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A cross-scale study of feldspar transformation in the Santa Catalina Mountain Critical Zone Observatory

Rebecca A. Lybrand*[a], Craig Rasmussen[a]

[a]Department of Soil, Water and Environmental Science, The University of Arizona, Tucson, AZ 85721, USA

Abstract

The critical zone evolves from coupled biological, physical, and geochemical processes that we quantify here across varying climatic and topographic conditions. The specific objective of this work was to examine how climate, landscape position, and vegetation drive feldspar weathering across the Santa Catalina Mountain Critical Zone Observatory, which exhibits considerable range in temperature (24 to 10°C), precipitation (25 to 85 cm), and vegetation community composition (desert scrub → mixed conifer). Granitic soils and parent rock were characterized using a profile development index, quantitative x-ray diffraction, and electron microprobe analyses. Profile development indices increased linearly with increasing MAP/PET ratios ($r^2 = 0.48$), with higher degrees of soil development in convergent footslope positions. Bulk soils from the desert scrub sites were enriched in total feldspar relative to quartz in both landscape positions, ranging from +2 to +24% compared to the mixed conifer soils, which exhibited maximum total feldspar depletions of -13% in the convergent soils and -3% in the divergent sites. Microscale Na depletions increased significantly from unaltered to altered feldspar grain sections, with more tightly constrained Na losses in the mixed conifer grains compared to those from the desert scrub environment. Greater soil development and feldspar transformation in the conifer soils documented interactive climate and vegetation controls on mineral weathering in bulk soils and at the microscale. Furthermore, the larger profile development indices in the convergent landscapes demonstrated the importance of studying hillslope-scale soil development along environmental gradients, where localized increases in mineral transformation likely results from greater moisture availability and organic inputs in water-gathering landscape positions.

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Keywords: critical zone; feldspar; microscale weathering; profile development index; environmental gradient; climate; landscape position

* Corresponding author. Tel.: + 1 760 271 5219; fax: + 1 520 621 1647.
E-mail address: rlybrand@email.arizona.edu

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1. Introduction

The critical zone is the interface between abiotic and biotic constituents that spans from the vegetation canopy through the groundwater[1] and represents an open system shaped by the climate, topography, and vegetation communities of a given environment[2]. Mineral transformation is a crucial component to landscape evolution, having thus been examined across varying climate/vegetation gradients[3-7], landscape positions[8-10], and scales of study[11-13]. Plagioclase feldspars are one of the first minerals to undergo alteration in the mineral weathering environment[14] and have been the focus of laboratory[15-16] and field studies[17-18].

The objective of this paper was to synthesize pedon to microscale observations of soil development and feldspar weathering across semiarid sites spanning the Santa Catalina Mountain Critical Zone Observatory (SCM-CZO). The Santa Catalina Mountain Critical Zone Observatory is located along an environmental gradient in southern Arizona where co-varying climate and vegetation community properties have generated distinct changes in soil development across a relatively short distance (<20 miles)[4,19].

2. Study area and methods

Soils and rocks were sampled on north-facing slopes within the SCM-CZO from five climate-vegetation zones, referred to as *desert scrub*, *desert grasslands/oak woodlands*, *low pine*, *mid pine*, and *mixed conifer* (Fig. 1). Within each climate-vegetation zone, samples were collected from two divergent summit and two convergent footslope landscape positions to account for topographic controls on mineral transformation (Fig. 2). Divergent positions shed water, soil materials, and dissolved organic carbon downslope to convergent footslopes where greater moisture availability generally results in enhanced mineral weathering processes[8-9]. The degree of soil development was quantified for all pedons in the study using Harden's profile development index (PDI)[20-21], which is an empirical method that calculates developmental indices based on morphological differences between a soil horizon and representative parent material. The *desert scrub* and *mixed conifer* sites represent the two climatic end members of the SCM-CZO environmental gradient and were selected for additional mineralogical and microscale characterization in this study. Total feldspar and quartz mineral weight percentages of the soils and parent rocks were determined by quantitative x-ray diffraction and were used as the respective mobile and immobile constituents in mass transfer calculations. Mineral losses and gains in the bulk soils were calculated using the dimensionless mass transfer coefficient that accounts for coarse fragments and organic matter content[22]. Microscale feldspar transformations were quantified by Na/Al ratios, where Na loss serves as a proxy for plagioclase feldspar alteration[23]. Elemental weight percentages determined by electron microprobe analyses were used to calculate the Na/Al ratios for unaltered, edge, and altered grain sections of feldspars in the desert scrub and mixed conifer sites. The results represent a cross-scale investigation of feldspar mineral transformation between soil profiles, within bulk soils, and across mineral grains (Fig. 3).

