INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO

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FRACTURE CONTROL OF GLACIAL EROSION WITHIN GREEN LAKES VALLEY, FRONT RANGE, COLORADO

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

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APATITE IN THE SOILS OF BETASSO PRESERVE, COLORADO

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

Processes in the critical zone, the life-sustaining surficial mantle of the earth, involve weathered geologic materials, water, and the biosphere, mediated by atmospheric processes that are controlled by changing climate. Field studies that investigate hydrologic and geochemical components of the critical zone provide valuable information about processes and the physical basis for integrating those data into models of short and long-term geomorphic, hydrologic and biochemical response. The Keck Colorado Project is working in cooperation with a large interdisciplinary study (Boulder Creek Critical Zone Observatory: Weathered profile development in a rocky environment and its influence on watershed hydrology and biogeochemistry—Suzanne Anderson, PI, Institute for Arctic and Alpine Studies, University of Colorado) of the critical zone. The “observatory” consists of 3 small, instrumented catchments in the Boulder Creek basin, Colorado Front Range: (1) Green Lakes Valley—a steep alpine area in the Boulder watershed; (2) Gordon Gulch—a forested, mid-elevation catchment developed in deeply weathered materials; and (3) Betasso gulch—a steep, lower-elevation basin where surficial deposits are of variable thickness (Fig. 1).

The spectacular glacially scoured headwaters, low relief surface, and bedrock canyons are developed in granitic or gneissic rocks and influenced by the strong gradient in elevation, climate and vegetation from west to east. The variation in critical-zone development in these different environments provides the potential to test coupled models of hydrology, weathering front-advance, regolith production and sediment transport in an accessible field setting. Land-use, vegetation and perhaps hydrologic response in each CZO catchment also reflect changes produced by anthropogenic activities over the past 150 years. A major focus of Keck Colorado studies involves using a variety of techniques to map and characterize the geologic materials and their properties in each of the study catchments.

SETTING

The middle Boulder Creek catchment (Fig. 1) extends from the glaciated alpine zone of the Continental Divide east to the semi-arid western edge of the Great Plains. Deep, U-shaped valleys in the glaciated areas become shallower eastward through a zone of low relief and relatively low slopes, deepen into steep bedrock canyons as they pass knickzones, and flatten to lower channel slopes near the piedmont margin. Small glaciers and late-persisting snowfields dot the alpine zone, which exposes
bedrock and relatively thin deposits related to the latest Pleistocene Pinedale glaciation. The thinly forested zone of low relief exposes thick (characteristically 3 to 8 m) zones of grus, saprolite and oxidized bedrock. In the vicinity of the knickzone and in downstream areas such as Betasso gulch, slopes near channels are steep with shallow, fresh bedrock whereas more distant areas retain a thicker weathered mantle.

**APPROACH**

In this first project year, we employed geophysical investigations, field mapping, and sampling in the three CZO catchments in order to provide basic data about the shallow geology of the critical zone and to help guide the location of future borings, test pits and monitoring instruments (Fig. 2). We ran shallow seismic refraction, ground-penetrating radar and resistivity lines in each of the catchments in cooperation with investigators from the University of Colorado, focusing on Betasso gulch. Keck students learned field measurement techniques and initial data reduction, processing and visualization methods in a variety of settings. Students chose from a variety of potential projects in the catchments, emphasizing those in the Betasso and Green Lakes catchments, since we had permission for only limited sampling in Gordon Gulch in 2008. Project topical areas included:

1. Surficial geology and soil development, Betasso catchment
2. Bedrock fracturing measurements
3. Phosphorus concentrations in soils and bedrock
4. Surface-water hydrology (Gordon Gulch)

**STUDENT PROJECTS**

Three Keck students (Evey Gannaway from University of the South--Sewanee, Kenneth Nelson from Macalester, and Miguel Rodriguez from Colgate) joined Eirik Burass (Williams), who was supported by NSF funding. David Dethier and Matthias Leopold supervised students on a daily basis and field teams frequently joined investigators and graduate students from the University of Colorado, Technical University of Munich and the US Geological Survey. Keck students, the only undergraduates, presented preliminary results of their field research at the 1st annual Boulder Creek CZO meeting on 12 August 2008. Keck Colorado research spread across the three Boulder CZO study catchments and students worked in pairs on a daily basis and sometimes as geophysical support teams, learning about seismic, ground-penetrating radar (GPR) and resistivity techniques (Fig. 3). Geophysical data is particularly valuable for Ken’s work.
Evey Gannaway studied the distribution of fractures in an extensive area of bedrock scoured by latest Pleistocene glaciers near Green Lakes 3 and 4, in the Boulder Watershed (Fig. 4).

