstream trends: four fining, and two coarsening. There was no correlation between these results and channel reach type.

Channel width measured from 1996 and 2000 aerial photography revealed negligible change in channel position or width. There is no evident downstream trend in channel width (Fig. 6). Channel meander wavelength measured from topographic maps and both 1 year and 500 year floodplain width measured from FEMA floodplain data decrease downstream.

Surficial geology varies over the study area. At Rkm 58, the channel crosses a fault and there is a distinct change in the surficial geology (Fig. 5). Upstream of Rkm 58, the channel meanders across broad fluviatile terrace deposits bounded by the Upper Member of the Glen Rose Limestone. Downstream of Rkm 58, the channel cuts into the lower member of the Glen Rose Limestone, Hensell Sand, and Cow

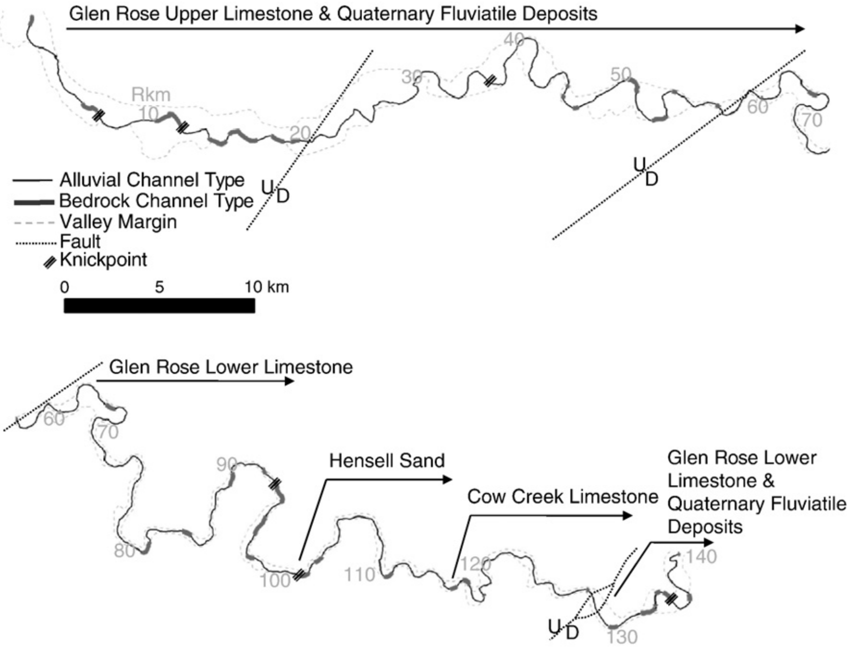

Fig. 5. Alluvial and bedrock channel type, valley width, geologic units, and the location of faults and knickpoints in the study reach.

Table 1
Comparison of physical properties of alluvial and bedrock reaches in the upper Guadalupe River.

	Alluvial reaches	Bedrock reaches	Total study reach
Channel coverage (km)	118	22	140
Percent of total channel coverage	84	16	100
Average reach slope	0.0023	0.0090	0.0045
Average reach length (channel widths)*	124	28	72
Standard deviation	179	42	134
Median	71	20	29
Average transition spacing (channel widths)	148	140	73
Standard deviation	180	167	134
Median	92	91	29
Average channel width (m)*	26	28	26
Standard deviation	9.0	8.9	9.0
Median	25	27	25
Average 1 year floodplain width (m)*	528	476	520
Standard deviation	417	349	407
Median	419	380	419
Average 500 year floodplain width (m)*	668	707	674
Standard deviation	472	429	466
Median	487	680	524
Average reach sinuosity*	1.25	1.09	1.16
Standard Deviation	0.32	0.09	0.30
Median	1.12	1.06	1.07

Measurements for the entirety of the study reach are recorded in the far right column. Statistically significant differences in feature measurements between alluvial and bedrock channel types are noted by * for 0.01 confidence level.

