Relict colluvial boulder deposits as paleoclimatic indicators in the Yucca Mountain region, southern Nevada

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ABSTRACT

Early to middle Pleistocene boulder deposits are common features on southern Nevada hillslopes. These darkly varnished, ancient colluvial deposits stand out in stark contrast to the underlying light-colored bedrock of volcanic tuffs, and they serve as minor divides between drainage channels on modern hillslopes. To demonstrate the antiquity of these stable hillslope features, six colluvial boulder deposits from Yucca Mountain, Nye County, Nevada, were dated by cation-ratio dating of rock varnish accreted on boulder surfaces. Estimated minimum ages of these boulder deposits range from 760 to 170 ka. Five additional older deposits on nearby Skull and Little Skull Mountains and Buckboard Mesa yielded cation-ratio minimum-age estimates of 1.38 Ma to 800 ka. An independent cosmogenic chlorine-36 surface exposure date was obtained on one deposit, which confirms an estimated early to middle Quaternary age. These deposits have provided the oldest age estimates for unconsolidated hillslope deposits in the southwestern United States.

We suggest that the colluvial boulder deposits were produced during early and middle Pleistocene glacial/pluvial episodes and were stabilized during the transition to drier interglacial climates. By comparison to modern periglacial environments, winter minimum monthly temperatures of −3 to −5 °C were necessary to initiate freeze-thaw conditions of such vigor to physically weather relatively large volumes of large boulders from the upper hillslopes of the Yucca Mountain area. These conditions imply that early and middle Pleistocene glacial winter temperatures were at least 1 to 3 °C colder than existed during the last Pleistocene glacial episode and 7 to 9 °C colder than present. We conclude that at least several early and middle Pleistocene glacial episodes were colder, and perhaps wetter, than glacial episodes of the late Pleistocene in the southern Great Basin.

Geomorphic processes necessary to form these colluvial boulder deposits are not active on modern hillslopes in the southern Great Basin. In addition, the lack of young, relatively unvarnished colluvial boulder deposits on these hillslopes suggests that boulder-forming conditions did not exist during the late Pleistocene in this region.

Modern semiarid hillslope processes primarily erode colluvium during infrequent high-intensity storms. The preservation of old, thin hillslope deposits and the less-than-2-m incision by hillslope runoff adjacent to these deposits, however, indicate that extremely low denudation rates have occurred on resistant volcanic hillslopes in the southern Great Basin during Quaternary time.

INTRODUCTION

Bouldery deposits of colluvium are common features on hillslopes in the Great Basin of southern Nevada. They range from near-continuous boulder mantles to narrow, isolated, linear boulder trains that seem to stream down hillslopes. Commonly coated with dark rock varnish, these boulder deposits stand out against lighter colored colluvium, bedrock, or straw-colored vegetation as dark, vertical rock bands on the landscape (Fig. 1). The processes responsible for the formation of these little-studied hillslope de-

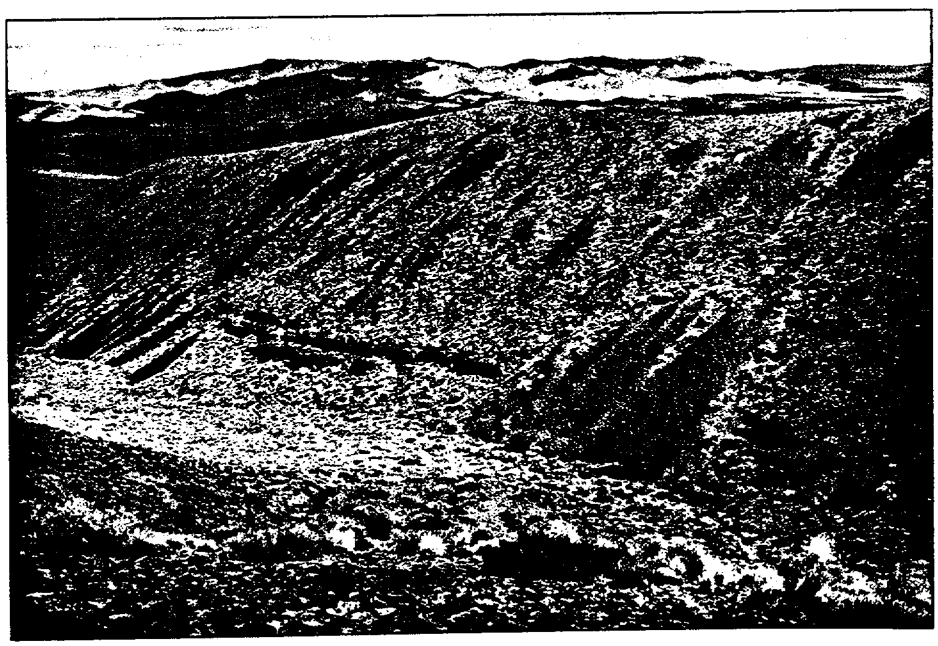

Figure 1. Typical, darkly varnished colluvial boulder deposits overlying a light-colored volcanic tuff on Yucca Mountain in Abandoned Wash. The relief of the hillslope is 70 m.

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posits are poorly understood. Furthermore, the true antiquity of these deposits has not been previously recognized because of the inability to determine their ages. Rock-varnish dating, used in this study, provides a new opportunity to determine their ages.

Many different terms have been used to describe a single geomorphic process or deposit, and sometimes the same term is used by different workers to describe dissimilar deposits (Embleton and King, 1975). Names and definitions of hillslope deposits are no exception, especially when authors borrow terms defined in one climatic zone for deposits believed to be analogous but found in a different climatic setting. Bouldery hillslope deposits of similar physical appearance can accumulate by different processes. We generically designate these deposits/landforms as colluvial boulder deposits, because they originate and are deposited by a suite of weathering and mass-movement processes. These processes range from *in situ* weathering of bedrock to very slow talus creep to slow-moving granular flows (Pierson and Costa, 1987). Most of the colluvial boulder deposits examined in this study are relict and are not moving under the present climatic conditions, which makes the interpretation of processes responsible for each deposit impossible at most sites. Thus, we prefer to use a term that does not imply a specific geomorphic origin.

Individual boulder deposits that are inferred to have moved slowly downslope by a combination of creep and saturated flow we term "colluvial boulder flows" (Whitney and Harrington, 1988). Other boulder deposits in this study, however, are primarily *in situ* weathered bedrock and have moved little, if any, distance downslope.