Fractures produced by tectonism (Molnar et al., 2007) and local stresses (Selby, 1980) play a central role in weathering, in preparing rock for erosion and in groundwater recharge and flow, but regolith masks fractures in most areas. By measuring fractures and their orientation on 30 traverses, Evey was able to demonstrate that fracture spacing has a mean value between about 0.5 and 1.0 m (n= 786) and that spacing varies depending on rock type and location in the basin. Fracture spacing in the foliated biotite gneiss and metasediments mainly reflects the influence of rock fabric but there are also zones of more widely spaced fractures. In the massive Silver Plume Granite, fractures are closely spaced (0.00 to 0.50 m) within the topographic step between Green Lakes 3 and 4; fracture spacing is wider at the top of the step (Figs. 5a and 5b).

Data from Evey’s reconnaissance study provide a sound basis for estimating the scale of blocks available for glacial quarrying and for rockfall, but do not suggest any simple control for local fracture density.

Ken Nelson’s work research involved characterizing soils developed in colluvial deposits and bedrock along a catena in Betasso gulch and laboratory measurements of soil properties. Calibrated 14C ages from two sites in a buried soil (Fig. 6) show that colluvial deposition isolated the soil from exchange with the surface by between 8400 and 9000 yrs BP.

Chemical and physical characteristics of the overlying Holocene soil, including clay concentration, mineralogy and CBD-extractable Fe (Fig. 7), suggest that the buried soil developed over a period of at least tens of thousands of years, probably under the influence of a different climate (Birkeland et al., 2003). Upslope from the colluvial deposits, saprolitic bedrock is exposed close to the surface. Field and
some laboratory characteristics suggest that soils on the saprolite are old, perhaps developed during hundreds of thousands of years of weathering in-situ and slow downslope transport as mobile regolith (Fig. 8).

Kaolinite and smectite are the dominant clay minerals, formed by the weathering of feldspar and mica. Smectite concentrations generally decrease and kaolinite increases upwards in the weathering profile. Smectite is not present in any modern A horizons and was found in only one modern B horizon. Measured trends imply that smectite is unstable near the surface in the modern temperate/semi-arid climate (Brady, 1974; Moore and Reynolds, 1997). Quantifiable amounts of smectite in the Ab and Bb horizons at the colluvial site suggest that the late Pleistocene/early Holocene climate was wetter than that of today. Soil chemical characteristics, however, generally indicate that eolian deposition and physical weathering are more significant than chemical weathering in this relatively dry environment.

Miguel Rodriguez measured the concentration and effects of weathering on apatite, generally the primary source of ecosystem phosphorus (Penn,
2005), in the Betasso catchment (Fig. 9). He also collected rock and sediment samples for phosphorus analysis, on a reconnaissance basis, at locations in the Gordon Gulch and Green Lakes catchments. Miguel separated and concentrated apatite and other heavy minerals using heavy liquid techniques and hand-picked the apatite grains. Bulk samples also were analyzed for total phosphorus using ICP-MS techniques. Miguel’s results from Betasso show that apatite concentrations in soils and unweathered colluvial deposits range from 0.10 to 0.27 weight percent. Concentrations are lowest in a soil profile buried in early Holocene time, which may reflect changes in parent material or weathering (Banfield and Eggleton, 1989). SEM morphology of the apatites does not appear to show any depth-related trends, suggesting that if weathering is significant it must involve chemical dissolution of the apatite. Total phosphorus concentrations increase in the soil profile where apatite concentrations decrease (Fig. 10). If chemical weathering controls this pattern, phosphorus may have been released from apatite and adsorbed by clays and FeO(OH) compounds.

