Stream piracy, tilting, and incision in the Upper Arkansas River basin: Evidence from High Plains terraces

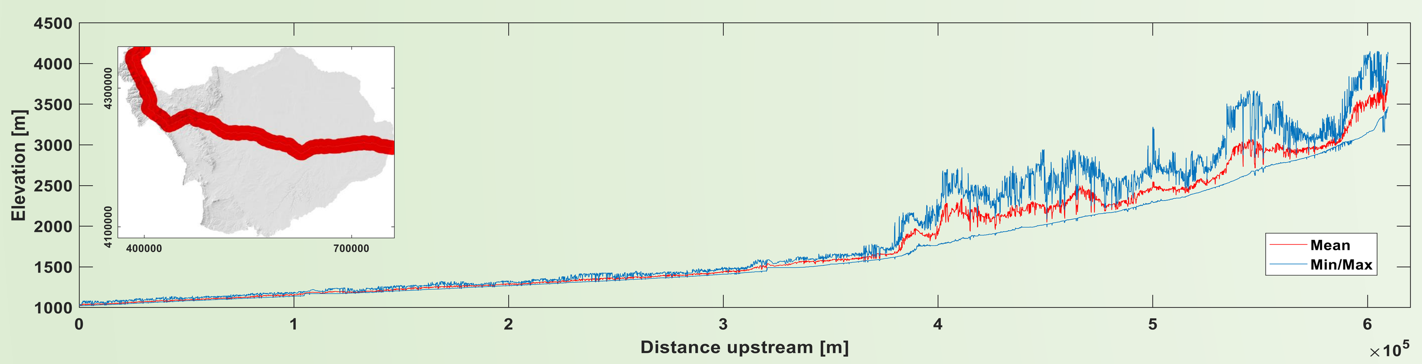
Eyal Marder and Sean F. Gallen

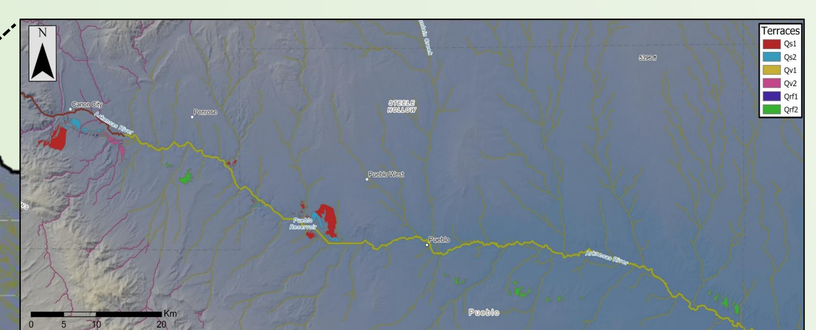
Department of Geosciences, Warner College of Natural Resources, Colorado State University

