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2009-2010 PROJECTS

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Faculty: David Dethier (Williams) Students: Elizabeth Dengler, Evan Riddle, James Trotta

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Faculty: Kirsten Nicolaysen (Whitman College) and Rick Hazlett (Pomona College)

Students: Adam Curry, Allison Goldberg, Lauren Idleman, Allan Lerner, Max Siegrist, Clare Tochilin

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**Keck Geology Consortium: Projects 2009-2010
Short Contributions – COLORADO**

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

Project Director: *DAVID P. DETHIER*: Williams College
Project Faculty: *MATTHIAS LEOPOLD*: Technical University of Munich

**FRACTURE DISTRIBUTION AND CHARACTERIZATION IN BETASSO
GULCH, CO**

ELIZABETH DENGLER
Bates College
Research advisor: Dykstra Eusden

**TALUS STRUCTURE AND EVOLUTION: A COMPARISON BETWEEN TALUS
NEAR GREEN LAKE 3 AND AT BUMMER'S ROCK, COLORADO**

EVAN RIDDLE
North Carolina State University
Research Advisor: Karl Wegmann

**THE DISTRIBUTION OF TORS IN GORDON GULCH, FRONT RANGE,
COLORADO**

JAMES TROTTA
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TALUS STRUCTURE AND EVOLUTION: A COMPARISON BETWEEN TALUS NEAR GREEN LAKE 3 AND AT BUMMER'S ROCK, COLORADO

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INTRODUCTION

The exposure of bedrock cliff faces in mountainous regions can subsequently lead to the accumulation of talus. Talus, deposits of coarse blocky detritus, forms at the base of cliff source areas (Caine, 1983). The modern Colorado Rocky Mountains formed during the late Cretaceous to middle Eocene Laramide Orogeny (Bird, 1988). This orogenic interval was followed by periods of glacial advance and retreat during the Pleistocene. Glacial valleys were cut in alpine regions and glaciers extended into Front Range river valleys (Kellogg et al., 2008).

The disappearance of ice allowed slope deposits to accumulate in the Boulder Creek Watershed. Talus abundance provides evidence for Holocene erosion and deposition in this area. Talus slopes are unstable and can pose a significant hazard to engineered structures such as roads, hiking trails, and other infrastructure. Studying the underlying structure and development of talus can help us better understand sediment generation from the cliff source to the base of the talus field. The purpose of this study is to observe how rock type, joint spacing, and weathering patterns control the size and rate of talus development.