Future Keck studies will build on initial work by the 2008 group and on the NSF-sponsored infiltration/hydrology studies of Eirik Buraas in Gordon Gulch. We hope to involve students in additional studies of fractures, in documenting the effects of anthropogenic influences on the Gordon Gulch and Betasso catchments and in more detailed analyses of the effects of eolian deposition on soil development and catchment chemistry in the Boulder Creek CZO.

ACKNOWLEDGMENTS

Our field studies and measurements in the Boulder Creek area were done in cooperation with the Boulder Creek CZO Project (National Science Foundation), the USDA Forest Service, and the City of Boulder Watershed and Parks and Recreation Departments. Nel Caine (University of Colorado) and Craig Skeie (City Watershed Manager) guided our studies in the Green Lakes basin, Pete Birkeland (University of Colorado) taught us about soils and Suzanne Anderson and Anne Sheehan (both at University of Colorado) shared their knowledge of the Critical Zone and how to study it in many field “teaching moments”. We gratefully acknowledge the ongoing cooperation and cogent advice of Joerg Voelkel (Technical University of Munich) and the hospitality of the Mountain Research Station.

REFERENCES


Selby, M. J., 1980, A rock mass strength classification for geomorphic purposes: with tests from Antarctica and New Zealand: Zeitschrift für Geomorphologie v. 24, p. 31-51.
INTRODUCTION

The critical zone has been defined as the region that supports life or more accurately, everything from the bedrock contact to the top of the canopy (Anderson et al 2007). By considering fractures as assistants to erosion, they can be seen as the lowermost extension of the critical zone. It is through such erosion that the critical zone boundary is able to propagate downwards. In regions of glacial activity, the critical zone has often been stripped bare by glacial quarrying, thus exposing the bedrock underneath to the effects of erosion and weathering. Green Lakes Valley is a glacially carved valley in the Front Range of the Rocky Mountains. Sitting near 3570m, the valley serves as the watershed for the City of Boulder, Colorado to the east.

At the head of the valley is the small remnant of the once massive Arikaree Glacier that carved into the Front Range during the Pinedale Glaciation, the last glacial maximum of 20,000 years ago. The long-valley profile of the Green Lakes Valley displays a series of topographic steps with five shallow lakes that serve as the headwaters of North Boulder Creek (Fig. 1). The Pinedale glacial activity exposed a complex fracture system in the bedrock of Green Lakes Valley, which is composed of various rock types. Fracture data allows us to interpret the influence of rock fracturing on various geomorphic processes including the difficulty of glacial quarrying, groundwater movement through bedrock, and nutrient supply to vegetation. Fracture density and orientation were measured in order to interpret the history of step cutting and profile development in the valley.

METHODS

In order to characterize fracturing, I surveyed a total of 30 transects in an area of roughly 0.50 km$^2$ that exposed four different rock types. Transects were

Figure 1. A) Aerial view of the topographic step between Green Lakes 3 and 4 indicating transect locations. B) Geologic map of the same area.
established using a 30-meter tape or laser range-finder. Transect lengths ranged from 8.0 to 59.5 m, and were placed both parallel and normal to foliation where possible to allow for maximum data collection. Transects were concentrated near the topographic step between Greens Lakes 3 and 4 (Fig. 1) including regions above, within, and below the step. Once transects were surveyed, I measured the distance between fractures. These measurements allowed me to calculate the density of fractures based on rock type, as well as location in the valley. Width, length, and nature of the individual fractures were recorded for fractures that extended at least one meter to either side of the 30m tape. Fractures were categorized as either major, minor, or trace. Field data was then grouped by transect, rock type, and location. Fracture densities were calculated for each individual transects and for the four separate rock types: biotite gneiss/metasediments, granite, latite dike, and monzonite. Fractures were also classified by location above, within, or below the topographic step.

Additionally, the orientations of the fractures were measured along 22 of the 30 transects using a Brunton compass to help determine if certain fracture patterns favored glacial quarrying in the step area. The orientations were plotted on individual stereo nets and rose diagrams for each transect, which allowed for a three-dimensional visualization of the fracture systems. The orientations of dominant fracture sets were then compiled to create a single rose diagram illustrating the intersecting nature of the dominant fractures.