Boulder deposits of a similar appearance in the western United States have been described by the colloquial terms "rock stripes," "stone stripes," "stone streams," and "block streams"; however, these terms are commonly used to describe linear landforms and deposits attributed to periglacial origin (for example, Williams, 1958; Malde, 1964; Prokopovich, 1987; Washburn, 1973). Melton (1965) used Bryan's (1923) term "block fields" to describe individual boulder deposits on debris-covered hillslopes in southern Arizona. Cluer (1988) described one variety of colluvial boulder deposits as "leveed boulder flows" to define coarse deposits that are similar to classic debris-flow levees but lack a fine-grained matrix. "Boulder flows" is a term originally suggested by Lovejoy (1972) for boulder deposits that moved quickly and clogged stream valleys, and that are also distinguished from true debris flows because a fine-grained matrix is missing. Lovejoy described this process as a "rock-fragment wet flow."

In this study, we report only on the darkly varnished colluvial boulder deposits that are so visually striking on the southern Great Basin landscape. Most well-varnished deposits overlie remnant mounds of colluvium and presently serve as minor drainage divides between the active hillslope rills and channels. The well-developed rock varnish on the boulder surfaces indicates that these hillslope deposits have been stable for relatively long periods of time. Some deposits are even cemented in place by calcium carbonate, a situation also observed on Arizona hillslopes (Melton, 1965; Ford and others, 1982). Consequently these stable, varnished colluvial boulder deposits contain a fragmentary, yet remarkably long, record of local hillslope processes and paleoclimates.

Age estimates of rock varnish may be obtained by cation-ratio dating (Dorn, 1983; Harrington and Whitney, 1987), and we apply this dating technique to determine the approximate time that colluvial boulder deposits became stable. The ages of these deposits are not only useful for paleoenvironmental reconstructions, but are also useful in calculating local, long-term erosion rates. Average hillslope erosion rates are estimated by calculating the volume of hillslope debris that has been removed subsequent to the stabilization of a colluvial boulder deposit.

The colluvial boulder deposits were studied on Skull, Little Skull, and Yucca Mountains and on Buckboard Mesa, located on the Nevada Test Site in southern Nevada (Fig. 2). Skull Mountain is 1,700 m in altitude and rises about 650 m above the adjacent basin

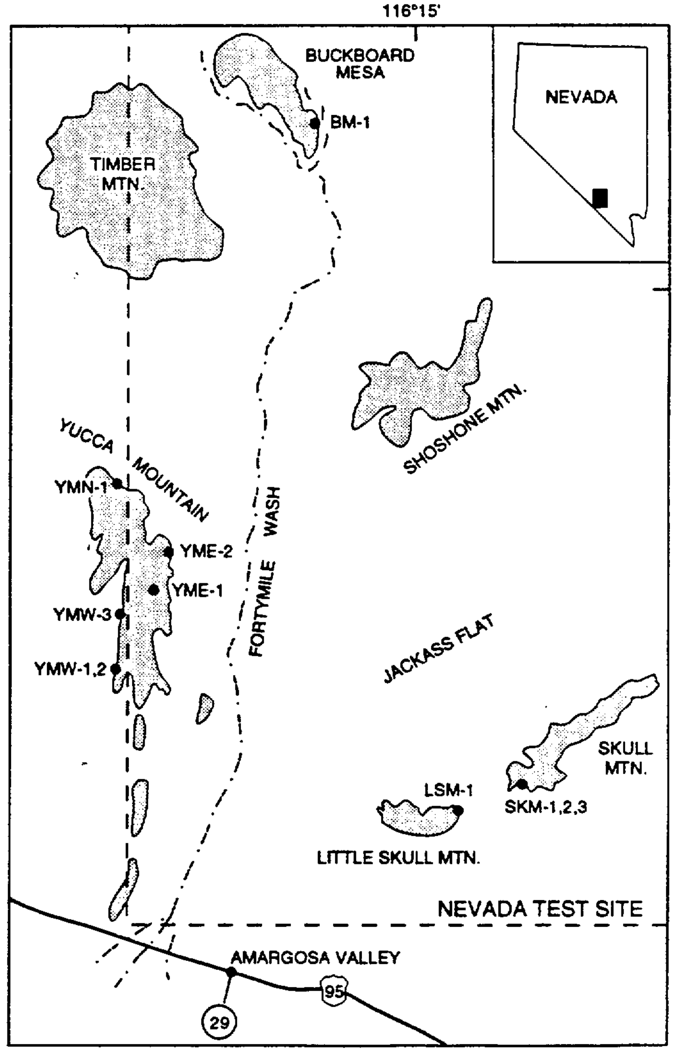

Figure 2. Map of major geographic features and sample sites in the study area.

floors. Yucca Mountain has a summit elevation of 1,508 m and a local relief of about 435 m. Each mountain is underlain by Tertiary welded volcanic tuff, except for relatively thin Pliocene basalt flows on the summits of Skull and Little Skull Mountains (Sargent and Stewart, 1971) and Buckboard Mesa. These fine-grained volcanic rocks are widely distributed across the Great Basin and are very resistant to weathering in semiarid climates.

PRESENT CLIMATIC CONDITIONS

The creosote- and sagebrush-covered hills of this investigation are situated in the northern Mojave Desert. A small number of Joshua trees are locally scattered across the tops of hills above 1,500 m altitude. The present climate at Yucca Mountain is characterized as dry semiarid with cool winters. Summers are hot and dry with occasional convective thunderstorms. Winters are cool and dry with evening freezing temperatures and snow distribution controlled by altitude. Skull and Yucca Mountains receive an average of 2.4 cm of snow 1–5 days a year that ordinarily melts quickly when the storms abate (U.S. Department of Energy, 1988).

Two years of meteorological data have been collected from the Yucca Mountain area (A. L. Flint, U.S. Geol. Survey, 1991, written commun.). During 1988–1989, the summit of Yucca Mountain received an average of 84 mm of precipitation (Fig. 3). The basin floor at 800 m elevation 15 km south of Yucca Mountain has averaged 110 mm of moisture a year at Amargosa Valley. Thus, the true long-term precipitation average on Yucca Mountain is estimated to be about double the recorded precipitation, because the summit lies 700 m above the Amargosa Valley. Moisture is distributed through three seasons: winter, spring, and late summer. Mean monthly temperatures range from 3.9 °C in January to 28.9 °C in July. Extreme temperatures range from −3.9 °C in January to 40.6 °C in July. The average annual temperature for the two years of record is 15.9 °C, which is comparable to the average annual temperature of 15.3 °C at Beatty, Nevada, from 1922–1960, located at the same latitude about 50 km to the west.