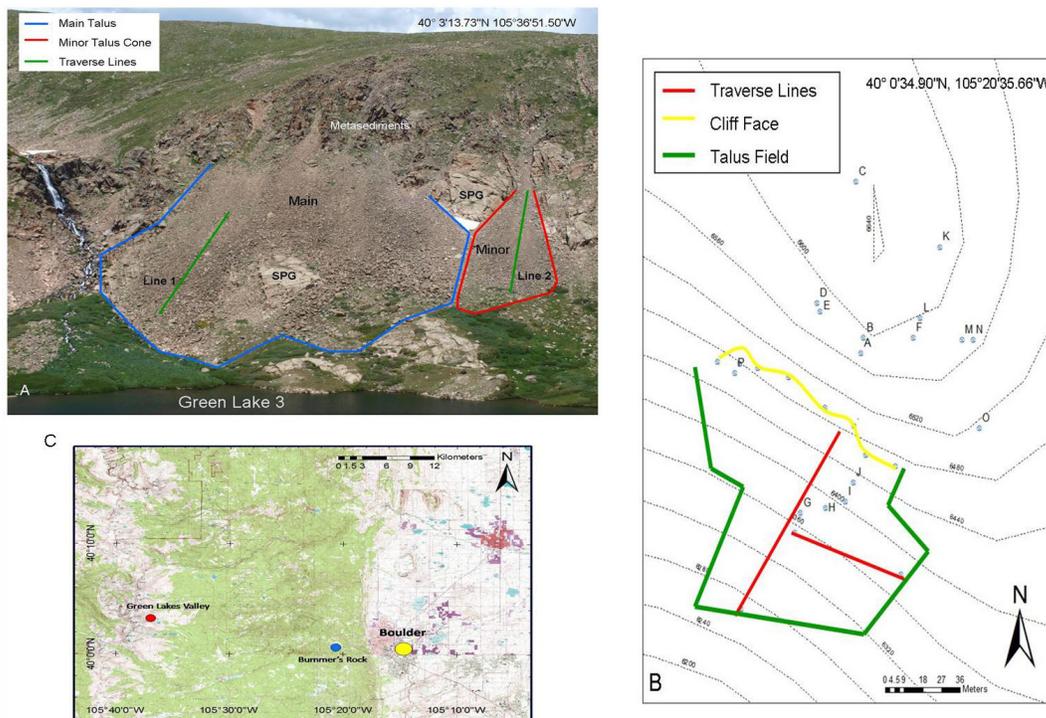


Figure 1. Images of Green Lake Valley and Bummer's Rock talus slopes. A. View looking northwest across Green Lake 3. Displayed are traverse lines and outlines of the major talus field and minor talus cone. B. Topographic map of Bummer's Rock. Shown are traverse line locations, the approximate location of the cliff face and locations of boulder graphs that correspond with table 1. Also shown is the approximate outline on the talus field on the southwest slope of Bummer's Rock. C. Location of field areas with respect to Boulder, CO.

Areas of Study, Rock Type, and Climate

Talus accumulation occurs throughout the Rocky Mountains, chiefly in alpine regions but also below tree line where bare cliff faces are exposed (Caine, 1986). Two talus fields were selected in two different climatic zones within the Boulder Creek Watershed for analysis: the first at the higher elevation Green Lakes Valley (GLV), and the second at Bummer's Rock, a lower elevation site within the Betasso Preserve (Fig. 1).

GLV is a stepped-profile valley in the upper Boulder Creek watershed that was excavated by the repeated advance and retreat of glaciers (CZO, 2010). The valley contains five alpine lakes. The abrupt topographic step between Green Lakes 3 and 4 was chosen for this study because of the active accumulation of talus across this step. The base of the talus accumulation zone is at an elevation of 3475 meters, has an mean annual temperature of -3.7°C , and averages 1000 mm of precipitation per year, 80% as snow (Caine, 1996; CZO, 2010). The upper basin (consisting of Green Lakes 3 and 4) supports alpine tundra with 71% of the area consisting of exposed bedrock and talus and 29% mantled by soil and vegetation (CZO, 2010).

A mixture of igneous and high-grade metamorphic rock dominates the GLV. The most prevalent rock type is high-grade, strongly foliated Proterozoic (1.7 Ga) metasediments (Gable, 1980). These metasediments are intruded by small silica-rich potassic-feldspar bodies of the 1.4 Ga Silver Plume granite (SPG; Braddock and Cole, 1990; Dethier and Lazarus, 2006). Two talus fields are clearly defined in GLV near Green Lake 3 (Fig. 1A). The north-western-most or "main" talus field is approximately 130 meters from tongue to its cliff source of heavily fractured metasedimentary rocks. A single outcrop of SPG is exposed within the field itself. The smaller "minor" talus field lies immediately to the southeast, is approximately 80 meters from tongue to source, and is supplied predominately by SPG with vegetated metasedimentary rock on the slope above the cliff face (Fig. 1A). Both talus fields lie below the Pleistocene glacial limit, indicating most accumula-

tion occurred after late Pleistocene glacial retreat (12 ka: Miriam Duhnforth, University of Colorado, pers. comm.).

Bummer's Rock (2030 m) is a small, boulder-dominated peak located 10 km west of Boulder, Co in the Betasso Preserve (CZO, 2010). Talus has accumulated on both the east and west slopes of the peak in a thinly vegetated zone. The site has a mean annual temperature ca. 11°C and receives about 500 mm of precipitation annually (Dethier and Lazarus, 2006; CZO, 2010).