**RESULTS**

Fracture attributes of the individual transects are highlighted by location and rock type in Table 1. These attributes include the strike or direction of the dominant fracture sets and spacing of the fractures. Additional qualitative analyses of the fractures will be detailed below.

Transects EGC-1A and EGC-1B are parallel to the

<table>
<thead>
<tr>
<th>Transect</th>
<th>Location</th>
<th>Rock Type</th>
<th>Dominant Direction</th>
<th>Fracture Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Just above the step between Green Lakes 3 and 4</td>
<td>Biotite Gneiss/Metaseds</td>
<td></td>
<td>Primarily 0.00-1.50m</td>
</tr>
<tr>
<td>1B</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td></td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td></td>
<td>Few fractures (up to 6.00m)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td></td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td></td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>5</td>
<td>Above the step near the edge of Green Lakes 4</td>
<td>Biotite Gneiss/Metaseds</td>
<td>45°, 298°, 61°, 351°</td>
<td>Primarily 0.55-1.00m</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td></td>
<td>Primarily 0.00-1.50m</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td></td>
<td>Primarily 0.00-1.50m</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td></td>
<td>Primarily 0.00-1.50m</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td></td>
<td>Primarily 0.00-1.50m</td>
</tr>
<tr>
<td>10</td>
<td>On the lip of the step between Green Lakes 3 and 4</td>
<td>Silver Plume Granite</td>
<td>48°, 64°</td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>Silver Plume Granite &amp; Latite Dike</td>
<td>280°, 352°</td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>Silver Plume Granite</td>
<td>84°, 351°</td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>Silver Plume Granite</td>
<td>46°, 290°, 313°</td>
<td>Primarily 1.00-1.50m</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>Silver Plume Granite</td>
<td></td>
<td>Few fractures (up to 3.20m)</td>
</tr>
<tr>
<td>15</td>
<td>Within the step between Green Lakes 3 and 4</td>
<td>Biotite Gneiss/Metaseds</td>
<td>31°</td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>Silver Plume Granite</td>
<td>82°</td>
<td>Almost entirely 0.00-0.50m</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>Silver Plume Granite</td>
<td>8°</td>
<td>Almost entirely 0.00-0.50m</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>Silver Plume Granite</td>
<td>63°</td>
<td>Almost entirely 0.00-0.50m</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>Silver Plume Granite &amp; Biotite Gneiss/Metaseds</td>
<td>82°, 60°</td>
<td>Almost entirely 0.00-0.50m</td>
</tr>
<tr>
<td>20</td>
<td>To the west of Green Lakes 4</td>
<td>Monzonite</td>
<td>79°</td>
<td>Primarily 0.00-0.50m</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td>47°</td>
<td>Primarily 0.00-0.50m</td>
</tr>
<tr>
<td>22</td>
<td>Below Green Lakes 3</td>
<td>Biotite Gneiss/Metaseds</td>
<td>354°</td>
<td>Primarily 0.00-0.50m</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td>337°, 352°, 12°</td>
<td>Primarily 0.00-0.50m</td>
</tr>
<tr>
<td>24</td>
<td>Step at Green Lakes 3 and 4</td>
<td>Biotite Gneiss/Metaseds</td>
<td>315°</td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>Biotite Gneiss/Metaseds</td>
<td></td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>26</td>
<td>To the west of Green Lakes 3</td>
<td>Silver Plume Granite</td>
<td>69°</td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>Silver Plume Granite</td>
<td>64°</td>
<td>Primarily 0.00-1.00m</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td>Silver Plume Granite</td>
<td>63°</td>
<td>Few fractures (up to 3.6m)</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>Silver Plume Granite</td>
<td>25°</td>
<td>Primarily 1.00-1.50m</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>Silver Plume Granite</td>
<td>29°</td>
<td>Primarily 0.00-1.00m (up to 7.90m)</td>
</tr>
</tbody>
</table>

*Table 1. Transects classified by location, rock type, and fracture attributes.*
foliation in the gneiss. Several fractures had substantial width and were significantly weathered. In two locations along transect EGC-1A, a block was detached from the outcrop due to intersecting fractures. Transect EGC-2 is perpendicular to foliation, and thus roughly normal to EGC-1A and EGC-1B. Transect EGC-3 is also perpendicular to foliation. Transect EGC-4 is along an extensive outcrop running parallel to foliation.

