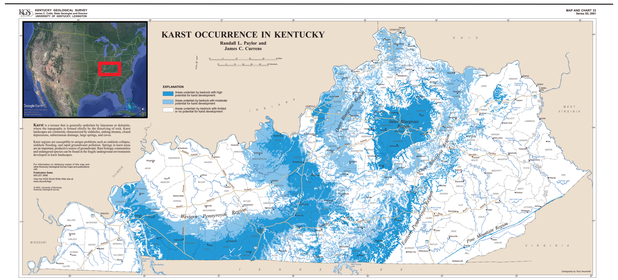
An (over-) simplified model of sinkhole plain development near multistory cave systems in dipping rocks

University of CINCINNATI

Dylan Ward (Dept. of Geosciences, University of Cincinnati, Cincinnati, Ohio, USA, dylan.ward@uc.edu)
Rai Bosch (AECOM, Cincinnati, Ohio, USA, Rachel.Bosch@aecom.com)

INTRODUCTION

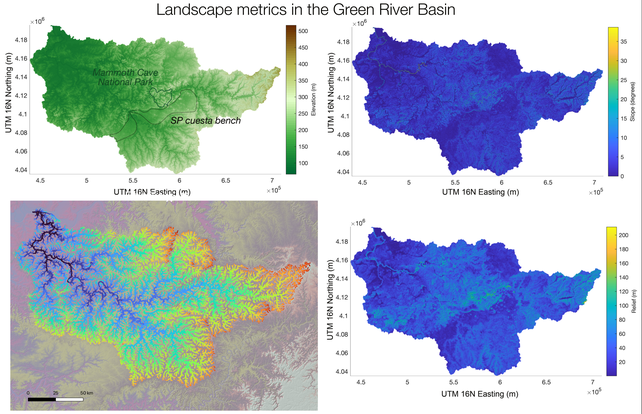


Why? Deciphering climate-driven and/or fault-driven incision episodes by the resulting landscape response is more difficult in karst areas, and in dipping and folded rock layers, and here we have both together.

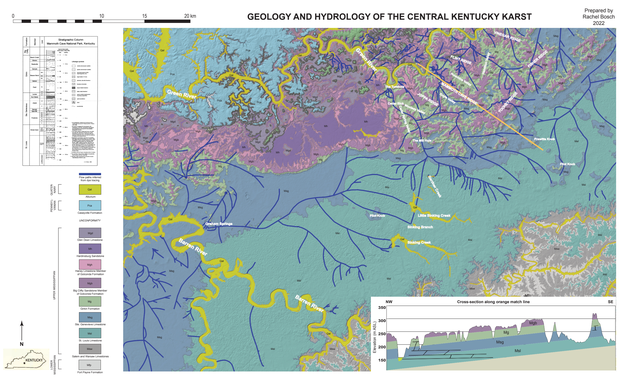
Do cuesta landforms respond similarly where their benches are connected to base level by karst conduits as to fluvial channels?

Do karst and fluvial modes alternate with periods of stablity and incision, or do they depend more on rock type, structural geology, and landscape preconditioning?

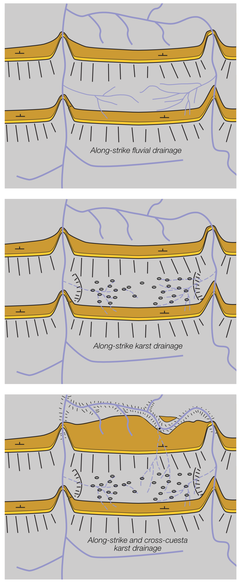
Landscape metrics in the Green River Basin

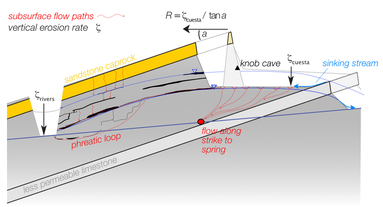


For example, relief in the Green River gorge adjacent to Mammoth Cave is higher than both upstream and downstream segments, possibly indicating drainage capture or fault activity through that reach. This could explain the greater dissection of the cuesta in that reach. Greater dissection could also result from the shallower dip of the caprock there relative to that downstream to the west. Topographic metrics indicate ongoing adjustment of fluvial networks related to incision through folded strata of differing resitstance to physical and chemical erosion, and the Ohio River base level is known to be unstable on glacial-interglacial timescales.



