KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FOURTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2011
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INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO
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ASSESSING EOLIAN CONTRIBUTIONS TO SOILS IN THE BOULDER CREEK CATCHMENT, COLORADO

JAMES A. MCCARTHY, Williams College
Research Advisor: David P. Dethier

INTRODUCTION

The Critical Zone

The Critical Zone extends from fresh rock to the top of the vegetation canopy and is where the biosphere, atmosphere, hydrosphere, and rock materials interact (Anderson et al., 2007). The complex processes occurring in the Critical Zone release raw materials from minerals and create substrates for terrestrial life, supporting microbial, plant, and faunal activity. Rates of chemical and mechanical processes vary temporally and spatially due to gradients in climate, rock materials, and slope. Soil is the highly weathered, top-most part of the regolith, but is distinct because of its unique layered habit. These layers (horizons), record more intense weathering conditions at the surface, and record downward transport of chemical weathering products and organic additions from the biosphere (Anderson and Anderson, 2010). Field and laboratory studies of soils enrich models of rock weathering, chemical and mechanical transport, and regolith formation. Results help to highlight the role of soil-forming processes as indicators of the geomorphic controls on Critical Zone processes.

The Critical Zone can be thought of as a bottom-up feed-through reactor in which physical and chemical weathering processes alter fresh rock material being supplied by uplift and erosion (Anderson et al., 2007). Simultaneously, physical erosion and chemical denudation processes transport mass out of the system. Thus, the rates of weathering and denudation together determine the thickness of the Critical Zone (Anderson et al., 2007). The balance of transport-limited and weathering-limited environments is largely determined by topographic and climatic factors.

Catenas

The bottom-up reactor model for regolith formation assumes that parent materials in the system derive only from the weathering of underlying bedrock or sediment. However, soil profiles on slopes are distinctly related to the soils above and below because of the influence of slope-controlled transport mechanisms. The term catena describes a sequence of soils on a slope, emphasizing that their variation is due to changes in both slope gradient and position (Birkeland, 1999). In this model, regolith and soils are thinnest at the shoulder and backslope, and gradually thicken, reaching a maximum at the toeslope. There is also a chemical gradient along slopes, driven partly by the physical transport of the mobile regolith, and enhanced by hydrologic factors; clay minerals and dissolved cations in a soil column may be transported down slope by throughflow, accumulating at the base of the slope. Climatic conditions determine both the mobility of soil materials and chemical constituents, and thus the effects of throughflow on pedogenesis vary spatially. Thicker soils and better-developed horizons may occur at the base of slopes due to the influx of weatherable materials and increased soil-moisture status via throughflow water.

Downslope transport of the mobile layer may be episodic, mediated by climate, and the regolith that eventually arrives at the toeslope includes a mixture of soil and saprolite. Models of sediment flux generally assume that hillslope processes are constant through time, but episodic transport suggests more stochastic conditions (Anderson and Anderson, 2010). Regolith moves downslope and episodic transport results in the burial of soils at the base of the slope; current soils in these positions form from materials derived from upslope rather than from bedrock. Thus, morphological differences along hillslopes may represent changes in the strength of pedogenesis and changes in parent material.

Significance of dustfall

Dustfall is not included explicitly in the Critical Zone reactor model; however, the enrichment of eolian silt and clay affects the “mineralogy, chemistry, nutrient status, and moisture-holding capacity of soils (Muhs and Benedict, 2006, p. 120),” and thus “may control the rate and direction of pedogenesis (Mason and Jacobs, 1998, p. 1135).” For this reason, characterizing the rate of eolian inputs is important for Critical Zone studies.

Transport, deposition, and subsequent weathering of eolian materials are controlled by climate. In areas distal from eolian source materials, fine sediments are deposited at relatively low rates; soil formation exceeds deposition, and the original parent material (e.g. crystalline bedrock) primarily influences pedogenesis (Birkeland, 1999; Muhs et al., 2008). Dust inputs are rapidly weathered at the surface, and potentially offset losses from the weathering of the original parent material (Mason and Jacobs, 1998). The volume and geochemistry of the dust determine its effect on pedogenesis.

Based on field observations and laboratory analysis, this study seeks to: (1) track the concentration of pedogenic iron within and between soil profiles to characterize weathering patterns in high-relief environments; and (2) assess the contribution and effects of eolian materials on montane soils.

