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YUCCA MOUNTAIN

YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT

TOPICAL REPORT

EVALUATION OF THE POTENTIALLY ADVERSE CONDITION "EVIDENCE OF EXTREME EROSION DURING THE QUATERNARY PERIOD" AT YUCCA MOUNTAIN, NEVADA

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UNITED STATES DEPARTMENT OF ENERGY

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ABSTRACT

The potentially adverse condition identified at 10 CFR 60.122(c)(16), evidence of extreme erosion during the Quaternary Period, has been determined to not be present at Yucca Mountain. A literature search for typical hillslope erosion rates in the U.S. and the world was performed to establish a range of typical values for erosion rates. Low to moderate erosion rates in the U.S. were identified to range from 2 to 50 centimeters per thousand years (cm/ka) in semiarid environments. Long-term average hillslope erosion rates established for Yucca Mountain were determined to be 0.19 cm/ka. The Yucca Mountain rates were established utilizing cation ratio dating of rock varnish on colluvial boulder deposits to establish age control and by measuring hillslope denudation and hillslope channel incision marginal to these boulder deposits. The geologic record examined for Yucca Mountain area hillslopes extend from 170 ka to about 1400 ka, and represents the longest geologic record obtained to date from hillslopes in the southwestern United States. Based upon a comparative evaluation of Yucca Mountain hillslope erosion with erosion rates in other analogous geologic and climatic regimes, DOE has concluded that consistent with NRC staff use and in keeping with the plain meaning of the term extreme, extreme erosion has not occurred at Yucca Mountain during the Quaternary Period. Therefore, the potentially adverse condition of evidence of extreme erosion during the Quaternary Period identified at 10 CFR 60.122(c)(16) does not exist at Yucca Mountain.

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GLOSSARY OF ACRONYMS

CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
ka	thousand years ago
LANL	Los Alamos National Laboratory
Ma	million years ago
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
QA	quality assurance
QARD	Quality Assurance Requirements Document
SCP	Site Characterization Plan
SEM	scanning electron microscope
SSQ	standardless semi-quantitative
USGS	U.S. Geological Survey
VCR	varnish cation ratio
YMP	Yucca Mountain Site Characterization Project

EXECUTIVE SUMMARY

This report addresses the provision at Title 10 of the Code of Federal Regulations Part 60.122(c)(16) to determine whether the potentially adverse condition of extreme erosion has existed at Yucca Mountain during the Quaternary Period. This report concludes that there is no evidence of extreme erosion at Yucca Mountain during the Quaternary Period and that the potentially adverse condition of extreme erosion as identified at 10 CFR 60.122(c)(16) does not exist at Yucca Mountain.

The conclusions in this report are based on a Regulatory Evaluation and a Technical Evaluation. The Regulatory Evaluation identifies the specific requirements addressed in the report and establishes the regulatory boundaries for the Technical Evaluation. The regulatory conclusion draws upon the Regulatory Evaluation and the Technical Evaluation to reach the conclusion. The Regulatory Evaluation establishes a time period of the most recent 1.6 million years as bounding the Quaternary Period. In determining whether there is evidence of extreme erosion at Yucca Mountain during the Quaternary Period, a comparative geologic evaluation of hillslope erosion rates at the site and erosion rates in analogous semiarid climatic regimes in accordance with both NRC staff use and the plain meaning of the term extreme is used to assess the presence of extreme erosion at the Yucca Mountain site.

The Technical Evaluation provides a detailed assessment of the scientific studies conducted to characterize and quantify hillslope erosion rates in the Yucca Mountain area and to determine average incision rates in Fortymile Wash and its tributaries and compares these rates to erosion rates in other geologic and climatic settings in the United States and the world. This comparison is used to establish whether the erosion rates at and in the vicinity of Yucca Mountain are considered extreme. Low to moderate rates of hillslope erosion for the U.S. were identified to range from 2 to 50 centimeters per thousand years (cm/ka) in several areas including semiarid environments in Texas, New Mexico, Idaho and California. Very low rates of erosion (less than 2 cm/ka) were documented for the Mojave Desert in California. The long term average hillslope erosion rate established for Yucca Mountain was 0.19 cm/ka. This rate was established by measuring the amount of hillslope channel incision and hillslope denudation marginal to hillslope boulder deposits. The time of deposition of the boulder deposits was dated using cation ratio dating of rock varnish on the surface of the boulders. The boulder deposits provided the age control for establishing the erosion rates for the hillslopes. The hillslope erosion rates established for Yucca Mountain are among the lowest rates found in the U.S. and are reasonable considering the rock type at Yucca Mountain and the climate that has existed at Yucca Mountain during the Quaternary Period. DOE concludes that the low rates of erosion at Yucca Mountain, when compared to other analogous geologic and climatic regimes in the U.S. and the world, are not extreme. Therefore, the associated potentially adverse condition identified in 10 CFR §60.122(c)(16) does not exist at Yucca Mountain and is no longer considered a potentially adverse condition at Yucca Mountain.

1.0 INTRODUCTION

The purpose of this Topical Report is to assess whether the potentially adverse condition, evidence of extreme erosion during the Quaternary Period, is present. This condition is found at 10 CFR §60.122(c)(16). The conclusions found in this report are based upon analyses contained in both the Regulatory Evaluation and Technical Evaluation sections.

The Regulatory Evaluation section provides a detailed assessment of the regulatory requirements associated with the determination of whether a potentially adverse condition exists. It also provides the regulatory requirements associated with the evaluation of the specific potentially adverse condition addressed in this Topical Report. The Technical Evaluation section provides a detailed assessment of the scientific studies conducted to characterize and quantify the erosion rates in the Yucca Mountain area and compares these rates to erosion rates in other geologic and climatic settings in the United States and the world.

2.0 REGULATORY EVALUATION

2.1 Current Regulatory Requirements

The applicable NRC regulatory requirements for the disposal of high-level radioactive wastes in geologic repositories are found in 10 CFR Part 60. Subpart E to Part 60 addresses the technical criteria which will support a finding that the issuance of a license to receive and possess high-level waste will not constitute an unreasonable risk to the health and safety of the public, given the uncertainty involved in such a determination. Additionally, Subpart E identifies performance objectives and siting and design criteria which, if satisfied, will support a finding of no unreasonable risk.

The siting criteria referred to above are identified at 10 CFR §60.122, which provides that favorable conditions associated with the geologic setting, together with the engineered barrier system, must provide reasonable assurance that the performance objectives relating to waste isolation will be met. In addition, this section also addresses the concern that if specifically identified potentially adverse conditions are present, then the ability of the repository to meet its performance objectives may be compromised. The potentially adverse conditions of concern are identified in §60.122(c).

2.2 Regulatory Evaluation of Potentially Adverse Condition, "Evidence of Extreme Erosion During the Quaternary Period"

The potentially adverse condition of evidence of extreme erosion during the Quaternary Period is found at 10 CFR §60.122(c)(16). The evaluation of a potentially adverse condition involves a two-step process. First, there must be an initial assessment of whether the given condition in fact exists. If the condition is not present, then the investigation is concluded and documented. However, if the condition is present, then an evaluation of the ability of the repository to meet its performance objectives must be conducted, taking into account whether the condition (1) is significant, (2) is compensated by other favorable conditions, or (3) can be remedied. Thus, as applied to extreme erosion, an assessment of this potentially adverse condition must address the existence of two coincident events: (1) the erosion at Yucca Mountain must have been "extreme" and (2) the extreme erosion must have occurred "during" the Quaternary Period.

Although the term "extreme erosion" is undefined in the Nuclear Waste Policy Act of 1982, as amended (NWPA) or in 10 CFR Part 60, the NRC Staff has provided guidance as to its meaning in response to an inquiry as to the definition of the term.[1] We note this guidance

[1] In the Staff Analysis of Public Comments on Proposed Rule 10 C.F.R. Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories, Office of Nuclear Regulatory Research, NUREG-0804, (NRC,1983), the Staff responded to a request to clarify the term and stated: "The staff has used the term 'extreme erosion'

also is generally consistent with the plain meaning of the term "extreme". That is, something at the far end of the range; exceeding the ordinary, usual or expected; extending far beyond the norm; or of the greatest severity. Thus DOE agrees with the NRC Staff concept of extreme erosion as stated in NUREG-0804 which refers to the occurrence of substantial changes in land forms (as a result of erosion) over relative short intervals of time. A determination of the existence of extreme erosion for the Yucca Mountain area is based on a comparative geologic evaluation of erosion rates in general and erosion rates in analogous semiarid climatic regimes. This evaluation is presented in the Technical Evaluation section of this report (Section 3.0).

There is some disagreement in the geologic community as to the precise beginning of the Quaternary Period. DOE has chosen to use a time period of the most recent 1.6 million years (Ma) to bound the Quaternary Period. This time period was chosen because it is the time period published and supported by the Geological Society of America (Palmer, 1983). Key dates for the Quaternary Period are presented in Table 1.

The exact date of onset of the Quaternary Period is not considered by DOE to be critical for evaluating extreme erosion so long as the geologic record is consistent and substantially complete for the more recent geologic time period. DOE believes that the more recent geologic past is a better indicator of possible future activity than the distant geologic past, and that in performing an evaluation of potential future activity and the effect such activity can have on a repository, a sufficient data base must be established to make the various projections. Furthermore, DOE believes that the reference to the Quaternary Period was intended to imply a concept related to the sufficiency of the geologic record to be used for projecting natural processes and events during the intended period of performance rather than a specified time interval. This position fits well within the regulatory framework articulated by the NRC where it addressed this very issue and stated that:

> The references to "the start of the Quaternary Period" have been removed because of the difficulties that might be involved in dating this point with precision; for present purposes, all that is important is that processes "operating during the Quaternary Period" be identified and evaluated, and this is reflected in the revised language.[2]

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to refer to the occurrence of substantial changes in land forms (as a result of erosion) over relatively short intervals of time." (emphasis added).

[2] 48 Fed. Reg. at 28,211 (June 21, 1983), This revision conformed the assessment of a favorable geomorphic condition in §60.122(b)(1) to a corresponding potentially adverse condition such as extreme erosion in §60.122(c)(16) so that both were consistent in their assessment of effects during the Quaternary Period.

Thus, the Regulatory Evaluation herein and NRC's administrative record are consistent that the only important issue is whether a given process, in this case extreme erosion, has occurred during the Quaternary Period, and that such a record is sufficient and reflective of what could be expected throughout the entire period.

This topical report provides evidence that DOE possesses an understanding of the processes and events that have occurred within the more recent geologic past within the geologic setting, and uses this understanding to make reasonable and conservative projections about the potential processes and events that could affect a geologic repository. Therefore, the data which have been gathered that embody a period of about 0.17 to 1.38 Ma at the Yucca Mountain area are considered to be sufficient and adequate to characterize the extent of erosional processes operating during the Quaternary Period. The boulder deposits analyzed in this report are the oldest landscape features that have been dated in the Yucca Mountain area and provide significant insight into the geomorphic processes that have acted upon the Yucca Mountain area during the Quaternary Period.

2.3 Regulatory Evaluation Conclusion

DOE concludes that the erosion rates in the Yucca Mountain area and the Yucca Mountain site are not extreme. Therefore, the associated potentially adverse condition identified at 10 CFR §60.122(c)(16) does not exist at Yucca Mountain and is no longer considered a potentially adverse condition.

The Technical Evaluation (Section 3.0) explains how this conclusion was reached and identifies how erosional rates in the Yucca Mountain area have been characterized and quantified. The data presented reflect the extent of the erosional processes acting in the vicinity of Yucca Mountain during the Quaternary Period. This section also summarizes the results of a literature search of erosion rates in the United States and the world for a number of rock types, including volcanic tuff, the rock type found at Yucca Mountain. Low to moderate hillslope erosion rates for the U.S. were identified to range from 2 to 50 cm/ka in several areas in the U.S. including semiarid environments in Texas, New Mexico, Idaho, and California. Very low rates of erosion (less than 2 cm/ka) were documented for the Mojave Desert in California. The literature search indicates that tuff is generally resistant to erosion, particularly in semiarid to arid regions such as the southwest U.S. where Yucca Mountain is located, and falls within the low range of erosion rates for all rock types. The Technical Evaluation section presents a detailed on-site assessment of erosion rates in the Yucca Mountain area and concludes that erosion at Yucca Mountain was very low during the Quaternary Period even within the geologic and climatic conditions which exist for similar areas. The long-term average hillslope erosion rate established for Yucca Mountain area was 0.19 centimeters per thousand years (cm/ka). The long-term incision rate for the first-order streams that cut several small canyons located above the repository block at Yucca Mountain is 0.8 cm/ka or less. The hillslope erosion rates calculated in this report are based on rock varnish surface exposure ages of stable colluvial boulder fields on hillslopes. This calculation is considered conservative because the rock varnish dating provides only a minimum age for

Table 1

DIVISIONS OF THE QUATERNARY AND THEIR BOUNDARY DATES *

YEARS AGO	PERIOD		EPOCH
	Quaternary	Late Quaternary	Holocene
10ka	Quaternary	Late Quaternary	Pleistocene
~ 128ka	Quaternary	Middle Quaternary	Pleistocene
~ 760ka	Quaternary	Early Quaternary	Pleistocene
~ 1.6Ma	Tertiary	Neogene	Pliocene

* Quaternary divisions and dates from Morrison (1991) and Palmer (1983)

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the boulder deposit. Using the age of the rock varnish as a proxy for the age of the boulder, therefore, will result in underestimating the time over which the process has been operative. Therefore, the calculated erosion rates in this topical report are somewhat overestimated.

3.0 TECHNICAL EVALUATION

3.1 Introduction

The purpose of this technical section is to characterize and quantify, within and adjacent to the controlled area of the Yucca Mountain site, the extent of hillslope erosion during the Quaternary Period and to comparatively evaluate that hillslope erosion rate with typical rates in the U.S. and around the world. This evaluation entails two parts. First, a survey of erosion rates for studies of areas around the world (Table 2) and within the U.S. (Table 3) is presented so that erosion rates for the Yucca Mountain area can be compared to the range of typical erosion rates from other areas. This survey incorporates studies that were performed, both under a variety of climatic conditions and for a variety of rock types. The climatic regions encompassed in the survey range from humid to arid, including dry semi-arid localities with conditions similar to the Yucca Mountain area. As detailed below, the survey also identifies a range of typical erosion rates for a variety of geologic conditions ranging from areas with erosionally nonresistant, unconsolidated materials to areas comprised of erosionally resistant rock types, including tuff, which is the type of rock that dominates the Yucca Mountain topography. The second part of this evaluation entails the determination of site specific erosion rates at Yucca Mountain and within the Yucca Mountain area.

The discussion of the assessment of erosion rates in the Yucca Mountain area includes: (1) the approach for assessing erosion rates; (2) a description of the Quaternary geologic record contained within the surficial deposits of the Yucca Mountain area; (3) the rationale for using hillslope boulder deposits to determine long-term erosion rates on Yucca Mountain area hillslopes, and using stream valley terraces to obtain long-term downcutting rates in stream valleys within the controlled area; and (4) a comparison of these long-term erosion rates to erosion rates for other areas of the U.S. and areas with similar climates on a global basis, including areas that possess both similar climatic conditions and rock types of similar erosional resistance to that occurring at Yucca Mountain.

This technical evaluation references published Yucca Mountain Site Characterization Project (YMP) data and interpretations and the extant literature. It also contains data and/or interpretations published for the first time. These data are used in the Regulatory Evaluation (Section 2.0) to demonstrate that within and adjacent to the controlled area for the Yucca Mountain site, there is no evidence of extreme erosion during the Quaternary Period and the potentially adverse condition does not exist.

3.2 Evaluation of Degradation Rates Around the World

The rate of erosion varies greatly over the face of the earth. Erosion rates are primarily influenced by three factors: climate, relief and rock type. Climate governs the chemical and physical weathering processes in each region that are responsible for weathering bedrock and transporting it to basin floors and into the ocean. Relief is a general indicator of the kinds and rates of tectonic activity in a region and thus reflects the potential energy available for surface erosional processes that are dependent on gravitational forces. Different rock types resist weathering and erosion at dissimilar rates because of differences in chemistry, mineralogy, internal structure and cementation. The great differences in kinds of bedrock exposed in varied tectonic terrains under the climates that range from desert to glacier to tropical rain forests account for the incredibly varied landscapes around the world.

The relationship between climate and erosion is well known because sediment data have been collected from streams and reservoirs around the world. In general, sediment yield and erosion is at a maximum in environments with 10 to 14 inches of precipitation, and these rates decrease sharply on both sides of this maximum (Langbein and Schumm, 1958). As precipitation increases, erosion of surficial weathered material retards because of increases in vegetation density. As the climate becomes drier, decreases in erosion are due to lack of effective surface water runoff.

