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Responses of chemical erosion rates to transient perturbations in physical erosion rates, and implications for relationships between chemical and physical erosion rates in regolith-mantled hillslopes

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ABSTRACT

Understanding the relationship between chemical erosion rates (W) and physical erosion rates (E) is of wide interest due to their roles in driving landscape evolution, supplying nutrients to soils and streams, and modulating the global carbon cycle. Measured relationships between W and E vary around the globe, with some regions exhibiting positive correlations between W and E , some negative correlations, and others no correlation within uncertainty. Here we use a numerical model for mineral weathering in well-mixed ridgetop regolith to explore how complex W – E relationships can be generated by simple transient perturbations in E . We show that a Gaussian perturbation in E can produce positive or negative responses in W , and can result in a variety of hysteresis loops – clockwise, counterclockwise, or figure-eight – in plots of W against E . The nature of the transient response depends on the shape of the steady-state W – E relationship, which is set by regolith mineralogy, and the ratio of E to the maximum possible regolith production rate. The response time of W is controlled by the response time of soluble mineral concentrations at low E , where soluble mineral concentrations are low, and by the response time of regolith thickness at high E , where regolith thickness is low. These complex W – E relationships arise in the absence of variations in climate and lithology, which suggests that transients may account for some of the observed differences in W – E relationships among field sites, even among sites that share the same climate and lithology.

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1. Introduction

As every designer of hydroelectric reservoirs knows, hillslopes persistently shed a great deal of material to rivers. Globally, $\sim 21 \cdot 10^9$ t/yr of sediment (Wilkinson and McElroy, 2007) and $\sim 2 \cdot 10^9$ t/yr of solutes (Gaillardet et al., 1999) are transferred from the continents to the ocean, reflecting the average dominance of physical erosion rates over chemical erosion rates across landscapes. This dominance belies a strong regional variability in the relative magnitude of chemical and physical erosion rates (Summerfield and Hulton, 1994). In some places, like the minimally weathered peaks of the Santa Rosa Mountains in Nevada, nearly 100% of the mass flux from hillslopes is due to physical erosion (Riebe et al., 2004a). In other places, like the highly reactive, freshly erupted basalts on Mauna Loa in Hawaii, nearly 100% of the mass flux from hillslopes is due to chemical erosion (Schopka and Derry, 2012).

Understanding what sets the relationship between chemical erosion rates (W) and physical erosion rates (E) is of wide interest due to their roles in driving landscape evolution (e.g., Mudd and Furbish, 2004), supplying nutrients to soils and streams (e.g., Lucas, 2001), and modulating the global carbon cycle (e.g., Berner, 1999). The relationship between W and E underlies a number of longstanding hypotheses about the coevolution of Earth's climate, topography, and regolith chemistry. A positive coupling between W and E would imply a strong regulation of Earth's long-term climate by plate tectonics, because silicate weathering regulates Earth's temperature through the consumption of atmospheric carbon dioxide, and because physical erosion rates are tightly coupled to tectonically-driven rock uplift rates (e.g., Stallard and Edmond, 1983; Raymo et al., 1988; Riebe et al., 2004b; Hilley et al., 2010). By contrast, a weak or negative coupling between W and E would imply the absence of a strong tectonic control on Earth's climate, and would imply that chemical erosion rates should be more sensitive to climatic factors than to tectonics (e.g., Berner and Caldeira, 1997; West et al., 2005; Maher and Chamberlain, 2014).

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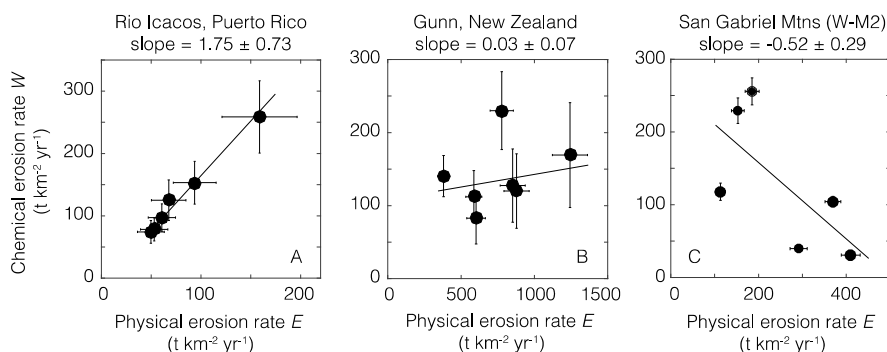


Fig. 1. Chemical erosion rates (W) have different relationships with physical erosion rates (E) in different places (Riebe et al., 2003; Dixon et al., 2012; Larsen et al., 2014). Slopes of best-fit linear regressions (mean \pm standard error) are reported in panel titles. Uncertainties in W in panel B were calculated under an assumed uncertainty of 0.05 in chemical depletion fractions (CDF), comparable to uncertainties in CDF in panels A and C.

