NEW PERSPECTIVES ON COLLUVIAL BOULDER DEPOSITS IN THE SOUTHWESTERN GREAT BASIN, USA

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Abstract: Colluvial boulder fields are ubiquitous on desert hillslopes in the Basin and Range Province. Five chronometric methods indicate that colluvial boulder fields in this region have been active in the late Pleistocene and Holocene: visual appearance, radiocarbon dating of wood, macrofossil analysis, varnish radiocarbon dating, and varnish cation ratio dating. A new method is presented to constrain the ages of colluvial boulder fields, using the presence of stable rock varnish and ^{36}Cl; this method indicates that colluvial deposits at Buckhorn Mesa, southern Nevada, must be $\leq$ 310 ka. Rather than interpreting colluvial deposits from the traditional desert geomorphology framework of "relict" or "active," we suggest that these features be studied from the perspective of ongoing processes using an independently established chronometic sequence. [Key words: colluvium, hillslopes, paleoclimatology, Quaternary dating methods, geomorphology, geochronology, rock varnish.]

INTRODUCTION

Relatively stable colluvium, consisting of linear fields of well-varnished hillslope boulders, is a ubiquitous slope feature in the Basin and Range Province of western North America and in other drylands (e.g., Blackwelder, 1935; Melton, 1965; Mabbutt, 1977; Péwé, 1983; Prokopovich, 1987; Nials and Davis, 1990; Cox and Hunt, 1990; Dorn and Dickinson, 1990; Whitney and Harrington, 1993). A traditional approach in desert geomorphology has been to interpret relatively inactive features as "'fossil,' 'stabilized' or 'relict' landforms" and this approach "has been central to studies of desert geomorphology" (Cooke et al., 1993, p. 9).

In a recent paper Whitney and Harrington (1993, p. 1008) work under this perspective and argue that "colluvial boulder deposits" are relict in the Yucca Mountain region of the Amargosa Desert of southern Nevada, having formed during "early and middle Pleistocene glacial episodes" that "were colder, and perhaps wetter, than glacial episodes in the late Pleistocene in the southern Great Basin." They argue that surficial processes operating in today's climate could not have formed these large boulder deposits. This finding would indicate that at least

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some Basin and Range hillslopes with angles >25° are as stable as Australian landscapes (Gale, 1992; Young and McDougall, 1993). If true, this geomorphological discovery has theoretical implications for rates of sediment transport on dryland slopes and public policy implications for the storage of high-level nuclear waste at the proposed Yucca Mountain repository. In support of their "fossil" colluvium hypothesis, Whitney and Harrington (1993, p. 1015) present rock varnish cation ratio ages, ^{36}Cl ages, and an analysis of present-day climate, and write that "no modern equivalents to the well-varnished colluvial boulder deposits are observed on southern Nevada hillslopes."

An alternative perpective, favored by Melton (1965), Wells et al. (1982), and Nials and Davis (1990), is that the development of colluvial boulder fields does not require colder conditions. Instead, they can be initiated and maintained by ongoing desert hillslope processes. In this paper, we present evidence in support of a process-based interpretation. At least some fields of large colluvial boulders have been active enough in the latest Pleistocene and Holocene to reset five independent chronometric indicators of hillslope movement. We also propose two new ways of constraining the age of colluvium on dryland slopes. Support for our argument comes mostly from the Amargosa Desert of southern Nevada and eastern California (Fig. 1).

EVIDENCE OF ACTIVE BOULDER SLOPES

The first clue that hillslope boulders are moving can be seen best in color photographs (see Whitney and Harrington, 1993, p. 1008). More varnished (darker) centers are surrounded by progressively lighter margins at the sides and tops of the boulder fields. In places, less varnished flow lines bisect darker patches. Since rock varnish development is time transgressive, starting in patches and growing vertically and horizontally (Dorn and Oberlander, 1982; Dorn, 1991), this intuitive visual evidence suggests a continuum of slope movement that is active enough to remove or inhibit varnishing.

An alternative explanation for this indicator of slope instability would be that the varnish itself has eroded, but without boulder movement. Varnish erosion does occur biochemically and mechanically. The secretion of organic acids by plants (e.g., conifer needles) or rock-surface organisms (e.g, lichens, microcolonial fungi) can reduce Mn (IV) and Fe (III) into mobile divalent forms—which dissolve the rock varnish (Dorn and Oberlander, 1982; Krinsley et al., 1990). Varnish also may be removed mechanically when the weathering rind under the varnish spalls (Dorn, 1989). Both mechanisms of varnish erosion occur today on boulder slopes in the Amargosa Desert, and the presence of dwarf woodland conifers from >45 ka to around 10 ka (Spaulding, 1985, 1990) likely enhanced acidity and contributed to varnish decay. However, varnish erosion by these mechanisms is patchy, rather than linear in nature. It is difficult to envision a process that would erode varnish in lines (other than slope movement) that would not also erode varnish from the entire colluvial boulder field.

A second indicator of ongoing activity comes from conventional radiocarbon ages on pieces of unidentified wood (~20 and 25 cm long dimension, subaerial wood with well-defined tree rings) that were crushed on their margins from

