How deep and how steady is Earth's surface?

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Weathering is the ubiquitous hallmark of the interaction of rock with environmental conditions on Earth's surface. Alteration of fresh rock both releases nutrients to organisms and consumes atmospheric CO_2. The disaggregated products of weathering provide substrate to anchor roots, and their production is the first step in sculpting landscapes. The porosity structure developed by weathering retains water and paces its flow back to the oceans. For all these reasons, we care a great deal about the rates of weathering, how deeply below the surface a rock is weathered, and if this zone of weathering is steady or changing in time.

Understanding the connections between weathering rate and erosion rate is a long-lived question in the study of Earth's surface, and inevitably requires knowledge of the depth to which weathering processes reach and the rates of these processes over time. The balance between the downward penetration of weathering agents (atmospheric fluids and organisms) and the damage they cause, and the removal of weathered material by erosion integrated over time, governs the thickness of the weathered zone. One could quite literally think of this zone as the thickness of Earth's surface. It is the chemical reactor through which unweathered rock must pass before being eroded.

Weathering is central to the long-term regulation of atmospheric CO_2. Two end-members of silicate weathering control are postulated, one limited by weathering kinetics, another by mineral supply (e.g., Hilley et al., 2010; Gabet and Mudd, 2009). If weathering kinetics dominates, chemical weathering fluxes will be modulated by temperature and mineral-specific reaction rate constants. This implies that climate and lithology control weathering fluxes, as outlined in the models of Walker et al. (1981) and Berner et al. (1983) and many refinements that have followed. If, on the other hand, mineral supply dominates, chemical weathering fluxes will be modulated by the rate of physical erosion, which both governs the flux of material through the reactor and exposes more reactive fresh mineral surfaces (White and Brantley, 2003). The notion that mineral supply may influence the weathering flux underpins the uplift-driven climate change hypothesis of Raymo and Ruddiman (1992); even now, 20 years later, this debate is unsettled (von Blanckenburg and Dixon, 2012).

Linkages between weathering and erosion are also important in landscape evolution (Sharp, 1982). In this context, weathering is often construed as the production of mobile regolith (e.g., Anderson and Humphrey, 1989); the material released into mobile regolith is subject to transport processes that shape the topography. With some notable exceptions (e.g., Mudd and Furbish, 2004), geochemical alteration is secondary in most of these landscape evolution models. The algorithms that incorporate mobile regolith formation commonly lack a process basis. What governs the transformation of rock into mobile regolith, a rate-limiting process in landscape evolution, is therefore a leading question faced by landscape evolution modelers.

The framework common to both geochemical and geomorphic models of weathering in natural settings is mass balance of a column of material at Earth's surface (Fig. 1). Advance of a weathering front downward sets the flux of material into the weathering zone (W_{rock}), while dissolved products of chemical weathering (W_{chem}) and erosion of solid material (E_{sed}) set fluxes of material out of the control volume. Under steady-state conditions, $W_{rock} = E_{sed} + W_{chem}$, and the thickness of the weathered zone is steady in time. Such a mass balance can be written for any control volume, with emphasis on terms of interest. Landscape evolution models focus on the production of mobile regolith from weathered rock, as this transition produces particles moved by sediment transport processes. Geochemical analysis focuses on depletion of elements or primary minerals, such as that expressed with mass transfer coefficients, $\tau_{i,j}$, which vary from –1 (100% loss) to 0 (no loss) (Brantley and Lebedeva, 2011).

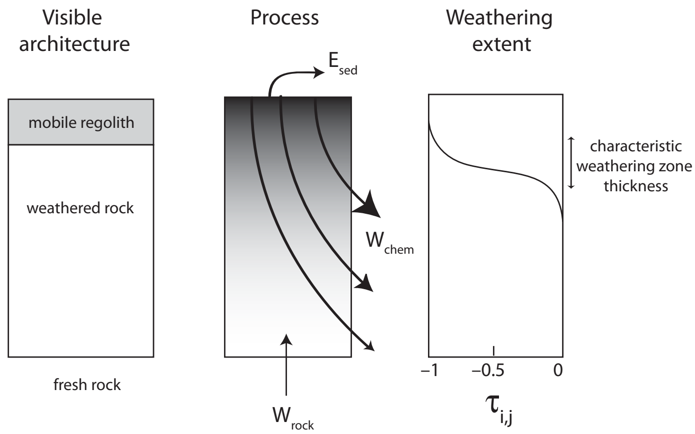

Figure 1. Three views of Earth's surface: the visible architecture of the weathered profile, a schematic of the processes and fluxes involved, and weathering extent depicted with a plot of a mineral depletion profile.

