Rates and variability of hillslope erosion in steepland catchments in the Oregon Coast Range, Pacific Northwest, USA

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Abstract

Hillslope soil residence time (average particle age making up the soil) reflects the rates of soil production (= bedrock erosion) and soil transport, and thus is a useful parameter for quantifying hillslope dynamics. On steady state hillslopes, the distribution of particle ages is determined by soil production rate, soil depth and soil and bedrock density. This distribution, used in combination with chronofunctions describing soil weathering at a particle scale, can be used to derive expressions relating hillslope soil properties to soil residence time. Thus soil properties can be used to estimate soil residence time and quantify hillslope dynamics. We analysed variability of soil residence time at a broad scale and a fine scale in the Oregon Coast Range in the Pacific Northwest, USA. Our results are consistent with an approximate balance of erosion rate and rock uplift rate for a large part of our study area, but at both scales, parts of the landscape with long soil residence time were identified. We attribute the lower erosion rates and slower soil transport (contributing to long soil residence time) in these areas to decoupling from base-level lowering.

Key Words

Soil residence time, soil chronosequences, chronofunctions, soil production.

Introduction

The use of soils as a surface exposure dating technique is well established. Typically, numerical ages are calculated from empirical chronofunctions calibrated locally from soil chronosequences, and soil properties from a surface of unknown age. Dating relies on a number of assumptions including: 1) monotonically increasing expression of soil development with increasing soil age, 2) rates and pathways of soil evolution have remained constant in space and time over the study area, 3) the manifestation of soil age in the chronosequence is the same as on the landforms for which an exposure age is to be determined. The last is usually assured by dating soils with similar soil forming factors to the calibration data set. For example, a chronofunction calibrated from soils on a flight of terraces should not be used to derive an exposure age for an eroding soil-mantled hillslope. In this case the factor of relief is different. More fundamentally, the distinction between these two situations, which confounds the application of soil surface exposure dating, lies in the fact that the population of grains comprising the soil on a terrace has a singular age (the age of the terrace), whereas the soil on the hillslope comprises a population of grains with a distribution of ages determined by the time since each grain was released from the substrate by soil production.

On hillslopes the concept of a soil/landsurface age is meaningless, but one can refer to the mean soil grain age, or *residence time* of the soil. The extent of chemical weathering of the bulk soil is the integration of weathering of individual grains of different age. But because chemical weathering and other pedological processes generally follow non-linear chronofunctions, there is not a simple correspondence (in terms of soil development) between soil residence time and soil age as defined in the non-eroding soil situation. In this paper we develop a conceptual framework which allows us to use a chronofunction, calibrated from a soil chronosequence on fluvial terraces, to calculate the residence time of hillslope soils from bulk soil weathering characteristics. We then interpret soil residence times in terms of landscape dynamics and the history of forcing of hillslope erosion.

Conceptual framework

For a steady state soil-mantled hillslope, where the rate of erosion is balanced by soil production, it can be shown that the residence time, $\tau = h\rho_s/E\rho_r$, where h is the soil depth, ρ_s and ρ_r are the densities of soil and rock, respectively, and E is the erosion rate (= soil production rate). The soil has a population of grain ages with probability density function given by

$$P(t) = \frac{1}{\tau} e^{-\frac{t}{\tau}} \text{ (Mudd and Furbish 2006).} \qquad (1)$$

If a chronofunction can be developed for a soil property for which processes can be scaled down to individual grains, then Eqn 1 can be used to integrate the effects of that process over the whole grain population to determine the bulk soil response. Thus, by measuring weathering-related properties of hillslope soils, armed with a suitable chronofunction, and making a steady-state assumption, hillslope erosion rate and the residence time of soils can be determined.