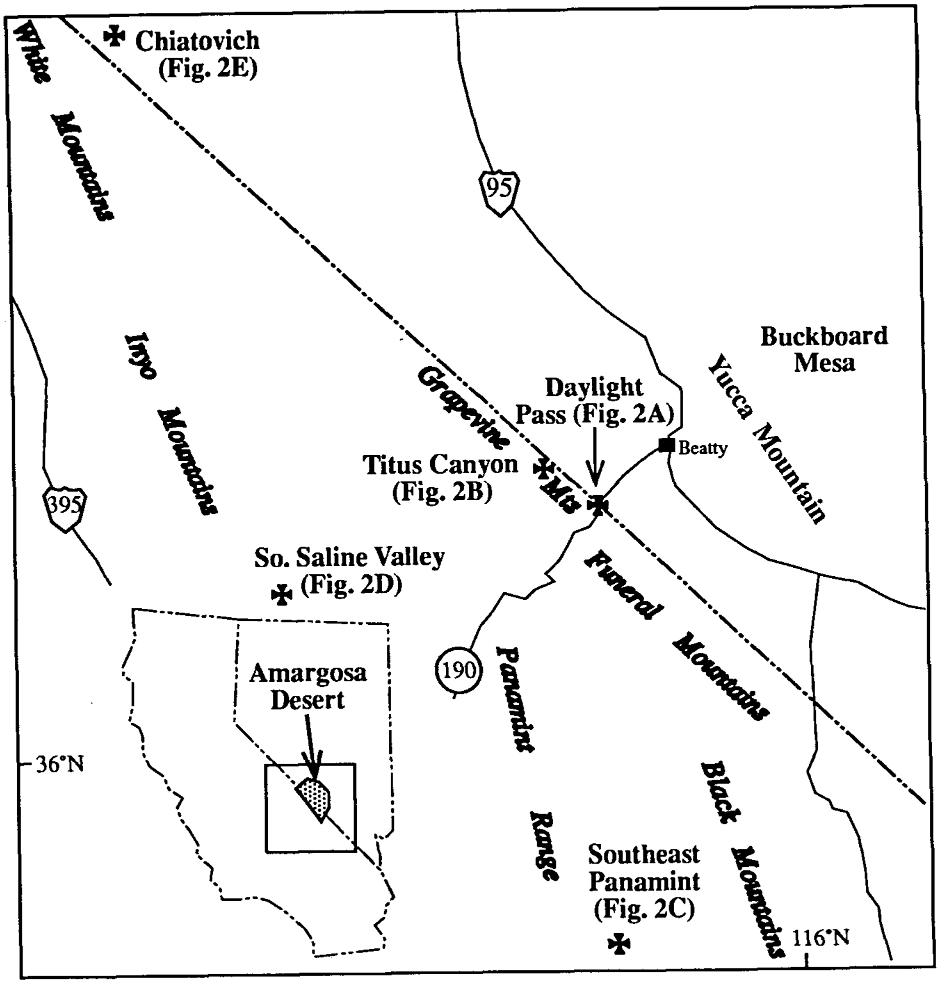

Fig. 1. Study sites in the Amargosa Desert and adjacent region.

transport downslope, and weathered on the outer few centimeters. They were collected from underneath boulders that were in the middle of boulder fields: at a depth of 0.4 m under two boulders (long axis ~0.6 m) at the site shown in Fig. 2A and a depth of 0.5 m under three boulders (long axis ~0.4 m) at the site indicated in Fig. 2B. The tops of these wood pieces were spotted in the large voids between boulders.

The weathered outer few centimeters were shaved off. Then the samples were boiled and washed free of adhering mineral matter and examined for rootlet contamination (none was present). Each sample was shredded for increased surface reaction area and treated by repeat-soakings in acid and alkali solution to remote carbonate or humic contaminants. After final rinsings to neutrality in hot distilled water, the wood was synthesized to benzene and counted for radiocarbon contents. The conventional ^{14}C age of the wood in Figure 2A is 120±50 (Beta 66042)

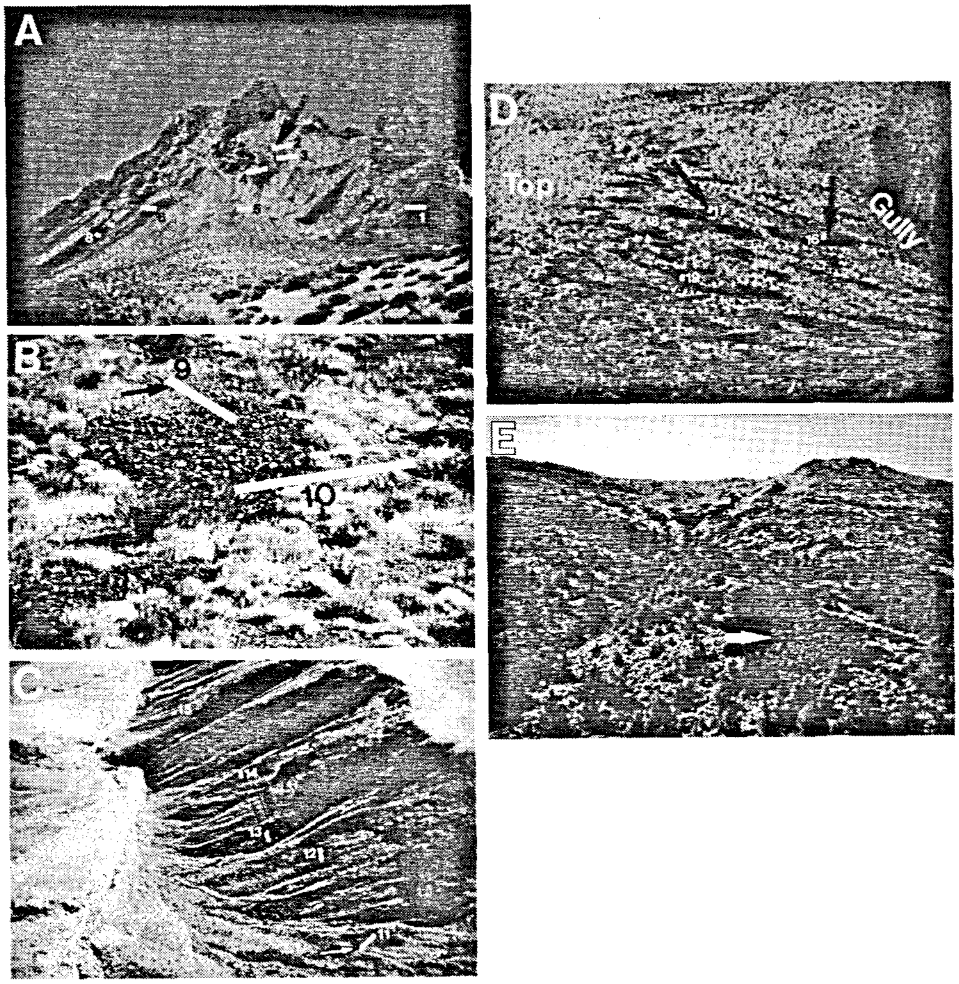

Fig. 2. Photographs of study sites discussed in the text and located in Fig. 2. Scale provided by creosote (Fig. 2B–D), sagebrush (Fig. 2A), and pinyon pine (Fig. 2E). (A) Titus Canyon colluvial boulder fields (~1400 m)—arrow indicates ^{14}C sample; lines 1–8 correspond to Table 1 and Figure 3. (B) Daylight Pass colluvial boulder field (~1250 m)—arrow indicates ^{14}C sample; lines 9 and 10 correspond to Table 1 and Figure 3. (C) Colluvial boulder fields, southeastern Panamint Range (~700 m)—arrow indicates location of creosote bush sample; lines 11–15 correspond to Table 1 and Fig. 3. (D) Saline Valley colluvial boulder fields (~600 m)—arrows indicate location of creosote bush samples; lines 16–21 correspond to Table 1 and Figure 3. (E) Lower Chiatovich boulder field (~2500 m), White Mountains—arrow indicates ^{14}C sample. Pinyon pine above boulder field is ~4 m tall.