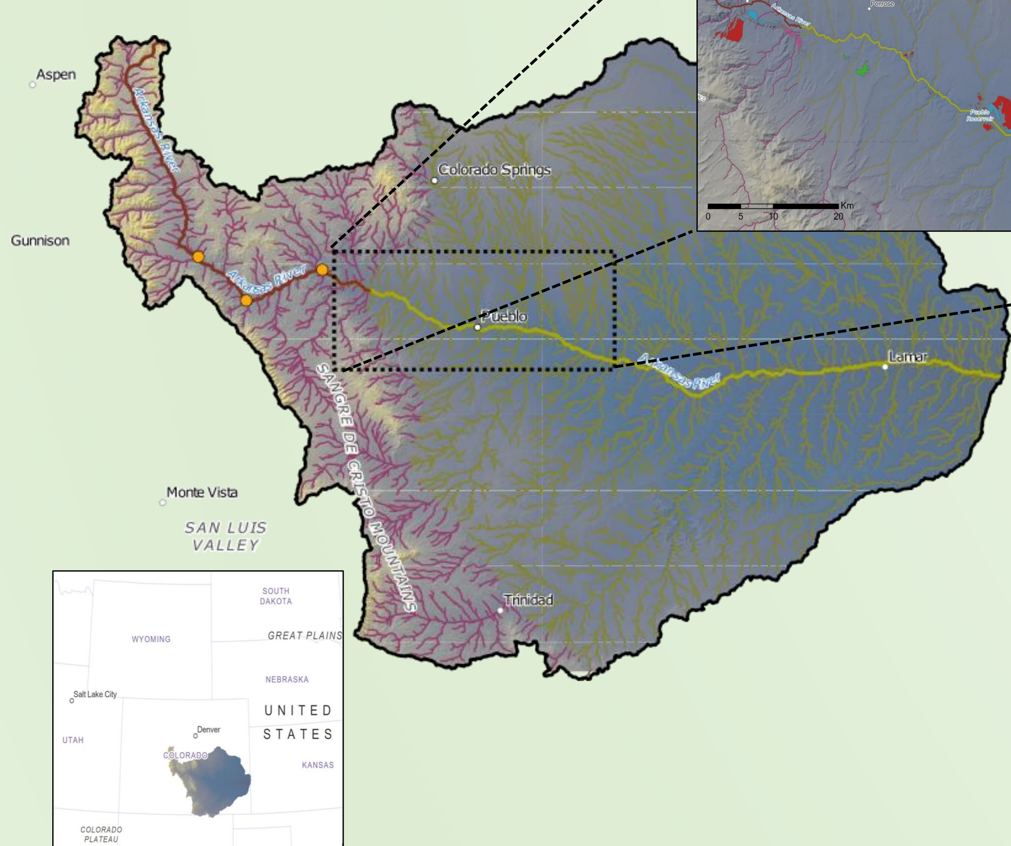
WARNER COLLEGE OF NATURAL RESOURCES
COLORADO STATE UNIVERSITY

Abstract

The Upper Arkansas River shows a peculiar map-view drainage pattern with a main stem displaying several nearly 90 degree turns that are thought to represent points of late Cenozoic stream capture events; however, the timing, magnitude, and drivers of stream capture and associated drainage reorganization are poorly understood. This knowledge gap is largely due to poor preservation of geomorphic markers in the Upper Arkansas drainage basin where most studies of river capture have focused, and limited diagnostic source area bedrock units that make traditional provenance analysis challenging. Previous models invoke regional tilting due to the Rio Grande rifting and/or recent dynamic topography as the mechanism driving drainage reorganization in the Upper Arkansas, yet direct supporting evidence is generally lacking. Here we present a new approach to unravel and quantify the recent drainage reorganization of the Upper Arkansas using river terraces preserved in the High Plains and a one-dimensional numerical river incision model. Using hypothesized points of river capture near the towns of Salida, Coaldale, and Canon City, we simulate the downcutting response of the Arkansas River to instantaneous drainage area gain and compare the model results to incision patterns recorded by the High Plains terraces. Our preliminary results suggest that large magnitude river capture events explain much of the incision history of the Arkansas basin in the High Plains. Future modeling, field, and geochronology studies are aimed at untangling the relative role of stream capture versus hypothesized regional tilting on the incision history of the Arkansas River. The preliminary and future results will explore and improve understanding of the role of geodynamic tilting as a driver of drainage reorganization, as well as the impact of stream piracy on geomorphic archives, which are often used to constrain tectonic signals.







(Top) 10 Km wide valley swath profile of the Arkansas main stem (Bottom) The Arkansas drainage basin, divided to the Front Range/Rockies (hereinafter the "Front Range") (purple) and the High Plains (yellow). The hypothesized stream capture locations are marked (orange circles). (Inset) The High Plains Slocum (~240 Ka), Verdos (~640 Ka) and Rocky Flats (~1.4 Ma) river terraces.

Pebbles and boulders on top of a terrace north of Salida (Left) and Coaldale (Right). Previous studies suggested capturing and integration of the Upper Arkansas Valley during the Neogene, yet emphasized the difficulty in using traditional provenance to assess the capture history (Sak et al., 2005). In this study, we estimate capture locations on the Arkansas main stem based on river planform geometry and field observations.

Motivation

The Arkansas basin is in a transient state of adjustment, likely due to several high-magnitude stream capture events and possibly tilting from the Rio Grande Rift. The mechanisms and timing of capture are poorly constrained in this setting. Determining the timing and rates of drainage reorganization will aid in understanding recent sediment flux changes, biodiversity zonation, local tectonics, erosion rates, and hazard management in the Arkansas basin. The aim of this research is to address these exogenic processes, constrain the magnitudes and rates of landscape adjustment, and identify potential locations for detailed field study that are key to understanding the basin transient behavior.

Methods

In detachment-limited bedrock river systems, the temporal change of fluvial topography can be described as a function of the uplift (U) and incision rate (E), in which the later is a function of the basin drainage area (A), slope (S), and erodibility (K) (Howard, 1994):

$$\frac{dz}{dt} = U - KA^mS^n \quad (1)$$

At steady-state where erosion is balanced by rock uplift rate (U) :

$$S = \left(\frac{U}{K}\right)^{1/n} A^{(-m/n)} \quad (2)$$

The normalized steepness index, a metric where local channel steepness is normalized to upstream drainage area is defined as:

