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

April 2009
Franklin & Marshall College, Lancaster PA.

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Faculty: *WILLIAM H. PECK*, *BRUCE W. SELLECK* and *MARTIN S. WONG*: Colgate University
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Students: *EVEY GANNAWAY*: The U. of the South; *KENNETH NELSON*: Macalester College; *MIGUEL RODRIGUEZ*: Colgate University

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Keck Geology Consortium: Projects 2008-2009
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Project Director: ***DAVID P. DETHIER***: Williams College
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EVEY GANNAWAY: The University of the South
Research Advisor: Martin Knoll

CHARACTERIZATION AND COMPARISON OF WEATHERING PROFILES WITHIN BETASSO CATCHMENT, FRONT RANGE, COLORADO

KENNETH NELSON: Macalester College
Research Advisor: Raymond Rogers

APATITE IN THE SOILS OF BETASSO PRESERVE, COLORADO

MIGUEL RODRIGUEZ: **Colgate University**
Research Advisor: Dr. Richard April

Funding provided by: Keck Geology Consortium Member Institutions and NSF (NSF-REU: 0648782)

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CHARACTERIZATION AND COMPARISON OF WEATHERING PROFILES WITHIN BETASSO CATCHMENT, FRONT RANGE, COLORADO

KENNETH NELSON: Macalester College
Research Advisor: Raymond Rogers

INTRODUCTION

Defined as the vertical expanse from unweathered bedrock to the top of all vegetation, the critical zone (CZ) is the primary habitat for terrestrial life (Anderson et al., 2007). As such, the CZ demands extensive interdisciplinary research to better understand the abiotic-biotic interactions of surficial environments. The component of the CZ central to geology is termed regolith and consists of weathered bedrock and soil, or the weathering profile, and is heavily dependent on rock type, elevation, climate, and time (Birkeland et al., 2003; Anderson et al., 2007). Consequently, the nature of regolith is spatially heterogeneous. Mountainous settings, such as the Colorado Front Range, provide environments in which all four variables can fluctuate widely; rock type and elevation can vary widely on the scale of meters, climate on the scale of kilometers, and adjacent deposits can differ in age by thousands of years due to recent gravity-driven processes.

Data obtained from regolith of such terrain can thus be used to make estimates about ages of Quaternary deposits in various depositional settings, estimates of long-term stability of landscapes, and inferences about past climatic change (Birkeland et al., 2003). Indeed, studies of Front Range regolith have been undertaken (Netoff, 1977; Birkeland et al., 2003; Dethier and Lazarus, 2006), but have tended to be regional in scope. Though useful for comparing regolith properties across the adjacent environments of the Front Range, such broad large-scale research is not useful for studying variations on the sub-kilometer scale within individual catchments. To supplement available regional-scale data, this study aims to determine and compare the relative ages, stabilities, and climatic histories of three sites of exposed regolith within Betasso catchment of the Front Range of Colorado through the analysis of select physical and chemical properties and clay mineralogy.

GEOGRAPHIC, GEOLOGIC, AND CLIMATIC SETTING

Flanked by Bummer's Rock and the Boulder Filtration Plant, Betasso catchment is located within Boulder Creek canyon some 9.5 km west of Boulder and is thus underlain by 1.65 Ga granodiorite uplifted 50-70 Ma during the Laramide Orogeny (Fig. 1; Dethier and Lazarus, 2006). Since uplift, bedrock in the area has been weathered and eroded primarily through gravity and fluvial processes; valley glaciers advanced repeatedly from alpine areas to fill tributary valleys of the Front Range during the Pleistocene, but till deposits indicate those advances did not descend to the elevations of Betasso (Dethier and Lazarus, 2006). As a result, Betasso catchment is mantled by regolith composed of soil, saprolite, oxidized bedrock, and colluvium of unknown age (Anderson et al., 2006; Dethier and Lazarus, 2006).