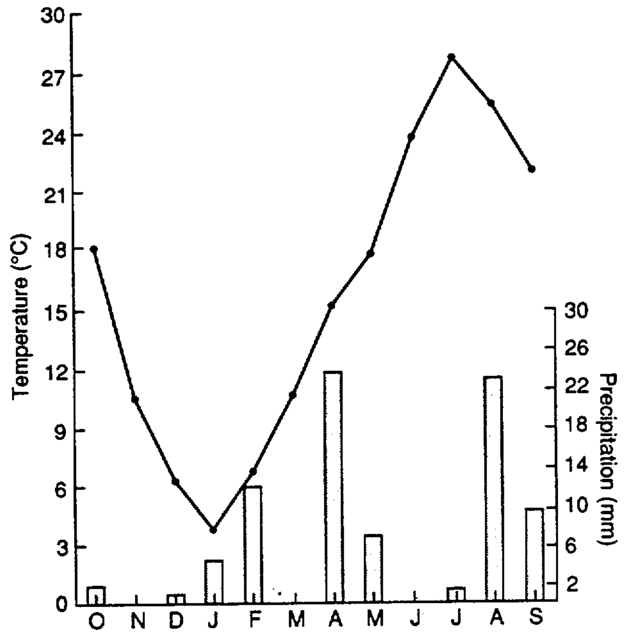

Figure 3. Graph of the mean monthly temperature and precipitation on the top of Yucca Mountain for 1988 and 1989. Mean annual temperature is 15.9 °C (60.6 °F), and average annual precipitation is 84 mm (3.5 in.). Data supplied by A. Flint, U.S. Geological Survey.

GENERAL DESCRIPTION OF COLLUVIAL BOULDER DEPOSITS

The size and shape of colluvial boulder deposits varies considerably, with individual linear deposits being the most common. The size of the deposit appears to be controlled by the abundance of boulders, the length of the hillslope, and the local erosional history. Typically, individual deposits are four to six times longer than they are wide. On Yucca Mountain, for example, widths vary from 4 to 6 m and lengths from 20 to 35 m. Small colluvial boulder deposits less than 2 m in length are found on some slopes and appear to be erosional remnants of originally larger deposits.

Continuously boulder-mantled hillslopes such as those on the southwestern flank of Skull Mountain (Fig. 4) are not common in southern Nevada. Only the lower parts of hillslope boulder mantles exhibit the distinctive linear geometry of isolated boulder deposits. Mantled slopes are present where the supply of boulders is great (well-jointed, fine-grained volcanic rocks) and the upper hillslopes are concave, which results in coalescing hillslope deposits. Strongly convex slopes, however, are typically barren of colluvial boulder deposits.

The linear form and lens-shaped cross section of some colluvial boulder deposits strongly suggest that they occupy former hillslope channels or rills. Commonly, modern channels have incised to bedrock on one or both sides of a deposit (Fig. 5), topographically inverting a former channel deposit. The elevated colluvial boulder deposit then serves as a relatively level local drainage divide, which enhances the preservation of the deposit.

Surficially, colluvial boulder deposits appear to be a jumble of boulders that overlie bedrock or colluvium. On typical Yucca Mountain hillslopes, colluvial deposits are patchy with large areas of volcanic bedrock exposed (Fig. 6). Ridge crest deposits are thin, averaging about 0.4 m thick. Colluvium thickens to about 4.0 m at the base of slopes; however, there is a noticeable lack of boulder deposits at the base of most hillslopes.

Most colluvial boulder deposits are stabilized on the middle and upper hillslopes. One group is located just below the ridge crest, and a second group is generally found about midway down the slope, or near the base if the slope is unusually steep. Ridge-crest deposits generally overlie bedrock (volcanic tuff) and are more irregular in shape than the lower group of deposits. Incision of upper-slope deposits has not occurred because runoff is unable to collect over small areas and channel the bouldery debris. Boulder deposits on the lower two-thirds of the slope commonly overlie, or are a part of, colluvial aprons (Fig. 6). Colluvial boulder deposits are found on slopes as steep as 31° on Skull Mountain and as much as 29° on Yucca Mountain. The slopes on both mountains have smooth topographic contours with gentle relief both along slope and downslope. These consistent slope gradients are attributable to uniform weathering of the thick and chiefly homogenous ash-flow tuffs that underlie all but the uppermost part of the hillslopes.

Young colluvial boulder deposits exist, but are uncommon. Two features of the younger deposits readily distinguish them from older, boulder deposits: (1) they are always composed of smaller sized rock debris, and (2) they have different rock-varnish characteristics. At some localities, such as Skull Mountain, overlapping relationships exist (Fig. 4).

Figure 4. Colluvial boulder deposits on southwest flank of Skull Mountain. Boulders originally mantled the entire slope and were weathered from a basalt flow that caps the mountain. The length of the largest hillslope deposit is about 200 m.

Figure 5. Mid-slope view up the Skull Mountain hillslope shown in Figure 5. Hillslope channels have incised 1 to 2.5 m below the colluvial boulder deposits.

Figure 6. Colluvial boulder deposits at two levels on west slope of Yucca Mountain. The large deposit on the lower slope is 65 m long, overlies a colluvial wedge, and has been topographically inverted by hillslope channels. Upper-slope deposits are thin, overlie bedrock, and are not bounded by well-defined channels.

arnish on overlapping boulder deposits is not only less dark, but it is commonly redder in color and less completely covers the rock surface than on the older boulder deposits.

SEDIMENTOLOGICAL DESCRIPTION OF COLLUVIAL BOULDER DEPOSITS

The most striking aspect of colluvial boulder deposits is the surface cover of large, angular boulders. Although large clasts at some localities must have moved hundreds of meters downslope, they exhibit little or no rounding, which indicates minimal grain-to-grain contact during transport. In fact, most observed rounding of boulders on darkly varnished flows seems to be due to *in situ* weathering after deposition. This weathering is easily recognizable because rocks have cracked in place, and rock chips are found lying nearby that can be matched to the nonvarnished or poorly varnished corners of the original rocks.

Clast sizes in colluvial boulder deposits are variable and probably due to differences in rock type, jointing, and fracture densities. Colluvial boulders on Skull Mountain and Buckboard Mesa are composed of Tertiary basalt (Sargent and Stewart, 1971) and are larger than colluvial boulders of the welded tuff on Yucca Mountain (Scott and Bonk, 1984). The average median diameter of basalt boulders is 0.6 m, and boulders as much as 1.5 m diameter are common, whereas boulders of welded tuff on Yucca Mountain are rarely larger than 0.7-m median diameter and are typically 0.2 m to 0.3 m in diameter. Clasts greater than 0.1 m on young colluvial boulder deposits are rare. The coarse nature of these deposits is a factor in their preservation.

Colluvial boulder deposits overlying bedrock are typically 0.4 m to 1.3 m thick, with a median thickness of 0.6 m for the deposits measured in this study. The thickness of a boulder deposit is more difficult to determine when it overlies coarse colluvium. Colluvial boulder deposits near hilltops are thinner than those on lower slopes, and younger (less varnished) deposits are commonly thinner than older ones.