$$k_{sn} = \left(\frac{U}{K}\right)^{1/n} \quad (3)$$

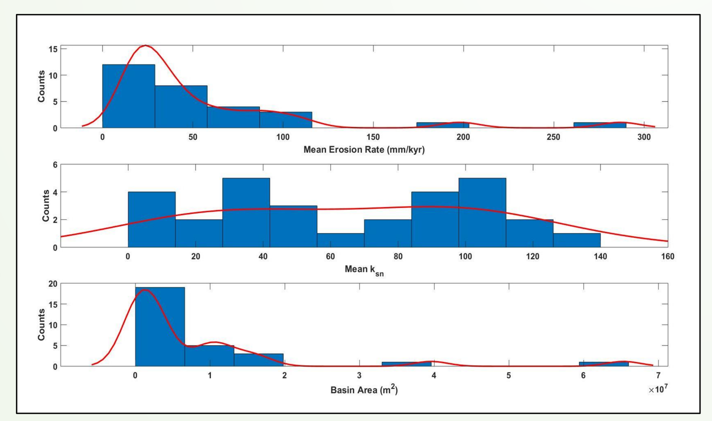
This parameter can be calculated using the transformed integrated parameter χ:

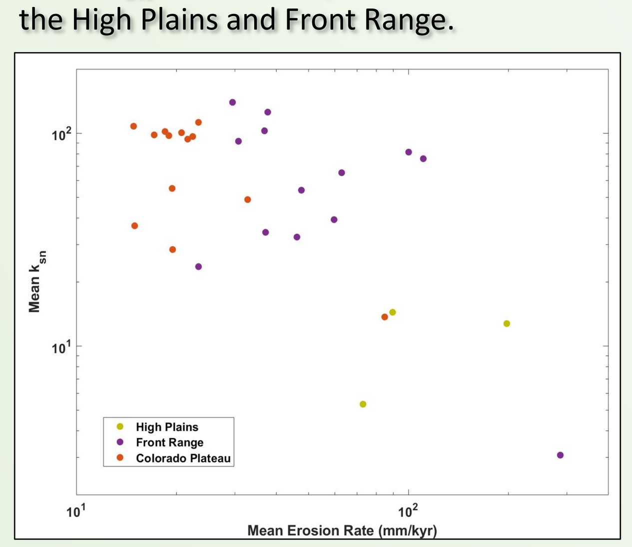
$$\chi = \int_{x_b}^{x} \left(\frac{A_0}{A(x')}\right)^{\frac{m}{n}} dx' \quad (4)$$

Through regression of elevation and χ data (e.g. the integral of EQ 2):

$$z(x) = z(x_b) + k_{sn} \cdot \chi \quad (5)$$

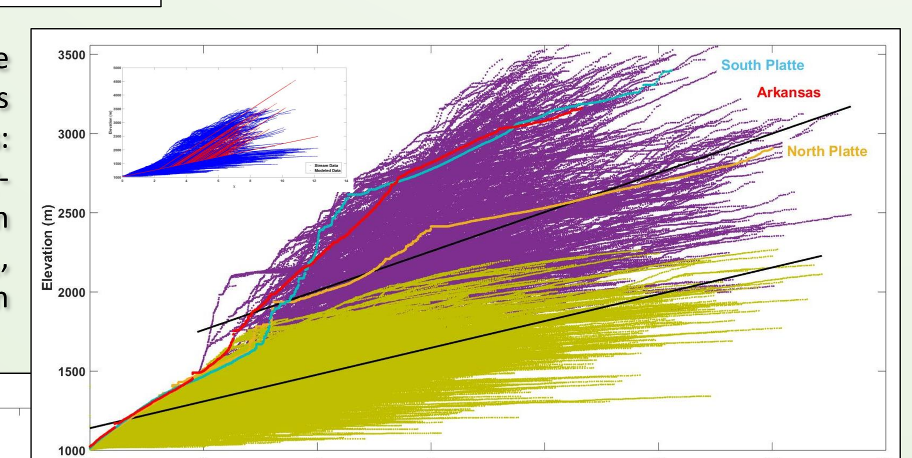
To model capture and tilting scenarios in the Arkansas basin, empirical parameters of the stream power model (K, n, m) need to be constrained. We assume steady state locally, a mean concavity of 0.5 and EQ 3, we use previously published erosion rates and mean k_{sn} in an attempt to infer K, n, m for the High Plains and Front Range.