Bummer's Rock, and most of Boulder Canyon to the south, consists of the Proterozoic (1714 ± 4.6 Ma) silica-rich Boulder Creek Granodiorite (Braddock and Cole, 1990; Premo and Fanning, 2000; Dethier and Lazarus, 2006). The talus fields beneath Bummer's Rock are stable and appear to be largely inactive. Talus stabilized by low-lying grass and sagebrush with scattered pine trees is common on both the east and west slopes of the peak.

Valley glaciers repeatedly advanced from cirque headwall regions to partially fill tributary valleys of the Boulder Creek watershed during cooler and wetter stadials of the Pleistocene (Dethier and Lazarus, 2006). Cosmogenic radionuclide dating indicates that the GLV was ice free by ca. 12 ka (Miriam Duhnforth, University of Colorado, pers. comm.), after which talus began accumulating along the steep valley margins below 3600 m. Bummer's Rock was below and east of the glacial limit during the late Pleistocene (Madole et al., 1999; Dethier and Lazarus, 2006).

METHODS

Several techniques were utilized to characterize the Green Lakes Valley and Bummer's Rock talus fields, including measuring: (1) boulder dimensional and rounding; (2) cliff face fracture spacing; and (3) talus profiles. Due to time constraints and accessibility some measurements were made at only one of the sites as noted below.

Boulder characterization and talus volume

Talus characterization was conducted in both Green Lakes Valley and Bummer's Rock and included measurements of size, rock type, and percent talus field coverage by boulders. We made line traverses transecting the talus cone from the tongue to the cliff face (source rock), and recording measurements every meter. Boulders that lay beneath meter marks were measured for their major, minor, and intermediate dimensional axes to the nearest millimeter. I also noted rock type and percent lichen cover. When the meter spacing fell on an area of vegetation this was noted and no measurements were taken, and if the point fell directly between two boulders, the downslope boulder (closer to talus tongue) was measured. I used a Garmin Etrex to record the latitude and longitude of line endpoints to the nearest 5 meters.

In Green Lakes Valley, two boulder characterization lines were run along the axis of each talus cone (Fig. 1A). Along the minor talus cone line, the slope angle of the talus surface, width of the cone, and estimated talus thickness were measured every 10 m. For volume measurements of the major talus, an estimated thickness of 2.5 meters was used, based on field observations. At Bummer's Rock, lines were run parallel and perpendicular to the cliff face on the southwest slope (Fig. 1B). For volume measurements at Bummer's Rock, I estimated a talus thickness of 1m, based on field observations. I used ArcMAP 9.3 and Surfer 8 software to calculate the volume of the minor talus cone.

Fracture Spacing

We collected fracture data along the cliff face at the Green Lakes Valley site along a line 1 m above the cliff face-talus contact. Traverse lines were run parallel and normal to the cliff face. The distance, strike and dip of every fracture that extended at least 2 m through the rock and that intersected the tape were recorded as was the bearing, slope, and rock type variations. Fractures were differentiated as 'major' or 'minor' if they either passed completely through the entire cliff or were truncated by another fracture,



Figure 2. Image of boulder measurement device used in the field. Four main measurements were taken: (1) distance along the meter sticks (red lines); (2) distance along the boulder (blue line); (3) distance from the apex of the meter sticks to the boulder (yellow line); and (4) the angle between the meter sticks.

respectively. The location of the endpoints of each cliff-face transect was recorded with GPS. I used StereoWin v. 1.2 to generate rose diagrams of fracture orientations. Fracture spacing data from the Bummer's Rock cliff face were collected by fellow Keck colleague Liz Dengler.

Boulder Rounding

Measurements of boulder rounding were recorded on both the east and west slopes of Bummer's Rock (Fig. 1B) on clasts greater than 50 cm in diameter with a device designed specifically for this study (Fig. 2), based upon the design of Kirkbride (2005).