Transects EGC-5, EGC-6, and EGC-7 are a set trending parallel and perpendicular to the foliation of the gneiss. Transects EGC-8 and EGC-9 also follow the trend of foliation in the gneiss and metasediments. Qualitative analysis of these transects indicates an even distribution of major and minor fractures.

Transects EGC-10 through EGC-14 are a series of transects mainly in the Silver Plume Granite. There was a rough balance between fractures classified as major and minor, with a low number of trace fractures described as well.

Transects EGC-15 through EGC-19 are within the metasediments and Silver Plume Granite; EGC-19 includes the contact between the two lithologies. These transects crossed several sets of closely fractured, roughly parallel joint sets.

Transect EGC-20 is within a monzonite and is at the base of a more minor step between Green Lakes 4 and 5. EGC-21 trends parallel to the foliation of the metasediments and is found within this step. There appears to be a balance between major and minor fractures along both transects.

Transects EGC-22 and EGC-23 cross metasediments and minimal gneisses and are located below Green Lakes 3 within a very gradual step in the valley profile down to Green Lakes 2. Along both of these transects, minor fractures are more common than major fractures.

Transects EGC-24 through EGC-30 are a series of transects that were established from the base of Kiowa Peak to the south of the valley north towards Niwot Ridge. Transects cross both gneisses and metasediments and the Silver Plume Granite. EGC-24 and EGC-25, both entirely within the metasediments, run parallel and perpendicular to foliation, respectively. EGC-26 through EGC-30 are within the Silver Plume Granite.

The spacing of fractures along all 30 transects indicates a high frequency of closely spaced fractures between 0.00 to 0.50m and 0.55 to 1.00m. As the distance between fractures increases beyond 1.00m, the frequency decreases gradually along most transects (Fig. 2). However, two locations within Green Lakes Valley demonstrate a slightly different pattern (Fig. 3). The transects found within the topographic step between Green Lakes 3 and 4 include EGC-15 through EGC-19. Along these transects were several visibly heavily fractured outcrops, which featured fracture spacing of almost only 0.00 to 0.50m. The transects found on the lip of the step between Green Lakes 3 and 4 include EGC-13 and EGC-14 and have distinctly wider fracture spacing. Fracture spacing along these transects was primarily 1.00 to 1.50m, but significantly wider in several locations. An additional feature of these transects was a general lack of extensive or major fractures.

The average orientations of dominant fracture sets along each transect are detailed in Figure 4. After plotting each transect on an individual stereo net,
rose diagrams were also created. The dominant fracture sets were then compiled in a single rose diagram, which featured strikes of 63° and 80° for the majority of fractures within Green Lakes Valley (Fig. 4). The extensive intersecting nature of these fractures is indicated by the range in strike from 8° to 354°. Groupings in the rose diagram were done in 18° increments and a total of 520 readings were used to create the stereo nets and rose diagrams.

**DISCUSSION**

The complex fracture system as seen in the bedrock of Green Lakes Valley has served, and will continue to serve, as a control on the erosion of the valley profile. Fracturing of the bedrock by tectonism involved with the Laramide Orogeny that uplifted the Rocky Mountains has assisted with the glacial erosion of Green Lakes Valley. More recent removal of material during glacial quarrying has resulted in additional sheet jointing, as well. Not only did the fractures assist with past erosion, they will also have a profound effect on the present and future erosion of the region (Molnar et al., 2007).

Tectonism that fractures the bedrock is essentially a method of disintegration of the rock that serves to accelerate the rates of erosion along those planes. The fragmented nature of the bedrock in the Front Range of the Rocky Mountains has persisted for roughly 50 million years. When the most recent period of glaciation on the North American continent ended 10,000 years before present, a stepped topography of Green Lakes Valley was exposed. The fractures allowed the glacier to effectively extract bedrock by quarrying processes. Even a geomorphic agent as powerful as a glacier has difficulty eroding a zone that has wide fracture spacing (Molnar et al, 2007).