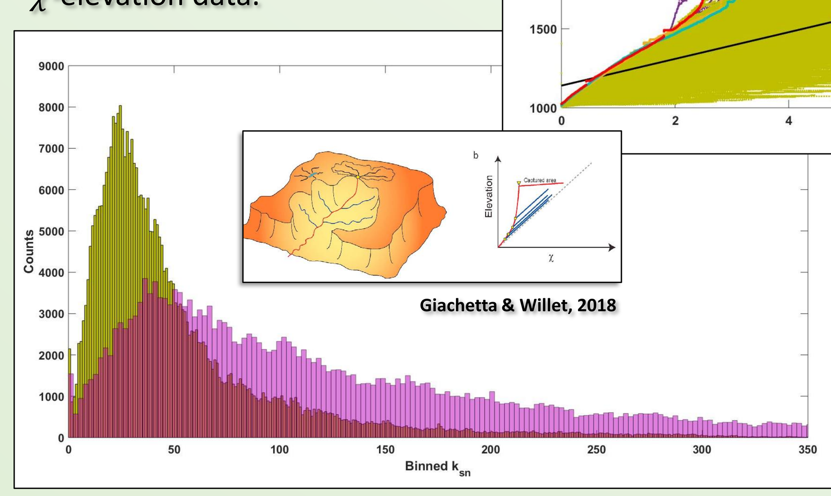




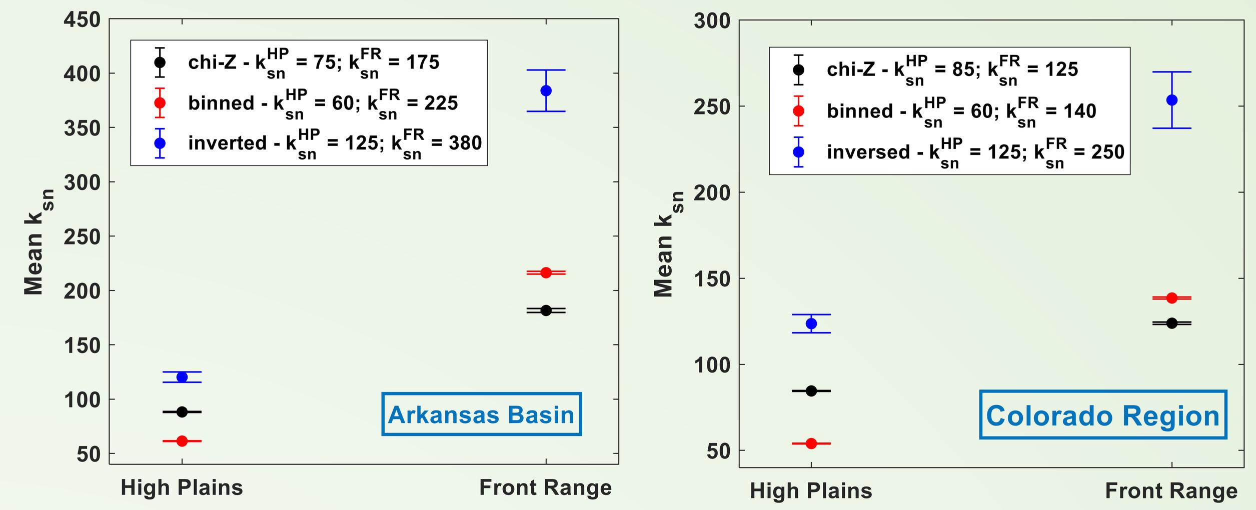
However, compilation of the erosion rates and k_{sn} data (Dethier et al. 2014) showed a large scatter among different physiographic domains. This scatter was likely due to small basin sizes sampled and the measurements affected by stochastic erosion processes (e.g. landslides) (Niemi et al., 2005; Yanites et al., 2009). As such, this data is not useful in constraining the stream power model.

We calculated mean k_{sn} for the Front Range and High Plains using three different methods: (right) a linear regression of χ-elevation data, (bottom) an average of a mean binned k_{sn}, and (upper inset) linear inversion χ-elevation data.