The approximate area of Betasso catchment is 1 km^2 and elevations range from 5880 m to 6640 m (Fig. 1). Much of this relief is accounted for at the bottom and middle portions of the basin, whereas the top is composed of relatively flat rolling hills. Nearly mirroring the topography, the lower areas of the catchment are sparsely forested by lodgepole pines and upper zones by grassland vegetation. Mean annual temperature and precipitation at Betasso are about 10°C and 50 cm, respectively, thus qualifying its climate as cool-temperate/semi-arid (Chamley, 1989; Dethier and Lazarus, 2006). In addition, estimates of yearly runoff average 10 cm (Dethier and Lazarus, 2006). It should be noted, however, that regional evidence provided by Leonard (1989) and Thompson (1991) suggests that the Pleistocene climate of the Betasso area was likely cooler by 8-12°C, wetter, and more variable than the current climate.

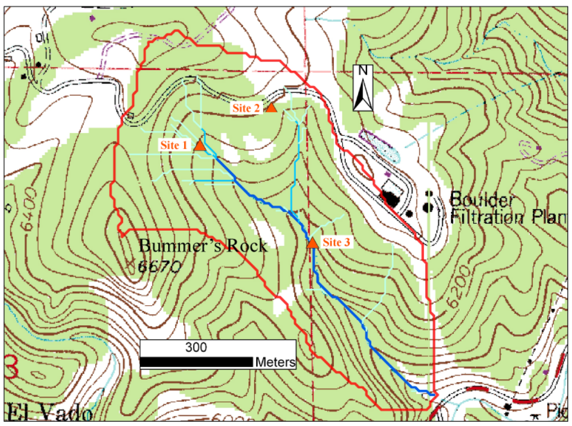


Figure 1: GIS image of Betasso catchment. Sites 1, 2, and 3 correspond to the locations of focused study for this project.

METHODS

Three work sites of laterally extensive weathering profiles were selected (Fig. 1) to help measure the spatial variability of the regolith within Betasso catchment. At each site at least one vertical profile was described in detail following the advice of Birkeland (1999). Samples were collected from each discernable horizon or lithology with a 250 mL tube where the substrates allowed so that the field densities, and thus relative stabilities, of those samples could be measured. For clarity, saprolite was differentiated from colluvial parent material.

Following field work, three splits of the <2 mm fraction of each sample were made. The first split was analyzed at Acme Labs using inductively coupled plasma (ICP) to determine the total abundances of total oxides and several minor elements and inductively coupled plasma-mass spectroscopy (ICP-MS) to determine the concentrations of rare earth and refractory elements. Prior to these analyses, the splits were ignited at 1000°C so that the total organic content of each sample lost on ignition (LOI) could be found.

Analysis for citrate-bicarbonate-dithionite (CBD) extractable iron was conducted on the second batch of sample splits to determine total free iron concentrations. The procedure used was that of Jackson (1979) and required the use of atomic absorption spectroscopy (AA). Results were recorded in ppm and converted to mass percent of the sample splits.

Finally, the third set of <2 mm sample splits was analyzed to determine the identities and relative abundances of the clay minerals present using X-ray diffraction (XRD) techniques described by Moore and Reynolds (1997) and Hillier (2003). To facilitate this, the samples were chemically treated to remove organic materials and iron oxides, centrifuged to remove the clay-sized fraction (<2 μm), and oriented on glass slides using the Millipore® filter transfer method. It should be noted that only samples from which ample amounts of clay material could be extracted were analyzed and, because techniques other than XRD were not used to analyze the clay-sized material, the identities of the clay minerals were not specified beyond the family level.

In addition to the three sample splits mentioned above, two samples (KN-09 and KN-27 in Tables 1 and 2) of the laterally extensive, buried, organic-rich A horizon (horizon Ab in Fig. 2A) of site 1 were ^{14}C dated and calibrated to determine the timing of burial. The analyses were carried out by BETA Analytic following the removal of roots and a number of acid washes.