An unseen factor in erosion rates is time. Both climates and rates of tectonism change over time, which, in turn, results in variations in erosion rates over time. Thus, any erosion rate must be examined in light of the time period over which erosion has taken place. Long-term erosion rates average a range of erosion rates that took place during several cycles of climate change and perhaps even through changes in rates of tectonic activity. Short-term erosion rates measure the present rate of an erosion process that can be related to the present climate and tectonic environment. Short-term rates may be lesser or greater than the long-term rate of a region, depending upon how great are the climate fluctuations in a given region over time. On Yucca Mountain, for example, a short-term hillslope erosion rate on one slope may be high due to measurements after a single storm. However, if similar measurements are made on a different slope unaffected by the same storm, the short-term erosion rates will be lower than the long-term average. For this reason, published erosion rates based on short periods of time, or individual events, are not included in Tables 2 and 3 below, that present erosion rates in a variety of environments in the U.S. and around the world. Examples of erosion rates in a variety of climatic environments are also given on Tables 2 and 3.

Denudation, the rate of lowering of the earth's surface, on each continent has been compared on the basis of solid and dissolved loads carried by major rivers to the oceans (Ritter, 1986, p. 203). Total denudation in Australia is the lowest of all continents at about 1 cm/ka. Africa is about 2 cm/ka, Europe is about 3 cm/ka, North and South America are both about 4 cm/ka, and Asia has the highest denudation rate at 14 cm/ka. The high rate of denudation in Asia is due to several factors, including the effects of high density populations and active uplift of some of the world's highest mountain ranges. Worldwide denudation rates, calculated by several methods, range from 2.4 to 8.4 cm/ka (Young, 1972). In the United States, denudation rates fall between 2.5 and 15 cm/ka for most drainage basins (Ritter, 1986, and Chorley et al., 1984). Thus, long-term erosion rates that fall between 2 and 15 cm/ka can be viewed as typical or normal rates of erosion for areas in the United States.

Table 2

Degradation Rates from Areas Around the World

REGION -- WORLD[a]	BEDROCK	CLIMATE	DEGRADATION RATE[b]	REFERENCE
Southern Israel	Limestone, igneous, & metamorphic	Semiarid-arid	100-600 cm/ka	Gerson, 1982
Norway	Gneiss	Subarctic	100-300 cm/ka [c]	Nesje et al., 1992
Kenya	Lacustrine deposits capped by gravels	Semiarid-arid	200 cm/ka	Frostick & Reid, 1982
Germany	Complex geologic terrain	Temperate	60 - 90 cm/ka	Ahnert (in Yair & Gerson, 1983)
Japan	Varied	Varied	33 cm/ka	Ohmori, 1983
Israel	Limestone, Dolomite	Arid	10 - 40 cm/ka	Yair & Gerson, 1983
Spitsbergen	Sandstone, limestone, cherts	Arctic	2-50 cm/ka	Rapp, 1960
Sweden	Mica schists, phyllites, limestones	Alpine	1 - 10 cm/ka	Rapp, 1957
Canada	Dolomite	Periglacial	1-10 cm/ka	Gray, 1972
Canada	Igneous	Moist continental	2 cm/ka	Pearce and Elson, 1973
Kenya	Sandy clay soils	Semiarid	0.84 - 7.9 cm/ka	Dunne et al., 1979
Australia	Shield, complex geology	Semi-arid	0.3 cm/ka [d]	Bishop, 1985
Australia	Shield, complex geology	Semiarid	0-0.2 cm/ka	Gale, 1992

a Data points exclude U.S. rates
b Erosion rates from authors have been converted to common units of cm/ka for consistency.
c Quaternary glacial erosion
d Tertiary rate

Table 3

Degradation Rates from Areas Within the U.S.

REGION -- USA	BEDROCK	CLIMATE	DEGRADATION RATE[a]	REFERENCE
Texas	Shale, sandstone, siltstones underlain by salt	Semiarid to subhumid	Scarp retreat 6000-8000 cm/ka	Gustavson & Simpkins, 1989
			Slope lowering 400-600 cm/ka	
Idaho	Granite (Quartz monzonite)	Mediterranean	1100 cm/ka	Megahan et al., 1983
Maxey, Kentucky	Shale	Temperate	192 - 316 cm/ka	Hupp & Carey, 1990
Colorado Plateau (Utah, Colorado, Arizona)	Sandstone caprocks	Semiarid	50 to 670 cm/ka	Schmidt, 1989
Piceance Basin, Colorado	Shale, sandstone	Semiarid	56-118 cm/ka [b,c]	Carrara & Carroll, 1979
Grand Canyon, Arizona	Limestone (Redwall Ls.)	Semiarid	18-72 cm/ka (Avg. 45 cm/ka)	Cole & Mayer, 1982
White Mountains California	Dolomite	Dry subalpine	24.4-36.6 cm/ka [c]	LaMarche, Jr., 1968
Central Idaho	Unconsolidated alluvial fan deposits	Semiarid	South-facing slopes 24 cm/ka	Pierce & Colman, 1986
			North-facing slopes 9 cm/ka	
East Texas	Limestone; marls & clay; fluvial & shallow marine sediment	Semiarid	4.4-16.9 cm/ka	Collins, 1982
			1.18-38.9 cm/ka	
Cima volcanic field, Southern California	Mostly quartz monzonite, some terrigenous clastics	Semiarid	0.9-46 cm/ka	Dohrenwend et al., 1984

REGION -- USA	BEDROCK	CLIMATE	DEGRADATION RATE[a]	REFERENCE
Española Basin, New Mexico	Sandstone; tuff & gravel; tuff & basalt	Semiarid	Sandstone 10 cm/ka Tuff & gravel <7 cm/ka Tuff & basalt ~4 cm/ka	Dethier et al., 1988
Oregon Coast	Sandstone	~ 2300 mm/yr precipitation - wet coastal forest	7 cm/ka (for last 4-15 ka)	Reneau & Dietrich, 1991
Washington	Tertiary sandstones, siltstones, and conglomerates	Moist, humid	4.5 - 5.0 cm/ka	Reneau et al., 1989
Sierra Nevada foothills	Granodiorite, metasediments	Mediterranean	4.3 cm/ka	Helley, 1966
Pennsylvania	Diverse	Temperate	2.7 cm/ka	Sevon, 1989
Cima volcanic field, California	Basalt	Semiarid	2.25 cm/ka	Dohrenwend et al., 1986
White Mountains, California	Dolomite & quartz monzonite	Dry subalpine	1-3 cm/ka [d]	Marchand, 1971
New Mexico	Volcanic tuff	Semiarid	1.8-2.8 cm/ka	Poths & Goff, 1990
Hawaii	Basalt	Subtropical	0.7-1.1 cm/ka	Kurz, 1986
Idaho	Quartz monzonite	Mediterranean Dry summers; cool, moist winters	.8 - .9 cm/ka	Clayton & Megahan, 1986
Mojave Desert, California	Granite	Arid	<0.8 cm/ka [d]	Oberlander, 1972 and 1974
Whole USA	Varied	Varied	2.5-15 cm/ka	Ritter, 1986

a Erosion rates from authors have been converted to common units of cm/ka for consistency.
b Rate was 220-330 mm/ka before cattle were introduced to the basin
c Short-term rate
d Long-term rate

Erosion rates for a variety of climatic environments around the world are given in Table 2. High rates of erosion occur in glacial environments (100-300 cm/ka), and moderate rates (10-90 cm/ka, the majority of rates in this table) can occur in any climate if a combination of bedrock type and relief is conducive to weathering. Low rates of erosion occur in Australia primarily because of low relief and resistant rock types in the interior of the Australian continent. The two studies from Kenya illustrate how diverse erosion rates (less than 8 cm/ka vs. 200 cm/ka) can be in regions underlain by different bedrock under similar climatic conditions.

Variations in typical erosion rates in the U.S. (Table 3) are similar to the range recorded for different global environments. High rates of denudation are observed in areas underlain by weak bedrock such as salt in Texas (6,000-8000 cm/ka), shale in Kentucky (192-316 cm/ka), and in shale (56-118 cm/ka) and sandstone in Colorado (50-670 cm/ka). Low and moderate rates of denudation (2-50 cm/ka) are recorded in diverse environments that include temperate Pennsylvania, moist Oregon coasts and Washington forests, semiarid environments in Texas, New Mexico, Idaho and California. Very low rates of erosion (less than 2 cm/ka) were measured in the Mojave Desert in California and on resistant basalt in Hawaii.

3.3 Yucca Mountain Erosion Rate Assessment

Yucca Mountain is located in a dry, semiarid environment and is underlain by erosionally resistant and within some units, welded volcanic tuff. Rates of erosion are thus anticipated to be in the low range of typical erosion rates measured in the U.S. Given the geologic and geomorphic data collected in the Yucca Mountain area, one would expect that Quaternary erosion rates on hillslopes of volcanic tuffs in the southern Great Basin has been very low.

The purpose of the erosion studies at Yucca Mountain was to determine the average long-term erosion rates on hillslopes within the Yucca Mountain area and to determine average incision rates by streams in Fortymile Wash and its tributaries overlying the repository block. Using the data gathered under these studies, a comparison is made to Quaternary erosion rates for other areas of the United States, including those with both similar rock types and with similar climatic conditions. This comparison demonstrates that erosion rates at Yucca Mountain are comparable to or lower than other published U.S. erosion rates. These low erosion rates result from a combination of the erosionally resistant welded tuffs that form the foundation of Yucca Mountain and the dry semi-arid climate that has existed in this region throughout much of the middle and late Quaternary. Furthermore, the Quaternary geologic record for the Yucca Mountain area yields no evidence of extreme erosion during the Quaternary Period.

To calculate the rate for any surficial process (e.g.; erosion rates on hillslopes or downcutting rates for stream valleys) two types of information must be obtained: (1) the age of a landscape feature or surface by using some Quaternary dating technique, and (2) the amount of work done by the process since the dated features were formed. To determine Quaternary average long-term erosion rates for Yucca Mountain hillslopes, hillslope deposits that consist of large boulders determined to be remnants of colluvium that covered the topographic lows on the hillslopes, such as paleochannels, were dated using the rock varnish cation ratio technique. The erosion that has occurred on these hillslopes since the time of formation of the hillslope boulder deposits was then determined by measuring the perpendicular distance from the surface of the boulder deposit to the present hillslope level. Two measurements were made: (1) the distance from the boulder deposit surface to the bottom of hillslope drainage channels that have been eroded to bedrock, marginal to the boulder deposit, to obtain long-term incision rates in hillslope channels (see measurement a, Fig. 12), and (2) the distance from the boulder deposit surface to the level of the present hillslope, 50 m to either side of the boulder deposit, to obtain long-term hillslope erosion rates (see measurement b, Fig 12).

Quaternary erosion rates at Yucca Mountain were determined utilizing the following approach:

1) Examine the available Quaternary geologic record for the Yucca Mountain area to establish the type and distribution of surficial deposits that existed on hillslopes on, and in the vicinity of Yucca Mountain during the Quaternary Period. (Section 3.3.1.1)

2) Interpret the early-to-middle Quaternary aged surficial hillslope deposits to establish paleoclimatic conditions that operated on early-to-middle Quaternary hillslopes and that formed the boulder deposits. (Sections 3.3.1.3 and 3.3.1.4)

3) Examine the effect of climate change and tectonics on the type and magnitude of erosional processes operating on hillslopes and drainage channels in the Yucca Mountain area. (Sections 3.3.1.2 and 3.3.1.5)

4) Establish the modern climatic conditions in the Yucca Mountain area and the resultant geomorphic processes that operate on the modern hillslopes, in order to understand the differences between modern and early to middle Quaternary climatic conditions. (Section 3.3.1.5)

5) Reconstruct the paleotopography of the hillslopes during the early and middle Quaternary using the dated boulder deposits for age control on the ancient hillslopes. (Section 3.3.1.5)

6) Date the rock varnish that forms on the surface of boulders in the early-to-middle Quaternary hillslope deposits. (Section 3.3.2.1 and 3.3.2.2)

7) Calculate the amount of erosion that has occurred on hillslopes during the Quaternary Period by measuring the depth of active hillslope channels marginal to dated boulder deposits and the average depth of hillslope degradation for 50 meters to either side of the dated deposit. (Section 3.3.3.1)

8) Determine the average long-term rate of erosion for Yucca Mountain and for area hillslopes by averaging the hillslope degradation rate calculated for each dated boulder deposit. (Section 3.3.3.1)

9) Calculate the amount of stream incision that has occurred along Fortymile Wash and its tributaries by measuring the distance between dated alluvial terraces formed during the middle to late Quaternary. (Section 3.3.3.4 and 3.3.3.5)

10) Compare long-term erosion rates on hillslopes for Yucca Mountain to areas of similar lithologic and climatic conditions within North America. (Section 3.3.3.2)

11) Determine whether erosion data for the Yucca Mountain area contain any evidence for "extreme" erosion during the Quaternary Period. (Section 3.5)

3.3.1 Physical Environment at Yucca Mountain

3.3.1.1 Geologic and Climatic Setting of Yucca Mountain

Yucca Mountain is situated in the southern part of the Great Basin(Figures 1 and 2). Generally defined, the Basin and Range province is that area of southwestern North America that is characterized by more or less regularly spaced subparallel mountain ranges and intervening alluviated basins formed by extensional faulting.

Yucca Mountain is part of the Cenozoic extended terrain in the southern Great Basin subprovince (Scott, 1990). It consists of a series of eastward-tilted structural blocks that are composed of fine-grained volcanic rocks, primarily welded tuffs, and are bounded by north-trending, high-angle, oblique faults that exhibit left-lateral motion (O'Neill et al., 1991).

The uplands of the Yucca Mountain area are composed of three general landform types: (1) ridge crests, (2) valley bottoms, and (3) the intervening hillslopes. Small cliffs exist mainly on the west side of ridges where the erosionally resistant Tiva Canyon Member of the Paintbrush Tuff outcrops. Bedrock outcrops are common on the upper slopes, particularly along free faces or small cliffs. Many hillslopes are discontinuously veneered with mantles of blocky talus, and wedges of poorly sorted colluvium cover lower hillslopes. Gullies locally cut these colluvial veneers and expose the underlying bedrock. The lower slopes also may be mantled with variable thicknesses of alluvial deposits, primarily poorly sorted alluvial fans. Locally, particularly along the flanks of Busted Butte and Fran Ridge, these lower slopes are deeply buried beneath wedge-shaped ramps of reworked eolian sand (DOE, 1988, p. 1-26).

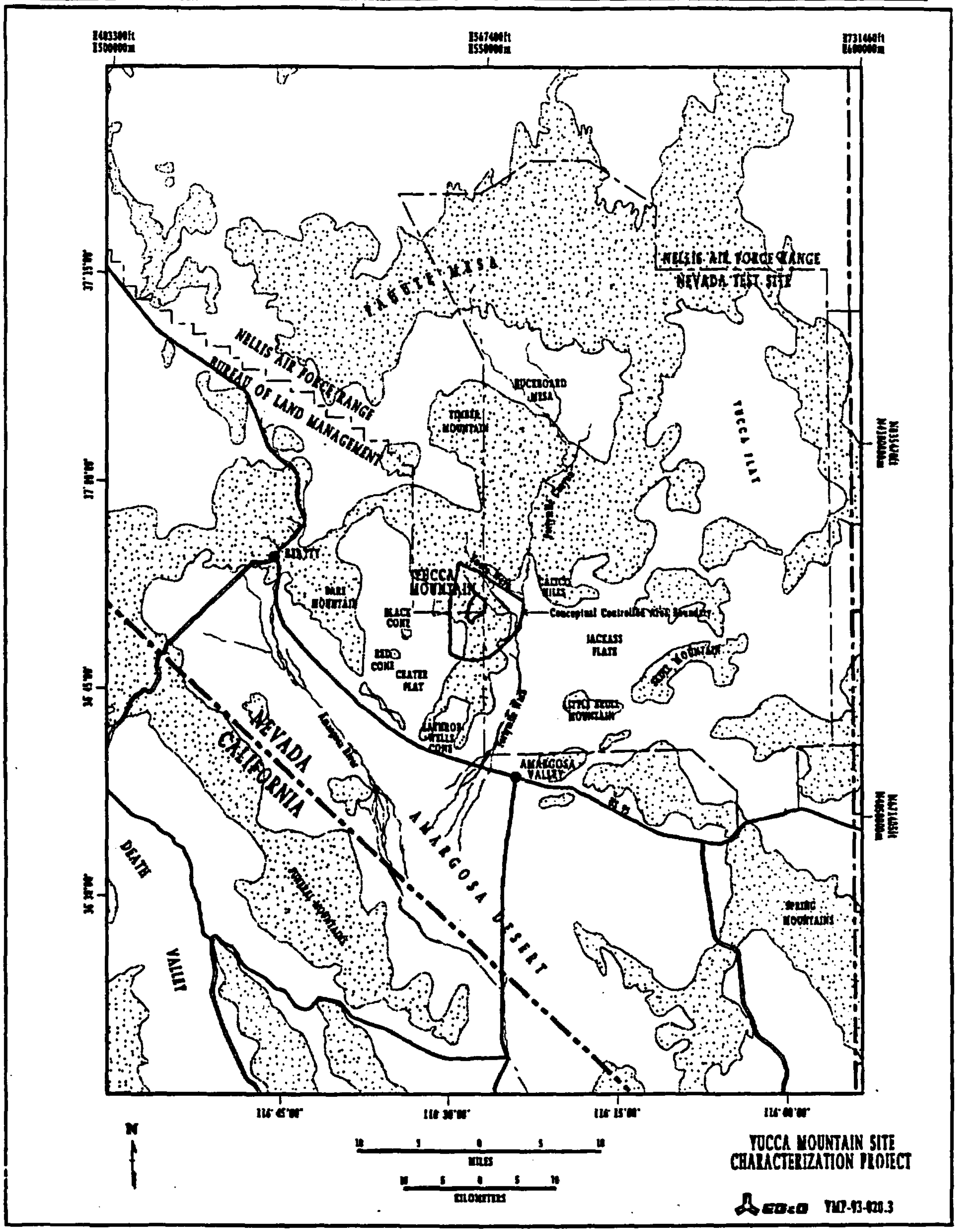

Figure 1. Map of the Yucca Mountain area depicting regional features. Yucca Mountain is situated in the southern part of the Great Basin, the northern most subprovince of the Basin and Range Province.