Study area

The Oregon Coast Range (OCR) is a humid, soil-mantled, mountainous landscape in the Pacific Northwest of the USA, largely composed of Eocene Tyee Formation (sand-rich turbidite deposits) that overlie volcanic basement accreted to the North American plate. The topography is steep and highly dissected with relatively uniform ridge and valley terrain (Dietrich and Dunne 1978; Montgomery 2001; Reneau and Dietrich 1991). Typically, soils are thin (~0.4 - 0.7 m) Inceptisols on hilltops and sideslopes, and thicker cumulate Inceptisols (~1 - 2 m) in unchanneled valleys. Both short- (~10 y) and long-term (~5000 y) studies of sediment yield suggest an approximate balance between erosion rate (0.10 - 0.15 mmy^{-1}) (Bierman *et al.* 2001; Heimsath *et al.* 2001; Reneau and Dietrich 1991) and rock uplift (Kelsey *et al.* 1996; Personius 1995), so that the topographic form may be relatively uniform with time (Montgomery 2001; Roering *et al.* 1999). Our soil residence time analysis covers two scales; a broad scale study encompasses the drainage of the Siuslaw River and the dividing range to Long Tom Creek which drains into the Willamette Valley. A finer scale study contrasts soil residence time distributions of the Hoffman-Peterson and the North Fork Smith drainage systems which drain to the lower reaches of the Siuslaw River. The Hoffman-Peterson drainage system (21.6 km^2, average slope = 60%, average relief = 270 m) exhibits regular ridge-valley topography with narrow valley floors. It drains directly into a tidal reach of the Siuslaw River (~20 km from the Pacific Ocean) and is thus tightly coupled to coastal rock uplift. The North Fork Smith drainage (27.8 km^2, average slope = 39%, average relief = 200 m) exhibits less regular ridge-valley topography with broad alluviated valley floors above a 70 m high gabbroic dike-controlled knickpoint (North Fork and Lower Kentucky Falls).

Methods

A soil chronosequence on fluvial terraces of the Siuslaw River was used to calibrate chronofunctions reflecting chemical weathering and formation of pedogenic oxides. The flight of seven terraces spanned approximately 3.5 ky to 1 My, with ages being assigned using calibrated radiocarbon ages for younger terraces and by calculation from terrace elevation and an approximate uplift rate for older terraces. Soils varied from Entisols to Inceptisols to Ultisols with increasing age. One of the most consistent aspects of soil development was increasing redness. For the broad scale study, a chronofunction (units of ky) describing development of Munsell soil hue of the reddest soil horizon, as assessed during field soil description, was calibrated ($Hue\ No. = 1.98 + 10.53\ (1-e^{-0.0067t})$). For the finer scale study, air-dried soil samples from the reddest horizon were crushed, sieved to <2 mm, placed in a petri dish and photographed with a digital camera. RGB data extracted from image analysis software were then converted to Munsell hue using the algorithm of Viscarra Rossel *et al.* (2006), and a second soil hue chronofunction (units of ky) was derived ($Hue\ No. = 22.4t^{-0.061}$).

In order to be able to relate soil development on hillslopes to soil residence time, we integrated the chronofunctions above across the particle age probability density function given by Eqn 1 to yield an expression relating soil hue to residence time. These expressions were then solved for residence time, τ, in ky for the chronofunctions for field soil hue and digital laboratory-measured hue, respectively:

$$\tau = \frac{H - 2.5}{0.0067(10.53 - (H - 2.5))} \qquad \text{2a}$$

$$\tau = \left[\frac{H}{22.4\Gamma(-0.061 + 1))}\right]^{-\frac{1}{0.061}} \qquad \text{2b}$$

where H = hue number, and Γ is the gamma function.

The pattern of variability of soil residence time at the broad scale was determined using Eqn 2a and a GIS spatial database of soil hue data taken from a relevant soil map. At the fine scale, the variability of soil residence time was determined using Eqn 2b and digital hue values measured from soil samples taken from the reddest horizon of soils along drainage divides within the Hoffman-Peterson and the North Fork Smith drainages.

Results and discussion

The broad scale analysis shows the majority of the study area, west of the drainage divide to the Willamette Valley, to be dominated by soils with residence time of 8 ± 5 ky (Figure 1).