and 720±50 in Figure 2B (Beta 67099), respectively. These ages indicate that these pieces of wood were entrapped in the boulder matrix in the latest Holocene, since the wood would predate the transportation event.

A third chronometric indicator involves macrofossil analysis. We have three samples of partially crushed *Larrea divaricata* sticks (subaerial portion of the plant, not roots) collected from boulder matrices from the centers of three other colluvial boulder fields (Figs. 2C and 2D). Radiocarbon measurement probably would reveal Holocene ages, because creosote bush does not occur in the region before about 10 ka (Wells and Hunziker, 1976; Wells and Woodcock, 1985; Spaulding, 1985, 1990).

The fourth chronometric indicator of activity comes from varnish radiocarbon dating. The goal of varnish radiocarbon dating is to sample organic matter from underneath evenly layered rock varnish, thus providing a minimum-limiting age for the onset of varnishing. A full discussion of the method and its uncertainties is presented elsewhere (Dorn et al., 1989; Dorn, Clarkson et al., 1992; Nobbs and Dorn, 1993; Dorn, 1994). We know of two ^{14}C ages that constrain colluvial development in the western Great Basin:

> (1) AMS ^{14}C date #51 identified in Figure 6B of Dorn et al. (1989) at ~28 ka is from a colluvial boulder patch with a slope angle of ~24° above the Death Valley Canyon alluvial fan, more than 1000 m in elevation below Yucca Mountain. At the time of sample evaluation, the possibility that the sample originated in a former crack position on the hillslope above the colluvium was not considered. A re-evaluation of the dated sample by backscatter microscopy (cf. Krinsley et al., 1990) reveals that the dated varnish initiated in a crevice, probably in a bedrock position prior to entrainment and deposition by hillslope processes. In other words, the crack varnish (Potter, 1979; Dorn and Oberlander, 1982; Dragovich, 1984; Dorn and Krinsley, 1991) started to form in a bedrock joint; the boulder was detached from bedrock; the boulder was transported and deposited on the hillslope; and newer varnish started to form on top of the original crack varnish. A conservative interpretation of this ^{14}C measurement would be as a *maximum-limiting* age for the colluvial deposit, because the varnish started to form in the rock crevice before the boulder was deposited in the boulder field.
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> (2) A second AMS ^{14}C age is from a sample in the foothills of the eastern White Mountains of Nevada at an altitude of about 2500 m (Fig. 2E). The sample was collected about 300 m below Dohrenwend's (1984) 0–1° isotherm for the last full glacial period. At this site, the collected varnish formed in a subaerial position. Although boulder spalling occurs in the colluvial field, crack varnishes thus exposed were not used in the radiocarbon dating. The AMS ^{14}C age of 27,660±550) (ETH 4475) on organic matter in the weathering rind under the varnish is best interpreted as a minimum age for the onset of varnishing. Although Dorn et al. (1989) and various others have suggested the potential for carbon contamination from "older sources," there are no empirical data to suggest that non-contemporaneous carbon has been encapsulated by rock varnish. The vast majority of potential contaminants would add carbon with more ^{14}C activity. In summary, there was enough geomorphic abrasion to reset the "varnish clock" in the late Pleistocene.

The fifth indicator of activity comes from cation ratios of rock varnishes collected along 6-m-long transects indicated on Figs. 2A–2D. The transects run from the darker center of the colluvial deposit to lighter-colored margins. Every 1.5 meters on the transect, the closest boulder >0.5 m (long axis) was sampled on its edges. Five cation ratios were measured in each transect (0, 1.5, 3, 4.5, 6 m).

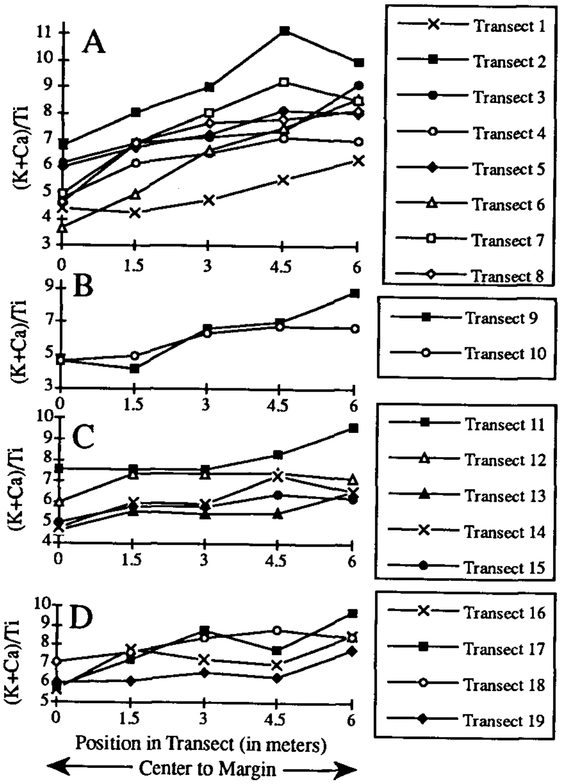

Fig. 3. Trend in cation ratios along the transects located in Figs. 2A–D with geochemical data provided in Table 1. The darker (more varnished) colluvium has lower cation ratios, and adjacent boulders of similar size have relatively higher ratios (younger surfaces)—indicating more recent slope activity on the margins of the boulder fields.

