Shale weathering rates across a continental-scale climosequence

Ashlee Dere[A], Tim White[B], Susan L. Brantley[C], Lixin Jin[D], David Harbor[E] and Meredith Townsend[F]

[A]Graduate Student of Geosciences, Pennsylvania State University, University Park, PA, USA, Email ald271@psu.edu
[B]Senior Research Associate, Pennsylvania State University, University Park, PA, USA, Email tsw113@psu.edu
[C]Faculty of Geosciences, Pennsylvania State University, University Park, PA, USA, Email brantley@essc.psu.edu
[D]Postdoctoral Researcher, Pennsylvania State University, University Park, PA, USA, Email luj10@psu.edu
[E]Faculty of Geology, Washington and Lee University, Lexington, VA, USA, Email harbord@wlu.edu
[F]Student of Geology, Washington and Lee University, Lexington, VA, USA, Email townsendm11@mail.wlu.edu

Abstract

A transect of sites has been established in North America as a Critical Zone Exploration Network (CZEN) to investigate the rates of soil formation across a climate gradient. Sites reported here are all underlain by an organic-poor, iron-rich Silurian-age shale, providing a constant parent material lithology from which soil is forming. This climosequence includes relatively cold and wet sites in Wales, New York and Pennsylvania, with temperature increasing to the south in Virginia, Tennessee and Alabama. Puerto Rico provides a warm/wet end member for the transect, although this site does not lie on the same shale formation as the Appalachian Mountain sites. Data, including geochemistry and mineralogy, will be measured similarly at all sites to allow direct comparisons and eventual modelling of the weathering processes. Preliminary results from Wales, Pennsylvania and Virginia show sodium depletion with depth, with the depth to bedrock significantly deeper at the wet/warm site in Virginia. The fraction of Na lost relative to parent material composition at each site varies linearly as a function of mean annual temperature. Overall, results from the transect will promote a better understanding not only of how climate is influencing soil production, but also the role of human impacts on soil formation rates.

Key Words

Soil, weathering, climate, shale.

Introduction

Terrestrial life is wholly dependent on the properties and processes within the critical zone, which encompasses the top of the tree canopy to aquifers beneath the earth's surface (Brantley *et al.* 2007). As the central constituent of this zone, soil serves as an interface for gas and water exchange and plays a major role in nutrient cycling that supports ecosystems (Amundson *et al.* 2007). However, the rate at which soil forms in the critical zone is not well understood. In working to address this question, numerous researchers have looked at how soils differ in form and function across environmental gradients. These studies have included quantifying physical erosion, pedogenic development, and geochemical fluxes as a function of climate and various parent materials (i.e. Rinaido *et al.* 1995; Chadwick *et al.* 1990; White and Blum 1995; White *et al.* 1999; Rasmussen *et al.* 2007; Jin *et al.* 2009). While these studies have included both field and laboratory measurements of chemical and physical weathering rates, they have focused on small-scale climo- or chronosequences, such as Hawaii or the Pacific Northwest, and generally only address one mineral or system component; scaling-up these results to understand more global processes is problematic. Additionally, literature synthesis studies, such as that by Bockheim (1980), have used previously published data to investigate the influence of gradients on soil properties, but not all data was collected in the same manner, complicating interpretation. There is a need, therefore, to understand weathering rates at a larger scale and to integrate geomorphology, pedology and geochemistry to interpret complex soil systems. A Critical Zone Exploration Network (CZEN), in which sites and scientists are linked across environmental gradients, is being developed to investigate rates of soil formation. Here, we report rates of soil formation on shale as a function of climate (Figure 1).

The conceptual framework of the CZEN sites is not unlike the soil formation model proposed by Jenny (1941) in which the type of soil formed at any given location varies as a function of climate, organisms, relief, parent material and time. When research sites are chosen based on manipulating one variable while holding the others relatively constant, processes, such as rock weathering, can be more effectively quantified. The approach of investigating large-scale environmental gradients has already been successfully employed in investigating the dissolution of feldspar in loess parent material along the Mississippi River in the United States (Williams *et al.* 2009). In much the same vein, the CZEN outlined here will test the hypothesis that shale weathering rates vary predictably as a function of climate.