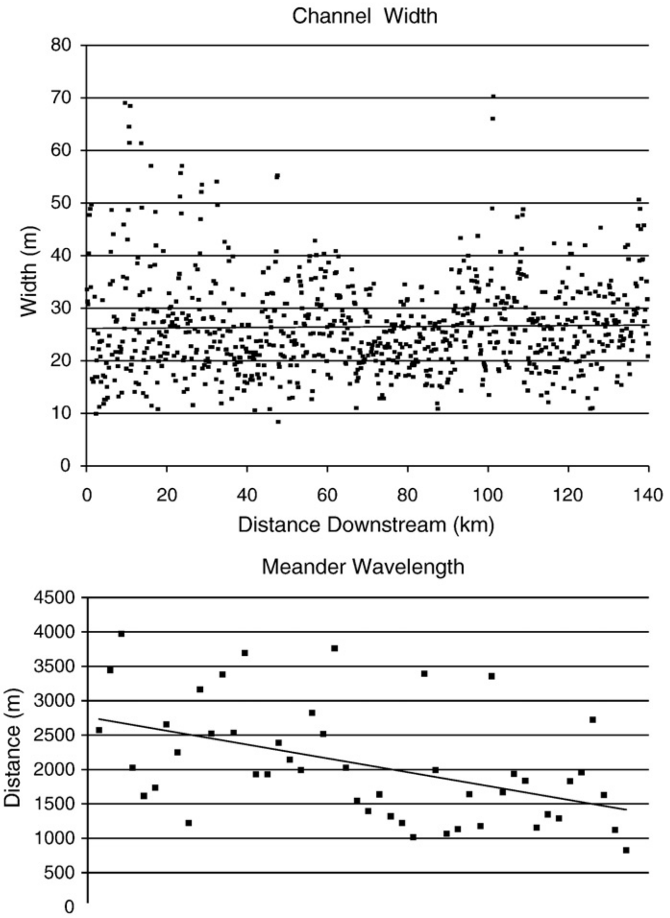

Fig. 6. Channel width remains constant in the study reach while meander wavelength decreases downstream.

Creek Limestone (Fig. 5). The floodplain is wider in the upstream section than it is downstream of Rkm 58 where the channel migrates across a much narrower valley width (Fig. 5).

Half of the observed bedrock reaches are downstream of Rkm 58 and occur where the outsides of channel meanders are in contact with the valley side. These outer bends are characterized by steep bluffs and gentler sloped inner bends where large point bars have been deposited. The one exception is a 2.5 km straight reach beginning at Rkm 95 where the valley is locally constricted by steep bluffs on both sides of the channel and the channel is incised into the narrow valley ~20 m, greater than the rest of the study reach (~5–10 m).

The bedrock reaches observed upstream of Rkm 58 have a different spatial pattern than the downstream section. Bedrock reaches upstream of Rkm 58 occur on the outside of a few bends, but also occur mid valley, and in straight reaches that are not constricted. In this section, bedrock reaches tend to be only slightly incised (1–2 m) into both bedrock and the overlying alluvium, or are bedrock floored and lined with gravel terraces or banks composed of vegetated alluvium (Figs. 2, 3, 7).

Table 2
Comparison of bar properties in alluvial and bedrock reaches in the upper Guadalupe River.

	Alluvial reaches	Bedrock reaches	Total study reach
Number of bars	**203**	**40**	243
Bars per kilometer	**1.72**	**1.81**	1.74
Percent coverage by bars	**22**	**15**	17
Average bar length (m)	**96**	**109**	102.5
Standard deviation	**105**	**98**	103
Median	**66**	**67**	67
Percent of total bars	**84**	**16**	100
Bar spacing (channel widths)*	**23**	**117**	38
D50 (mm)	**32**	**30**	32
Standard deviation	**13**	**11**	13
D84 (mm)	**67**	**73**	68
Standard deviation	**28**	**25**	28

Measurements for the entirety of the study reach are recorded in the far right column. Statistically significant differences in feature measurements between alluvial and bedrock channel types are noted by * for 0.01 confidence level.