Boulder edges were sampled in order to maximize the chance of abrasion in the last transport event. Samples were selected in the field, preselected by laboratory analysis, prepared, and chemically measured according to the procedure detailed elsewhere (Dorn, 1989, 1994; Dorn et al., 1990; Dorn, Jull et al., 1992; Krinsley et al., 1990).

Table 1 presents cation ratios, as measured by wavelength dispersive electron microprobe, that correspond to the graphs in Figure 3. We do not try to "calibrate" our cation ratios, but use the most basic assumption of those that have used cation-ratio dating (Dorn, 1983; Glazovskiy, 1985; Pineda et al., 1988, 1990; Zhang, 1990; Bull, 1991; Whitney and Harrington, 1993) that progressively lower ratios of (K+Ca)/Ti indicate progressively older ages. Given this assumption, Figure 3 records a rough continuum of relative ages from the lighter margins to the darker interiors of the boulder patches. Figure 3 shows that activity has been ongoing on colluvial boulder fields, and that more recent activity has occurred on the margins. This pattern suggests that lower magnitude (higher frequency) transport events occur on the margins of colluvial fields. The higher magnitude transport events that would erode varnish in the center of these boulder fields occur less frequently.

Table 1. Cation Ratios Measured by Wavelength-Dispersive Electron Microprobe from Boulders Collected along 6-m Line Transects[a]

(K+Ca)/Ti	MGO	AL_2O_3	SIO_2	P_2O_5	SO_3	K_2O	CAO	TIO_2	MNO	FE_2O_3	BAO	Total
						Transect 1						
4.46	2.00	20.20	24.67	2.52	0.00	2.13	1.40	1.03	20.23	15.95	0.00	90.13
4.27	2.41	15.97	18.27	7.78	0.00	0.90	1.82	0.78	11.98	12.00	0.03	71.94
4.75	1.19	13.83	18.23	1.63	0.67	0.84	0.97	0.48	26.86	11.90	0.96	77.56
5.58	0.63	20.43	32.26	2.11	0.02	1.45	1.25	0.62	17.92	7.33	0.00	84.02
6.31	1.21	15.77	26.98	2.13	0.08	1.55	1.40	0.60	23.02	12.55	0.06	85.34
						Transect 2						
6.82	0.23	16.03	36.74	3.37	0.12	0.69	2.93	0.63	13.94	8.63	0.00	83.31
8.06	1.50	18.32	20.27	1.68	0.08	1.63	1.24	0.46	12.83	14.80	0.09	72.91
9.00	1.30	17.79	28.47	2.28	0.12	1.57	1.77	0.47	7.99	13.34	0.18	75.26
11.18	0.82	19.56	29.75	4.25	0.42	2.44	0.62	0.37	13.04	15.50	0.37	87.14
9.98	1.44	15.34	27.97	1.87	0.00	1.94	1.71	0.47	14.59	17.3.1	0.00	82.67
						Transect 3						
6.17	1.88	19.94	23.82	1.89	0.17	1.91	1.05	0.63	19.65	15.07	0.19	86.22
6.92	7.96	17.99	25.81	1.12	0.26	1.60	0.46	0.40	13.56	12.39	0.30	81.84
7.14	1.42	18.82	19.75	2.02	0.19	1.57	1.44	0.54	12.01	14.76	0.22	72.74
7.41	1.35	18.30	28.44	2.31	0.08	1.52	1.48	0.52	9.71	15.02	0.10	78.84
9.15	2.17	14.18	23.03	4.07	9.31	1.00	1.18	0.30	12.29	16.33	8.33	92.19
						Transect 4						
4.81	0.68	14.49	28.27	1.15	0.00	2.46	0.43	0.82	20.11	14.40	0.07	82.88
6.18	1.88	20.87	26.43	1.80	0.26	2.08	1.05	0.67	15.00	16.81	0.35	87.20
6.56	1.63	17.42	24.32	2.04	0.08	1.98	1.47	0.68	12.83	15.87	0.11	78.42
7.14	1.74	20.67	25.53	1.60	0.14	2.19	0.97	0.58	11.79	16.78	0.18	82.17
7.04	1.25	16.26	27.08	1.73	0.11	1.49	1.35	0.52	10.54	13.68	0.13	74.14
						Transect 5						
6.00	1.59	18.45	26.23	1.81	0.14	1.70	1.11	0.61	19.35	16.10	0.08	87.16
6.77	2.18	20.36	26.23	2.60	0.26	2.29	1.49	0.73	16.39	15.30	0.30	88.11
7.24	2.08	19.07	31.17	2.14	0.10	1.51	1.32	0.50	8.77	15.14	0.06	81.86
8.14	1.41	15.77	31.52	1.97	0.19	1.71	1.01	0.44	6.16	14.00	0.22	74.39
8.06	1.47	14.96	23.04	1.72	0.18	1.59	1.77	0.53	5.33	19.37	0.22	70.18