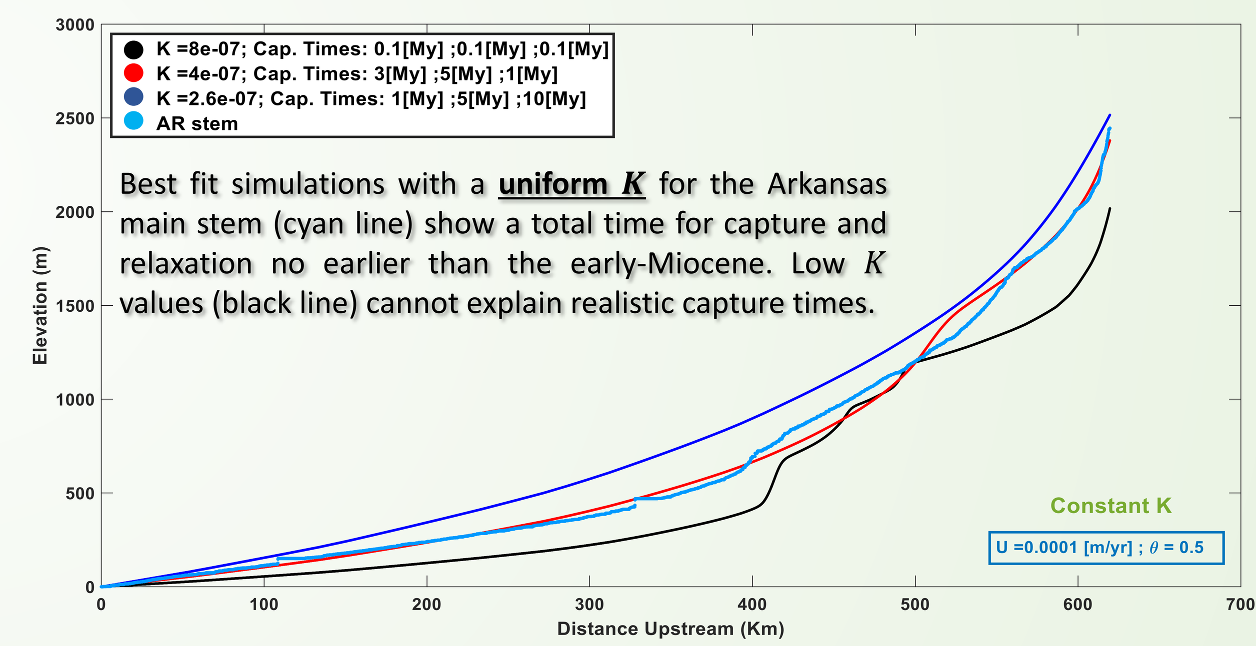
The χ-profiles of the Arkansas and South Platte main stems show steep profiles that deviate from the regional trend. This systematic shift is consistent with expectations for recent drainage area gain due to river capture (Willett et al., 2014).



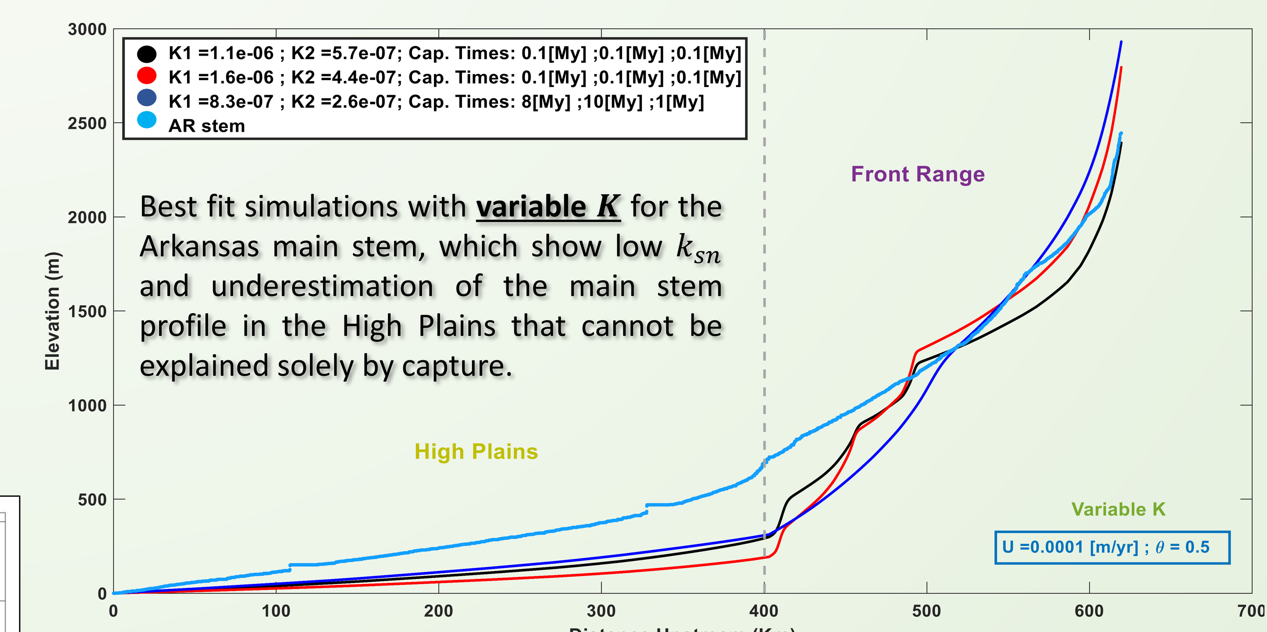
Mean k_{sn} results from the three different methods for the Arkansas basin (Left) and the entire Colorado region (Right). Assuming that these values are representative of the steady-state geometry of the river profiles (which we acknowledge as an oversimplification) and that $n = 1$ (an assumption we will vet in later studies), we can use estimates of incision rates in the region (0.05 – 0.1 mm yr^{-1}) to infer the erodibility K from k_{sn}.