Figure 1. Photographs of the five field sites examined in the study including a) desert scrub, b) desert grasslands/oak woodlands, c) low pine, d) mid pine, and e) mixed conifer.

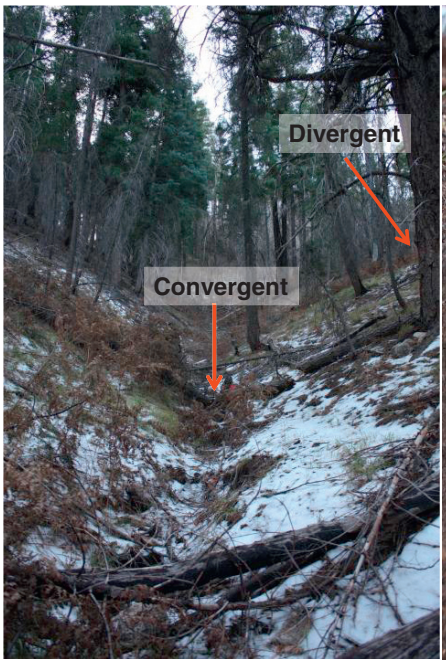

Figure 2. A photograph demonstrating the convergent and divergent landscape positions sampled within each climate-vegetation zone.

Figure 3. A schematic depicting the scales addressed in this study, ranging from the (a) soil profile, (b) bulk soil samples, and (c) microscale investigations of mineral grains.

3. Results and Discussion

3.1 Profile development indices

The greatest degree of pedon-scale soil development was observed in the convergent landscape positions of the pine and conifer sites, as indicated by steeper increases in PDIs for convergent positions compared to more gradual PDI increases in divergent sites[24]. For example, PDIs increased from 7.5 in the desert scrub convergent soils to 17 in the mixed conifer soils compared to an increase from 2.5 to 7.4 for the respective divergent sites. These findings coincide well with the catena model where the local redistribution of water, soil materials, and nutrients contribute to greater soil development in convergent footslope positions versus summit and backslope landscape positions[8,25-26]. The SCM profile development indices are also similar to other desert ecosystems of the southwest, where PDIs spanned 2.3 to 34 for Holocene-aged systems[21,27]. Furthermore, the PDIs calculated for the convergent and divergent landscape positions in this study exhibited similar trends to other toposequence studies where PDIs were at least two times greater in footslopes compared to other positions on the hillslope[28-30]. The profile development index was an effective tool for quantifying climate and landscape position controls on soil development across the SCM-CZO and exhibited similar ranges to other semiarid ecosystems.

3.2 Feldspar mineral transformations

Feldspar weathering was examined in bulk soil and microscale grain samples where climate and landscape position both played a role in mineral alteration processes. The desert scrub soils were all enriched in total feldspar mineral weight percentages relative to quartz with gains from +2 to +21% in convergent sites and +3 to +24% in divergent sites[31], which resulted in distinct addition profiles that did not differ by landscape position. Addition profiles here are indicative of dust input to the soil surface with subsequent redistribution within the pedon[32]. Feldspar additions have been documented through electron microprobe analyses of dust collected from dust traps installed at the desert scrub field site (Fig. 4). The mixed conifer soils exhibited variable bulk soil feldspar mass transfer coefficients that differed by landscape position. For example, the feldspar losses were relatively uniform with depth in the convergent positions where depletions ranged from -13% to a slight enrichment of +0.2%. The mixed conifer divergent soils were generally enriched in total feldspar with gains of +2 to +10%. However, feldspar losses of -0.9 to -3% were detected in the subsurface of the second divergent pedon. The variation in feldspar mass transfer coefficients for the mixed conifer soils suggests a combination of feldspar weathering and dust deposition, particularly in the divergent summit positions where dust capture may be more effective than in downslope convergent sites.