Colluvial boulder deposits on lower slopes commonly exhibit an internal coarsening-upward texture and are interpreted to be colluvial boulder flows. A cobbley gravel layer underlies the surface boulders of these deposits and overlies a predominantly sandy gravel layer. The sandy gravel commonly grades downward into a finer grained unit of silty sand containing scattered gravel and variable amounts of clay and calcium carbonate (Fig. 7). The volume of fines in the lower part of a colluvial boulder deposit appears to be chiefly dependent upon the amount of eolian

Figure 7. Vertical exposure of a colluvial boulder deposit on Little Skull Mountain in an active hillslope channel. Matrix has largely accumulated by episodic eolian deposition. Base of deposit is cemented to the underlying volcanic tuff by $CaCO_3$.

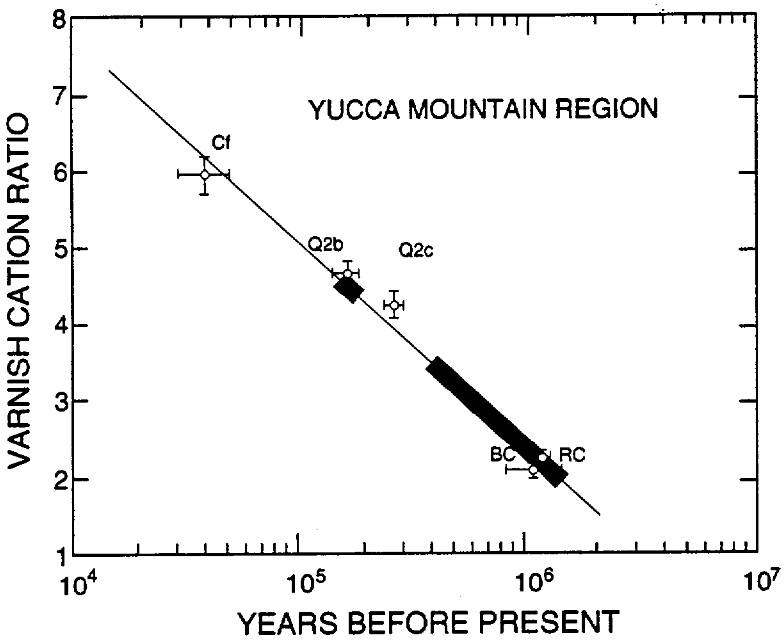

Figure 8. Rock-varnish dating curve for the Yucca Mountain region. The shaded area on the curve represents the cation ratios for the deposits analyzed in this study.

Figure 9. In contrast to the well-varnished boulders in the relict deposits, modern weathering of welded tuff on Yucca Mountain produces small, unvarnished clasts commonly less than 15 cm in diameter.

material that has settled on the deposits, which are excellent dust traps (Wells and others, 1982).

Textural analyses indicate that the matrixes of three colluvial boulder deposits are remarkably similar, consisting of predominantly quartz-rich, silty, fine sand. The source of most of this fine sand and coarse silt is not from weathered volcanic bedrock on the hillslope, but is reworked from adjacent basin floors and stream valleys. Volcanic ash, basaltic sand, pumice, and/or fine-grained tuffaceous sediment derived from the underlying bedrock are present only as minor components of the present matrix. Because colluvial boulder deposits are coarse grained with an open fabric, original matrix may be washed out of the hillslope deposit in the same manner as channel sieve deposits (Hooke, 1967). Therefore, in the older colluvial boulder deposits, it is not possible to estimate how much fine-grained sediment, or matrix, existed when the deposit was actively moving, or how much of the original matrix is preserved.

DATING COLLUVIAL BOULDER DEPOSITS BY VARNISH CATION RATIOS

Rock varnish is a Mn-rich coating that accretes on stable rock surfaces in arid and semiarid regions. Rock-varnish cation-ratio dating is a method used to estimate the exposure age of a surface or deposit (Dorn, 1983) and is based on the premise that a ratio of minor elements within the varnish systematically decreases with increasing exposure age. Rock-varnish ages for these surfaces are estimated from empirical calibration curves constructed using independently dated geomorphic surfaces within the study region (Dorn, 1983; Dorn and others, 1986; Harrington and Whitney, 1987; Pineda and others, 1988).

Sampling Method

Ten colluvial boulder deposits were sampled for cation-ratio dating on the north, east, and western flanks of Yucca Mountain; the southwest flank of Skull Mountain; and the northeast flank of Little Skull Mountain. Colluvial boulder deposits sampled on Yucca Mountain include one about 100 m above the base of the slope on the north flank (YMN-1), one 50 m below the ridge crest (YMW-1), two (YMW-2 and YMW-3) lying 20 m to 40 m above the base of the west flank, one near the crest of the east flank (YME-1), and one about 15 m above the base of Boundary Ridge (YME-2), a ridge spur projecting from the east flank. A colluvial boulder deposit was also sampled in Skull Mountain Pass 20 m above the base of the slope comprising the northeast flank of Little Skull Mountain (LSM-1). Three additional deposits were sampled along the lower slope on the south and southwest flank of Skull Mountain (SKM-1, SKM-2, SKM-3, and SKM-3A). Sample SKM-3 was collected from the toe and SKM-3A from the upper part of a large boulder deposit of more than 50 m in length. A boulder deposit was also sampled on the slopes of Buckboard Mesa north of Yucca Mountain (BM-1).

An attempt was made to distinguish and to sample the oldest colluvial boulder deposit on each slope in order to determine the antiquity of hillslopes within the study area. Selection of the oldest deposits on a slope used the following criteria: (1) position: deposits near the base of a slope are more likely to be preserved than deposits on the upper, steeper slopes that commonly have been subjected to more erosion; (2) size: the interior of the largest deposits will most likely preserve the oldest, unmodified varnish on boulders; (3) elevation above the general slope: deposits having the greatest topographic relief are most likely the oldest on the slope; and (4) varnish characteristics: deposits whose clasts possess the darkest (Mn-rich), thickest, and most complete varnish coats are most likely the oldest.

Individual clasts were selected from stable positions on the surface of a colluvial boulder deposit. Such clasts are (1) those away from the edge of the deposit, which minimizes the likelihood of vegetation inhibiting varnish development or contributing to the erosion of the varnish; (2) the larger varnished clast sizes, because larger clasts are more stable and not easily rotated; (3) those with no varnish on the underside of the clast, indicating the clast has not been overturned since varnish formation began; (4) tabular clasts, because they are least likely to be overturned; and (5) clasts possessing large, gently sloping surfaces on which extensive varnish coats can accrete. In addition, criteria of Harrington and Whitney (1987) were also used for selecting individual varnished clasts.