One-dimensional River Profile Evolution from Capture

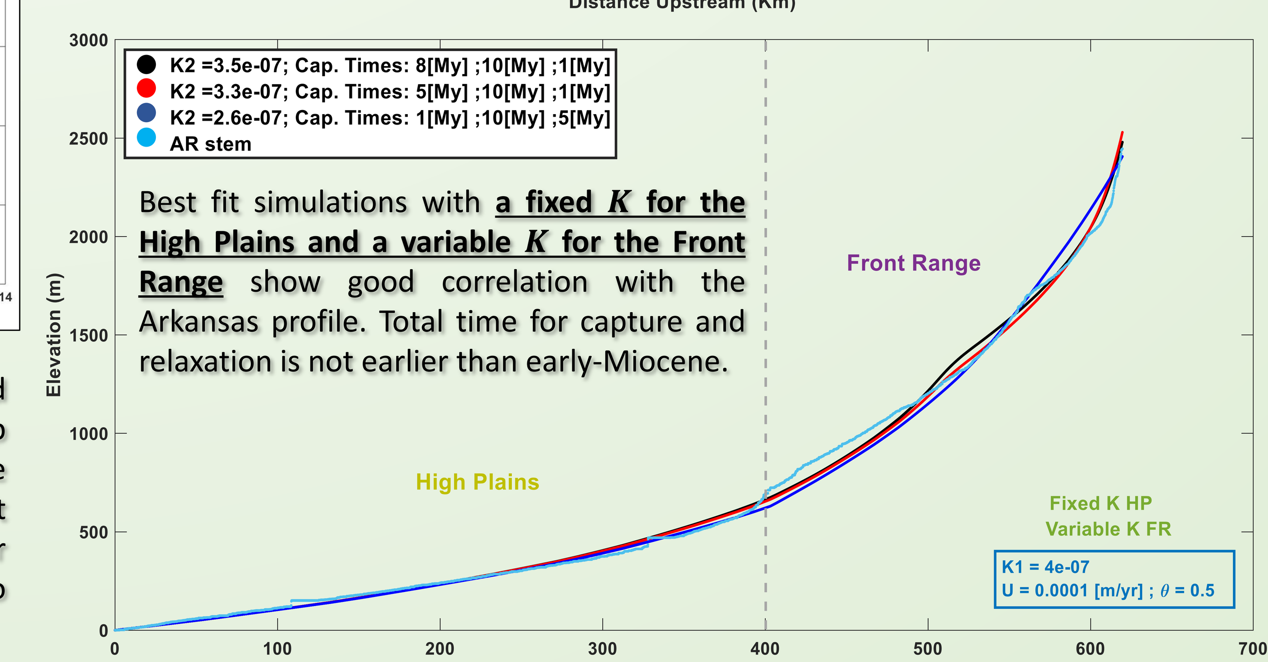
Using our estimated capture locations and inferred parameters, we simulate river profile evolution using a 1-D detachment-limited incision model (EQ. 1) in response to sequential capture at three locations. To estimate the timing of capture, we used a brute-force parameter search and tested different scenarios: (1) capture for a uniform K along the Arkansas, (2) same as (1) but different K for the High Plains and Front Range, (3) same as (2) but with a fixed K for the High Plains and a changing K for the Front Range.