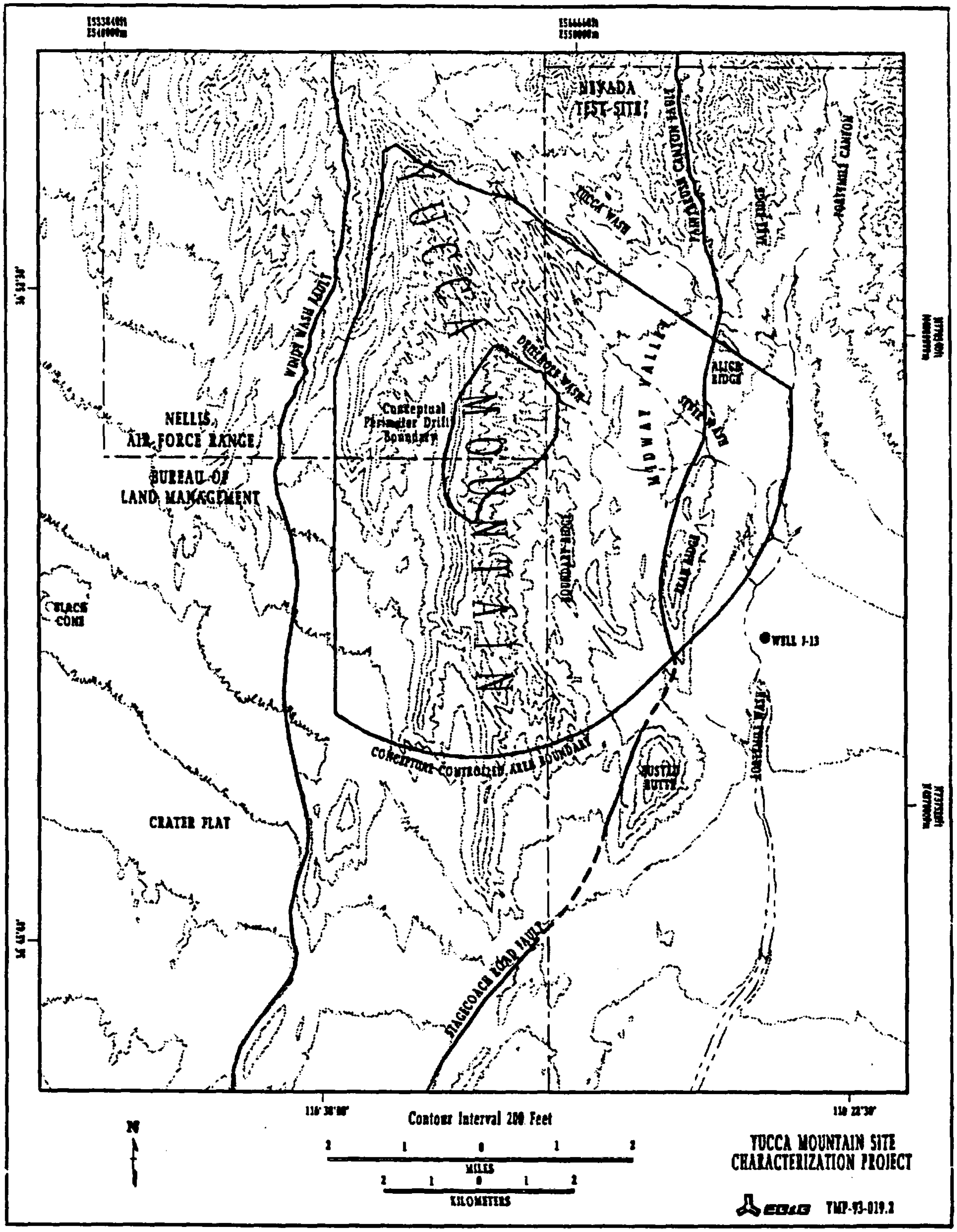

Figure 2. Map of Yucca Mountain depicting local features.

The open basins surrounding Yucca Mountain, including Crater Flat and Jackass Flats, are floored almost entirely by gentle piedmont slopes. These piedmonts are complex mosaics of dissected early to mid Quaternary surfaces juxtaposed against slightly dissected to undissected late Quaternary surfaces. Remnants of older surfaces are generally most common from the mid slopes to the base of hillslopes or along range fronts where they are typically dissected into a complex of ridges and washes. Ridges and interfluve ridges in this dissected terrain that are formed in the older, early to mid Quaternary deposits, are typically rounded and highly degraded, and the intervening washes are mostly steep sided and V-shaped. Intermediate piedmont slopes underlain by younger, late Quaternary deposits, are little dissected and individual depositional units are typically thin (less than a few meters thick). Thus, alluvial surfaces of all ages lie at approximately the same level and spatial relations among the various ages of surfaces and their associated deposits are commonly highly complex (DOE, 1988, p. 1-27).

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 (Figures 3 and 4).

Rock varnish is a natural veneer that in semi-arid to arid regions begins to coat the exposed rock surfaces as soon as they become stabilized and are no longer being moved or modified by processes operating on the hillslope. The age of rock varnish on these boulders represents the time since these deposits became stable features on the hillslope. Because these boulder deposits cover and preserve patches of the landscape that existed at the time of boulder deposit formation, these deposits can serve as the basis for reconstruction of the paleohillslope and they also provide a means for assessing the depth of erosion that has taken place on these hillslopes since deposition of the bouldery deposits occurred. Such an erosional assessment will incorporate all erosion that has occurred, regardless of the erosional process by which it happened.

The colluvial boulder deposits discussed in this report were studied on Skull, Little Skull and Yucca Mountains and on Buckboard Mesa, that are located on and adjacent to the Nevada Test Site (Figure 5). Skull Mountain is 1700 m in altitude and rises about 650 m above the adjacent basin floor of Jackass Flats. Yucca Mountain is somewhat lower with a summit elevation of about 1500 m and a local relief of more than 400 m. Each mountain is underlain primarily by Tertiary welded tuffs, although relatively thin Pliocene basalt flows cap the summits of Skull and Little Skull Mountains (Sargent and Stewart, 1971) and Buckboard Mesa (Byers, et al., 1976a and 1976b). These fine-grained volcanic rocks are widely distributed across the Great Basin and are very resistant to weathering in semiarid climates (DOE, 1988, Figure 1-28).

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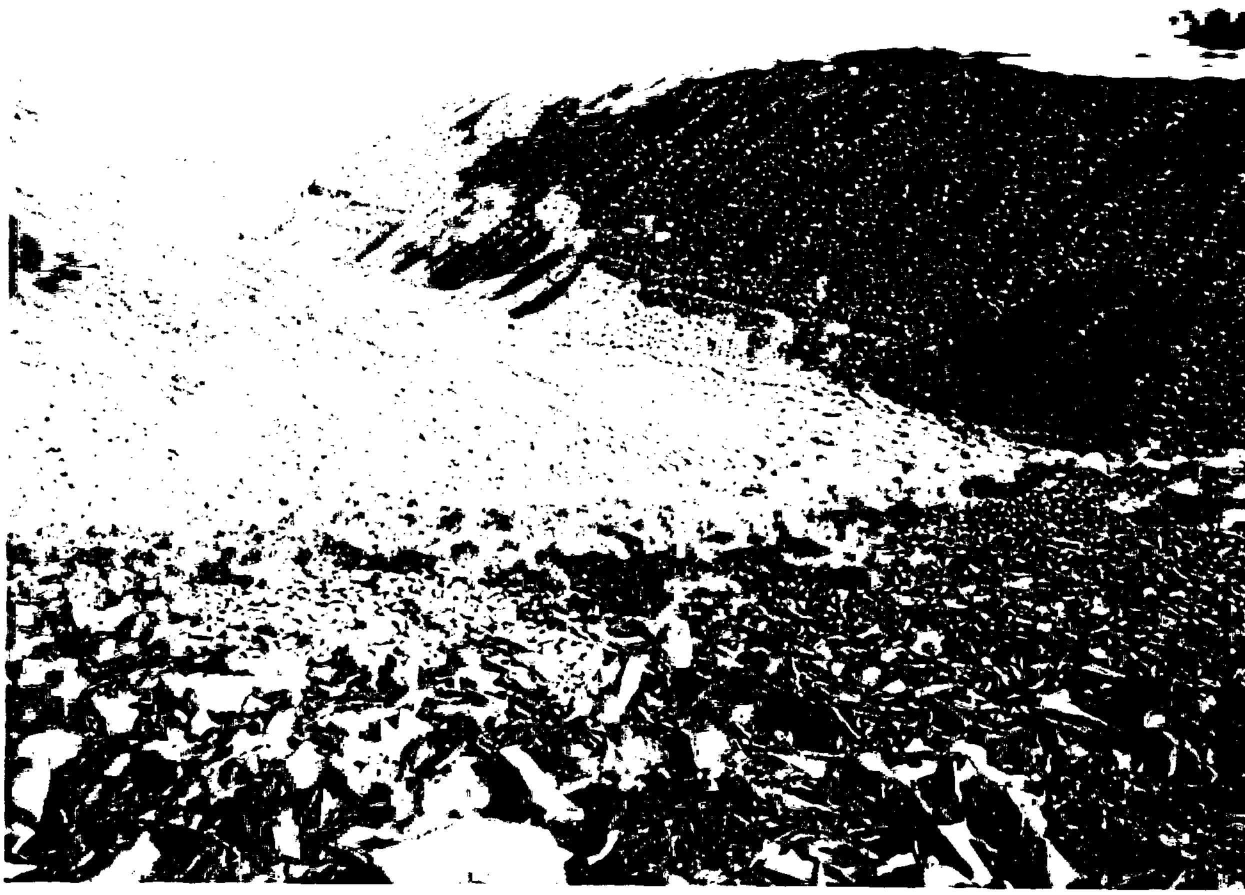

Figure 3. Typical boulder deposits on east flank of Yucca Mountain along Abandoned Wash. Deposits in the foreground have weathered *in situ* and have not been transported down slope. Note the black patina (rock varnish) on the surface of boulders. The deposit in the foreground is the site of sample location YME-1.

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Figure 4. Typical boulder deposit on lower west flank of Yucca Mountain. The large deposit on the lower hillslope is the site of sample location YMW-3.

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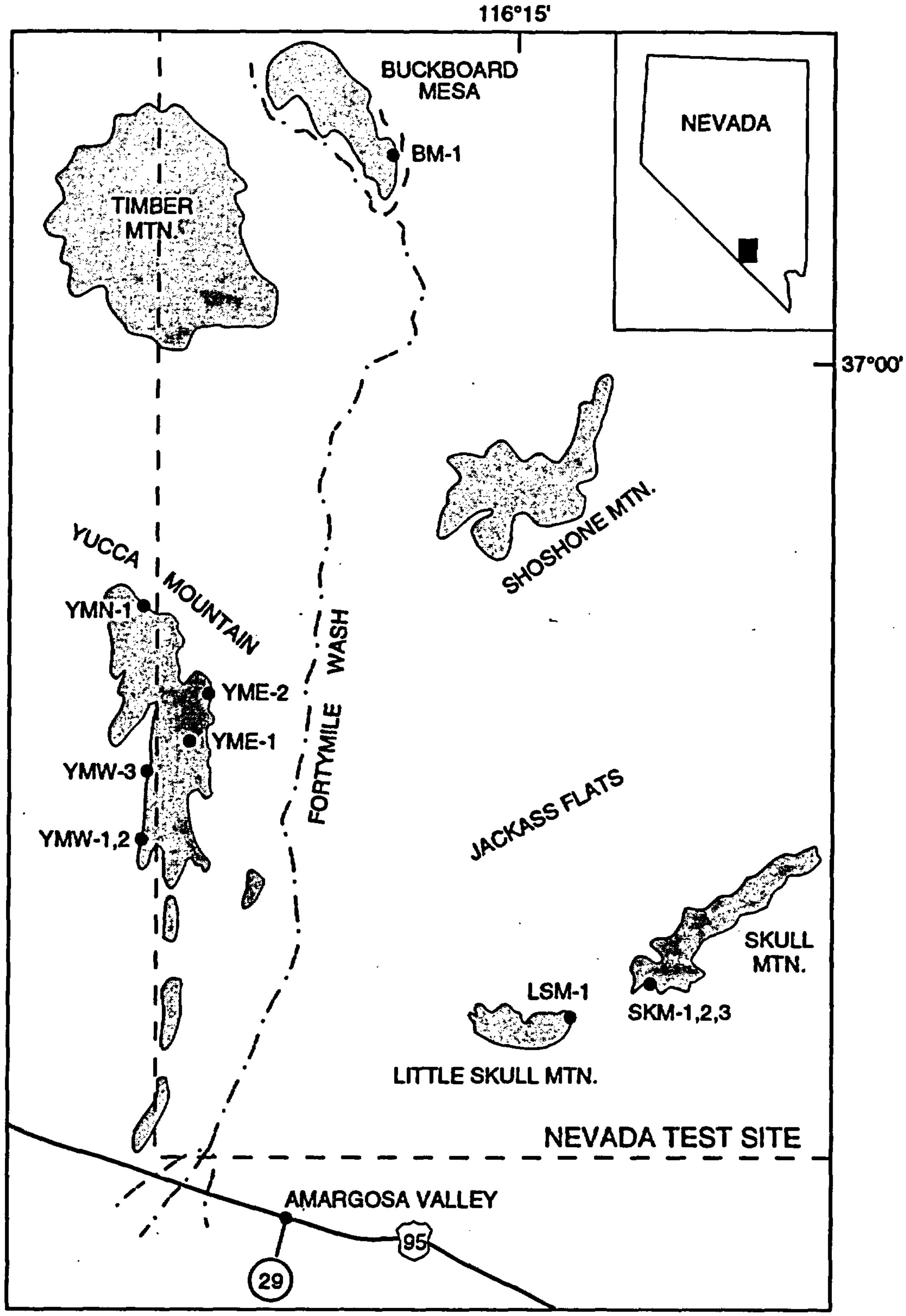

Figure 5. Location map of boulder deposit sample site locations.

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 between deposits. 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 bases 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 boulder 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 channelize the bouldery debris. Boulder deposits on the lower two thirds of the slope commonly overlie or are a part of colluvial aprons. The colluvial aprons are generally dissected by gullies that have been formed on the mid to lower hillslopes and have cut their channel to bedrock, around, not through the boulder deposits. 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 Skull and Yucca Mountains have smooth topographic contours with gentle relief both along and down slope. 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 Skull Mountain hillslopes. Gullies on the mid to lower hillslopes tend to be shallow and cut through the hillslope deposits with little or no incision into the underlying bedrock, indicating that the bedrock is much more resistent to erosion than the unconsolidated hillslope deposits.

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 (Figures 1 and 6). Varnish on the overlapping boulder deposits is not only less dark, but it is commonly more red in color and less completely covers the rock surface than on the older boulder deposits. These characteristics indicate (1) that older varnish is generally darker than young varnish and (2) that the older boulder deposits required a different set of conditions for their formation (i.e., conditions that produce large boulder sizes) than the conditions under which the younger deposits formed (conditions that produce smaller sized rock debris).

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 (DOE, 1988).

Two years of meteorological data have been collected from the Yucca Mountain area. During 1988-1989 the summit of Yucca Mountain received an average of 84 mm of precipitation as reported in Table 3.1-1 of the meteorology study plan (DOE, 1991). At Beatty, Nevada, which is at 1006 m elevation and 25 km west of Yucca Mountain, annual precipitation has averaged 113 mm from 1931 to 1960 (SCP Table 5-4)(DOE, 1988). The long-term precipitation average on Yucca Mountain, the summit of which is 500 m above Beatty, is estimated to be about 150 mm/yr. Moisture at Yucca Mountain 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 from 1922 to 1960, located at the same latitude (SCP Table 5-3)(DOE, 1988).