GPS positions were taken to mark the locations of each boulder group. Boulders were also chosen and rated on the following visual weathering class parameters:

- 1) Freshly fractured rock. Boulder still in original position on cliff face. Little or no weathering or edge-rounding.
- 2) Boulder still in original position. Edges slightly weathered with less than 10% lichen covering the exposed faces of the boulder.
- 3) Boulder is near original position, but completely detached from cliff face. Edges relatively angular

with less than 35% lichen on boulder faces.

4) Loose boulder near cliff face showing significant weathering. Edges are rounded and some boulder faces have 35-70 percent lichen cover.

5) Boulder severely weathered. Edges and boulder faces almost unrecognizable. Boulder is covered with 70% or more lichen.

The roundness of in-situ blocks, boulders on Bummer's Rock and boulders in a roadcut from a recently blasted area at the Boulder Canyon Hydroelectric Plant ~1 km south of Bummer's Rock were used as test populations for measuring the degree of boulder rounding (weathering). I measured one representative area of each boulder. The rounding device was adjusted so that the meter sticks lay flat along two

faces of the boulder with the desired edge pointing to the intersection of the meter sticks. From this position four measurements were taken (Fig. 2). Combined, these measurements allowed me to estimate the amount of rock lost due to weathering. Volume data were estimated based on a 1 cm-wide strip. My calculation of the volume removed due to weathering involved converting measurements into Cartesian coordinates and utilizing MatLab R2009b software.

DATA

Green Lakes Valley Main Talus Field

Boulder characterization of the main talus reveals that 96% of the talus surface is covered with loose boulders; exposed bedrock and soil comprise 3 and 1%, respectively. Metasedimentary and SPG sources account for 52 and 48% of the measured boulders, respectively. Boulder sizes range from 4.6 to 340 cm with 51% within the 10 to 40 cm size class (Fig. 3A). For my comparison of rock fracture spacing and corresponding boulder size for the metasedimentary rock unit I removed SPG boulders (Fig. 3B).

In the metasediments, 39% of the cliff-face fractures are in the 10 to 40cm spacing range (Fig. 3C). The metasedimentary rocks are dominated by one fracture set with a mean orientation of $188^\circ, 83^\circ E$ (Fig. 3D). The horizontal length of the cliff face above the major talus cone is approximately 150 m. The major talus has an area of $\sim 19,000 \text{ m}^2$. Using a talus thickness of 2.5 m the approximate volume is $38,000 \text{ m}^3$.

Minor Talus Cone

The minor talus cone in GLV has complete boulder surface coverage with no exposed bedrock or vegetation. The cliff source for this talus field is SPG with minor exposed metasedimentary rock (Fig. 1A). Metasedimentary and SPG sources generate 55 and 45% of the boulders measured, respectively. Boulder sizes range from 1.7 to 69 cm while 75% of boulders fell between the 0 to 30 cm size class (Fig. 3A); boulder size in relation to distance from the cliff face are plotted (Fig. 3D). Metasedimentary