Mineral transformations were also examined at the microscale where significant decreases in Na/Al ratios were measured across feldspar grains from the desert scrub and mixed conifer field sites[33]. Backscattered electron images document the relative differences in transformation between the desert scrub and mixed conifer feldspar grains (Fig. 5a,b). The Na/Al ratios calculated for feldspars in the desert scrub soils decreased minimally from unaltered to edge sections, and exhibited significant decreases in the transition from center and edge sections to altered materials ($p<0.001$). The mixed conifer samples demonstrated the greatest degree of microscale feldspar alteration in the study (Fig. 5b). The most pronounced Na losses occurred between the unaltered and altered grain sections where Na/Al averages decreased

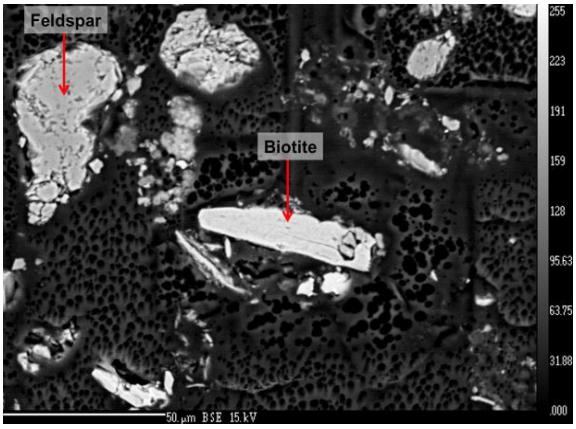

Figure 4. Backscattered electron image documenting feldspar and biotite grains in dust samples collected at the desert scrub site.

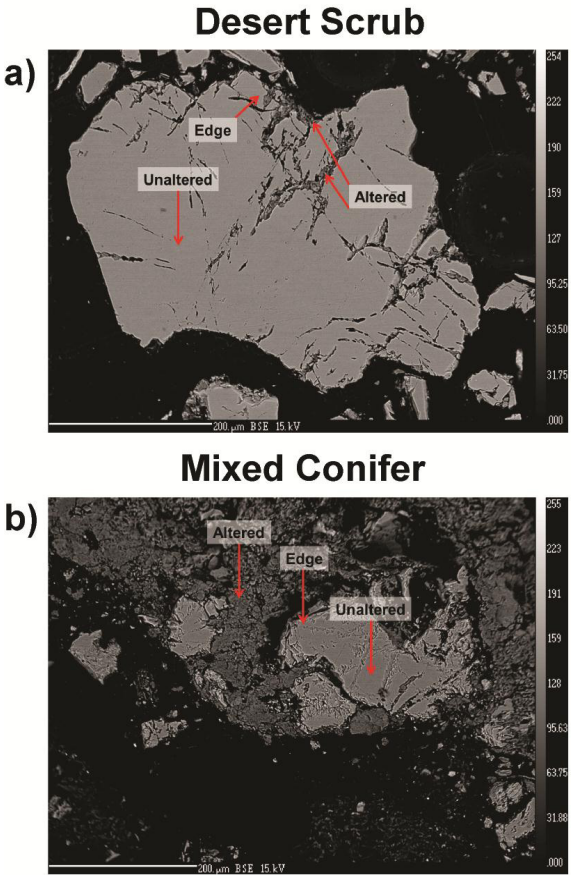

Figure 5. Plagioclase grains analyzed from the a) desert scrub and b) mixed conifer field soils. The labels denote how grain sections were classified across sites[33].

from ~0.6 to ~0.04. The enhanced feldspar transformations in the mixed conifer soils are likely due to a combination of factors including greater moisture availability[23,34] and increased biological weathering processes resulting from higher rates of primary production and organic acid inputs to the soil environment[35-36].

