Soils and the variability of erosion in steepland catchments

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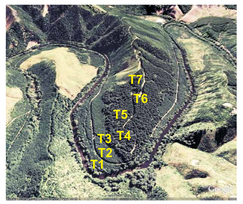
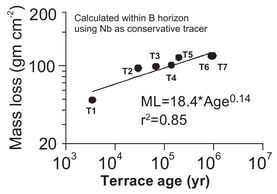
Using soil chronosequence data to estimate soil residence time

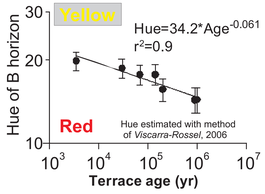


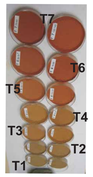
Analysis of a flight of 7 fluvial terraces along the Siuslaw River, Oregon Coast Range, provides quantitative constraints on the evolution of soil properties on stable surfaces (*Almond et al.*, 2007).

The terrace chronology was established using a radiocarbon age on T2 and extrapolation of the incision rate of 0.15 mm yr^{-1}.

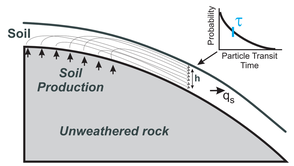
Weathering (as measured via soil description and mass balance calculations) and **rubification** of the B horizon increase systematically with terrace age (*Lindeburg et al.*, 2008)







On hillslopes, constituents of the soil mantle originate from numerous upslope locations. At a given location on a slope, particles have experienced highly variable transit times, the average of which is termed **the soil residence time,** τ.



For a steady state hillslope, soil residence time is constant: $\tau = \frac{h}{E}\frac{\rho_s}{\rho_r}$

where ρ_s, ρ_r are bulk density of soil and rock, respectively, h is soil depth, and E is erosion rate.

To apply the hue-age relationship from our chronosequence to colluvial soils, we used a steady-state assumption to integrate the hue-age relationship for the range of possible soil particle transit pathways and obtained an expression for the average hue:

$$\overline{Hue} = a\tau^{b}\Gamma(b+1)$$

where a and b are parameters from the age-huge calibration above (a=34.2, b=-0.061) and Γ(b+1) is the gamma function for b+1.

Rearranging to solve for τ, gives an expression for soil residence time as a function of average soil hue:

$$\tau = \left(\frac{\overline{Hue}}{a\Gamma(b+1)}\right)^{1/b}$$

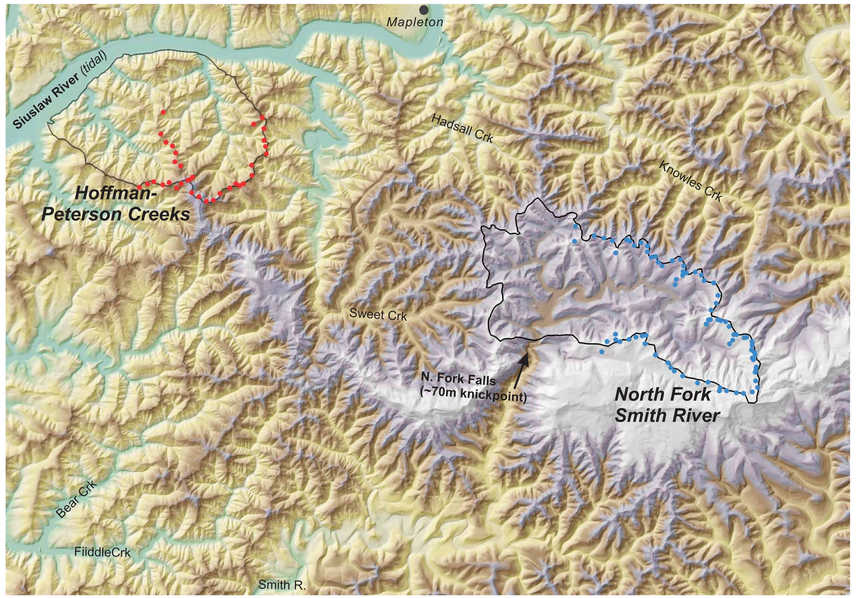
This equation can be combined with the **residence time equation** above to estimate local erosion rate.

How variable are erosion rates in steep, soil-mantled landscapes?

In the unglaciated Oregon Coast Range, the correspondence of rock uplift and basin-averaged erosion rates (~0.1 mm/yr)* and the relative uniformity of precipitation, vegetation, and lithology, presumably favor the maintenance of steady-state topography and *uniform residence time soils*.

In the absence of uniform soil residence times, to what extent does variability in erosion depend on *internal dynamics* (e.g., process stochasticity) and *external forcing* (e.g., differential baselevel lowering)?**





Soil sampling sites

- Hoffman-Peterson
- North Fork Smith River

elev (m)
870
0

N

4km

* Reneau & Dietrich, 1991;

** Hasbargen & Paola, 2003

Hypotheses & Methodology

Despite the apparent uniformity of terrain in the Oregon Coast Range, systematic variations in catchment morphology and longitudinal profiles are common, as illustrated by the contrasting form of the catchments draining Hoffman-Peterson Creeks and the North Fork Smith River. *What do these observations imply about landscape denudation? Are these topographic patterns reflected in soil residence time distributions?*

1) At our Hoffman-Peterson study site (which exhibits regular ridge-valley topography that flows unimpeded to the coast), we hypothesize that **the distribution of soil residence times reflects natural variability for an approximate steady-state landscape**.