The lithology of varnished clasts collected from the colluvial boulder deposits on Yucca Mountain is volcanic tuff; that from Skull and Little Skull Mountains is basalt. Varnished chips were collected from boulders with median diameters ranging in size from 0.25 to 1.0 m. We originally collected ~20 clasts from a deposit and then culled them to the best 8 to 10 clasts, based on the quality of each varnish coat. This sample-selection procedure is used to reduce the analytic variability in varnish cation ratios for an individual deposit.

Sample Preparation

Our preparation of clasts for scanning electron microscope (SEM) analysis follows the methods described in Harrington and Whitney (1987). Clasts are hand washed in deionized water to remove surficial detritus and are air dried. Circular cores of varnish and clast substrate are drilled from areas where the varnish is best developed. The substrate of each core is ground off to produce a 0.5-cm-thick disk. Disks are mounted on glass slides, varnish side up, and are carbon coated for SEM analysis.

Sample Analysis

Samples are analyzed using an ISI scanning electron microscope equipped with a Tracor Northern (TN-5500) energy-dispersive X-ray analyzer. Standard machine settings used are a 40° takeoff angle and a counting time of 150 sec. Counting dead time is held between 15% and 25%. The software package used for analysis is a Tracor Northern standardless semi-quantitative program (SSQ) wherein X-ray peak intensities are corrected for atomic weight, absorption, and fluorescence before elemental weight percentages are calculated. Relative abundances of elements are based on relative X-ray peak intensities. SSQ is an analytic program that does no decomposition of peak overlaps during analysis.

Harrington and others (1989) noted the presence of Ba in rock varnishes from Nevada and commented on the inclusion of part of this Ba in all earlier analyses of rock varnish that were made using analytical software (such as Tracor's SSQ program) that did not perform decomposition of elemental peak overlaps. Harrington and others (1991) further noted that if no peak decomposition was performed during analysis, then approximately one-third of the Ba concentration would be included as Ti. Thus, the cation ratio calculated is $(Ca+K)/(Ti+\sim\frac{1}{3}Ba)$ instead of $(Ca+K)/Ti$ as originally believed. Bierman and Gillespie (1991) used the same analytic argument of inclusion of Ba in rock-varnish analyses to support their contention that all earlier calibrated rock-varnish curves include

TABLE 1. VARNISH CATION RATIOS AND ESTIMATED AGES OF COLLUVIAL BOULDER DEPOSITS OF THE YUCCA MOUNTAIN AREA

Sample location	Sample number	Number of analytical sites (n)*	Cation ratio	Calculation of uncertainty		Age	Estimated age (ka) and estimated uncertainty
				1 Scr†	95%CL‡		
Yucca Mountain:							
East flank	YME-1	55	2.99	0.19	0.05	640	[610–670]
Boundary ridge	YME-2	80	4.52	0.55	0.12	170	[140–180]
West flank (1)	YMW-1	55	3.34	0.47	0.13	465	[400–515]
West flank (2)	YMW-2	40	2.97	0.08	0.03	645	[630–660]
West flank (3)	YMW-3	65	2.88	0.19	0.05	710	[680–740]
North Flank	YMN-1	40	2.79	0.27	0.09	760	[710–820]
Little Skull Mt.	LSM-1	160	2.52	0.21	0.03	960	[930–990]
Skull Mt. (1)	SKM-1	45	2.74	0.21	0.06	800	[760–830]
Skull Mt. (2)	SKM-2	30	2.68	0.16	0.06	830	[800–880]
Skull Mt. (3)	SKM-3	35	2.28	0.26	0.09	1180	[1110–1270]
Skull Mt. (3A)	SKM-3A	50	2.49	0.11	0.03	990	[960–1030]
Buckboard Mesa	BM-1	40	2.09	0.35	0.11	1380	[1260–1510]

*(n) = number of SEM analytic sites per geomorphic surface.
†Scr = standard deviation calculated for the mean cation ratio for a surface.
‡95% CL = 95% confidence level for the mean cation ratio for a geomorphic surface calculated using the formula of Bierman and others, 1991.

Ba as a component in the calculated cation ratios. Harrington and others (1991) and Bierman and others (1991) suggested that the included Ba may contribute to the observed decrease in cation ratios with increasing rock-varnish age.

The rock-varnish dating curve for Yucca Mountain (Harrington and Whitney, 1987) was calibrated using cation ratios calculated from data derived using the SSQ program. Thus, our age estimates for these colluvial boulder deposits are obtained by plotting SSQ–generated cation ratios on this dating curve, and no additional uncertainties arising from mixing analytical procedures are introduced. The ratio of [(K+Ca)/(Ti+~⅓Ba)] is calculated for six overlapping sites on a disk (each about 25 mm^2 in area) and averaged, effectively producing an integrated analysis of the varnish surface. A varnish cation ratio (VCR) is calculated by the average of the varnish analyses on each sample clast. A VCR for a colluvial boulder deposit is determined by averaging the VCRs for all sample clasts. The time over which surface clasts have been stable in a colluvial boulder deposit is estimated by plotting the VCR for the deposit on the calibrated cation ratio curve.

Bierman and others (1991) noted that the uncertainty in a calculated mean cation ratio for a geomorphic surface is a function of the number of analyses that are used to calculate the mean cation ratio. Cation ratios that incorporate fewer than five analyses have a significantly higher uncertainty than that of one standard deviation calculated for a cation ratio. In our analyses of colluvial boulder deposits, we have analyzed between 30 and 160 sites for each surface being dated. The magnitude of the uncertainty at a 0.95 probability in our calculated cation ratios varies from a maximum of 0.127 (compared to one standard deviation of 0.47 calculated for the same cation ratio) to a minimum of 0.026 (compared to one standard deviation of 0.08). In this study, the uncertainty in the estimated ages of boulder deposits (Table 1) is reported using the technique of Bierman and others (1991), because it is a more accurate measure of the true uncertainty of a calculated cation ratio than the uncertainty measured as one standard deviation. Our age estimates and uncertainties are calculated using the cation ratio curve for Yucca Mountain (Fig. 8).

Three darkly varnished boulders were sampled from near the toe of the rock-varnished dated colluvial boulder deposit at Buckboard Mesa for surface exposure dating using cosmogenic ^{36}Cl (Phillips and others, 1986). These samples integrate rock chips from the surface to a depth of 30 cm in each boulder. Although the sampled boulders each had well-varnished surfaces, no systematic attempt was made to identify and sample the oldest rock varnish present on this deposit.