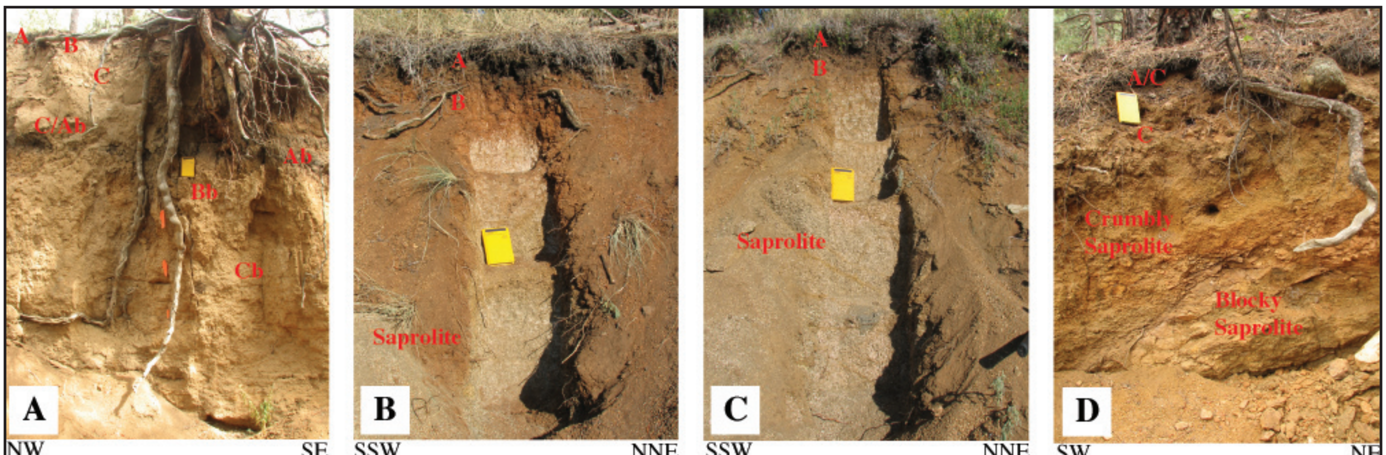
RESULTS

Included in Table 1 is a sample catalogue that indicates the sites, profiles, and horizons from which the samples were taken, as well as their depths below the surface, dry Munsell colors, and densities. Also included in Table 1 is a brief set of notes about each Betasso study site.

Figure 2 contains outcrop photographs of the deepest regolith profiles at each site and the depths to the boundaries of their respective horizons. From this figure, one can see that site 1 (Fig. 2A) is composed of a well-developed buried soil and a modern one, both of which possess thick, colluvial C horizons. Similarly, it can be seen that site 2 (Fig. 2B and Fig. 2C) is made of a thick and crumbly saprolite blanketed by a clay-rich illuvial B horizon and an A horizon with abundant aplite clasts. Finally, the deeply oxidized saprolite, aplite-rich

Site/ Profile	Sample	Horizon	m (cm)	Dry Munsell Color	Density (g/cm^3)	Site Notes
1A	KN-29	Cb	225	dark yellowish brown	n/a	Gulley outcrop, deepest profile at Profile 1D (4 m), in-situ oxidized saprolite (crumbly) outcrops up-gulley at Profile 1C, large saprolitic boulder rests above the contact of in-situ saprolite and Cb horizon, lens of rounded aplite cobbles in colluvial Cb horizon, Bb and Ab horizons diverge from modern soil up-gulley of Profile 1D and converge down-gulley, thick prismatic joints and many clay films in Bb horizon, admixed Ab/colluvial C horizon above Ab horizon, covered by patch of lodgepole pines
1B	KN-30	Ab/C	110	dark brown	n/a	
	KN-27	Ab	130	very dark gray	n/a	
	KN-28	Bb	160	yellowish brown	n/a	
1C	KN-07	saprolite	350	yellowish brown	n/a	
1D	KN-13	A	2	very dark grayish brown	1.00	
	KN-12	B	10	dark brown	1.36	
	KN-11	C	25	brown - dark brown	1.82	
	KN-10	Ab/C	100	brown - dark brown	1.55	
	KN-09	Ab	130	very dark gray	1.48	
	KN-08	Bb	175	brown - dark brown	1.50	
2A	KN-22	A	10	very dark grayish brown	1.48	Trail outrop, profiles described from ~2 m trenches, in-situ granodiorite-derived saprolite at base, rotted xenolith and weathered joints in Profile 2B saprolite, top of saprolite enriched with illuviated clay, abundant clay films in B horizon abundant aplite rounded aplite pebbles in A horizon, clear color distinction between profiles, profile 2B lies to the SSW of profile 2A, covered by a patch of grass
	KN-23	B	30	reddish brown	1.50	
	KN-24	saprolite	55	brown - dark brown	1.85	
	KN-25	saprolite	150	brown - dark brown	1.90	
2B	KN-19	A	10	dark grayish brown	1.28	
	KN-20	B	35	dark yellowish brown	1.73	
	KN-21	saprolite	50	dark yellowish brown	1.60	
	KN-26	saprolite	160	pale brown	1.84	
2C	KN-18	saprolite	450	pale brown	2.11	
3A	KN-14	AC	5	dark yellowish brown	1.48	Deepest profile at Profile 3A (1.7 m), deeply oxidized in-situ saprolite (blocky) at base capped by cm Mn seam, loose saprolite (crumbly) above seam, oxidized colluvial C horizon with rounded aplite pebbles and boulders, weakly developed A/C horizon (no B horizon), much spatial variability in horizon thickness and gravel content below AC horizon covered by lodgepole pines
	KN-15	C	40	dark yellowish brown	1.60	
	KN-16	saprolite	85	yellowish brown	1.88	
3B	KN-17	C	80	yellowish red	n/a	
-	-	-	-	-	-	