CONCEPTUAL MODEL



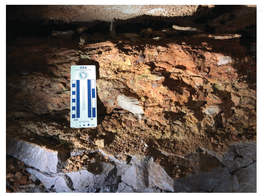


Levels in multi-level caves are often inferred to result from periods of stability of the base level river, such that larger and longer passages have more time to develop near the water table, or from changes in rock solubility as the base level river incises through layered stratigraphy. At Mammoth Cave, USA, cave passages that drain to the Green River are connected hydrologically along dipping bedding planes to the cuesta bench of the Dripping Springs Escarpment, which is retreating down dip toward the river. This escarpment is capped by chemically resistant and relatively impermeable sandstone.

The cuesta bench (i.e., the Sinkhole Plain; SP) hosts only dissected, deranged fluvial catchments that each drain to one of thousands of sinkholes connected through karst conduits under the cuesta escarpment to the Green River.

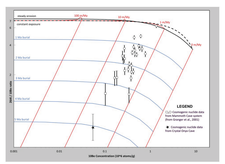
Cosmogenic geochronology

White (2009) and Kaufman and Braun (2001) suggest similar efficiencies of fluvial and karst denudation in the same drainage basin over long timescales, but base level changes and other disequilibrium processes must introduce lags in the response of different parts of the landscape. Our recent cosmogenic data suggest a reduced lowering rate for the Sinkhole Plain relative to incision of the Green River.



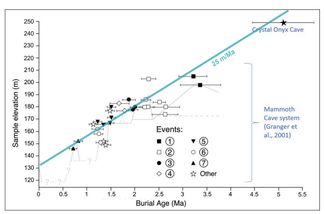
Crystal Onyx Cave

- Knob cave ~36 m above SP surface
- $^{26}Al/^{10}Be$ paired cosmogenic dating of cave-buried sediments
- Burial age of ~5.1 Ma, consistent with the chronology established for Mammoth Cave by Granger et al. (2001).
- SP lowering rate: 36 m / 5.1 My = **7 m/My**



Interpreted results from the Al/Be burial dating:

- Burial age of ~5.1 Ma is quite a bit older than Granger et al. (2001) dates for Mammoth Cave levels.
- Plots within the same range of inheritance / erosion rates, consistent with lowering rate based on cave elevation, above.
- A linear trend can be regressed through the Granger et al. (2001) data and the burial data from Crystal Onyx Cave. This yields **25 meters per million years for the long-term average Green River incision rate.**



Little Sinking Creek
Sinking stream with clastic sediment draining the Glasgow upland
^{10}Be cosmogenic erosion rate from stream sediments





- Cut bank material: basin-average erosion rate of **~4.4 meters per million years.**
- Modern sand: **~4.6 meters per million years.**

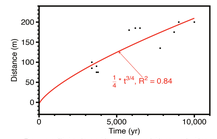
Rates are consistent with the knob cave results above that indicate ~7 m/My longer-term denudation on the SP.

ANALYTICAL MODEL

Across a series of incision and stability periods, the model tracks the position of the dip-projection of base level to the surface, the position of the cuesta escarpment, and the expected length of conduit development during periods of base level stability.

There are not simple general scaling relationships for conduit length growth rate vs time. Here we assume a superdiffusive but still sublinear function of time, supported by some prior modeling results.