						Transect 6						
3.67	0.35	16.40	29.71	4.11	0.00	0.69	1.31	0.67	20.99	12.09	0.00	86.32
4.99	1.70	19.33	22.97	2.26	0.14	1.57	1.33	0.74	19.82	19.03	0.15	89.05
6.63	1.27	17.02	27.77	2.15	0.06	1.54	1.44	0.57	17.09	14.14	0.08	83.13
7.49	1.80	19.06	25.93	1.91	0.12	2.19	1.38	0.62	10.59	12.14	0.15	75.89
8.61	0.66	18.03	30.29	1.76	1.30	0.57	1.57	0.30	4.08	19.42	2.70	80.68
						Transect 7						
4.97	1.40	16.07	19.51	4.00	0.00	1.40	1.20	0.67	25.41	13.41	0.08	83.15
6.93	2.40	15.69	26.45	4.00	1.00	2.05	2.16	0.77	20.48	9.94	0.90	85.84
8.06	1.14	12.82	27.04	4.62	2.89	1.47	1.73	0.50	10.82	12.40	3.01	78.44
9.24	1.82	18.26	30.20	1.68	0.08	2.42	0.81	0.47	5.58	15.52	0.11	76.96
8.53	1.29	13.77	27.71	1.79	0.69	1.40	1.46	0.42	4.83	19.14	0.77	73.27
						Transect 8						
4.66	1.63	18.28	22.99	0.94	0.00	1.94	0.80	0.78	23.98	10.08	0.10	81.52
6.94	1.84	18.84	24.29	1.68	0.42	2.04	0.97	0.57	20.03	15.81	0.45	86.96
7.69	1.44	15.48	27.97	1.85	0.00	1.81	1.32	0.53	14.54	10.93	0.00	75.86
7.81	1.44	17.67	29.30	2.20	0.08	1.56	1.62	0.52	7.08	15.53	0.10	77.09
8.15	1.71	19.38	30.50	2.22	0.23	1.57	1.84	0.53	6.35	13.08	0.29	77.70
						Transect 9						
4.60	1.19	14.36	17.61	1.72	0.10	0.87	0.95	0.50	27.66	13.57	0.11	78.64
4.16	2.29	15.92	20.47	3.01	0.14	1.72	1.22	0.91	27.85	13.11	0.15	86.79
6.59	1.50	18.81	25.47	2.33	0.14	1.59	1.43	0.58	13.25	17.88	0.18	83.15
7.03	1.44	18.04	28.03	1.91	0.17	1.56	1.48	0.55	10.06	13.99	0.19	77.43
8.84	0.91	16.00	28.37	0.44	0.25	1.58	1.27	0.42	3.92	17.50	0.28	70.94
						Transect 10						
4.61	1.24	16.38	24.88	1.65	0.00	1.11	0.98	0.58	20.31	13.77	0.66	81.56
4.93	2.19	18.74	23.72	2.63	0.18	1.93	1.52	0.90	15.49	20.64	022	88.16
6.36	1.18	15.50	15.34	2.36	0.12	1.47	1.32	0.56	31.62	11.24	0.09	80.81
6.72	1.59	19.05	30.77	2.05	0.07	2.00	0.66	0.53	14.21	9.16	0.00	80.09
6.64	1.24	16.09	17.13	1.55	0.11	1.55	1.57	0.60	27.29	11.96	0.15	79.24
						Transect 11						
7.55	1.27	16.28	16.89	1.91	0.17	1.50	1.80	0.55	19.92	12.05	0.22	72.57
7.58	0.02	18.49	34.33	4.00	0.02	1.08	1.00	0.35	8.40	10.16	0.00	77.85
7.57	4.22	17.07	23.81	4.05	0.17	1.36	1.45	0.47	13.31	13.39	0.00	79.30
8.30	1.31	17.55	29.69	1.83	0.17	1.67	1.11	0.44	7.45	13.32	0.25	74.79
9.63	0.85	21.21	31.85	2.00	0.05	1.81	1.15	0.40	5.77	16.37	0.08	81.54

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Table 1. (continued) Cation Ratios Measured by Wavelength-Dispersive Electron Microprobe from Boulders Collected along 6-m Line Transects[a]

(K+Ca)/Ti	MGO	AL_2O_3	SIO_2	P_2O_5	SO_3	K_2O	CAO	TIO_2	MNO	FE_2O_3	BAO	Total
Transect 12												
5.95	1.22	16.10	16.06	2.49	0.08	1.56	1.26	0.61	31.98	11.98	0.06	83.40
7.37	1.71	18.72	24.49	1.76	0.86	1.73	1.35	0.54	20.94	15.10	1.03	88.23
7.38	1.90	17.81	33.48	4.07	1.35	2.66	1.06	0.67	13.32	10.93	1.49	88.74
7.40	1.33	16.62	19.90	2.01	0.08	2.09	1.06	0.56	22.11	10.27	0.11	76.16
7.16	1.66	17.33	21.39	2.15	0.10	1.46	1.47	0.52	16.84	15.20	0.07	78.19
Transect 13												
4.58	1.53	18.10	20.27	2.41	0.08	1.65	1.40	0.85	23.85	18.52	0.11	88.78
5.57	1.82	20.50	25.50	1.42	0.08	2.21	0.99	0.76	21.33	15.73	0.11	90.45
5.44	1.27	16.41	17.26	2.28	0.08	1.6A	1.43	0.72	31.14	13.12	0.06	85.41
5.50	1.30	17.33	17.62	2.39	0.08	1.63	1.28	0.68	32.24	12.96	0.11	87.60
6.52	2.71	19.26	36.46	1.50	0.20	1.53	0.69	0.45	12.41	15.37	0.23	90.82
Transect 14												
4.75	1.26	14.72	14.74	2.02	0.25	1.29	1.54	0.75	27.48	8.51	0.24	72.80
6.00	1.87	18.33	24.52	0.85	0.00	1.23	0.59	0.40	19.24	10.71	0.05	77.79
5.93	1.23	11.17	10.50	2.75	1.35	0.99	1.02	0.43	36.10	7.17	1.38	74.09
7.28	1.50	18.62	20.27	2.07	0.17	1.57	1.36	0.52	14.56	16.58	0.18	77.41
6.50	2.07	20.51	24.08	2.30	0.14	1.88	1.22	0.62	18.04	20.95	0.19	92.00
Transect 15												
4.99	1.62	18.69	21.89	2.10	0.14	1.62	1.27	0.74	20.20	17.38	0.15	85.79
5.73	1.92	19.27	26.51	1.08	0.10	1.22	0.66	0.43	16.95	12.08	0.08	80.30
5.76	0.06	21.21	34.81	2.00	0.02	0.89	1.18	0.45	18.46	14.20	0.00	93.28
6.36	1.84	14.81	23.10	1.99	0.42	1.48	1.92	0.67	15.15	14.98	0.38	76.74
6.17	1.19	15.82	27.95	1.19	0.07	1.04	1.05	0.43	16.90	10.15	0.09	75.88
Transect 16												
5.72	1.84	16.12	20.26	1.63	0.40	1.54	1.72	0.72	22.20	9.39	0.35	76.17
7.78	0.11	8.11	31.00	3.62	0.40	1.08	2.09	0.50	11.00	12.59	0.00	70.50
7.27	1.23	17.70	28.59	2.13	0.15	0.94	1.55	0.43	13.86	18.67	0.09	85.34
7.06	1.16	14.79	25.96	1.76	0.15	0.82	2.11	0.52	12.52	17.54	0.22	77.55
8.49	1.47	17.50	28.65	2.10	0.08	1.44	1.64	0.46	5.11	15.30	0.06	73.80