It is commonly assumed that the system is in steady state, meaning the mass within the column under consideration is not changing over time, because it simplifies an inherently open system. Steady-state implies steady soil thickness (e.g., Brantley, 2008), or a landscape in steady form, with perfectly matched erosion and weathering (mobile regolith or soil production) rates (Hack, 1960). These notions were employed in the classic analysis of G.K. Gilbert (1909), in which he argued that convex hilltops were a consequence of steady-state soil thickness, uniform lowering of the landscape, and soil flux that is proportional to slope. Hilltop curvature is used even now to infer denudation rates where steady conditions and slope-dependent transport applies (e.g., Roering et al., 2007). The steady-state assumption also underlies the use of cosmogenic radionuclide (CRN) concentrations to determine mobile regolith production rates (e.g., Heimsath et al., 1997; Small et al., 1999). Because the CRN production rate declines exponentially with depth below the surface, the CRN production rate at the base of the mobile regolith layer (which is used to invert measured CRN concentrations for mobile regolith production rates) is sensitive to any temporal variations of mobile layer thickness.

Two papers in this issue of *Geology* offer contributions to our understanding of steady-state erosion systems and the depth of weathering, addressing the two aspects of mass balance that are most difficult to constrain. One (Sweeney et al., 2012, p. 807) uses the state of weathering within soils to assess the spatial uniformity of weathering in a landscape, and hence to evaluate the validity of the notion of steady state. The other (West, 2012, p. 811) computes a depth of weathering, or thickness of the weathering layer, from measures of weathering flux and erosion rate, while assuming that the steady state does prevail.

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Sweeney et al. (2012) use a novel and low-cost approach to characterize the degree of weathering in many soil profiles in the well-studied Oregon Coast Range (western United States). Owing to a temperate Pleistocene climate and balanced rock uplift and erosion rates of the accretionary prism of the Cascadia subduction zone (Willett and Brandon, 2002), the Oregon Coast Range is thought to be a steady-state landscape, in which erosion rates and soil development are spatially uniform. Sweeney et al. test this hypothesis with soil redness, measured with visible–near-infrared (visNIR) spectroscopy, which they have calibrated against soil residence time (Mudd and Yoo, 2010). Despite the steadiness of the landscape as a whole, they find a wide range of residence times in ridge-top soils: 18.8 k.y. (+31.2/–11.8 k.y.) in a watershed adjusted to base level, and 72.9 k.y. (+165.6/–50.6 k.y.) in a watershed whose denudation rate is reduced due to a resistant rock sill. Soil residence times (and by extension, erosion rates) are steady only in an ensemble sense. The spatial scale of variability is <100 m, which leads Sweeney et al. to suggest that trees may drive much of this heterogeneity. Interestingly, the mean residence times they found are much greater than the ~5 k.y. one would infer from the mean soil thickness and total denudation rates. This observation suggests that particles enter the soil having already undergone weathering to some extent (i.e., some of their redness is inherited from residence in the immobile weathered rock beneath the soil), a finding that is supported by the equal contributions of soil and bedrock to stream water chemistry in an Oregon Coast Range headwater stream (Anderson and Dietrich, 2001).

West (2012) focuses on the thickness of the zone of weathering that produces solute fluxes measured in rivers. Steady state predicts an adjustment between chemical weathering fluxes, total erosional mass losses, and thickness of the weathering system. West draws on a data set of measured river chemical-weathering fluxes and total denudation rates for granitic catchments that he has analyzed previously for erosional and tectonic controls on weathering (West et al., 2005). In this contribution, he uses theoretical relationships between denudation and soil depth to determine an "implied thickness" of the weathering zone from the measured chemical-weathering fluxes. The interesting outcome of this exercise is that the thickness of this weathering reactor varies by only 30% around a mean thickness, while denudation rates vary over four orders of magnitude. In other words, there is very little variation in the thickness of the zone of active chemical weathering over a very large range of erosion rates.

Perhaps the most interesting aspect of West's work is that he disconnects the locus of chemical weathering from the more visible layers, such as defined by soil or even regolith boundaries. He finds an apparent consistency in the thickness of this active weathering zone across regions where soils may be absent, as well as regions where weathering fronts are deeply advanced into rock. This leads us away from thinking that the absence of soil implies an absence of weathering, an idea perhaps not far-fetched for anyone who has pondered water seeping out of fractured rock faces in the mountains of the world.

Taken together, these two contributions support a view that Earth's surface behaves as a steady system if we look across scales greater than the scale of mixing processes, but suggest that our concept of the zone of active chemical weathering should be decoupled from the visible architecture of the subsurface. Models quantitatively linking the evolving topography of Earth's surface, rates of denudation, and their interaction with and influence on tectonic or climatic forcing are on the leading edge of surface process research (National Research Council of the National Academies, 2010). Tests of the steady-state condition, and infusion of geochemical processes into landscape evolution models, are contributions likely to produce the broadest impact on these leading-edge questions.

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