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The effects of climate and landscape position on chemical denudation and mineral transformation in the Santa Catalina mountain critical zone observatory

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ABSTRACT

Understanding the interactions of climate, physical erosion, chemical weathering and pedogenic processes is essential when considering the evolution of critical zone systems. Interactions among these components are particularly important to predicting how semiarid landscapes will respond to forecasted changes in precipitation and temperature under future climate change. The primary goal of this study was to understand how climate and landscape structure interact to control chemical denudation and mineral transformation across a range of semiarid ecosystems in southern Arizona. The research was conducted along the steep environmental gradient encompassed by the Santa Catalina Mountains Critical Zone Observatory (SCM-CZO). The gradient is dominated by granitic parent materials and spans significant range in both mean annual temperature (>10 °C) and precipitation (>50 cm a^{-1}), with concomitant shift in vegetation communities from desert scrub to mixed conifer forest. Regolith profiles were sampled from divergent and convergent landscape positions in five different ecosystems to quantify how climate-landscape position interactions control regolith development. Regolith development was quantified as depth to paralithic contact and degree of chemical weathering and mineral transformation using a combination of quantitative and semi-quantitative X-ray diffraction (XRD) analyses of bulk soils and specific particle size classes. Depth to paralithic contact was found to increase systematically with elevation for divergent positions at approximately 28 cm per 1000 m elevation, but varied inconsistently for convergent positions. The relative differences in depth between convergent and divergent landscape positions was greatest at the low and high elevation sites and is hypothesized to be a product of changes in physical erosion rates across the gradient. Quartz/Plagioclase (Q/P) ratios were used as a general proxy for bulk regolith chemical denudation. Q/P was generally higher in divergent landscape positions compared to the adjacent convergent hollows. Convergent landscape positions appear to be collecting solute-rich soil–waters from divergent positions thereby inhibiting chemical denudation. Clay mineral assemblage of the low elevation sites was dominated by smectite and partially dehydrated halloysite whereas vermiculite and kaolinite were predominant in the high elevation sites. The increased depth to paralithic contact, chemical denudation and mineral transformation are likely functions of greater water availability and increased primary productivity. Landscape position within a given ecosystem exerts strong control on chemical denudation as a result of the redistribution of water and solutes across the landscape surface. The combined data from this research demonstrates a strong interactive control of climate, landscape position and erosion on the development of soil and regolith.

1. Introduction

1.1. Critical zone systems

Critical zone systems are constantly evolving with respect to energy and water fluxes through the environment. The research being performed at the SCM-CZO is focused on understanding how energy and water fluxes change along a well-constrained climate gradient in a "sky island" system of southern Arizona. The combined effects of biological, chemical and physical processes are being studied to predict and quantify the relative magnitude of these fluxes. Critical zone development is altered by landscape evolution and the redistribution of water through the system. Climate, erosion and landscape position have all been linked to landscape evolution. Erosion and climate strongly correlate with plagioclase weathering, mass loss and rates of chemical weathering (Rasmussen et al., 2011). Water availability is a critical factor that controls mineral transformation and chemical denudation processes within the landscape. The predicted changes in precipitation due to climate change would likely alter water

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availability dynamics in soil and regolith environments. Therefore, understanding the interactive control among climate, landscape position and erosion on regolith development is essential for predicting ecosystem responses to climate change. In semiarid environments, it is hypothesized that geologic parent material, water availability and topographic position are the dominant factors that control the amount and degree of chemical denudation and mineral transformation in an ecosystem.

1.2. Topographic position

Research conducted over a range of climates has demonstrated topographic position control on soil and regolith properties such as local distribution of clays, ions and minerals across a landscape (Weitkamp et al., 1996; Tardy et al., 1973; Jenny, 1941). Following the conceptual model of Ruhe and Walker (1968), the upper divergent landscape positions of a steep-sided, erosional hillslope serve as a source for clays, minerals and other soluble soil materials to lower, more energetically favorable convergent positions (Fig. 1b). Soil accumulation at these lower slope positions is a reflection of water availability in a given environment and the steepness of the hillslope. Yoo et al. (2007) investigated topographic position with respect to chemical denudation rates and soil transport. This research provides support for quantifying the combined effects of soil chemical weathering and physical erosion processes on regolith development with respect to landscape position. Mass loss and chemical denudation have also been established as contributing factors to the lowering of landscape surfaces (Green et al., 2004). The research here builds from this general framework to explicitly quantify landscape position effects on water and mass redistribution across a broad climate space.