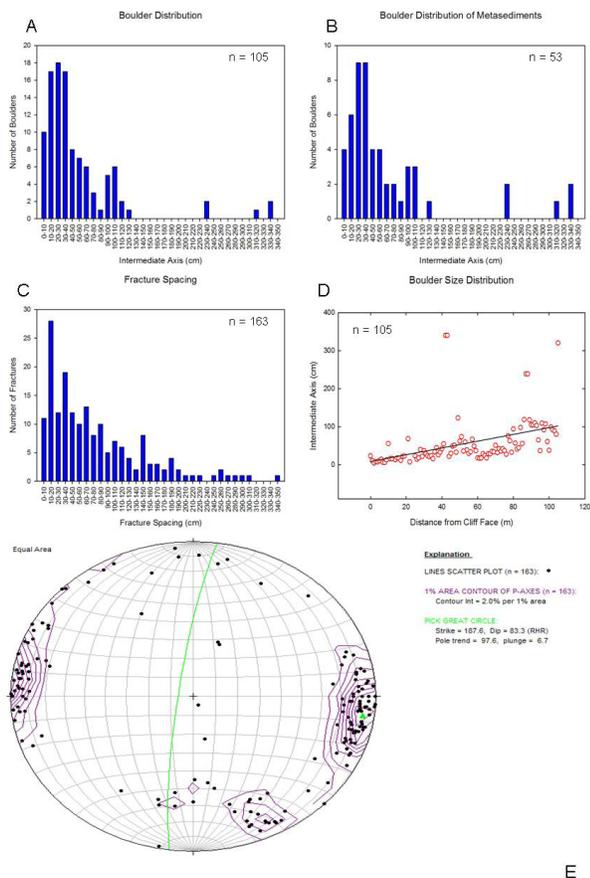


Figure 3. Boulder rounding and fracture data for the main talus. A. Boulder size distributions for both metasediment and SPG boulders. B. Boulder size distributions for metasediment boulders (SPG boulder data removed). C. Fracture spacing for the metasediment cliff face above the main talus cone. D. Plot of boulder size and distance from the cliff face for the major talus. E. Rose diagram of metasediment fracture orientation. Shown are 1% area contours and poles from fracture planes.

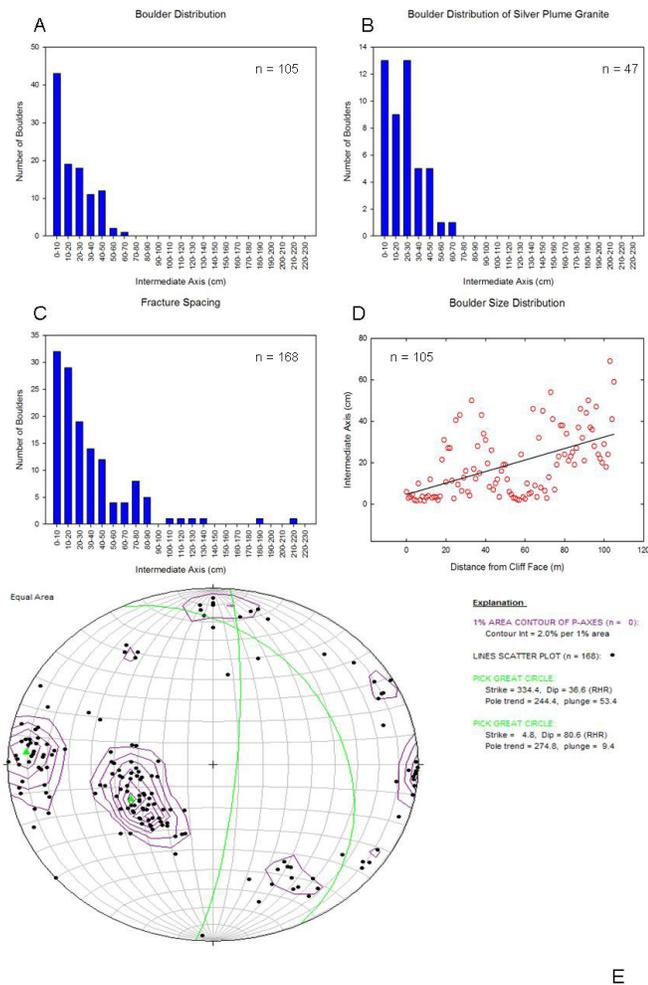


Figure 4. Boulder rounding and fracture data for the minor talus cone. A. Boulder size distributions for both metasediment and SPG boulders. B. Boulder size distributions for SPG boulders (metasediment boulder data removed). C. Fracture spacing for the SPG cliff face. D. Plot of boulder size and distance from the cliff face. E. Rose diagram for SPG fracture orientation. Shown are 1% area contours and poles from planes.

boulders were removed from the dataset to allow for direct comparison between fracture spacing and boulder size within the SPG rock unit (Fig. 3B).

Over 60% of fracture spacings in the SPG are between 0 and 30 cm (Fig. 3C). The SPG fractures are dominated by two distinct sets with orientations averaging 334°, 37° W and 5°, 81° W (Fig. 3E). These two fracture sets yield strikes that are separated by approximately 30° degrees. The horizontal length of the cliff face above the minor talus cone is approximately 55 m.