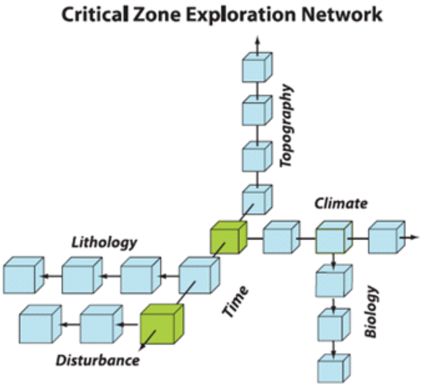

Figure 1. Conceptual diagram for the Critical Zone Exploration Network (CZEN) used to test environmental gradients. Figure from Brantley *et al.* (2007).

Methods

Site selection

The climosequence is defined by the following seven sites: Wales, New York, Pennsylvania, Virginia, Tennessee, Alabama and Puerto Rico (Figure 2). Wales provides a cold/wet end member of the transect and Puerto Rico represents a warm/wet end member. Sites are located on the same Silurian-age, Fe-rich, organic poor shale, with the exception of Puerto Rico, which is located on a chemically similar, but younger, shale. To identify sites, GIS was used to isolate similar locations with respect to lithology, aspect, topography and land use. After locating potential sites, field work at each site confirmed similarities. Furthermore, all sites were located on "1-D" profiles, along ridgetop topographic positions, to represent the simplest model of soil-rock interaction (Jin *et al.* 2009). In a "1-D" profile water enters the top of the profile and proceeds vertically to bedrock, at which point lateral flow may occur; this simple model facilitates comparison across sites (Brantley and White 2009). Also, stratigraphy was considered to ensure similar sampling locations within the shale unit (Giri 2008). Finally, attempts were made to minimize the contributions from glacial till and colluviums as much as possible. Variables which varied unavoidably among sites included vegetation and exposure age. An implicit hypothesis underlying our study is therefore that the effects of these variables on rates of soil formation are minor compared to climate.

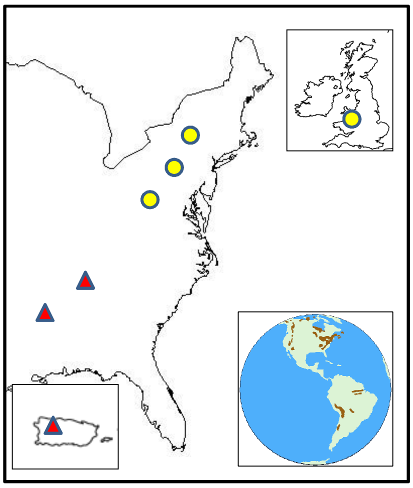

Figure 2. Sample site locations on the climosequence. Circles represent sites already sampled while triangles represent future sampling sites. Lower left inset shows Puerto Rico, upper inset shows Wales (Plynlimon watershed) and inset globe shows distribution of Silurian-age shales in the western hemisphere.

Soil sampling and chemistry

Soils at each site were sampled by depth (10 cm increments) using a 5 cm diameter auger. Bedrock depth was defined as depth to refusal. Bulk soil chemistry was measured by grinding soils with a mortar and pestle to pass through a 100 mesh sieve (150 µm). A Li metaborate digestion followed by inductively coupled plasma atomic adsorption spectroscopy (ICP-AES) determined major elemental oxides (Medlin *et al.* 1969). To quantify the relative mass of elements lost from the parent rock, the dimensionless coefficient τ was calculated, with a value < 1 indicating depletion of an element relative to unweathered bedrock and a value > 1 showing enrichment relative to bedrock (Brimhall and Dietrich 1987; Chadwick *et al.* 1990). For these calculations, titanium was used as the immobile element and parent was defined as the average of multiple bedrock samples collected at each location. Error was propagated from analytical error plus the standard deviation of parent compositions for multiple shale analyses on samples collected near the auger sites.