The oldest ^{36}Cl age estimate from this deposit is 600 +71/−59 ka (Table 2). The following concerns are relevant to the interpretation of this age estimate. The ^{36}Cl accumulation in rock is calibrated in radiocarbon years. The adjustment of radiocarbon years to calendar years will decrease ^{36}Cl production rates and increase calculated ages by ~10% (F. M. Phillips, New Mexico Inst. Mining and Technology, 1991, written commun.) and yield a corrected age estimate of 660 ka (~595–740 ka). This maximum calculated age estimate is only a minimum limiting age for the Buckboard Mesa deposit. The ^{36}Cl content measured for the oldest sample is >92% of the saturation value for ^{36}Cl. Because this value is close to theoretical saturation, this sample may represent the maximum ^{36}Cl concentration effectively measurable. This age estimate may then represent the practical upper limit of this dating technique and not closely limit the age of the deposit. It does, however, provide an independent age determination that demonstrates the antiquity of these boulder deposits.

Results and Discussion

Varnish cation ratios (see Table 1) indicate that colluvial boulder deposits on hillslopes in the Yucca Mountain area have considerable antiquity. The estimated ages of boulder deposits in this study range in age from early to middle Pleistocene, the oldest being nearly 1.4 Ma. These are the oldest known dated

TABLE 2. DATA FOR CHLORINE 36 SURFACE EXPOSURE DATING OF BUCKBOARD MESA COLLUVIAL BOULDER DEPOSIT

Sample* number	Measured $^{36}Cl/10^{15}Cl$	Corrected† $^{36}Cl/10^{15}Cl$	Cl (ppm)	K_2O (wt%)	CaO (wt%)	$[\Sigma_i N_i]$‡ ($cm^2 kg^{-1}$)	^{36}Cl age** (ka)
40MC1	1,930 ± 100	1,080	146	1.77	9.0	7.27	420 $^{+39}_{-34}$
40MC2	2,000 ± 100	1,115	186	1.75	8.9	7.27	600 $^{+71}_{-59}$
40MC3	1,560 ± 80	870	154	1.78	9.0	7.33	310 $^{+26}_{-22}$

*All samples from 36.40°N, and 914 m elevation.
†Corrected to 90°N and sea level (scaling factor, 1.887) using formulation of Lal (1991), and for effect of topographic shielding (scaling factor, 0.95).
‡i = thermal neutron absorption cross section of element i.
N_i = atoms of element i per kg rock.
$\Sigma_i N_i$ = total thermal neutron absorption cross section of rock.
**Calculated using production parameters (at 90°N and sea level) of 4,160 atoms ^{36}CL/(mole K)/yr, 3050 atoms ^{36}CL/(mole Ca)/yr, and 3.07 × 10^5 thermal neutrons absorbed/(kg rock)/yr (Zreda and others, 1991).

TABLE 3. THERMOLUMINESCENCE ANALYSES OF FINE-GRAINED SEDIMENT IN COLLUVIAL BOULDER DEPOSITS ON LITTLE SKULL AND YUCCA MOUNTAINS

Deposit	Depth (cm)	Lab no.	Uranium	Thorium	K_2O	TL age (yr B.P.)
YME-2	12–18	A-2880	6.8 ppm	17.4 ppm	3.55%	3,900 ± 550
YME-2	30–35	A-2879	5.7 ppm	17.1 ppm	3.34%	11,240 ± 1,370
YME-2	55–60	A-2878	5.6 ppm	15.6 ppm	4.14%	9,940 ± 1,030
LSM-1	8–13	A-2874	6.4 ppm	17.1 ppm	2.39%	7,750 ± 780
LSM-1	20–26	A-2875	3.8 ppm	10.4 ppm	2.52%	15,600 ± 3,100

hillslope deposits in the southwestern United States.

The oldest dated deposits on Yucca Mountain range from 640 ka on the east slope to about 760 ka on the north flank. Older deposits exist on slopes up to 31° at Skull Mountain and Buckboard Mesa. The antiquity of these deposits suggests that even on the steepest slopes of the Yucca Mountain area, rates of slope denudation have been remarkably low since these deposits were stabilized.

The youngest episode of colluvial boulder stabilization identified in this study (YME-2) is estimated to have occurred near the end of the middle Pleistocene ca. 170 ka. Varnish cation ratios of older deposits on the east and west flanks of Yucca Mountain (YME-1, YMW-2, and YMW-3) are remarkably similar and suggest that these deposits may have stabilized during one period ca. 650 ka (Table 1).

VCRs of two colluvial boulder deposits on Skull Mountain (SKM-1 and SKM-2) closely correspond and are nearly the same as that for the deposit on the north flank of Yucca Mountain (YMN-1), suggesting that these three deposits may have formed during an earlier episode of colluvial boulder deposition ca. 800 ka. The similarity of VCRs for two older deposits on Skull (SKM-3) and Little Skull (LSM-1) Mountains possibly represents a fourth episode of stabilization ca. 1 Ma. A fifth and earliest episode of hillslope deposit stabilization may be indicated, ca. 1.3 Ma, by the similarity of VCRs for the oldest boulder deposit on both Skull Mountain (SKM-3A) and Buckboard Mesa (BM-1).

Rock-varnish dating indicates that extensive bouldery hillslope mantles are probably composed of colluvial boulder deposits of varying age. The VCRs from the Skull Mountain boulder deposit (SKM-3 and SKM-3A) suggest that the toe of the deposit was emplaced earlier than the clasts that now form the upper part of the deposit. Sample YMW-1 is situated about 35 m upslope from, and has a higher cation ratio than, sample YMW-2 on the west slope of Yucca Mountain. This relationship suggests that one or more episodes of hillslope erosion took place between the times of emplacement of these deposits. The present data suggest that the process of boulder production and stabilization are episodic, although too few deposits have been dated to demonstrate this statistically.

THERMOLUMINESCENCE DATING OF MATRIX IN COLLUVIAL BOULDER DEPOSITS

Samples of the fine-grained sediment from two colluvial boulder deposits were dated by thermoluminescence (TL) analyses to determine at what time the eolian silt was trapped in the hillslope deposits. Sediment was collected from two positions below the top of the matrix in the colluvial boulder deposit LSM-1 on Little Skull Mountain; one sample collected from 8–13 cm below the surface was dated at 7750 ± 780 yr B.P., and a second sample at 20–26 cm dated at 15,600 ± 3100 yr B.P. (Table 3). Matrix also was collected from three depths in the colluvial boulder deposit (YME-2) on Yucca Mountain. Samples from 12–18 cm, 30–35 cm, and 55–60 cm were dated at 3900 ± 550 yr B.P., 11,240 ± 1370 yr B.P., and 9940 ± 1030 yr B.P., respectively. The overlap of TL ages at 30–35 cm and 55–60 cm depths suggests that the eolian sediment from 30–60 cm was deposited about 10,000 yr ago at the end of the Pleistocene.