METHODS

Field

I selected 24 sites in the Boulder Creek catchment for field description and sampling (Fig. 1). The sites together represent varying elevation, slope, aspect, parent material, moisture regime, and inferred age. Sites include upper montane Gordon Gulch (14), the alpine and subalpine Green Lakes basin (5), a highway road cut near the town of Ward (2), and Betasso Gulch (2). Ten of the lower Gordon Gulch sites comprise two catenas (5 sites in each) that face north and south. Lower Gordon Gulch is oriented so that slopes have near north-south aspect directions. Sites on both transects stretch from just below the catchment crest to just above the break in slope with valley fans and terrace deposits. At each site, I dug soil pits with my Keck colleagues until excessive depth or hard saprolite prevented further excavation. I followed standard soil description procedures and used a Garmin GPS device to record the site location and elevation. I collected approximately 750g of soil from all horizons (98 total samples), with the exception of O and L horizons when present.

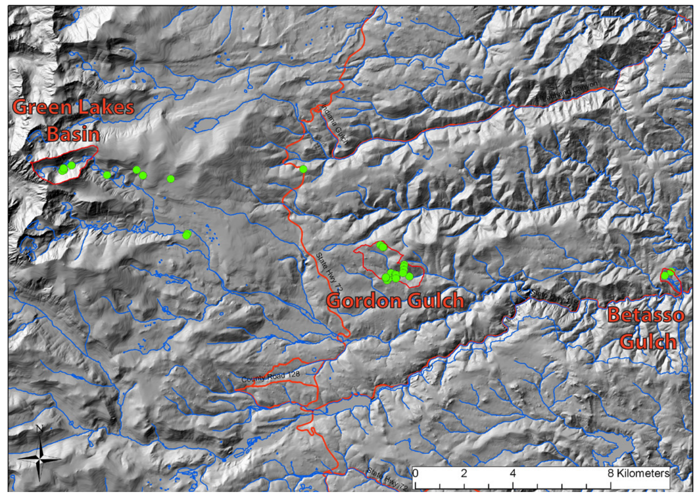

Figure 1. Locations of soil pits that were dug, described and sampled in the Boulder Creek watershed.

Laboratory

In the laboratory I dry-sieved all samples using USDA standard soil sieves. I then subdivided the <2mm fraction for multiple analyses. I determined soil moisture and dry soil color (using the Munsell color system) by standard methods and analyzed soil texture by hydrometer method (Gee and Bauder, 1986). Percent sand, silt and clay were determined, as well as more specific analysis of the silt-fraction. I did this by making measurements at 15, 30, 60, and 90 seconds and at 5, 20, 90, and 1440 minutes (24 hours). I performed a selective extractive analysis of the <150µm fraction from each sampled horizon, using sodium-dithionite in a sodium bicarbonate-sodium citrate buffer (McFadden and Hendricks, 1985), and ran the extract for iron in an AAS to determine dithionite-extractable iron (Fe_d). I determined the mass of Fe_2O_3 in individual horizons by multiplying the concentration of extractable Fe_2O_3 by the horizon thickness and bulk density. Using calculated Fe_2O_3 concentrations from unweathered parent material horizons (Cu) or from bedrock bulk chemistry (data obtained from D.P. Dethier), I established background values for Fe_2O_3 for each site. I then calculated the mass of accumulated Fe_2O_3 at each site by subtracting the background from the total mass of Fe_2O_3 to yield total accumulated Fe_2O_3 (in g cm^{-2}). I calculated total accumulated clay by the same method. I also ran samples from previous field studies in the Front Range for comparison, including a profile formed in Bull Lake (130ka) till.

RESULTS

Field

Soil morphology varies widely across the study area, reflecting the differences in parent material, relief, and climate within the Boulder Creek CZO (Fig. 2). Soils in the Green Lakes basin formed from glacial till and periglacial debris and, at stable sites, typically exhibit A/Ej/Bw/Cox/Cu profiles. Soils in the Betasso Gulch derive from either weathered colluvium or highly weathered saprolite, and sample sites show thick (>50cm) Bt horizons and, locally, a thick buried soil.