Grouping transects first by location and then by lithology allowed for the varying fracture densities to be assessed in relation to the valley profile. The prominent closely spaced fracture system featured in transects EGC-15 through EGC-19, found within the step between Green Lakes 3 and 4, confirm the assumption that the closer the fractures, the weaker the rock strength and, thus the more susceptible the bedrock to erosion by a glacier (Selby, 1980). The more evenly balanced collection of narrowly, as well as widely spaced fractures (EGC-1A through EGC-14), corresponds to a lesser amount of glacial erosion, forming the broad bench where Green Lakes 4 is located. Transects EGC-24 through EGC-30 have a similar balanced fracture density that results in another broad bench where Green Lakes 3 is located.
A preliminary evaluation can be made of the importance of lithology in the fracturing of Green Lakes Valley. The fabric and foliation in certain rock types lend themselves to increased fracturing because of pre-existing weaknesses along those planes (Manda et al., 2007). Fracture density in the biotite gneiss and metasediments was consistently 0.00m-0.50m and 0.55m-1.00m, most likely attributable to the fabric and foliation of the host rock, but also featured zones of wider spaced fractures. In the Silver Plume Granite, however, the fracture spacing varied by location. Within the step between Green Lakes 3 and 4, fracture spacing is limited to primarily 0.00m-0.50m, but along the lip of that step, fracture spacing is generally much wider, up to 3.20m in some locations (Fig. 3). Because the Silver Plume Granite lacks a definitive and controlling foliation, it is unlikely that the fracture patterns are due to the host rock fabric. Fractures within the monzonite intrusion and latite dike were not studied extensively enough to determine their influence on fracturing.

The fractures found in the varying bedrock types were more than just an effective control of erosion during glacial activity. Even today, the fractures continue to provide sites for accelerated erosion due to a significant increase in surface area. Instead of purely being an assistant to mechanical erosion, the fractures also serve to enhance chemical erosion (Molnar et al., 2007). It is this currently occurring form of erosion that provides insight into the nature of the critical zone in Green Lakes Valley. Following suit, these fractures will then provide a conduit for groundwater flow into the subsurface. Intersecting fracture systems, as seen in the variable fracture orientations, have created a complex interconnected bedrock aquifer for increased groundwater flow over time due to continued weathering and erosion of the critical zone. The fracture attributes recorded during this study, such as spacing, orientation, and width, allowed for an initial determination of the connectedness of the system (Manda et al., 2008). However, only additional study of the fracture attributes will allow a comprehensive statement to be made on groundwater flow pathways in the bedrock of Green Lakes Valley.
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 km² 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.

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 14C 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 in-
cluded 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...
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$_2$O$_3$ ratio (a proxy for soil development) of each sample vs. sample depth and Figure 3B is a plot of sample P$_2$O$_5$ 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-

<table>
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<th>Site/Profile</th>
<th>Sample</th>
<th>Horizon</th>
<th>m (cm)</th>
<th>Rel. Wt. % Illitic Material</th>
<th>Rel. Wt. % Chlorite</th>
<th>Rel. Wt. % Illite Smectite</th>
<th>Rel. Wt. % Illite Vermiculite</th>
<th>Rel. Wt. % Illite Saponite</th>
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<td>n/a</td>
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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 these 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.

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**INTRODUCTION**

Phosphorus, an essential limiting macronutrient for plants, is found most abundantly in soils in its inorganic form as the mineral apatite (Welch, 2002). Some previous studies have concluded, however, that decomposition of the organic component in soil may provide 30% to 80% of the total available phosphorus to an ecosystem through recycling (Tarafdar and Claassen, 1988). Commonly occurring as an accessory mineral, apatite plays a crucial role in plant growth because its weathering provides a continuous source of non-organic phosphorus. Phosphorus is incorporated in the transportation of cellular energy in adenosine triphosphate (ATP) and serves as part of the structural framework in RNA and DNA. The purpose of this study is to determine the source of phosphorus and to quantify the amount of apatite in fresh bedrock and soils of the Betasso subcatchment of the Boulder Creek watershed in Colorado.