These TL dates suggest that eolian deposition on local hillslopes began during the transition from cooler glacial/pluvial conditions at about 18 ka (Spaulding, 1985) to warmer, interstadial conditions of the Holocene. Eolian deposition has continued through the Holocene and is presently active. This period of eolian deposition correlates with a change toward greater aridity as recorded in vegetation in packrat middens that span the past 18,000 yr (Spaulding and Graumlich, 1986). About 100 km south of Yucca Mountain, pulses of loess deposition during interpluvial climates are recorded in soils developed on volcanic flows in the eastern Mojave Desert (McFadden and others, 1986). Recent erosion on Skull and Little Skull Mountains has exposed vertical sections through colluvial boulder deposits (Fig. 7). Below an upper unconsolidated horizon of probable late Quaternary matrix, there is a calcium-carbonate–cemented layer. The lower part of the matrix is cemented to the underlying bedrock, making present boulder movement unlikely, even if the entire slope were to be saturated. The lower part of the present matrix may represent original matrix or eolian additions during the middle Pleistocene.

The late Pleistocene and Holocene ages for the upper silty sand matrix strikingly contrast with the early to middle Pleistocene ages of the colluvial boulder deposits. The late Quaternary TL dates indicate that much of the present matrix is clearly not the original matrix. Thus, we suggest that several, if not many, episodes of eolian activity associated with warm, inter-pluvial climates have contributed fine-grained sediment to southern Nevada hillslopes. Eolian sediment that was not subsequently washed off the hillslopes by overland flow became an effective matrix, and when saturated, served as a lubricant for colluvial boulder transport during colder and wetter pluvial climates. During semiarid climates, the fine-grained eolian sediment may also have retained the moisture needed to facilitate debris-flow activity in hillslope colluvium.

PALEOCLIMATIC IMPLICATIONS

No modern equivalents to the well-varnished colluvial boulder deposits are observed on southern Nevada hillslopes. Modern volcanic-bedrock hillslopes are commonly mantled with only a thin, discontinuous cover of small rock fragments, commonly less than 15 cm in median diameter, which are the products of physical weathering under the present semiarid climate (Fig. 9). Present production of medium-to-large boulders is nearly non-existent, as indicated by well-varnished outcrops of bedrock on the ridges of both Yucca and Skull Mountains. Thus, we conclude that the well-varnished boulders in colluvial boulder deposits were formed under substantially more rigorous climatic conditions than presently exist, a deduction shared by the majority of observers who have described similar deposits in the southwestern United States (for example, Denny and Drewes, 1965; Melton, 1965; Prokopovich, 1987; Shafer, 1986).

A study of modern debris production in southern Ontario supports this interpretation.

Fahey and Lefebure (1988) demonstrated that greater volumes of debris were physically weathered from an escarpment during high-intensity, long-duration cycles of freeze-thaw in which the freezing phase lasted several days rather than during 1- to 2-day cycles. Duration of the freezing phase is also related to boulder size, because crack propagation is time dependent. The relatively large volumes of large-sized boulders in the early-middle Pleistocene colluvial deposits on Yucca and Skull Mountains were most likely produced under colder winter conditions than prevailed during late Pleistocene glacial episodes when much smaller clasts were produced in significantly smaller volumes. Spaulding (1985) reconstructed the climate of the latest Pleistocene glacial episode in the vicinity of Yucca Mountain by identifying plant macrofossils in ancient packrat middens. At about 18,000 yr B.P., the average annual temperature was at least 7 °C lower than present values, and the slopes of Yucca and Skull Mountain probably supported a juniper woodland. Plants sensitive to frigid temperatures or moist environments were not found in glacial-age middens, which suggests that during the latest glacial period, conditions were not optimum for freeze-thaw cycles of long duration.

Cryogenic deposits have been described in central and eastern Nevada mountain ranges (Shafer, 1986; Wayne, 1982). Dohrenwend (1984) studied the distribution of Pleistocene nivation hollows on mountain ranges in the western Great Basin and calculated that a mean annual temperature of 0–1 °C was necessary to form these nivation features. In addition, Dohrenwend (1984) plotted the elevation of Pleistocene nivation hollows along a north-south transect of the Great Basin. By comparing the altitude of these nivation features with the modern temperature distribution, he concluded that mean annual, full-glacial temperatures in the western Great Basin were at least 5.5 °C less than present. If winter precipitation amounts were not significantly higher than present amounts, then the temperature difference would be closer to 7 °C (Dohrenwend, 1984).

At the latitude of our study area, the projected elevation of the full-glacial 0–1 °C isotherm is ~2,800 m, about 1,400 m above the summit of Yucca Mountain and 1,200 m above Skull Mountain (Dohrenwend, 1984, Fig. 6). Using the mean annual terrestrial lapse rates provided by Dohrenwend of 0.76 °C per 100 m for elevations above 2,000 m and 0.57 °C per 100 m below 2,000 m, we calculate that the full-glacial mean annual temperature at the top of Yucca Mountain was between 9 and 10 °C. This temperature compares favorably with Spaulding's minimum decline of 7 °C for the late Wisconsinan full-glacial mean annual temperature at the Nevada Test Site. The present mean annual temperature of Beatty, Nevada, is 15.3 °C (38 yr of record), and the mean annual temperature for the top of Yucca Mountain in 1988–1989 was nearly 16 °C. If we apply the late Wisconsinan, full-glacial temperature decline of 7 °C from Spaulding (1985), then the mean annual temperature at Yucca Mountain was about 10 °C, virtually the same temperature projected from the position of the late Wisconsinan 0–1 °C isotherm calculated by Dohrenwend (1984).

The absence of colluvial boulder deposits with young rock-varnish coatings on hillslopes in the study area strongly suggests that boulder deposits did not form during the last glacial episode. Thus, mean annual temperatures below about 10 °C are probably required to initiate the frost-wedging processes necessary for boulder production. If precipitation amounts during these earlier glacial episodes were significantly higher than during the last glacial, then these temperature depressions would be somewhat less (Porter, 1977). Because the full range of nivation features are not found on Yucca or Skull Mountains, we believe that mean annual temperatures necessary for the formation of colluvial boulder deposits were clearly higher than those for active nivation.

Colluvial boulder deposits do not provide any paleotemperature information about full-glacial summers, which prevents us from suggesting a mean annual temperature that can be related to the formation of these deposits. They do, however, provide insight about winter temperatures necessary to produce moderate volumes of medium-to-large boulders. Effective freeze-thaw cycles of boulder production require minimum temperatures of −3 to −5 °C (Lautridou, 1971; McGreevey and Whalley, 1982). We suggest that the colluvial boulder deposits in this study were produced during full glacial winters with a minimum monthly temperature at least this low. The present minimum monthly temperature is about 4 °C on Yucca Mountain, about 7 to 9 °C warmer than the winter temperatures necessary to physically weather boulders out of the local volcanic ridges. Thus, early and middle Quaternary glacial winters were at least 1 to 3 °C colder than the 6 °C winter temperature depression calculated by Spaulding (1985) for the last Quaternary glacial.