Present hillslope erosion occurs during infrequent summer thunderstorms when individual storm cells stall over ridges long enough to saturate hillslope colluvium and initiate debris flows. Debris flows are a primary mechanism for modern hillslope erosion in the region around Yucca Mountain. Modern debris flows are infrequent events on Yucca Mountain slopes, as evidenced by the preservation of middle Pleistocene colluvium and the lack of erosion scars on hillslopes. However, severe storms that result in debris flows occur each year within a 400-km radius of Yucca Mountain. Eyewitnesses at the Nevada Test Site report that Fortymile Wash had a significant discharge following a large storm in 1969. However, no hillslope scars related to this event are visible.

On July 21 or 22, 1984, debris flows occurred as a result of an intense precipitation event on the south-facing hillslope of Jake Ridge, about 6 km east of Yucca Mountain (Figure 2). With aerial photographs taken before and after the storm, the volume of debris eroded off the southern slope of Jake Ridge was calculated photogrametrically (Coe et al., 1992). About 3,650 m^3 of sediment was eroded off a hillslope area of 77,100 m^2 by debris flows. About 10% of the debris was deposited on the slope in channel levees and small lobes, 35% was deposited near the base of the slope, 40% was deposited in a tributary of Fortymile Wash, and 15% flowed into Fortymile Wash. Hillslope erosion, then, results in channel aggradation in the present dry, semiarid climate.

The significance of the Jake Ridge debris flow event is that it provides evidence: (1) to support the interpretation that hillslope stripping occurs primarily during warm, dry climatic conditions similar to those of today, and (2) that hillslope stripping occurs by debris flow activity that results in the removal of colluvium from the hillside and its delivery to the adjacent basin floor. Debris flow activity that occurs today on these hillslopes is only effective in removing the weathered rock material that constitutes the hillslope colluvium and it is not an effective process for eroding the unweathered bedrock that underlies these slopes.

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Figure 6. Colluvial boulder deposits on the southwest flank of Skull Mountain. Boulders originally mantled the entire slope and were weathered from a basalt flow that caps the mountain. Note the overlapping and lighter color of the deposits of younger boulders that have been deposited on top of the older (darker) boulders in the large boulder deposit in the center of the picture (arrow).

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3.3.1.2 Quaternary Tectonic Activity

Five of the six major north-south trending faults near the potential waste repository block exhibit Quaternary movement. Estimated rates of Quaternary slip on the major faults range from less than 0.5 cm/ka on the Bow Ridge and Paintbrush Canyon faults to about 1.0 cm/ka on the Windy Wash fault (Scott, 1990 and Whitney and Muhs, 1991). The Paintbrush Canyon-Stagecoach Road fault system and the Windy Wash fault both exhibit left oblique-slip motion.

This level of tectonic activity has had minimal impact on the geomorphic evolution of Yucca Mountain during the Quaternary. Tectonic landforms that are typically associated with active mountain fronts are absent at Yucca Mountain. For example, large, active alluvial fans, such as those found at the base of the Spring Mountains, in Death Valley, and on the east side of Bare Mountain (about eleven km west of the Yucca Mountain crest), are not present around the edges of Yucca Mountain. In addition, concentrations of loose, undisturbed, well-varnished boulders are common on Yucca Mountain ridgetops and hillslopes, and the lack of these boulders on the lower hillslopes indicates that seismic shaking has not disturbed these deposits. Although small scarps are visible along traces of a few of the major faults, scarps are rare in the Yucca Mountain area and most of the deposits offset are of middle Quaternary, not late Quaternary, age which indicates that tectonic activity has been low during the late Quaternary when compared to early or mid Quaternary activity.

The recent earthquake that occurred at Little Skull Mountain (June 29, 1992 - magnitude 5.6) dislodged large blocks of volcanic tuff that slid or tumbled downslope. Many of these displaced blocks are conspicuous in that those that are rotated possess fresh unweathered and unvarnished upper surfaces. No such systematic concentrations of possibly seismically disturbed boulders, related to either the Little Skull Mountain or other recent earthquake activity have been noted at Yucca Mountain.

3.3.1.3 Distribution of Quaternary Deposits Around Yucca Mountain

Surficial geological mapping around Yucca Mountain (Swadley et al., 1984) reveals extensive lower and middle Quaternary deposits (Figure 7). Over 85 percent of the surficial deposits and geomorphic surfaces exposed adjacent to the Yucca Mountain tilted blocks were formed during the early to middle Quaternary. Exposed upper Quaternary deposits are confined to small areas on hillslopes and are probably buried below a thin veneer of Holocene alluvium in Fortymile Wash and its tributaries, as well as the unnamed streambeds that cross Crater Flat.

Deposits of late Quaternary age are chiefly confined to present stream valleys. The lack of late Pleistocene and Holocene deposits at the base of Yucca Mountain hillslopes demonstrates that erosion rates from these slopes have been low during the past 100,000 years. Confinement of late Quaternary deposits to valleys and channels indicates the volume of material eroded off hillslopes has been smaller than during the early and middle Quaternary and this in turn indicates that the weathering processes that produced large quantities of bouldery debris in early to mid Quaternary have had a lower weathering efficiency during the late Quaternary.

The paucity of late Pleistocene deposits on and around Yucca Mountain has climatic, as well as tectonic, significance. A marked contrast exists between the geomorphic processes that operate under the present semiarid-to-arid climate and those that prevailed during cooler and wetter climates that occurred during the Quaternary. A significant portion of the surficial deposits on and around Yucca Mountain formed during the early and middle Quaternary by processes related to cool pluvial climates or during the transition from warmer to colder climates. Two periods of alluvial deposition in Fortymile Wash, one which ceased prior to about 270 ka and one which ceased prior to about 145 ka, are likely related to the transition from drier (interpluvial) to wetter (pluvial) conditions.

Shallow entrenchment (3-6 m) of streams, along the margins of Crater Flat, through older deposits suggests slow uplift of Yucca Mountain or slow subsidence in adjacent basins.. This geomorphic response is consistent with the slow rates of tectonic activity measured on the major Yucca Mountain faults. Alternatively, stream incision may reflect changes in fluvial processes due to Quaternary climate changes. Such valley entrenchment likely occurred during pluvial climatic conditions.

3.3.1.4 Quaternary Climate Changes in the Southern Great Basin and at Yucca Mountain

Evidence for colder, and possibly wetter, conditions in the Yucca Mountain region during glacial periods in the early and middle Quaternary is found in basins of the northern Mojave region. Hillhouse (1987) estimated that former Lake Tecopa, located about 70 miles 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 around a half million years ago (Smith et al., 1983).

Eolian activity in the Mojave Desert is commonly associated with interpluvial climates (McFadden et al., 1986), and multiple episodes of middle Pleistocene dune activity have been recorded in large sand ramps in the northern Amargosa Desert (Whitney et al., 1985). These interpluvial climates have episodically supplied fine-grained sand and silt to southern Nevada hillslopes during times of Quaternary aridity.

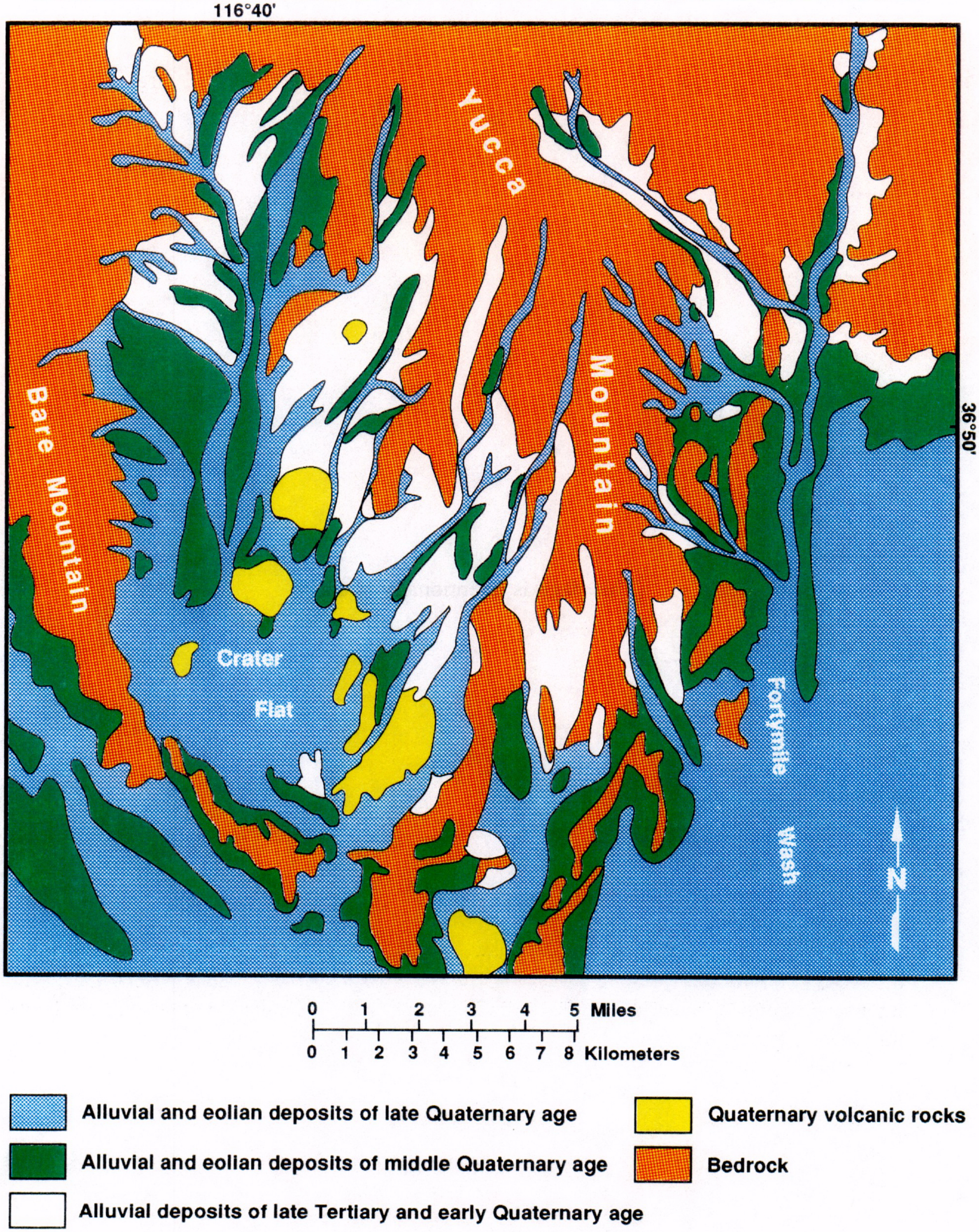

Figure 7. Map of surficial deposits around Yucca Mountain. Modified after Swadley et al., 1984.

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In the Yucca Mountain area, the well-developed rock varnish on the boulder surfaces indicates that these hillslope deposits have been stable for relatively long periods of time. Most well-varnished deposits overlie remnant mounds of colluvium and presently serve as minor drainage divides between the active hillslope rills and channels. Some deposits are even cemented in place by calcium carbonate, a situation also observed on Arizona hillslopes (Melton, 1965; Ford et al., 1982). Consequently, these stable, varnished colluvial boulder deposits contain a fragmentary, yet remarkably long, record of local hillslope processes and paleoclimates, and provide a unique opportunity to reconstruct the evolution of these hillslopes in early and mid Quaternary time.

No modern equivalents of the well-varnished colluvial boulder deposits are observed on southern Nevada hillslopes indicating they do not form under conditions similar to the modern dry semi-arid climates. 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 dry semiarid climate. Present production of medium to large boulders is nearly nonexistent, as evidenced by well-varnished outcrops of bedrock on the ridges of both Yucca Mountain and Skull Mountain. Thus, it is concluded that the 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 (Denny and Drewes, 1965; Melton, 1965; Prokopovich, 1987; Shafer, 1986). During these pluvial (colder and wetter) episodes, the hillslopes in the Yucca Mountain area experienced colluvial aggradation, at least on the mid to lower hillslopes. Stripping of these hillslopes was ineffective in these pluvial climates. Such hillslope stripping ensued only after climates reverted to more arid conditions.

A study of modern debris production in southern Ontario supports this climatic interpretation of boulder formation. 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 lasts several days or weeks rather than during 1-2 day cycles. Duration of the freezing phase is also related to boulder size, because crack propagation is time dependent. Thus, longer periods of freezing would be required to break out large boulders than would be necessary to produce small rock sizes. The relatively large volumes of boulders in the early-middle Pleistocene colluvial deposits on hillslopes in the Yucca Mountain area 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 years ago, the average annual temperature was at least 7 °C lower than present values and the slopes of Yucca and Skull Mountain supported a juniper woodland. Plants sensitive to frigid temperatures or moist environments, however, were not found in glacial-age middens, which demonstrates that, during the latest glacial period, conditions were not optimum for freeze-thaw cycles of long duration as they were during glacial periods in the early-to-middle Quaternary.

Cryogenic deposits (deposits formed by freeze/thaw processes) of the last glacial period 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 a mean annual temperature of 0 °C to 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 (approximately 18 ka to 15 ka) temperatures in the western Great Basin were at least 5.5 °C lower than present. If winter precipitation amounts were not significantly higher than present, then the temperature difference would be closer to 7 °C (Dohrenwend, 1984).

At the latitude of Yucca Mountain the projected elevation of the 0 °C full-glacial isotherm is approximately 2,800 m, about 1,300 m above the Yucca Mountain summit and 1,100 m above Skull Mountain (Dohrenwend, 1984). The full-glacial mean annual temperature at the top of Yucca Mountain is calculated to be about 10 °C using the mean annual terrestrial lapse rates provided by Dohrenwend, 0.76 °C per 100 m for elevations above 2000 m and 0.57 °C per 100 m below 2,000 m. This temperature compares favorably with Spaulding's minimum decline of 7 °C for the late Wisconsin full-glacial mean annual temperature at the Nevada Test Site. The present mean annual temperature of Beatty, Nevada is 15.3 °C (38 years of record) and the mean annual temperature for the top of Yucca Mountain in 1988-89 was nearly 16 °C. If we apply the late Wisconsin, full-glacial temperature decline of 7 °C from Spaulding (1985), the mean annual temperature at Yucca Mountain was about 9 °C to 10 °C, virtually the same temperature projected from the position of the late Wisconsin 0 °C isotherm calculated by Dohrenwend (1984).

The absence of colluvial boulder deposits with young rock-varnish coatings on hillslopes in the study area indicates that boulder deposits were not formed during the last glacial episode. Thus, mean annual temperatures below about 10 °C are 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 the temperature depressions required would be somewhat lower (Porter, 1977). Because the full range of nivation features is not found on Yucca Mountain or Skull Mountain, the mean annual temperatures necessary for the formation of colluvial boulder deposits were clearly higher than those necessary for active nivation. Thus, mean annual temperature during early to middle Quaternary episodes of colluvial boulder deposit formation was less than 10 °C and most likely was near, but not below 0 °C.

Colluvial boulder deposits do not provide any paleotemperature information about full-glacial summers, which prevents one from suggesting a mean annual temperature that can be related to the formation of these deposits. However, they do 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 °C to -5 °C (McGreevey and Whalley, 1982). 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 °C to 9 °C warmer than the winter temperatures necessary to physically weather boulders out of the local volcanic bedrock ridges. Thus, early and middle Quaternary glacial winters were at least 1 °C to 3 °C colder than the 6 °C winter temperature depression calculated by Spaulding (1985) for the last Quaternary glacial.

3.3.1.5 Hillslope Processes and Climate Response in the Yucca Mountain Region

The primary colluvial process on the present hillslopes is debris-flow activity (DOE, 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.

During dry, interglacial conditions, as have existed for most of the Holocene, small tributaries of Fortymile Wash became choked with debris flows that originated on adjacent hillslopes. Runoff has been insufficient, however, to transport much of the coarse debris through Fortymile Wash to the basin floor of the Amargosa desert. Thus, the entire drainage system is slowly aggrading with sediment eroded during infrequent summer convective storms.

In contrast, cycles of intense weathering on ridge crests and hillslopes during Quaternary glacial (pluvial) episodes have resulted in relatively thin mantles of bouldery colluvium that have been only partly removed by interpluvial erosion. The preservation of relatively large volumes of early and middle Quaternary deposits on and around Yucca Mountain is evidence that both weathering and erosional processes have not been as effective, and climates have not been as extreme, during the late Quaternary as they were during the early and middle Quaternary. The distribution of these ancient hillslope deposits and the large volumes of middle Quaternary alluvium in Crater Flat, Midway Valley, and Jackass Flats, implies that significantly less debris has been weathered and transported during the late Quaternary. This indicates that the overall climate has become increasingly more arid in the southern Great Basin from the middle Pleistocene to the present. This climatic interpretation is supported by the hydrologic behavior of several nearby basins that contained large lakes in the middle Pleistocene, such as Lake Tecopa (Hillhouse, 1987) and Searles Lake (Smith et al., 1983), but have been mostly dry since the late Pleistocene.

The wetter full glacial climates were times of sediment storage on hillslopes in southern Nevada with relatively little material being delivered to the basin floors. In contrast, the dryer interglacial periods were times of debris flow activity that 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 for the arid Negev Desert (Gerson, 1982) and for southern California (Bull, 1986, 1991).