Table 1: Sample catalogues and profile descriptions for each study site of Betasso catchment.



Horizon	Depth (cm)
A	0-3
B	3-12
C	12-95
C/Ab	95-115
Ab	115-155
Bb	155-195
Cb	105-400

Horizon	Depth (cm)
A	0-12
B	12-49
C	49-180

Horizon	Depth (cm)
A	0-15
B	15-43
Saprolite	43-182

Horizon	Depth (cm)
AC	0-12
C	12-67
Crumbly Saprolite	67-147
Blocky Saprolite	147-173

Figure 2: Outcrop photographs of regolith profiles of each study site within Betasso catchment (A) Outcrop photograph of profile 1D; (B) Profile 2A; (C) Profile 2B, about 20 m to the SSW of profile 2A; (D) Profile 3A.

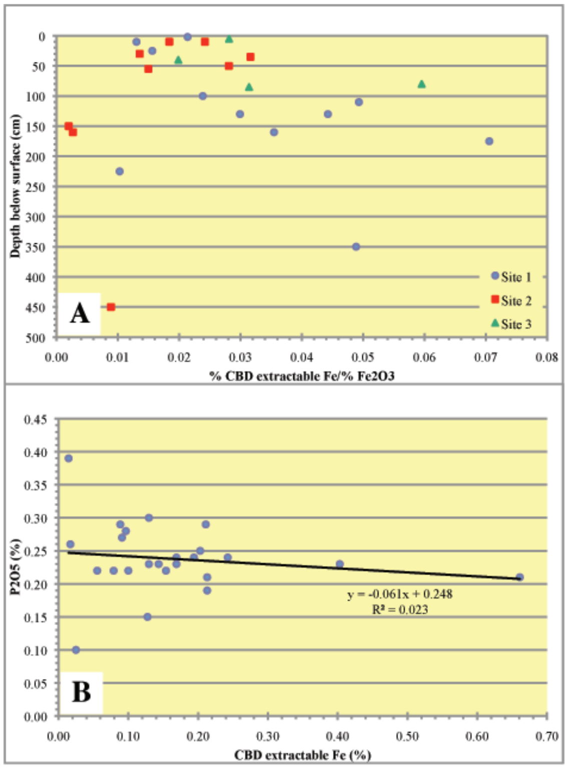


Figure 3: Plots of selected chemical data pertinent to the study of weathering profiles: (A) Plot of %CBD extractable Fe/%Fe_2O_3 ratio (a proxy for soil development) vs. depth, broken up by site; (B) Plot of %P_2O_5 vs. %CBD extractable Fe.

colluvial C horizon, and poorly developed A horizon of site 3 become evident through observation of Figure 2D. Most, but not all, horizons at each site were composed of roughly 30% gravel.

Plots of chemical data highly relevant to the study of soils are given in Figure 3. Namely, Figure 3A is a plot of the CBD extractable iron/Fe_2O_3 ratio (a proxy for soil development) of each sample vs. sample depth and Figure 3B is a plot of sample P_2O_5 vs. sample CBD extractable iron.