2. Results and discussion

2.1. General site characteristics

Soil samples were collected along the SCM environmental gradient (Figs. 1 and 2). The geological and biological components of the SCM are well-constrained, making the system ideal for the study of climatic variation and landscape structure across the established ecosystems (Whittaker and Niering, 1965). Soils were described and sampled from the following vegetation zones: desert scrub, desert grasslands/oak, low and mid-elevation Ponderosa Pine sites, and mixed conifer. The climate gradient currently consists of five ecosystems formed on granitic parent materials and two ecosystems formed on schist. The sites have been selected in convergent–divergent landscape unit pairs from zero order catchments for a total of four soil pedons per ecosystem (Fig. 3). The landscape unit pairs were sampled from north-facing positions in a latitudinal belt consisting of sites similar to one another in terms of slope and landform type (convergent hollows and divergent noses). The sampling scheme allowed for comparisons between soils developing in contrasting climates, landscape positions and on different geologic parent materials in the high elevation locations.

2.2. Depth to paralithic contact

Soil thickness, defined here as the depth to a paralithic contact, generally increased with elevation in both the convergent and divergent granitic sites (Fig. 4a). The relative difference in depth between the two landscape positions was largest at the low elevation desert scrub site and the high elevation mixed conifer site. These differences are hypothesized to be a function of changes in physical erosion rates and vegetation cover. Erosion rates estimated based on ^{10}Be concentration at the saprolite–bedrock interface from divergent granitic profiles spanning the Rincon Mountain environmental gradient (a Critical Zone Exploration Network seed site adjacent to the SCM-CZO) indicate substantial variation with elevation (Fig. 1, Rasmussen, 2008). These data were used as a general proxy for understanding trends between erosion rates and soil thickness at the current study sites. The cosmogenic nuclide constrained physical erosion rates were relatively high in the desert scrub ecosystem, decreased for mid-elevation ecosystems, and increased to relatively high rates in the mixed conifer ecosystem (Fig. 4b). Based on soil depth and physical erosion rates, soil mean residence times vary from ~3 ka in desert scrub locations to