The results of studies at Yucca Mountain imply that boulder production, talus mantle creep, and boulder flow activity occurred during colder, wetter, glacial climates and were stabilized during transitions to drier interglacial climates. The rock varnish ages of the older hillslope deposits indicate that these climatic conditions existed in southern Nevada at several times during the early and middle Quaternary.

Colluvial boulder deposits in the southern Great Basin are believed to form in the following manner. Intense physical weathering of resistant, fine-grained volcanic rocks, under climatic conditions both colder and wetter than present, is essential to produce the large boulders that form all colluvial boulder deposits. Large blocks are broken/weathered from cliffs and ridge crests by intense freeze-thaw processes and accumulate on upper hillslopes. If boulder production is from a bedrock unit that is exposed across the entire hillslope, and the hillslope has little surface relief, then boulder accumulation on the slope is uniform and results in a talus mantle. If significant surface relief with gullies and ridges exist on a hillslope, then hillslope debris moves down slope off ridges and accumulates as linear boulder deposits in the axes of hillslope hollows (Mills, 1981). Small rocks and gravel are washed in among large boulders and accumulate behind larger ones until the channel becomes clogged with coarse rock debris. These channel deposits are more susceptible to down-slope movement than talus mantles, because runoff and snowmelt are concentrated in these pre-existing drainage channels. If surface relief increases downslope, boulders, cobbles, and gravels are transported away from talus mantles into hillslope channels and rills, forming the linear hillslope boulder deposits most commonly seen on hillslopes of the southern Great Basin.

Colluvial boulder deposits become "stranded" on the hillslopes when the conditions necessary for their formation and movement terminate as climates became milder. The absence of thick colluvial boulder deposits at the base of slopes in southern Nevada confirms that the episodes of boulder production and movement were relatively brief and not frequent during the middle and late Quaternary.

Eolian sand and dust accumulate on deposits during interpluvials. These fine-grained sediments wash down to the base of the deposit and serve as the matrix necessary for renewed downslope movement when moisture is available. The accumulation of dust over time may result in a build-up of calcium carbonate that effectively cements the base of the colluvial boulder deposit to the bedrock slope. In the semiarid-to-arid environment of southern Nevada, such cemented calcium carbonate horizons require hundreds of thousands of years to form and their presence attests to the relative antiquity and long-term stability of these relict hillslope deposits.

The calculation of Yucca Mountain hillslope erosion rates assumes generally low relief on the Yucca Mountain hillslopes when the boulder deposits were deposited, because boulder deposit formation occurs during wetter parts of the climatic cycle when weathering of the bedrock takes place and when the hillslopes are being aggraded with colluvium. This colluvium forms aprons on the lower hillslopes onto which some boulder deposits advance. Boulder deposits that form on the mid slopes primarily fill the drainage channels that are present on this part of the midslope. The deposition of these colluvial materials would result in a reduction of the relief on these hillslopes, creating a rather smooth low relief profile along the slope.

Stripping of the weathered, colluvial mantle on these hillslopes would occur during times of drier climates, either during the pluvial-to-arid transitions or within times of arid conditions. Such stripping events are initiated by infrequent, intense, short-duration storms that provide large amounts of moisture to individual hillslopes. Debris flow activity results from such storms and these flows are commonly generated on the upper mid slopes and transport colluvial material off the slope along drainage channels on the lower slope and for short distances onto the adjacent basin floor.

The erosion rates calculated in this study are long-term erosion rates that average the effects of processes operating on these hillslopes through at least several, probably many, cycles of hillslope aggradation and degradation.

3.3.2 Dating Methodology

To establish erosion rates at Yucca Mountain it is first necessary to establish the age of those landscape features to be used in determining erosion rates. Several techniques exist that can be used to date landforms; however, selection of a method must be sensitive to limitations of individual techniques and the depositional make up (large bouldery deposits) of the features that need to be dated. The following discussion outlines the dating method used to establish age control for hillslope features at Yucca Mountain, and why this method was chosen over other dating methods.

3.3.2.1 Cation-Ratio Dating of Yucca Mountain Hillslope Deposits

Rock varnish is a black to red brown manganese-rich coating that accretes on stable rock surfaces in arid and semiarid regions (Figure 8). Rock varnish cation-ratio (VCR) 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 (Dorn, 1983; Dorn et al., 1986; Harrington and Whitney, 1987; Reneau, Raymond, and Harrington, 1992). The complex depositional and diagenetic processes by which successively accreted layers of varnish, are in general, progressively more depleted of a variety of these minor cations is not yet completely understood (Reneau, Raymond, and Harrington, 1992; Dorn and Krinsley, 1991; Reneau and Raymond, 1991). Thus, rock varnish ages for these surfaces are estimated from empirical curves that calibrate the decreasing trend of the cation ratio with time, using independently dated geomorphic surfaces within the study region for the calibration (Dorn, 1983; Dorn et al., 1986; Harrington and Whitney, 1987; Pineda et al., 1988).

Rock varnish dating provides the means by which the exposure age of boulder deposits on these hillslopes can be estimated. Rock varnish begins to form on the surface of boulders after they have been deposited as part of the hillslope debris. To obtain a rock varnish surface exposure age that most closely approximates the age of the deposit, the oldest varnish on the boulder deposit would have to be sampled and analyzed. There is a time lag of uncertain duration between the deposition of the boulders and the beginning of varnish accumulation on the surface of the boulder. Thus, rock varnish dating provides only a minimum age for the boulder deposit. Using the age of the rock varnish as a proxy for the age of the boulder deposit, therefore, will result in underestimating the time over which the process has been operative. Additionally, if the varnish sampled from the boulder deposit is not the oldest formed on the deposit or if some event on the hillslope occurs after the deposition of the boulders and results in either the stripping of varnish from the clasts or in the overturning of the clasts on the deposit, then, any new varnish forming on the clast surface would yield an erroneously young varnish age for the deposit. Thus, the use of any varnish, other than the oldest occurring on the deposit, to calculate the deposit age results in the age being erroneously underestimated and the process rate calculated being overestimated. The erosion rates calculated in this report, because they are based on rock varnish surface exposure ages of the boulder deposits, are therefore somewhat overestimated.

3.3.2.1.1 Criteria for Selection of a Dating Methodology

The rock varnish cation-ratio dating technique is one of a large number of calibrated dating techniques, such as lichenometry, amino acid racemization, and obsidian hydration, that can be used for dating Quaternary events (see Pierce, 1986 for a discussion of Quaternary dating methods). Cation ratio dating of rock varnish was utilized to provide the dating of hillslope surfaces rather than other Quaternary dating techniques for a number of reasons:

a) It was recognized that the best age control on the hillslopes would result from the dating of boulder deposits because: (1) these deposits were common on Yucca Mountain and other regional hillslopes; (2) they had been stabilized on the hillslope for a long period of time; and (3) they could be used to reconstruct the form of the paleohillslope. Thus, the dating technique had to be appropriate for the dating of deposits with large clasts. A variety of Quaternary dating techniques such as radiocarbon, uranium trend, and amino acid racemization dating, and thermoluminescense, are useful for dating fine-grained deposits, but are not useful in dating deposits composed of large boulder sized clasts.

b) The direct dating of hillslope surfaces is necessary to define the time that a specific paleohillslope existed, rather than the dating of some hillslope aspect that can often only be generally related to the age of the hillslope surface. For this reason soils dating techniques and isotopic techniques such as uranium series dating of soil

Figure 8. Boulders at Red Cone in Crater Flat coated with black rock varnish.

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carbonates were not considered because they provide only a minimum limiting age for the hillslope surface and may not closely reflect the true age of the surface.

c) Boulder deposits consist of basalt or tuff boulders and the dating technique utilized had to be appropriate to both lithologies. A variety of techniques including several of the cosmogenic techniques could not be used to reliably date both quartz rich tuff and basalt boulders and were eliminated from consideration for this reason.

d) The surface exposure age of the deposit was needed to calculate erosion rates rather than the age of the rocks of which the boulders consisted (i.e., the age of the deposit, not the time that the basalt or tuff was formed). Thus, techniques such as K-Ar and Ar-Ar which are commonly used to date the formation of lava flows were not useful in dating features formed at a later time from boulders broken from the lava flow.

e) The dating technique needed to be able to date deposits with a broad range in ages covering the Quaternary Period. Such techniques as radiocarbon, uranium series, and uranium trend dating have applicable ranges too short to span the time period of interest in dating of hillslope deposits (see Pierce, 1986). Additionally, because the intent was to calculate long-term erosion rates, the dating of deposits having a wide range in ages was required, rather than the dating of very young (<100 ka) deposits with a high degree of accuracy.

f) The technique needed to be one unaffected by the possibility that boulders in the deposit may have been exposed as part of a rock outcrop for some long time period prior to being broken apart and incorporated into a boulder deposit. Thus, cosmogenic techniques were problematic in that cosmogenic isotopes could have accumulated in the rock in the outcrop and retained this dose throughout the depositional process, leading to an erroneously old age for the deposit.

A basic assumption in the use of rock varnish dating to obtain age estimates of the relict hillslope boulder deposits is that the upper surface of boulders within these deposits possessed no pre-existing rock varnish when the boulder deposits were initially formed. The likelihood that this assumption is valid for the vast majority of boulders in the dated hillslope deposits is very high because:

1) Most boulders were broken out of rock outcrops on the upper hillslope, then fell, toppled, or rolled onto steep slopes (gradients of 28 to 31 degrees) and were subsequently transported tens to hundreds of meters downslope as part of the bouldery hillslope debris to the place of deposition on the mid to lower hillslope.

2) To retain rock varnish on the upper surface of the boulder following deposition, each clast would have to arrive on the upper steep hillslope, after being broken from the rock outcrop, with the upper surface of the rock on the hillslope having the same

orientation as it initially possessed in the outcrop. This would necessitate delivery of the boulder onto the hillslope with no tipping or rotation of the clast during movement from the outcrop to the hillslope.

3) Finally, the rock clast would have to undergo tens of meters of downslope transportation and deposition as part of the bouldery debris moving down the hillslope without either upper varnished rock surfaces being broken or overturned during impacts with other boulders. Additionally, this soft and easily eroded rock varnish on the rock surface would have to withstand degradation during the transportation and deposition process.

DOE concludes that the probability is low that this scenario would occur for large numbers of clasts provides a high degree of confidence in the validity of the assumption that the upper surface of boulders selected for rock varnish analysis possess only rock varnish that has formed on the rock surface after deposition of the boulder deposit.

To further preclude that such an earlier varnished clast might be collected as one of the samples for rock varnish analysis, the 20 or more clasts initially collected are culled to the 8 to 10 ultimately analyzed (see Section 3.3.2.1.4). The clasts selected from this process are those possessing consistent and mature varnish development.

Lastly, to ensure that cation ratios of rock varnish represent the ages of deposits formed on boulder surfaces after deposition, conclusions need to take account of anomalous clasts. If the varnish chemistry from one clast is anomalous compared to that from the other clasts and the majority of varnished clasts possess a consistent varnish chemistry (see Section 3.3.2.1.5), then the analyses from the anomalous clast are disregarded during calculation of the cation ratio for that deposit.

After consideration of the temporal window for which a geochronology needed to be established and the variety of techniques available, their advantages, disadvantages, utility and limitations, the inherent uncertainties, and aspects of techniques that were not well constrained (e.g., production rates for some of the cosmogenic isotopes and the nature of their calibration), rock varnish cation-ratio dating of the boulder deposits was identified as an acceptable technique, because it satisfied the criteria for selection (i.e., it provided surface exposure ages of hillslope features), it was able to date 100 ka to 2000 ka deposits, it could date bouldery deposits, and it was useable on any fine grained volcanic rock such as basalts and tuffs.

3.3.2.1.2 Calibration of the Cation Ratio Dating Technique

Cation-ratio dating is a calibrated technique that uses the chemistry of rock varnish formed on geologic features of known age to establish a calibration of varnish chemistry to varnish age. Rock varnish formation involves complex depositional and diagenetic processes that result in stratigraphic variations in rock varnish chemistry (Reneau, Raymond, and Harrington, 1992). Other calibrated techniques commonly used in Quaternary studies, include soils dating techniques such as the Harden Index, carbonate accumulation in soils, and techniques that utilize the sequential development of a feature or set of geomorphic features through time.

For the rock varnish dating curve for the Yucca Mountain area (Figure 9), surfaces dated by other techniques provide the necessary calibration (Harrington and Whitney, 1987). Lava flows in Crater Flat with K-Ar ages in excess of 500 ka were used to calibrate the older part of the rock varnish dating curve (calibration points Black Cone (BC) and Red Cone (RC) on Figure 9). The K-Ar dating technique (see section by Damon, in Rosholt et al., 1991), yields the time of lava flow formation, and the chemistry of rock varnish that has formed on exposed lava flow rock surfaces is calibrated to this K-Ar age of lava flow formation. Volcanic features less than 500 ka were not used for calibration because of the controversy as to the reliability of K-Ar ages determined for younger volcanic features in the Yucca Mountain area (Crowe et al., 1992). Uranium-trend ages (see section by Szabo and Rosholt, in Rosholt et al., 1991, for details of the uranium-trend dating method) of alluvial surfaces were used for calibrating that part of the curve within the period from 40 ka to 500 ka (calibration points Crater Flat (Cf), and stream terraces near Fortymile Wash (Q2b and Q2c) on Figure 9). The Uranium-trend dating technique yields the time that the alluvial material was deposited and it is calibrated to the chemistry of rock varnish formed on the exposed surface of rocks following formation of the deposit. Uranium-trend ages were used for calibration only where the deposits had been dated more than once with resultant comparable ages being obtained.

Rock varnish age estimates have been evaluated within the geologic context and constraints of two study areas, the Española basin in New Mexico (Dethier et al., 1988) and the Yucca Mountain area. In the Española basin the rock varnish age estimates were compared to amino acid racemization ages of deposits underlying the rock varnish covered surfaces and were found to be comparable and slightly younger than the ages of the underlying deposits. Additionally, a rock varnish age estimate of 550 ka (Dethier et al., 1988) was obtained for an alluvial fan surface in the Española basin overlying deposits containing the Lava Creek B tephra (620 ka) and therefore representing an event happening more recently than deposition of the volcanic ash. This also supports the contention that the rock varnish age estimates are geologically reasonable.

In the study area in southern Nevada, similar geologic comparisons were made and it was noted that varnish thickness is greatest on the deposits that yield the oldest age estimates (Figure 10 and Table 4) and that the thickest carbonate soil horizons are likewise noted in the deposits with the oldest estimated ages (Ford et al., 1982; Whitney and Harrington, in press). Finally, rock varnish on a surface in Las Vegas Wash yields a 600-ka age estimate and is underlain by deposits that contain the Lava Creek B tephra (620 ka) at a depth of two meters (Whitney et al., 1988). Thus, it is believed that the Yucca Mountain rock varnish age estimates are reasonable when placed within the geologic constraints of the area. There are no noted examples where geologic constraints conflict with rock varnish age estimates.

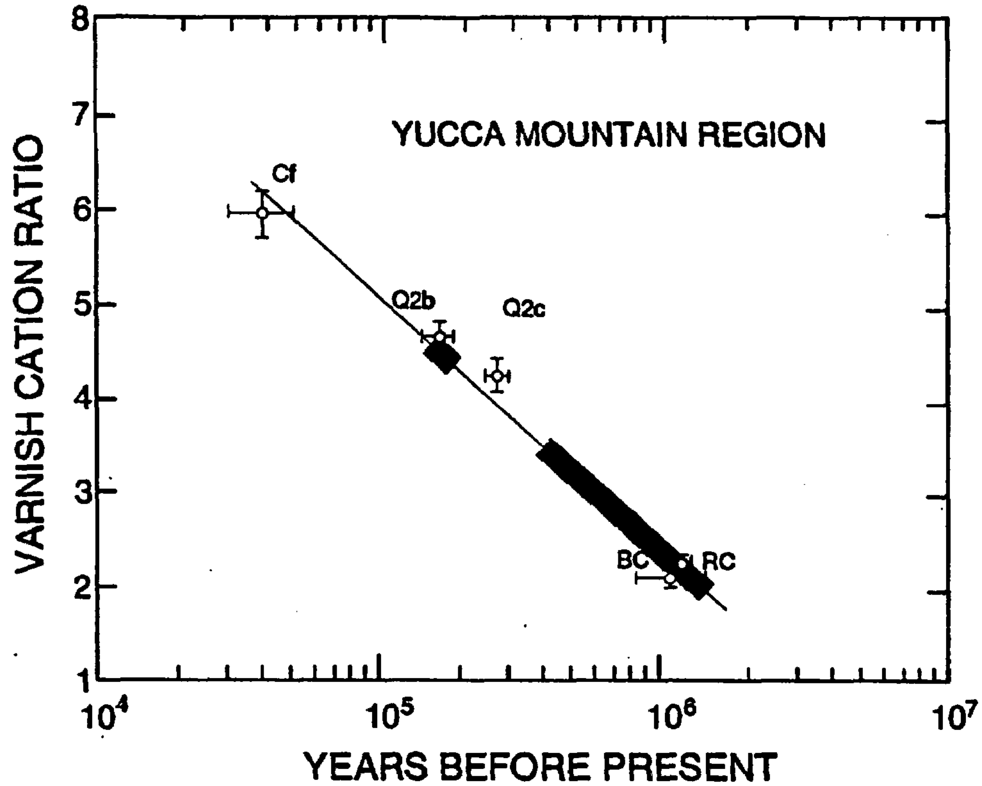

Figure 9. Rock varnish dating curve for Yucca Mountain. Shaded area represents the range of boulder deposit ages from this study. The data points Cf, Q2b, Q2c, BC and RC represent independently dated surfaces in the Yucca Mountain area used for calibration points on the rock varnish dating curve. (See Harrington and Whitney, 1987, for more detail.)