These hypotheses have motivated the extensive acquisition of field measurements of W and E in regolith-mantled hillslopes over the past two decades. A global compilation of these data shows that W and E are broadly positively correlated (albeit with considerable scatter) across sites that span a range of climates (0.2 to 11.5 m in mean annual precipitation and 2 to 25 °C in mean annual temperature) and a range of lithologies (granite, granodiorite, and schist; Larsen et al., 2014). W – E relationships in smaller geographic regions, however, vary substantially among sites. In some regions, W and E are positively correlated, as observed in the Rio Icacos basin in Puerto Rico (Fig. 1A; Riebe et al., 2003), but in other regions, W and E exhibit negative or flat relationships, as observed in portions of the San Gabriel Mountains and the New Zealand Southern Alps (Figs. 1B–C; Dixon et al., 2012; Larsen et al., 2014). Our goal in this study is not to reinterpret the measurements of W and E at the particular sites in Fig. 1; this would require more information than is presently available at these sites, as described in the Discussion. Instead, we show these data because they are illustrative examples of a broader puzzle that is the motivation for this study. Given that W and E are positively correlated globally across a range of climates and lithologies, why aren't W and E positively correlated within smaller regions, where variations in climate and lithology are much smaller than they are across the global compilation?

A number of possible causes for these variations have been proposed. Some of the observed differences in W – E relationships may be due to regional differences in a number of environmental factors that can affect W and E , including rock strength, mineralogy, and grain size (e.g., Sklar and Dietrich, 2001; Bluth and Kump, 1994), temperature (e.g., White and Blum, 1995; Anderson et al., 2013; West et al., 2014; Marshall et al., 2015; Li et al., 2016), and precipitation rate (e.g., White and Blum, 1995; Owen et al., 2011; Moon et al., 2011; Ferrier et al., 2013; Maher and Chamberlain, 2014; Murphy et al., 2016). Given that W and E have different sensitivities to a variety of climatic and lithologic factors, it is reasonable to expect that the relationship between W and E may be affected by climate and lithology too.

Another possibility is that different regions have different W – E relationships because they occupy different regions of the same nonlinear steady-state W – E relationship. Some models predict that W should increase with E at low values of E and approach a steady maximum value at high values of E (West, 2012), and others predict that W and E should be positively correlated at low values of E and negatively correlated at higher values of E (Anderson et al., 2002; Gabet, 2007; Ferrier and Kirchner, 2008; Gabet and Mudd, 2009). Geographic regions with low E might thus be expected to have different W – E relationships than regions with high E .

In this study, we use a model of regolith mineralogy (Ferrier and Kirchner, 2008) to explore an additional control on W – E relationships: the response of W to transient perturbations in E (e.g., Brocard et al., 2015). Our goal is to examine the transient W – E relationships that arise during perturbations in E in regolith-mantled hilltops, and to explore the sensitivity of transient W – E relationships to bedrock mineralogy and the initial erosional conditions. Because this model pertains to regolith-mantled hilltops, these model results are most applicable to landscapes that maintain a continuous regolith cover during erosional perturbations. These results are therefore complementary to, but distinct from, studies of transient chemical weathering responses in glaciated terrain, where pulses of physical erosion during glacial–interglacial cycles may have periodically stripped the surface of regolith (e.g., Vance et al., 2009). Our analysis shows that a variety of modeled W – E relationships can arise in response to simple transient perturbations in E , even in the absence of variations in climate and lithology. This suggests that some of the variations among measured W – E relationships in hilltop regolith may be a result of differences in the transient responses to perturbations in E .

2. Regolith mineralogy model

2.1. Overview of regolith mineralogy model

To investigate the effects of transients in physical erosion rates on chemical erosion rates, we apply the model of Ferrier and Kirchner (2008), which computes changes in the mineralogy of mobile regolith at a ridge under a prescribed time-varying physical erosion rate (Fig. 2). For brevity, we use the term “regolith” to refer to the mobile layer of material nearest the surface, following the conventional usage in the geomorphic literature. This aligns with the definition of soil in some studies (e.g., Dixon et al., 2012) and the definition of the partially disturbed zone in others (Yoo and Mudd, 2008). This differs from the conventional usage in the geochemical literature, in which “regolith” refers to all the altered material above unweathered bedrock, and thus can include weathered rock in addition to the mobile layer (e.g., Brantley et al., 2017). Likewise, we use the term “rock” to refer to the parent material of the mobile layer, while recognizing that the parent material of the mobile layer is often partly weathered itself. Here we briefly review the foundation of this model, and refer the reader to Ferrier and Kirchner (2008) for details of the model.

This model is based on the following assumptions: 1) the regolith is vertically mixed; 2) rock is incorporated into the regolith at a rate that declines exponentially with regolith thickness (e.g., Heimsath et al., 1997); 3) the rock mineralogy is uniform with depth; and 4) the chemical erosion rate from a given mineral phase is proportional to its concentration in the regolith (Waldbauer and Chamberlain, 2005). This model considers

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