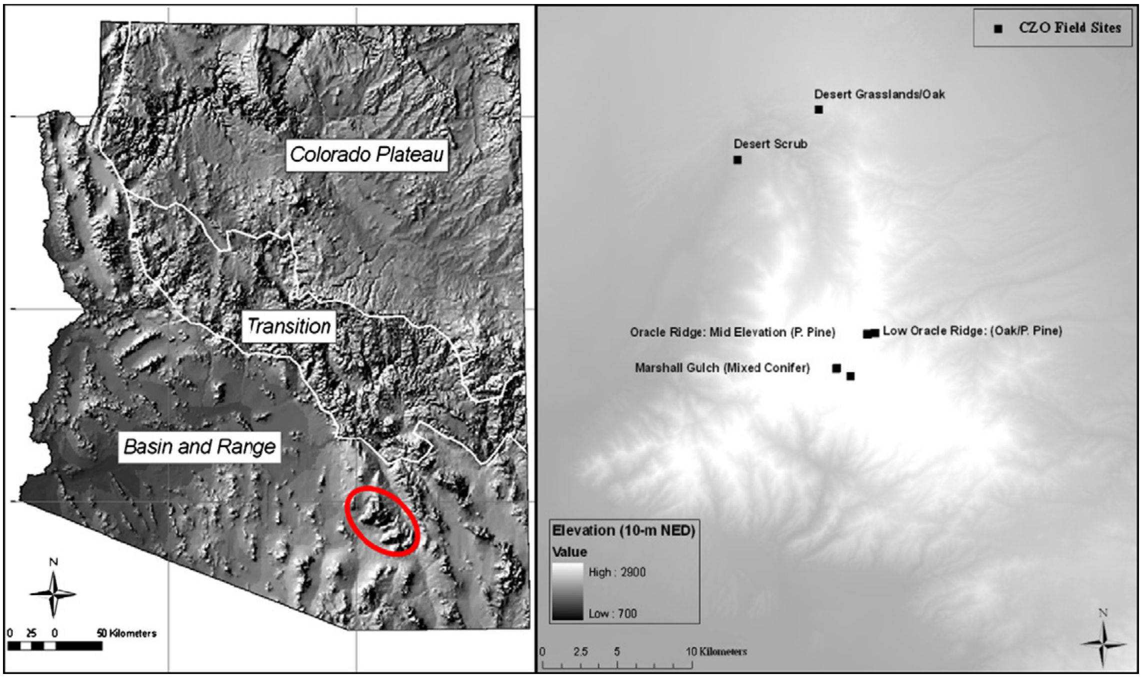

Fig. 1. (a) Map showing the location of the Santa Catalina Mountains in southern Arizona (from Rasmussen (2008)). (b) DEM (Digital Elevation Model) containing the granitic site locations of five ecosystems sampled for this research.

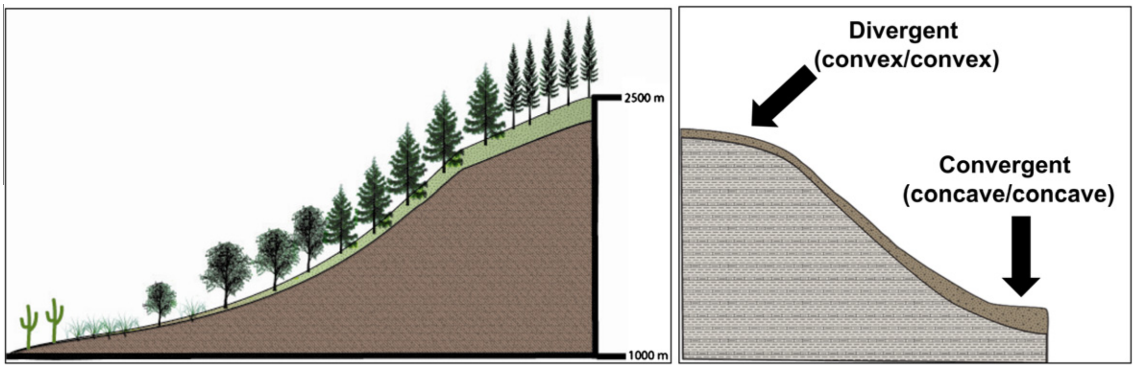

Fig. 2. (a) General broad scale depiction of vegetation zones encompassing the environmental gradient of the Santa Catalina Mountains, Arizona. (b) Local scale representation of divergent and convergent landscape positions sampled in the current study.

Fig. 3. Photographs showing the vegetation differences between a (a) low elevation desert scrub site and a (b) high elevation mixed conifer convergent site.