Results

Presented here are preliminary results from sites in Wales, Pennsylvania (PA) and Virginia (VA). Depth to bedrock is nearly identical in Wales and Pennsylvania (35 cm and 30 cm, respectively) while depth to bedrock in Virginia is 100 cm. Sodium, which is inferred from detailed mineralogy at the PA site to be present as feldspar, shows depletion profiles at all three sites that vary in extent with location (Figure 3) (Jin *et al.* 2009). In Wales and PA, approximately 20% depletion of Na is observed at land surface, whereas almost 50% depletion relative to parent composition is observed in VA. The bottommost sample for all three profiles, however, does not return to the average parent composition for that site, suggesting that the depth to unweathered rock is significantly deeper than the bottom of the augered profile.

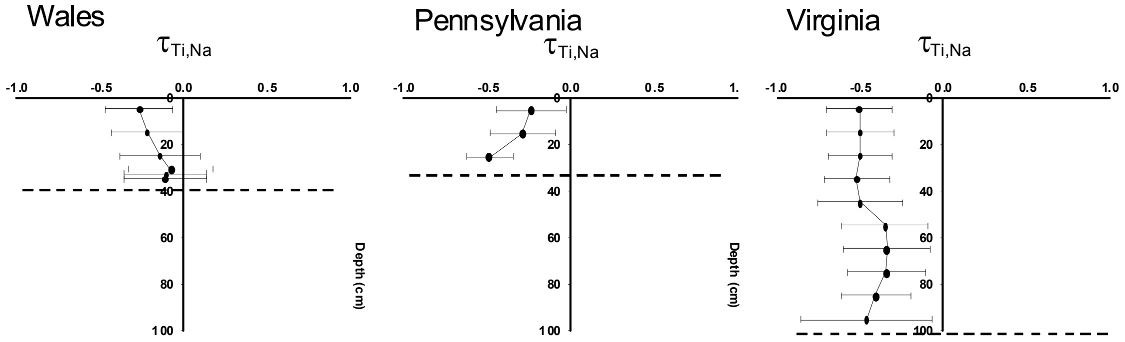

Figure 3. τ values for Na as a function of depth in Wales, Pennsylvania and Virginia. Dotted lines represent depth to bedrock at each site.

The fraction of Na depleted relative to the average parent composition varies as a function of both mean annual temperature (MAT) and mean annual precipitation (MAP). The total fraction of Na depleted from the entire augered profile increases linearly with MAT, from only 20% Na lost at the coldest site in Wales to almost 50% at the warmest site in VA. In contrast, the fraction of Na lost as a function of MAP increases from PA to VA but decreases in Wales. While the site in Wales receives 1.6 to 2.5 times more precipitation than VA or PA, the fact that soils are the least depleted in Na in Wales documents the strong role of temperature in controlling weathering of feldspar.

Conclusion

Preliminary data from a large-scale climosequence suggests soil chemistry and depth to bedrock vary with changes in temperature and precipitation. Na has been depleted in all profiles examined thus far, with more depletion relative to bedrock at the warmest site. In the colder, wetter sites, only 20% of Na has been weathered from the soil profile while the warmer, wet VA site has lost 44% of Na compared to original parent. Na depletion varies monotonically with temperature but not with precipitation. Although data are preliminary, the climosequence approach to addressing the question of shale weathering rates shows potential for quantifying weathering processes in soils underlain by the same lithology. The approach outlined here will also be used to investigate other environmental variables. For example, lithologic contrasts will be analysed between the organic-poor shale reported here and another site located on organic-rich shale, also in PA. Also, land use contrasts can be compared in Wales, where two catchments, roughly identical in size and lithology, are managed as grassland and forest – these sites can therefore provide insight on the effects of land use on shale weathering. Finally, this climosequence could eventually be extended to an equator-to-pole gradient study of Silurian-age shale soils extending from West Africa to Spain, Wales, Norway and Svalbard.

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