In Gordon Gulch the two catenas are broadly similar, but show marked differences near the footslope. Soils on the south-facing slope transect are thin (<1m) and have thin A horizons, underlain by Cox horizons that are progressively rockier with depth, limiting the depth of pits. As a result, a true saprolite horizon (Cr) was only reached at SFT-00, the lowest pit in the catena. Soils along the north-facing slope transect are less than 1m deep and weakly developed at the shoulder and upper backslope. The profiles are comprised of thin (<10cm) A and Bw horizons, underlain by Cox horizons that are blockier with depth. Soils thicken dramatically on the lower backslope (175cm and 188cm), and have complex profiles consisting mostly of thick, weakly weathered colluvium.

Soils in upper and middle Gordon Gulch formed from saprolite on lower slopes than in lower Gordon Gulch. At these sites, the saprolite-soil interface occurs at less than 1m depth. Bt horizons were noted at both upper Gordon sites. A well-developed, stable soil of Pinedale age from the Green Lakes basin, a thin backslope soil, and a thick colluvial footslope soil (Fig. 3) illustrate the range of soils I analyzed.

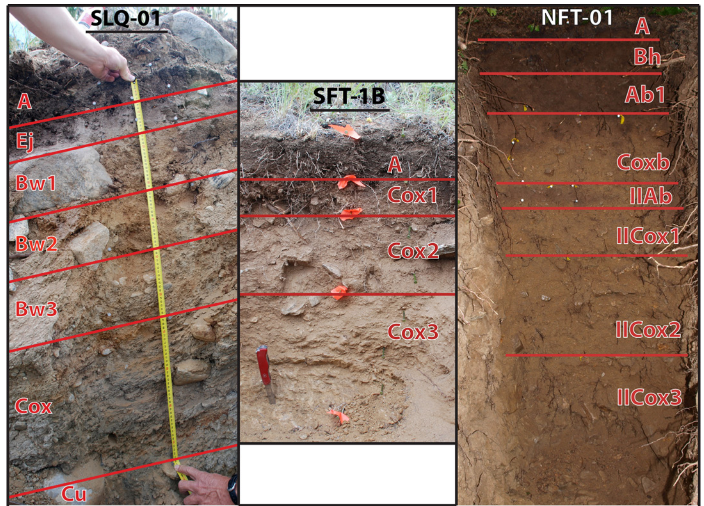

Figure 2. Three soil profiles from the Boulder Creek CZO. SLQ-01 is a soil from the Green Lakes basin formed in Pinedale glacial till (~15 ka), reaching a depth of approximately 110 cm in the field of view. SFT-1B is a 68 cm-thick soil from the south-facing slope of lower Gordon Gulch. NFT-01 is a 188 cm-thick soil from the north-facing slope of Gordon Gulch.

Profile: BCW_SLQ-01		Dry Soil	Texture			$\%Fe_d$ as	Accumulated	
Horizon	Depth (cm)	Color	% Sand	% Silt	% Clay	$\%Fe_2O_3$	Fe_2O_3 (g/cm^2)	
A	0 - 9	7.5YR 4/2	75.81	18.19	6.00	0.668	-0.02	
Ej	9 - 15	10YR 6/2	75.86	21.56	2.57	0.550	-0.02	
Bw1	15 - 32	10YR 5/4	74.86	20.54	4.60	2.769	0.74	
Bw2	32 - 48	10YR 5/4	80.08	15.76	4.16	2.062	0.47	Total
Bw3	48 - 66	10YR 6/4	80.57	17.12	2.30	1.067	0.17	Accumulated
Cox	66 - 102	2.5Y 5/3	80.68	17.41	1.91	0.702	0.07	Fe_2O_3 (g/cm^2)
Cu	102 - 112	2.5Y 6/1	68.79	21.63	9.58	0.625	0.00	1.42
Profile: SFT-1B		Dry Soil	Texture			%Fed as	Accumulated	
Horizon	Depth (cm)	Color	% Sand	% Silt	% Clay	$\%Fe_2O_3$	Fe_2O_3 (g/cm^2)	
A	0 - 10	10YR 4/2	82.00	12.46	5.54	1.607	0.06	Total
Cox1	10 - 18	7.5YR 5/4	82.73	13.06	4.21	1.879	0.10	Accumulated
Cox2	18 - 38	7.5YR 5/4	83.77	12.22	4.01	1.879	0.33	Fe_2O_3 (g/cm^2)
Cox3	38 - 68	7.5YR 5/4	86.92	11.13	1.95	1.697	0.46	0.95
Profile: NFT-01		Dry Soil	Texture			%Fed as	Accumulated	
Horizon	Depth (cm)	Color	% Sand	% Silt	% Clay	$\%Fe_2O_3$	Fe_2O_3 (g/cm^2)	
A	8 - 15	7.5YR 4/2	75.11	19.25	5.64	1.291	0.01	
Bh	15 - 28	7.5YR 4/3	75.19	18.45	6.36	1.658	0.12	
Ab1	28 - 44	7.5YR 4/3	76.90	17.18	5.92	1.687	0.15	
Coxb	44 - 69	7.5YR 6/4	92.01	5.63	2.36	1.633	0.29	
IIAb	69 - 76	7.5YR 5/3	90.09	6.35	3.56	1.607	0.08	Total
IICox1	76 - 97	7.5YR 6/4	89.44	7.45	3.11	1.374	0.19	Accumulated
IICox2	97 - 140	7.5YR 5/4	93.52	4.00	2.49	1.247	0.30	Fe_2O_3 (g/cm^2)
IICox3*	140 - 188	7.5YR 5/4	89.75	7.03	3.22	1.951	1.02	2.16