Location	Boulder	Volume (cm ³)	Visual Weathering Class
A	1	86.4	1
	2	605.9	5
	3	513.1	3
	4	259.9	4
	5	49.8	2
B	6	95.7	5
	7	182.2	5
	8	555.7	5
C	9	96.5	2
	10	77.7	2
D	11	125.5	4
	12	109.9	2
	13	79.6	4
	14	107	4
E	15	125.6	3
F	16	53.4	4
G	17	145.1	3
H	18	36	2
	19	7.5	1
	20	19.7	1
	21	7	1
	22	34.8	1
	23	4.9	1
	24	78.7	3
I	25	119.3	3
	26	61.8	2
	27	209.1	5
J	28	155.1	4
K	29	158.6	5
L	30	125	4
M	31	31.5	2
N	32	94.6	3
O	33	514.6	5
P	34	83.7	3

Table 1. Rounding data for boulders on and around Bummer's Rock. Locations (A,B,C, etc.) correlate with location points shown in Fig 1b.

Talus thickness measurements taken along the minor talus cone produce a solid fill volume of 5656 m³. A standard void space correction of 20% (Hinchliffe and Simon, 1999) was used to yield a total talus volume of 4,525 m³.

Bummer's Rock

Boulder characterization at Bummer's Rock reveals that the surface cover of the southwest talus field is 45% boulders, 38% soil and vegetation, and 17% bedrock. Boulder sizes were variable with most intermediate axis measurements falling between 0 and 30 cm (Fig. 4A); boulder measurements are plotted in relation to the distance from the cliff face (Fig. 4B).

Boulder rounding measurements are displayed with the boulder number, location as related to Figure 1, visual weathering class, and volume removed from boulder due to weathering in cm^3 (Table 1). Boulder weathering volumes vary between 5 and 606 cm^3 . The degree of weathering of boulders ranged significantly from position to position.

Fracture spacing data was collected along Bummer's Rock cliff face (Fig. 4D). Fractures within the Boulder Creek granodiorite were on average 106 cm apart and ranged between 10 and 680 cm. The area of the talus field was calculated to be $3,200 \text{ m}^2$. This produces an approximate talus volume of $2,560 \text{ m}^3$, after applying the void space correction.

DISCUSSION

Green Lakes Valley

Data collected from both talus fields clearly show a correlation between rock type, boulder size, and fracture spacing. Fracture orientations in the metasediments above the main talus are dominated by one set of near vertical fractures with some minor, horizontal fractures. This one, dominant fracture set (Fig. 3E) generates fractures that are widely spaced (in most cases greater than 20 cm apart). On the other hand, the SPG displays two distinct fracture orientations intersecting at an acute angle of approximately 30° and producing fracture spacing distance that is significantly less than that of the metasediments.

This difference in fracture orientation correlates with boulder size between the two rock types on the talus fields. The smaller fracture spacing of the SPG produces smaller boulders than the widely spaced fractures of the metasediments. The direct link between fracture spacing in the two rock types and boulder size on the talus cones indicates that fracturing of boulders during rockfall events is not a significant control on boulder size. Boulders generally remain the same size after separation from the cliff and have not broken into fragments after removal.

In GLV, the lithology of the cliff source does not

necessarily control the lithology of the boulders in the talus below. The main talus field is below cliffs composed entirely of metasediments yet over 48% of boulders within the field originate from the SPG, suggesting that the SPG must be exposed beneath the main talus and has contributed to its development in the past. Some of the SPG material could also have been left as morainal material after glacial retreat.