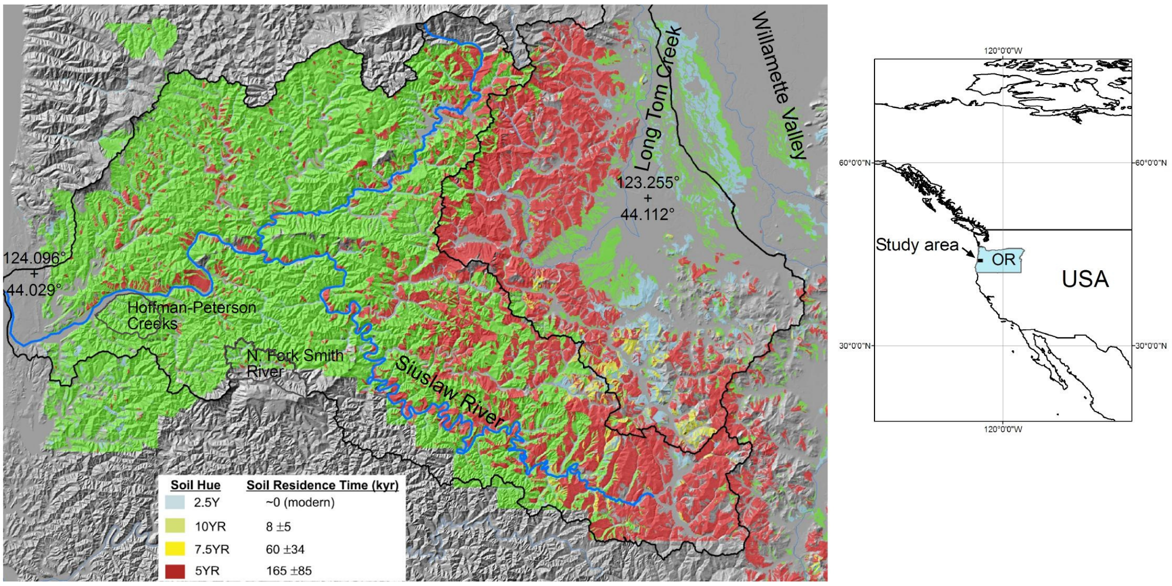

Figure 1. Soil residence times for the study area.

This is consistent with steady state erosion at between 0.10 and 0.15 mmy^{-1} beneath soils with thickness and bulk density typical of the hillslopes of the Coast Range. This part of the study area is well coupled to the Siuslaw River, and it appears that the signal of base-level lowering is being effectively transmitted to hillslopes by processes operating at timescales similar to or less than the soil residence time. Figure 1 also shows inliers of soils of much longer residence time (~165 ky). These areas correspond to river terraces, typically on the inside of migrating meander bends, or deep-seated landslides, which have been temporarily decoupled from base-level lowering owing to their topographic form. Both the landslides and terraces form broad, low-gradient surfaces on which soil transport is minimal, erosion rate is low, and chemical weathering is advanced. The area east of the drainage divide to the Willamette Valley has average soil residence times approaching 150 ky. The long soil residence time probably relates to structurally controlled diversion of east to west flowing streams, formerly contributing to the Siuslaw River system, into the Willamette Valley (Baldwin and Howell 1949). In contrast to the Siuslaw, Long Tom Creek is broad and alluviated and base level is stable or rising. Consequently, hillslopes are relaxing and accumulating soil, thus developing deep weathering profiles.

The fine scale study illuminates differences in hillslope behaviour in the two drainage systems with contrasting base-level control. The soil residence time data for Hoffman-Peterson Creeks (Figure 2 - red) is log-normally distributed with a mean of ~10 ky, consistent with the expected residence time for steady state erosion at 0.10 - 0.15 mmy^{-1}. We suggest that the variation in residence time values (std. dev is 6-14 ky) reflects intrinsic stochasticity of processes of soil production and transport that ultimately drive variability of denudation at the divides where we sampled. The 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 (Figure 2 - blue). The abundance of long residence time soils likely reflects reduced base-level lowering and slow denudation in the catchment above North Fork Falls. We propose that our Hoffman Creek data reflect random variability for a catchment that approximates a 'steady-state' condition. For the North Fork Smith River 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.