*Table 1. Field descriptions, dry soil color, texture, dithionite-extractable iron as $\%Fe_2O_3$, and accumulated Fe_2O_3 from the three soils pictured in Figure 2. *Note: IICox3 is a composite of three samples taken at specific depth intervals within the depth range of that horizon.*

Laboratory

Textural results show that all horizons at all sites classify as either sandy loam, loamy sand, or sand on the USDA texture diagram (Birkeland, 1999). The average percent clay of the surface horizon and subsurface horizons from all 24 sites is 6.17% (1 sigma = 1.71) and 5.02% (1 sigma = 3.21), respectively. This indicates slight enrichment of the surface horizons in clay. Along the Gordon Gulch transects (9 sample sites), the average percent clay of surface and subsurface horizons is 5.07% (1 sigma = 1.08) and 3.12% (1 sigma = 1.07), respectively. Differences in silt concentration between surface and subsurface horizons are insignificant across the entire catchment. However, along the two Gordon Gulch transects, surface horizons may be slightly enriched in silt.

Dithionite-extractable iron (Fe_d), as $\%Fe_2O_3$, is slightly lower in surface horizons than subsurface horizons; average $\%Fe_2O_3$ of the surface horizon and subsurface horizons from 24 sites is 1.52% (1 sigma = 0.44) and 1.81% (1 sigma = 0.65), respectively. In Gordon Gulch, average $\%Fe_2O_3$ of the surface and subsurface horizons is 1.43% (1 sigma = 0.22) and 1.74% (1 sigma = 0.46), respectively. Total profile accumulated Fe_2O_3 values are extremely variable across the catchment, with an average value of 1.84 g cm-2 and a standard deviation of 1.51 g cm^{-2}. The maximum value is 5.1 g cm^{-2} at the site "WRC-01"; the minimum accumulated Fe_2O_3 is 0.19 g cm-2 at the site "SFT-03."

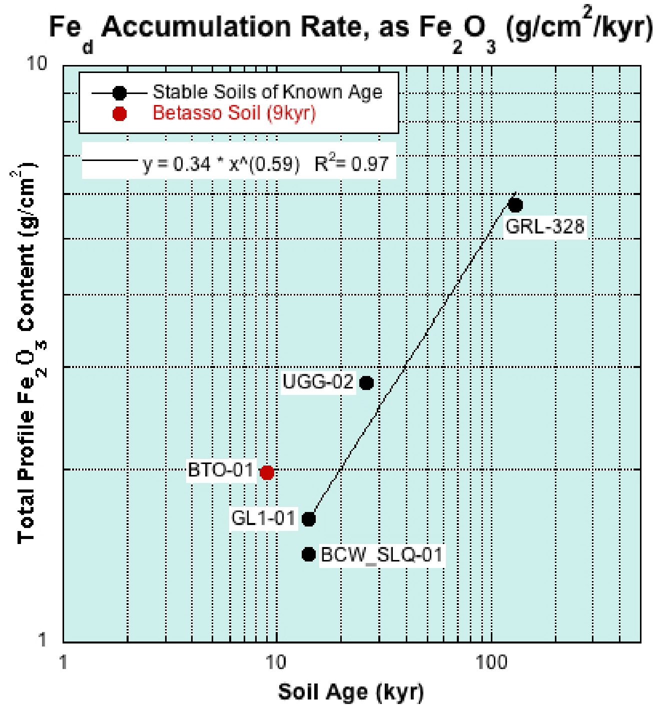

Figure 3. Fe_d accumulation rate, determined by using total profile Fe_d content of four soils of known age. The soil from Betasso Gulch (red bullet) formed from deep, weathered colluvium and an uncertain portion of the Fe_2O_3 content is inherited. For this reason, the profile was not used to fit the curve.