3.3.2.1.3 Sampling Method

Twelve colluvial boulder deposits were sampled for cation-ratio dating on the north, east, and west flanks of Yucca Mountain, the southwest flank of Skull Mountain, and the northeast flank of Little Skull Mountain and on Buckboard Mesa (Figure 5). 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 lying 20 m to 40 m above the base of the west flank (YMW-2 and YMW-3), 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 (Figure 2). 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 lower slopes of Buckboard Mesa north of Yucca Mountain (BM-1)(Figures 1 and 5).

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. The oldest deposits on a slope were selected using the following criteria: (1) position - deposits near the base of a slope are more likely to be preserved than deposits higher on the mid slopes that commonly have been subjected to more erosion; (2) size - the center of the largest deposits will most likely preserve the oldest, unmodified varnish on boulders because they are not affected by vegetation growing around the edges of the deposit that may hinder the development of varnish on the boulder surfaces, or erosional modification and channel incision along the margins of channelized relict boulder deposits. Thus, they have the highest probability among boulders in the deposits of retaining original unmodified rock varnish; (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 boulders 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. These criteria include collection of samples from (1) stable, well-drained geomorphic surfaces, (2) similar lithologic substrates, and (3) areas having similar environmental conditions. These criteria help to reduce the potential variability in varnish thickness and composition.

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Figure 10. SEM cross-section of rock varnish on a basalt boulder from Buckboard Mesa boulder deposit (BM-1). Average thickness of the rock varnish is approximately 200 microns. Note the distinct boundary between the rock varnish and the fresh, unweathered basalt substrate, demonstrating rock varnish coatings are relatively impermeable and inhibit weathering of rock substrate.

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The lithology of varnished boulders collected from the colluvial boulder deposits on Yucca Mountain is volcanic tuff; that from Skull and Little Skull Mountains and Buckboard Mesa is basalt. Varnished chips were broken from boulders when the median diameter of the boulders exceeded 0.25 m. Originally, chips from approximately twenty boulders were collected from a deposit and then culled to the best eight to ten sampled boulders, based on the quality of each varnish coat. This sample selection procedure was used to reduce the analytic variability in varnish cation ratios for an individual deposit.

3.3.2.1.4 Sample Preparation

The preparation of rock varnish samples for scanning electron microscope (SEM) analysis follows the methods described in Harrington and Whitney (1987). Varnished chips are hand washed in deionized water to remove surficial detritus and are air dried. A circular core of the varnish and rock substrate (2 to 2.5 cm in diameter) is drilled from each area designated to be analyzed. Two disks are made for each boulder sampled, where possible. A flat 0.5-cm-thick disk is then made from the core by grinding the rock substrate parallel to the varnish surface. Disks are mounted on glass slides, varnish side up, and are carbon coated for SEM analysis (Figure 11). Cross sections of the varnish and substrate (as shown in Figure 10) were analyzed to determine varnish thickness.

3.3.2.1.5 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 degree takeoff angle and a counting time of 150 seconds. 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 Whitney, 1987).

Harrington et al. (1989) noted the presence of Ba in rock varnishes from Nevada and commented on the uncorrected Ba/Ti 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 et al. (1991) further noted that if no peak decomposition was performed during analyses, approximately 1/3 of the Ba concentration would be included as Ti. Thus, the cation ratio calculated is (Ca+K)/(Ti+~1/3Ba) instead of (Ca+K)/Ti as originally believed. Bierman and Gillespie (1991) use the same analytic argument of inclusion of Ba in rock varnish analyses to support their contention that all earlier calibrated rock varnish curves include Ba as a component in the calculated cation ratios. Harrington et al. (1991) and Bierman et al. (1991) suggest that the included Ba may contribute to the observed decrease in cation ratios with increasing rock varnish age.

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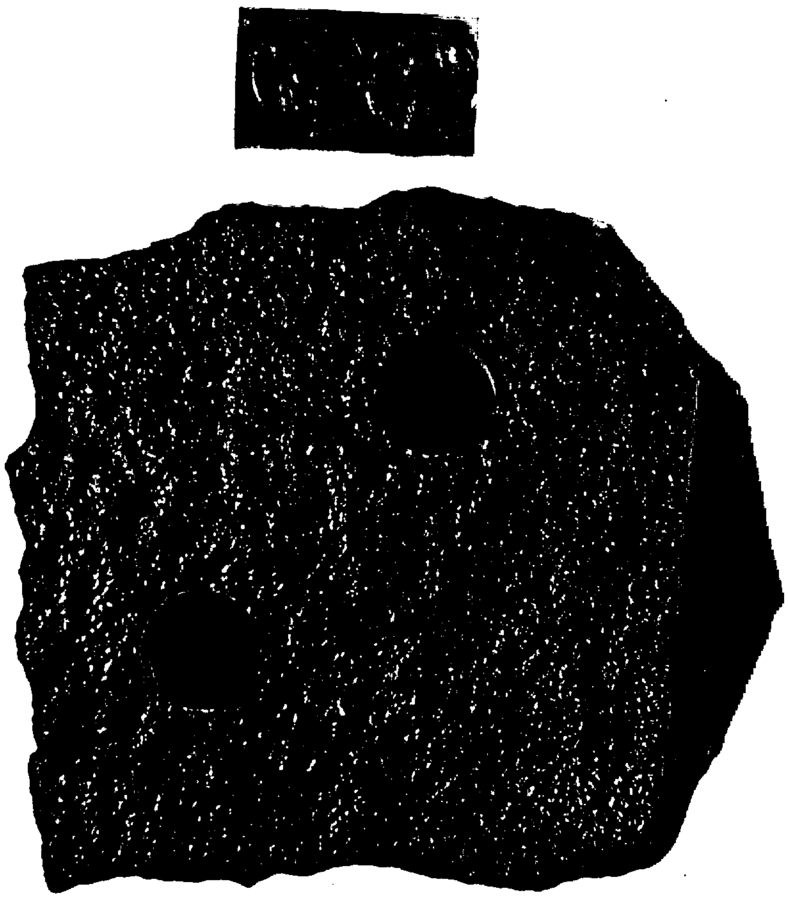

Figure 11. Rock-varnish disks prepared for SEM analysis. Rock-varnish disks made from cores cut from a varnished boulder and mounted on a glass slide in preparation for SEM analysis.

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The rock-varnish dating curve for Yucca Mountain (Harrington and Whitney, 1987) was calibrated using cation ratios calculated from the data derived using the SSQ program. Thus, the 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+~1/3Ba)] 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 the average of all the varnish analyses on each sample boulder. A VCR for a colluvial boulder deposit is determined by averaging the VCRs for all the sample boulders from that deposit. 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. This is the estimated surface exposure age for the boulder deposit.

3.3.2.1.6 Calculation of Uncertainties for Cation Ratios

Bierman et al. (1991) note 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 the analyses of colluvial boulder deposits between 30 and 160 varnish sites for each deposit being dated have been analyzed. The magnitude of the uncertainty at a 0.95 probability in calculated cation ratios varied 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 4) is reported using the technique of Bierman et al. (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. The age estimates and uncertainties are calculated using the cation-ratio curve for Yucca Mountain (Figure 9).

Although more data points might reduce the curve uncertainty to a minor degree, the concentration of data points is adequate to establish a calibration curve. Most age estimates for the boulder deposits in this report are derived from within the calibrated interval of the dating curve (11 of 12 deposits). The remaining point lies in immediate proximity to the calibrated interval. Any additional reduction in the uncertainty of the curve that could be obtained with the addition of a greater number of calibration points would not affect any of the technical conclusions in this report that are based on the dating curve.

3.3.2.2 Age Estimates of Varnished Boulder Deposits

The estimated age of a boulder deposit is obtained by plotting the SEM-derived cation ratio on the Y-axis (ordinate) and then using the rock varnish dating curve to establish the corresponding geologic age estimate on the X-axis (abscissa) (Table 4). The range in age, representing the estimated age uncertainty (last column, in brackets, Table 4) is calculated by first, subtracting the cation ratio uncertainty from the cation ratio for a deposit (yields minimum age) and secondly, adding the cation ratio uncertainty to the deposit cation ratio (yields maximum age) and plotting these values on the cation ratio dating curve for Yucca Mountain. A conservative approach has been incorporated in the use of age estimates and in calculation of erosion rates because the minimum age of the age range (last column, in brackets, Table 4) is used in the calculation of erosion rates.

The estimated ages derived from the varnish cation ratios in Table 4 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 million years old (Ma). This deposit is the oldest dated hillslope deposit in the southwestern United States. The range in ages of these boulder deposits (170 ka to ~1400 ka) spans at least 75 % of the Quaternary Period and is the longest Quaternary hillslope geologic record yet constructed for areas in the southwestern U.S.

The oldest dated deposits on the slopes of Yucca Mountain range from 640 ka on the east slope to about 760 ka on the north flank. Older deposits occur on steeper slopes (up to 31°) at Skull Mountain and Buckboard Mesa. The antiquity of these bouldery deposits indicates that even on the steepest slopes of the Yucca Mountain area, hillslope erosion has been remarkably ineffective at removing hillslope colluvium during the Quaternary.

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 at about 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 indicate that these deposits may have stabilized during one period at around 650 ka. 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), indicating that these three deposits formed during an earlier episode of colluvial boulder deposition around 800 ka. Similarity of VCRs for two even older deposits on Skull (SKM-3) and Little Skull (LSM-1) Mountains could represent a fourth episode of stabilization about 1 Ma. A fifth and earlier episode of hillslope deposit stabilization is indicated, at about 1.3 Ma, by the similarity of VCRs for the oldest boulder deposits on both Skull Mountain (SKM-3A) and Buckboard Mesa (BM-1).

Rock-varnish dating indicates that extensive bouldery hillslope mantles are 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. Although too few deposits have been dated to demonstrate it statistically, the clustering of the boulder deposit age data indicate that the processes of boulder production and stabilization are episodic and that boulder deposits have formed at several and probably many times during the Quaternary Period.

Table 4

Varnish Cation Ratios and Estimated Ages of Colluvial Boulder Deposits of the Yucca Mountain Area

SAMPLE[1] LOCATION	SAMPLE NUMBER	NUMBER OF ANALYTICAL SITES (n)[2]	CATION RATIO	CALCULATION OF UNCERTAINTY 1 Scr[3]	95%CL[4]	ESTIMATED AGE (ka) AND AGE UNCERTAINTY
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 MOUNTAIN						
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]

NOTES:

1 Sample numbers are from the sample location map (Figure 5).

2 (n) = Number of SEM analytic sites per geomorphic surface.

3 Scr = Standard deviation calculated for the mean cation ratio for a surface.

4 95%CL = 95% Confidence level for the mean cation ratio for a geomorphic surface calculated using the formula of Bierman et al., 1991.

Rock varnish development is commonly found on bedrock outcrops on the top of Yucca and Skull Mountains as well as 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 more than 100,000 years indicating little, if any, rock material has been broken from these outcrops, by freeze and thaw processes, since mid Quaternary time (<128 ka).

3.3.2.3 Preservation of Colluvial Boulder Deposits on Yucca Mountain Area Hillslopes

Several conditions contribute to the long-term preservation of these hillslope deposits:

(1) Boulders in the hillslope deposits are erosionally resistant volcanic rocks.

(2) Rock varnish coatings on the surface of boulders inhibit weathering, and the large boulder sizes are difficult to move by modern hillslope processes.

(3) Incision of hillslope channels isolates colluvial boulder deposits by topographic inversion (see Figure 12) and removes them from the zone of active erosion by runoff.

(4) Debris flows, although effective in removing bouldery colluvium from upper slopes, are generally restricted to active channels on middle and lower hillslopes and rarely strip debris from non-channelized areas.

The most important reason for the preservation of old, colluvial boulder deposits is the dense, slow-weathering rock types of which the clasts are composed. Physical weathering, by freezing of water at considerable depth, along joints and fractures in welded tuffs and basalts produces boulders and smaller clasts that become colluvial boulder deposits. At Yucca Mountain, the Tiva Canyon Member of the Paintbrush Tuff (Scott and Bonk, 1984) is the ridge-forming bedrock that is the source of coarse bouldery debris on hillslopes, while basalt is the bedrock source on Skull and Little Skull Mountains and on Buckboard Mesa (Sargent and Stewart, 1971). In southern Nevada, colluvial boulder deposits are noticeably absent on hills composed of limestone, sandstone, and coarse-grained igneous rocks that are susceptible to solution or grain-to-grain physical weathering. In short, colluvial boulder deposits are most commonly found in parts of the southern Great Basin where resistant fine-grained volcanic rocks comprise most of the hillslope bedrock (Whitney and Harrington, in press).

3.3.3 Erosion Rate Estimates

3.3.3.1 Long-Term Hillslope Erosion Rates on Yucca Mountain, Skull Mountain, Little Skull Mountain, and on Buckboard Mesa

Any geomorphic rate can be calculated using the following standard formula:

Process Rate (R) = Process Magnitude (M) / Time Process Operative (T)

Thus, to calculate erosion rates (R) on hillslopes a dated surface on the hillslope must be available to provide the time (T) over which the process has been operative. The magnitude of erosion (M) can be measured as the distance between this dated surface and the present hillslope.

For deposits on mid to lower hillslopes, long-term Quaternary erosion rates have been calculated for the hillslopes on which the colluvial boulder deposits occur. The surface of the oldest dated boulder deposit on a hillslope was used to define the topography that existed when the boulders were deposited and rock varnish began forming. The erosion that has occurred on the hillslope since that time was measured as the perpendicular distance between the modern hillslope and the top of relict hillslope deposits (Figure 12). The level of the paleohillslope was assumed to be represented by the surface of the relict boulder deposit and incision or degradation was measured below this surface. Because colluvial boulder deposits commonly possess a lenticular cross-section shape, it is believed that these colluvial deposits were deposited in and filled topographic lows and hollows, and spilled over onto adjacent slopes; this assumption maximizes the erosion rate. At present, these boulder deposits form slight topographic highs, commonly 0.5 to 1 m above bedrock (or thinly mantled) hillslopes.

Measurements were made of depth of maximum incision in drainage channels marginal to these deposits (measurements a_1 and a_2, Figure 12) and the average hillslope degradation was measured over the slope, 50 m to each side of the deposit (measurement b, Figure 12). The 50 m distance was chosen: (1) to incorporate a large enough area so as to minimize the effect of incised channels marginal to the deposit and other local hillslope irregularities, and (2) to not extend into the zone of effects of adjacent deposits or associated incised channels. The calculated rate of degradation does not factor in upper hillslope deposits where little, if any, erosion has occurred and may therefore overestimate the amount of hillslope degradation when averaged over the entire hillslope. General hillslope degradation on Yucca, Skull, and Little Skull Mountains and Buckboard Mesa averages less than one meter below colluvial boulder deposits that range from 170 ka to over a million years old, attesting to the very low rates of hillslope erosion that has occurred in the Yucca Mountain area during the Quaternary Period.

Long-term, average hillslope erosion rates have been calculated for the Yucca Mountain area from the dated hillslope boulder deposits. These rates range from <0.1 to 0.6 cm/ka and average ≤0.12 cm/ka (Table 5). Erosion rates for the hillslopes on Yucca Mountain are also very low, averaging ≤0.19 cm/ka (Table 5). This rate is considered to be a maximum rate because in situ boulder deposits are found on several Yucca Mountain ridges that are well varnished and show no signs of significant movement resulting from hillslope erosion since they were formed.