						Transect 17						
5.86	1.2A	11.17	25.31	0.71	0.17	1.06	0.34	0.32	16.93	15.74	0.18	73.17
7.26	1.82	15.92	24.41	1.42	0.07	1.45	2.17	0.62	17.48	10.12	0.25	75.73
8.74	1.59	19.19	30.50	1.95	0.12	1.64	1.75	0.49	5.97	14.45	0.08	77.73
7.76	1.33	17.38	29.22	1.79	0.23	1.68	1.20	0.48	6.37	14.98	0.30	74.95
9.73	1.50	16.70	35.59	1.32	0.17	1.64	1.60	0.42	2.20	19.27	0.16	80.57
						Transect 18						
7.11	1.04	16.59	19.90	1.58	0.70	1.63	1.55	0.57	16.06	18.69	0.84	79.15
7.63	1.53	18.26	21.42	2.22	0.00	1.70	1.44	0.53	23.86	16.58	0.00	87.54
8.39	0.87	14.81	31.42	1.50	0.08	1.10	1.01	0.32	6.20	18.28	0.10	75.69
8.78	1.47	18.59	29.05	2.28	0.26	1.56	1.97	0.50	2.16	15.21	0.34	73.38
8.46	1.77	21.40	31.23	1.85	0.12	1.93	1.36	0.50	2.13	15.18	0.15	77.61
						Transect 19						
6.06	1.21	15.68	18.42	1.37	0.10	1.01	1.15	0.45	25.92	9.94	0.16	75.41
6.16	1.14	15.02	15.42	2.38	0.05	1.33	1.23	0.53	28.28	12.72	0.07	78.17
6.59	1.07	17.90	23.75	1.55	0.00	1.15	1.04	0.42	17.97	9.91	0.00	74.76
6.36	1.13	14.55	17.18	1.95	0.20	0.77	1.60	0.47	28.06	14.06	0.23	80.20
7.74	0.71	13.79	32.49	0.39	0.05	2.28	0.38	0.47	16.84	14.92	0.11	82.43

[a] The closest boulder (>0.5 m, long axis) to 0, 1.5, 3.0, 4.5, and 6.0 m was sampled from boulder edges in order to maximize the chance of sampling the last abrasion event.

NEW APPROACHES TO CONSTRAIN AGE OF HILLSLOPE COLLUVIUM

Since we have established that at least some boulder fields have been active in the Holocene and latest Pleistocene in the Amargosa Desert and vicinity, we turn to recently presented evidence indicating considerable antiquity for boulder fields, namely varnish cation-ratio and ^{36}Cl ages in the Yucca Mountain area (Whitney and Harrington, 1993). In the discussion that follows we will present a new method, using the assumption of rock varnish stability and ^{36}Cl ages, to show that the Buckboard Mesa colluvial boulder field (Fig. 1) must be $\leq$ 310 ka, rather than 1380 ka as claimed by Whitney and Harrington (1993).

The ^{36}Cl ages measured by F.M. Phillips and co-workers and presented by Whitney and Harrington (1993) are sound. ^{36}Cl and other cosmogenic nuclides offer a set of methods that have the potential to revolutionize geomorphology (Dorn and Phillips, 1991; Nishiizumi et al., 1993). The presentation of these ages, however, did not consider inheritance of ^{36}Cl from prior exposure. The Buckboard Mesa samples have two possible sources of "inherited" ^{36}Cl: (a) exposure in the "relative thin Pliocene basalt" from Buckboard Mesa (Whitney and Harrington, 1993, p. 1010) before detachment from the flow and entrainment in the colluvium; and (b) build-up ^{36}Cl in boulders at positions higher on the hillslope, before they were transported to the locale "sampled near the toe of the rock-varnish dated colluvial boulder deposit" (Whitney and Harrington, 1993, p. 1014).]

The apparent ^{36}Cl ages of ~310 ka, ~420 ka, and ~600 ka (Whitney and Harrington, 1993, p. 1014) for hillslope colluvium at Buckboard Mesa are explained by:

$$^{36}\mathrm{Cl}_a = {}^{36}\mathrm{Cl}_i + {}^{36}\mathrm{Cl}_c \qquad (1)$$

where $^{36}\mathrm{Cl}_a$ is the age calculated from the contemporary exposure constraints (cf. Zreda et al., 1991), $^{36}\mathrm{Cl}_i$ is the build-up of inherited ^{36}Cl in the Pliocene basalt flow and build-up higher on the hillslope (before deposition at the toe ot the colluvial patch), and $^{36}\mathrm{Cl}_c$ is time of exposure at the surface of the colluvial deposit. Because $^{36}\mathrm{Cl}_i$ is unknown and because *all* of the ^{36}Cl could *potentially* derive from prior exposure in an upslope position, apparent ^{36}Cl ages on exposed colluvium cannot be treated as a "minimum limiting age" (Whitney and Harrington, 1993, p. 1014).

In the following section, we propose a new approach on how to constrain the age of colluvial boulder fields by using a cosmogenic nuclide such as ^{36}Cl, rock varnish, and different process geomorphology models. In the first case, we assume a geomorphic context where (a) the colluvial boulder deposit has detached from the source of the colluvium; and (b) the rock varnish on the colluvial boulders is an indicator of zero boulder erosion or very low rates of boulder spalling. The first assumption can be supported by field evidence, for example, where "modern channels have incised to bedrock on one or both sides of a deposit . . ., topographically inverting a former channel deposit" (Whitney and Harrington, 1993, p. 1010). The second assumption can be supported by: (i) similar cation ratios for boulders in a deposit (e.g., average standard deviation of ~9% for sites given in Table 1 of Whitney and Harrington); (ii) similar development of rock varnish stratigraphy (Dorn, 1986, 1993; Nobbs and Dorn, 1993); (iii) similar enhancement of heavy metals in varnish (Dorn, Jull et al., 1992). If the second assumption is not true, varnish dating cannot be used, because even a micron of boulder surface erosion would erode rock varnish.