DISCUSSION

Data collected in this study permit evaluation of weathering rates and eolian sedimentation in the Boulder Creek catchment. Dithionite-extractable iron (Fe_d) represents the concentration of secondary iron oxides and organically bound iron complexes in a soil (McFadden and Hendricks, 1985). Higher concentrations of Fe_d in a sample thus indicate higher amounts of "free" iron that have been released by weathering and total profile Fe_d content typically increases with soil age and may correlate with total profile clay content (McFadden and Hendricks, 1985). This relationship is expected in soils, as clay minerals and iron oxides are both products of weathering, and time positively influences the degree of weathering (Birkeland, 1999). Therefore, variation in total profile Fe_d may indicate relative ages of soils across a study area.

Total profile Fe_d increases with age at stable sites in the Boulder Creek catchment (Fig. 3). The strong positive correlation of Fe_d with age suggests that pedogenic clay should also increase. However, textural data show that surface horizons, relative to subsurface horizons, are commonly enriched in clay but depleted in Fe_d (Table 1). The enrichment of clay in surface horizons, coupled with relatively low Fe_d values, suggests that clay content indicates eolian enrichment of soils in the catchment. Clay-sized sediment suggests a distal source.

Total profile Fe_d and clay content suggest both weathering and transport mechanics on slopes in Gordon Gulch (Fig. 4). On both north-facing and south-facing slopes, Fe_d and clay content in soil and regolith increases downslope.

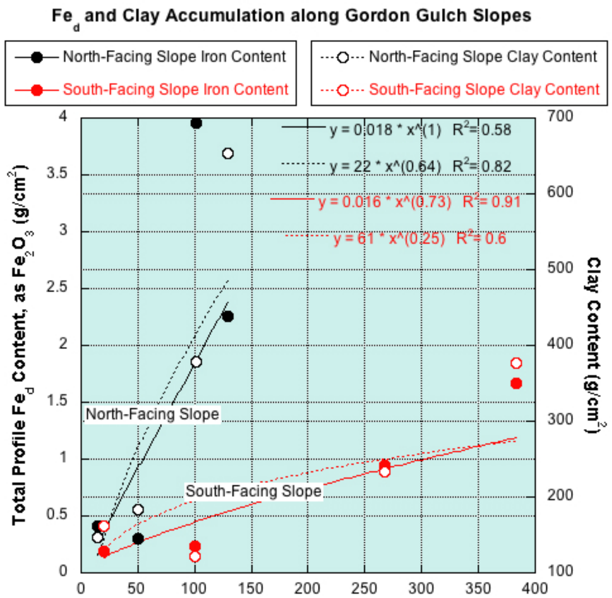

Figure 4. Total profile accumulated Fed content and total profile clay content along the two Gordon Gulch transects. The north-facing slope is in black and the south-facing slope in red. The filled markers and solid lines represent Fed content, and the hollow markers and dashed lines represent clay content.

The correlation of clay and Fe$_d$ content on both slopes indicates that regolith is "older" downslope. Fed and clay accumulate more rapidly on the north-facing slope than on the south-facing slope. Therefore, weathering rates may be higher on the north-facing slope, perhaps reflecting differences in temperature and moisture content due to aspect.

CONCLUSIONS

Pedogenic iron in the Boulder Creek catchment increases with age. Total profile Fe$_d$ content correlates with total profile clay content; this suggests that clays in sampled profiles are primarily pedogenic. However, clay content is slightly higher in surface horizons than in subsurface horizons and Fe$_d$ content is slightly reduced, indicating that the surface horizons are enriched in clay. High clay and low iron content in surface horizons suggests an eolian source rather than intensified in-situ weathering.

Future work will focus on (1) determining the significant factors affecting eolian deposition (e.g. elevation, MAP, aspect, etc.); (2) incorporating trace-element data in surface and parent material horizons to determine local or distant provenance of eolian clays and (3) using Fe$_d$ accumulation rate to infer ages of sample sites in the catchment.

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