The relative abundances of the Betasso catchment clay minerals are given in Table 2. As stated above, the identities of the clay minerals present were not specified beyond the family level. Also, due to peak overlap and the very small peak intensities of the mixed-layer minerals mica-vermiculite and mica-smectite, these minerals could not be quantitatively analyzed and were consequently excluded from the quantitative results.

Finally, the ^{14}C ages of non-root organic material from samples KN-09 and KN-27 were found to be 8640 ka (calibrated from 9000 ka) and 8420 ka (cali-

Site/ Profile	Sample	Horizon	m (cm)	Rel. Wt.% Smectite	Rel. Wt.% Illitic Material	Rel. Wt.% Chlorite	Rel. Wt.% Kaolin	Re. Wt.% Illite-Vermiculite	Rel. Wt.% Illite-Smectite
1A	KN-29	Cb	225	12.0	49.2	0.0	38.8	trace	0.0
1B	KN-30	Ab/C	110	3.5	66.1	0.9	29.6	trace	0.0
	KN-27	Ab	130	7.2	61.4	0.0	31.4	treace	trace
	KN-28	Bb	160	17.6	47.7	2.7	32.0	trace	0.0
1C	KN-07	saprolite	350	3.7	33.6	1.5	61.2	trace	trace
1D	KN-13	A	2	0.0	60.2	3.2	36.6	trace	0.0
	KN-12	B	10	0.0	59.7	2.8	37.4	trace	0.0
	KN-11	C	25	0.8	56.9	2.4	39.9	trace	trace
	KN-10	Ab/C	100	2.2	61.7	1.2	34.9	trace	0.0
	KN-09	Ab	130	4.2	53.1	1.0	41.8	trace	0.0
	KN-08	Bb	175	13.6	46.0	1.4	39.0	trace	trace
2A	KN-22	A	10	0.0	63.2	0.7	36.1	0.0	0.0
	KN-23	B	30	0.0	78.5	0.0	21.5	trace	0.0
	KN-24	saprolite	55	0.0	72.2	0.0	27.8	trace	0.0
	KN-25	saprolite	150	n/a	n/a	n/a	n/a	n/a	n/a
2B	KN-19	A	10	0.0	60.5	0.0	39.5	0.0	0.0
	KN-20	B	35	2.0	59.3	2.0	36.6	trace	0.0
	KN-21	saprolite	50	6.2	60.2	0.0	33.6	trace	0.0
	KN-26	saprolite	160	n/a	n/a	n/a	n/a	n/a	n/a
2C	KN-18	saprolite	450	n/a	n/a	n/a	n/a	n/a	n/a
3A	KN-14	AC	5	8.9	55.9	2.2	33.1	trace	0.0
	KN-15	C	40	7.8	39.6	1.0	51.7	trace	trace
	KN-16	saprolite	85	10.2	53.9	0.0	35.9	trace	trace
3B	KN-17	C	80	12.2	38.7	0.0	49.1	0.0	0.0

Table 2: XRD determined relative abundances of clay minerals identified from Betasso catchment regolith profile samples. Samples KN-16, KN-18, and KN-26 did not yield enough clay-sized material to be analyzed.

brated from 8530 ka), respectively. The average of these ages is 8530 ka and is taken to be the timing of burial of horizons Ab, Bb, and Cb at site 1.

DISCUSSION

Field and ^{14}C Data

Since each study site possesses weathering profiles with unique arrangements of stratal components, each site appears to have a unique history of regolith development. To begin, site 1 is composed of soils over and buried by thick colluvial deposits. The presences of an oxidized saprolite boulder, a lens of rounded aplite cobbles, and abundant other gravelly material in theses colluvial C horizons suggest that they are composed of saprolitic material transported by fluvial processes from upslope and likely products of a wetter climate than exists today. This climatic interpretation is supported by timing of burial of the A horizon between the colluvial deposits determined through ^{14}C age dating; an age of 8530 ka places the Ab soil horizon in the early Holocene when the local climate was likely more in line with that of the wetter and more variable Pleistocene climate (Leonard, 1989; Thompson, 1991). Furthermore, the prismatic joints and clay films of the Bb horizon, as well as the organic-rich Ab horizon, suggest that thousands of years of stability existed at site 1 between colluvial deposits, pushing the buried colluvial deposit fully within the Pleistocene (Chamley, 1989; Birkeland, 1999). The lack of structure of the modern A and B horizons hint that either it has been unstable for some time, possibly due to gravity-driven or seasonal fluvial processes, or the modern horizons are very young as a result of erosion by an unrecorded mass movement.