With these assumptions, the youngest cosmogenic isotope age on a group of colluvial boulders must provide a *maximum limiting age* for the separation of the colluvial deposit from its upslope bedrock source. Consider the circumstance where the colluvial deposit has been stable for 1.38 Ma based on *in situ* cation-ratio dating of rock varnish, as is argued for Buckboard Mesa by Whitney and Harrington (1993). Substituting 1380 ka for $^{36}Cl_c$ in equation (1),

$$^{36}Cl_a = {}^{36}Cl_i + 1380 \text{ ka}, \qquad (2)$$

the inherited $^{36}Cl_i$ age must be -1070 ka for the $^{36}Cl_a$ of 310 ka for 40MC1, -960 ka for $^{36}Cl_a$ of 420 ka for 40MC2, and -780 ka for $^{36}Cl_a$ of 600 ka for 40MC3. All cases require a negative ^{36}Cl concentration, which is not possible. Because this model has no boulder erosion or boulder movement that would disturb varnish formation, the oldest that $^{36}Cl_c$ can be is 310 ka. Further ^{36}Cl dating would help constrain the maximum age for the Buckboard Mesa deposit; for example, if a fourth boulder yielded an age of 90 ka, the deposit would have to be $\leq$ 90 ka.

A further interpretation of the cosmogenic ages for Buckboard Mesa colluvium depends upon the geomorphic model assumed. If the transport system was active before the colluvial boulder field was detached from its source, then the youngest apparent age would provide a *maximum limiting* age for the entire surface. By "active" we mean that all the boulders in the deposit had been deposited in a period of time *within* the error of the ^{36}Cl measurement (e.g., ~26 ka for 310 ka boulder). In other words, the ~310 ka boulder at Buckboard Mesa indicates that the deposit must be $\leq 310 \pm 26$ ka. If the transport system was slower than the ^{36}Cl error, with a few boulders breaking loose and moving down the slope every few tens of thousands of years, then the ~310 ka boulder at Buckboard Mesa is only the last *known* event before detachment from the source took place. There could be younger boulders that were not sampled.

In the second geomorphic model, we still assume a field context where (a) the rock varnish on the colluvial boulders is an indicator of zero boulder erosion or very low rates of boulder spalling; but we change the second assumption and consider that (b) the colluvial patch is still connected to its source along a reasonable transport pathway. The youngest ^{36}Cl age still provides a maximum age for the colluvial deposit—under the condition that the transport system is acting like a "sheet of moving boulders" where all the surface boulders were detached from bedrock and transported in a time range within the error of the ^{36}Cl age. If a stop-and-go transport system is assumed, where the boulders move in a time frame that exceeds the ^{36}Cl error, the youngest ^{36}Cl age then is interpreted as a maximum age for the last *known* transport event.

A completely independent approach to dating colluvial boulder deposits would be to take samples from depth (e.g., $\geq$ 3 m). Although there is no way to assess the inheritance of cosmogenic nuclides in boulders on the surface, inheritance can be measured if boulders were sampled from deep in the deposit. Following the reasoning of Nishiizumi et al. (1993), cosmogenic radionuclides (e.g. ^{36}Cl, ^{26}Al, ^{14}C, ^{10}Be) in deeply buried boulders would decay, while stable cosmogenic nuclides (e.g., ^{3}He, ^{21}Ne) would not. The time since a boulder was buried (time of deposition) could be determined by the offset between the radionuclide and stable nuclide age in the same boulder—assuming that the boulder had not experienced multiple cycles of exposure and burial.

This entire discussion on the Buckboard Mesa samples places at odds the *in situ* cation-ratio age of ca. 1380 ka with maximum ^{36}Cl age of ≤ 310 ka. As noted earlier, Whitney and Harrington (1993) interpret the ^{36}Cl date of ca. 600 ka as a minimum age estimate. Although no reasoning is supplied, this could be because of either (a) progressive boulder erosion, (b) progressive boulder detachment from the Pliocene flow and transportation to the colluvium patch, (c) boulder flipping over, or (d) some combination.

All of the aforementioned mechanisms, which would make the ^{36}Cl date a minimum age, also would falsify the rock varnish ages. Several centimeters of boulder erosion would not alter the ^{36}Cl age (Zreda et al., 1991), yet even a micron of surface erosion or abrasion will remove the varnish and reset the varnish clock. It is, therefore, astounding that the varnish ages are more than 600 ka greater than the oldest apparent ^{36}Cl age, and ~1.07 Ma years older than the youngest ^{36}Cl age.

Varnish ages could only pre-date ^{36}Cl ages under three circumstances. First, the varnish started in a rock crevice (cf. Dorn and Oberlander, 1982; Dorn, 1994; also see discussion for Yucca Mountain in Carlos et al., 1993) hundreds of thousands of years before exposure in the colluvium. Second, the varnish started from a position on the bottom side of the boulder (which provides additional shielding) and then the boulder flipped over somehow. Yet this would contradict the sedimentological discussion in Whitney and Harrington (1993) on fine matrix removal, carbonate cementation, and the overall stability of the landform. Also, a process that can cause boulder flipping for 100% of the three boulders sampled for ^{36}Cl should also erode the varnish from 40 boulders sampled for cation ratio dating. Third, a cover blanket of several meters settled over the colluvium, allowing the inherited ^{36}Cl to decay while varnish cations leached out and lowered the cation ratio. Then this hypothetical cover blanket eroded away (leaving no trace)—and the deposition and erosion of this cover blanket did no erosion to the pre-existing varnish.

There also is a much greater scatter of ages (~100%) among the ^{36}Cl ages than the varnish ages (~10%). A few millimeters or centimeters of boulder erosion would not impact the ^{36}Cl age, but would completely reset the varnish clock. Therefore, we would expect a far greater scatter of varnish ages than ^{36}Cl ages, if boulder erosion was the cause of the greater scatter. If the greater ^{36}Cl scatter is a result of ongoing boulder transportation from 1.2 Ma (varnish age) to 0.3 Ma (youngest ^{36}Cl age), we think it highly unlikely that such an active transportation corridor would not have reset the varnish clock—either through emplacement of newer boulders or erosion of older boulders. In either possible explanation for younger ^{36}Cl ages, there should be a greater scatter in varnish ages than ^{36}Cl ages.