A combination of modeling and field observations yields talus volumes of $38,000 \text{ m}^3$ and $4,525 \text{ m}^3$ for the major and minor fields, respectively. These volumes, along with the deglaciation date of 12 ka (Miriam Duhnforth, University of Colorado, pers. comm.) give a minimum rate of talus accumulation of 0.38 m^3 per year for the minor talus cone and 3.17 m^3 per year for the major talus field. Since both cliff faces are the same approximate height (45 m), comparing the length of the source cliff to talus accumulation rate provides a relative rate for both talus fields. Observing the ratio of talus accumulation rate to cliff size reveals that the major talus and minor cone produce at relative rates of 0.021 and $0.007 \text{ m}^3/\text{year}$ per meter of cliff space, respectively. This result suggests that the main talus field has accumulated material at 3x the rate of the minor talus cone, indicating that closer fracture spacing within the SPG does not result in more talus. The bigger control on talus production is the rock type of the cliff source; the metasediment cliff face has larger fracture spacing but produces more talus. This could be due to weaknesses along pre-existing foliation planes.

Bummer's Rock

The talus field along the west slope of Bummer's rock represents a semi-stable talus slope. Some boulders are stabilized by low-lying vegetation while others remain loose on the surface. Approximately 38% of the talus surface is covered by soil and low-lying vegetation. This produces a talus profile that is poorly sorted. The size of boulders is not correlated with distance from the cliff face (Fig. 5A), in comparison to the strong component of sorting observed at the GLV sites (Fig. 3). The presence of

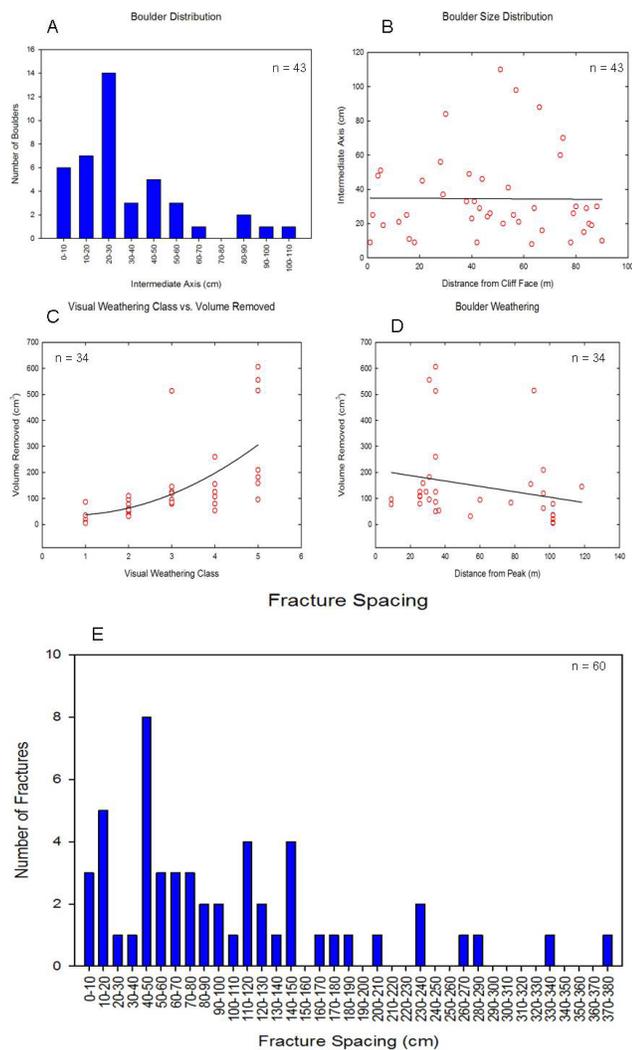


Figure 5. Bummer's Rock boulder distribution and rounding data. A. Boulder size distribution data along talus field traverse. B. Boulder size distribution in relation to distance from the cliff source (NOTE: meter 0 is the cliff face and meter 92 is the talus tongue). C. Comparison of visual weathering class and the volume removed by weathering. Trendline indicates estimated trend of visual weathering class vs. area removed. D. Plot of volume removed from boulders versus distance from the cliff face. E. Fracture spacing along the peak of Bummer's Rock.

low lying spruce and brush along with sporadic large woody vegetation (immature spruce and pine trees) at Bummer's Rock may help prevent larger boulders from reaching the talus tongue where normal transport would carry them.