Contrary to site 1, site 2 regolith profiles do not contain any colluvial deposits, but are composed of A and B soil horizons directly on top of in-situ granodiorite-derived saprolite. In addition to this deficiency of transported material, the dark B horizons of profiles 2A and 2B (Fig. 2) and the presence of abundant illuviated clay in those horizons imply that site 2 has been relatively stable for an extend amount of time, possibly for thousands of years (Birkeland, 1999). Though, it should be noted, the reddish color of the B horizon of profile 2A implies that it is older than its counterpart at profile 2B, which is yellowish (Birkeland, 1999). One possible explanation for this discrepancy is that the A and B horizons of profile 2B were preferentially eroded while those of profile 2A remained in place at some point in the Holocene due to fluvial and/or gravity-driven processes. The existence of abundant rounded aplite clasts in the A horizons, dissimilar to the characteristics of the B horizon, hint at ongoing downslope transportation of material at site 2. However, such downhill movement would likely be restricted to the A horizons due to the greater densities of the B horizons and saprolites below.

Finally, site 3 weathering profiles are composed of soils overlying both colluvial material and in-situ saprolite. Given the deeply oxidized nature of the saprolite base of the site 3 profiles, it seems likely that the substrate was exposed to large quantities of water at some point in the past. This may be explained, as may be the manganese seam above the saprolite, by the fact that gulley in which site 3 is located appears to have been formed by a pipeline failure of the filtration plant upslope. Like site 1, the colluvial C horizons of site 3 possess many rounded aplite cobbles and suggest water induced downslope movements. Since no distinct modern A or B soil horizons exist at this lower catchment site, the soil is either relatively young or seasonally disturbed by fluvial and gravity mechanisms. If the former is true, the supposed pipeline break may be to blame. If the latter is true, site 3 may again be similar to site 1. However, since site 1 presents discrete A and B horizons, its modern soil is interpreted to be older (Birkeland, 1999).

Chemical Data

As is evident in Figure 3, the non-mineralic components of the Betasso samples of greatest interest were CBD extractable iron, total iron, and phosphorous. Both measures of iron were of great concern because the ratio of CBD extractable iron to total iron is a great proxy of soil development and relative age (Pope, 2000). Figure 3A indicates that the samples with the greatest CBD extractable iron to total iron ratios were those from the buried horizons of site A followed by the B horizons of site 2, the AC horizons of site 3, and the modern soil horizons of site 1. Minus the modern horizons of site 1, these results support the relative age interpretations based on field observations above.

Another reason CBD extractable iron was of interest in this study was its well-established ability to adsorb phosphorous (Fig. 3B). Phosphorous is important because it is essential to all forms of life and is typically the limiting factor on the growth of plant communities (Brady, 1974; Birkeland, 1999). Consequently, higher quantities of CBD extractable iron are predicted to correlate with higher quantities of phosphorous available to plant life. However, as shown in Figure 3B, this positive relationship does not exist for the samples collected from Betasso catchment. Rather, it may be the case that the available phosphorous is preferentially being removed from horizons with abundant free iron and its accumulation in those horizons are muted (Brady, 1974).

Clay Mineral Data

Per Netoff (1977), the most abundant clay minerals expected to be produced through the weathering of granodiorite in Boulder Creek canyon are illite, mixed-layer illite-smectite, vermiculite, and mixed-layer mica-vermiculite. However, the results presented in Table 2 do not agree with these predictions; all Betasso samples possess large relative abundances of kaolinite and most contain at least some discrete smectite. Despite this disagreement, the results of Table 2 agree with the general predictions of Chamley (1989) based on the cool and temperate climate of the Betasso area and those of Brady (1974) for granodiorite parent material.