The study site is the Betasso catchment of middle Boulder Creek, located west of Boulder, Colorado, in the Front Range. It is the most weathered of the three catchments studied in the Boulder Creek Critical Zone Observatory (Anderson, Boulder Creek Proposal). The critical zone is the area above fresh bedrock that has weathered in response to exposure to the forces of the hydrosphere, atmosphere, and biosphere that bedrock does not experience at depth (Anderson, 2007; Anderson, 2008). The ultimate source of nutrients, it is imperative to understand the weathering processes and mechanisms of this zone. The soils in this veneer represent the zone where minerals break down and release nutrients such as phosphorus.

The presence of apatite in granitic rocks as a source of phosphorus has been confirmed in bedrock similar to that found in Boulder Creek, including the Bemboka and Bullenbalong granodiorites of New South Wales (Banfield and Eggleton, 1989; Taunton, 2000; Banfield, 1990), the Trois Seigneurs granodiorites (Oliva, 2004), and in the granodiorites of the Front Range (Condie, 1995). Preliminary investigations of the mineralogy and chemistry of Boulder Canyon granodiorites sought to characterize the weathering rates of major minerals such as plagioclase and potassium feldspars. Condie (1995) provided preliminary evidence of phosphorus concentrations in bedrock, saprolite and soils. Dethier and Lazarus (2006) calculated the average denudation rates of grus, saprolites, and bedrocks near the glacial limit. Based on the bulk chemistry of the rocks investigated by these studies, we assume the primary mineral source of phosphorus is apatite. However, apatite has not been studied in local bedrock and soils. This study focuses on quantifying the presence of apatite in soils and to identify mechanisms of apatite weathering in the Betasso catchment.

The Betasso catchment has not been glaciated, but it is likely that climate change affected the area at the same time as the Pleistocene glaciations that have been documented from nearby areas (Madole et al., 1999). There is evidence of an older glacial history, but local deposits preserve best the Bull Lake glaciation, which lasted from about 200,000 to 130,000 years ago, and the Pinedale glaciation, from about 30,000 to 15,000 years ago. Deeply weathered and covered mainly by undated saprolite, unconsolidated materials, and alluvial deposits, seismic tests, electrical resistivity lines and, ground penetrating radar have all found the soils, grus and saprolite to extend to as much as eight meters below the surface in the Betasso area.
The sampling site for soils is a gully exposure, four meters deep, assumed to have been excavated by a flood from a break in a water pipeline, located uphill. Positioned in an area classified as alluvial and colluvial deposits of Pinedale age, a buried soil profile, more than a meter below the surface, has been radio-carbon dated. Results suggest the preserved weathered profile was buried deeply enough to stop exchanging carbon with the atmosphere about 8,500 years ago. Based on the development of the profile, it represents exposure times to surface weathering on the order of tens of thousands to perhaps a hundred thousand years.

METHODS AND MATERIALS

Grain mounts were prepared by sonicating soil samples for sixty seconds to shake off clays and then wet sieved for a 63-125 micron fraction. The fine-sand fraction has been found to be the most proportionally representative fraction of mineral assemblages for most soils (Manage, 1992). A trace mineral in the bedrock (Condie, 1995), it is necessary to concentrate the apatite. Heavy minerals were separated from an initial mass of ten grams following the gravity separation technique described in Manages’ Heavy Minerals in Colour (1992). The density of the methylene iodide liquid was 3.1 g/cm³, just below the 3.14 to 3.26 g/cm³ density of apatite. The liquid was drained, recalibrated, and reused. The heavy minerals were sonicated for four minutes in acetone and dried before weighing.

Epo-tek epoxy #201 was used to mount the grains for analysis. Epoxy was first spread on a glass slide so that the grains could be evenly distributed onto the slide by shaking them through a 125-micron sieve. After drying for an hour in a 90°C convection oven, more epoxy was poured over the mount and dried overnight in the oven. The slides were polished on the 600 and 320 micron grit wheels until grains were exposed. A grid was etched into the grain mounts using a metal scribe template with four-millimeter tick marks on both axes. The purpose of the grid was to establish a method in which a section of the slide could be aligned under the SEM so that the EDS could be used to map grains with calcium and phosphorus.

Each slide was carbon coated and then analyzed in a JEOL JSM636OLV Scanning Electron Microscope (SEM) with a PTG Electron Dispersive X-ray Spectrometer (EDS). Each mineral with both elements was assumed to be apatite because other calcium phosphate minerals, such as monetite and brushite, are very rare. At least 300 total grains were counted to ensure a statistically representative population (Manage, 1992). Individual grains were identified, photographed, and described for both the young and older, buried soils. A simplified version of the methods is illustrated in Figure 1.