The bedrock reaches upstream of Rkm 58 occur in two main groups: just upstream of Rkm 58 and just upstream of Rkm 21 where the channel flows across faults (Fig. 5). Both groups of bedrock reaches have low stepped translational knickpoints at their upstream-most ends near the fault crossing. These faults are at the most western extent of the Balcones Escarpment Fault Zone at this latitude. In addition to the grouping of bedrock reaches just upstream of these faults, spatially discontinuous strath and alluvial terraces, and the presence of knickpoints at the upstream end of the bedrock reach group suggest a history of phased incision into the valley (Fig. 8). The faults cause 0.5–1 m displacements and lower the local base level enough to initiate knickpoint retreat which translates the adjustment to base level change upstream. There is no evidence of scarps in the channel bed or banks, which suggests that erosion has equaled the amount of vertical displacement at the fault and is further geomorphological evidence for upstream translation of changes in base level.

The fault pattern is more complex in the downstream end of the study reach. There are two faults with a drag block between at Rkm 127 where the river crosses the fault (Fig. 5). Downstream of Rkm 127, the valley and floodplain widen entering the backwaters of Canyon Lake Reservoir. We observe some knickpoints between Rkm 58 and 127, and it is likely that phased incision has occurred in this reach, although it is not as geomorphically evident as in the section upstream because of differences in lithology. The fluvial response to base level changes is likely more complex closer to the Balcones Escarpment because there are more faults and the complexity in the fault pattern increases.

Fig. 7. Examples of knickpoints in the study reach.

Dams, roads, tributary confluences, large woody debris, and individual (or groups of) boulders >1 m in diameter mapped in the field were carefully checked for evidence of local control on channel reach type. The large wood observed consisted of either single felled trees parallel to and against the channel banks or riparian flood debris that does not obstruct flow or sediment transport enough to affect the channel boundary. The single exception is where woody debris is trapped behind a low bridge. In one location, the channel has avulsed around a bridge that has trapped enough large wood to obstruct flow through the opening under the bridge (Fig. 9). Individual boulders or groups of individual boulders did not affect channel boundary type because the boulders were not clustered close enough together to trap sediment and did not extend across the channel width. Of the 41 tributaries in the study reach, only one tributary at Rkm 97 had a concurrent channel boundary change from alluvial to bedrock directly downstream of its confluence with the main channel. No stream gage exists on this tributary and, therefore, no quantitative evidence to establish that the channel transition results from increased flow at the location, but circumstantial and morphological evidence indicate that the channel type is forced at this location.

Many of the road crossings in the study area are elevated bridges well above the elevation of the water surface even at high flows and have no observed effect on the geomorphology of the river. Of the 29 road crossings mapped in the study reach, six are low water crossings where the elevation of the road is the same, or built on top of, the channel bed and water flows over the top of the road. Four road crossings trap enough sediment to cause scour downstream, locally forcing the boundary type from alluvial upstream to bedrock downstream. Two small weir type dams also trap sediment resulting in scour down to a flat plane of bedrock downstream. The longitudinal extent of scour to bedrock downstream of roads and dams in the study reach ranges from 0.5–2 km. As mentioned in the previous paragraph, at one location, wood is trapped beneath a low bridge and the channel has avulsed around the entire structure.

Fig. 8. Examples of strath terraces in the study reach.

5. Discussion

The spatial distribution of bedrock reaches in the Upper Guadalupe River is controlled regionally by structural geology and locally by channel intersection with the valley margins and obstruction disturbances such as dams and low water road crossings. Bedrock reaches occur where lithology controls the lateral extent of channel migration resulting in a narrow valley, upstream of small regional faults that represent a change in local base level, and downstream of dams and road crossings.

Surprisingly, unlike other studies that compare alluvial and bedrock characteristics, (Montgomery et al., 1996; Montgomery and Buffington, 1997; Massong and Montgomery, 2009) we find little difference in slope between alluvial and bedrock reaches and no correlation between slope breaks and channel type transitions. The channel slope threshold relationship has been used to successfully predict the occurrence of alluvial or bedrock channel type in other studies on mixed alluvial bedrock rivers (e.g. Howard, 1980; Montgomery et al., 1996; Montgomery and Buffington, 1997; Sklar and Dietrich, 1998; Massong and Montgomery, 2000). A likely explanation for our study's divergence from others is that slope threshold relationships do not account for variations in discharge, peak discharges, or lithology (Pazzaglia et al., 1998), all of which are important in forming the morphology of central Texas Rivers. It is also possible that small differences in slope between alluvial and bedrock reaches are undetectable with the method used here. As we interpret the results of the techniques used in this stage of the research, with respect to comparisons between alluvial and bedrock reaches, our results are more comparable to Ashley et al. (1988) than to other studies even though many of our reaches are incised into small bedrock canyons while their study reach was bedrock floored with alluvial banks.

