Beyond the Mean: Distributions of Cosmogenic Nuclide Concentrations in Transient Catchments

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Outstanding Student & PhD candidate Presentation contest

1 Abstract

1. We think many landscapes evolve according to [1]

$$\frac{\partial z}{\partial t} = U - KA^m \left(\frac{\partial z}{\partial x}\right)^n.$$

2. What are erodibility (K), area exponent (m), and slope exponent (n)? Often estimated using cosmogenic nuclide compilations from many basins, **but we don't know when that is valid!**
3. We show that these parameters can be derived from an individual basin, if we know the distribution of cosmogenic nuclide concentrations (Figure 1)!

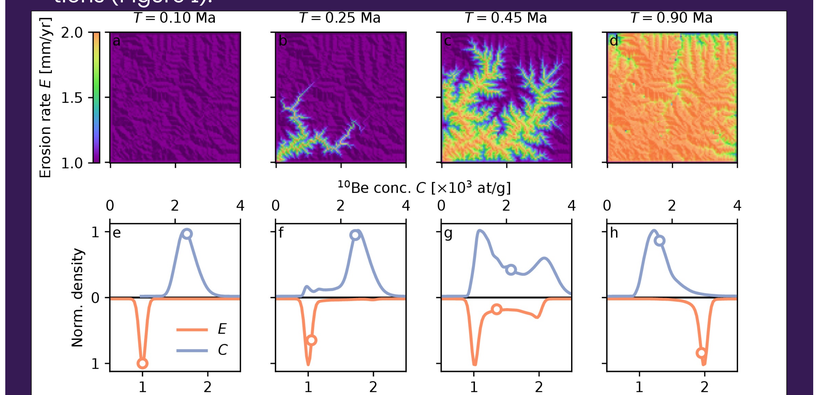


Figure 1: Results of the synthetic landscape evolution model. (a–d) Erosion rates at different time-steps throughout the model run. Note that there is a single outlet in the lower left corner of the model grid. (e–h) KDEs of modelled erosion rates (orange), and ^{10}Be concentrations. (Weighted) means are highlighted with circle markers.

2 Synthetic Playground

- **Idea**: Evolve a synthetic landscape and track nuclide concentrations
- Infer relative erosion rates with the channel steepness index

$$k_s = A^{\frac{m}{n}} \left(\frac{\partial z}{\partial x}\right) = \left(\frac{E}{K}\right)^{\frac{1}{n}}$$

- Estimate n and K to go from relative to absolute erosion
- **Test 1**: How does the mean concentration relate to n and K?
- **Test 2**: How does the shape of the concentration distribution relate to n and K?
- **Result**: Means are invariant to n and K, but distributions are sensitive for transient basins (Figure 2)

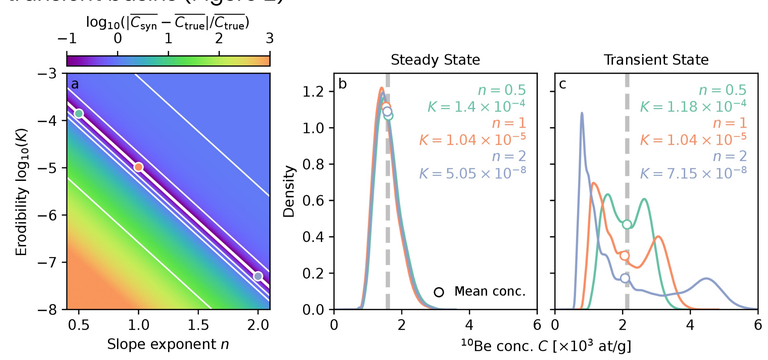


Figure 3: (a) Misfit space when attempting to fit mean concentrations for different n, K. (b) Nuclide concentration distributions for different n, K combinations for a catchment in steady state. (c) Same as (b), but for a catchment with a knickpoint. Note that mean values in (b) and (c) stay constant, but the distribution shape changes in (c).

