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

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JAMES N. WINKLER, University of Connecticut
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ALEXANDRA HORNE, Mt. Holyoke College
Research Advisor: David Dethier

INTRODUCTION

Bedrock weathering is a crucial part of critical zone geomorphology because it is a fundamental control in regolith development (Anderson, R. et al., 2011). By quantifying rock strength, we can better interpret the influence of bedrock weathering on landscape evolution. Rock strength itself depends on the microfabric of a rock, because as weathering alters the microfabric, it reduces the rock's strength (Tugrul, 2004). However, weathering rate can also be influenced by fracture spacing, mineralogy, and topoclimate (Linton, 1955; Moore et al., 2009). Therefore, this study measured both compressive strength and fracture characteristics to assess the degree of bedrock weathering.

One of the research goals of the Boulder Creek Critical Zone Observatory (BcCZO) has been to interpret the morphology of separate hillslopes that have different aspects. In one area of interest, Gordon Gulch, about 10% of the hillslopes consist of tors. Tors are independent, remnant exposures of bedrock that have been exhumed after intense rock weathering along anisotropic subsurface fracture systems (Linton, 1955; Street, 1973; Twidale, 1990). Their development is closely linked to topographic position, groundwater interaction, and fracture density; and previous local studies have compared variations in tor density within Gordon Gulch to slope angle, soil development, and vegetation (Trotta, 2010; Befus et al., 2011). This study characterizes rock strength across the broader landscape in order to quantify rock weathering throughout the BcCZO.

FIELD AREAS

This study was conducted in the Colorado Front Range, where a steep climate gradient exists as elevation decreases from around 4,000 m in the alpine to 1,600 m near the city of Boulder. In the alpine, there is higher precipitation and lower mean annual temperatures than in areas of lower relief (e.g. Boulder). Vegetation cover also increases with elevation, until roughly 3,450 m, where tundra dominates the landscape (Dethier and Lazarus, 2006).

Two groups of rock exist in the studied areas. A suite of Paleoproterozoic biotite schists and gneisses, metamorphosed around 1,713 ±30 Ma, which are complexly and irregularly banded (Cole and Braddock, 2009). The other group is made up of Boulder Creek granodiorite, which intruded approximately 1,716 ±3 Ma, and granite of Longs Peak Batholith, which intruded 1,400 Ma (Cole and Braddock, 2009).

Four areas were selected for the study: Green Lakes Basin, Gordon Gulch, Betasso Gulch, and a suite of highway road cuts in the vicinity of Gordon Gulch (Fig. 1).

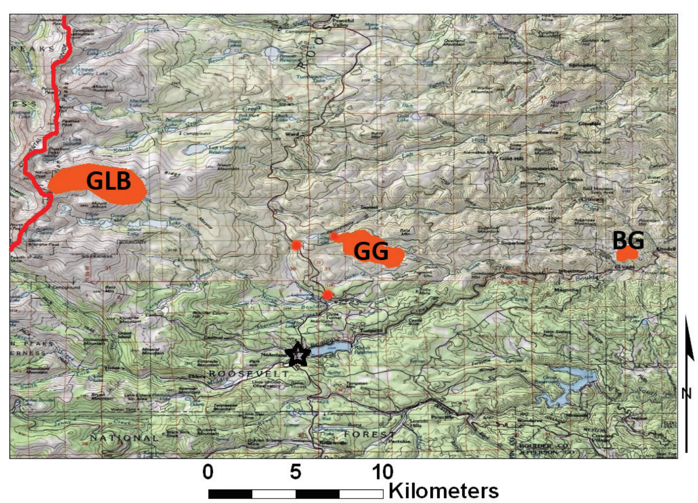


Figure 1. Map showing all field locations (in orange) GLB=Green Lakes Basin, GG=Gordon Gulch, and BG=Betasso Gulch. The small orange points are the road cuts. A black star marks the town of Nederland and the red line indicates the continental divide.

Green Lakes Basin, above 3,300 m elevation, was last glaciated 15 Ka, and has exposures of both glacially polished bedrock and more weathered bedrock within close proximity. Both Gordon Gulch and Betasso Gulch, at elevations of 2,550 m and 2,000 m respectively, have tors representing weathered and exposed bedrock, as well as adjacent saprolite illustrating extremely weathered bedrock. Neither of these catchments has been glaciated, but it is likely that erosion and weathering rates have been influenced by post-glacial climatic changes.