As for trends in semi-quantitative clay mineralogy at each of the work sites, smectite concentrations generally decrease and those of kaolin increase as one moves up a given weathering profile. In fact, smectite is not found in any modern A horizons and only in one modern B horizon. Such trends suggest that the former is unstable near the surface and readily converts to the latter, likely a result of the prevailing temperate/semi-arid climate (Brady, 1974; Moore and Reynolds, 1997). Therefore, the presence of quantifiable amounts of smectite in the Ab and Bb horizons of site 1 provide another line of evidence that the late Pleistocene/early Holocene climate was wetter than that of today.

CONCLUSIONS

To supplement research concerning variations in regolith age, stability, and climatic histories in adjacent environments of the Front Range of Colorado, this project set out to determine and compare such characteristics of three sites of exposed regolith within Betasso catchment through the analysis of select physical and chemical properties and clay mineralogy. Field observations clearly indicate that the regolith profiles of each site have experienced unique histories. Since they are weakly-developed, the modern soils at sites 1 and 3 appear to be relatively young or seasonally disturbed by fluvial- and/or gravity-driven processes. Contrarily, the soils at site 2 are well-developed modern soils and are likely thousands of years old. The presence of an 8530 ka buried soil at site 1 indicates that a period of relative stability existed in the early Holocene and the thick colluvial deposits that bracket it indicate that a wetter climate than persists today was present.

Using the ratio of CBD extractable iron to Fe2O3 of each sample as a proxy of the degree of development of the samples' respective horizons, the interpreted relative ages of soils at each site were verified, with the buried soil of site 1 being the oldest and most well-developed. Finally, the presence of abundant kaolin and illitic materials in the clay-fractions of modern A and B soil horizons at each site reflect the current temperate/semi-arid climate, though the presence of discrete and quantifiable smectite in the buried soil horizons of site 1 provide another line of evidence that the climate of the late Pleistocene/early Holocene was wetter.

REFERENCES

Anderson, P.A., von Blackenburg, F., and White, A.F., 2007, Physical and chemical controls on the critical zone: Elements, v. 3, p. 315-319.

Anderson, R.S., Riihimaki, C.A., Safran, E.B., MacGregor, K.R., 2006, Facing reality: Late Cenozoic evolution of smooth peaks, glacially ornamented valleys, and deep river gorges of Colorado's Front Range: Geological Society of America, Special Paper 398, p. 397-418.

Birkeland, P.W., 1999, Soils and Geomorphology: New York, Oxford Univiversity Press, 430 p.

Birkeland, P.W., Shroba, R.R., Burns, S.F., Price, A.B., Tonkin, P.J., 2003, Integrating soils and geomorphology in mountains—an example from the Front Range of Colorado: Geomorphology, v. 55, 329–344.

Brady, N.C., 1974, The Nature and Properties of Soils: New York, MacMillan Publishing Co., 639 pp.

Chamley, H., 1989, Clay Sedimentology: Berlin, Springer-Verlag, 623 p.

Dethier, D.P., Lazarus, E.D., 2006, Geomorphic inferences from regolith thickness, chemical denudation and CRN erosion rates near the glacial limit, Boulder Creek catchment and vicinity, Colorado: Geomorphology, v. 75, p. 384-399.

Hillier, S., 2003, Quantitative analysis of clay and other minerals in sandstones by X-ray powder diffraction (XRPD): International Association of Sedimentologists, Special Publication, v. 34, p. 213-251.

Jackson, M.L., 1979, Soil chemical analysis-advanced course, 2nd ed: Madison, Published by the author.

Leonard, E.M., 1989, Climatic change in the Colorado Rocky Mountains: estimates based on modern climate at late Pleistocene equilibrium lines: Arctic Alpine Research, v. 21, p. 245– 255.

Moore, D.M. and Reynolds, R.C. Jr., 1997, X-ray Diffraction and the Identification and Analysis of Clay Minerals, 2nd ed: New York, Oxford University Press.

Netoff, D. I., 1977, Soil clay mineralogy of Quaternary deposits in two Front Range–Piedmont transects, Colorado: Ph.D. thesis, University of Colorado, 169 p.

Pope, R.J.J., 2000, The application of mineral magnetic and extractable iron (Fed) analysis for differentiating and relatively dating fan surfaces in central Greece: Geomorphology, v. 32, p. 57-67.

Thompson, R.S., 1991, Pliocene environments and climates in the western United States: Quaternary Science Reviews, v. 10, p. 115–132.