The volume removed from boulders due to weathering does not appear to correlate to boulder location (Fig. 5D). Boulder rounding, as expected, is related

to visual weathering class (Table 1, Fig. 5). Boulders still in place along the cliff face (Class 1 and 2 boulders) had lost the least mass. This indicates that boulders in this area weather in-situ. When the boulder edges have rounded to a point where they cross a threshold, boulders can separate from adjacent bedrock and eventually topple. In some cases this toppling event leaves the boulder close to the source, less than 1 m in some cases. Boulders on the peak of Bummer's Rock had 50 to 556 cm³ removed. This is comparable to boulders 100 m from the peak, which had 95 to 515 cm³ removed. This shows that boulder rounding is not a function of distance traveled from the source.

CONCLUSIONS

The processes and rates of talus formation can vary greatly as a function of climate, rock type, and local environment. In Green Lakes Valley, talus is unstable and well-sorted downslope. Boulder sizes are a function of rock type and fracture spacing. High amounts of precipitation and low temperatures combine to widen inherited tectonic fractures through freeze/thaw events, producing a talus accumulation rate of ca. 0.38 m³ per year for the minor talus cone and 3.17 m³ per year for the major talus field, respectively. Although fracture spacing and orientation control boulder size, these parameters play a small role in the rate of talus accumulation. Some other measure of rock strength may control talus accumulation rates within Green Lakes Valley.

At Bummer's Rock, the rockfall rate is controlled by slow weathering and vegetation along the slopes stabilizing the talus, minimizing the downslope sorting of boulders. Lower elevation and precipitation rates decrease freeze/thaw action along this peak. Boulders are subject to weathering in place; as the edges begin to round they either "topple" from the cliff to the talus field below or simply slump out of their original position, remaining along the cliff.

REFERENCES

Bird, Peter, 1998. Formation of the Rocky Mountains, Western United States: A Continuum

- Computer Model: *Science*, v. 239, p. 1501-1507.
- Braddock, W.A., Cole, J.C., 1990. Geologic map of Rocky Mountain National Park and vicinity, Colorado. U.S. Geol. Surv. Misc. Invest. Series Map I-1973
- Caine, T.N., 1983, The mountains of northeastern Tasmania: a study of alpine geomorphology, Rotterdam: Balkema; Salem, NH, USA. ISBN 906191289X.
- Caine, T.N., 1986, Sediment movement and storage on alpine slopes in the Colorado Rocky Mountains, in Abrahams, A., *Hillslope Processes*: Boston: Allen & Unwin, p. 115-37.
- CZO, 2010, Boulder Creek Critical Zone Observatory Sites. Retrieved Mar. 1, 2010, from Boulder Creek Critical Zone Observatory, Boulder, CO. Web site: <http://czo.colorado.edu/html/sites.shtml>.
- 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.
- Hinchliffe, S., & Ballantyne, C. K., 1999, Talus accumulation and Rockwall retreat, Trotternish, Isle of Skye, Scotland: *Scottish Geographical Magazine*, v. 15, p. 53-70.
- Kellogg, K.S., Shroba, R.R., Bryant, Bruce and Premo, W.R., 2008, Geologic map of the Denver West 30' x 60' quadrangle, north-central Colorado: U.S. Geological Survey Scientific Investigations Map 3000, scale 1:100,000, 48-p. pamphlet.
- Kirkbride, M. P., 2005, Boulder Edge-roundness as an Indicator of Relative Age: A Lochnagar Case Study: *Scottish Geographical Journal*, v. 121, p. 219-236.
- Madole, R.F., VanSistine, D.P., Michael, J.A., 1999, Pleistocene glaciation in the upper Platte River drainage basin, Colorado: U.S. Geological Survey, Geologic Investigative Series I-2644.
- Premo, W. R., & Fanning, M. C., 2000, SHRIMP U-Pb zircon ages for Big Creek gneiss, Wyoming and Boulder Creek batholith, Colorado: Implications for timing of Paleoproterozoic accretion of the northern Colorado province: *Rocky Mountain Geology*, v. 35, p. 31-50.