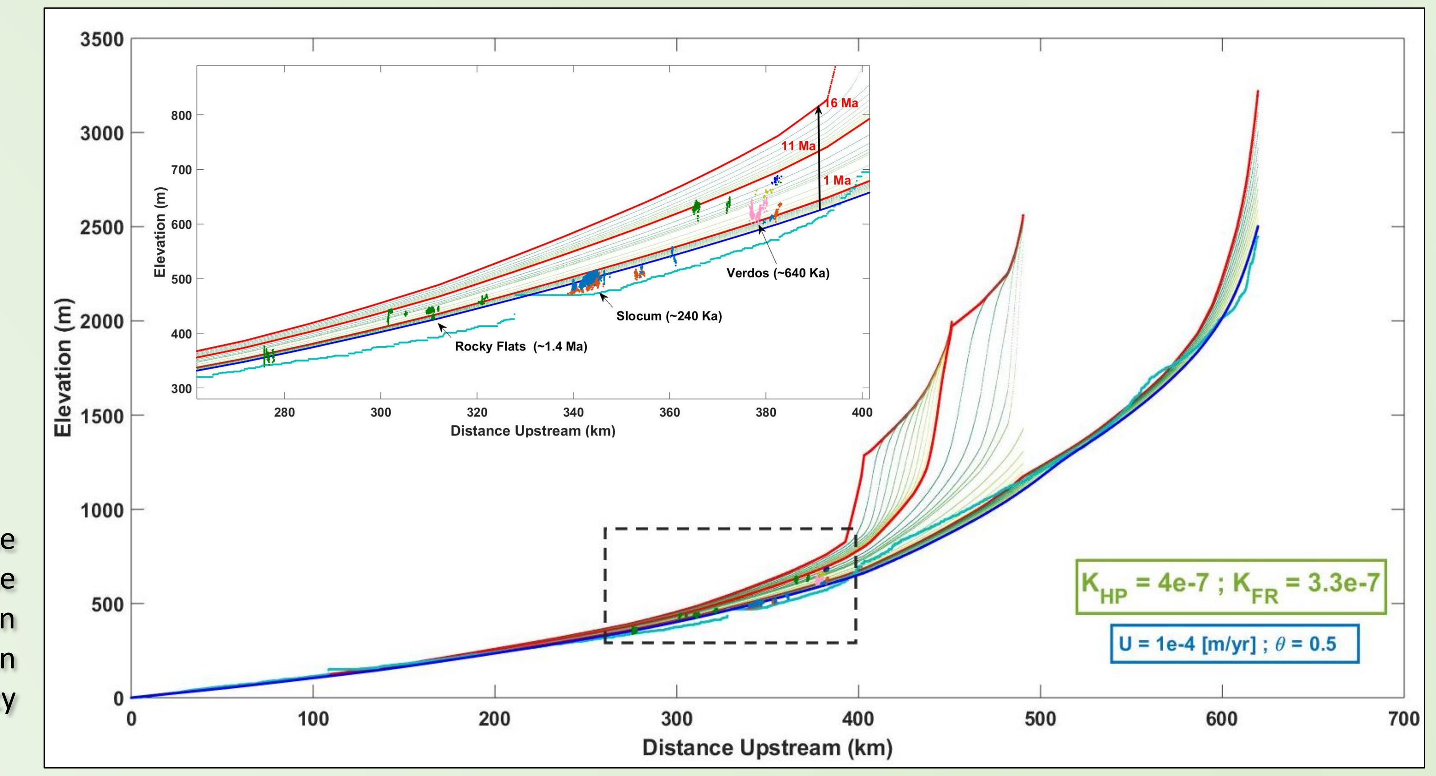
Best fit simulations with a **uniform K** for the Arkansas main stem (cyan line) show a total time for capture and relaxation no earlier than the early-Miocene. Low K values (black line) cannot explain realistic capture times.



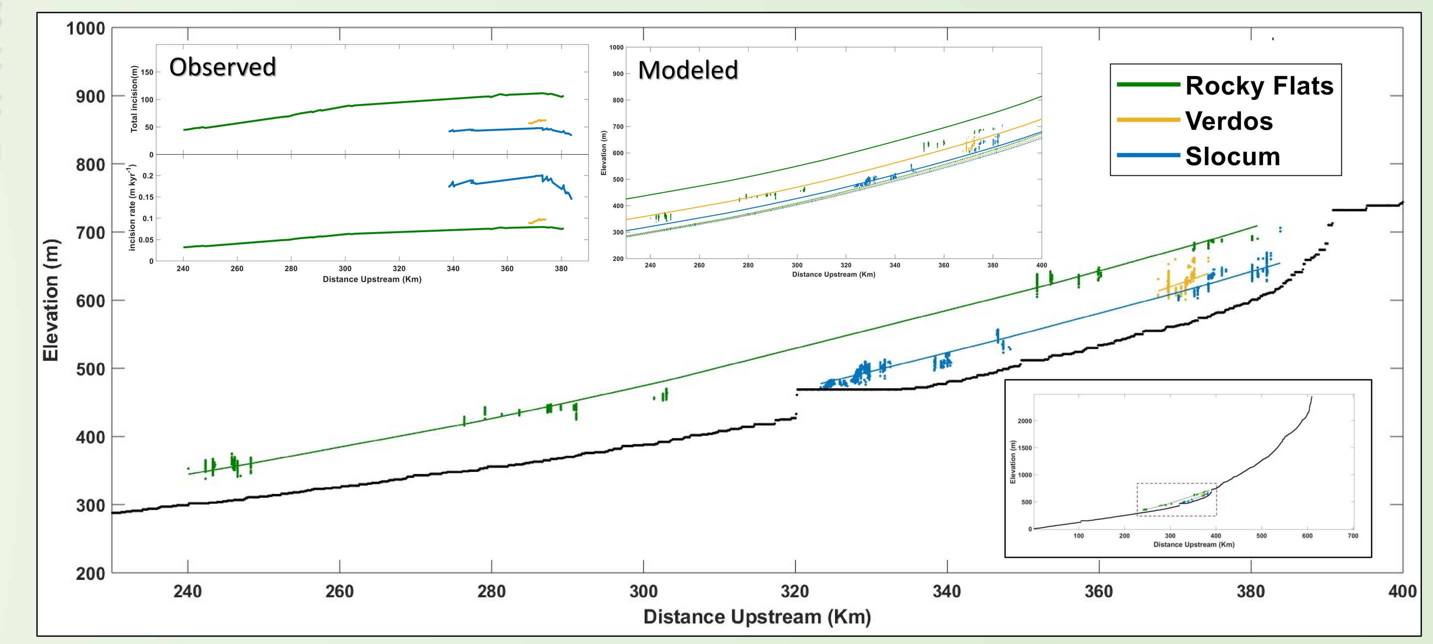
Best fit simulations with **variable K** for the Arkansas main stem, which show low k_{sn} and underestimation of the main stem profile in the High Plains that cannot be explained solely by capture.