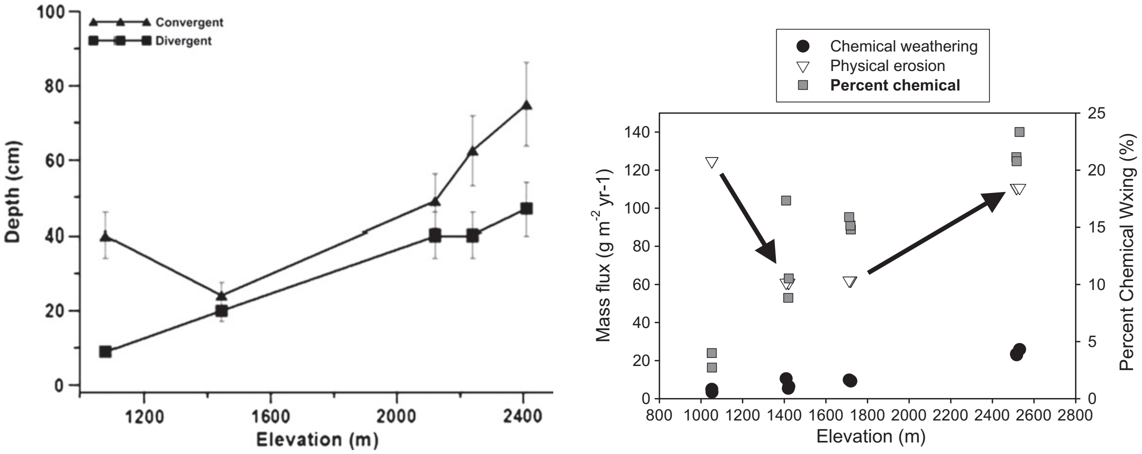

Fig. 4. (a) Average depth to paralithic contact measurements recorded for soils collected from convergent and divergent landscape positions across the Santa Catalina Mountains gradient. (b) Physical and chemical erosion rate calculations based on ^{10}Be data collected from granitic saprolite–bedrock samples in the Rincon Mountains in southern Arizona (from Rasmussen (2008)).

~15 ka in mixed conifer systems. The varying physical erosion rates are hypothesized to be a function of vegetative cover and transport mechanisms, with relatively bare surfaces of desert scrub sites favoring surface wash and removal, whereas the relatively dense grass cover of mid-elevation locations limits surface removal (Fig. 4a and b). In contrast, physical erosion in the high elevation locations is likely dominated by bioturbation and tree throw, a mechanism with the ability to move substantial material downslope. The erosion pattern for divergent landscapes and the supply of physical material corresponds with the relative differences in regolith depth between divergent and convergent landscape positions in the SCM-CZO.

2.3. Quantitative mineralogy

Quantitative XRD results of the bulk fine-earth fraction indicated significant differences in chemical denudation between landscape positions, and between granite and schist parent materials in the high elevation environments (Fig. 5). The Quartz/Plagioclase (Q/P) ratio was used to quantify the general rates of feldspar weathering whereby high Q/P indicates greater plagioclase loss from the system via chemical weathering. The Q/P data indicated greater relative plagioclase loss in the divergent landscape positions for both schist and granitic soils. The relative lack of weathering in the convergent positions suggests these positions are

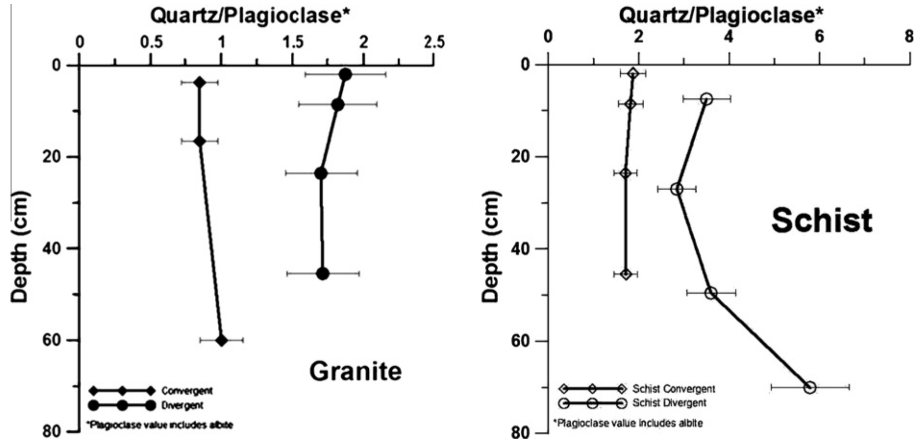

Fig. 5. Quartz/Plagioclase ratios for soils formed on (a) granite and (b) schist parent material (Rasmussen, C., Unpublished data). Q/P ratio is a general proxy for soil mineral weathering with higher Q/P ratios indicating that more plagioclase loss has occurred.