In agreement with previous studies (Montgomery et al., 1996; Montgomery and Buffington, 1997; Massong and Montgomery, 2000; Lancaster and Grant, 2006), we find that local disturbances affect the distribution of bedrock reaches. The weir type dams and low water-crossing roads in the Upper Guadalupe River are analogous to large wood and debris in other studies in that they obstruct the channel and influence hydraulic processes and sediment transport, trapping sediment upstream and resulting in scour downstream. In two instances, we observed a dam or low water crossing in aerial photography from 1996 that had been removed or partially removed by the time of field work in 2005–06. In both instances, sediment deposits that were observed behind the structure in aerial photography were not observed in the field and there was no evidence of a channel type transition. These results are analogous to observations by Massong and Montgomery (2000) in that there is a relatively rapid response following obstruction removal.

Regional lithology and structure create two distinct patterns of bedrock reach distribution and characteristics in the Upper Guadalupe River. Variation in lithology result in variation in valley characteristics that largely control the spatial pattern and characteristics of bedrock reaches such that bedrock reaches generally occur on the outside of channel meanders in the narrow valley downstream of Rkm 58. Differences in lithology and erodibility have been observed by others to result in variations in channel type and bedrock exposures in mixed alluvial bedrock channels (e.g. Howard and Kerby, 1983; Howard, 1994; Stock and Montgomery, 1999; Massong and Montgomery, 2000;

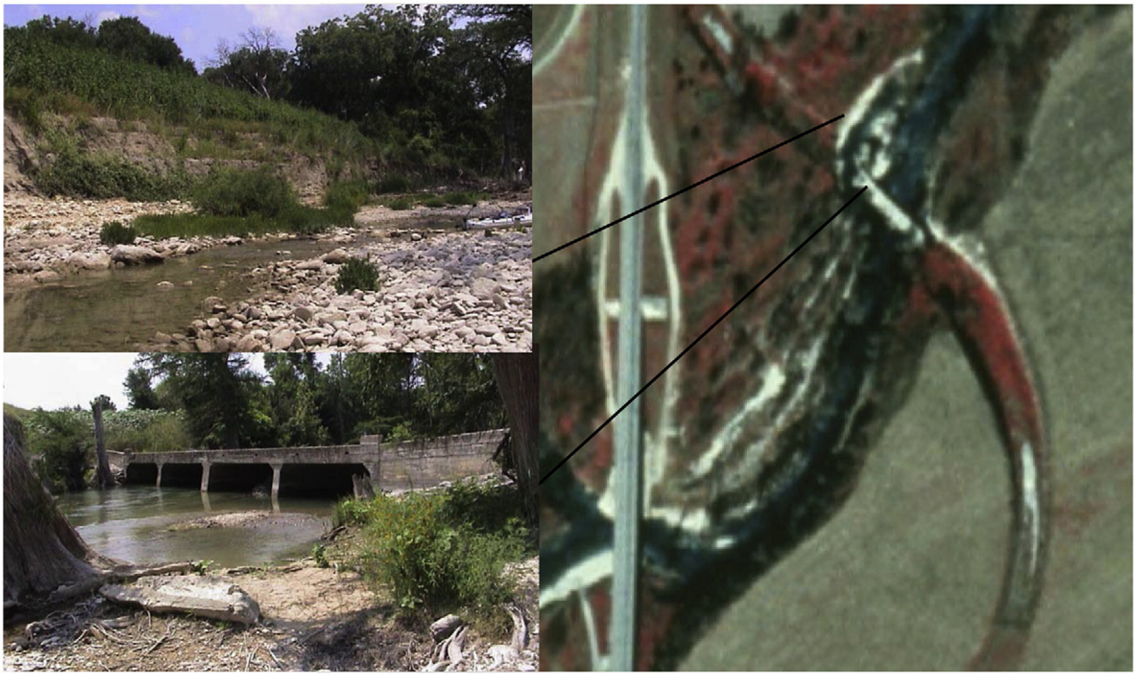

Fig. 9. The pre-existing low elevation road crossing was left in place after the new bridge was built. Wood and flood debris is trapped in the bridge openings and the channel is reworking avulsing around the old bridge. The new channel is shown in the photos on the left of the aerial photo.