Best fit simulations with **a fixed K for the High Plains and a variable K for the Front Range** show good correlation with the Arkansas profile. Total time for capture and relaxation is not earlier than early-Miocene.



A 1-D incision full simulation with changing K between the High Plains and the Front Range, and with mapped river terraces overlain. There is a mismatch between the observed and model profile in the High Plains, suggesting that some parameter adjustments are needed. However, the overall pattern of incision depicted by the terraces is consistent with our model.



(Lower inset and main) The High Plains terraces and regressions through each terrace level. (Left upper inset) Total incision and incision rates along the High Plains terraces from the regressions. (Right upper inset) 1-D simulations of "terraces" with (solid lines) and without (dashed lines) uplift. The modeled "terraces" exhibit a slight "fanning" pattern associated with capture that is less pronounced relative to the observed terraces profiles. This difference can be explained by regional tilting not accounted for in our model (e.g. McMillian et al, 2006; Willet et al., 2018).

Conclusions and Future Work

Our preliminary result show that k_{sn} is systematically higher in the Front Range/Rockies relative to the High Plains, suggesting a major change in erodibility across the physiographic boundary. Existing k_{sn} and erosion rate data from the region are insufficient to constrain stream power parameters. The 1-D stream capture incision models can partly explain the transient river profile of the Upper Arkansas River, but more research is needed to better the model misfits and better constrain model parameters. Future work will include quantifying erosion and incision rates along the Arkansas main stem (^{10}Be, OSL), and documenting hypothesized differences in erodibility (e.g. Schmidt Hammer and fracture density measurements) among different rock units in the study area.

References

- *Dethier, D. P., Ouimet, W., Bierman, P. R., Rood, D. H., & Balco, G. (2014). Basins and bedrock: Spatial variation in 10Be erosion rates and increasing relief in the southern Rocky Mountains, USA. Geology, 42(2), 167-170.*
- *Howard, A. D. (1994). A detachment-limited model of drainage basin evolution. Water resources research, 30(7), 2261-2285.*
- *Giachetta, E., & Willett, S. D. (2018). Effects of river capture and sediment flux on the evolution of plateaus: insights from numerical modeling and river profile analysis in the upper Blue Nile catchment. Journal of Geophysical Research: Earth Surface, 123(6), 1187-1217.*
- *McMillan, M. E., Heller, P. L., & Wing, S. L. (2006). History and causes of post-Laramide relief in the Rocky Mountain orogenic plateau. Geological Society of America Bulletin, 118(3-4), 393-405*
- *Niemi, N. A., Oskin, M., Burbank, D. W., Heimsath, A. M., & Gabet, E. J. (2005). Effects of bedrock landslides on cosmogenically determined erosion rates. Earth and Planetary Science Letters, 237(3-4), 480-498.*
- *Sak, P. B., Leonard, E. M., Miller, S. R., Biscontini, A. J., & Jemison, E. (2005, October). Late Cenozoic drainage reorganization of the Arkansas River, central Colorado, and history of the Royal Gorge. In 2005 Salt Lake City Annual Meeting.*
- *Willett, S. D., McCoy, S. W., Perron, J. T., Goren, L., & Chen, C. Y. (2014). Dynamic reorganization of river basins. Science, 343(6175), 1248765.*
- *Willett, S. D., McCoy, S. W., & Beeson, H. W. (2018). Transience of the North American High Plains landscape and its impact on surface water. Nature, 561(7724), 528.*
- *Yanites, B. J., Tucker, G. E., & Anderson, R. S. (2009). Numerical and analytical models of cosmogenic radionuclide dynamics in landslide-dominated drainage basins. Journal of Geophysical Research: Earth Surface, 114(F1).*