2) Above the North Falls knickpoint, alluviated valley floors and gentle ridge-valley terrain are consistent with landscape adjustment to a decrease in baselevel lowering rate. We predict that these topographic properties will be reflected in ***longer soil residence times* as the upland terrain adjusts to a slower pace of incision.**

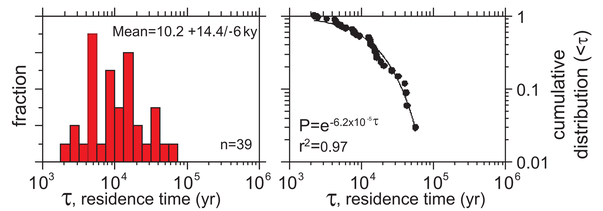
To quantify soil residence time (and thus variability in erosion rates), we sampled the B horizon of hilltop soils along the divides of our study catchments. These samples were dried, crushed, sieved, pressed, and digitally analyzed for hue values. Using our chronosequence calibration data, we converted hue values to estimates of soil residence time.

Results: Soil residence time distributions

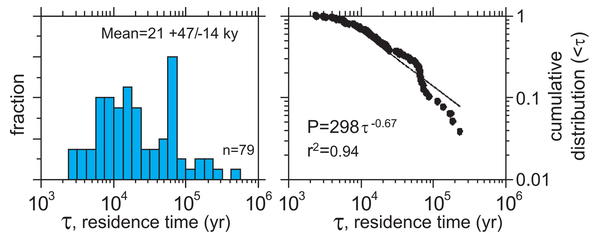
The soil residence time data for Hoffman-Peterson Creeks (red) is log-normally distributed with a mean of ~10ky, consistent with the expected residence time of Oregon Coast Range soils when denudation is 0.1 mm/yr and average soil depth is ~0.8m. We suggest that the variation in residence time values (std. dev is 6-14ky) reflects intrinsic process stochasticity such as soil production processes and debris flow incision that drive deviations in divide denudation.

Our North Fork Smith River samples are more variable (std dev = 14-47 ky), have a larger mean (21 ky), and exhibit a long-tail, approximated by a power law. The abundance of long residence time soils likely reflects reduced baselevel lowering and slow denudation in the catchment above North Fork Falls.

Hoffman-Peterson Crk



N. Fork Smith River



Abstract

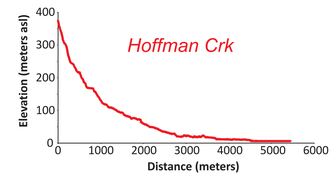
Efforts to model and interpret the evolution of landscapes are often hindered by the lack of data that describe variability in erosion rates for real landscapes. Nearly all landscape evolution simulations are evaluated after the model surface attains a precise balance between rock uplift and erosion, yet it is highly unlikely that real landscapes achieve this steady-state condition across broad areas. Because most erosion rate data are obtained via catchment-averaged analysis of cosmogenic radionuclides or suspended sediment, we have sparse information on the variability of erosion rates in upland regions. Here, we use a novel analysis of hilltop soil properties, in particular rubification, to calculate soil residence time (which is inversely related to erosion rate) for two catchments in the Oregon Coast Range (OCR). Using a soil chronosequence derived from dated fluvial terraces along the Siuslaw river, we observed systematic reddening (as well as geochemical alteration) of soils over ~1 Ma. When coupled with a continuity- based equation for soil production and transport, our weathering (or reddening) function enables us to estimate soil residence time based on the digitally-derived redness value of dried, crushed, sieved, pressed, and photographed soil samples. We collected >200 soil samples from hilltops along the drainage divides of Hoffman and Jump Creeks and generated a soil residence time distribution for both sites. Hoffman Ck features uniformly-spaced ridge-valley terrain (as determined by wavelet transformation of topographic data) characteristic of the OCR and its outlet directly connects with a tide-dominated reach of the Siuslaw river. In contrast, the nearby, low-gradient, irregularly-dissected Jump Ck catchment has an outlet that flows over a >30m igneous dike-controlled waterfall that retards the upstream passage of baselevel lowering. Consistent with these opposing geomorphic settings, Hoffman Ck soils are young with little variability (10 +14/-6 ka) whereas Jump Crk soil residence times are older (22 +48/-14 ka) and their distribution is well-described by a power law. We propose that our Hoffman Ck data reflect random variability for a catchment that approximates a 'steady-state' condition. For the Jump Ck site, by contrast, the heavy tail of the residence time distribution reflects slow-eroding surfaces upstream of the knickpoint while the shorter residence time soils result from impingement of surrounding catchments and drainage divide migration. Our findings provide spatially- extensive, quantitative constraints on landscape dynamics at geomorphic timescales and should be useful for calibrating emerging stochastic models for hillslope evolution.

Study site properties: Contrasting catchments

Hoffman-Peterson Drainage Basins

1) Exhibits regular ridge-valley topography with narrow valley floors and a debris flow dominated 3rd order channel network.
2) Drains directly into a tidal reach of the Siuslaw River (~20km from the Pacific Ocean) and is thus tightly coupled to coastal rock uplift.
3) Basin area = 21.6 km^2
   average slope = 60%
   average relief = 270 meters

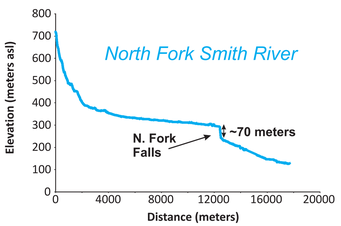




North Fork Smith River Drainage Basin

1) Exhibits less regular ridge-valley topography with broad alluviated valley floors above a 70m high gabbroic dike-controlled knickpoint (N. Fork and Lower Kentucky Falls).
2) The longitudinal profile shows high concavity upstream of the knickpoint.
3) Basin area = 27.8 km^2
   average slope = 39%
   average relief = 200 meters





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