Whipple et al., 2000; Whipple and Tucker, 2002; Tooth et al., 2004; Jansen, 2006; Sklar and Dietrich, 2006).

The characteristics and pattern of bedrock reaches resulting from regional structure is different upstream of Rkm 58 than in the downstream narrow valley section in that extensive sections of bedrock reaches occur upstream of currently inactive faults. The groups of bedrock reaches are characterized by translational knickpoints at their upstream extents and by spatially discontinuous strath and alluvial terraces downstream. These groups of bedrock reaches create two large knickzones, each composed of a series of short bedrock reaches that represent propagating base level fall upstream. Knickpoints have been described as a response to base level disturbance that migrate upstream (Howard et al., 1994; Whipple and Tucker, 1999; Whipple et al., 2000; Bishop et al., 2005; Crosby and Whipple, 2006). The two bedrock dominated knickzones represent the channel adjustment to base level disturbance that occurred in association with the Balcones Escarpment Fault Zone. However, the timing of response to changes in base level on the Upper Guadalupe River is complex as the system adjusts to small local faults, catchment wide shifts as the Guadalupe River incised the Balcones Escarpment, and changes in sea level in the Gulf of Mexico.

It is important to note the role of ground water interaction and chemical weathering on the geomorphology of the Upper Guadalupe River. The substrate is almost entirely limestone and is highly susceptible to ground water–surface water interaction and chemical weathering, which may account for more erosion than the mechanical means alone. Sapping is evident and decreases the stability of canyon walls, increasing the propensity for blockfall and eventual valley widening. The ground water is supercharged with calcium carbonate in many alluvial sections, and cut banks appear to be stabilized by the formation of calcrete from calcium deposition by ground water as ground water levels fluctuate. Although the geochemical denudation rate of the Glen Rose Limestone at the Guadalupe River is only 25 mm/Ka (Veni, 1997), the effect of geochemical weathering increases the propensity towards detachment by mechanical means. Abrasion scars were observed in areas where geochemical weathering at low flows increases the friability of the channel bed. In a few alluvial reaches, gravel and cobbles on the channel bed were found to be so weathered that they easily broke apart. The combination of geochemical and mechanical processes in karst systems is likely to account for the removal of more material and landscape denudation in fluvial systems than mechanical means alone.

6. Conclusions

In the Upper Guadalupe River, the spatial distribution of bedrock channel reaches is the result of a combination of local disturbances, interaction of the channel and valley sides, variation in lithology, and regional structural control. In comparing bedrock and alluvial channel reaches, we find a large degree of parallelism, particularly with respect to the distribution of gravel bars, surface grain size distributions of bars, and channel slope and width. Observations made on the Upper Guadalupe River in this study and observations of other central Texas rivers that flow across the Balcones Escarpment indicate that the fluvial systems have adjusted to changes in base level associated with the Balcones Escarpment Fault Zone by phased incision into alluvial sediment and the underlying bedrock, essentially shifting from a fully alluvial river to a mixed alluvial bedrock river. However, the rate and timing of incision is unknown.

While the understanding of bedrock incision and mixed alluvial bedrock channels has increased in recent decades, little work has been done on long term timing of incision or on the role of geochemical processes and mechanical–chemical interaction. More field based studies of gravel mantled streams and mixed alluvial bedrock streams can elucidate bedrock incision models by providing natural analogues to experimental studies and improve understanding across a range of environmental settings. Studies of local conditions as well as regional patterns of structure and lithology that may influence channel type are important to understanding fluvial processes and controls operating at different scales. Work in geochronology can add understanding of the temporal aspects to bedrock incision, especially where incision rates are slow and the possibility of episodic incision exists.

Our future work will employ geochronologic techniques to compare rates of incision upstream and downstream of the Balcones

Escarpment in order to establish differences in timing and between fluvial response to sea level and to the Balcones Escarpment Fault Zone. This work will allow comparisons of base level connectedness across the escarpment which ultimately controls landscape evolution between the Great Plains and the Coastal Plain.

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