The highway road cuts are comprised of three outcrops, each representative of a different rock type: granodiorite, schist, and gneiss. They have been exposed within the last century and provide a weathering profile from the surface to fresh, unweathered bedrock 6-8m below.

METHODS

The primary bedrock characteristics measured in the field were uniaxial compressive strength (UCS) and fracture spacing and orientation. The location of each measurement site was recorded (within 6m accuracy) with a Garmin Etrex GPS.

UCS was measured with a Proceq type N Original Schmidt Hammer, which is a portable tool designed to non-invasively measure the UCS of material in-situ (Day and Goudie, 1977; Aydin and Basu, 2005; Proceq, 2006). At each site, 20 to 30 different measurements were taken across approximately 1m^2. An additional 10 measurements were taken if the initial measurements were highly variable. The device was always used perpendicular to the test surface; however, surfaces were not buffed or prepared for testing and the angle of incidence was not recorded. However, the methods used were consistently applied, and are therefore not expected to bias data interpretation.

In Green Lakes Basin, exposures of glacially polished bedrock were tested with the Schmidt Hammer, as were several adjacent glacially sculpted bedrock exposures that did not display polish.

In Gordon Gulch, tors around the valley were tested with the Schmidt Hammer on three separate faces (the top of the tor, the up-slope facing side of the tor, and the down-slope facing side of the tor, Fig. 4) to evaluate if there was a quantifiable spatial difference in rock strength. Fracture spacing was quantified by recording where fractures (≥1m) intersected a horizontal transect (≥1.5m) across an outcrop face. Fracture and foliation orientation were also measured. Bedrock and saprolite in 19th century prospector's pits and modern research pits were also tested with the Schmidt Hammer where saprolite and bedrock exposures were adequate.

In Betasso Gulch, Schmidt Hammer measurements were taken at saprolite exposures along Betasso Road, as well as at Bummer's Rock, a ridge top tor just off the road.

Two of the highway road cuts, two were on the Peak-to-Peak highway and the third was on the old Switzerland Railway. At each of the road cuts, Schmidt hammer measurements were taken at the bottom, middle, and top of the exposure. Depth below the surface was determined using a TruPulse 360 Laser Rangefinder.

Since the Schmidt Hammer assigns unit-less values of rebound, "R_{value}", measures of compressive strength were calculated using:

$$\text{Log } \sigma_{ult} = 0.00014\,\gamma\, R_{corrected} + 3.16 \quad \text{(Eqn. 1)}$$

where σ_{ult} is UCS (in psi x 10^3 = 0.006895 GPa), γ is the dry unit weight of the sample (lb/ft^3), and $R_{corrected}$ is the Schmidt Hammer Rebound value, corrected for the incidence angle during measurement (Deere and Miller, 1966). Reference unit weights were used from Deere and Miller, 1966 and R_{values} were not corrected for angle of incidence.

The Schmidt Hammer generates a non-Gaussian data series, since it frequently underestimates, and can very rarely overestimate, UCS. Causes include unprepared test surfaces, subsurface fractures within the rock, and variations in the angle of incidence. Thus, statistical analyses of Schmidt Hammer data should not assume gaussian distribution, but rather consider the abundance of underestimated, and scarcity of overestimated, measurements (M. Cooke, University of Massachussets, Amherst, personal communication, Feb, 2012). Therefore, the 3rd quartile of the data set (between the 50th and 75th percentiles), seems most appropriate for analyzing the distribution of UCS measurements.

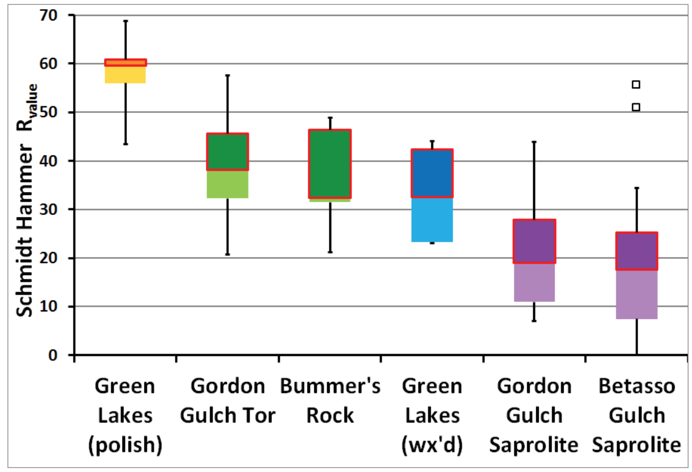
Hand samples from three test sites were used for laboratory testing of UCS. All three were from anthropomorphically exposed roadways; including a gneissic and a granitic sample from Green Lakes Basin, as well as a granitic sample from 6.5m depth at Peak-to-Peak highway road cut AR1. Samples were cored and tested with an ELE Uniaxial Compression Test MSachine (Geomechanics Laboratory, University of Massachusetts, Amherst).