A more likely explanation for the greater scatter of ^{36}Cl ages is a different prior exposure history for each different boulder. Assume that the surface of the relatively flat Pliocene basalt flow was stable for the last 1.38 Ma. A boulder with a ^{36}Cl age of ~310 ka could have built up the entire ^{36}Cl accumulation at a depth of

~3 m within the lava flow (Zreda, written communication, 1993). Or the boulder with a ^{36}Cl age of ~600 ka could have built up the ^{36}Cl at a depth of ~1.5 m within the flow. Or, more likely, the scatter in ^{36}Cl ages is from a different combination for each boulder of prior exposure in the flow and higher up on the colluvial boulder slope.

DISCUSSION AND CONCLUSION

There are two schools of thought on the origin of colluvial boulder fields in the Basin and Range Province: (a) that colluvial boulder fields are relicts of a colder period in the past (Péwé, 1983; Whitney and Harrington, 1993); or (b) that they develop as a result of ongoing dryland slope processes (Melton, 1965; Wells et al., 1982; Nials and Davis, 1990).

Five chronometric indicators reveal that colluvial boulder fields have been active in the Amargosa Desert and Death Valley region during the Holocene and latest Pleistocene: (a) the range in visual rock varnish development suggests a relative continuum of activity from more stable centers to less stable margins; (b) Holocene radiocarbon ages on transported wood shows movement in the last thousand years; (c) the presence of transported *Larrea divaricata* (creosote bush) twigs (not roots), trapped in boulder matrix, provides evidence of Holocene movement; (d) radiocarbon dating of organics entrapped by rock varnish indicates boulder transport in the latest Pleistocene; (e) cation ratios for rock varnish collected from transects across 19 colluvial boulder deposits reveal a relative sequence of more recent activity on the margins than in the centers.

There is a key question, however, that has been avoided in the dating of colluvial boulder fields: what does "instability" mean from a chronometric perspective? The dating techniques that we and Whitney and Harrington (1993) used could be reset by movement of the upper layer of one or two boulders. However, a colluvial boulder field could have formed well before these chronometric clocks were reset by more recent activity on the very surface.

Nials and Davis (1990) provide a different type of support for recent activity associated with colluvial boulder deposits. They find boulder fields on entirely Holocene landforms in the western Great Basin. We concur with their observation, noting that some colluvial boulder fields cross the latest Pleistocene highstands of Lakes Lahontan and Bonneville. At the same time, there are other colluvial boulder fields that are truncated by these around 14 ka (Benson et al., 1990) shorelines.

Chronometric data cannot be used to prove either hypothesis for the origin of colluvial boulder fields. Instead, age determination can be used only to disprove one (or both) of these conceptual frameworks. Our chronometric analyses show that deposits of large boulders were active on Amargosa Desert slopes in the Holocene and latest Pleistocene—at least active enough to reset all five of the chronometric clocks used here. This does not negate the possibility that some boulder fields have great antiquity. Available evidence simply contradicts the contention that "no modern equivalents to the well-varnished colluvial boulder deposits are observed on southern Nevada hillslopes" (Whitney and Harrington, 1993, p. 1015).

We do not maintain that all fields of large colluvial boulders in the Amargosa Desert and vicinity are Holocene and latest Pleistocene in age, only that some are. We suspect that part of landform development can involve a period of great stability that is not dependent upon any particular climate. The presence of a petrocalcic horizon (cf. Whitney and Harrington, 1993, p. 1012) is certainly consistent with a lengthy, but unknown time of hillslope stability. We have observed petrocalcic horizons >1 m thick in road cuts in the Phoenix metropolitan area that cement well-varnished basaltic colluvium at angles over 20°. There is a vital distinction here, however, between stable colluvium and fossil colluvium. Fossil colluvium is interpreted as a deposit from a past climate. Stable colluvium, in contrast, can be interpreted from the study of ongoing processes.

Since the relict hypothesis has been falsified, the chronometric issue now rests in whether there are *any* colluvial boulder deposits (surficial or at depth) old enough to belong to a mid-Pleistocene paleoclimatic period where temperatures were much colder. If so, some of the processes responsible for constructing colluvial boulder fields potentially could be enhanced by a relict climatic period. Concomitantly, if some colluvial boulder fields have been stable for 10^4 to 10^5 years, it would severely constrain process-based interpretations. Such antiquity would imply that these hillslopes evolve in such a way as to make boulder fields relatively stable geomorphic features for lengthy periods.

An important objective of chronometric dating is to obtain data on the magnitude and frequency of geomorphic events, in this case hillslope movements. Based upon available data, we know that some colluvial boulder deposits have formed entirely within the Holocene (Nials and Davis, 1990). Data presented here indicate that boulder fields in the Amargosa Desert and vicinity have been subjected to slope movements in the Holocene and latest Pleistocene, with the margins of boulder fields being more active than centers. Very little can be said about the magnitude or frequency of geomorphic events associated with colluvial boulder fields. The effort to obtain a reliable dataset, even for one hillslope, using the cosmogenic approaches suggested here, would be very expensive.

There are a great number of basic questions that have remained unanswered by an empirical chronometric approach, and almost no data exist on the processes that might form colluvial boulder fields in the southwestern United States. We do not know: how many boulders move in any given event; the distance of movement of individual or groups of bouders in an event; rates of movement over time; boulder denudation rates; and whether aeolian fines accumulate as hypothesized by Wells et al. (1982), whether they wash through the matrix, or both, or whether processes vary over time. Boulder monitoring (painted and surveyed boulders) experiments and dust trap/monitoring stations have been established. However, results may not be available in our lifetime, since an analysis of historic rephotography of four colluvial boulder slopes in Death Valley reveals no apparent movement in four decades.

An alternative approach to the study of the long-term evolution of colluvial boulder fields is not to try and date the colluvium, but instead to work with entire slopes that have started to form at different points in time—and to study how these colluvial boulder fields have changed over time. The hypothesis of Melton (1965), Wells et al. (1982), and Nials and Davis (1990) is that the development of colluvial boulder fields can be initiated from slope deposits and maintained by ongoing desert hillslope processes. Available chronometric data, indicating a *rough* continuum of ages, are consistent with this perspective. The key to testing this hypothesis lies in acquiring basic morphometric and sedimentological data on slopes with a range of independently established starting ages; this would test if and how colluvial boulder fields evolve over time.

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