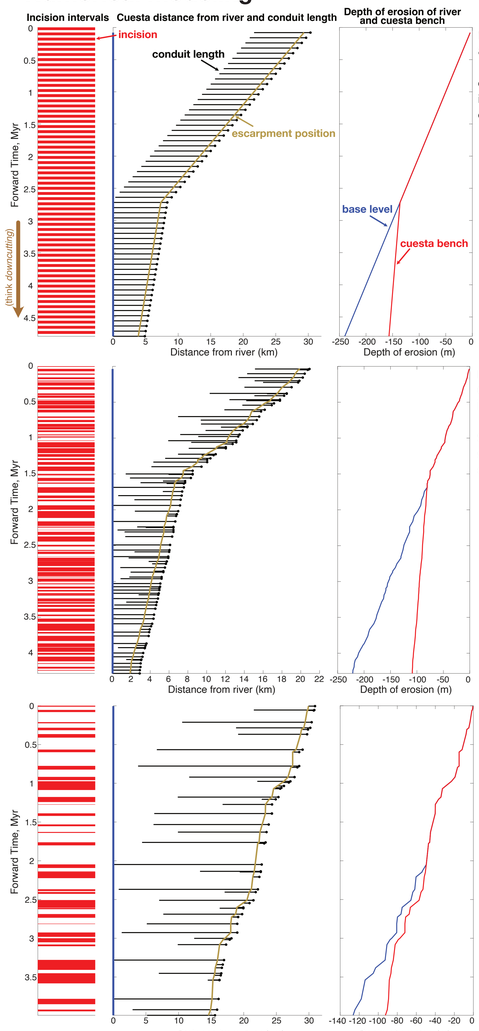
As the base level river in the model lowers, the fluvially-connected cuesta bench lowers at the same rate, and the cuesta escarpment retreats toward the river. If base level becomes stable for long enough, growing karst conduits break through and create efficient drainage of the bench through the subsurface. At this time, the model erosion rate on the bench is decreased as the surface streams become disconnected from each other and from base level.



Power fit to length vs. breakthrough time of developing conduits, extracted from simulations in Kaufmann and Romanov (2019). Possibly does not generalize.

Given a long enough period of incision, it is assumed that the fluvial network recaptures the karst plateau by knickpoint propagation, and erosion rates on the bench catch up with base level lowering.

Numerical modeling



regular intervals of incision and stasis

conduit growth is constant in each interval, so cumulative incision determines when a connection is made

random intervals, similar distribution of stasis and incision periods

Similar behavior to regular intervals, but slightly earlier connection due to timing of a sufficiently long stasis period

random intervals, stasis periods longer than incision periods

connection time is similar, but dynamics are different. longer priods of stasis favor connection, but shorter periods of incision slow escarpment retreat.

here we also see the effect of the fluvial recapture time, increasing cuesta erosion rates after a time of slower karst erosion

SYNTHESIS & CONCLUSIONS

The reduced erosion rate of the bench upon karst capture is supported by cosmogenic analyses in the Mammoth Cave area. This increases its relief above base level and slows cuesta retreat.

Both long periods of stablity and long periods of incision promote connection: by giving time for conduit development, and by promoting escarpment retreat, respectively.

For any given period of incision followed by a period of base level stasis, connection to the cuesta bench is likely if the ratio of conduit length to cross-cuesta distance exceeds unity.

$$\frac{\beta\, T_{stasis}^{\,3/4}}{D_{init} - \frac{\xi\, T_{incision}}{\tan\alpha}}$$

β scaling coefficient on conduit growth
D_{init} initial escarpment distance from river
ξ base level lowering rate during incision periods
α stratigraphic dip

The outcomes of these dynamics are path-dependent, such that the timing of connection of one cave level to the bench influences the likelihood and timing of future episodes of connection, and dictates the specific periods over which a sinkhole plain forms. Phillips (2018) also highlights field evidence for path-dependent evolution in fluviokarst.

The model is vastly oversimplified. Conduit network growth depends on many factors such as bedrock fracture width, distribution, and orientation, and water and rock chemistry. In developed cave systems, connection rates may be much more rapid once an existing connection exists. And the extrinsic landscape factors described in the introduction almost certainly overwhelm the simple systematics described here.

TLDR: None of this makes for easier interpretability of landscape signals in karst landscapes. But overall, cuesta evolution seems to work similarly whether the bench is fluvial or karst, and perhaps we have provided some organization of thought on karst development as drainages lower through deformed strata of different properties.



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