RESULTS

Distinguishing Degree of Weathering

Schmidt Hammer measurements from all of the field locations separate into three groups of similar uniaxial compressive strength (Fig. 2a). The glacially polished bedrock in Green Lakes Basin had the highest UCS, the tors and the weathered alpine bedrock had an intermediate UCS, and the saprolite in Gordon Gulch and Betasso Gulch had the lowest UCS (Table 1).

The highway road cuts are similarly divided into three separate groups of UCS (Fig. 2b, Table 1). The shallowest rock, 0m below the surface, had the lowest mean R_{value}, which was comparable to the R_{value} of saprolite in Gordon Gulch and Betasso Gulch. At depths of approximately 3m, the mean R_{value} of the road cuts was comparable to the tors and weathered alpine bedrock. The deepest bedrock in the road cuts, 6.5-8.5m



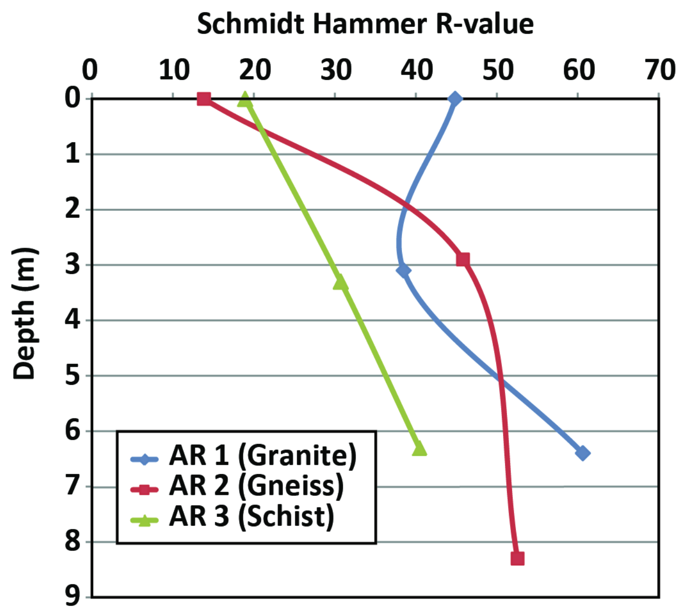


Figure 2. A. The distribution of Schmidt Hammer R_{values} from each study site, with the 3rd quartile of each data set boxed in red. The three groupings of strength are apparent: polished Green Lakes bedrock, Gordon Gulch tors/Bummer's Rock/weathered Green Lakes bedrock, and Gordon Gulch/Betasso Gulch saprolite. B. Depth-Strength profiles of the highway road cuts in which strength increases with depth.

	Green Lakes (Polish)	*Road Cuts (depth=6.5-8.5m)*	Gordon Gulch TOR	*Road Cuts (depth=3m)*	Bummer's Rock	Green Lakes (Wx'd)	Gordon Gulch Saprolite	Betasso Gulch Saprolite	*Road Cuts (depth=0m)*
N	20	3	84	3	5	4	11	20	3
Average Schmidt Hammer R-value	54	50	39	38	36	33	21	20	15
sigma 1 (Gpa)	191.6	155.5	83.6	80.4	72.5	61.1	31.8	30.2	22.7
3rd Quartile Raqnge (Gpa)	255-284.6	-	80.4-124.8	-	57.8-124.8	61.1-100.2	28.3-46.4	26.8-39.4	-

Table 1: Reports the in situ measurements of R_{value} UCS for each study site.

below the surface, had a mean R_{value} equivalent to the recently exposed, glacially polished bedrock in Green Lakes Basin.

Rock Strength on Different Slopes in Gordon Gulch

When comparing the north-facing and south-facing slopes in Gordon Gulch, the tors on the south-facing slope exhibited slightly stronger UCS (Fig. 3). The mean R_{value} for tors on the south-facing slope was 40 R_{value} and the mean 3rd quartile spans between 40-43 R_{value}, which is higher than on the north-facing slope, where mean compressive strength was only 33 R_{value}, and the 3rd quartile was between 36-37 Rvalue.