4. Conclusions

A cross-scale analysis of feldspar mineral transformation connected measures of pedon-scale soil development to changes in total feldspar and sodium distribution in bulk soils and across feldspar grains. Greater soil development in the mixed conifer pedons corresponded to increased total feldspar and sodium losses. Desert scrub soils presented less evidence for feldspar transformation including lower profile development indices, gains in total feldspar percentages attributed to dust deposition, and less Na chemical depletion at the microscale. Greater soil development in convergent positions relative to adjacent divergent sites was consistent across all sites, with the highest degree of total feldspar depletion occurring in the conifer convergent locations. These findings confirm the interactive role of climate, vegetation, and landscape position in shaping the critical zone, where increased moisture availability and biological production are likely driving feldspar transformation across various scales of study.

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References

1. NRC. Basic research opportunities in earth sciences. National Academies Press. National Research Council, Washington DC; 2001.
2. Chorover J, Troch PA, Rasmussen C, Brooks PD, Pelletier JD, Breshears DD, Huxman TE, Kurc SA, Lohse KA, McIntosh JC, Meixner T, Schaap MG, Litvak ME, Perdrial J, Harpold A, Durcik M. How Water, Carbon, and Energy Drive Critical Zone Evolution: The Jemez-Santa Catalina Critical Zone Observatory. *Vadose Zone J* 2011;**10**:884-899.
3. Jenny H. *Factors of Soil Formation: A System of Quantitative Pedology*. New York: McGraw-Hill; 1941.
4. Whittaker R, Niering W. Vegetation of the Santa Catalina Mountains, Arizona: a gradient analysis of the south slope. *Ecology* 1965;**46**:429–452.
5. Dahlgren RA, Boettinger JL, Huntington GL, Amundson RG. Soil development along an elevational transect in the western Sierra Nevada, California. *Geoderma* 1997;**78**:207–236.
6. Graham RC, O'Geen AT. Soil mineralogy trends in California landscapes. *Geoderma* 2010;**154**: 418-437.
7. Rasmussen C, Dahlgren RA, Southard RJ. Basalt weathering and pedogenesis across an environmental gradient in the southern Cascade Range, California, USA. *Geoderma* 2010;**154**:473–485.
8. Huggett RJ. Soil landscape systems: a model of soil genesis. *Geoderma* 1975;**13**:1–22.
9. Muhs DR. The influence of topography on the spatial variability of soils in Mediterranean climates. In: Thorn CE, editors. *Space and Time in Geomorphology*. London: George Allen and Unwin; 1982. p. 269-284.
10. Khomo L, Hartshorn AS, Rogers KH, Chadwick OA. Impact of rainfall and topography on the distribution of clays and major cations in granitic catenas of southern Africa. *Catena* 2011;**87**:119–128.
11. Merritts DJ, Chadwick OA, Hendricks DM, Brimhall GH, Lewis CJ. The mass balance of soil evolution on late Quaternary marine terraces, northern California. *Geol. Soc. Am. Bull.* 1992;**104**:1456-1470.
12. Jordan G, Higgins SR, Eggleston CM, Swapps SM, Janney DE, and Knauss KG. Acidic dissolution of plagioclase: In situ observations by hydrothermal atomic force microscopy. *Geochim. Cosmochim. Acta* 1999;**63**:3183-3191.
13. Hellmann R, Penisson JM, Hervig RL, Thomassin JH, Abrioux MF. An EFTEM/HRTEM high-resolution study of the near surface of labradorite feldspar altered at acid pH: evidence for interfacial dissolution-reprecipitation. *Phys. Chem. Miner.* 2003;**30**:192–197.
14. White AF, Bullen TD, Schulz MS, Blum AE, Huntington TG, Peters NM. Differential rates of feldspar weathering in granitic regoliths. *Geochim. Cosmochim. Acta* 2001;**65**:847–869.
15. Blum AE, Stillings LL. Feldspar dissolution kinetics. In: White AE, Brantley SL, editors. *Chemical Weathering Rates of Silicate Minerals*. Washington DC: Mineralogical Society of America; 1995. p. 463–481.
16. White AF, Brantley SL. The effect of time on the weathering of silicate minerals: why do weathering rates differ in the laboratory and field? *Chem. Geol.* 2003;**202**:479–506.