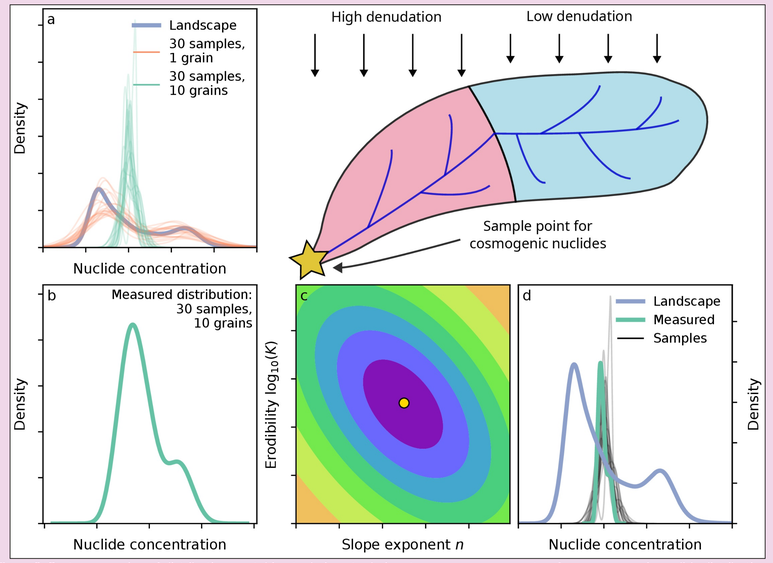


Figure 3: Cartoon overview of distribution-matching technique to derive stream-power parameters from cosmogenic nuclide distributions. (a) Landscape concentration distribution, and example sample sets with different number of grains per sample (30 or 1), each with 30 samples. (b) An example distribution with 30 samples, with 10 grains per sample. (c) Example misfit space for the Wasserstein-2 distance for predicted concentration distributions of different n and K values. (d) The best-fit predicted landscape distribution, and example draws from that distribution compared to the measured distribution.

3 Method and Testing

- Measure nuclide concentrations on N samples with M grains each (Figure 3b)
- We know these concentrations represent topography + denudation rate (Figure 3c), and we already know the topography!
- Measure channel steepness indices and vary n and K, create synthetic nuclide distributions
- Measure how similar these are compared to the actual distribution using Wasserstein-2 distance (Figure 3e) [2]
- Best n and K minimize Wasserstein-2 and result in similar looking distributions (Figure 3f)
- **Test**: How does the number of samples (N), and grains per sample (M) impact recovery of n and K?
- **Result**: Number of samples dominates error: More samples = more robust estimate of n and K (Figure 4b)

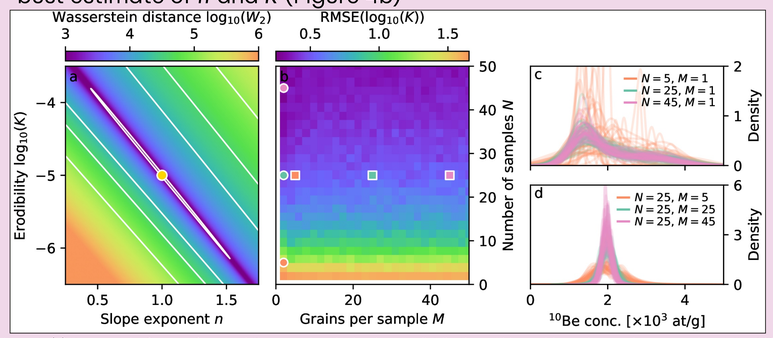


Figure 4: (a) Wasserstein-2 space for n and K, comparing the landscape distributions. This would equal a very large sample set $N > 100$ of single-grain aliquots. (b) Root Mean Square Error (RMSE) in predicted K using different sized sample sets (N) with different number of grains per aliquot (M). Larger sample sets significantly improve accuracy prediction. (c) and (d) Example distributions for varying number of samples and varying number of grains per sample.