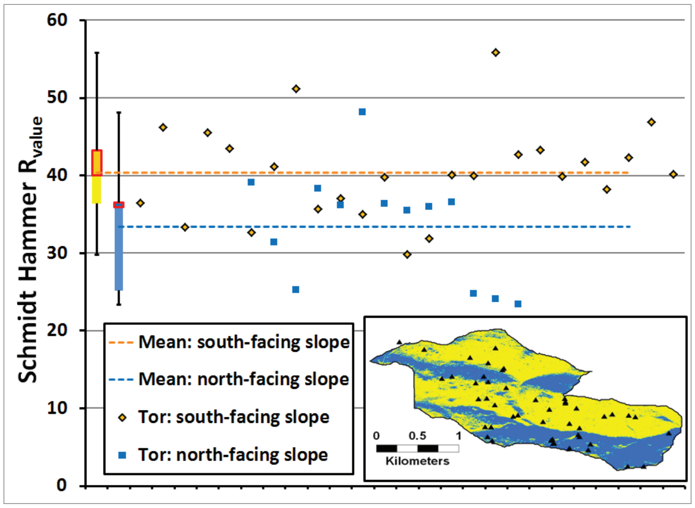


Figure 3. R_{values} for each tor measured in Gordon Gulch, distinguished by tors on north- or south-facing slopes. Dashed lines represent average R_{value} and the 3rd quartile is boxed in red. The inset shows Gordon Gulch with sample sites marked by triangles. North-facing slopes are colored blue and south-facing yellow.

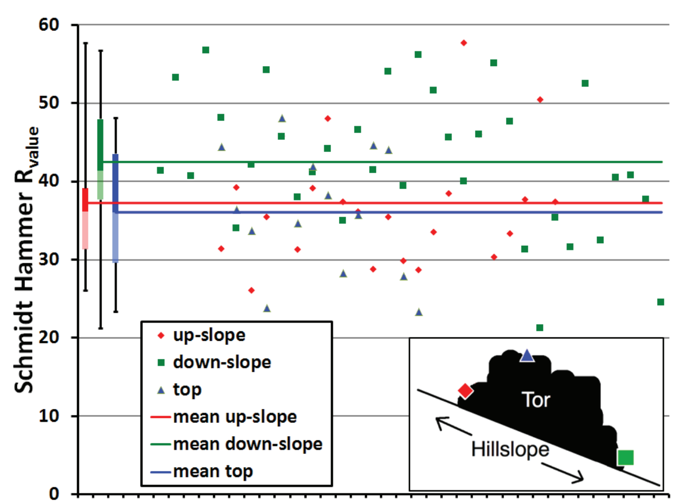


Figure 4. Comparison of Schmidt Hammer R_{values} from the up-slope, down-slope, and top faces of tors. Average R_{values} are plotted as solid lines and the 3rd quartile range of each data set is highlighted by darker red, green, or blue boxes. The inset shows the distinction between the up-slope, down-slope, and top faces of a tor.

Since previous work has shown that there are more granitic tors on the south-facing slopes relative to the north-facing slopes (Trotta, 2010), the Schmidt Hammer measurements of each rock type were compared to see if the observed difference in UCS on each slope was related to the dominant rock type. Tors of metasedimentary composition had a 3rd quartile range of 40-44 R_{value}, while the granitic tors range only between 36-41 R_{value}. Therefore, because the 3rd quartile overlaps, the difference in UCS on each slope does not appear related to the dominant rock type of that slope.

The influence of fractures was also considered in this study. On the south-facing slopes, fractures were less densely spaced (43cm) than on the north-facing slopes (32cm). However, when compressive strength and mean fracture spacing were compared at discrete locations, there was no evidence of a direct relationship between the two. Fracture orientations were also examined, and while no preferential orientation was apparent, the majority display a moderate dip (~30-60°).

Quantifying the Differential Weathering of Tors

The data taken from up-slope, down-slope, and the tops of tors were compared to see if the Schmidt Hammer could quantify variations in weathering on a tor (Linton, 1955).

The up-slope and down-slope sides appear to be slightly different, because their 3rd quartile ranges (36-39 R_{value} for the up-slope side and 41-48 R_{value} for the down-slope side) are discrete (Fig. 4). However, the measurements taken from the apparent tops of the tors are similar to both up-slope and down-slope faces since the 3rd quartile ranges overlap (range of 36-44 R_{value} for top faces).

The differences in strength on the up-slope faces vs. down-slope faces do not appear to be related to an overarching lithological difference, since both metasedimentary and granitic tors show slightly higher UCS on down-slope faces than on the top and up-slope faces. However, on the north-facing slope, the metasedimentary tors have nearly identical UCS on every face.