Conclusion

Soil residence time in the Oregon Coast Range supports the contention of an approximate equality of erosion rate and regional rock uplift rate over large areas. However, long soil residence times in some parts of the landscape highlight decoupling from base-level lowering, resulting from large scale drainage realignment or smaller scale fluvial or mass movement modification of topography. A detailed study of the distribution of soil residence time in two small catchments with contrasting base level controls identified contrasting patterns of erosion. These data provide spatially-extensive, quantitative constraints on landscape dynamics at geomorphic timescales and should be useful for calibrating emerging stochastic models for hillslope evolution.

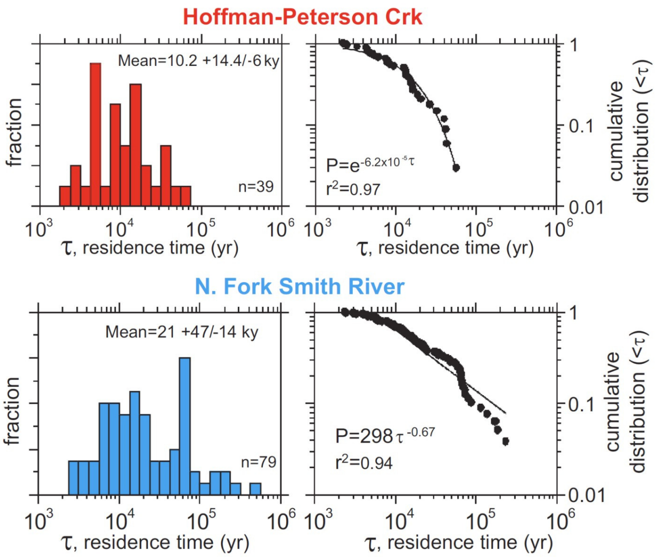

Figure 2. Frequency distributions for soil residence time for the Hoffman-Peterson and North Fork Smith drainages.

References

Baldwin EM, Howell PW (1949) The Long Tom, a former tributary of the Siuslaw River. *Northwest Science* **23**, 112-124.

Bierman P, Clapp E, Nichols K, Gillespie A, Caffee M (2001) Using cosmogenic nuclide measurements in sediments to understand background rates of erosion and sediment transport. In 'Landscape Erosion and Evolution Modeling'. (Eds Harmon, Doe) pp. 89-115. (Kluwer Academic Plenum: New York).

Dietrich WE, Dunne T (1978) Sediment budget for a small catchment in mountainous terrain. *Zeitschrift fur Geomorphologie, Supplement* **29**, 191-206.

Heimsath AM, Dietrich WE, Nishiizumi K, Finkel RC (2001) Stochastic processes of soil production and transport; erosion rates, topographic variation and cosmogenic nuclides in the Oregon Coast Range. *Earth Surface Processes and Landforms* **26**, 531-552.

Kelsey HM, Ticknor RL, Bockheim JG, Mitchell CE (1996) Quaternary upper plate deformation in coastal Oregon. *Geological Society of America Bulletin* **108**, 843-860.

Montgomery DR (2001) Slope distributions, threshold hillslopes, and steady-state topography. *American Journal of Science* **301**, 432-454.

Mudd SM, Furbish DJ (2006) Using chemical tracers in hillslope soils to estimate the importance of chemical denudation under conditions of downslope transport. *Journal of Geophysical Research-Earth Surface* 111.

Personius SF (1995) Late Quaternary stream incision and uplift in the forearc of the Cascadia subduction zone, western Oregon. *Journal of Geophysical Research* **100**, 20193-20210.

Reneau SL, Dietrich WE (1991) Erosion rates in the Southern Oregon Coast Range: Evidence for an equilibrium between hillslope erosion and sediment yield. *Earth Surface Processes and Landforms* **16**, 307-322.

Roering JJ, Kirchener JW, Dietrich WE (1999) Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology. *Water Resources Research* **35**, 853-870.

Viscarra Rossel RA, Walvoort DJJ, McBratney AB, Janik LJ, Skjemstad JO (2006) Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties. *Geoderma* **131**, 59-75.