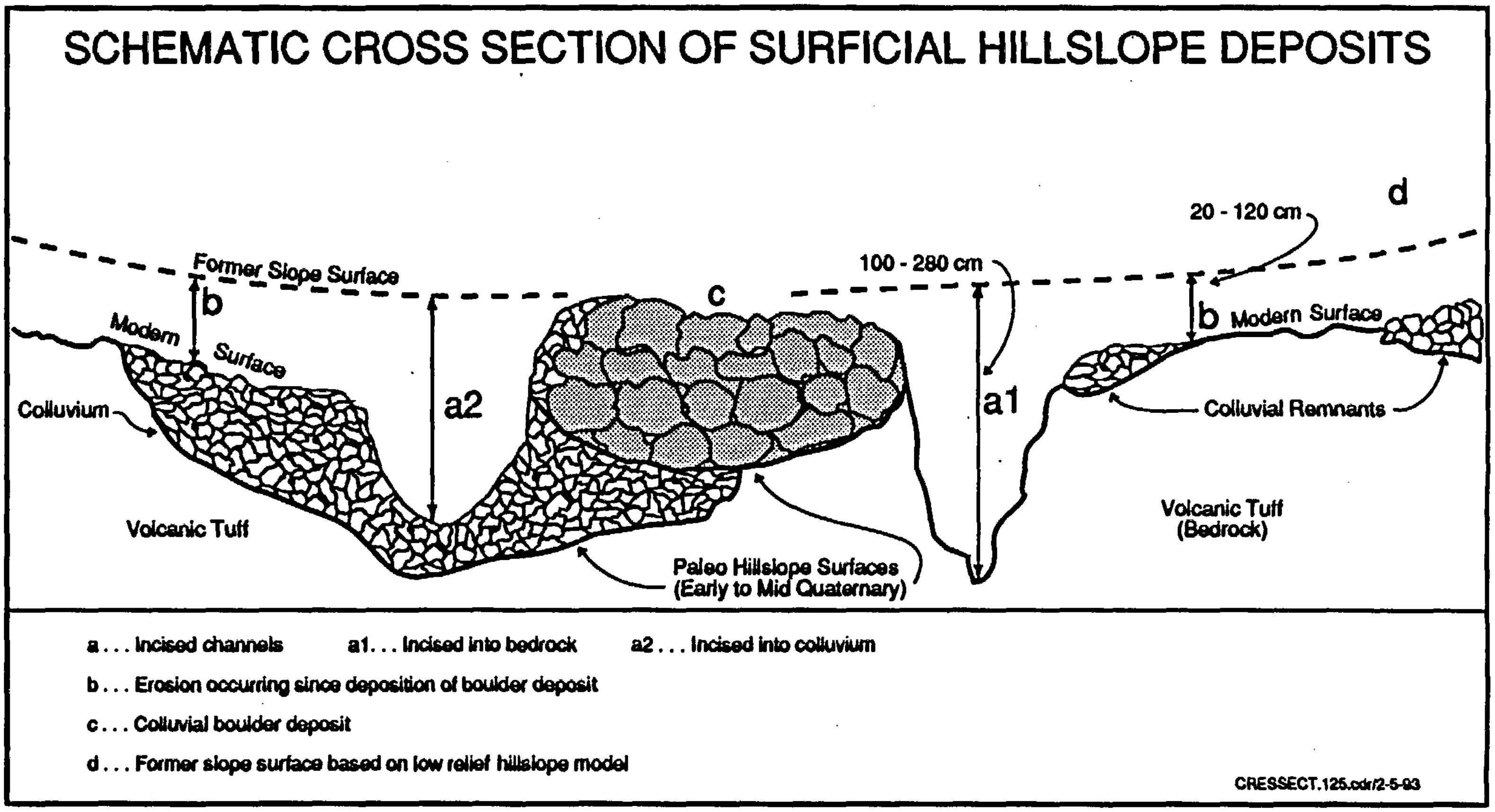

Figure 12. Cross section of typical surficial hillslope deposits.

Table 5

Hillslope Degradation Rates and Characteristics of Colluvial Boulder Deposits in the Yucca Mountain Area

DEPOSIT	SLOPE OF DEPOSIT (degrees)	EXPOSED DEPOSIT THICKNESS (meters)	MAXIMUM CHANNEL INCISION (meters)	AVERAGE HILLSLOPE DEGRADATION (meters)	ESTIMATED AGE (1000 years) [age range]	LONG-TERM AVERAGE HILLSLOPE DEGRADATION RATE[4] (cm/ka)
Yucca Mountain:						
East Flank Yucca	21-28	1.4	<0.4[2]	<0.2	640 [610-670]	0.033
Boundary Ridge	23	>0.5	1.0[2]	0.8	170 [140-180]	0.571
West Flank Yucca (1)	31	0.4	<0.3[2]	0.2	465 [400-515]	0.050
West Flank Yucca (2)	28	2.4	1.3[3]	1.1	645 [630-660]	0.175
West Flank Yucca (3)	27-31	0.6-2.1	2.8	1.1	710 [680-740]	0.162
North Flank Yucca	25	>1.6	1.6[1]	≤1.0	760 [710-820]	0.141
Little Skull Mountain	15	0.9	0.9	0.3	960 [930-990]	0.032
Skull Mountain						
Skull Mountain (1)	32	1.6	2.0[3]	≤1.0	800 [760-830]	0.132
Skull Mountain (2)	31	0.8	1.8	<0.5	830 [800-880]	0.063
Skull Mountain (3)	30	0.7	2.8	<0.3	1180 [1110-1270]	0.027
Skull Mountain (3A)	19	1.0	1.5[1]	≤0.5	990 [960-1030]	0.052
Buckboard Mesa	32	1.2	0.3	<0.2	1380 [1260-1510]	0.016

Average rate for Yucca Mountain ≤ 0.19 cm/ka
Average rate for Yucca Mountain region ≤ 0.12 cm/ka

1 Channel not cut into bedrock
2 Channel poorly defined or non-existent
3 Maximum depth of "stairstep" channel; maximum depth is not continuous
4 Rate calculated = average hillslope degradation divided by the youngest estimated age. Age estimates are based on varnish cation ratios.

3.3.3.2 Comparison of Yucca Mountain Erosion Rates with Other Semiarid Environments

Rates of hillslope erosion are related to local relief, climate, the type of rock undergoing erosion and its degree of resistance to the erosional process. Because quartz is highly resistant to erosion and chemical weathering when compared to the other common rock forming minerals, rocks that are rich in quartz are generally very resistant to erosion. In contrast, areas that are formed on: (1) unconsolidated or lacustrine sediments, (2) shale, siltstone or poorly cemented sandstones, and (3) limestones, especially in more humid environments, are generally not resistant to erosion. Hillslope degradation rates from several regions around the world are shown in Table 2 and from different climatic environments within the U.S. in Table 3.

The lowest hillslope erosion rates are found in areas that possess a combination of several favorable characteristics: (1) a dry climate, because there will be a lack of surface runoff and insufficient water for effective physical and chemical weathering to occur; (2) rocks that are resistant to erosional processes, most commonly this means that quartz rich rocks are present; and (3) areas with low rates of tectonic activity, because tectonism will increase the local relief and increase the effectiveness of erosional processes that are enhanced by gravitational forces. Yucca Mountain possesses several of the conditions that favor low erosion rates. These are: (1) a dry semiarid climate; (2) quartz rich volcanic tuffs, strengthened by welding of many of the tuff units; and (3) low rates of tectonic activity during the Quaternary. Therefore, long-term, low rates of hillslope erosion are an anticipated characteristic of the Yucca Mountain area.

The lowest erosion rates noted in Table 2, for various areas around the world, are in the tectonically stable Australian shield region. This region also possesses a dry semiarid climate and erosionally resistant quartz rich rocks. Erosion rates from this region of Australia (0.2-0.3 cm/ka) are nearly the same as hillslope erosion rates at Yucca Mountain (0.19 cm/ka, Table 5).

Long-term average erosion rates for the U.S., including a variety of climates and diverse rock types are 2.5-15 cm/ka (Table 3). Hillslope erosion rates at Yucca Mountain (0.19 cm/ka, Table 5) are at least two orders of magnitude lower than this average. Published long-term erosion rates for areas of New Mexico and California that possess dry climates, range from 1.0-4.3 cm/ka on hillslopes underlain by resistant rock types. Hillslope erosion rates at Yucca Mountain are an order of magnitude lower than rates in these areas. Erosion rates (<0.8 cm/ka) similar to Yucca Mountain have been calculated in the arid southern Mojave Desert (Oberlander, 1972 and 1974) on quartz rich, granitic terrain.

Hillslope erosion rates at Yucca Mountain, an area possessing a climate and rock type that generally are erosion inhibiting, are more than two orders of magnitude less than the norm for the U.S. and are as low as other areas with similar rock types and climatic conditions. These very low Quaternary erosion rates do not constitute sufficiently high rates to even be considered near average or normal for the U.S., and therefore, are not extreme using any general definition of the term.

The preservation of middle Quaternary deposits on Yucca Mountain indicates that there has been insufficient runoff during interpluvial climates to remove bouldery colluvium from hillslopes. The lack of young bouldery colluvium on these slopes also suggests that pluvial climates during the late Quaternary have not been cold enough to physically produce large volumes of debris. Thus, the low rates of erosion are in part due to relatively small fluctuations in climate at Yucca Mountain during the late Quaternary.

The field measurements made to calculate the amount of hillslope degradation reported in Table 5, assume that the top of the measured hillslope deposits represent the average land surface position at the time they were emplaced. Alternative hillslope erosion rates can be calculated from hypothetical models that assume the general hillslope surface may have possessed 2-3 times greater relief than the low-relief model assumed in this study. There is, however, no field geomorphic evidence to support a hypothesis of such an increase in hillslope relief during the early to middle Quaternary. In fact, because boulder deposits formed during periods of hillslope aggradation would result in reduction of general hillslope relief by filling in the drainage channels on the hillslope, boulder-mantled hillslopes probably possessed less relief than that on the modern hillslope.

Assumptions of higher relief will yield higher erosion rates than the measured rates; however, these rates clearly demonstrate that degradation under the most severe conditions imaginable will lower hillslope surfaces less than 1 meter over the next 10,000 years. If it is assumed that the ancient land surface had 2-3 times greater relief than the modern hillslope, then the hillslope degradation rates would still increase to no more than 0.6 cm/ka (three times the average degradation rate of 0.19 cm/ka calculated for Yucca Mountain hillslopes - Table 5) and this still constitutes a very low erosion rate.

3.3.3.3 Evolution of Fortymile Wash

Yucca Mountain is located in the upper Amargosa River drainage basin. Most runoff from Yucca Mountain flows into small tributaries of Fortymile Wash, which drains 728 km^2 of the southern part of the Timber Mountain area located just north of Yucca Mountain. Timber Mountain is the remnant of a large volcanic caldera, of which the southeast rim was breached by Fortymile Canyon.

The basic drainage pattern of Fortymile Wash and its tributaries was established in the middle Miocene soon after collapse of the Timber Mountain caldera and resurgent dome formation about 11 million years ago (Huber, 1988). Little has changed in the basic drainage pattern since then, although subsequent volcanic activity temporarily blocked drainage channels. The 11.4-9.2 Ma rhyolite lavas of Fortymile Canyon flowed down the precursor to the present Fortymile Canyon, and in this section of the canyon the basal contact of these lavas is 45 m below the bottom of the present alluvial fill. Thus, incision by Fortymile Wash during the past 9 million years has not recorded extreme downcutting because the wash has not even returned to its former Miocene depth (Huber, 1988). In fact, the net activity recorded by Fortymile Wash during the past 2-3 million years is aggradation, not incision.

Fortymile Wash continues south from Timber Mountain along the east side of Alice and Fran Ridges and Busted Butte (Figure 2), and across this section is incised 15-20 m into a low-gradient alluvial fan complex derived primarily from the Calico Hills. The channel shallows downstream from Busted Butte until it merges with the alluvial fan surface 23 km to the south of Busted Butte. Inset below the alluvial fan surface are several alluvial fills that underlie stream terraces that formed along this section of the wash in response to major Quaternary climate changes.

Fluvial activity since the middle Quaternary (<128 ka) in Fortymile Wash and its principal tributaries has been limited to aggradation and reentrenchment through its own alluvial fill. During the past half million years four stream terraces have formed in Fortymile Wash (see Figure 13). Remnants of this terrace sequence are preserved east of Alice Ridge. The ages of these deposits are discussed in Hoover, 1989 and Taylor, 1986.

Dating of the alluvial materials that directly underlie these terrace surfaces indicates that maximum aggradation of Fortymile Wash that occurred during Quaternary time, culminated in the formation of the highest terrace along the wash (28 m above the modern valley floor - Figure 13). Deposits that underlie this oldest terrace have been correlated to other deposits dated at about 430 ka (see Szabo and Rosholt, 1991). Since the formation of the highest (oldest) terrace surface, two other terraces have been formed, each as a result of channel incision and some amount of subsequent aggradation. Deposits that directly underlie the main, or most extensive, terrace surface (25 m above the valley floor) correlate to deposits dated at about 270 ka (see Szabo and Rosholt, 1991). The next younger terrace is about 10 m above the present channel and is underlain by alluvium that correlates to deposits dated at about 150 ka. The lowest (youngest) terrace is situated just above the active flood plain/channel of the wash and is of Holocene age. The depth of the alluvial fill below the modern channel of Fortymile Wash, as measured at well J-13 (Thordarson, 1983) across from Busted Butte, is 108 m, although the number, thicknesses and ages of the fills that comprise this sequence are unknown. Therefore, the depth from the 270 ka terrace surface to the bottom of the alluvial fill as measured at well J-13 is 133 m (see Figure 13).

3.3.3.4 Stream Incision Rates on Fortymile Wash

Long-term (average) stream incision rates on Fortymile Wash can be calculated by a) comparing the differences in elevation of the dated terrace surfaces along the wash and b) by comparing the terrace surfaces to the base of valley alluvium as defined in boreholes. Wells UE-29A#1 and UE-29A#2 are located in Fortymile Canyon about 15 km upstream from Fran Ridge. These wells were drilled to bedrock from the surface of the main, 270 ka alluvial fill. The thickness of this fill is only about 20 m and no younger alluvial terrace is present at this locality. If the downcutting assumption is made that incision of the 20 m of fill occurred in half the time interval from 270 ka to present and aggradation of the new younger fill occurred during the other half of this time interval, then Fortymile Wash would have a long-term average incision rate of about 15 cm/ka in this upstream segment of Fortymile Canyon.

About 30 km downstream, near Highway 95, the channel of Fortymile Wash merges with the general alluvial plain of the Amargosa Desert. No canyon or record of Quaternary downcutting exists at this locality; thus, the lower reaches of Fortymile Wash appear to have been primarily in a state of aggradation for much of the Quaternary Period.

Two scenarios can be hypothesized for the Quaternary evolution of the terraces along the middle section of the wash from Fran Ridge downstream to Busted Butte, and the implication for incision rates along the wash. The two scenarios are shown in a cross section diagram in Figure 13. A theoretical maximum incision scenario proposes that between the formation of any two sequentially dated terraces (e.g., the 430 ka and the 270 ka terrace, or the 270 ka and the 150 ka terrace) Fortymile Wash first incised to the base of the alluvial fill before aggrading back to the next younger terrace level. A minimum incision scenario for valley evolution hypothesizes that each episode of incision was to a level below, but not far below, the next lower terrace and the subsequent aggradation resulted in only a thin (3-8 meters) new fill underlying each terrace surface. Use of the theoretical maximum incision for valley evolution results in the calculation of maximum possible incision rates for Fortymile Wash, whereas utilization of the incision scenario would result in significantly lower incision rates calculated for Fortymile Wash east of Fran Ridge.

A maximum, long-term average downcutting rate on Fortymile Wash was calculated for the time interval between formation of the main terrace at 270 ka and the formation of the lower terrace at 150 ka, by assuming the wash cut down to the base of the valley fill (a total depth of 133 m) before aggradation filled the valley back to the 150 ka terrace level. It was further assumed, for the worst case assumption, that the downcutting took place during the first half of that time interval (270 ka - 150 ka) and aggradation of the channel occurred during the second half of the time interval. Therefore, Fortymile Wash would have downcut 133 m in 60 ka, or at an average incision rate of 222 cm/ka. A slightly lower incision rate is obtained if the terraces used in the worst case scenario are either the 150 ka and Holocene terraces or the 430 ka and the 270 ka terraces.

If the minimum incision scenario is used and if: (1) incision is assumed not greatly to exceed the vertical distance between sequentially developed terrace surfaces, and (2) incision occurred during half of the time interval between terrace formations, then a minimum incision rate of 42 cm/ka (25 m in 60 ka) is calculated.