Laboratory Testing

Laboratory testing of UCS demonstrated that the unweathered gneissic metasedimentary rock from Green Lakes Basin has a σ_1 value of 184.7 MPa at failure, which is higher than the unweathered granitic rock from the same area and AR1 (σ_1 value of 111.7 MPa). This relationship of stronger metasedimentary rock and weaker granitic rock is consistent with the relationship seen in the in situ Schmidt Hammer measurements of UCS in Gordon Gulch.

DISCUSSION AND CONCLUSIONS

As expected, the road cuts show that UCS increases and bedrock weathering decreases with depth. Since UCS measurements from across the watershed also differentiate into similar groups, we can correlate this trend across the landscape.

The glacially polished rock in Green Lakes Basin and the deepest road cut bedrock have the highest UCS. Therefore, they are the strongest, least weathered bedrock of all the field areas.

The slightly lower UCS of tors and intermediate depth road cut bedrock represents the weathered, but still relatively strong state of these lithologies. Since the weathered, glacially sculpted bedrock in Green Lakes Basin has a similar UCS to this intermediate weathered group, it suggests that once bedrock starts to weather, it becomes comparable to the strong but weathered rock at lower elevations.

The saprolite and most shallow road cut bedrock have the lowest UCS of all, which means they have experienced the most weathering. However, at lower elevations, there is saprolite immediately adjacent to stronger, relatively less weathered, tors. Here, the geomorphic processes governing the development of tors (Twidale, 1990) can explain the vastly different adjacent UCS. Tors develop where fractures and jointing are less dense, whereas the denser fracturing of adjacent areas facilitates greater weathering. In Gordon Gulch, tors are likely representative of pockets of less densely spaced fractures. Saprolite, on the other hand, may have formed in areas where fracturing, which is still present in the subsurface rock, is more dense and facilitates the propagation of further weathering. Since this study finds that tors on the north-facing slopes have more closely spaced fractures than those on the south-facing slopes, the fracture density may explain why Trotta, 2010 found smaller tors on the north-facing slope.

Furthermore, tors only become visible relief on the landscape after regolith has been stripped. If regolith is not removed, subsurface weathering will persist and subsequent relief will be smaller (Twidale, 1990). Since numerous studies (such as Anderson, S. P. et al., 2011) disclose that regolith is deeper on the north-facing slope than on the south-facing slope, the tors there may experience more weathering, and thus be smaller, than those on the south-facing slopes.

The relationship between south-facing slopes having higher UCS than the north-facing slopes may also be related to thicker regolith driving further weathering; however, moisture content could also influence the discrepancy. Since the north-facing slopes are wetter and likely experience more frost cracking (Anderson, S. P. et al., 2011), it is possible that the increased moisture and physical weathering there has led to a decrease in the tors' UCS (Vasarhelyi and Van, 2006; Matsukura and Tanaka, 2000).

Also, lithology does not seem to be the primary influence in the UCS discrepancy. Even though there are more granitic tors on the south-facing slope, the granitic suite of rock observed in this study had a slightly lower UCS when measured with both the Schmidt Hammer in situ and when measured in the laboratory.

On a smaller scale, the weathering of adjacent faces of the same tor shows that up-slope faces have slightly lower measures of compressive strength than down-slope faces. One explanation is that the tor could behave like a braking block (Putkonen et al., 2010), accumulating regolith up-slope and allowing down-slope mass movement of newly mobilized regolith away from the tor's down-slope face. If true, fresher rock with a higher UCS would be more frequently exposed on the down-slope face of tors.

However, metasedimentary tors on the north-facing slope have more homogeneous UCS measurements. The near parallel relationship between the hillslope and foliation orientation, coupled with smaller tors on the north-facing slope (Trotta, 2010), may explain this anomaly, since UCS measurements taken at each location were probably measuring the same bedding layer.

In conclusion, this study has shown that there is a change in bedrock strength across the Front Range that decreases with increased weathering. The strongest rock is both the deepest (road cuts) and that which has maintained glacial polish. Once bedrock begins to weather, it weakens to an intermediate range of uniaxial compressive strength, and with increased chemical and physical weathering becomes the weakest rock measured in the Front Range. In Gordon Gulch, it appears that structural anisotropy, microclimate, and regolith removal are the dominant forces governing tor location and size. Furthermore, location on a hillslope may facilitate slight differences in weathering around individual tors, as weathered material may be more effectively removed from down-slope faces.

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