Evidence for colder, and possibly wetter, glacial conditions during the early and middle Pleistocene is also found in nearby basins. Hillhouse (1987) estimated that former Lake Tecopa, located about 70 mi south of Yucca Mountain, existed until about 450 ka before it desiccated. Searles Lake in the Owens River drainage also exhibited a marked increase in aridity about a half million years ago (Smith and others, 1983). Part, but probably not all, of this increase in aridity may be attributed to the uplift in the Sierra Nevada and Transverse Ranges (Winograd and others, 1985). Sarna-Wojcicki and others (1987) also found increased pluvial conditions during the early-middle Pleistocene in central and southern California basins such as in the southern San Joaquin Valley.

The upper part of the present matrix in colluvial boulder deposits is much younger than the rock varnish on the surface of the bouldery colluvium. The thermoluminescence-dated samples indicate that dry, windy conditions began soon after the last glacial maximum and continued into late Holocene time. This increase in eolian activity correlates with an increase in xeric vegetation around the Nevada Test Site and in the Amargosa Desert (Spaulding, 1985).

Eolian activity in the Mojave Desert is commonly associated with interpluvial climates (McFadden and others, 1986), and multiple episodes of middle Pleistocene dune activity have been recorded in large sand ramps in the Amargosa Desert (Whitney and others, 1985). We suggest that these interpluvial climates episodically supplied the fine-grained sand and silt to southern Nevada hillslopes during the Quaternary, and that these sediments became the matrix necessary to facilitate downslope creep of the boulder deposits.

The primary colluvial process on the present hillslopes is debris-flow activity (U.S. Dept. of Energy, 1988). Isolated debris flows occur during infrequent, high-intensity, short-duration thunderstorms on the sparsely vegetated hillslopes. Modern debris-flow activity does not appear to be effective in eroding or removing well-varnished, stabilized colluvial boulder deposits, because debris flows are commonly confined to present hillslope channels between the topographically inverted boulder deposits. Continued channel erosion enhances the topographic inversion of the older colluvial boulder deposits and increases their stability.

We suggest that full glacial climates were times of sediment storage on hillslopes in southern Nevada with relatively little material being delivered to the basin floor. In contrast, interglacial episodes of debris-flow activity resulted in hillslope stripping, active fan aggradation, and rapid delivery of these sediments to the basin floors. Similar models of hillslope development have been proposed by Gerson (1982) for the arid Negev Desert, by Bull (1986, 1991) for southern California, and by Mills (1981, 1987) for the southern Appalachians.

IMPLICATIONS FOR LONG-TERM EROSION

Strong varnish development is commonly found on bedrock outcrops on the top of Yucca and Skull Mountains and on other ridges in the area. Dark rock varnish has accumulated on these surfaces over at least several tens of thousands of years and at some outcrops probably over 100,000 yr. Although bedrock outcrops were not dated in this study, the dark rock varnish indicates that little physical weathering had taken place on these ridges during late Quaternary time. The paucity of rock weathering and the preservation of early and middle Quaternary colluvial boulder deposits on the present slopes indicate the relative ineffectiveness of erosional processes during the late Quaternary. Furthermore, these deposits are thin and lie only 0.5–2.0 m above modern hillslope channels. Although short-term erosion rates may be locally high for isolated slopes that have undergone intense thunderstorms, the long-term rates of sediment removal off hillslopes in the northern Mojave Desert region of the Great Basin are extremely low.

Rates of hillslope erosion are related to local relief, climate, and lithostratigraphy. Slope retreat in the similar dry, semiarid climates of Israel and Kenya, however, is significantly more rapid than on the fine-grained volcanic slopes of the southern Great Basin. Gerson (1982) estimated that slope retreat in Israel ranges from 1–6 m/ka on slopes underlain by limestone, dolomite, igneous, and metamorphic rocks. In northern Kenya, Frostick and Reid (1982) calculated a slope retreat of 2 m/ka on hills and escarpments composed of lacustrine sediments capped by a resistant gravel deposit. Oberlander (1972), however, calculated a long-term degradation rate 0.001–0.008 m/ka on granitic rock in the southern Mojave Desert.

Hillslope evolution on southern Great Basin volcanic hillslopes has been remarkably slow. General hillslope degradation on Yucca and Skull Mountain is less than 1 m below colluvial boulder deposits that range from 170 ka to more than a million years old. The overall degradation on these slopes is less than 0.008 m/ka (Harrington and Whitney, 1991), which is more than two orders of magnitude lower than rates measured in Israel, Kenya, and the mountains of California, but comparable to erosion rates measured in the southern Mojave Desert. The higher degradation rates in the Sierra Nevada foothills and the White Mountains are due to the erosional processes accelerated by Mediterranean and subalpine environments and to active uplift during the Quaternary. By comparison, the low degradation rate on Yucca and Skull Mountains is a reflection of a drier climate, the slow weathering of welded ash-flow tuff, and lower rates of Quaternary tectonic activity (Scott, 1990).

SUMMARY

The rock-varnish ages of ten stabilized hillslope deposits indicate that boulder production, talus mantle creep, and hillslope stabilization occurred during several episodes between about 1.4 Ma and 170 ka. During the latest Pleistocene glacial episode, however, where the mean annual temperature was about 6–7 °C lower than present temperatures, insignificant amounts of coarse bouldery debris were weathered from bedrock ridges in the Yucca Mountain region. We conclude that a winter minimum monthly temperature −3 to −5 °C was necessary to initiate freeze-thaw conditions of enough rigor to produce relatively large volumes of coarse boulders. These climatic conditions suggest that some early to middle Pleistocene glacial periods were characterized by winter monthly temperatures more than 7 to 9 °C colder than present and 1 to 3 °C colder than the last full glacial period in southern Nevada.

Thermoluminescence analyses indicate that the upper part of the matrix from two colluvial boulder deposits accumulated during late Pleistocene and Holocene time. The presence of this young silty sand matrix indicates that eolian sediment has been deflated from nearby basin floors during interpluvial climates and deposited on adjacent hillslopes. Earlier eolian episodes may have contributed fine-grained sediments to the matrix that is, in places, cemented by calcium carbonate at or near the base of the older colluvial boulder deposits.

The preservation of early and middle Pleistocene hillslope deposits indicates low long-term erosion rates on resistant volcanic hillslopes in the southern Great Basin. The long-term general degradation rates on these hillslopes is about 0.01 m/ka, and the maximum incision rate by hillslope channels is only 0.02 m/ka. Several conditions contribute to these low erosion rates: (1) hillslope bedrock and boulders composed of fine-grained volcanic rocks that are relatively unsusceptible to weathering in dry climates, (2) insufficient runoff during interpluvial climates to remove bouldery hillslope colluvium, and (3) a topography little affected by Quaternary tectonic activity.

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