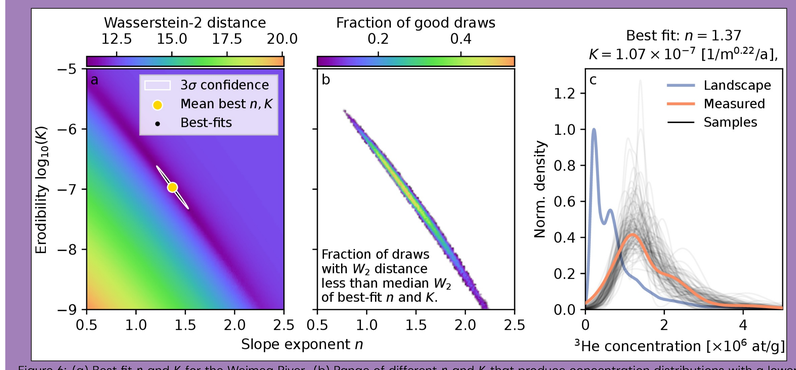


Figure 6: (a) Best fit n and K for the Weimea River. (b) Range of different n and K that produce concentration distributions with a lower Wasserstein-2 distance than the medium distance for the best n and K with a probability greater than 5 %. (c) Distributions for the best-fit parameter combinations.

4 Case Study: Weimea River, Kauai (Hawaii)

- We test our approach on a transient catchment on Kauai (Figure 5). A set of 26 nuclide concentrations is available from [3]
- Estimates for n and K fall into expected intervals (Figure 6)

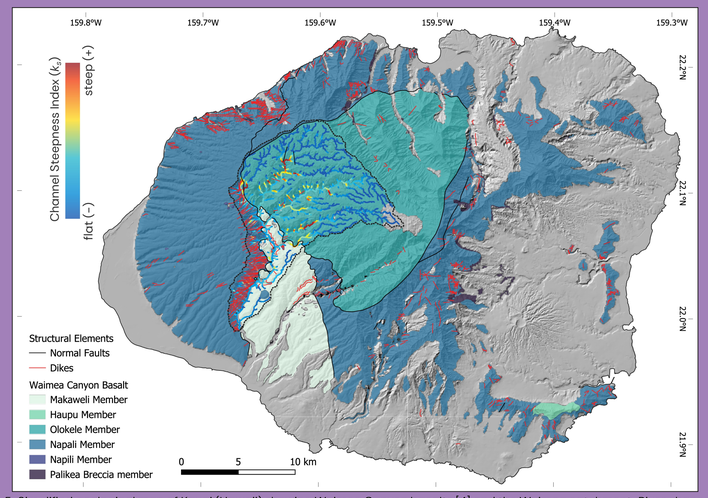


Figure 5: Simplified geological map of Kauai (Hawaii) showing Waimea Canyon basalts [4] and the Waimea catchment. River channels are colored according to steepness index (k_s). A abrupt transition from high steepness (red colors) to lower values in the Olokele Caldera indicates the presence of a knickpoint. It is possible that post-shield subsidence associated with pressure decrease in magmatic chambers below Kauai caused the formation of the Makaweli depression [4], which resulted in the formation of a knickpoint.

5 Conclusions

1. Transient catchments produce bimodal concentration distributions suitable for inferring n, K
2. The major control on accuracy is the number of independent samples, even if each sample consists of multiple grains
3. Our case study reveals that for the given sample size, uncertainty is ca. one order of magnitude for K, and 25 % for n

[1] Adams, B. A., Whipple, K. X., Forte, A. M., Heimsath, A. M., & Hodges, K. V. (2020). Climate controls on erosion in tectonically active landscapes. Science Advances, 6(42), eaaz3166. https://doi.org/10.1126/sciadv.aaz3166 [2] Lipp, A., & Vermeesch, P. (2023). Short communication: The Wasserstein distance as a dissimilarity metric for comparing detrital age spectra and other geological distributions. Geochronology, 5(1), 263–270. https://doi.org/10.5194/gchron-5-263-2023 [3] Gayer, E., Mukhopadhyay, S., & Meade, B. J. (2008). Spatial variability of erosion rates inferred from the frequency distribution of cosmogenic 3He in olivines from Hawaiian river sediments. Earth and Planetary Science Letters, 266(3–4), 303–315. https://doi.org/10.1016/j.epsl.2007.11.019 [4] Macdonald, G. A., Davis, D. A., & Cox, D. C. (1960). Geology and ground-water resources of the island of Kauai, Hawaii. Bulletin, 13. Article 13. https://pubs.usgs.gov/publication/70160871