The low rates of channel incision calculated for the wash both upstream and downstream from the Fran Ridge-Busted Butte segment of the wash support a downcutting history through the midsection of the wash that closely approximates the minimum calculable incision rate scenario. Additionally, the well-defined incision along this middle segment of Fortymile Wash did not migrate upstream to the tributaries on Yucca Mountain located above the

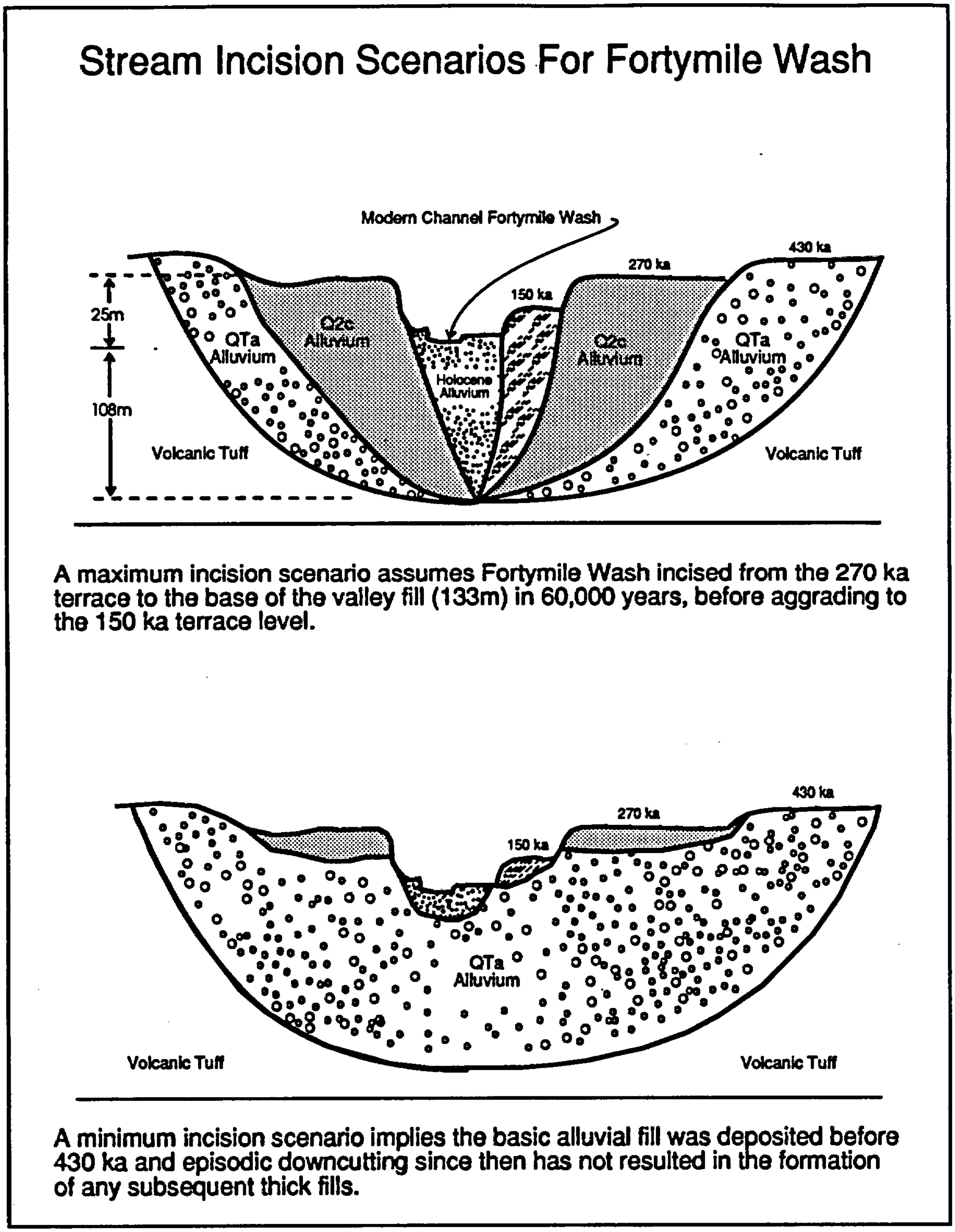

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Figure 13. Stream incision scenarios for Fortymile Wash

proposed repository block. In fact, only minor incision is observed in Midway Valley west of the Fortymile Wash terraces. Therefore, incision rates on Fortymile Wash can not be used to describe or predict stream incision in small canyons on Yucca Mountain.

That long periods of protracted downcutting at high incision rates have not occurred in Fortymile Wash is proven by the fact that Fortymile Wash has not excavated down to its former valley floor of 9 million years ago. Assuming our theoretical high incision rate of 222cm/ka, the wash could potentially have cut down to its former valley floor (at a depth of 178 m) in about 80,000 years. As stated above, the primary process occurring along Fortymile Wash during the Quaternary has been aggradation, not degradation. Therefore, extreme erosion by stream incision in Fortymile Wash has not taken place during the Quaternary.

3.3.3.5 Downcutting Above the Yucca Mountain Surface

Several narrow canyons exist on the land surface within the boundaries of Yucca Mountain. These canyons descend east from the main ridge of Yucca Mountain and contain small first- and second-order streams that drain into Midway Valley, which in turn drains into Fortymile Wash. The bedrock surface into which these small canyons were incised is formed of the 12.7-Ma Tiva Canyon Member of the Paintbrush Tuff (Scott and Bonk, 1984). The canyons decrease from 100 m to 60 m deep eastward, which translates into a maximum average canyon-cutting rate of about 0.8 cm/ka through bedrock.

The canyons are underlain by thin alluvial fill, generally less than 5 m thick. The fill thickens as the canyons approach the open Midway Valley. A bulldozer trench across Drill Hole Wash shows that the canyon floor is smooth and concave in cross section, and the fill is primarily composed of late Quaternary debris-flow deposits (Glancy, in press). The smooth, concave profile and lack of an incised channel into the bedrock floor demonstrates that there has not been an episode of accelerated downcutting, or extreme erosion, in later phases of the canyon's evolution.

3.3.3.6 Summary of Yucca Mountain Erosion Rates

Long-term, average erosion rates have been calculated from dated hillslope deposits. These rates range from <0.1 cm to 0.6 cm/ka (Table 5) for hillslopes in the Yucca Mountain area. Erosion rates on Yucca Mountain hillslopes are very low, averaging 0.19 cm/ka. This average rate is only this high because the erosion rate determined for the Boundary Ridge location (Table 5) is much higher than the individual rates determined from all other locations sampled. This rate is considered to be a maximum rate because *in situ* boulder deposits are found on several Yucca Mountain ridges that are well varnished and show no signs of significant movement by hillslope erosion since they were formed. The degradation rate for slopes in the Yucca Mountain area is slightly lower than for hillslopes on Yucca Mountain, averaging 0.12 cm/ka, because older deposits were found on hillslopes north and east of Yucca Mountain.

Two types of stream incision rates were calculated for the Yucca Mountain area. Minimum and maximum hypothetical downcutting rates were constructed for Fortymile Wash on the basis of stream terrace elevations above the modern channel and the total thickness of alluvium in the valley. A minimum downcutting rate is about 42 cm/ka and the maximum is 222 cm/ka. The true long-term downcutting rate for the present incised canyon is believed to be closer to the minimum rate because (1) it is highly unlikely that the wash incised to bedrock during each downcutting episode, (2) headcutting from the main wash did not migrate upstream into Yucca Mountain tributaries, and (3) the overall behavior of Fortymile Wash during the Quaternary has been aggradation, not degradation.

Several small canyons are located above the potential repository block on Yucca Mountain. Each of these canyons is cut 60-100 m into 12.7 Ma volcanic tuff and they shallow eastward toward Midway Valley into which the canyons drain. The drainage system of Fortymile Wash and its tributaries was established in Miocene time and has changed little in basic plan since then. Thus, the long-term incision rate for the first-order streams that cut the small canyons on Yucca Mountain is 0.8 cm/ka or less.

3.4 Technical Evaluation Conclusion

An unusually long Quaternary record is preserved in the Yucca Mountain landscape. The primary evidence that no extreme erosion has taken place at Yucca Mountain during the Quaternary is the fact that the Yucca Mountain landscape has changed very little during the past several hundred thousand years. The evidence for a lack of extreme Quaternary erosion includes:

1. Early and middle Quaternary hillslope and basin alluvial deposits are common, while late Quaternary deposits are generally confined to the present washes. The preservation of these deposits, which range to over 1 million years in age, indicates an unusual geomorphic stability has existed on these hillslopes and basin surfaces during the Quaternary. This stability has existed because of low rates of tectonic activity in this area and small fluctuations in climate during the Quaternary.

2. The evolution of Fortymile Wash indicates that the overall process in this drainage system during the Quaternary has been aggradation, not downcutting. The original valley floor formed during Miocene time, over 9 million years ago, has not been subsequently re-exposed by stream incision during the past few million years.

3. Temporary episodes of Quaternary downcutting in Fortymile Wash have not migrated upstream into Yucca Mountain tributaries; thus, incision on Fortymile Wash has had a very minor effect on stream incision in small canyons on Yucca Mountain.

4. Canyon cutting on Yucca Mountain has averaged only 0.8 cm/ka for the past 12 million years.

5. Erosion on Yucca Mountain hillslopes, determined by measuring degradation below dated deposits, is very low. The degradation rate for the last several hundred thousand years is measured to be 0.19 cm/ka. This rate is lower than, although comparable to, those rates measured in nearby regions. The erosion rates calculated in this report, because they are based on rock varnish surface exposure ages of the boulder deposits, are therefore somewhat overestimated.

Degradation over the whole United States ranges from 2-15 cm/ka and averages about 4 cm/ka. Degradation at Yucca Mountain is 40 times less than the average for the whole U.S. Not only has erosion not been extreme during the Quaternary at Yucca Mountain, but it has been significantly less than average.

APPENDIX A

Qualification of Data

A.1 Data Qualification Background

DOE committed to implement the appropriate staff guidance for qualifying the data. Staff guidance is presented in a Generic Technical Position, "Qualification of Existing Data for High-Level Nuclear Waste Repositories," NUREG-1298 (NRC, 1988).

Almost all of the collection and dating of samples that provide the basis for the conclusions in this report occurred prior to NRC acceptance of DOE's Quality Assurance Requirements Document (QARD) (DOE, 1990). For the purpose of data qualification, OCRWM acceptance of the Yucca Mountain Site Characterization Project participants QA programs are noted to be September 12, 1990, for the U.S. Geological Survey (USGS) and January 22, 1991, for the Los Alamos National Laboratory (LANL). Therefore, the methodologies for technical data gathering prior to acceptance of the participant QA programs were evaluated to determine whether the collection and dating methodologies used would produce results that would be significantly different than results from data gathered under the current methodologies.

A.2 Data Qualification Methodology

Established processes for qualifying data at Yucca Mountain provide for two methods: technical assessment and peer review. The technical assessment method includes provisions for review criteria which can include a determination of equivalent QA program implementation, confirmatory testing, or corroborative data. Both data qualification methods were utilized in the qualification of erosion data at Yucca Mountain.

Performance of the technical assessment was completed by a team of five professionals. Team members were chosen based upon their professional standing in the geomorphological field and/or their expertise in the high-level-waste site characterization work. None of these professionals has worked within the Erosion Study Program on Yucca Mountain except as independent reviewers of specific portions of the study.

The Technical Assessment was conducted in two phases. Phase I of the assessment consisted of reviewing the procedures that were in place during the collection and evaluation of rock varnish samples and comparing those procedures with the procedures that are currently in place under the NRC approved QA program. The purpose of this review was to determine whether there were procedural differences that were significant enough to affect the technical results of the activities. This review was performed for both principal investigators involved in data gathering and dating activities (USGS and LANL).

Phase II of the assessment consisted of an on site review of field notebooks relating to erosion studies, particularly those sections on sampling of boulders for rock varnish (cation ratio) dating. This review was performed to determine whether the technical data sample collection and evaluation process conformed to the procedures in-place during the period of collection and evaluation. Reviews of field notebooks and processes were performed for both of the principal investigators.

In addition to the reviews performed by the Technical Assessment Team, an independent peer review group of leading geomorphologists was assembled to examine the varnish cation-ratio dating technique. This Peer Review Panel concluded that the age determinations being performed by this process were the best presently being done at that time in the scientific community (Hawley et al., 1989).

A.3 Data Qualification Conclusions

A final report documenting the results of the Technical Assessment Team was issued in August 1992 (DOE, 1992). The Technical Assessment Team compared current and previous QA and Technical Procedures that control erosion data sample collection and analyses and field measurements for erosion. In addition, field and laboratory notebooks of the Principal Investigators were examined and evaluated against these procedures.

Conclusions were drawn independently by each of the team members for their part of the reviews. Questions and concerns resulting from the procedural review portion of the technical assessment (Phase I) were pursued as part of the review of the scientific notebooks (Phase II). After examining the methods and activities documented in the scientific notebooks, the Technical Assessment Team members unanimously agreed that the sampling and sample analysis processes are the same as those processes that would be performed under the current procedures in accordance with the NRC accepted QA program. Secondly, as to whether or not there were any differences that would be significant enough to affect technical results, the Technical Assessment Team concluded that the sampling and evaluation processes actually used and the consistency of repeating these processes is documented and demonstrated in the scientific notebooks and would not be significantly different than if the tests were performed today. The software package used in SEM analyses for dating of rock varnish, "SSQ" (Standardless Semi-quantitative Analysis), has been qualified by LANL under DOE's Quality Assurance Requirements Description, revision 4, document.

In conclusion, the erosion data evaluated were found acceptable to be used to support the methodologies and conclusions presented in this topical report. The quality of these data was determined to be equivalent to data collected under the current DOE and participant QA program guidelines.

APPENDIX B

Glossary

ALLUVIUM - detrital material deposited by stream flow.

ARID - as used in this report is the same as true deserts which are areas with less than 150 mm of annual precipitation and less than 10% perennial plant cover.

CLAST - An individual piece of a rock produced by the physical disintegration of a larger mass.

COLLUVIUM - heterogeneous, unsorted sediments of any particle size which accumulate on or adjacent to hillslopes.

CONTROLLED AREA - has been defined at 10 CFR 60.2 as "a surface location, to be marked by suitable monuments, extending horizontally no more than 10 kilometers in any direction from the outer boundary of the underground facility, and the underlying subsurface, which area has been committed to use as a geologic repository and from which incompatible activities would be restricted following permanent closure." For the purpose of this report, data outside of the controlled area has been considered. Throughout this report Yucca Mountain is used as the surrogate for controlled area; however, DOE has defined the strict boundary to lie 5 kilometers from the outer boundary of the underground facility consistent with the 10 CFR 60.2 definition. This boundary is shown on Figures 1 and 2.

DENUDATION - is the laying bare, uncovering, or exposure of bedrock or a designated rock formation through the removal of overlying material by erosion. The term is wider in its scope than erosion, although it is commonly used as a synonym of that term. Some authorities regard 'denudation' as the actual process and 'degradation' as the results produced.

EROSION - the loosening and transporting of rock debris at the Earth's surface, aptly described as the wearing away of the land.

ESCARPMENT - is a cliff or steep slope of some extent, generally the edge of a plateau or the steep face of an asymmetrical ridge. Escarpments, or scarps, may be produced by faulting, erosion, or sapping of less resistant underlying strata to create cliffy rock faces in massive layers above, as on the walls of the Grand Canyon of the Colorado River. Given the geomorphologic setting at Yucca Mountain, the term hillslope is a synonym for escarpment.

FLUVIAL - is described as an activity relating to running water in streams. Fluvial erosion is the erosion and transportation of geologic materials by running water. Erosion and transportation by running water are intensified by the topographic relief resulting from uplift. Running water is the most important of all the processes which fashion the landscape. Water flowing in streams is responsible for carving most of the valleys of the continents.

FULL-GLACIAL - a widely used synonym for the Wisconsin maximum (Spaulding, 1985). This term is descriptive of a time period or climate that characterized conditions during a maximum advance of the continental glaciation in North America. Yucca Mountain was not glaciated at any time during the Quaternary Period.

GEOMORPHOLOGY - the science that treats the general configuration of the earth's surface: specifically, the study of the classification, description, nature, origin, and development of present landforms, their relationships to underlying structures, the processes by which they are formed or modified, and of the history of geologic changes as recorded by these surface features.

INTERFLUVE - the area between drainage channels; especially the relatively undissected upland between adjacent drainage channels flowing in the same direction.

NIVATION - the process of excavation of a shallow depression in a mountainside by removal of fine material around the edge of a shrinking snow patch or snowbank, chiefly through freeze and thaw activity, sheetwash, rivulet flow, and solution in meltwater.

PLUVIAL - a climate characterized by relatively high precipitation, or of the time interval during which such a climate prevailed. Also considered a geologic episode, change, process, deposit, or feature resulting from the action or effects of rain. The term includes the fluvial action of rainwater flowing in a stream channel, especially in the channel of an ephemeral stream. It also describes any one of several wetter intervals during the Quaternary Period when precipitation was greater and evapotranspiration was less.

QUATERNARY - the second period of the Cenozoic Era, following the Tertiary. It began approximately 1.6 million years ago and extends to the present. It consists of two epochs: the Pleistocene, up to about 10,000 years ago and the Holocene since that time (see Table 1).

RECENT (HOLOCENE) - an Epoch of the Quaternary Period, from the end of the Pleistocene, approximately 10,000 year ago, to the present time (see Table 1).

ROCK (DESERT) VARNISH - a thin dark shiny film or coating, composed principally of iron and manganese oxide that incorporates quantities of silica and clay minerals, formed on the surfaces of pebbles, boulders, and other rock fragments in desert regions after long exposure, as well as on ledges and other rock outcrops.

SCARP - see escarpment.

SEMIARID - as used in this report is characterized as more than 150 mm of annual precipitation and less than 500 mm annual precipitation, and greater than 10 % perennial plant cover. The area surrounding Yucca Mountain is considered to be a dry-semiarid environment.

SLOPE RETREAT - generic term for overall hillslope erosion by all processes; the response of a slope to erosional processes.

TERTIARY - the first period of the Cenozoic Era (after the Cretaceous Period of the Mesozoic Era and before the Quaternary), thought to have covered the span of time between 65 and approximately 1.6 million years ago (see Table 1).

APPENDIX C

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