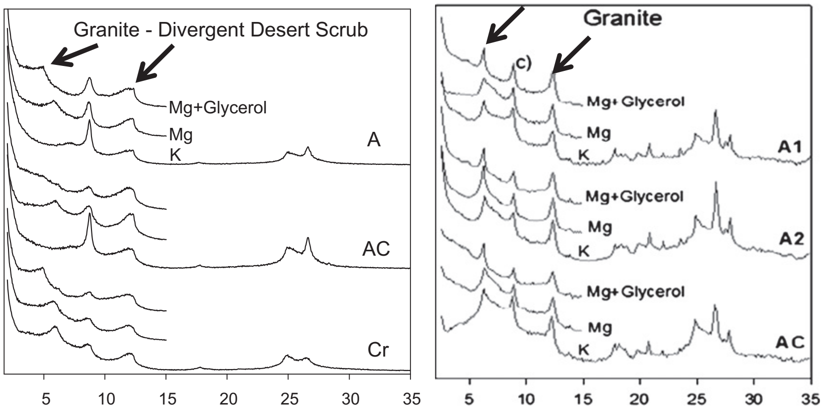

Fig. 6. X-ray Diffraction patterns for clay mineralogy treatments on samples from (a) a low elevation, desert scrub site and (b) a high elevation, mixed conifer site (from Heckman and Rasmussen (in press)). The arrows highlight smectite and halloysite (left to right) as two of the dominant clay minerals in (a) and vermiculite and kaolinite as dominant clay minerals in (b).

likely accumulating solute-rich soil–water from adjacent divergent landscape units, thus shutting down the local chemical weathering gradient in these positions.

2.4. Clay mineralogy

Clay minerals in the granitic desert scrub convergent and divergent landscape positions were dominated by smectite, illite, and partially to fully dehydrated halloysite (Fig. 6a). A minor amount of vermiculite was also identified. Smectite is a common mineral weathering end product in dry, silica-rich environments, consistent with the findings here. However, smectite addition via dust may also contribute to the smectite found in these soils. In contrast, halloysite is typically found in warm, humid environments and would not be expected to form in the hot, dry desert scrub soils. It is hypothesized that a combination of climate and soil mean residence time control halloysite formation in these soils. The limited water availability in the desert scrub vegetation zone likely leads to the incomplete transformation of a primary feldspar mineral to kaolinite, favoring the accumulation of the intermediate weathering product halloysite. Further, the mean residence times of the low elevation soils are relatively short, on the order of ~3 ka, suggesting that time may be a factor limiting mineral transformation in this environment.

Clay minerals in high elevation, mixed-conifer soil were dominated by vermiculite, illite and kaolinite. Minor amounts of smectite were suggested in saprolite layers as indicated by a 1.4 nm peak that showed partial expansion to 1.8 nm with Mg-glycerol solvation. The kaolinite peak in these soils was sharp and well-defined (Fig. 6b). Kaolinite and vermiculite are both indicative of greater mineral transformation to stable end products. Larger amounts of these minerals would be expected in high elevation sites because of increased water availability, allowing for more mineral transformations.

3. Conclusions

The current data showed a strong relationship among pedogenesis, climate, landscape position and erosion. Depth to paralithic contact increased with elevation in both convergent and divergent landscape positions, likely related to increased water availability and primary productivity. The greatest difference in relative depth between landscape positions was observed at the low and high elevation sites where calculated physical erosion rates were highest. Q/P ratios were higher in the divergent landscape positions compared to the adjacent convergent sites. Chemical denudation in the convergent landscape positions has possibly been inhibited by the accumulation of solute-rich soil–waters from divergent positions. The clay mineral assemblage was dominated by smectite at the low elevation sites compared to vermiculite and kaolinite at the higher elevation sites. Partially dehydrated halloysite was identified at the low elevation sites. The “incomplete” mineral transformations found at the hot, dry, and young low elevation sites are hypothesized to be a result of age and climatic conditions. The results from this study support previous findings indicating strong interactive controls among climate, erosion and landscape position on regolith development and landscape evolution.

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