RESULTS

The primary phosphorus-bearing mineral identified by the SEM/EDS was apatite. Zircon, sphene, and magnetite composed the majority of the remaining fraction. The data allowed the calculation of the amount of the heavy minerals in the total mineral assemblage. The apatite in the soils were graphed against depth to illustrate the vertical special relationships (Fig. 2). Assuming that the heavy minerals are of equal weights, we are able to determine the weight of apatite in soils of the gully by knowing the amount of heavy minerals in the fine fraction and the percent of apatite within this fraction. Bulk chemical data compared to point counting data is illustrated in Figure 3.
The weathering of individual grains of apatite is similar both the surface and buried profiles at similar depths and horizons. Etching into grains of the A- and B-horizons of the buried soils is comparable to that in the surface O-horizon in the younger soils, however, there is sufficient evidence to suggest that the primary mechanism of weathering is chemical, as if apatite is dissolved away. Even in horizons where we expect intense erosion, the edges of apatite grains are relatively smooth. There is no evidence of any alteration of apatite at rims or along fractures, but several areas of iron, potassium, and titanium rich clays were identified along fractures and as partial rims to the grains, but these may be clays that were not fully removed (Fig. 4). At greater depths within each profile, more euhedral and less fractured grains are more abundant. Observations of other minerals has led us to conclude that the buried soil have experienced more intense weathering than the younger upper soils.
DISCUSSION

Presence of apatite in the buried profile suggests exposure to weathering from tens of thousands to perhaps beyond one hundred thousand years. In the buried profile, the apatite may have experienced more intense weathering near the surface. Since Betasso is not known to be acidic through natural or anthropogenic mechanisms, presently, the sources of weathering for the apatite could be a consequence of the production of acids from naturally occurring organic processes in the O-horizon during its exposure to the surface. We believe that the conditions under which these buried soils were at the surface existed under dense forest material likely to produce organic acids. Based on observation of the minerals in the grain mounts, we believe that the apatite has been chemically dissolved. It is possible that partitioning of the bulk phosphorus has resulted in increased amounts of phosphorus in clays and Fe(OH)$_x$ compounds (Penn, 2005).

The Holocene soil has a similar abundance of apatite compared to maximum of the preserved profile. Mass waste transports materials down slope with the deposits retaining mineral assemblages representing parent bedrock or less weathered materials from upslope. Because the lower soil was buried about 8,500 years ago, this young soil has experienced only minimal weathering, so we do not see depletion of apatite.

Even with expected trends, potential error in this study was the assumption that all the heavy minerals had the same density. Other heavy minerals may have a density greater than apatite. This would result in decreased lower the weight of the apatite in the soils by a fraction of a percent.

CONCLUSION

This study suggests that apatite is the primary mineral source of phosphorus in Betasso. It is present in the bedrock and is therefore weathered and available in the Betasso soils and colluvial materials, ranging in weight from 0.1 to 0.27% of the soils. The buried soil profile represents exposure times of tens of thousands of years, perhaps more than one hundred thousand years. The overlying, younger soil is likely regolith derived from less weathered materials upslope and has had less time to weather. The primary weathering mechanism seems to be chemically dissolving the apatite. Also, phosphorus that has been removed from apatite but is still present in the soil was possibly partitioned into clays and Fe(OH)$_x$ compounds.

Additional study is needed to characterize the weathering of phosphorus-bearing minerals more thoroughly. This data can be normalized against zircon to compare apatite’s weathering relative to a highly resistant mineral. Others working in the Colorado Critical Zones Observatory can integrate ideas discussed in this research to create a more comprehensive understanding of the chemical properties of this critical zone.

ACKNOWLEDGEMENTS

Support for this study came from several people and programs. First, I would like to extend my gratitude for my advisors, Dr. Richard April and Dr. David Dethier for their support, review, and guidance of my study. Also, I am grateful for the support, critique, and advice from the Colgate Geology Department, both faculty and students, and for the Keck Geology Consortium.

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