17. White A, Blum A, Schulz M, Bullen TD, Harden JW, Peterson ML. Weathering rates of a soil chronosequence on granitic alluvium: I. Quantification of mineralogical and surface area changes and calculation of primary silicate reaction rates. *Geochimica et Cosmochim. Acta* 1996;**60**:2533–2550.
18. Zhu C, Veblen DR, Blum AE, Chipera SJ. Naturally weathered feldspar surfaces in the Navajo Sandstone aquifer, Black Mesa, Arizona: Electron microscopic characterization. *Geochim. Cosmochim. Acta* 2006;**70**:4600–4616.
19. Whittaker RH, Buol SW, Niering WA, Havens YH. A Soil and Vegetation Pattern in the Santa Catalina Mountains, Arizona. *Soil Sci.* 1968;**105**:440–450.
20. Harden, JW. A quantitative index of soil development from field descriptions: Examples from a chronosequence in central California. *Geoderma* 1982;**28**:1-28.
21. Harden JW, Taylor EM. A quantitative comparison of soil development in four climatic regimes. *Quaternary Res* 1983;**20**:342-359.
22. Porder S, Hilley GE, Chadwick OA. Chemical weathering, mass loss, and dust inputs across a climate by time matrix in the Hawaiian Islands. *Earth Planet. Sci. Lett.* 2007;**258**:414-427.
23. Rasmussen C, Brantley S, Richter D, Blum A, Dixon J, White AF. Strong climate and tectonic control on plagioclase weathering in granitic terrain. *Earth Planet. Sci. Lett.* 2011;**301**:521–530.
24. Lybrand RA, Rasmussen C. Quantifying climate and landscape position controls on soil development in semiarid ecosystems. *Soil Sci. Soc. Am. J.* (In review).
25. Ruhe RV, Walker PH. Hillslope models and soil formation. I. Open systems. *Transactions of the 9th International Congress of Soil Science* 1968;**4**:551-560.
26. Birkeland PW. *Soils and Geomorphology*. New York: Oxford University Press; 1999.
27. Harden JW, Taylor EM, Hill C, Mark RK, McFadden LD, Reheis MC, Sowers JM and Wells SG. Rates of soil development from four soil chronosequences in the southern Great Basin. *Quaternary Res* 1991;**35**:383-399.
28. Swanson DK. Soil catenas on Pinedale and Bull Lake moraines, Willow Lake, Wind River Mountains, Wyoming. *Catena* 1985; 12:329-342.
29. Miller DC, Birkeland PW. Soil catena variation along an alpine climatic transect, northern Peruvian Andes. *Geoderma* 1992;**55**:211-223.
30. Applegarth MT, Dahms DE. Soil catenas of calcareous tills, Whiskey Basin, Wyoming, USA. *Catena* 2001;**42**:17-38.
31. Lybrand, RA, Rasmussen C. Mineralogical and geochemical properties of granitic soils and parent rock along the Santa Catalina Critical Zone Observatory. (In prep).
32. Brantley SL, Goldhaber MB, Ragnarsdottir KV. Crossing disciplines and scales to understand the critical zone. *Elements* 2007;**3**:307-314.
33. Lybrand RA, Rasmussen C. Linking soil element-mass-transfer to microscale mineral weathering across a semiarid environmental gradient. *Chem. Geol.* 2014; http://dx.doi.org/10.1016/j.chemgeo.2014.04.022.
34. Egli M, Mirabella A, Sartori G, Fitze P. Weathering rates as a function of climate: results from a climosequence of the Val Genova (Trentino, Italian Alps). *Geoderma* 2003;**111**:99–121.
35. Stillings LL, Drever JI, Brantley SL, Sun Y, Oxburgh R. Rates of feldspar dissolution at pH 3-7 with 0-8 m M oxalic acid. *Chem. Geol*. 1996;**132**:79-89.
36. Ullman WJ, Kirchman DL, Welch SA, Vandevivere P. Laboratory evidence for microbially mediated silicate mineral dissolution in nature. *Chem. Geol.* 1996;**132**, 11-17.